2016

Calumet Harbor – Bedrock Removal to Authorized Depth

Appendix C of Draft EA

Supporting Documents & Information

Lake County, IN
Cook County, IL

July 2016

US Army Corps of Engineers ®
Chicago District

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CECW-EG

ETL 1110-8-11(FR)

Technical Letter
No. 1110-8-11(FR)

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Engineering and Design
UNDERWATER BLAST MONITORING

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Engineering and Design
UNDERWATER BLAST MONITORING

1. Purpose, Scope, and Applicability

a. This ETL describes criteria for predicting blast effects from detonations in water and instrumentation techniques for monitoring such effects. The information presented here applies to all HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities concerned with Civil Works.

b. The purpose of this ETL is to assist USACE Commands in the intelligent use of underwater blast monitoring to prevent damage or injury to nearby structures, equipment, or aquatic life from water shock effects. Rock blasting in lake or river bottoms will produce a combination of ground and water shock effects. Blast monitoring the ground shock effects is addressed in references ETL 1110-2-142 and "The Modern Technique of Rock Blasting," (see paragraph 2c and 2g, p. 1). These references should be used in conjunction with this ETL to develop a comprehensive monitoring program. Some items that are of concern during underwater blasting are: gates, structures, boats, fish, fish eggs, etc. Damage or injury thresholds for these items are difficult to quantify or are not readily available. These damage thresholds must be set or assumed by the user.

2. References

a. ETL 1110-1-142. "Blasting Vibration Damage and Noise Prediction and Control."

b. Armstrong, B. J. 1979 (Mar). "Destruction of Bridge Decking With Explosion-Produced Water Plumes," Miscellaneous Paper SL-79-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

c. Cole, Robert H. 1948. "Underwater Explosions," Dover Publications, Inc., New York, NY.

d. Hendry, Debra K., and Welch, Charles R. "Water Shock from a Surface-Flush Explosion Over a Silty-Clay Bottom" (to be published 1991), US Army Engineer Waterways Experiment Station, Vicksburg, MS.

e. Johnson, Stanley M. 1971. "Explosive Excavation Technology," NCG TR 21, US Army Engineer Nuclear Cratering Group, Livermore, CA.

f. Keevin, T. M., Hempen, G. L., Nico, L. G., and Schaeffer, D. "The Use of a Bubble Screen Curtain to Reduce Fish Mortality Resulting from Underwater Explosions" (to be published 1991), North American Journal of Fisheries Management.

g. Langefors, U., and Kihlstrom, B. 1978. *The Modern Technique of Rock Blasting*, Halsted Press, Wiley, New York, NY.

h. Miller, L., Strange, J. N., and Pinkston, J. M. 1971 (May). "Water Shock Reflection Properties of Various Bottom Materials - Final Report - Volume 1: Main Text," Technical Report 1-704, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

i. Petes, J., Miller, R., McMullan, R. 1983 (Mar). "User's Guide and History of ANFO as a Nuclear Weapons Effect Simulation Explosive," Defense Nuclear Agency, Washington, DC.

j. Strange, J. N. 1963 (Jan). "The Attenuating Effects of a Bubble Screen on Underwater Shock," Miscellaneous Paper 2-553, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

k. Swisdak, Michael M., Jr. 1975 (Oct). "Explosion Effects and Properties, Part 1 - Explosion Effects in Air," NSWC/NOL/TR 75-116, White Oak Laboratory, Naval Surface Weapons Center, White Oak, MD.

l. Tussing, Ronald B. 1982 (Jul). "Accuracy and Response of Tourmaline Gages for Measurement of Underwater Explosion Phenomena," NSWC TR-82-294, Naval Surface Weapons Center, White Oak, MD.

3. Water Shock Characteristics

a. Water shock generated by an underwater detonation of high explosives travels at a speed of about 5,000 ft/sec for pressure levels less than 30,000 psi (Cole 1948). In shallow water, the disturbance is characterized by the arrival of four principal waves (see Figure 1): (1) an exponentially-decaying, direct wave from the explosive source, (2) a surface-relief wave (tensile image of the direct wave), (3) a bottom-reflected wave, and (4) a wave transmitted through the bottom materials and radiated back into the water (Miller, Strange, and Pinkston 1971). The effect of these different waves on the resultant pressure history is shown schematically in Figure 2. The resultant pressure-time history is the time-phased superpositioning of the direct, surface relief, reflected, and refracted pressure waves at a point.

b. For shot geometries where the water surface and bottom are far removed from the explosion source and measuring locations, the direct wave is the predominant factor.

c. For a TNT explosive, the amplitude of the direct wave can be estimated from the graph shown in Figure 3 (Cole 1948), in which the abscissa is in units of "scaled" range ($R/W^{1/3}$), where R is in feet and W is the explosive weight in pounds. The water shock impulse (time integral of the pressure history) for the direct wave from a TNT explosive source can be estimated from the graph shown in Figure 4. The ordinate in Figure 4 is in units of "scaled" impulse ($I/W^{1/3}$), where I is in pounds per square inch-seconds. Table 1 provides approximate conversion factors for converting several common explosives to an equivalent weight of TNT. If the actual value of the equivalency factor is unknown, an upper estimate value of 2.0 will cover most common explosives (i.e., 1 lb of explosive is equivalent to no more than 2 lb of TNT).

d. The approximate value of the water shock pressure (in pounds per square inch), as a function of time (t, in sec), for the direct wave is described in Cole (1948) as:

$$P(t) = P_m e^{-\left(\frac{t - t_a}{\theta}\right)} \tag{1}$$

Where P_m, the peak pressure (in psi) is

$$P_m = 21{,}600(\lambda)^{-1.13} \tag{2}$$

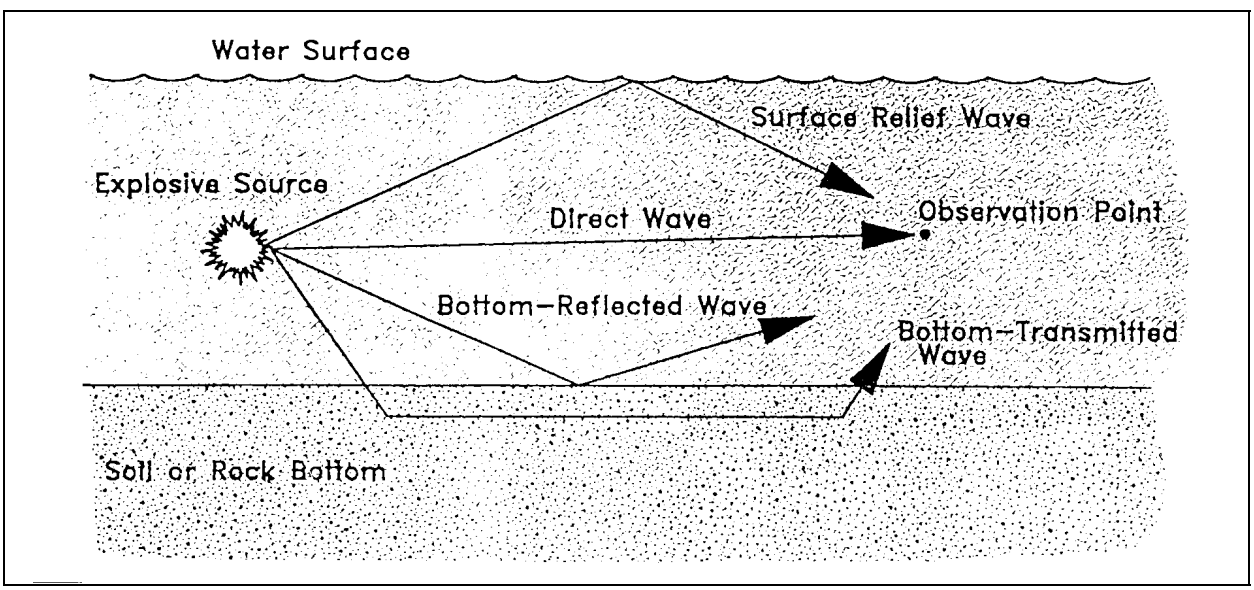

Figure 1. Four principal waves associated with shallow-water explosions

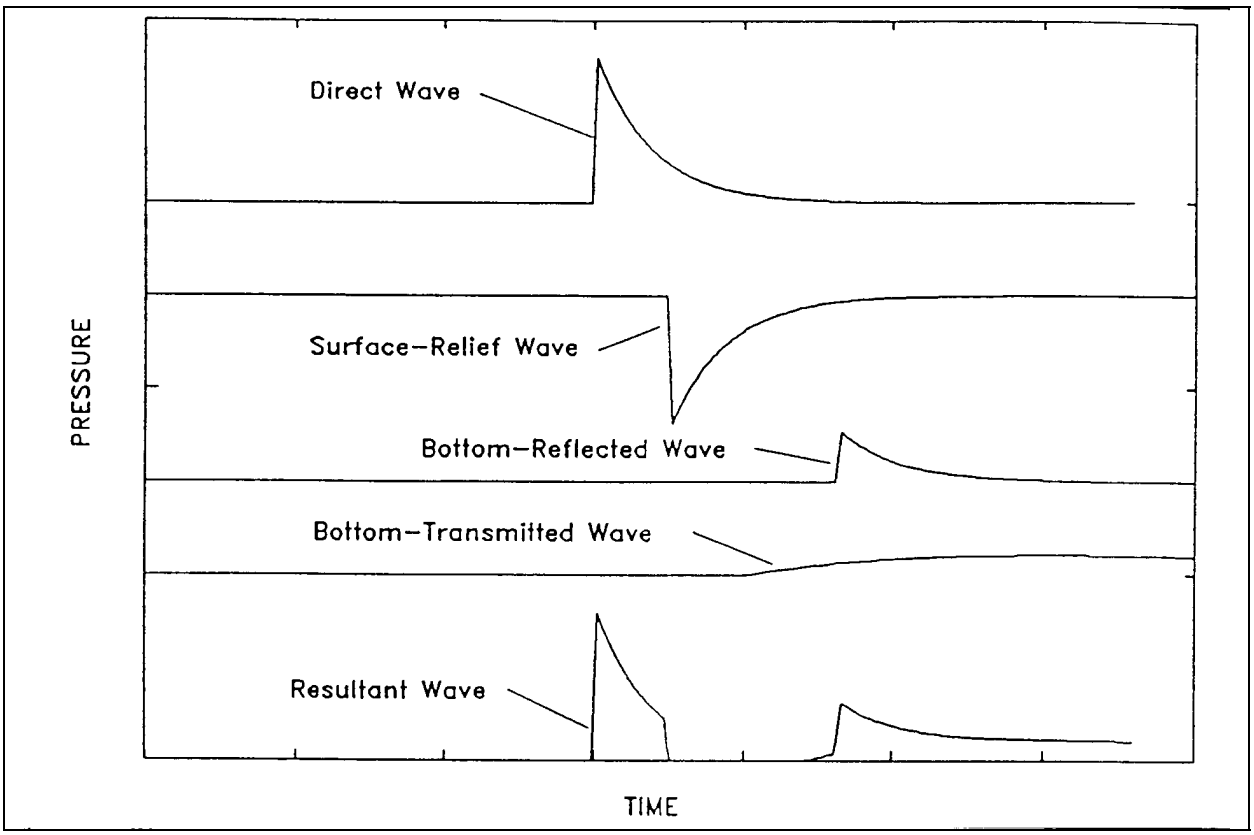

Figure 2. Effects of different wave components on the water shock measured at a point

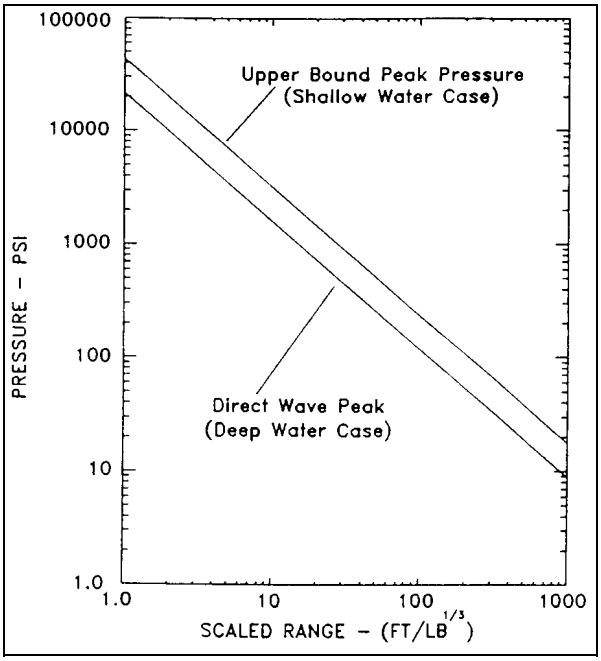

Figure 3. Peak pressure as a function of scaled range for the direct wave from a TNT explosion

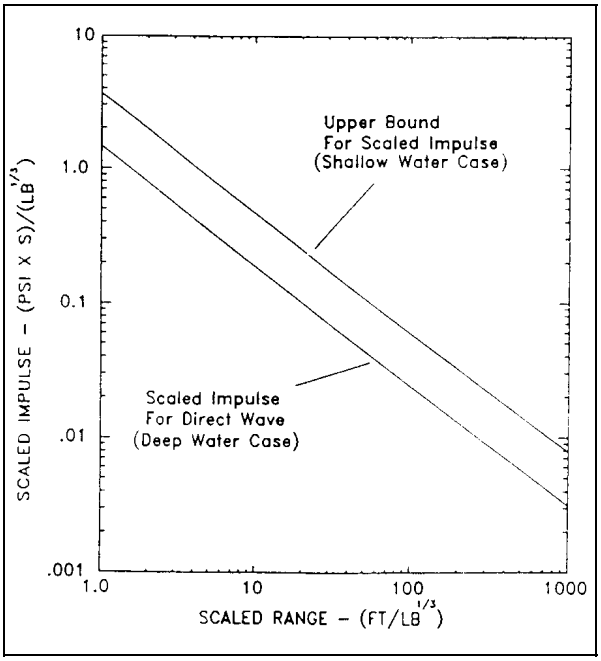

Figure 4. Scaled impulse from the direct wave from a TNT explosion

Table 1
Approximate TNT Conversion Factors for Selected High Explosive

Explosive	Approximate Conversion Factor by Weight for Pressure
TNT	1
Nitromethane	1.1[1]
Pentolite	1.04[2]
ANFO	0.3-0.82[3]
C-4	1.37[4]
Ammonia Dynamite	0.7-0.9[4]
Gelatin Dynamite	0.7-0.8[4]
Nitroglycerin Dynamite	0.9[4]

[1] Hendry and Welch (to be published 1991).
[2] Cole (1948).
[3] Dependent on percent fuel oil; factors estimated based on energy content taken from Petes, Miller, and McMullan (1983).
[4] Estimate based on airblast data and energy content (Swisdak 1975).

θ, a time constant (in sec), is

$$\theta = 6.0 \times 10^{-5} \; W^{1/3}(\lambda)^{0.18} \tag{3}$$

t_a, the shock arrival time (in sec) at the point of interest, is

$$t_a = R/5{,}000$$

and λ is the scaled range (in ft/$W^{1/3}$), where W is the explosive weight (TNT equivalent (in lb)).

The water shock impulse at a scaled range of λ is

$$I(t) = 1.46 \times W^{1/3}(\lambda)^{-0.89} \tag{4}$$

e. The effect of the relief wave on the direct signal will be to shorten abruptly the duration of the pressure history seen at the point of interest. The effect of the bottom-reflected and bottom-transmitted waves, for most bottom materials, will be to increase the pressure history duration.

f. Approximate upper bound estimates for the peak pressures and impulses generated by the presence of all four of these wave components is shown in Figures 3 and 4. Upper bound limits of pressure and impulse can also be approximated by multiplying the value obtained from Equation 2 by 2.0, and that obtained from Equation 4 by 2.5 (from Miller, Strange, and Pinkston 1971). Note that, because of the interaction of the direct wave with the surface relief wave, actual peak pressures and impulses for shallow-water explosions can be a factor of 10 less than those given by Equations 2 and 4. Since variations in water depth can strongly affect the water shock levels produced, especially at long ranges from a detonation, it is important to monitor the actual pressure and impulses generated by the explosive activities.

g. Significant secondary pressure pulsations can be caused by the rapid, repeated collapse and expansion of the explosion gas bubble in deep water. The peak pressures produced by these pulsations are less than 20 percent of the direct pulse. However, because the pulsations are of much longer duration, their associated impulse can be a factor of 4 larger than the impulse associated with the direct wave (Cole 1948).

h. Water shock levels can be significantly reduced by the use of bubble screens between the area to be protected and the explosion source. This mechanism has been studied to prevent fish kills and structural damage to nearby marine structures (Strange 1963, Keevin et al., to be published 1991). Reductions of peak pressures by a factor of 5 have been observed. The reduction mechanism appears to be two-fold: (1) the initial part of the direct wave is strongly attenuated by the bubble screen, and (2) the remaining portion of the direct wave is slowed down so that the surface relief wave can catch up and reduce the effect of the direct wave.

i. Care must also be taken to avoid nuisance damage from airblast generated by the detonation of a high explosive charge in shallow water. Figure 5 (from Swisdak 1975) provides isopressure contours of the airblast generated by underwater explosions as a function of scaled depth ($D/W^{1/3}$), scaled range ($R/W^{1/3}$), and at a constant scaled height above the water surface of 0.25 ft/lb$^{1/3}$. In all cases, the charge should first be converted to its TNT equivalency before scaling. The airblast data is available only down to 0.25 psi. Because of scatter in the airblast data used in constructing the isopressure contours, the contours are considered accurate only within plus or minus 30 percent. Table 2 (Johnson 1971) provides anticipated damage caused by airblast at various overpressure levels.

j. The water plume created by underwater explosions can be quite destructive to overhead structures; so much so, in fact, that the water plume is one mechanism recommended for military use in bridge demolition (Armstrong 1979). Special attention must be paid to this risk when overhead structures exist in the vicinity of underwater detonations.

4. Water Shock Monitoring Equipment

a. Water shock pressures at a point of measurement are equal in all directions (i.e., they are hydrodynamic). Thus, the orientation of a water shock pressure gage is not important. The tourmaline crystal pressure gage is the preferred transducer for measuring water shock pressure because of its proven reliability and accuracy, ease of use, high-frequency response, and low sensitivity to temperature effects (Cole 1948, Tussing 1982). Tourmaline crystal is piezoelectric, which enables it to convert pressure (force per unit area) to electric energy. It should be noted, however, that piezoelectric crystals, are not able to detect static or very slowly changing pressure levels.

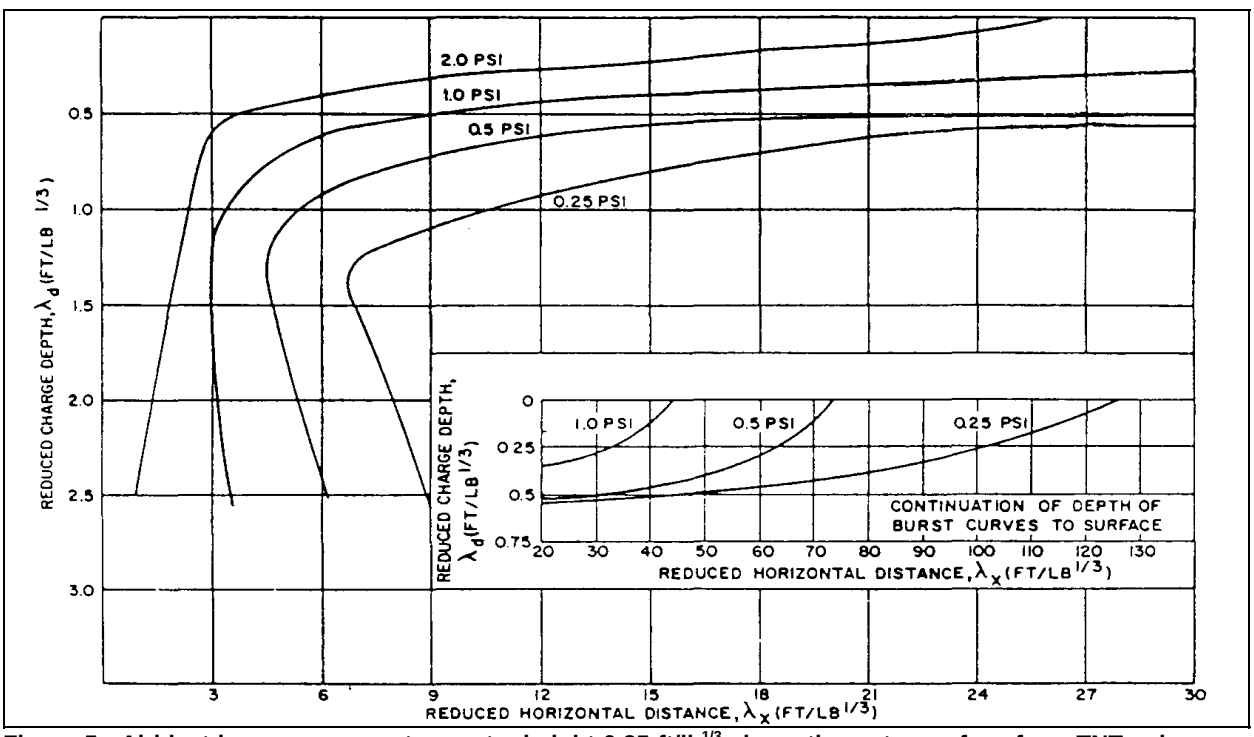

Figure 5. Airblast isopressure contours at a height 0.25 ft/lb$^{1/3}$ above the water surface from TNT spheres fired at various scaled depths (from Swisdak 1975)

Table 2
Airblast Damage Criteria (Johnson 1971)

Overpressure (psi)	Degree of Estimated Damage
0.029	Possible window damage, particularly to large store windows
0.044	Some damage to large plate glass windows can be expected
0.065	Some damage to average size windows can be expected
0.19	Extensive damage to windows; probably damage to average wooden doors
0.58	Most small casement windows smashed
>0.58	Structural damage possible

b. Tourmaline crystal water shock gages can be manufactured, purchased commercially (e.g. PCB Piezotronics, Inc.), or sometimes acquired via government sources (e.g. Naval Surface Weapons Center, US Army Engineer Waterways Experiment Station). In all cases, the tourmaline must be encapsulated in an insulating material to prevent the generated charge from bleeding into the surrounding water. The encapsulating material should have an acoustic impedance (sound speed times density) as close as possible to water to minimize distortion of the pressure measurements. It is extremely important that the encapsulating material have a high dielectric constant and not generate charge when stressed. This would cause errors in the measurements. One method of construction which satisfies these requirements is to use a tygon or PVC boot filled with silicone oil (Figure 6) to encapsulate the tourmaline crystal (Tussing 1982).

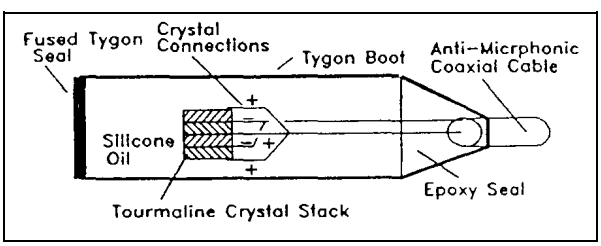

Figure 6. Four-stack tourmaline crystal water shock pressure gage employing tygon boot filled with silicone oil

c. The amount of charge developed by the gage, the gage sensitivity, is directly proportional to the area of the tourmaline crystal being loaded. Tourmaline crystals used for water shock measurements range from 1/8 to 2 in. in diameter . The diameter of the crystal selected is a compromise between choosing one that is physically small (gage transit time small relative to shock duration) but large enough to provide adequate electrical output for the recording system. A rule of thumb to estimate the error in the peak measured pressure due to the gage transit time *Td*, for θ/Td ratios > 5 is given by (from Tussing 1982):

$$\%\ \text{peak error} = \frac{0.5Td}{\theta} \times 100\% \qquad (5)$$

d. The equation applies to cases in which the amplitude of the direct wave is not affected by surface-relief or bottom-reflected waves during the engulfment time of the gage. The effect of the error is to cause the measured peak pressures to be below the actual peak pressures. The engulfment time, *Td*, of the gage is the gage diameter divided by the wave velocity in water (5,000 ft/s). "Theta" is given by Equation 3. For gages using the silicone fluid as the encapsulating material around the gage, the calculated transit time should be increased by 50 percent (Tussing 1982).

e. Tourmaline crystals are often stacked together and connected in a parallel network to increase the sensitivity of the gage without increasing the diameter of the gage (Figure 6). Typical gage sensitivities range from 2.5 picocoulombs per psi for a 1/4-in.-diam doublet crystal gage, to 90 picocoulombs per psi for an eight-stack pile of 1-1/8-in.-diam crystals (Cole 1948).

f. Most water shock gages used in the past, and those presently in use by the US Navy, employ tourmaline gages connected by coaxial cable to the associated signal conditioning, amplifying, and recording systems. Tourmaline crystal water shock gages employed in this manner are high-impedance devices. As such, they are not compatible with normal low-impedance instrumentation amplifier circuits. To achieve compatibility, the high-impedance gage is coupled to the low-impedance amplifier through a charge amplifier or impedance converter. These are available from several commercial sources. The charge amplifier or impedance converter is placed as near as possible to the gage to reduce the length of the connecting cable. However, the connecting cable can be several hundred feet long for the impedance converter and possibly 1,000 to 2,000 ft long in the case of the charge amplifier.

g. Water shock measurements of this type are particularly susceptible to two noise sources: (1) that induced by low-circuit resistance to ground (gage and cable in contact with the water), and (2) water shock-induced cable noise.

h. Care must be taken to ensure that the electrical resistance between the water shock transducer circuit (gage and connecting cable) is as high as possible to limit system background noise. Electrical resistance to ground and across the tourmaline crystal should be 10,000 M ohms or greater. Circuits submersed in water with low resistance to ground pick up stray electrical noise from the surroundings and are susceptible to noise from electrical energy given off by the detonation of the explosive charge. Leakage across the crystal produces drift in charge amplifiers and degraded low-frequency response in impedance converters.

i. Coaxial cables used to connect the tourmaline water shock gages to the charge amplifier should be antimicrophonic or "low noise" cable. Standard coaxial cable generates electrical noise when subjected to the high-shock environment which exists in water near a detonation. Antimicrophonic coaxial cable has graphite between the outer shield and the inner insulator. This greatly reduces the amount of charge generated on the cable due to water shock.

j. Figure 7 is an idealization of a tourmaline gage connected to a charge amplifier via a coaxial cable. The RC-time constant for the circuit is determined by the electrical resistance across the crystal in

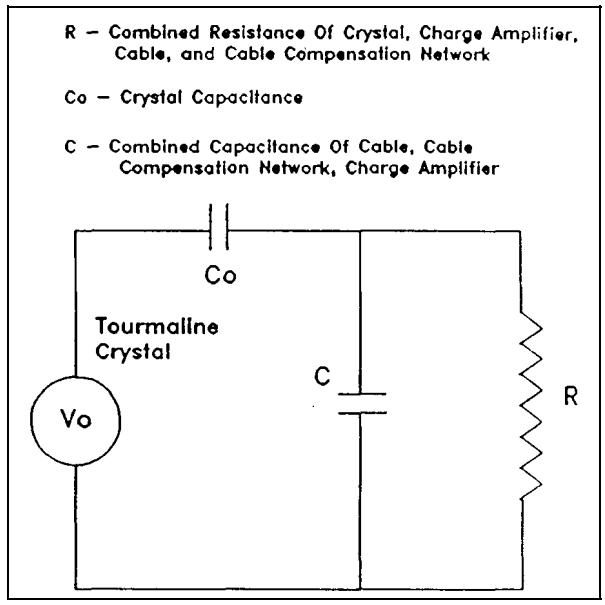

Figure 7. Idealization of circuit components which determine RC-time constant of tourmaline gage

parallel with the input impedance of the charge amplifier, the combined capacitance of the crystal and the coaxial cable in parallel, and cable compensation networks. The RC-time constant is the time it takes for the voltage from the gage due to a suddenly applied hydrostatic pressure to fall to 1/e = 0.368 of its maximum value. Thus, the larger the RC-time constant the better the low-frequency response of the gage. RC-time constants of several seconds are possible with proper precautions (Cole 1948).

k. To determine the calibration factor, *KA*, in picocoulombs per pounds per square inch, for the tourmaline water shock gage, a dynamic pressure environment is desirable but usually not practical. The calibration method normally adopted, providing the RC-time constant of the gage and calibration circuit is long enough, is to statically pressurize the gage to some desired pressure, and then quickly release the pressure (Cole 1948).

l. An electrical calibration, which takes into account amplifier gain settings and other attributes of the electrical circuit that is connected to the gage, must also be performed. The standard technique is the "Q-step" calibration circuit shown in Figure 8 (from Cole 1948). If a voltage, V_s, is applied to the capacitor, C_s, then the resulting voltage, V_c, at the open end of the circuit is given by:

$$V_c = \frac{C_s V_s}{C + C_o + C_s} \tag{6}$$

where C is the capacitance of the cable and C_o is the capacitance of the gage. The voltage, V_p, produced by an applied pressure P to the gage is then given by:

$$V_p = P\left[\frac{V_c(KA)}{C_s V_s}\right] \tag{7}$$

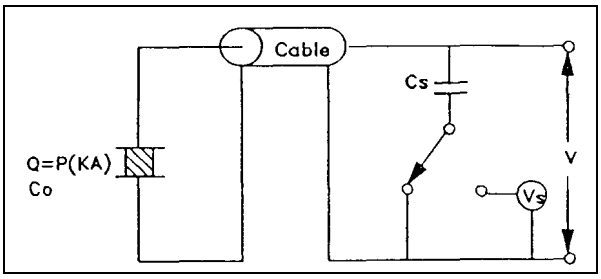

Figure 8. "Q-step" calibration circuit (from Cole 1948)

m. A potential problem which exists for very high-frequency, short duration water shock measurements is "ringing" or oscillation of the electrical signal in the coaxial cable. Circuit ringing manifests itself as oscillations in the signal output. Proper termination of both ends of the coaxial cable with capacitor/resistor networks, as shown in Figure 9,

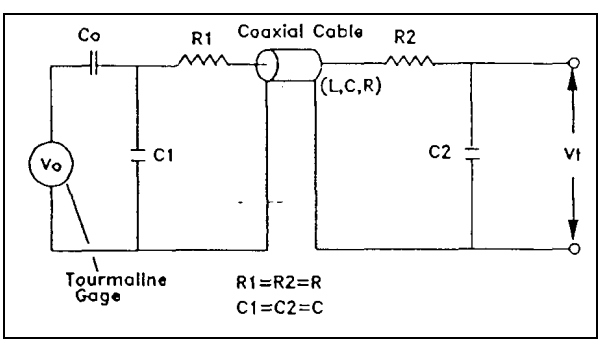

Figure 9. Schematic showing cable compensation network *R*1, *R*2, *C*1, and *C*2 which minimizes circuit ringing (from Cole 1948)

prevents this oscillation while still providing acceptable frequency response (from Cole 1948). If L is the total distributed inductance of the cable (i.e., the inductance per unit length times the total cable length), and C is the total distributed capacitance of the cable, then the "surge" resistance, $R0$, is defined to be:

$$R0 = \sqrt{LC} \tag{8}$$

n. In Figure 9, $R1$ and $R2$ are made to be approximately equal to the "surge" resistance $R0$ of the cable, and the capacitors $C1$ and $C2$ are equal to the distributed capacitance, C, of the cable.

o. Some commercial water shock gages (e.g. PCB Piezotronics, Inc.) have in-line impedance converters built into the gage housing. This eliminates the need for low-noise cable, reduces the requirements for high impedance between the cable and the water, and eliminates the need for charge amplifiers. These types of instruments are more convenient than the older circuits. They also usually do not have as good a low-frequency response as the tourmaline crystals connected via properly handled coaxial circuits to a charge amplifier. There appears, however, to be no intrinsic reason why the commercial gages could not be configured to have longer RC-time constants.

p. Although high cable insulation (>100 M ohms) is not required for the commercial gages, care must be taken not to allow moisture contamination of the cable and gage. If this occurs, then the recorded pressure histories will fall off more rapidly than the actual phenomena. Another symptom is the recording, during part of the pressure history, of apparent negative pressures below the combination of atmospheric and hydrostatic pressures of the overlying water.

q. The "Q-step" method is not used to provide an electrical calibration of the transducer circuit when using tourmaline crystal gages with the in-line impedance converters. Instead, the manufacturer provides a calibration constant, in terms of pounds per square inch per volt of gage output, which takes into account the characteristics of the tourmaline crystal and the charge amplifier (assuming proper power is provided to the in-line amplifier). For this situation, a known voltage step is normally applied to the input to the recording system and used as a calibration step or scale. A signal generator, available from the manufacturer, is used to simulate the water shock gage and validate the signal amplifying system. To provide proper circuit dampening, a series resistor

is used between the gage and power supply. Rise-times of 2 to 3 µsec have been achieved with cable lengths of l,000 ft between gage and amplifier.

r. Amplifier and recording systems selected to record water shock induced pressures, for both the basic tourmaline crystal gage and the tourmaline crystal gage with in-line impedance matching circuit, should have sufficient sensitivity to provide a low signal-to-noise ratio for the recorded pressure-time history.

s. System frequency response is limited by the frequency response of the individual components of the system. Piezo-electric gages and properly terminated coaxial cables, in general, pass higher frequencies than amplifiers and recording systems. Therefore, care must be taken to ensure that the amplifiers and recording system have sufficient frequency response to reliably record the phenomena. The smaller the explosive charge or the closer the free surface of the water to the measurement, the shorter the duration of the water shock pulse. For example, water shock pressure measurements from a 10-lb TNT equivalent explosive charge in 4 ft of water at a 32.5-ft range show pressure durations of the initial pulse in the order of 20 µsec (Hendry and Welch, to be published 1991). From a practical stand point, instrumentation amplifiers with 5-percent down points of 50 to 100 khz are readily available.

t. A variety of recording systems exist for storing the measured electrical records from water shock gages. FM magnetic tape machines offer acceptable frequency response (80 Khz) and provide extended record times (minutes) so that the sequencing of tape machine turn-on and explosive charge detonation presents little problem.

u. Digital transient recorders operating at a minimum of 500,000 samples a second, with 12-bit accuracy, offer better resolution than tape recorders as well as ease of data handling with computers. These systems, however, record for much less time (generally from 16,000 to 256,000 data points, or 32 to 512 msec) than tape machines, and the sequencing between charge detonation and data capture is more critical.

v. Digital oscilloscopes usually have lower data resolution (8-bit) but have higher frequency response (several megasamples per second) than the transient recorders.

w. Analog storage oscilloscopes, or analog oscilloscopes with photographic capture, provide frequency response into the 100's of megahertz, but have much worse signal amplitude resolution than the digital recording systems. Similar to the digital recording systems, the sequencing of data capture is critical with the oscilloscopes.

FOR THE DIRECTOR:

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THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS WITH METHODS TO MITIGATE IMPACTS

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August 1997

ACKNOWLEDGEMENTS

Preparation of this manual and the original research that made parts of this possible were funded by the LEGACY Program and by the St. Louis District, U.S. Army Corps of Engineers.

We owe a special note of thanks to Dr. David Schaeffer (University of Illinois) who was extremely helpful in the development of study designs, statistical analysis, and publication of reports. Dr. Schaeffer participated in much of the original research effort.

We appreciate the assistance of the St. Louis District Library, Arthur Taylor (Director), Sandra Argabright, Phyllis Thomas and Hazel Schnatzmeyer. They were given the task of obtaining hundreds of reports and publications, most very obscure.

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INTRODUCTION

In- or near-water use of explosives (i.e., construction or demolition projects; ordinance testing and disposal; as well as, harbor maintenance projects; and use of explosives during training exercises) can adversely affect significant aquatic ecosystems or organisms. Many of the potential environmental problems associated with use of explosives in aquatic environments are unique to the Department of Defense (i.e. ordinance testing & training). The literature on blasting effects is obscure and would be difficult to gather in a timely fashion by environmental planners and resource managers attempting to practice good stewardship of Department of Defense managed water resources. The goal of this manual is to provide resource planners/managers with information, which allow quick assessments of potential problems associated with underwater explosive use.

This handbook summarizes available literature (e.g., published, state and Federal reports) on the environmental effects of underwater explosions and provides information on the potential use of mitigative strategies to reduce impacts to significant biological systems and species. Chapter 1 outlines natural resource agency concerns and regulatory authority concerning explosive use. Chapter 2 provides information concerning explosives, the physics of explosions, and how explosives react in various media. It is not the intent of this chapter to provide an exhaustive review of the physics of explosions. We have attempted to provide enough information to make the chapters on environmental effects more understandable. The effects of underwater explosions on aquatic plants (Chapter 3), aquatic invertebrates (Chapter 4), fish (Chapter 5), amphibians and reptiles (Chapter 6), aquatic mammals (Chapter 7) are reviewed. Chapter 8 provides information on mitigation techniques to reduce adverse environmental effects of underwater explosions.

A user-friendly computer program with users manual for planners/managers which allows quick assessments of potential environmental problems is also being developed under this LEGACY project. The computer program will provide impact analysis (kill radius for fish) based on the amount, depth, and use (open-water versus confined blast) of the explosive being detonated.

There is a considerable amount of research on the environmental effects of underwater explosions still in progress by the authors. In addition, the authors have established a Natural Resources Working Group within the International Society of Explosives Engineers to tackle some of the outstanding questions in this field, such as standardization of pressure transducer calibration, standardization of pressure measurement and reporting, standardization of experimental designs for mortality assessment, and identification of data gaps and prioritization of data collection needs. As such, this manual should be considered a working document. If you have any comments or questions, please feel free to contact the authors. Dr. Thomas Keevin is an Aquatic Ecologist and Dr. Gregory Hempen is a Geophysical Engineer.

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REFERENCES CITED

Alperin, L. M. 1967. Marine fisheries and geophysical exploration-a review. Massachusetts Department of Natural Resources Publication No. 646.

American Fisheries Society 1982. Monetary values of freshwater fish and fish-kill counting guidelines. American Fisheries Society Special Publication 13. American Fisheries Society, Bethesda, MD.

American Fisheries Society. 1992. Investigation and valuation of fish kills. American Fisheries Society Special Publication 24. American Fisheries Society, Bethesda, MD.

American Fisheries Society. 1993. Sourcebook for investigation and valuation of fish kills. Supplement to American Fisheries Society Special Publication 24. American Fisheries Society, Bethesda, MD.

Anonymous. 1948. Effects of underwater explosions on oysters, crabs and fish. Chesapeake Biological Laboratory, Publication No. 70, pp. 1-43.

Anonymous. 1962. Tests to investigate effects of seismic explosions on flatfish and crabs. Oregon Fish Commission Report, Portland, Oregon.

Anonymous. 1978. Seismic primacord as an energy source. Technical bulletin of Primacord Seismic Services, Inc. Houston, Texas.

Aplin, J. A. 1947. The effect of explosives on marine life. California Fish and Game 33:23-30.

Atlas Powder Company. 1990a. Atlas Powder Company data sheet: APEX AND APEX PLUS. ICI Explosives, London, England.

Atlas Powder Company. 1990b. Atlas Powder Company data sheet: PELLITE/PELLITE HD. ICI Explosives, London, England.

Ayme-Bellegarda, E. J. 1990. Collapse and rebound of a gas-filled spherical bubble immersed in a diagnostic ultrasounic field. Journal of the Acoustical Society of America 88:1054-1060.

Baldwin, W. J. 1954. Underwater explosions not harmful to salmon. California Fish and Game 40:77.

Baxter, L. II, E. E. Hays, G. R. Hampson, and R. H. Bachus. 1982. Mortality of fish subjected to explosive shock as applied to oil well severance on Georges Bank. Woods Hole Oceanographic Institution Technical Report WHOI-82-54.

Bellrose, F. C., F. L. Paveglio and D. W. Steffeck. 1979. Waterfowl and the changing environment of the Illinois River Valley. Illinois Natural History Survey Biological Notes 32:4-6.

Bjarnholt, G. 1980. Suggestions on standards for measurement and data evaluation in underwater explosion test. Propellants and Explosives 5:67-74.

Bottin, R., Jr., and D. G. Outlaw. 1987. Explosion-generates waves in shallow water. Coastal Engineering Research Center. Report CERC-87-13. Waterways Experiment Station. Vicksburg, MS. 53p.

Brinkmann, J. R. 1990. An experimental study of the effects of shock and gas penetration in blasting. Pp. 55-66. In: Third International Symposium on Rock Fragmentation by Blasting, Brisbane, Australia.

Brower, J. S. 1977. Guide to Underwater Explosive Excavation. J.S. Brower & Associates, Inc., Ponoma, CA. 106 p.

Brown, C. L., and R. H. Smith. 1972. Effects of underwater demolition on the environment in a small tropical marine cove. U. S. Naval Underwater Systems Center, Norfolk, Virginia. Technical Report 4459. 19 p.

Brown, F. A. 1939. Responses of the swimbladder of the guppy, Lebistes reticulates, to sudden pressure decreases. Biological Bulletin 76:48-58.

Cairns, S. D., D. R. Calder, A. Brinckmann-Voss, c. B. Castro, P. R. Pugh, C. E. Cutress, W. c. Japp, D. G. Fautin, R. J. Larson, G. R. Harbison, M. N. Arai, and D. M. Opresko. 1991. Common and scientific names of aquatic invertebrates of the United States and Canada: Cnidaria and Ctenophora. American Fisheries Society Special Publication 22. American Fisheries Society, Bethesda, MD.

Cameron, G. R., R. H. D. Short, and C. P. G. Wakeley. 1944. Abdominal injuries due to underwater explosion. British Journal of Surgery 31:51-66.

Clark, S. L., and J. W. Ward. 1943. The effects of rapid compression waves on animals submerged in water. Surgery Gynecology and Obstetrics 77:403-412

Christian, E. A. 1973. The effects of underwater explosions on swim-bladder fish. Technical Report NOLTR-73-103. Naval Ordnance Laboratory, White Oak, Silver Springs, MD.

COASTLINE Environmental Services Ltd. 1986. Operator's manual and guidelines for use of a predictive model (IBLAST) to determine the effects of underwater explosive detonations to fish in shallow water areas. Prepared for Department of Fisheries and Oceans, Habitat Management Division, Vancouver, B.C.

Coker, C. M., and E. H. Hollis. 1950. Fish mortality caused by a series of heavy explosions in Chesapeake Bay. Journal of Wildlife Management 14:435-444.

Cole, R. H. 1948. Underwater Explosions. Princeton University Press, Princeton, NJ. 437 p.

Dick, R. A., D. V. D' Andrea, and L. R. Fletcher. 1993a. Back to basics: Properties of explosives. Journal of Explosives Engineering 10(6):28-30, 33-35, 43, 45.

Dick, R. A., D. V. D' Andrea, and L. R. Fletcher. 1993b. Back to basics: The chemistry and physics of explosives. Journal of Explosives Engineering 10(5):33-36, 38-41.

Domenico, S. N. 1982a. Acoustic wave propagation in air-bubble curtains in water-Part I: History and theory. Geophysics 47:345-353.

Domenico, S. N. 1982b. Acoustic wave propagation in air-bubble curtains in water-Part II: Field experiments. Geophysics 47:354-375.

Dunning, D. J., Q. E. Ross, P Geoghegan, J. J. Reichle, J. K. Menezes, and J. K. Watson. 1992. Alewives avoid high-frequency sound. North American Journal of Fisheries Management 12:407-416.

Duronslet, M. J., C. W. Caillouet, S. Manzella, K. W. Indelicato, C. T. Fontaine, D. B. Revera, T. Williams, and D. Boss. 1986. The effects of an underwater explosion on the sea turtles Lepidochelys kempi and Caretta caretta with observations of effects on other marine organisms. Unpublished report submitted to National Marine Fisheries Service Biological Laboratory, Galveston, Texas.

Ecklund, A. M. 1943. The pathology of immersion blast injuries. U.S. Naval Medical Bulletin 41:19-26.

Eklund, C. R. 1946. Effect of high explosive bombing on fish. Journal of Wildlife Management 10:72.

Falk, M. R., and M. J. Lawrence. 1973. Seismic exploration: its nature and effect on fish. Technical Report Series No. CEN T-73-9. Department of the Environment, Fisheries and Marine Service, Central Region, Winnipeg.

Ferguson, R. G. 1962. The effects of underwater explosions on yellow perch (Perca flavescens). Canadian Fish Culturist 29:31-39.

Fitch, J. E., and P. H. Young. 1948. Use and effect of explosives in California waters. California Fish and Game 34:53-70.

Flynn, H. G., and C. C. Church. 1988. Transient pulsations of small gas bubbles in water. Journal of the Acoustical Society of America 84:985-998.

Fry, D. H., and K. W. Cox. 1953. Observations on the effect of black powder explosions on fish life. California Fish and Game 39:233-236.

Gage, E. L. 1945. Immersion blast injury - clinical experiences. U.S. Naval Medical Bulletin 44:225-231.

Gaia Northwest, Inc. 1990. Report on the assessment of the fish assemblages in the Duwamish Water Way before and after underwater demolition operations to remove the West Seattle bridge piers in summer and fall of 1989. Report submitted to: The Seattle Engineering Department. Gaia Northwest, Incorporated, Seattle, WA.

Gaspin, J. B. 1975. Experimental investigations of the effects of underwater explosions on swimbladder fish. 1. 1973 Chesapeake Bay tests. Technical Report NSWC/WOL/TR-75-58. Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD.

Gaspin, J. B., M. L. Wiley, and G. B. Peters. 1976. Experimental investigations of the effects of underwater explosions on swimbladder fish. II: 1975 Chesapeake Bay tests. Technical Report NSWC/WOL/TR 76-61. Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD.

Gitschlag, G. R. 1990. Sea turtle monitoring at offshore oil and gas platforms. Pp. 223-246 in Proceedings of the 10th Annual Workshop on Sea Turtle Biology and Conservation, T. H. Richardson, J. I Richardson, and m. Donnelly. compilers. NOAA Technical Memorandum NMFS-SEFC-278.

Gitschlag, G. R., and B. A. Herczeg. 1994. Sea turtle observations at explosive removals of energy structures. Marine Fisheries Review 56:1-8.

Gitschlag, G. R., and M. Renaud. 1989. Sea turtles and the explosive removal of offshore oil and gas structures. Pp. 67-68 in Proceedings of the 9th Annual Workshop on Sea Turtle Conservation and Biology, S. A. Eckert, K.L. Eckert, and T. H. Richardson, compilers. NOAA Technical Memorandum NMFS-SEFC-232.

Goertner, J. F. 1978. Fish killing potential of a cylindrical charge exploded above the water surface. Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD. Technical Report NCSWC/WOL/TR 77-90.

Goertner, J. F. 1981. Fish kill ranges for oil well severance explosions. Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD. Technical Report NSWC TR-81-149.

Goertner, J. F. 1982. Prediction of underwater explosion safe ranges for sea mammals. Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD. Technical Report NSWC TR-82-188.

Goertner, J. F., M. L. Wiley, G. A. Young, and W. W. McDonald. 1994. Effects of underwater explosions on fish without swimbladders. Technical Report NSWC TR 88-114. Naval Surface Warfare Center, Dahlgren Division, White Oak Detachment Silver Spring, MD.

Gordon, G., and D. Nies. 1990. Small borehole blasting in high liability locations. Pp. 459-473. In: Proceedings of the Sixth Conference on Explosives and Blasting Techniques, Orlando, FL. Society of Explosive Engineers, Cleveland, OH.

Gowanlock, J. N. 1946a. Effects of seismographic dynamite underwater explosions on marine aquatic life. Pp. 143-148. Louisiana Department of Wildlife and Fisheries. First Biennial Report.

Gowanlock, J. N. 1946b. Effects of underwater dynamite explosions explosions on oysters. Pp. 195-198. Louisiana Department of Wildlife and Fisheries. First Biennial Report.

Gowanlock, J. N. 1948. Further seismographic dynamite explosion experiments. Pp. 299-305. Louisiana Department of Wildlife and Fisheries. Second Biennial Report.

Gowanlock, J. N. 1950. The effects of underwater seismographic exploration. Univ. Miami Mar. Lab., Proc. Gulf and Caribbean Fish. Inst., 2nd Ann Sess., 1950, p. 105-106.

Gowanlock, J. N. and J. E. McDougall. 1944. Louisiana experiments pave ways for expanded oil research. Louisiana Conservationist. 3:3, 6.

Gowanlock, J. N. and J. E. McDougall. 1945. Effects from the detonation of explosives on certain marine life. Louisiana Conservationist 4: 13-16. (Note: This paper is cited in the literature but does not exist. It was a typo for the publication in Oil.)

Gowanlock, J. N., and J. E. McDougall. 1945. Effects from the detonation of explosives on certain marine life. Oil 4: 13-16.

Gowanlock, J. N., and J. E. McDougall. 1946. The biological effects on fish, shrimp, and oysters of the underwater explosion of heavy charges of dynamite. Transactions of the 11th North American Wildlife Conference p. 212-219.

Grant, F. S., and G. F. West. 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill, New York, NY. 584 p.

Haymes, G. T., and P. H. Patrick. 1986. Exclusion of adult alewife, Alosa pseudoharengus, using low-frequency sound for application at water intakes. Canadian Journal of Fisheries and Aquatic Science 43:855-862.

Hempen, G. L. 1993. Air-screen reduction of water-born energy from underwater blasting. Ph.D. Dissertation University of Missouri-Rolla. 205 p.

Hempen, G.L. 1993. Reducing underwater blast damage with air-screens. Pp. 337-346. In: Proceedings of the Nineteenth Annual Conference on Explosives and Blasting Technique, Pp. 337-346. International Society of Explosives Engineers, San Diego, CA. International Society of Explosive Engineers, Cleveland, OH.

Hempen, G. L., and T. M. Keevin. 1995. Underwater blasting effects models: A critical evaluation of I-Blast. Pp. 236-247. In: Proceedings of the Twenty-first Annual Conference on Explosives and Blasting Technique (Volume 1), Nashville, Tennessee. International Society of Explosive Engineers, Cleveland, OH.

Hempen, G. L., and T. M. Keevin. 1997. Underwater pressure recording: Industry standardization. Pp. 237-246. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH.

Hill, S. H. 1978. A guide to the effects of underwater shock waves on Arctic marine mammals and fish. Pacific Marine Science Report 78-26. Institute of Ocean Sciences, Patricia Bay, Sidney, B.C. 50 p.

Hirsch, A. E., and A. K. Ommaya. 1972. Head injury caused by underwater explosion of a firecracker. Journal of Neurosurgery 37:95-99.

Hogan, J. 1941. The effects of high vacuum on fish. Transactions of the American Fisheries Society 70:469-474.

Holland, C. K., and R. E. Apfel. 1990. Thresholds for transient cavitation produced by pulsed ultrasound in a controlled nuclei environment. Journal of the Acoustical Society of America 88:2059-2069.

Hubbs, C. L., and A. B. Rechnitzer. 1952. Report on experiments designed to determine effects of underwater explosions on fish life. California Fish and Game 38:333-366.

Hubbs, C. L., E. P. Schultz, and R. Wisner. 1960. Investigations of effects on caged fish from underwater nitro-carbo-nitrate explosions. Unpublished Preliminary Report. Scripps Institute of Oceanography, La Jolla, CA.

Indrambarya, B. 1949. Note on the effect of explosives on fish in Siamese coastal waters. Thai Science Bulletin 6:1-6.

Jeppson, P. 1957. The control of squawfish by use of dynamite, spot treatment, and reduction of lake levels. The Progressive Fish-Culturist. 19:168-171.

Joachim, C. E., and C. R. Welch. 1997. Underwater shocks from blasting. Pp. 525-536. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH.

Karr, J. R., L. A. Toth, and D. R. Dudley. 1985. Fish communities of Midwestern rivers: A history of degradation. Bioscience 35:90-95.

Kearns, R. K., and F. C. Boyd. 1965. The effect of marine seismic exploration on fish populations in British Columbia coastal waters. Canadian Fish Culturist 34:326.

Keevin, T. M. 1995. The effects of underwater explosions on fish with techniques to mitigate those effects. Ph.D. Dissertation, University of Illinois, Champaign/Urbana. 279 pp.

Keevin, T. M. In Press. A review of natural resource agency recommendations for mitigating the impacts of underwater blasting. Reviews in Fisheries Science

Keevin, T. M., G. L. Foley, G. L. Hempen, and D. J. Schaeffer. In Press. Evaluation of three methods to quantify mortality in bluegill (Lepomis macrochirus) exposed to underwater blast pressures. North American Journal of Fishery Management

Keevin, T. M., G. L. Foley, F. L. Hempen, and D. J. Schaeffer. In Prep. Explosive pressure related internal organ damage in bluegill (Lepomis macrochirus).

Keevin, T. M., and G. L. Hempen. 1995. A tiered approach to mitigating the environmental effects of underwater blasting. Pp. 228-235. In: Proceedings of the Twenty-first Annual Conference on Explosives and Blasting Technique (Volume 1), Nashville, Tennessee. International Society of Explosive Engineers, Cleveland, OH.

Keevin, T. M., and G. L. Hempen. 1995. A tiered approach to mitigating the environmental effects of underwater blasting. Journal of Explosives Engineering 13: 20-25. (Reprinted by the International Society of Explosives Engineers from their conference proceedings).

Keevin, T. M., G. L. Hempen, L. G. Nico, and D. J. Schaeffer. In Press. The use of an air bubble curtain to reduce fish mortality resulting from underwater explosions. North American Journal of Fishery Management

Keevin, T. M., G. L. Hempen, and D. J. Schaeffer. 1997. Use of a bubble curtain to reduce fish mortality during explosive demolition of Locks and Dam 26, Mississippi River. Pp. 197-206. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH.

Keevin, T. M., G. L. Hempen, J. M. Pitlo, Jr., and D. J. Schaeffer. 1997. Are repelling charges effective in mitigating the impacts of underwater explosions? Pp. 185-195. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH.

Keevin, T. M., D. J. Schaeffer, and G. L. Hempen. In Press. The effects of underwater explosive pressure waves on aquatic invertebrates: A critical review of the literature. Reviews in Fisheries Science.

Kemp. R. J. 1956. Do seismographic explosions affect marine life? Texas Game and Fish 14:11-13.

Ketten, D. R. 1995. Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. Pp. 391-407. In: Sensory Systems of Aquatic Mammals. R. A. Kastelein, J. A. Thomas and P. E. Nachtigall [editors). De Spil Publishers, Woerden, The Netherlands.

Kinsler, L. E. and A. R. Frey. 1950. Fundamentals of Acoustics. Wiley and Sons, New York, NY. 516 p.

Klima, E. F., G. R. Gitschlag, and M. L. Renaud. 1988. Impacts of the explosive removal of offshore petroleum platforms on sea turtles and dolphins. Marine Fisheries Review 50:33-42.

Knight, A. P. 1907. The effects of dynamite explosions on fish life. A preliminary report. Further contributions to Canadian Biology Being Studies from the Marine Biological Station of Canada 1902-1905. 39th Annual Report of the Department of Marine and Fisheries, Fisheries Branch. Sessional Paper No. 22a, pp. 21-30.

Knudsen, F. R., P. S. Enger, and O. Sand. 1994. Avoidance responses to low frequency sound in downstream migrating Atlantic salmon smolt, Salmo salar. Journal of Fish Biology 45:227-233.

Konya, C. J., and J. Davis. 1978. The effects of stemming on retention in blastholes. Pp. 102-112. In: Proceedings of the Fourth Conference on Explosives and Blasting Techniques, New Orleans, Louisiana. Society of Explosives Engineers, Cleveland, OH.

Konya, C. J., and E. J. Walter. 1985. Seminar on blasting and overbreak control (rock blasting). U.S. Department of Transportation, Federal Highway Administration, Contract DTFH 61-83-C-00110. National Technical Information Service. Springfield, VA.

Kostyuchenko, L. P. 1973. Effects of elastic waves generated in marine seismic prospecting on fish eggs in the Black Sea. Journal 9:45-48.

Kramer, F. S., R. A. Peterson, and W. C. Walter (Editors). 1968. Seismic Energy Sources 1968 Handbook. United Geophysical Corporation. Tulsa, OK. 55 p.

Langefors, U., and B. Kihlstrom. 1978. The modern technique of rock blasting. John Wiley and Sons, New York, NY.

Lewin, P. A., and L. Bjorno. 1981. Acoustic pressure amplitude thresholds for rectified diffusion in gaseous microbubbles in biological tissue. Journal of the Acoustical Society of America 69:846-852.

Linton, T. L., A. M. Landry, Jr., J. E. Buckner, Jr., and R. L. Berry. 1985a. Effects upon selected marine organisms of explosives used for sound production in geophysical exploration. Texas Journal of Science 37:341-353.

Linton, T. L., A. M. Landry, Jr., N. Hall and D. LaBomascus. 1985b. Data base development for exploration guidelines - an annotated bibliography and literature review. Report prepared by Texas A&M University, for the International Association of Geophysical Contractors, Denver, Colorado.

Lubbers, L., W. R. Boynton, and W. M. Kemp. 1990. Variations in structure of estuarine fish communities in relation to abundance of submersed vascular plants. Marine Ecology Progress Series 65: 1-14.

Ludwig, M. 1977. Environmental assessment of the use of explosives for selective removal of eelgrass (Zostera marina). Pp. 63-68. In: G. A. Young (Editor). Proceedings of the Second Conference on the Environmental Effects of Explosives and Explosions. Naval Surface Weapons Center. NSWC/EOL YT 77-36.

Mate, B. R., and J. T. Harvey (eds.) 1987. Acoustical deterrents in marine mammal conflicts with fisheries. ORESU-W-86-001, Oregon State University Sea Grant College Program, Corvallis, OR. 116 pp.

McAnuff, A. L., M. V. van Bers, and A. C. Curic. 1994. Environmental effects of marine blasting in Canadian game rivers. Pp. 479-490. In: Proceedings of the Twentieth Annual Conference on Explosives and Blasting Techniques, Austin, Texas. International Society of Explosive Engineers.

McAnuff, A. L., and R. T. Booren. 1989. Fish mortality study during underwater blasting operations in Lake Erie off Nanticoke, Ontario. Pp. 131-145. In: Proceedings of the Fifteenth Conference on Explosives and Blasting Techniques, New Orleans, LA. Society of Explosive Engineers, Cleveland, OH.

Medwin, H. 1975. Speed of sound in water for realistic parameters. Journal of the Acoustical Society of America 58:1318.

Mellor, M. 1986. Blasting and blasting effects in cold regions, Part II: Underwater explosions. Special Report 86-16. USA Cold Regions Research and Engineering Laboratory, Handover, New Hampshire. 60 p.

Metzger, R.J., and P. L. Shafland. 1986. Use of detonating cord for sampling fish. North American Journal of Fisheries Management 6:113-118.

Miller, R. R., J. D. Williams, and J. E. Williams. 1989. Extinctions of North American fishes during the past century. Fisheries 14:22-38.

Mobil Oil. 1984. The environmental impact of chemical explosives near Sable Island. Draft report by Environmental Planning and Management Division - Mobil Oil Canada Ltd.

Moxon, N . T ., S . B. Richardson, and L. W. Armstrong. 1993. The effects of confinement on fragmentation and movement. Pp. 119-128. In: Proceedings of the Ninth Annual Symposium on Explosives and Blasting Research, San Diego, California. International Society of Explosives Engineers, Cleveland, OH.

Muir, J. F. 1959. Passage of young fish through turbines. Journal of the Power Division, Proceedings of the American Society of Civil Engineers 8S: 23-46.

Munday, D. R., G. L. Ennis, D. G. Wright, D. C. Jeffries, E. R. McGreer, and J. S. Mathers. 1986. Development and evaluation of a model to predict effects of buried underwater blasting charges on fish populations in shallow water areas. Canadian Technical Report of Fisheries and Aquatic Sciences 1418.

Myrick, A. C. Jr., E. R. Cassano, and C. W. Oliver. 1990. Potential for physical injury, other than hearing damage, to dolphins from seal bombs used in the yellowfin tuna purse-seine fishery: Results from open-water tests. Admin. Rep. LJ-90-08. U.S. National Marine Fishery Service, La Jolla, Ca. 28 pp.

NCR (National Research Council). 1990. Decline of the Sea Turtles: Causes and Prevention. Board on Environmental Studies and Toxicology. National Academy Press. Washington, D. C.

NCR (National Research Council). 1996. An Assessment of Techniques for Removing Offshore Structures. Marine Board, Commission on Engineering and Technical Systems. National Academy Press. Washington, D. C.

Nix, P., and P. Chapman. 1985. Monitoring of underwater blasting operations in False Creek, B.C.. Pages 194-211 in G. D. Greene, F. R. Engelhardt and R. J. Paterson, editors. Proceedings of the workshop on effects of explosive use in the marine environment, 29-31 January 1985, Environmental Protection Branch Technical Report No. 5, Canada Oil and Gas Lands Administration, Ottawa, Ontario.

Ogawa, T., I. Fukuyama, and I. Ito. 1976. Injuries to fish due to underwater pressure waves. Journal of Industrial Explosives Society, Japan 37:291-299. (English Translation: Blast and Blasting 37:188-201).

Ogawa, T. , I. Fukuyama, and I. Ito. 1979. Injuries to fish due to underwater pressure waves. 4. Dynamic response to internal organs. Journal of the Industrial Explosives Society, Japan 40: 86-94. (English Translation: Blast and Blasting 40: 198-211).

Ogawa, T., I. Fukuyama, and S. Sakaguchi. 1977. Injuries to fish due to underwater pressure waves. II. Injuries to internal organs. Journal of the Industrial Explosives Society, Japan 38:349-356. (English Translation: Blast and Blasting 38:392-404).

Ogawa, T., I. Fukuyama, S. Sakaguchi, and T. Narahira. 1978. Injuries to fish due to underwater pressure waves (III). Journal of the Industrial Explosives Society, Japan 39:196-204. (English Translation: Blast and Blasting 39:84-96).

O'Keeffe, D. J. 1984. Guidelines for predicting the effects of underwater explosions on swimbladder fish. Naval Surface Weapons Center, Silver Spring, MD. NSWC TR 82326.

O'Keeffe, D. J., and G. A. Young. 1984. Handbook on the environmental effects of underwater explosions. Naval Surface Weapons Center. NSWC TR 83-240.

Oriard, L. L. 1983. Underwater explosives detonations and structural responses, Guri Hydro Project, Venezuela. Pp. 921-930. Waterpower '83, International Conference on Hydropower.

Oriard, L. L. 1985. Seismic waves transmitted from rock to water: theory and experience. Pp. 1-12. In: Proceedings of 1st Mini-Syomposium on Explosives and Blasting Research. San Diego, California. Society of Explosives Engineers, Cleveland, OH.

Oriard, L. L. 1992. Letter to G. L. Hempen on Blast Damage and Air Screens. Huntington Beach, CA. 5 August 1992.

Palma, J., and J. J. Uldall. 1943. Immersion blast injuries. U.S. Navy Medical Bulletin 41:3-8.

Patterson, C. G., and W. R. Turner. 1968. The effect of an underwater explosion on fish of Wentzel Lake, Alberta. Canadian Field Naturalist 82: 219-220.

Persson, P., R. Holmberg, and J. Lee. 1994. Rock Blasting and Explosives Engineering. CRC Press, London. 541 p.

Puke, C. 1948. Experiments in Lake Vaner on the influence on fish of bomb dropping. Rep. Inst. Freshwater Res. Drottningholm 29:71-74.

Reiter, G. A. 1981. Cold weather response F/V Ryuyo Maru No. 2 St. Paul, Pribiloff Islands, Alaska. pp 227-231 In: Proc. 1981 Oil Spill Conference. American Petroleum Institute Publication 4334, Washington, D.C. 742 pp.

Richmond, D. R., J. T. Yelverton and E. R. Fletcher. 1973. Far-field underwater-blast injuries produced by small charges. Defense Nuclear Agency, Department of Defense, Washington, D. C. Technical Progress Report, DNA 3081 T.

Roguski, E. A., and T. H. Nagata. 1970. Observations on the lethal effect of under ice detonations on fish. Alaska Dep. Fish Game Inform. Leafl. 139. 30 p.

Ross, C. W., C. V. Hurley and J. Parsons. 1985. The environmental impact of linear explosives on fish in nearshore waters near Sable Island, Nova Scotia. Pages 152-193 in G. D. Greene, F. R. Engelhardt and R. J. Paterson, editors. Proceedings of the workshop on effects of explosive use in the marine environment, 29-31 January 1985, Environmental Protection Branch Technical Report No. 5, Canada Oil and Gas Lands Administration, Ottawa, Ontario.

Rozas L. P., and W. E. Odum. 1988. Occupation of submerged aquatic vegetation by fishes: testing the roles of food and refuge. Oecologia 77:101-106.

Sakaguchi, S., D. Fukuhara, S. Umezawa, M. Fujiya, and T. Ogawa. 1976. The influence of underwater explosion on fishes. Bulletin of Nansei National Fisheries Research Institute 9:33-65.

Sieling, F. W. 1954. Experiments on the effects of seismographic exploration on oysters. Proceedings National Shellfish Association 1953:93-104.

Skinner, F. W., L. Miller, and W. Harvey. 1973. Protection of the environment during demolition activities. Miscellaneous Paper N-73-6. U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg Mississippi.

Slurry Explosive Corporation. 1991. Data sheet: T-100 Two Component Sticks. Slurry Explosive Corporation, Oklahoma City, Oklahoma.

Smith, M. 1996. Effects of underwater explosions on aquatic vegetation, submerged and emergent. Report Submitted to the U.S. Army Corops of Engineers, Project #DACW43-96-P1584. Southern Illinois University, Edwardsville, IL.

Strange, J. F. 1963. The attenuating effects of a bubble screen on underwater shock. Miscellaneous Paper No. 2-553. U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

Susanszky, A. 1977. Environmental effects of blasting operations in subfluvial strata. Pp. 206-215. In: Proceedings of the Third Conference on Explosives and Blasting Techniques, Pittsburgh, PA. Society of Explosives Engineers, Cleveland, OH.

Sverdrup, A., E. Kjellsby, P. G. Kruger, R. Floysand, F. R. Knudsen, P. S. Enger, G. Serck-Hanssen, and K. B. Helle. 1994. Effects of experimental seismic shock on vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the atlantic salmon. Journal of Fish Biology 45: 973-995.

Tansey, D. O. 1980. A delay sequencing blasting system. Pp. 345-375. In: Proceedings of the Sixth Conference on Explosives and Blasting Techniques, Tampa, FL. Society of Explosives Engineers, Cleveland, OH.

Taylor, C. A., M. L. Warren, Jr., J. F. Fitzpatrick, Jr., H. H. Hobbs III, R. F. Jezerinac, W. L Pflieger, and H. W. Robison. 1996. Conservation status of crayfishes of the United States and Canada. Fisheries 21:25-38.

Teleki, G. C., and A. J. Chamberlain. 1978. Acute effects of underwater construction blasting on fishes in Long Point Bay, Lake Erie. Journal of the Fisheries Research Board of Canada 35:1191-1198.

Todd, S., P. Stevick, J. Lien, F. Marques, and D. Ketten. 1996. Behavioural effects of exposure to underwater explosions in humpback whales (Megaptera novaeangliae). Canadian Journal of Zoology 74:1661-1672.

Tollefson, R., and L. D. Marriage. 1949. Observations on the effects of the intertidal blasting on clams, oysters and other shore inhabitants. Oregon Fish Comm. Res. Briefs 2(1): 19-23.

Traxler, S. L., B. R. Murphy and T. L. Linton. 1993. Subsediment seismic explosions do not injure caged fishes in a freshwater reservoir. Journal of Freshwater Ecology 8: 73-75.

Tsvetkov, V. I., D. S. Pavlov, and V. K. Nezdoliy. 1972. Changes of hydrostatic pressure lethal to the young of some freshwater fish. Journal of Ichthyology 12:307-318.

Turgeon, D. A., A. E. Bogan, E. V. Coan, W. K. Emerson, W. G. Lyons, W. L. Pratt. C. F. E. Roper, Amelie Scheltema, F. G. Thompson, and J. D. Williams. 1988. Common and scientific names of aquatic invertebrates from the United States and Canada: mollusks. American Fisheries Society Special Publication 16. American Fisheries Society, Bethesda, MD.

Tyler, R. W. 1960. Use of dynamite to recover tagged salmon. U.S. Fish and Wildlife Service Special Scientific Report Fisheries 353:1-9.

Upton, H. F. 1992. Biodiversity and conservation of the marine environment. Fisheries 17:20-25.

Urick, R. J. 1983. Principles of Underwater Sound. (3rd Edition). McGraw-Hill Book Company, New York, NY. 423 Pe

U.S. Army, Corps of Engineers (USAGE). 1991. Underwater blast monitoring. Engineer Technical Letter No. 1110-8-11 (FR). Washington, D.C. 9 p.

U.S. Fish and Wildlife Service. 1993. Endangered and threatened wildlife. 50 CFR 17.11.

Walker, D. 1987. The use of the oxygen electrode and fluorescence probes in simple measurements of photosynthesis. Ocygraphic Limited, Sheffield, UK.

Warren, Jr., M. L. and B. M. Burr. 1994. Status of freshwater fishes of the United States: Overview of an imperiled fauna. Fisheries 19:6-18.

Wiley, M. L., J. B. Gaspin, and J. F. Goertner. 1981. Effects of underwater explosions on fish with a dynamical model to predict fishkill. Ocean Science and Engineering 6:223-284.

Williams, A. B., L. G. Abele, D. L. Felder, H. H Hobbs, Jr., R. B. Manning, P. A. McLaughlin, and I. Perez Farfante. 1989. Common and scientific names of aquatic invertebrates from the United States and Canada: decapod crustaceans. American Fisheries Society Special Publication 16. American Fisheries Society, Bethesda, MD. (1989).

Williams, J. D., M. L. Warren, Jr., K. S. Cummings, J. L. Harris, and R. J. Neves. 1993. Conservation status of freshwater mussels of the United States and Canada. Fisheries 18:6-22.

Williams, J. E., J. E. Johnson, D. A., Hendrickson, S. Contreras-Baleras, J. D. Williams, M. Navarro-Mendoza, D. E. McAllister, and J. E. Deacon. 1989. Fishes of North America endangered, threatened, or of special concern: 1989. Fisheries 14:2-20.

Williams, J. E., and R. J. Neves. 1992. Introducing the elements of biological diversity in the aquatic environment. Transactions of the North American Wildlife and Natural Resources Conference 57:345-354.

Wright, D. G. 1982. A discussion paper on the effects of explosives on fish and marine mammals in the waters of the Northwest Territories. Canadian Technical Report of Fisheries and Aquatic Science 1052:v + 16 p.

Wright, D. G. 1994. (Draft) Guidelines for the use of explosives in Canadian fisheries waters. Department of Fisheries and Oceans. 24 p.

Wright, D. G. In Press. Guidelines for the use of explosives in Canadian fisheries waters. Canadian Technical report of fisheries and Aquatic Science.

Wright, D. G. 1997. Guidelines for the use of explosives in Canadian Fisheries waters - An introduction of the guidelines and the process of their development. Pp. 565-573. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH.

Wright, R. A. 1971. Effects of underwater overpressures on sea otters and other aquatic animals. Amchitka bioenvironmental program. U.S. Atomic Energy Comm. Final Rep. Contract No. AT (26-1). 171 pp.

Yaguda, A. 1945. Pathology of immersion blast injury. U.S. Navy Medical Bulletin 44:232-240.

Yelverton, J. T., D. R. Richmond, E. R. Fletcher, and R. K. Jones. 1973. Safe distance from underwater explosions for mammals and birds. Technical Report DNA 3114 T. Defense Nuclear Agency, Department of Defense, Washington, D.C.

Yelverton, J. T ., D. R. Richmond, W. Hicks, K. Sanders, and E. R. Fletcher. 1975. The relationship between fish size and their response to underwater blast. Topical Report DNA 3677T. Defense Nuclear Agency, Department of Defense, Washington, D.C.

Young, G. A. 1991. Concise methods for predicting the effects of underwater explosions on marine life. NAVSWC NO 91-220. Naval Surface Warfare Center. Silver Spring, Maryland.

CHAPTER 1
UNDERWATER EXPLOSIVES USE: NATURAL RESOURCE AGENCY CONCERNS AND REGULATORY AUTHORITY

RATIONAL FOR NATURAL RESOURCE AGENCY CONCERNS

Population growth and economic development have resulted in frequent changes in our hometown landscapes and their waterways due to housing developments, shopping malls, industrial development, and roadways. Population growth and development have resulted in a loss of aquatic habitat and a general decline in water quality, both important factors in sustaining aquatic species. For example, since 1850, 67% of the fish species from the Illinois River and 44% from the Maumee River have become less abundant or have disappeared (Kerr et al. 1985). These are just two examples of aquatic degradation and loss of fish species that are occurring throughout the United States (Warren and Burr 1994). The list of aquatic invertebrates and vertebrates that are federally protected or under consideration for protection (candidates) continues to increase and totals more than l,O00 taxa (Williams and Neves 1992). In fact, 27 species and 13 subspecies of fish have become extinct in North America during the past 100 years (Miller et al. 1989).

Marine resources are suffering similar assaults on their biological integrity as described for freshwater ecosystems. Overharvesting, toxic and nutrient pollution, costal development, and increasing ultraviolet radiation threaten marine species (Upton 1992).

Habitat degradation has jeopardized the continued existence of many species. Both federal and state laws afford protection to numerous aquatic organisms. The following listing makes it clear that it is difficult to utilize explosives underwater, in a major river basin or in the marine environment, without the potential for adversely impacting a federally threatened or endangered species or a species of special concern to federal and state natural resource agencies.

Aquatic Mammals. The U.S. Fish and Wildlife Service (1993) lists 15 species of marine mammals that occur in U.S. coastal waters or near our trust territories as threatened and endangered, including such species as the West Indian manatee (Florida manatee), Southern sea otter, Steller sea lion, 3 species of seals, and eight species of whales.

Reptiles. Of special concern for the blaster, in U.S. coastal marine environments there are 6 sea turtle species listed as either threatened or endangered (U.S. Fish and Wildlife Service 1993).

Fish. Williams et al. (1989) considered 364 fish species and subspecies in North America that warrant protection because of their rarity. Their list consists of 147 fishes classified as special concern, 114 as threatened, and 103 as endangered. Twenty-two of the fishes occur in Canada, 254 in the United States, and 123 in Mexico. Some occur along international borders and, therefore, inhabit two countries.

Freshwater mussels. Of the 297 native freshwater mussels of the United States and Canada, Williams et al. (1993) considered 213 taxa (71.7%) as endangered, threatened, or of special concern; only 70 (23.6%) were considered as currently stable. Twenty-one taxa (7.1%) were listed as possibly extinct, 77 (26.0%) as endangered, 43 (14.5%) as threatened, 72 (24.2%) as of special concern, and 14 (4.7%) as undetermined.

Crayfish. Of the 338 crayfish of the United States, Taylor et al. (1996) considered 162 taxa (48%) as possibly extinct, endangered, threatened or of special concern. Of these, 2 (<1%) are possibly extinct, 65 (19.2%) are endangered, 45 (13.3%) are threatened, and 50 (14.8%) are of special concern. Taxa classified as currently stable total 176 (52%).

The above litany of extinctions and aquatic species classified as threatened, endangered or of special concern form the basis of natural resource agency concerns over aquatic resources. As population growth and economic development continues, there will be more and more habitat degraded and species placed in jeopardy. Underwater explosives use is often considered by natural resource agencies as another assault on the resources that the agency is mandated to protect.

Natural resource agencies are challenged with permitting, under various regulatory authorities, underwater explosive use while at the same time protecting aquatic resources. Deciding on whether or not to allow use of explosives requires striking a balance between development and aquatic resources protection. On a positive note, natural resource personnel are generally willing to work with and accommodate the blaster.

NATURAL RESOURCE AGENCY REGULATORY AUTHORITY

In the United States, there currently are no national guidelines or regulations concerning mitigation of explosive use impacts. Decisions are left to individual state agencies and regulatory authority may rest with more than one state agency. In Canada, National guidelines for the use of explosives in Canadian fisheries waters have been prepared by the Department of Fisheries and Oceans under the Fisheries Act (Wright In press).

Keevin (In press) reviewed state natural resource agency permit requirements for underwater explosive use within waters under their jurisdiction (Table 1.1). To determine current agency policies on the use of explosives, a questionnaire was sent to fish and wildlife agency directors in each state. Questions were developed to determine current state fish and wildlife agency policies concerning the use of explosives for legitimate purposes (i.e., military testing programs, demolition, construction) within waters under their jurisdiction. Questions targeted three areas of concern for fish and wildlife agencies: (1) what type permit, if any, was required; (2) what information did the agency provide to the applicant; and (3) what mitigative techniques were required of the applicant by a agency or recommended to protect aquatic life from explosive pressures (Issue #3 is covered in Chapter 8).

1. Permit Requirements. Thirty three state natural resource agencies require permits to conduct underwater blasting. There is often more than one agency responsible for permitting within a given state, depending on the location of the blasting, (freshwater, marine, or wetland), or the type of project, (demolition or seismic exploration).

Most agencies require permits based on existing fish and wildlife codes, codes that are nonspecific to underwater blasting (i.e. fishing codes, stream protection acts, or wetland protection laws). For example, the Montana Department of Fish, Wildlife and Parks' permitting authority rests with the Stream Protection Act and The Natural Streambed and Land Preservation Act. However, many states permitting or review authority is based on fishing codes; since many codes specifically indicate that it is illegal to take fish with explosives. In some states taking fish with explosives is illegal by default, since explosives are not listed as an approved fishing method.

Two states, Oregon and Pennsylvania, have permit application forms specific to underwater explosive use and resource protection. The Oregon Department of Fish and Wildlife's In-Water Blasting Permit Application Form requires that the applicant provide detailed information on explosive type, amount, size and number of charges to be detonated, detonation delay information, and estimated start and completion data. The Oregon applicant is also required to provide information concerning project impacts and proposed mitigation measures including: fish and wildlife species which occur in the blast area and predicted effects of the blasting on these species, fish and wildlife habitat within the affected area and the predicted effects of blasting on these habitats, estimated distance of impacts and area affected, and measures the blaster (before and after construction) will use to prevent injury to fish and wildlife and their habitats including an analysis of their effectiveness under the environmental conditions at the project site.

The "Guidelines for the Use of Explosives in Canadian Fisheries Waters" require that the blaster prepare an environmental impact assessment of the project describing the potential adverse effects on the fish and marine mammal resources and their habitats in the project area. This document is submitted to the Department of Fisheries and Oceans regional/area authority. The blaster is also required to prepare a plan to mitigate adverse effects on fish and fish habitat identified in the environmental impact assessment. The blaster must complete a detailed application form, specific to underwater explosive use, for authorization to kill fish by means other than fishing. Detailed information is required on the type, weight and weight per delay of explosives, shot pattern, detonation depth, delay period (msec), and method of detonation. The environmental impact assessment and mitigation plan are required as part of the application submittal. Although these guidelines are draft they are currently in use by the Department of Fisheries and Oceans.

Seventeen state natural resource agencies responded that they do not require permits for the use of explosives in waters under their jurisdiction. However, these agencies may provide input to other agencies within their state and to federal agencies. Under the Fish and Wildlife Coordination Act, state natural resource agencies have the authority to review and comment on applications for U.S. Army Corps of Engineers' Section 404 (Clean Water Act) permits as a means of providing input to the decision making process. Federal explosive use projects (including any military related activities), projects requiring federal permits or receiving federal funding also fall under the jurisdiction of the National Environmental Policy Act (NEPA) and the Endangered Species Act. The NEPA requires Environmental Assessments of project impacts and possibly Environmental Impact Statements.

The Endangered Species Act requires a Biological Assessment of potential impacts to Federally threatened and endangered species and species Proposed for listing.

2. Information package on explosive-use provided to applicant by agencies. Only five states provide an information package to the blaster (Table 1.1). The majority of the information packages are related to use of explosives for seismic exploration. For example, the Mississippi Department of Natural Resources provides a booklet outlining rules and regulations governing geophysical and seismic exploration on state-owned lands. The Louisiana Department of Wildlife and Fisheries provides information outlining regulations governing explosive use for seismic exploration within the state. Both packages, which are not lengthy, provide information concerning requirements for observers, explosive charge size limits, minimum shot hole depths for a range of explosive sizes, and measures to mitigate impacts. The Canadian Department of Fisheries and Oceans provides the blaster with their "Guidelines for the Use of Explosives in Canadian Fisheries Waters," which explains environmental impact assessment and mitigation planning requirements and contains permit application forms.

Table 1.1 Summary of State Natural Resource Agency Responses

	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA
AGENCY PERMIT	Y	Y	N	N	Y	N	Y	Y	Y	N
AGENCY PROVIDES INFORMATION PACKG	N	Y	N	N	N	N	N	N	N	N

	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD
AGENCY PERMIT	Y	N	Y	Y	N	N	N	Y	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	N	Y	N	N

	MA	MI	MN	MS	MO	MT	NE	NV	NH	NJ
AGENCY PERMIT	Y	Y	Y	Y	N	Y	Y	N	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	Y	N	N	N	N	N	N

	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC
AGENCY PERMIT	N	Y	Y	Y	Y	N	Y	Y	Y	Y
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	Y	Y	N	N

	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY
AGENCY PERMIT	N	N	Y	N	Y	Y	Y	N	Y	N
AGENCY PROVIDES INFORMATION PACKG	N	N	N	N	N	N	N	N	N	N

CHAPTER 2
MECHANICS OF UNDERWATER EXPLOSIONS

INTRODUCTION

Underwater blasting is a science well understood in direct terms. The chemical and physical effects of detonation are well known. Wave passage is accurately developed in theory. The application of explosives and blasting agents is an art, because it is expensive to study in detail and because the variability of the media exposed to detonation waves is extremely complex. Testing explosives or utilizing the detonation in some manner can easily be accomplished by the art of blasting without fully understanding, or needing to understand, the science and details of detonations and wave passage. The physical aspects of underwater blasting are described herein; more complete treatments of underwater blasting may be found in Cole (1948) and Mellor (1986).

Three aspects of blasting are the detonation, the media transmitting the blast effects, and the effects of blast on its ambient environment. Some blast effects may be the desirable reasons for the shooting (examples, removing a bridge pier, explosive/ordnance testing, producing seismic waves). Other effects may be adverse impacts, resulting in damage to the natural and/or built environment. The primary interest of this document is the passage of the water-borne pressure waves and its negative impacts. These pressure waves are produced in water when the explosive charge is in the water column or when the shot is beneath or adjacent to the body of water.

Underwater blasting is conducted for a number of uses: rock excavation, demolition, grade preparation for foundations, structural rehabilitation, waterway applications (deepening channels/harbors, dike removal, and emergency levee-raises during extreme flooding), geophysical exploration, fish sampling, metal forming, military operations, and other uses. Shock-wave pressures in column from explosions can have adverse impacts on nearby submerged structures and on aquatic life. Regulatory agencies, depending on the circumstances, do not permit underwater blasts (nor blasts near aquatic environments) without mitigation of the adverse effects of pressures.

EXPLOSIONS

Modern blasting products release energy in two forms: <u>detonation</u> and <u>burning</u>. Detonation is the term for the rapid pressure front moving through the explosive ahead of a chemical transition front. The property of detonation makes that particular formulation an explosive, such as Cyclonite (RDX) and Trinitrotoluene (TNT). RDX is a primary explosive, only a small quantity of RDX is required to begin detonation. TNT, like dynamite, is a high explosive, which start to detonate only when a greater amount than critical volume or critical diameter is present. A blasting agent is a term for a material that can be made to detonate when initiated properly, examples are Ammonium Nitrate with Fuel Oil (ANFO) and Water Gel Slurries. A minimum charge diameter is required to achieve and sustain detonation. Dick et al. (1993a) shows that some dynamites require less than 20 mm diameter to initiate detonation, ANFO requires a 50 mm diameter with confinement to detonate. Burning (deflagration) releases the chemical energy of the materials, including explosives, but more slowly. Deflagration occurs without the rapidly expanding, detonation pressures. Black powder is a material that only deflagrates and has been called a low explosive. High explosives and blasting agents burn when their charge diameter is less than the critical diameter to achieve detonation.

The chemical energy of a detonating explosive is released as physical, thermal, and gaseous products. The detonation wave rapidly densifies the explosive material.

This physical shock front moves faster than the acoustic velocity of the explosive material. The detonation is only sustained within the limits of the explosive. The detonation ceases at the boundary with the medium containing the explosive. The shock wave passes into the medium. The thermal and detonation effects are only important near the explosion. Consideration of the thermal and detonation impacts may usually be ignored beyond a short distance (three to ten diameters of the explosive's volume) from the blast. The two main impacts in the far field (beyond the zone where thermal and detonation effects are important) from an explosion are the shock waves and the expanding gaseous reaction products. The original shock wave is the primary cause of damage to aquatic life or other structures at great distance from the shot point. The expanding gaseous products can cause: a noisy airblast pressure concussion when exploded in the air, but produce little shock wave amplitude in surface water or earthen media; a water plume and/or a gas bubble for blasts in the water column, and less intense, recurring pressure waves when a pulsating gas bubble occurs; and, lengthening of fractures and displacement of solids when a confined explosion occurs in sediment or rock.

Water is displaced and pressurized both by burning and detonation within the water column. Water is somewhat compressible in the near-blast region by extremely elevated pressure due to the explosion. The water column depth and work accomplished by the blasting (due to its confinement) are significant conditions in determination of the explosion's effects. Besides the compression waves produced by the explosion, other impacts could include noise, projectiles and gaseous chemical products, which are vented to the water or air. Water is nearly incompressible at standard temperature and pressure and cannot support shear waves. The extreme pressures and temperatures of explosives' detonation complicates the analysis of their adverse effects.

Use of explosives within or beneath or adjacent to the water column requires a greater effort of safety and planning, relative to blasting under dry conditions. The greatest concern is worker safety. The safety of underwater blasting is directly related to planning and safe work practices. Worker safety must be paramount in mitigation planning to avoid the severe potential that could result in accidental detonation. Accidental detonation could shoot a large quantity of explosives, cause worker mortality, and create greatly increased losses in the natural environment. The variety of other concerns includes water flow rate, turbidity, floating debris, and working depth beneath the water surface. Maintenance of exact horizontal spacing within and between rows of shotholes and loading explosives overwater increases the difficulty of accurate shooting. These limitations also compound the potential for misfires and overshooting. With submerged shooting, the chance of crossfiring closely spaced holes or overloading voids/crevices in the material contribute to the increased pressure and energy in the shot.

Important underwater blasting parameters include, but are not limited to: types of explosives and their properties; energy releases from underwater explosions - amplitude, duration, frequency, pressure, impulse, energy flux density; charge weight and explosive-gas diameter versus water column depth; unconfined test explosion properties versus confined blasting to perform work; scaling laws of underwater blasting; wave mechanisms - spherical, cylindrical and planar wave propagation; and, measuring equipment and its calibration.

Explosives perform two types of mechanical work: material fracturing (crushing and extending fractures) or material displacement. Both shock and gas energy are released by the detonation process. Varying explosive types release differing total energy and fractions of the shock and gas component energies. All detonations have some fraction of both brisant (shock) energy and expansion (gas) energy. The shock component may be used for unconfined explosions, as the gas energy is lost to the ambient environment without confinement. Common, unconfined applications in the

water column include explosives/ordnance testing, severing steel members, seismic exploration sources, and boulder breakage. The more useful component for more typical blast applications is gas development. These typical applications are mineral production or mass demolition by placement of explosives in boreholes with stemming. Stemming is the (normally granular) fill material placed in the boring over the explosives material and extending to the surface. [For rock quarrying, the impedance (density times velocity) are matched between the rock and the explosive. Higher impedance explosives typically have more shock energy.] The expanding gases displace material volumes when placed in such confinement that the gaseous reaction products are not quickly vented to the atmosphere or marine environments.

Commercial explosives and blasting agents are designed as oxygen-balanced chemical reactions (Dick et al. 1993b). The explosive's fuel and the oxidizing agent achieve the greatest energy of reaction when there is neither an oxygen debt nor surplus. The importance to underwater shooting is that a poor reaction is further water cooled or "dampened" to make the reaction energy lower than if conducted above the water surface. Unbalanced, water-cooled detonations may produce excess amounts of toxic gaseous products, besides not achieving the desired work.

Two factors are important to underwater blasting: increasing charge weights and lowering shock energy. Brower (1977) cites the need to displace both the blast's host material and water to produce the desired outcome in typical work. The placed weight of explosives is commonly increased several multiples in comparison to the same work effort above the water surface. Oriard (1983) questions the need for greater charge weights and recommends increased burden for greater water depths. While shock energy may be important to fracture the media to be displaced, gas energy must be capable of moving the material and the water load. Explosives in underwater blasting obviously should be selected, in part, by the fraction of available gas energy. Further, the shock energy component causes the peak, shock pressures. For underwater blasting, this brisant pressure wave and its negative, reflected pressure component at the air-water surface are the chief parameters in undesirable damage to structures and aquatic life.

Optimized blasting is the environmental awareness of the impact of blasting on the objective and ambient media. It also recognizes the host medium has a primary effect on the blasting efficiency. Controlled blasting (Konya and Walter 1985) is an industry term that is similar to, but different from, optimized blasting. Optimized blasting utilizes the media's properties, i.e. varying the shooting pattern to take advantage of the bedding and jointing of the removed rock, to achieve efficient production. Optimized blasting attempts to optimize the production and diminish the effects on the surroundings. Optimized blasting for underwater programs: reduces the total weight of explosive by carefully considering the media and the blasting pattern's relationship to the material's properties; increases the number of delays used to allow movement of material (reducing the burden) prior to causing additional material to displace; and, increases confinement with added stemming to assure that premature venting of gases does not occur.

Blasting materials are rated by a variety of factors, many of which have little commonality between manufacturers. The producers provide the values of common properties to the purchasers of explosives and blasting agents. Konya and Walter (1985) and Persson et al. (1994) describe the array of explosives' and blasting agents' properties. The properties of selected explosives can enhance performance and reduce the hazards of blasting. For the considerations herein, the shock energy should be diminished to limit the pressure pulse reaching the surrounding media. The maximum shock pressure at some distance from the blast is related to the detonation pressure, the travel path and the media of passage.

a. Density. The density is the mass of the product per unit volume, usually expressed by Specific Gravity (SG_e). The more dense the explosive the greater the power of the shot. SG_e can vary from 0.5 to 1.7 (Dick et al. 1993a). An explosive is easier to handle and place submerged, if it is heavier than water, $SG_e > 1.0$. Density is one of two factors contributing to the detonation pressure within the detonating material.

b. Detonation Velocity The detonation velocity (v_e), by title, is the propagation rate through the detonating media. The v_e ranges from 1,900 to 7,500 meters/second (mps). Konya and Walter (1985) provide an equation for the detonation pressure, P_d, [converted to metric units]

$$P_d = 4.50e\text{-}4\ SG_e\ V_e2\ /\ (1. + O.80\ SG_e) \qquad \{1\}$$

where the pressure units are megapascals (Mpa, see Table 2.1 for common pressure conversions) for V_e in mps. The peak pressure at the wall of the explosive's containment (typically a borehole) may be one half the P_d , while Konya and Walter (1985) feel that the detonation state does not exist at this boundary. The shock pressure due to the P_d must extend to the surrounding media, and is related empirically to the wall pressure and, ultimately, to the P_d.

Table 2.1. Pressure Unit Conversions

	kPa	bar	psi	atm
1 kPa	1	.0100	.1450	.009869
1 bar	100	1	14.50	.9869
1 psi	6.895	.06895	1	.06803
1 atm	101.3	1.013	14.70	1

The compression-wave pressure at any location in the water column is related to the shock pressure in the detonating material. Since the maximum pressure, P_m, within the water is the cause of hazard, its relation to P_d and to the square of V_e is extremely relevant. The need to fracture a mass prior to its displacement (an explosive with large shock energy) is an argument some authors and blasters make. Contrarily, Dick et al. (1993a) indicates that "typical of most operations, it is of little importance." Given two explosives of the same charge weight, A with a V_e of 4,250 mps and B with a V_e of 6,000 mps, the P_m for explosive B would be twice the P_m value at the same distance as for A. Thus, an explosive with a low V_e should be considered for submerged shooting when the hazard of shock pressure is a concern. The doubling of pressure is contrary to unpublished data by Keevin (1995) that three commercial explosives of differing V_e produced similar pressures and the same mortality in fish for unconfined, shallow, water-column shots. Other factors may be more important in reduction of the shock-wave pressures (Oriard 1983).

c. Fumes. Fumes are the toxic gaseous by-products (chiefly carbon monoxide and nitrous/nitric oxides) of the detonation reaction. The fume class or quality for each blasting compound is a relative measure from poor (excessive toxic gas creation) to excellent (insignificant toxic gas production). Some of these toxic products remain as a dissolved hazard in the ambient water body, which may have a detrimental effect on aquatic life. Underwater blasting creates conditions that may

lead to increased fume production: inadequate water resistance and inadequate priming (Konya and Walter 1985). "Permissible explosives" used in underground coal mining should not be considered an alternative explosive for underwater blasting. Permissible explosives are purposely less efficient, cooler reactions to avoid igniting coal dust, and have worse fume quality than other blasting materials.

MEDIA CONSIDERATIONS

Blasting in solids beneath or adjacent to the water column is normally conducted to remove obstacles. [Some removal methods may have the charge resting on the solid's surface in air or in water.] Explosives are placed typically in boreholes drilled into the mass to be removed. The shock front travels most rapidly down the centerline of the explosive column. Detonation proceeds more slowly at the boundary of the explosive with its container and passes into the surrounding medium. The shock wave, after passage into the enclosing material, does work crushing, fracturing and/or compressing the material. The loss of the energy supply, use of energy to produce work on the medium, and the ever-expanding surface of the compression front causes the shock wave to slow to the sonic velocity of the medium. Particle disturbance at this transition distance from the explosive becomes the commonly known compression or Primary wave (P-wave). The shock wave within the supersonic zone, called the near field, exceeds the elastic strength of the medium producing fractures and permanent deformation. The P-wave beyond the transition distance, termed the far field, remains within the elastic limits of the material (causing no lasting effects in rigid solids).

Seismic exploration, fish sampling, military use and explosives research may be conducted by blasting in the water column (open-water shot) of natural environments. Explosions in the water column produce P-waves in the far field. The P-waves originate from the shock wave. P-waves also are created from the contraction points of the pulsating gas bubble of gaseous reaction products, when the gas bubble does not reach the air-water surface before reaching its contracted state.

The more important differences between water-borne blasting and shooting within solids are the properties of water. Water's elastic moduli are not nearly as great as solids and, by its nature, water (like all fluids and gases) does not support shear waves.

The shock wave emanating from the explosive's detonation is "converted suddenly into potential energy of compression and kinetic energy of outward motion in the water medium" (Kramer et al. 1968). Cole (1948), in his landmark publication, describes the important processes and subsequently develops analytical and empirical equations of state for the expanding waves. The shock wave expands into the surrounding water medium applying a compressive load to the water. In a planar shock front, the amplitude of the pressure pulse will retain its size for some distance. Cole (1948) indicates that the particle velocity, u, is related to pressure, P. by

$$u = (P - P_o) / Z_w, \qquad \{2\}$$

where the hydrostatic pressure is P_o and the acoustic impedance, Z_w, is the density times the velocity of water.

The pressure amplitude for cylindrical and spherical wave forms diminishes with radial distance from the explosive. The nonplanar explosions produce two elements of the original waveform: the shock wave (or compressive flow) and the afterflow, or surge. The ever-expanding radial volume affected by the shock front must act

also tangentially to compensate for the "side load," called spherical divergence. It is this side pressure accommodation that contributes to the second term, surge. These two effects, shock and surge, occur simultaneously along the shock wave path to the transition distance. Beyond the transition distance, the velocity of the disturbance falls to the P-wave velocity for water and the surge term has become infinitesimal. The transition distance bounds the near-field region where acoustic radiation and afterflow are important from the far-field where only compressive flow is a factor.

A gas bubble or, as Cole (1948) terms it, gas sphere expands from the gaseous products of detonation well after the shock wave has passed. The gas bubble with its momentum expands to a maximum value, if the explosion is sufficiently deep so that the bubble does not break the water surface with the atmosphere. Bjarnholt (1978) provides a term for the maximum bubble radius, a_b, in m:

$$a_b = [1.3\ Q\ W\ /\ (1 + 0.1\ d_w)]^{1/3} \qquad \{3\}$$

for Q as the heat of detonation in megajoules/kilogram (MJ/kg), W being the charge weight in kg, and d_w is the explosive's water depth in m. Bjarnholt (1980) gives Q for a variety of explosives; for an estimate of a_b use a Q of 4.44 or 4.27 MJ/kg for Nitromethane or TNT, respectively.

The gas expansion forms an oscillating system with the gas' momentum and hydrostatic pressure of water. The gas bubble initially extends beyond the equilibrium state with the water load. The gas sphere cannot easily rise toward the air-water surface while in its larger size, because of the great volume of water that must be displaced for the bubble to rise. The surrounding water pressure causes the bubble to rapidly shrink to a minimum size of much greater dimensions than the original solid explosive's volume. The gas sphere at this contraction has greater internal pressure than the ambient water pressure, and expands a second time. A smaller shock wave is released at the instant the bubble is at its minimum diameter, in transition to its expansion phase. The gas bubble rises quickly while in the compressed volume. The oscillation in size continues until the gas sphere breaks the surface with episodic releases of energy and rapid vertical displacement at gas-volume minima. Cole (1948) shows that the period of bubble oscillation is a function of d_w, Q. W and fraction of remaining energy for the nth bubble oscillation, f_n. Cole indicates that the energy remaining is merely 14% and 7.6% for f_1 and f_2, compared to the total energy.

Pressure. The pressure between the dominant shock energy and the pulse from the gas sphere takes a declining exponential form. Depending on the distance from the blast, the pressure outside the explosive rises to a maximum pressure, P_m , in microseconds (μ s). USACE (1991) and Joachim and Welch (1997), in a form similar to that provided by Cole (1948), give the value of pressure in time after reaching the peak (P_m) as

$$P(t) = P_m e^{-(t - ta)/\Theta} \qquad \{4\}$$

for t_a as the arrival time and Θ , the time constant. USACE (1991) and Joachim and Welch (1997) give the equations for the parameters of {4} [which herein have been converted to metric units].

$$P_m = 53.1\ R_s^{-1.13} \quad \text{[MPa]} \qquad \{5\}$$

$$t_a = r / c_w \qquad \{6\}$$

$$\Theta = 9.2e\text{-}5\ W^{1/3}\ R_s^{\ 0.18} \quad [s] \qquad \{7\}$$

$$R_s = r / W^{1/3} \quad [m/kg^{1/3}] \qquad \{8\}$$

Equations {5} through {8} use the lateral distance, r, in m, pressure in MPa, time in seconds (s), velocity in mps, and equivalent weights of TNT in kg. R_s is the scaled range, the distance normalized by the explosive weight factor. USACE (1991) and Joachim and Welch (1997) give the TNT-equivalence for several explosives types and, in particular, the 1.1 weight conversion for Nitromethane. Medwin (1975) provides an equation for the sonic velocity of water (in mps) as a function of depth (d_w), temperature (T), and salinity (S) in parts per thousand (ppt).

$$c_w = 1449.2 + 4.6\ T - 0.055\ T^2 + 2.9e\text{-}4\ T^3 + (1.34 - 0.01\ T)(S - 35) + 0.016\ d_w \ [mps] \qquad \{9\}$$

for O m < d_w < 1,000 m, 0 ppt < S <45 ppt, and 0° < T < 35°C.

Scaled range, R_s, is an important term. R_s allows the comparison of differing explosive weights. It provides the means to "scale" the pressure, vibration, and mortality effects of blasts. The distance of comparison will need to be large enough to be well beyond the transition distance, in the far field, for the larger explosive weight. Equation {8} indicates that the same effect will occur at double the distance when the charge weight, W. is cube of two, or eight times, greater. The blast effect (pressure or mortality) will be the same at about twice the distance for: 16 kg replacing 2 kg of the same explosive material; 80 pounds (lb) substituted for 10 lb; and, 3,200 kg replacing 400 kg.

Equation {4} is an empirical form and does not resolve the variation of pressure due to boundary effects nor time duration to the bubble pressure arrival. The pressure in very deep water without nearby surfaces will fall below P_o termed "negative pressure," due to the inflow of water on the collapsing gas sphere. Negative pressure merely indicates that the ambient pressure falls below the gage hydrostatic level. The pressure does not decline below zero absolute pressure, as water has minuscule tension capacity. Other travel paths of the shock wave can complicate the waveform, when approaching other surfaces. Figure 2.1, reproduced from USACE (1991), shows the four major wave types affecting pressure at a point. The first arrival at some location in the water column due to a blast also in water (when the shot is well removed from a higher velocity bottom material) is the <u>direct wave</u>. The upper wave of Figure 2.1 shows its rapid rise and the decay form of equation {4}. After some additional time there will be two (or many more multiple) <u>reflections</u>. The reflection off the air-water interface is negative, due to yielding (displacement) of the surface. The air-surface reflection is of nearly the exact amplitude as the direct wave, because of the impedance contrast with air. As shown in Figure 2.1, the air-surface reflection arrives later than the direct arrival, due to the added distance traveled in reflection. The bottom surface is not a perfect reflector; this surface accepts energy, so the bottom-reflection's amplitude is less than the direct wave's. The amplitude from the bottom reflector is in the same positive sense as the direct wave for the bottom and will not yield in displacement, like the air-water surface. The bottom reflection is shown third in Figure 2.1. The arrival of the two reflections depends upon where in the water the shot and receiver are located. For Figure 2.1, the shot/receiver locations are much nearer the air surface than the solid bottom. The bottom medium refracts some energy and, at a critical refraction distance (for a bottom medium's acoustical velocity exceeding the speed in water), induces a <u>refraction wave</u> that imparts

energy back into the water. The refraction wave is the fourth in Figure 2.1. The resultant wave for the assumed geometry of the example is the lowest graph. This example does not show possible multiple reflections between the air surface and the bottom, nor arriving bubble sphere peaks.

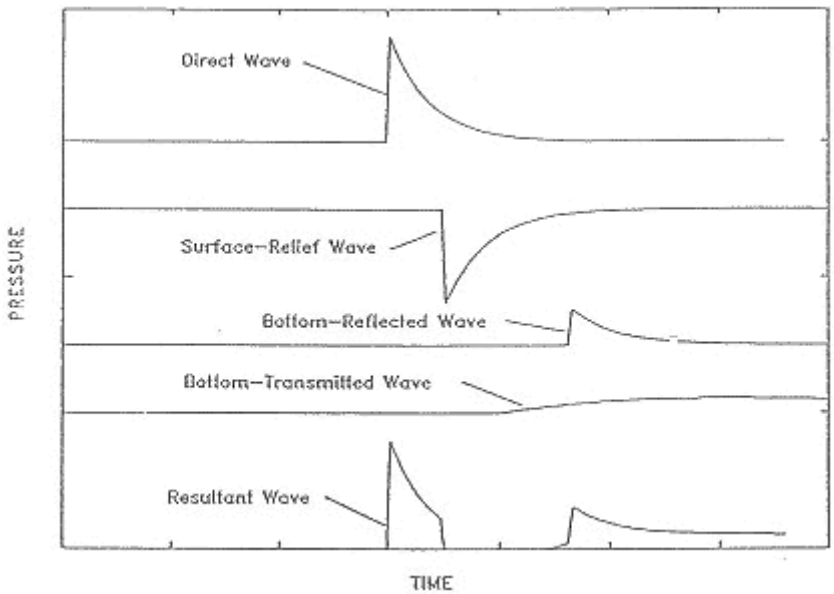

Figure 2.1. Shock-wave components and resultant wave (USACE, 1991)

Blasts created by an explosion located near the air surface have no oscillating bubble of explosion gases. The gases will be vented to the air as a column or plume, when $d_w < a_b$. There will be no latter pressure wave arrivals in this case from a gas sphere. Bottin and Outlaw (1987) provide an estimate of the water plume radius, a_p, [converted to a metric relation]

$$a_p = 18.9\ W^{1/3}\ (d_w + 10\ \text{m})\ \ [\text{m}] \qquad \{10\}$$

for W in kg and d_w in m. A column of water and gas is ejected into the air of radius apt The displaced water column extends to the hemisphere of like radius, centered at d_w. The water rushing to replace the vented plume volume can cause adjacent negative gage pressures from the venting gas and water displacement long after the shock-wave's passage.

The explosive's shock energy, when sufficient, can produce a sizable "cavitation hat" near the air surface just beneath the water. Cavitation is the negative gage pressure effect exhibited by explosives near the air-water surface and by boat propellers. The cavitation is caused by the tensile movement in the water toward the air. The proximity to the air surface assures that there will be a negative pressure reflection as part of the wave form. The P_m using equation {4}, is 9 MPa for just 10 g (not kg) of high explosive. In perspective, this is 90 times the atmospheric pressure of 0.1 MPa; thus, the air-surface reflection of a tiny explosive weight will produce negative pressures. The water near the surface can only accommodate a gage pressure of -0.1 MPa, but the reflection attempts to produce pressures to -9 MPa and results in cavitation. Christian (1973) defined the cavitation's cylindrical volume of radius, R_c, and thickness from the air-water surface to depth Do (not to be confused with the explosive's charge depth, d_w). This "cavitation hat" is a flattened disc of diameter $2R_c$, centered vertically above the

midpoint of the blast. There is a potential within the cavitation hat for overextending air-filled organs due to the negative pressure; this damage potential can produce organ damage or mortality. By equations, Christian reports [converted to metric units]:

$$0.036\ d_w^{1/2}$$

$$R_c \approx 40\ d_w^{1/2}\ (2.2\ W)\ [m] \qquad \{11\}$$

$$D_c \approx 3\ W^{0.3}\ [m] \qquad \{12\}$$

for $d_w \leq 15$ m and $W \leq 450$ kg.

Impulse. Empirical estimates of pressure, strength and energy were required prior to the recent development of accurate and inexpensive recording equipment. Piezoelectric pressure transducers, commercially available only recently, can measure these large, rapid pressure wave variations. The strength, or impulse, of the wave is its momentum as it crosses a surface. The integral of pressure over time is momentum per unit area and is called impulse, I.

$$I = \int_{ta}^{t'} P\ dt \qquad \{13\}$$

The units of impulse are merely pressure-time, e.g. Pa-s. The impulse is the area under the pressure-time curve, for example the bottom graph of Figure 2.1. The length of time to evaluate the integral depends on the purposes and geometry of the blast. Cole (1948) recommends $(t' - t_a)$ be 6.7Θ , but he accepts that this is arbitrary. Cole (1948) chose 6.7Θ to resolve the strength in only the wave's exponential-decay portion prior to the bubble pulse. Gaspin (1975) and some subsequent authors use a long integration time without clearly stating their method of period evaluation. Different authors calculate impulse over varying periods and use either or both the positive pressure interval and the negative gage pressure duration. The decision for the integration period must account for the blasting's intent and waveform complexities. Cole (1948) estimates [converted to metric form]

$$I(6.7\Theta) = 7.41\ W^{1/3}\ R_s^{-1.05}\ [kPa\text{-}s] \qquad \{14\}$$

for W in kg and R_s in $m/kg^{1/3}$. USACE (1991) and Joachim and Welch (1997) furnish an impulse estimate without specifying an integration interval [converted for metric values]:

$$I(t) = 5.75\ W^{1/3}\ R_s^{-0.89}\ [kPa\text{-}s] \qquad \{15\}$$

for W in kg and R_s in $m/kg^{1/3}$. A much more accurate determination of strength is provided by obtaining pressure readings at about 1. μ s intervals for the full pressure range and integrating the pressure record in time by {13}. While this latter method is preferred, there are many difficulties in properly recording the pressure wave with pressure transducers (USACE 1991, Joachim and Welch 1997, and Hempen and Keevin 1997).

Energy. Shock-wave intensity is assessed by determining the energy flux density, E. The intensity is a measure of flow or change of energy across a unit surface "normal to the direction of [wave] propagation" (Cole, 1948). Cole develops E for

both shock-wave terms of compressive flow and afterflow as components of one formula. He proves that the surge term theoretically is negligible beyond 10 to 20 times the effective explosive's charge radius (a_e). Cole (1948) gives

$$E = Z_w^{-1} \int_{ta}^{t'} P^2 \, dt \qquad \{16\}$$

the intensity as for $P \leq 135$ MPa. E is in units of J/m^2 for Z_w in SI units. The units of intensity are energy or work per unit area. Cole recommends the same integration period of 6.7Θ for E. The integration period should be determined by the intent of the blasting, like the discussion above for impulse. Cole (1948) approximates the intensity as [converted for metric values]

$$E(6.7\Theta) = 105 \, W^{1/3} \, R_s^{-2.12} \; [J/m^2] \qquad \{17\}$$

for W in kg and R_s in $m/kg^{1/3}$

The integrals of equations {13} and {16} accurately resolve the strength and intensity of the shock wave at any point in the water column where pressure is measured. Both formulae are correct when the explosion is mid-water or when the shot is embedded, because each measures its parameter based on the pressure wave recording at the point of interest. The empirical formulae are estimates for the water-column shots at best, and are not intended to represent explosions in solids overlain by a water mass.

TRANSMITTING MEDIA

Explosive shooting is conducted in solids beneath the water surface for removal or demolition uses. The work accomplished by the gas expansion phase is energy consumed. Less gas energy can be converted to P-waves to enter the water, since the gas bubble will not pulsate as it rises. Conversely, the shock energy rapidly disturbs all surrounding environs. The P(r,t) for the first arrival must be resolved by the properties of the blasted medium, blast geometry, and wave transmissions across boundary surfaces.

The propagation of waves across surfaces between media has been developed by text authors, such as Kinsler and Frey (1950) and Grant and West (1965). Oriard (1985) shows that the energy transmitted to water from rock of specified properties varies from 0.0 to 0.37 of the total shock energy for varied angles of incidence (Figure 2.2). Oriard (1985) shows that for land-based blasting adjacent to a water body the pressure wave's amplitude "is about 1/40 to 1/400 of" that amplitude which would be calculated for perpendicular (0.°) incidence between water and ideal rock. Shock-wave energy would be considerably greater when the blasted medium is directly beneath the water column. In this latter case, 30% to 37% (for 30° down to 0° incidence, respectively) of the generated energy enters the water. Blasting would not usually be accomplished in weak material of low P-wave velocity and Elastic Modulus. The solid's properties would almost always be significantly greater than water's, thus the pressures and energies should be comparable to those of Figure 2.2, in general. At large incidence angles (greater lateral distances from the blast within a submerged solid), less energy enters the water from the solid, but the water-borne energies from directly above the shot persist in the water beyond the critical refraction angle. For the case cited by Oriard in Figure 2.2, this angle is 19.1° (Grant and West 1965). The water column acts as a wave guide at incident angles within the water greater than the refraction angle while continuing to receive energy from the solid. In other words, some energy at large lateral distances from the shot is captured and retained by the water column.

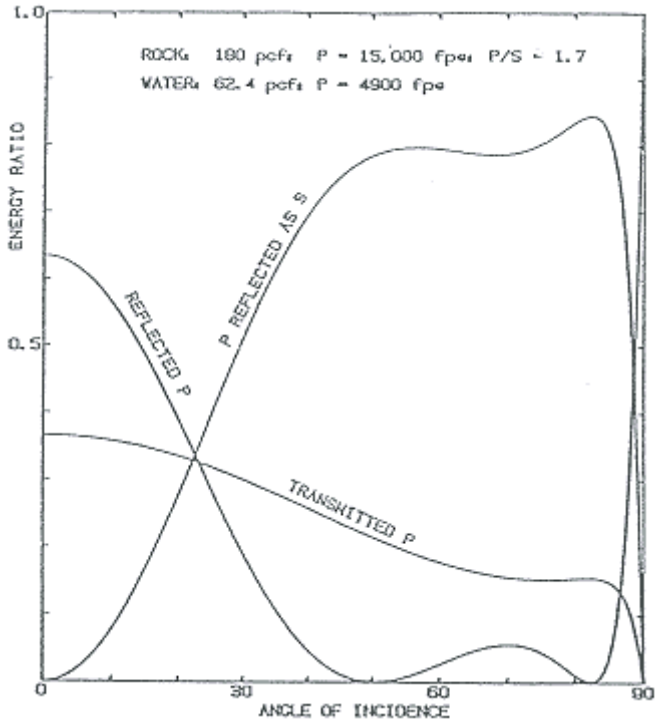

Figure 2.2. Relative energy entering the water column from a rock material versus the incident angle at the boundary (Oriard, 1985)

Another consideration of the shock wave from a solid-confined blast is the direction of the explosive's detonation. Initiation of shots is normally at the deepest part of the explosive charge. The detonation begins near the bottom of the boring and continues to propagate up the explosive column toward the surface. The detonation wave is focused toward a narrow cone in the direction of travel. Less shock energy is transmitted radially and only a small percentage of shock disturbance emanates opposite the detonation direction (Konya and Walter 1985). The shock wave from the completed upward detonation is focused toward the water column. Thus, the strongest intensity of shock energy in the water column is directly above the blast for a confining solid. The shock energy crossing the boundary, which is generally normal to the explosive's placement borings, into the water is the largest (0.37 for the cited example) of all the transmission angles.

Blasting in a solid beneath the water surface allows gas energy to be released to the water. The extreme cases for gas energy production are comparable to two scenarios: the blast detonated in the water column (maximum gas energy contribution) and the explosive shot within a material of sufficient strength to retain the blast products. There is no gas energy component for a mid-water explosion, if the explosion occurs within a container that totally contains the reaction gases. There would also be no oscillating gas bubble since the container retained the expansion products. All the work (in actual production blasting) accomplished by the detonation's gases in moving the solid mass is work that cannot contribute to bubble oscillation energy release in the water column. Premature venting of the explosives' gases reduces the displacement of the mass and imparts this gas energy to the water column. Having sufficient stemming (the granular filling from the top of the blasting material to the top of the borehole) length eliminates the early release of the detonation's gases.

Shallow Water Environments. The term "shallow water" may be defined for several circumstances. A useful consideration relates water to its sonic velocity. Relationships to blasting could be used to define what is shallow. Lastly, shallow

can be defined by the blasting objective and limitations on the depths of mitigation.

Equation {9} shows that velocity is heavily dependent on water temperature and pressure, or depth. Several naturally occurring temperature layers exist in bodies of water. Urick (1983) indicates that four major layers may exist: surface layer, seasonal thermocline, main thermocline and deep thermocline. A thermocline is a unit of water which has a uniform gradient of temperature (and dissolved oxygen) with depth. The surface layer produces a daily variation of water's sonic velocity; It's velocity may be constant or variable with depth. Beneath the surface layer lies the tier of the seasonal thermocline, which has an annual variation and a negative thermal (and velocity) gradient. In deeper bodies of water, the main thermocline develops with a nearly permanent, uniform negative gradient. The deep isothermal layer occurs in waters below the main tier (occasionally below 1,000-m depth - Urick 1983). The deep isotherm has a roughly constant temperature of 4.°C and its increasing velocity with depth is due to hydrostatic pressure. Shallow water depth may mean the level above the interface of the main and deep thermoclines, if they exist. At this surface, water's velocity is a minimum and refractions above or below this horizon tend to remain on their increasing velocity side. Shallow may mean the depths of water bodies that do not develop a main thermocline. For impoundments without main thermoclines, shallow may be the depth of the winter velocity minimum.

Shallow water depth in conjunction with blast parameters may apply to depths above which no gas sphere develops or may be considered the lowest depth of the cavitation hat. Both of these shallow depth definitions depend on the explosive's weight. The greater the instantaneously shot charge weight, the deeper the allowable depth to avoid venting of the reaction gases or by equation {20} the greater is D_C . A reduced environmental impact occurs for low detonation velocity explosives with sizable gas energy components. None of the vented reaction gases may oscillate in the water column for these reduced impact explosives with significant confinement. By this gas energy definition of "shallow," the correct choice of explosive and confinement parameters would result in great depths with no gas energy contribution of pressure to the water column.

Shallow water depth may be defined by the working limit of typical underwater blasting. Only occasional, special purpose blasting for engineering work would require blasting deeper than 20 m for even oceanic harbors. Location of borehole positions would be more difficult at this 20-m water depth. Harbor depths are infrequently maintained below 15 m. Tunnel or mineral blasting beneath water bodies is conducted at much greater depths, but the blast displaced solid mass is not exposed to the water body. Shallow water at depths within (an arbitrary) 20 m of the water surface represents herein the relative ease of conducting blasting work, or its more frequent use, and the zone of increased environmental harm.

PRESSURE-WAVES

Shock waves from underwater blasting are of interest not only from an academic sense, but also because they may be important to blast production and damage due to explosive use. The explosive selection has a bearing on both the production and damage potential. The hole diameter, for example, for charge placement is related to the minimum removal height, called the bench height, by the "Rule of Five" (Konya and Walter 1985). Minimum bench heights of 3. m require 50. mm, or smaller, diameter holes. There are fewer blasting agents with small critical-diameter sensitiveness that will detonate in this hole size. Both dynamites and water gels meet the sensitiveness criterion and are water resistant; however, dynamites have higher detonation velocities (Dick et al. 1993a). The choice of a water gel blasting agent would lead to less shock energy, and therefore less aquatic mortality potential, while allowing proper rock breakage.

> In practice, nearly all underwater blasting will be done with holes larger than 50 mm, regardless of depth. The greatest expense is that associated with drilling, and that expense is dramatically reduced by drilling holes of larger diameter on wider spacings (Oriard, 1983).

Brower (1977) was one of the earlier authors to recognize:

> The two basic reasons for restricting or limiting the water shock levels are: (a) preventing damage to nearby structures and (b) minimizing environmental damage.

Brower was concerned with both structures and fauna. While other authors had one concern or the other, Brower recognized the need to mitigate both. Brower provides Cole's estimate for P_m like equation {6}. Brower's provisions to moderate water shock were limited to care with the actual blasting measures.

<u>Effects on Structures</u>. Several authors estimated blast effects on structures by pressure waves, as related to the Pm and impulse (I). Langefors and Kihlstrom (1978) emphasized that the reduction of both P_m and I are important to the safety of structures. Oriard (1983) presented:

> ...the damage potential of underwater waves is not directly related to the peak pressure, but to impulse... it may be more damaging to lengthen the duration of the pressure pulse than to lower its peak pressure depending on the characteristics of the structure in question.

Oriard (1992) suggests that dynamic strain cannot be related to the static stress regime of most analyses. He also implies that negative pressures from venting (and from cavitation) cause plucking from tension at the concrete-water interface.

Structures should be addressed like the Oriard (1985) analysis to estimate dynamic stress and strains on the submerged form. Oriard (1985) chose a procedure of conducting small production shots to evaluate "the pressures in the water adjacent to the powerhouse walls and stoplogs." This allowed the development of one program to full scale without damage to the extremely important adjoining structures.

CHAPTER 3

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AQUATIC PLANTS

INTRODUCTION

Aquatic plants, both submerged and emergent, have great importance as a food source and shelter for both aquatic (Rozas and Odum 1988; Lubbers et al. 1988) and terrestrial organisms (Bellrose et al. 1979). Extensive damage and mortality to aquatic plant beds resulting from an underwater explosion could possibly upset the balance of the ecosystem being altered.

DAMAGE AND MORTALITY OF AQUATIC PLANTS EXPOSED TO UNDERWATER EXPLOSIONS

Data on the effects of underwater explosions on aquatic plants are very limited. Ludwig (1977) used explosives as a "herbicide" to remove eelgrass (Zostera marina) to create a channel within the Niantic Estuary at Waterford, Connecticut in an attempt to improve water quality and containment of egg and larval stages of the bay scallop (Argopectens irradians). A contractor demonstrated the efficiency of eelgrass removal techniques with in situ observations being performed on the detonation of single and multiple charges as well as a weighted length of detonation cord alone. During an eight week period following the explosions, the eelgrass experienced an orderly dieback. In no instance was the disappearance less than complete along an expanding circle of defoliation. In the case of the single charged detonations, the circular defoliation had a final diameter of approximately seven to eight meters. The chain or string detonations created overlapping rings of impact ultimately clearing a rectangular area approximately 40 m long and 7 to 8 m wide. The detonation cord created a similar impact but the final zone of influence was limited to approximately 2 to 4 m of total width. Unfortunately no information was provided concerning the charge type or weight.

Removal was restricted to eelgrass, with green algae (Codium sp.) and rockweek (Fucus sp.) thriving in the defoliated areas following eight weeks. Ludwig (1977) hypothesized that the orderly species-specific defoliation was the result of a disruption of the cellular structures within the rhizomes. As the cellular destruction radiated outward the thallus structures separated in a manner reminiscent of normal exfoliation during the late autumn or winter period. Examination of the rhizomes, however, clearly indicated cell wall failure internally while the epidermal fibers continued to hold the structure together.

Without explosive weight information or pressure wave data it is impossible to compare aquatic plant mortality levels with other aquatic organisms.

Smith (1996) examined the effects of underwater explosions on two types of aquatic vascular plants (emergent and submerged), and three algal species. Two species of vascular plants (Ludwigia peploides (HBK) Raven and Myriophyllum heterophyllum (Michx.)) and three algal species (Chara zelandica (Willd.), Chara contraria (A. Braun), and Nitella acuminate (A. Braun)) were exposed to 2 kg of T-100 Two Component (green stick) explosive with a #8 instantaneous electric blasting cap. Explosive charges were suspended from a float to a depth of 1.5 m below the water surface. Plants were placed in hardware cloth cages and set out at 2.5, 4.5, 6.5, 8.5 and 10.5 m from the blast. Cages were attached to a buoyed rope of appropriate length to maintain the cage centers at a depth of 1.5 m below the water surface. A control cage contain each of the plant species was used for each blast. Controls received the same treatment (i.e., transported to and from the blast area) as

experimental plants with the exception of exposure to blast pressures. Each test was replicated (test blast 1 and test blast 2).

Plants were weighed pre-test and exposed to the test blast on September 30, 1996. All plant material remaining after the explosions was transported back to the laboratory and re-weighed, using the same procedures as before the blast. Plants were maintained in 10-gallon aquaria in a greenhouse. At the end of the first week, plants were removed from the tanks and all dead tissue was removed. Remaining plant tissue was weighed and recorded. This procedure was repeated on October 8, 17, 24, and November 26 at which time the project was concluded.

Aqueous phase measurements of photosynthesis were made in the laboratory using the methods of Walker (1987) with the Hansatech DW2/2 (Hansatech, Inc., UK) oxygen electrode and a 2.5 ml chamber.

Effect of the explosion on biomass: Individual species

Chara zelandica lost an average of 18.06% of its biomass over all distances. The greatest loss was seen at 6.5 m (24.3%) and the least at 2.5 m (15.5%) for blast 1. The greatest loss of biomass for blast 2 occurred at 6.5 m (19.3%) and the least at 2.5 m (10.3%). Plants for blast 1 had survival at 6.5 m, 8.5 m and lO.5 m. Plant survival for blast 2 was seen only at 4.5 m. No surviving plants regained 100% of their original biomass while the control plants had 109% of their original biomass at the end of the project, a net gain of 9.3%.

Ludwigia peploides gained biomass in some instances, as high as 5.3% for blast 2 at 4.5 m. Biomass losses ranged from 10.7% at 4.5 m and less than 1% at 8.5 m for blast 1. Blast 2 losses were seen only at 4.5 m (1.5%). Plants at 2.5 m for blast 1 were the only group of *L. peploides* to have 100% mortality. The surviving test plants had a greater increase in biomass than the control plants, which gained only 1.7%; however, none of the surviving plants regained 100% of their original biomass.

Myriophyllum heterophyllum lost biomass in both test blasts. Blast 1 had the greatest loss at 2.5 m (24.3%) and the least at 4.5 m (<1%). Greatest loss of biomass for blast 2 was also at 2.5 m (19.3%) and the least at 4.5 m (1.5%). Mortality was 100% for both test shots at 2.5 m, 4.5 m and 6.5 m. Mortality was also 100% in blast 1 at 8.5 m. None of the surviving test groups regained 100% of their original biomass. The control group had a net gain of 17.9% for both tests. Plants at 4.5 m for blast 2 had a small gain in biomass (3.2%) after the test. Biomass loss for blast l ranged from 13.2% (6.5 m) to 8.6% (4.5 m). Biomass losses for blast 2 ranged from 23.9% (10.5 m) to 8.9% (6.5 m). Growth curves for all test groups became positive after the second week. The control group had a net gain of 19.9% over its original biomass by the end of the study. Five of the ten test groups had greater biomass than before the test. The group at 2.5 m in blast 1 gained more biomass than the control (39.4%).

Nitella acuminata lost biomass in all test groups as a result of the explosion. Losses for blast 1 ranged from 9.6 (10.5 m) to 5. 5% (8.5 m), while blast 2 ranged from 14.0% (2.5 m) to 2. 8% (6.5 m). All plants at 2.5 m for both test blasts and at 4.5 m for test 2 had 100% mortality. The control group had 26.2% greater biomass at the end of the project. For blast 1, groups at 87.5 m and 10.5 m had greater biomass than their original biomass. Biomass for test 2 was greater at 8.5 m than originally, although other surviving groups had greater than 95% of their original biomass.

Effect of the explosion on photosynthetic rates

All species responded to the explosion in a similar manner, i.e., a reduction in photosynthetic rate in the treatment group of plants, relative to the control. The effect on photosynthesis was greatest nearest the blast (2.5 m), and became progressively less severe with each increment in distance (4.5 m, 6.5 m, 8.5 m, and 10.5 m). Two species, *N. acuminata* and *C. contraria*, maintained positive, but low, rates of photosynthesis at 2.5 m. At 4.5 m, *M. heterophyllum* began to show photosynthetic activity, followed by *C. zelandica* at 6.5 m. By 8.5 m, all species demonstrated photosynthetic activity. As a percent of the photosynthetic rate of the Control the species ranked as follows:

2.5 m, NA > CC > MH=LP=CZ;

4.5 m, NA > MH > CC > LP=CA;

6.5 m, NA > MH > CC > CZ> LP;

8.5 m, NA > MH > CC > CZ> LP;

10.5 m, NH=NA > CC > CZ > LP.

These results are preliminary and are currently being prepared for publication. Work is currently in progress to establish the relationship between pressure waveform and plant damage and mortality.

MITIGATION TECHNIQUES TO PROTECT AQUATIC PLANTS FROM UNDERWATER EXPLOSIONS

Mitigation techniques described for fish are also applicable to aquatic plants (see Chapter 8). Any attempt to reduce the pressure waveforms will reduce the potential kill zone of aquatic plants.

CHAPTER 4

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AQUATIC INVERTEBRATES

INTRODUCTION

The potential for injury and mortality to aquatic invertebrates, resulting from underwater blasts, has been well documented in agency and contractor reports and the scientific literature. However, with the exception of brief literature reviews concerning the effects of seismic exploration (Alperin 1967, Linton et al. 1985b) and ordnance testing (O'Keeffe and Young 1984), a comprehensive critical review of the literature does not exist.

The purpose of this review is to provide a comprehensive description of the experimental designs for each reported investigation. The study design aspects reviewed are: species tested, how organisms were caged, type and weight of the explosive charge, location of the explosive charge and test organisms in the water column, duration of the mortality test, pressure wave recording techniques and author's conclusions. This review also provides a critical evaluation of the studies based on their experimental designs and analysis of data.

APPROACH

Existing literature was reviewed in chronological order based on publication date. This approach was taken rather than a phylogenetic analysis in order to best evaluate study results for each investigation based on their experimental design. In addition, inadequacies in study design (e.g., small sample size, inadequate or no controls, differences in post-explosion mortality observation periods, and differences in cage material) make comparison among studies difficult, if not impossible. All of the studies, with the exception of Linton et al. (1985a), were originally designed and conducted using English measurements. To maintain the integrity of the original studies, all data are reported in English measurements and followed with metric equivalents in parentheses. Conversions were rounded to one decimal place. Metric conversions have been made to reproduce the English unit; added significant digits of the metric conversions do not represent the precision of the original research.

Common and scientific names follow Cairns et al. (1991) for Cnidaria, Turgeon et al. (1988) for mollusks, and Williams et al. (1989) for decapod crustaceans. Common and scientific names not covered in American Fisheries Society publications are used as given in the original publication. In some instances, either the common or scientific name of the organism being tested was given in the original publication, but not both. In such cases the appropriate common/scientific name has been provided in parentheses with an equal sign to indicate that the name has been added and was not part of the original publication.

INVERTEBRATE LITERATURE REVIEW

The first published investigation of invertebrate mortality resulting from underwater explosions was conducted by Knight (1907) in response to a "doleful tale of a poor lobster fisherman" related to Knight by a young seaman. The young seaman's story was that "when the lobster fisherman had accumulated about 500 animals in his pound (a pound is a cubical box made of wooden slats, anchored from shore, which allows water to pass through), some mischievous or ignorant person put off a dynamite blast about 150 or 200 yd (137.2 or 182.9 m) away, and killed every

lobster." As the young seaman first told the tale, "the lobster pound was 500 yards [457.2 m] away, but on cross-examination he was compelled to reduce the distance."

To test the accuracy of this story, six lobsters (=American lobster, Homarus americanus) were obtained from a local fisherman and tested with varying charge sizes and distances from the blast in water 12 to 15 ft (3.7 to 4.6 m) deep. In the first experiment, 3 large sticks of dynamite (of undefined weight) were detonated at a distance of 80 ft (24.4 m) from a lobster trap containing 2 lobsters, and at a distance of 40 ft (12.2 m) from a small lobster that was tethered by a piece of twine. The explosion produced no effect upon any of the lobsters.

In a second experiment, 2 large sticks of dynamite (of undefined weight) were exploded at a distance of 20 ft (6.1 m) from the small lobster. The animal was uninjured. The third experiment consisted of detonation of two sticks of dynamite within 10 ft (3.0 m) of a medium sized lobster. Knight (1907) indicated that there was "No result." In the last experiment, 3 sticks (of undefined weight) were exploded 15 ft (4.6 m) away from a trap which contained 5 lobsters which had all been used in previous experiments. The explosion overturned the trap, nearly overturned one of the piles on which the wharf was built, but "it seemed to have no effect on the lobsters."

Knight (1907) concluded that the 500 lobsters of the sailor's yarn had died, not from the effects of a dynamite explosion, but from suffocation. He surmised that the lobsters had been confined in too small a pound for too long a period, and the explosion was coincident with the fisherman's discovery of the dead lobsters.

The next published series of experiments evaluating the effects of explosives on invertebrate mortality occurred in response to a request from the Magnolia Petroleum Company to utilize dynamite charges up to 800 lb (362.9 kg) during the course of a refraction seismograph survey in waters off the coast of Louisiana. The area involved was in the heart of Louisiana's "jumbo" shrimp fishing grounds. Descriptions of the study design and results are presented in various degrees of detail in five separate non-refereed publications (Gowanloch and McDougall 1944, 1945, 1946; Gowanloch 1946a, 1950)

The first series of experiments, best described in Gowanloch and McDougall (1945), involved the firing of one 200 lb (90.7 kg) and two 800 lb (362.9 kg) charges of 60 percent gelatin dynamite unconfined and placed on the sea bottom in 18 ft (5.5 m) of water. Forty-five shrimp (Peneus setiferus) and thirty oysters (Ostrea virginica) were placed in 30 inch (762 mm) cubicle cages, positioned at 50, 100, 150, 200, 300, and 400 ft (15.2, 30.5, 45.7, 61.0, 91.4 and 121.9 m) from the shot point, and suspended midway between the surface and bottom in 18 ft (5.5 m) of water. Test animal were held in their positions for 48 hours before the charges were fired, were examined immediately before the shot, immediately after the shot, and at 24 and 48 hours post detonation exposure. Gowanloch and McDougall (1946) state that "adequate controls were established located far beyond any possible influence from the dynamite blasts." However, no details are given concerning control handling or subsequent mortality. Geophones, located at selected cages, recorded "the amplitudes of each charge." However, no pressure data were presented.

Gowanloch and McDougall (1945) concluded that shrimp were uninjured at 50 ft (15.2 m) by the 800 lb (362.9 kg) charge. They noted that "the shrimp still remained normal six days after the explosion. Yet the shock shook an oyster tugger ten miles away, and threw water 300 ft [91.4 m] into the air." They concluded that "No differential mortality could be found among the oysters, but for various biological reasons the authors consider that more experimental work is necessary before a satisfactory definite decision can be reached." No statistical basis for their conclusions or supporting data in tabular form are given on which statistical analysis could be conducted by the present authors.

A second series of experiments was conducted, "Since oysters constitute a highly valuable aquatic resource, damage to which was not apparent, when the experimental oysters were suspended as individuals in cages it was decided to re-examine effects of dynamite blasting on oysters where the oysters were part of an integrated reef" (Gowanloch and McDougall 1946). Descriptions of the study design and results are again presented in various degrees of detail in four separate non-refereed publications (Gowanloch and McDougall 1946; Gowanloch 1946b, 1948, 1950). It was concluded that the "seismographic explosions caused no subsequent mortality to the oysters."

Gowanloch and McDougall (1945) used cages that were 30 in (760 mm) cubes, constructed with a strong external wooden slatted frame (picture of cage on page 303 of Gowanloch (1948)). Specimen confinement was accomplished by attaching 1/2 in (13 mm) shrimp netting to the inside of the frame. Each cage was divided into two compartments by a vertical wall of shrimp netting. Anonymous (1948) questioned Gowanloch and McDougall's (1945) results since slatted wooden cages had been used in their experiments. Anonymous (1948) contended that use of the slatted wooden cages would "tend to produce a decrement in the shock and pressure reaching the enclosed animals." In addition, Aplin (1947) noted that during experiments previously conducted in Louisiana (presumably by Gowanloch and McDougall) "it was found wooden cages would be broken up by the explosions unless so heavily built as to give the impounded fish definite protection from the shock." Neither Anonymous (1948) nor Aplin (1947) provided experimental support for their contention.

Linton et al. (1985b) make reference, in their annotated bibliography, to a paper by Gowanloch and McDougall published in Louisiana Conservationist 4(12):13-16. The publication date, title, volume, and page numbers are identical to Gowanloch and McDougall (1945) published in Oil. A check of the Louisiana Conservationist indicates that this article does not exist.

Aplin (1947) conducted a series of experiments to determine the effects of explosives used in geophysical survey work to locate oil deposits along the California Coast. Four rough abalones (*Haliotis corrugata*) and four green abalones (*Haliotis fulgens*) were exposed to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The abalone were on the bottom, 55 ft (16.8 m) from the explosion. An hour after exposure the abalones were able to move when given tactile stimulation. However, none of them extended their mantles when put into an aquarium and all were dead within a few hours. Aplin (1947) noted "that further experiments will have to be made as they may have been killed by handling and transportation."

Aplin (1947) exposed eight lobsters (*Panulirus interruptus*) 270 to 300 mm long to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The lobsters were on the bottom, 55 ft (16.8 m) from the shot and almost directly below it. Five hours post exposure the lobsters were all alive and active. In a second test shot, 13 lobsters ranging from 170 to 230 mm in length were exposed to a 20 lb (9.1 kg) charge of 60 percent petrogel, fired 4 ft (1.2 m) below the surface. The lobsters were positioned 4 ft (1.2 m) below the surface and 50 ft (15.2m) away from the shot. Three hours post exposure the test lobsters were alive and examination of internal organs found no signs of damage. Aplin (1947) concluded that "Apparently lobsters are very resistant to concussion..." Aplin, as with his abalone test, did not use controls. However, since there was no mortality in the test lobsters it can be assumed that those factors which would be controlled for (i.e., handling, transportation, and water quality) did not cause mortality.

Both the abalone and lobster studies suffer from serious experimental design flaws including extremely small sample sizes, no replicate tests, and complete lack of controls. No description of how the abalones and lobsters were caged is provided in the text; although, fish were held in 3 ft (910 mm) square and 18 in (460 mm) deep

cages made of welded iron frames covered with 1/2-in (13 mm) mesh wire hardware cloth. Because of the small sample sizes and lack of controls, no conclusions can be made from this study.

Anonymous (1948, pp. 16-18) conducted a series of tests utilizing oysters (=eastern oyster) (Ostrea virginica) held in wire bags placed on the bottom. Table 4.1 provides data on two tests conducted with the largest explosive charge, 300 lb (136.1 kg) of TNT. They concluded that "Deaths among these over the two-week period all occurred within the 200 ft (61.0 m) radius except for a single dead oyster found in a bag exposed at a distance of about 960 ft (292.6 m). Excluding this one, it was found that the two week's loss was 5.4%, or a little more than double that observed immediately after the explosion." No attempt was made to measure explosive pressure waves during mortality testing. No statistical analysis of the data was conducted by the authors.

An analysis of the oyster data provided in Anonymous (1948) using a Cochran-Armitage Trend Test on a 2 X C stratified contingency table (strata = shot) were not significant (P>0.2) for distances to 960 or 400 ft (292.6 or 121.9 m) from the blast. It is concluded that the relatively low numbers of dead oysters did not change with distance from the blast. Furthermore, some mortality occurred in the controls and it is likely that some oysters dying at 2 or 16 weeks died from causes not related to the blast.

Table 4.1- Immediate, 2-week and 6-week live/dead counts for oysters (=eastern oyster, Ostrea Virginica) placed on bottom at 30 ft (9.1 m) depth and exposed to a 300 lb (136.1 kg) charge of TNT suspended 15 ft (4.6 m) (From Anonymous 1948).

SHOT 16

Distance from Explosion		Initial Observation 10-5-1945		2 Week Observation 10-18-45		6 Week Observation 11-16-45	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
25	7.6	19	1	17	2	15	2
50	15.2	19	0	16	3	13	3
100	30.5	23	1	21	2	19	2
200	61.0	20	0	19	1	18	1
400	121.9	20	0	20	0	18	2
960	292.6	20	0	19	1	16	3
Control		20	0	20	0	Lost	

SHOT 17

Distance from Explosion		Initial Observation 10-6-1945		2 Week Observation 10-19-45		6 Week Observation 11-17-45	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
25	7.6	21	0	21	0	20	1
50	15.2	23	1	22	1	22	0
100	30.5	26	0	25	1	23	2
200	61.0	29	1	29	0	25	4
400	121.9	26	0	26	0	21	5
Control	292.6	30	0	30	0	27	3

Anonymous (1948) conducted a series of tests utilizing blue crabs (Callinectes sapidus). They provided data, shown in Table 4.2, that summarizes four tests where blue crabs were held in cages placed on the bottom (depth not given) and exposed to

a 30 lb (13.5 kg) charge of TNT. Based on the results presented in Table 4.2, Anonymous (1948) noted that about 90% of the blue crabs were killed at 25 ft (7.6 m), under peak pressures exceeding 800-900 pounds/square inch, psi (5,516-6,206 kPa), and very few died at 150 ft (45.7 m), where pressure reached about 270 psi (1,862 kPa). Anonymous (1948) noted that intermediate distance gave surprising results, marked by the absence of any trend. This was confirmed by the present authors, utilizing a chi-square test. However, first value, and last value, differ from intervening four values ($P<0.001$), and first and last values differ ($P<0.001$). The second and third values do not differ ($P>0.1$), and values (2, 4, and 5) versus value (3) has $P=0.05$. Anonymous (1948) suggested that the erratic variation may be due to the irregular transmission of the shock wave along the bottom or to other unestablished causes. Although, external and internal damages were not quantified, they observed loss of part or all of the carapace, cracking of the carapace, heart rupture, broken spines and, autonomous loss of one or both claws. However, many of the crabs killed showed no macroscopic changes. Anonymous (1948) provided no data for control mortality, nor did they indicate that controls were used. Although the true mortality levels due to the blast cannot be known exactly, the data at 150 ft (45.7 m) give an upper bound of 7% on the "control" (e.g., handling) mortality.

No discussion is provided describing pressure recording. It is not clear if pressures were recorded specifically for this set of four experiments or if they used generic pressures given in Figure 7. This is an important point since pressure readings may vary with depth of charge, depth of pressure gauges and nearness of gauges to either the water-air (surface) interface or water-substrate (bottom) interface. In addition, Anonymous (1948) used copper ball crusher gages, which only record peak pressure.

The authors provide no information on how long crabs were held prior to determining mortality (i.e., instantaneous, 24 hr. 48 hr. or 96 hr. mortality). Period of observation could easily affect mortality levels, with longer periods having higher mortality, especially with no controls to evaluate the effect of holding time.

Table 4.2- Effect of 30 lb (13.5 kg) charges of TNT on blue crabs (*Callinectes sapidus*) held in cages on the bottom (bottom depth not given). Summary of four tests (From Anonymous 1948).

Distance from charge		No. held	% killed	% surviving
Feet	Meters			
25	7.6	37	89%	11%
50	15.2	55	38%	62%
75	22.9	22	55%	45%
100	30.5	37	38%	62%
125	38.1	23	48%	52%
150	45.7	14	7%	93%

Tollefson and Marriage (1949) evaluated the effects of channel blasting on three species miscellaneous crab species (*Cancer sp.*), and Pacific oysters (*Ostera gigis*). Cockles were captured the week prior to testing and held in an aquarium. They ranged in size from 60 to 79 mm rib length, average 70 mm. Oysters were clusters, ranging from 4-12, average 8.4 per cluster, of one and two year old taken from adjacent beds. Crabs used were small miscellaneous specimens brought from the Newport laboratory where they had been held for several months or more. They ranged in back width from 115 to 144 mm, average width 129 mm.

All specimens, except oysters, which were placed at 20 ft (6.1 m) or less from the center of the blast were placed in separate canvas sample bags with labels to facilitate locating and to prevent any mixing of specimens following the blast. It

is not clear how oysters and organisms beyond 20 ft (6.1 m) were handled. Tollefson and Marriage (1949) noted that they did not believe the canvas bags would affect the results. No control organisms were used. Four cases of 50 percent dynamite were fired as a single shot along a 95 ft (29.0 m) line in a sandy mud bottom intertidal area at Bayocean, Oregon. The mean depth of planting of dynamite was about 3 ft (0.9 m) below the surface. Water depth was 1 to 3 ft (0.3 to 0.9 m). No pressure measurements were taken.

Tollefson and Marriage (1949) found that a number of miscellaneous organisms, crabs (Cancer magister), a small snail (Thais Ep.), a small mud clam (Macoma sp.), and a single specimen of a commensal clam (Pseudopythina rugifera), were unaffected, while three sand worms (Nereis sp.) and several ribbon worms (Nemertinea) were found dead within 25 ft (7.6 m) of the blast. A number of ghost shrimp were found within 25 ft (7.6 m) of the blast. Seven of nine Callianassa sp. and 39 of 76 Upogebia pugettensis were found dead or died within 24 hours of the blast. The authors concluded:

1. "Little or no damage to surface cockles located 10 ft [3.0 m] or further from the center.

2. No damage to sub-surface cockles located 15 ft [4.6 m] or further from the center.

3. No damage to crabs located 30 ft [9.1 m] or further from the center.

4. No damage to oysters located 10 ft [3.0 m] or further from the center. (The foregoing does not consider any possible after-effects such as silting.)

5. A 50 to 75 percent mortality of ghost shrimp was found within 25 ft [7.6 m] of the center.

6. In the case of the invertebrates involved it is likely that almost all damage done by blasting is grossly physical in nature, that there is little shock or other after effects."

This study suffers from a number of serious design flaws and omissions of methodology information. Sample sizes were extremely small. There were no control animals. No information is provided on total weight of explosive detonated, other than "four cases" were exploded. A typical case of dynamite contains 50 lb (22.5 kg) of explosives; however, the strength and size of each cartridge causes the weight of each "stick" to have considerable variation. No information is provided on the canvas sample bags. Contrary to the authors' statement that the bags would not have "exerted any appreciable cushioning effect", the bags could have reduced pressure wave transmission and thereby reduced mortality levels. In addition, no information is provided on how test organisms were held beyond 20 ft (6.1 m). Pressure wave measurements were not made. The lack of explosive weight data, use of a linear charge pattern, and burial of the explosive, make prediction of explosive pressures using existing empirical relationships, for example Cole (1948), impossible. As such, it is impossible to determine the magnitude of pressure experienced by the organisms. Thus, the results are, at best, lower trend estimates of the mortality that unconfined organisms would experience.

Fry and Cox (1953) made casual observations on the effects of black powder on invertebrates off the coast of California during seismic exploration activities. The major objective of the study was to determine if fish were being killed by seismic exploration charges. A 45 lb (20.4 kg) charge of E.P. 138 Seismograph Black Powder was detonated within 6 ft (1.8 m) of the surface and divers were sent down

to make observations of damage. The authors noted that "Clams and tube worms were found, none of which had suffered ill effects from the blast. These animals all responded in the normal manner by quickly withdrawing siphons and tentacles when touched by the divers." After the second day of testing, the authors noted that "None of the invertebrates seemed to be affected; the sea anemones were extended, as were the tube worms; none of the corals had been broken; the sea urchins were still on the rocks and the sea cucumbers had not contracted."

Fry and Cox (1953) gave no information concerning the distance of the explosion from the invertebrates being observed by the divers. As such, it is impossible to even conclude that the invertebrates were unaffected at a given distance from a known size explosion.

It is quite possible that Fry and Cox's (1953) observations are related to the type of explosive utilized. It had been previously observed that black powder, a combusting medium and not an explosive, has little effect on fish (Baldwin 1954; Fry and Cox 1953; Ferguson 1962; Hubbs and Rechnitzer 1952) when compared to high explosives such as dynamite. For example, Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite explosions varied from 276 to 483 kPa. Peak pressures from slowly detonating black powder, producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes. The difference in fish mortality between black powder, a low explosive, and high explosives appears to be related to the waveform produced by each explosive type. Black powder produces a pressure waveform with a slow rise time and low amplitude whereas high explosives have an abrupt rise time, high amplitude, and short frequency. In addition, high explosives have a much higher negative pressure than black powder, as shown in Figures 8 and 9 in Hubbs and Rechnltzer (1952). The amplitude and short frequency of the negative pressure wave and resulting damage to the swim bladder may be the causative factor of mortality in fish exposed to high-explosive pressure waveforms.

Sieling (1954) conducted two experiments, carried out in separate locations during 1949-1950, to evaluate the effects of seismic exploration for oil on oysters in the Barataria Bay, Louisiana, region. Work in Bay de Chene was referred to as Experiment 1 and Bay Batiste work was referred to as Experiment 2.

Two explosive charges were used in each shot hole, one of 50 lb (22.7 kg) and one of 20 lb (9.1 kg) of Nitranon (nitro-carbonitrate), and these were exploded at a depth of 50 ft (15 2 m) and 30 ft (9.1 m) respectively. Charges were placed in pipes which were in holes drilled into the bottom. The general procedure was to drill the hole from a drilling barge, then move to the next location. A barge carrying shooting equipment and explosive would then move in and load the first charge into the pipe and fire it, then as quickly as was safe load the second charge in the pipe and fire that. The two pieces of equipment would then move around the other four shot holes and fire the charges at each hole in the same manner.

Shot points formed a diamond with the points 1,000 ft (304.8 m) apart and one shot point in the middle. Sieling (1954) noted that this distance simulated the worst operating conditions possible under the law as when two lines of seismographic explosions cross at right angles. There was no attempt to measure pressures.

Oysters (=eastern oyster, Ostrea virainica) were placed at 20, 60, 130 and 250 ft (6.1, 18.3, 39.6 and 76.2 m) from the point of explosions and in a staggered line. Control stations were located 750 ft (228.6 m) from the nearest shot point. At both the experimental and control stations oysters were put in trays and placed on racks above the bottom in Experiment 1 and placed on the bottom in Experiment 2. Water depth was not given. Additional controls, which are not described here, were established to evaluate the influence of various other environmental factors.

Results of this study are presented in Table 4.3. Sieling (1954) concluded that there was no correlation between the distance of the oysters from the explosions and the survival rate.

Kemp (1956) evaluated the effects of seismograph explosions by conducting a series of three tests with fish, shrimp (=Penaeus sp., three possible species occur in the area), oysters (=eastern oyster, Crassostrea virginica) and blue crab (=Callinectes sapidus) under actual exploration conditions. Test 1 was conducted in Corpus Christi Bay in water 13 ft (4.0 m) deep with a bottom of very soft, gray, mud. Test 2 was also conducted in Corpus Christi Bay in water 2 1/2 to 3 ft (0.8 to 0.9 m) deep with a bottom of hard sand. Test 3 was conducted in Aransas Bay in water 7 ft (2.1 m) deep with a bottom of soft, gray mud.

Specimens were held in 1/2 in (13 mm) mesh hardware cloth cages, except oysters which were in heavy wire trays. In each test one set of specimens was placed at the shot hole and 25, 50, 100 and 200 ft (7.6, 15.2, 30.5 and 61.0 m) from the shot hole. A set was also placed 1/4 to 1/2 mile (0.4 to 0.8 km) away as a control. Organisms were held on the bottom in all tests reported here. In test 1, organisms were also suspended 3 ft (0.9 m) below the surface; however, numbers were so small and at sporadic distances from the blast, that results are not presented here.

Test organisms were exposed to a 40 lb (18.1 kg) charge of Nitramon, the maximum allowed by law, at a depth of 20 ft (6.1 m) below the bay bottom, which is the minimum depth allowed. Charge weight and burial depth were the worst possible conditions permissible under the law. Pressure waves were not measured.

Kemp (1956) provides no indication of the waiting time period used prior to making live-dead counts. The results are shown in Table 4.4.

Table 4.3- Percent survival of oysters (=eastern oyster, Ostrea virginica) at Bay de Cene (Experiment 1) and Bay Bastiste (Experiment 2). Two explosive charges were used in each shot hole (see text for description of shot design), one of 50 lb (22.7 kg) and one of 20 lb (9.1 kg) of Nitranon (nitro-carbonitrate), and these were exploded at a depth of 50 ft (15.2 m) and 30 ft (9.1 m) respectively. Oysters were on the bottom (depth not given) (Modified from Seiling 1954, Tables 1 and 2).

Distance from Explosion		Number Tested	Number Surviving 4 Months	Percent Survival 4 Months	Number Surviving 7.5 Months	Percent Survival 7.5 Months
Experiment 1 - Bay de Chene						
Feet	Meters					
20	6.1	345	289	83.7	---	---
60	18.3	348	302	86.7	---	---
130	39.6	336	287	85.3	---	---
250	76.2	333	281	84.4	---	---
Control		338	257	76.0	---	---
Experiment 2 - Bay Batiste						
Feet	Meters					
20	6.1	334	275	82.3	253	75.7
60	18.3	326	269	82.4	256	78.5
130	39.6	324	281	86.8	255	78.7
250	76.2	329	280	85.1	242	73.5
Control		341	294	86.2	264	77.4

Table 4.4- Live-Dead counts for shrimp (=Penaeus sp., three possible species occur in the area), oysters (=eastern oyster, Crassostrea virginica), and blue crab (Callinectes sapidus) in cages placed on the bottom of Corpus Christi Bay, TX and exposed to a 40 lb (18.1 kg) charge of nitramon buried 20 ft (6.1 m) below the bay bottom. For shot 1, organisms were in 13 ft (4 m) of water, bottom type was very soft gray mud. For shot 2, organisms were in 2 1/2 to 3 ft (0.8-0.9 m) of water depth, bottom type was hard sand (Modified from Tables 1 and 2 in Kemp (1956)).

SHOT 1

Distance		Shrimp		Oysters		Blue Crab	
Feet	Meters	Live	Dead	Live	Dead	Live	Dead
<5	<1.5	25	0	18	7	2	0
25	7.6	25	0	34	4	2	0
50	15.2	25	0	30	1	2	0
100	30.5	25	0	25	1	2	0
200	61.0	25	0	24	1	2	2
Control		25	0	32	0	2	0
<5	<1.5	25	0	37	4	1	0
25	7.6	24	1	41	1	1	0
50	15.2	25	0	38	1	1	0
100	30.5	25	0	47	0	1	0
200	61.0	25	0	38	0	1	0
Control		No control due to boat mechanical problems					

Kemp (1956) concluded that shrimp and crabs were "found to be completely immune to underwater explosions, since they suffered no ill effects whatsoever during the tests." The sample sizes for shrimp and crabs are adequate but they are too small to accurately estimate mortality. However, from the data provided, the upper 95% bound on the shrimp mortality at a given distance is 0.06 (n=50 by pooling both shots) to 0.11 (n=25 for individual shots). For blue crab the upper 95% bounds are 0.95 (n=1) and 0.78 (n=2). Pooling the data for both shots, the upper 95% bound on blue crab mortality is 0.63 (n=3) at distances 550 ft (167.6 m). The data suggest that the death of 2/2 blue crabs in shot 1 is an artifact and does not represent the effects of the blast. Pooling the data from both shots at $\leq$ 50 ft (15.2 m), the upper bound is 0.28 (n=9). Kemp noted that damage to oysters was most severe within a 25 ft (7.6 m) radius of the blast and some oysters were found as far as 200 ft (61.0 m). Based on these results he concluded "If the minimum distance (from the shot) from an oyster reef were extended from 300 to 500 ft (91.4 to 152.4 m), it would probably afford a more comfortable safety margin." Statistical analysis supports this conclusion. Pooling the data at 200 ft (61.0 m), the mortality is 1/62 = 0.016 + 0.016. For shot 1, the mortality is 1/24 = 0.042 + 0.040. For shot 2, the upper 95% bound on the proportion (12/38) is 0.075.

Anonymous (1962) conducted a series of tests with Dungeness crabs (=Cancer magister) to evaluate the effects of underwater explosions from oil seismic exploration. Tests were conducted off the Oregon coast north of the Alsea River in an area normally fished for crabs. Small crabs, less than 80 mm maximum carapace width, were caught in tide pools six weeks previous to testing. Adult crabs, over 130 mm minimum carapace width, were caught in commercial crab pots in Yaquina Bay a few days prior to the experiments. All were held in live tanks. Commercial crab pots were used as cages (12 test and 3 control). Eight crabs were placed in each of 14 pots -3 large hard shell, 3 large soft shell, and 2 small soft shell to a pot. A similar assortment was used for the remaining pot, excluding 1 large soft shell. Small crabs were placed inside a hardware cloth box, 6 x 6 x 12 in (150 x 150 x 305 mm) dimensions. Chelae of all crabs were tied with rubber bands prior to placement

in pots.

Two series of tests were conducted. In the first series, one 5 lb (2.3 kg) charge of nitro-carbonitrate suspended 2 ft (0.6 m) beneath the surface was fired between two crab pots placed about 50 ft (15.2 m) apart on the bottom at each of two depths, 8 and 15 fathoms (14.6 and 27.4 m). A 25 lb (11.3 kg) charge was exploded at a depth of 4 ft (1.2 m) over two additional pots similarly spaced in 35 fathoms (64.0 m) of water. In the second series, equivalent size charges and number of pots were used. All other conditions were similar to the first experiment except that the charges were detonated 20 ft (6.1 m) beneath the surface in the 8 and 15 fathom (14.6 and 27.4 m) depths and 40 ft (12.2 m) in the 35 fathom (64.0 m) depth. Pressure measurements were not made.

One pot was recovered and crabs were examined at each depth in both series within 30 min after the explosion. The remaining pots were recovered at 96 hr. Divers examined the condition of crabs on the bottom and at the 8 and 15 fathom (14.6 and 27.4 m) depths of both series prior to recovery immediately following the blasts.

Three of 15 pots were placed on the bottom in the study area and retrieved at 96 hr. After the blast one pot was placed about 100 ft (30.5 m) from the remaining test pot at each depth in the first series.

The results for all charge sizes, cage depths, carapice condition (soft or hard), and crab sizes tested are combined and summarized in Table 4.5. Totals of 37 live undamaged and 11 dead or damaged (including 3 live) crabs were observed in test pots recovered immediately after the explosions. The test pots recovered at 96 hr contained 31 live undamaged and 16 dead or damaged (including 5 live) crabs. The control pots, examined at 96 hr. contained 16 live undamaged and 8 dead or damaged (including 2 live) crabs. No small crabs were found dead or damaged in any group. A Kruskal-Wallace test, utilizing data in Table 4.5, on a singly ordered r x c (treatment+day x response, where for response = alive, injured, dead) was not significant ($P>0.4$). Anonymous (1962) concluded the following:

1. There was no significant difference in the mortalities or damage between the test and control groups.

2. There was no significant difference in mortalities or damage with the crab pots placed at different depths.

3. There was no significant difference in numbers of mortalities or damage between surface and submerged shots.

4. There was no significant difference in numbers of crabs dead or damaged between 5 and 25 lb (2.3 and 11.3 kg) charges.

Brown and Smith (1972) evaluated the effects on marine life of three charges, 40 to 60, 400 and 2,170 lb (18.1 to 27.2, 181.4 and 984.3 kg) of C-4, used to clear a beach area and create a boat lane on in a cove at Cross Cay, a small island located east of Roosevelt Roads, Puerto Rico.

Table 4.5- Blast related mortality and injury of Dungeness crabs (=Cancer magister). The results for all charge sizes, cage depths, carapice condition (soft or hard), and crab sizes tested are combined and summarized. A Kruskal-Wallace test, utilizing the combined data, on a singly ordered r x c (treatment+day x response, where for response = alive, injured, dead) was not significant (P>0.4) (Modified from Anonymous 1962, Table 5, page 12).

Aliv	e	Injured	Dead	Total
Day 0 Treatment	37 (77.08 %)	3 (6.25 %)	8 (16.67 %)	48 (100 %)
Day 4 Treatment	31 (65.96 %)	5 (10.64 %)	11 (23.40 %)	47 (100 %)
Day 4 Control	16 (66.67 %)	3 (12.50 %)	5 (20.83 %)	24 (100 %)

A single large snail (conch type) and a sea urchin (Lytechinus sp.) were placed in one of three cages containing fish. Pressure measurements were taken at three locations for the largest shot. Casual observations of the cove were made after the explosion.

Neither the caged snail or sea urchin were killed by the blast. However, the hydrophone nearest the cage was apparently defective so no pressures were measured for these two animals. Two hours after the last explosion, turbidity in the cove had cleared sufficiently for an in-water survey. Live sea urchins and chitons were observed. Almost all of the staghorn coral (Acropora palmata) colonies were broken off near their bases and encrusting coral (Millepora complanta) appeared to have suffered some abrasion.

Small sample sizes, lack of adequate pressure readings, and lack of information concerning charge distance from the staghorn coral and encrusting coral make it impossible to form any quantitative conclusions from this observational study. However, the original authors concluded: "...[B]ased on the results of the experiment and the observations of the environmental effects of the explosions, it is felt that the proper precautions were taken to keep the damage to the environment to a minimum." Considering the study and report production costs, the present authors question why this poorly designed study was conducted.

Gaspin (1975) and Gaspin et al. (1976) conducted a series of tests using blue crabs (Callinectes sapidus) and eastern oysters (Crassostrea virginica) to investigate the effects of naval ordnance testing in Chesapeake Bay.

In 1973, explosive effects were conducted (Gaspin 1975). Test animals were collected in the Patuxent River in the vicinity of Solomons Island. Crabs were collected in the Patuxent River with a 25 ft (7.6 m) semiballoon otter trawl with a 1/2 in (13 mm) stretch mesh liner. Oysters were collected with a 48 in (1.2 m) oyster dredge at an unspecified site. Organisms were held in cages until used. No information on holding time prior to testing was provided. Cages, constructed with plastic mesh fabric on steel frames, were cylinders 20 in (510.0 mm) long and 12 in (305.0 mm) in diameter. Organisms were placed in cages and positioned at a depth of 5 ft (1.5 m), referred to as surface cages, and on the bottom in 25 ft (7.6 m) of water, at horizontal standoff distances from the charge (Table 4.6). Crabs were placed in both the surface and bottom cages, while oysters were placed only on the bottom. Sample size was small and variable, ranging from 9-20 individuals per distance tested. There is no indication that controls were utilized.

The organisms were exposed to 200 lb (90.7 kg) Mk 82 general purpose bomb, placed on the bottom. Shot #532 was loaded with tritinol and shot #533 was loaded with H-6. The pressure wave was recorded. However, the gain on some of the recording

system channels was set too high and the records were clipped. As such, good pressure measurements were not made.

Crabs and oysters were examined for obvious external damage and those still alive after an explosion were held in flowing water for 24 hours to detect any delayed mortality. Results are given in Table 4.6. Gaspin (1975) stated "Little can be concluded... Some oysters and crabs were killed at stations nearest the explosions but many survived."

In 1975, (Gaspin et al. 1976) a single shallow water test was conducted in approximately 25 ft (7.6 m) of water in the Patuxent River. Test oysters (Callinectes sapidus) were collected with an oyster dredge in the vicinity of Solomons Island. Blue crabs (Ostrea virginica) were either captured by otter trawl and oyster dredge, or purchased. Organisms were placed in cages and positioned at a depth of 5 ft (1.5 m), referred to as surface cages, and on the bottom, at six horizontal standoffs from the charge. Crabs were placed in both the surface and bottom cages, while oysters were placed only on the bottom. A description of the cages was not provided. The organisms were exposed to a 106 lb (48.1 kg) spherical pentolite charge, placed on the bottom. Peak pressure measurements were recorded.

After exposure, crabs and oysters were examined for obvious external damage and then the test cages were immediately submerged in holding tanks, later to be transferred and held in wet tables at the Chesapeake Biological Laboratory. A small sample of test crabs was dissected and examined for internal damage, but all examinations were inconclusive and the procedure was later abandoned. With the exception of the severed muscle tissue and ruptured organs that resulted from massive fractures in the carapace, no internal damage was discernable.

Percentage of cumulative blue crab mortality for test distances and controls is presented in the original text as a figure (p. A4). However, total numbers of test and control organisms are not given in the text or figure. As such, it is impossible to determine if adequate sample sizes were employed. In addition, control mortality exceeded or closely approached exposure mortalities, which questions the usefulness of the results. Gaspin et al. (1976) noted that the high mortalities which occurred within the control groups might be (in part) attributable to the differences in handling between controls and test crabs. Due to space limitations within the holding tanks, the cages containing the controls were held out of water several hours longer than the control cages during transfer to the laboratory.

Table 4.6.-Blast related mortality of blue crabs (Callinectes sapidus) and eastern oysters (Crassostrea virginica). Charges erer 200 lb (90.7 kg) Mk 82 general purpose bombs. Shot 532 was loaded with tritinol and Shot 533 was loaded with H-6 (Modified from Gaspin 1975, Table A-1).

Species	Distance		Cage Depth		Pmax	Survival	Mortality
Feet		Meters	Feet	Meters	(kPa)		
Shot 532							
crabs	50	15.2	25	7.6	1,679	7	2
110		33.5	5	1.5	484	15	5
110		33.5	25	7.6	1,264	10	0
oysters	50	15.2	25	7.6	1,679	10	0
110		33.5	25	7.6	1,264	12	0
Shot 533							
crabs	40	12.2	25	7.6	1,600	11	1
75		22.9	5	1.5	1,206	9	1
75		22.9	25	7.6	1,637	7	3
oysters	40	12.2	25	7.6	1,600	6	7
75		22.9	25	7.6	1,673	11	2

The only oyster mortality occurred at the 20 ft (6.1 m) bottom station. Twenty hours after the shot, 5 of 20 oysters were dead. Between 20 and 41 hours, one additional oyster died. There was no change after 140 hours, giving 6 of 20 dead (30% mortality). It was indicated that there were no other oyster mortalities in 140 hours of observation.

Gaspin et al. (1976) concluded: "The great resistance exhibited by the test oysters is, therefore, a good indication of the reaction that can be expected to occur in natural oyster populations. However, there is at least one problem with methodology. No indication of sample sizes at each exposure distance or control are given, other than 20 oysters were used at the 20 ft (6.1 m) location. During the 1974 testing program (Gaspin 1974), variable sample sizes ranging from 9 to 20 individuals were used for both crabs and oysters. As such, it is impossible to say that the sample size was 20 individuals for each exposure distance and control.

Linton et al. (1985a) conducted a test with both fish and invertebrates, with the intention of determining adequacy of regulations imposed by governmental agencies that permit geophysical exploration intended to minimize detrimental effects of geophysical exploration on marine organisms. American oysters (=eastern oyster) (Crassostrea virginica), white shrimp (Penaeus setiferus) and blue crab (Callinectes sapidus) were used as test invertebrates.

All test organisms were collected in Trinity Bay, north of Smith Point, Texas within one kilometer of the detonation site. Blue crabs were captured with commercial traps, oysters with a commercial dredge, and white shrimp with an otter trawl. Test organisms were selected for uniform size within species. Range and average were: white shrimp, 7-11, 85 mm total length; blue crab 14-18, 170 mm-carapace width. Oysters were not measured individually, but none was less than 150 mm in total shell length.

Crabs and oysters were transported in aerated tanks to open-water holding pens immediately after capture. They were held there for at least 24 hr prior to the experiment to monitor injuries and mortalities resulting from capture and handling. Shrimp were captured the day of the experiment and transferred directly to test cages. No attempt was made to determine shrimp mortality or injury resulting from

capture or handling. All organisms were acclimated to test-cage conditions for at least one hour prior to detonation.

During testing, organisms were held in cylindrical holding cages, 900 by 750 mm, and enclosed with 18 mm nylon mesh webbing. Cages holding shrimp also contained a 5 mm mesh liner. Ten crabs and 10 oysters were caged together. White shrimp were caged alone, 10 individuals per cage. Shrimp were held in paired cages at surface and bottom locations (4 cages per location), whereas crabs and crabs and oysters were only deployed in paired bottom cages.

Linton et al. (1985a) stated that surface and bottom cages were deployed at five stations arranged perpendicular to, and at logarithmic distances of 1, 11, 23, and 46 m from the detonation line. However, based on their Figure 2 (p. 345) showing the test array of cages, distances are from the explosive to the vertical line maintaining both surface and bottom cages. Actual or slant distances from the explosion to the surfaces cages would have been 24.0, 26.4, 33.2 and 51.9 m. Distances from explosion to bottom cages are as stated.

Bottom cages were deployed at 24 m depth and surface cages were floated at the surface. Controls were established at a distance of 136 m from the detonation site. Control organisms received the same treatment (that is, method of capture, and holding time as test organisms), with the exception that they were not in the water at the time of the explosion.

Test organisms were exposed to a 33 m strand of 100 g/33 cm Primacord detonation cord laid perpendicular to the transect of test cages. It was positioned to form the top of the letter "T" and the line of cages forming the base. Both Primacord ends were weighed to hold the cord on the bottom, 24 m depth. A blasting cap was used to initiate the detonation. No pressure measurements were made.

After the test, observers raised the cages and recorded mortality among test animals. Criteria used to denote death were: oysters-shell permanently agape; shrimp-cessation of gill movement; and crabs-cessation of movement of chela, appendages, and mouth parts. Dead organisms were removed from their cages. Cages with living organisms were returned to the position they occupied at the time of detonation and observed 24 hours later and separated as to living or dead.

The results are presented in Table 4.7. Surface cage distances are corrected from those presented in the original publication (Table 1, p. 346) to reflect actual distance from the explosion.

White shrimp exhibited no well-defined pattern relative to survival and distance from the detonation site (Table 4.7).

Without pressure wave measurements it is impossible to determine if cages received variable pressures that would explain the observed mortality pattern.

Blue crab mortality, immediately following the blast, ranged from 40 percent at 1 m to 10 percent at 47 m. Twenty-four hour mortality ranged from 60 percent at 1 m to 10 percent at 47 m.

No mortality was observed in control cages.

Eastern oyster mortality, immediately following the blast, was minimal with 1 (5%) dead oyster at 1 and 11 m and two (10%) dead at 23 and 46 m. There was 1 (5%) dead oyster at 1 and 11 m and 3 (15%) dead at 23 and 46 m. There was no control mortality.

Table 4.7.- Percent mortality for white shrimp (Penaeus setiferus), American oysters (=eastern oyster, Crassostrea virginica) and blue crab (Callinectes sapidus) as a function of cage depth (surface and bottom = 24 m), lapsed time, and distance from detonation site. Test organizms were exposed to a 33m strand of 100 g/33 cm Primacord detonation cord laid on the bottom at 24 m depth and perpendicular to the transect of test cages (Modified from Linton et al. 1985a)

				Percent Mortality				
	Number	Cage	Lapsed	Distance (m) from Detonation Site				
Species	Per Cage	Depth	Time(hr)	24	26.4	33.2	51.9	control
White shrimp	20	Surface	0	0	5	0	20	5
			24	5	10	25	20	5
				Distance (m) from Detonation Site				
				1	11	23	46	control
White shrimp	20	Bottom	0	5	30	5	0	0
			24	5	35	10	--	0
Blue crab	20	Bottom	0	40	35	35	10	0
			24	60	50	35	10	0
Eastern oyster	20	Bottom	0	5	5	10	10	0
			24	5	5	15	15	0

Percent mortality at 24 hours is cumulative (e.g., 0 hr + 24 hr) to reflect total mortality at 24 hr. Linton et al. (1985a, Table 1) removed from their cages and counted dead organisms at O hr (instantaneous mortality). Living organisms were returned to the position they occupied at the time of detonation and observed 24 hr later. Their 24 hr values were not cumulative. For surface shots Linton et al. (1985a) gave distances from the explosive to the vertical line maintaining both surface and bottom cages. These values have been modified to provide the actual or slant distances from the explosion to the surfaces cages.

SUMMARY AND DISCUSSION

The results of all the studies reviewed indicate that invertebrates are insensitive to pressure related damage from underwater explosions. This may be due to the fact that all the invertebrate species tested lack gas-containing organs which have been implicated in internal damage and mortality in vertebrates. Underwater explosion produce a pressure waveform with rapid oscillations from positive pressure to negative pressure which results in rapid volume changes in gas-containing organs. In fish, the swimbladder, a gas-containing organ, is the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). It is subject to rapid contraction and overextension in response to the explosive shock waveform (Wiley et al. 1981). Species lacking swimbladders or with small swimbladders are highly resistant to explosive pressures (Aplin 1947; Fitch and Young 1948; Goertner 1994). For example, Wiley et al. (1981) and Goertner et al. (1994) noted that hogchokers (Trinectes maculatus), which lack swimbladders, were extremely tolerant of underwater explosions, and greatly exceeded the tolerance of any species with swimbladders that they had tested. Goertner et al. (1994) found that hogchokers were not killed beyond a distance of 1 m from a 4.5 kg charge of pentolite.

Gas-containing organs have also been implicated as a causative factor of internal damage and mortality in other vertebrate species exposed to underwater explosions. Sailors exposed to depth charges and torpedo explosions, while escaping their sinking ships during World War II, suffered damage to gas-containing organs (Cameron et al. 1944; Ecklund 1943; Gage 1945; Palma and Uldall 1943; Yaguda 1945).

The lungs, stomach, and intestines, all gas-containing organs, were ruptured or hemorrhaged, while other organs were relatively unaffected. Similar results have been observed in underwater explosion tests with other mammalian species (Richmond et al. 1973).

Experimental design has progressed little since the early investigative study conducted by Knight (1907). Invertebrate mortality studies have used inadequate sample sizes, lacked adequate controls, and failed to conduct pressure waveform analysis of the explosion (Table 4.8). In addition, investigators have failed to give adequate information concerning testing conditions (e.g., type and weight of explosive, cage type, testing site conditions, post-test invertebrate holding times).

It is essential to not only record invertebrate mortality at given distances from an explosion but to also record the pressure waveform at each test distance. Three parameters of underwater explosive waveforms have been implicated as being responsible for fish mortality: pressure (Teleki and Chamberlain 1978), impulse (Gaspin 1975; Gaspin et al. 1976; Yelverton et al. 1975), and energy flux density (Ogawa et al. 1976, 1977, 1978; Sakaguchi et al. 1976). Peak pressure has been dismissed as a causative mortality factor by Hubbs and Rechnitzer (1952) and Yelverton et al. (1975).

The pressure waveform parameter responsible for invertebrate mortality has not been experimentally determined. The pressure (force per unit area), impulse (strength) and energy flux density (intensity) of the shock-wave are complex physical measures that vary in time. With recent technological advancements in recording equipment and computer programs for waveform analysis, there is no reason why peak pressure, impulse, and energy flux density can not be analyzed and reported. Investigators would make a substantial contribution to the "state of the science" by reporting all aspects of the waveform or by making digital information available to other researchers. This is extremely important, since waveforms change considerably under various test settings (i.e., depth, bottom type, embedment, etc.). In addition, investigators attempting to duplicate study designs to test additional species need precise details of how waveform analysis was conducted.

Pressure waveform-mortality relationships can be used to develop models to predict invertebrate mortality at untested charge sizes and distances from the explosion based on scaling laws of explosives (Cole 1948). It is essential that adequate test distances from the explosion be used and pressure measurements be made at each distance to construct mortality-pressure waveform relationships, or LD50 curves. Without such data collection, little useful information is gained.

Table 4.8.- Summary of study type (experimental or observational), study design, and type of publication for each study reviewed.

Species	Type Study	Adequate Sample Size	Adequate Control	Measured Pressures	Type of Publication	Reference
sea anemone--	Obs.	No	No	No	Refereed	Fry and Cox 1953
corals--	Obs.	No	No	No	Refereed	Fry and Cox 1953
staghorn coral (*Acropora palmata*)--	Obs.	No	No	No	Gray	Brown and Smith 1972
encrusting coral (*Millepora complanta*)--	Obs.	No	No	No	Gray	Brown and Smith 1972
ribbon worms (*Nemertinea sp*).--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
sand worms (*Nereis sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
tube worms--	Obs.	No	No	No	Refereed	Fry and Cox 1953
Rough abalones (*Haliotis corrugata*)--	Exp.	No	No	No	Refereed	Alpin 1947
Green abalones (*Haliotis fulgens*)--	Exp.	No	No	No	Refereed	Alpin 1947
snail (*Thais sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
snail (conch type)--	Exp.	No	No	No	Gray	Brown and Smith 1972
cockles (*Cardium corbis*)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
muc clam (*Macoma sp.*)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
commensal clam (*Pseudopythina rugifera*).--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
oysters (*Ostrea gigas*)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
oyster bed (*Ostrea virginica*)--	Exp.	?	?	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946b, 1948, 1950
oysters (*Ostrea virginica*)--	Exp.	Yes	No	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946b,

						1948, 1950
oyster (Ostrea virginica)--	Exp.	Yes	No	No	Gray	Sieling 1954
oysters (Ostrea virginica)--	Exp.	Yes	No	No	Gray	Kemp 1956
oysters (Ostrea virginica)--	Exp.	No	No	Yes[1]	Gray	Gaspin 1975
oysters (Ostrea virginica)--	Exp.	?[2]	?[2]	No	Gray	Gaspin et al. 1976
American oyster (Ostrea virginica)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
shrimp (Peneus setiferus)--	Exp.	Yes	No	No	Gray	Gowanloch and McDougal 1946; Gowanloch 1946a, 1950
white shrimp (Peneus setiferus)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
shrimp (Peneus sp.)--	Exp.	Yes	No	No	Gray	Kemp 1956
ghost shrimp (Upogebia pugettensis)--	Obs.	No	No	No	Gray	Tollefson & Marriage 1949
blue crab (Callinectes sapidus)--	Exp.	Yes	No	Yes[3]	?	Anonymous 1948
blue crab (Callinectes sapidus)--	Exp.	Yes	No	No	Gray	Kemp 1956
blue crab (Callinectes sapidus)--	Exp.	Yes	No	Yes[1]	Gray	Gaspin 1975
blue crab (Callinectes sapidus)--	Exp.	?[2]	?[2]	No	Gray	Gaspin et al. 1976
blue crab (Callinectes sapidus)--	Exp.	Yes	Yes	No	Refereed	Linton et al. 1985a
Dungeness crabs (Cancer magister)--	Exp.	Small	Yes	No	Gray	Anonymous 1962
crabs (Cancer sp.)--	Exp.	No	No	No	Gray	Tollefson & Marriage 1949
lobster (Homarus americanus)--	Exp.	No	No	No	?	Knight 1907
lobsters (Panulirus interuptus)--	Exp.	No	No	No	Refereed	Aplin 1947
sea urchins--	Obs.	No	No	No	Refereed	Fry and Cox 1953

sea cucumbers-- sea urchin	Obs.	No	No	No	Refereed	Fry and Cox 1953
(Lytechinus sp.)--	Exp.	No	No	No	Gray	Brown and Smith 1972

[1]The pressure wave was recorded. However, the gain on some of the recording system channels was set too high and the records were clipped. As such, good pressure measurements were not made.

[2]Mortality is provided as percent mortality. Number of organisms exposed at each distance tested is not provided.

[3]Peak Pressure is provided for the distance nearest and farthest from the explosion.

For example, Aplin (1947) tested only one distance from the explosion and did not record the pressure waveform. It is only possible to conclude that at the distance from the explosion and water depth tested there was no mortality. The data can not be used to extrapolate to other charge sizes or distances from the explosion.

All of the invertebrate studies reviewed were conducted with organisms suspended in the water column or on the substrate and with open-water explosions. Explosives in open water, which are not contained completely by rigid structures, will produce both higher amplitude and higher frequency shock waves than contained detonation. Thus, the use of blasting in structure demolition, when the explosives are enclosed within the structure being razed, should result in lower mortality than when the same explosive detonated in open water. For example, "burning" a steel beam underwater with perimeter charges to sever it would cause higher mortality than the severance of a concrete pier using an explosive of the same weight placed within the pier by drilling and covering. The more work accomplished by a detonation in cracking and moving a rigid volume, and the greater the energy dissipated into solid media, the lower the capacity of the water-borne shock wave will have to cause mortality. Explosives buried in the substrate or placed in bore holes and adequately stemmed (Keevin, In press) produce less impact than open-water explosions. For example, Traxler et al. (1992) found no mortality or internal injuries in largemouth bass (Micropterus salmoides), bluegill (Lepomis macrochirus) or channel catfish (Ictaluris punctatus) in a cage 7.6 m from each of two shot holes drilled 27.4 and 33.5 m into the sediment and charged with 4.5 and 9.1 kg of dynamite.

Natural resource managers making impact assessments based on the existing literature should consider that explosive demolition and seismic testing using explosives buried in the sediment will produce effects less than open-water shots.

CHAPTER 5

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: AMPHIBIANS AND REPTILES

INTRODUCTION

To date, there has not been a single comprehensive study to determine the effects of underwater explosions on either amphibians or reptiles that defines the relationship between distance/pressure and mortality or damage.

INJURY AND MORTALITY OF REPTILES EXPOSED TO UNDERWATER EXPLOSIONS

There have been a number of studies which demonstrate that sea turtles are killed and injured by underwater explosions (Duronslet et al 1986; Gitschlag 1990; Gitschlag and Herozeg 1994 ; Gitschlag and Renaud 1989 ; Klima et al. 1988; O'Keeffe and Young 1984) . Currently, there is no information available for amphibians (i.e., frogs, salamanders, etc.). There are few reports of turtle mortality because turtles can be difficult to observe, and turtles killed by explosions may not float to the surface until sufficient bacterial activity has occurred, which takes several days (NRC 1990). The NRC has concluded that data on the effects of underwater explosions, in relation to oil and gas platform explosive removal, are inadequate and that further research is needed.

In March and April of 1986, 51 dead sea turtles, primarily Kemp's ridleys, washed ashore on Texas beaches after the removal of platforms that involved 22 underwater explosions. Because shrimp fishing (another cause of sea turtle mortality) was at a very low level in the area, the explosions were identified as the probable cause (Klima et al. 1988).

To document the effects of underwater explosions on sea turtles, the National Marine Fisheries Service undertook an experiment to determine the extent of injuries to sea turtles placed at 700 ft. 1,200 ft. 1,800 ft. and 3,000 ft (213.4, 365.8, 548.6, and 914.4 m) from an explosive removal of an oil platform (Klima et al. 1988). On June 21, 1986, a platform in 30 ft (9.1 m) of water was removed by detonating 50 lb (22.7 kg) of nito-methane inside each of four jacket legs 15 ft (4.6 m) below mudline. One Kemp's ridley and one loggerhead were placed in a cage at each of the four distance. Just before detonation, the cages were lowered to a mid-water depth of 15 ft (4.6 m). The cages were retrieved shortly after detonation. The four turtles within 1,200 ft (365.8 m) of the explosion were unconscious, as was the loggerhead in the cage at 3,000 ft (914.4 m). If they had been left in the water these turtles may have drowned. Turtles in all of the cages were affected. Some suffered averted cloaca and vasodilation, which lasted for two to three weeks.

Two observations of sea turtles severely wounded by explosive removals of platforms have been made. A dead or injured turtle drifting about 10 ft below the surface was sighted 1.5 hr after the explosive removal of a structure in 1986 (Gitschlag and Renaud 1989). At a removal site of a caisson in 1991, a loggerhead with a fracture down the length of its carapace surfaced within one minute of detonation (Gitschlag, personal communication in NRC 1996).

Two immature green turtles (100 to 150 ft) (30.5 to 45.7 m) were killed when 20 lb (9.1 kg) of plastic explosives (C-4) were detonated in open water by a U.S. Navy Ordnance Disposal Team. Necropsies revealed extensive internal damage, particularly to the lungs (Schroeder, personal communication in NRC 1996).

Three sea turtles were unintentionally exposed to underwater shock tests by the Naval Coastal Systems Center in 1981 off the coast of Panama City, Florida. Three detonations of 1,200 lb (544.3 kg) of TNT at mid-depth (in approximately 120 ft (36.6 m) of water) injured one turtle at a distance of 500 to 700 ft (152.4 to 213.4 m) and another at 1,200 ft (365.8 m). A third turtle at 2,000 ft (609.6 m) was apparently uninjured (O'Keeffe and Young 1984; Klima et al. 1988).

Young (1991) developed the following equation to estimate sea turtle safe ranges.

$$R_t = 560\ W_E^{1/3}$$

R_t = Range in feet
W= Weight of explosive in pounds

The metric form of this equation for the safe sea turtle range is

$$R_t\ (m) = 222\ W(\text{in kg})^{1/3}$$

The estimated sea turtle safe range equation was based on Gulf of Mexico oil platform criteria established by the National Marine Fisheries Service (NMPS). As the sea turtle literature review indicated, there has not been a single study establishing the relationship between underwater explosive pressures and mortality. Young (1991) suggested that the calculated sea turtle safe ranges should only be used for preliminary planning purposes.

There are no data on nonlethal damage from underwater explosions or delayed mortality, both of which may have a greater impact on sea turtle populations than immediate death from explosions.

INJURY AND MORTALITY OF AMPHIBIANS EXPOSED TO UNDERWATER EXPLOSIONS

There currently is no data available on the effects of underwater explosions on amphibians (i.e., frogs, salamanders, etc.). Although untested, amphibians with air-containing organs, such as lungs, probably have mortality comparable to fish with swimbladders. For impact assessment purposes, the relationship between distance/pressure and fish mortality/injury are probably fairly close (See Chapter 6 for details). Although untested, amphibians without air-containing organs, are probably immune to underwater explosives as are benthic fish species without swimbladders (Goertner et al. 1994).

MITIGATION TECHNIQUES TO PROTECT REPTILES AND AMPHIBIANS FROM UNDERWATER EXPLOSIONS

Reptiles

The simplest method to protect sea turtles from underwater explosions is to either avoid periods when they are in the blasting zone or to remove the sea turtles. Avoidance of sea turtles can be achieved in two manners. Depending on location, there may be time periods when sea turtles are not in the project area due to their life history characteristics (e.g. migration patterns). This can be determined by coordination with the state natural resource agency or NMFS. Blasting can be planned during time periods of low sea turtle abundance. If sea turtles are potentially in the area during blasting, an aerial survey using a light plane or helicopter can be conducted prior to detonation. If sea turtles are observed in the project area, blasting can be halted until they move out of a pre-determined blast zone. As a last resort, turtles can be physically captured and removed from the

blast zone prior to detonation.

The NMFS developed a series of mitigation features for a Incidental Take Statement under the auspices of the Endangered Species Act to protect sea turtles from the use of underwater explosives during salvage of offshore oil and gas structures (Table 5.1).

An example of the above strategy is in place for explosive removal of oil and gas structures in state and federal waters of the Gulf of Mexico (Gitschlag 1990). For at least 48 hr prior to detonation, NMFS observers watch for sea turtles from the surface. Helicopter aerial surveys within a mile radius of the removal site are conducted 30 min prior to and after detonation (Gitschlag and Herczeg 1994). If sea turtles are observed, detonations are delayed until the sea turtles have been safely removed or have left the area.

Amphibians

Mitigation techniques described for fish in Chapter 8 are applicable to amphibians with air-containing organs.

Table 5.1.- Summary of "generic" incidental take statement. From Gitschlag and Herczeg (1994)

1. Qualified observers monitor for sea turtles beginning 48 hours prior to detonations.
2. Thirty minute aerial surveys within one hour prior to and after detonation.
3. If sea turtles are observed within 914 meters of the structure, detonations will be delayed and the aerial survey repeated.
4. No detonations will occur at night.
5. During salvage-related diving, divers must report sea turtle and dolphin sightings. If sea turtles are thought to be resident, pre- and post-detonation diver surveys must be conducted.
6. Detonation of sequential explosive charges must be staggered by at least 0.9 seconds to minimize cumulative effects of the explosions.
7. Avoid use of "scare" charges to frighten away sea turtles which may actually be attracted to feed on dead marine life.
8. Removal company must file a report summarizing the results.

CHAPTER 6

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: FISH

INTRODUCTION

The potential for injury and mortality to both marine and freshwater fishes, resulting from underwater blasts, has been well documented (Hubbs and Rechnitzer 1952; Ferguson 1962; Teleki and Chamberlain 1978).

PRESSURE RELATED MORTALITY OF FISH

Three parameters of underwater explosive waveforms have been implicated as being responsible for fish mortality: pressure (Teleki and Chamberlain 1978), impulse (Gaspin 1975; Gaspin et al. 1976; Yelverton et al. 1975), and energy flux density (Ogawa et al. 1976, 1977, 1978; Sakaguchi et al. 1976). Peak pressure has been dismissed as a causative mortality factor by Hubbs and Rechnitzer (1952) and Yelverton et al. (1975). Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite (DV = approximately 17,000 m/s) explosions varied from 276 to 483 kPa. Peak pressures from slowly detonating black powder (DV = 1,709 m/s), producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes.

Based on the findings of Hubbs and Rechnitzer (1952), Teleki and Chamberlain (1978) concluded that the lethality of an explosive is directly related to its detonation velocity. Detonation velocity (DV) is the rate at which a blasting agent ignites. It ranges from about 1,650 to 7,650 m/s for products used commercially today (Dick et al. 1993a). Teleki and Chamberlain (1978) suggested that the more rapid the detonation velocity the more abrupt was the resultant hydraulic pressure gradient and the more difficulty fish had adjusting to the pressure changes. They felt that a knowledge of the detonation velocity is critical to a true understanding of the impact of blasting on fish.

Keevin (1995) tested Teleki and Chamberlain's (1978) suggestion by comparing the mortality of bluegill (Lepomis macrochirus) exposed to three high-explosive types (T-100 Two Component, Pellite, and Apex 260) spanning the range of detonation velocities within commercially available explosives (Table 6.1).

Table 6.1.- Characteristics of explosives used during testing. (Atlas Powder Company 1990a,b; Slurry Explosive Corporation 1991)

	Pellite	APEX 260	T-100
Detonation Velocity (m/s)	3,6	5,033	6,314
Density (gm/cm^3)	0.81-0.85 1.25		1.22
Relative Bulk Strength 1.00 (ANFO=1)	1.00	1.45	1.60

Using equivalent weights of explosives, there was no significant difference in mortality curves based on distance from the explosive charge. The results suggest that detonation velocity of commercially available explosives, with the exception of black powder, is not an important factor in fish mortality. The misconception concerning the relationship between lethality and detonation velocity is "probably" based on field observations and research (Baldwin 1954; Fry and Cox 1953; Ferguson 1962; Hubbs and Rechnitzer 1952) which indicated that black powder, a low

detonation velocity explosive, had little effect on fish. Ferguson (1962) found that caged yellow perch (Perca flavescens) were unaffected by 45 kg charges of black powder, fired with an electric squib (detonator). Black powder charges detonated with a nitrone detonator, itself a high explosive, were damaging to fish. Even a 0.45 kg nitrone charge killed caged perch up to 60.7 m away. Fry and Cox (1953) reported that fish and game observers, attached to seismic operations which normally used 40 to 50 shots of 20.3 or 40.5 kg charges of black powder per day, reported almost no damage to fish. On one occasion, three divers located a school of rockfish (Sebastodes sd.) in approximately 16.7 m of water. A 20.3 kg charge was detonated above the school at a depth of 1.8 m. The divers descended and found no mortality in the school. Baldwin (1954) observed "many salmon (Oncorhynchus) swimming about in the blasting area prior to detonation" of either a 20.3 or 40.5 kg charge of black powder at a depth of 1.8 m. None were harmed by the explosion.

The difference in fish mortality between black powder, a low explosive, and high explosives appears to be related to the waveform produced by each explosive type. Black powder produces a pressure waveform with a slow rise time and low amplitude whereas high explosives have an abrupt rise time, high amplitude, and short frequency. In addition, high explosives have a much higher negative pressure than black powder, as shown in Figures 8 and 9 in Hubbs and Rechnitzer (1952). The amplitude and short frequency of the negative pressure wave and resulting damage to the swim bladder may be the causative factor of mortality in fish exposed to high-explosive pressure waveforms.

The exact pressure waveform measurement responsible for fish mortality is unknown. As previously noted, peak pressure is not a good predictor of mortality when comparing very different types of explosives (Hubbs and Rechnitzer 1952). Baxter et al. (1982) reviewed overpressure waves versus damage effects data and concluded that impulse strength was the most predictive damage parameter for water depths of less than 3 m. Energy flux density was found to be more accurate in predicting effects on fish in water depths greater than 3 m. Yelverton et al. (1975) compared peak pressure and impulse as mortality predictors by keeping the depth of charge and slant range constant and by varying the depth of the fish, thus varying the impulse levels and keeping the peak pressure constant. The impulse for 50-percent lethality in carp (Cyprinus carpio) was 189 Pa-s (at 52. m), 162 Pa-s (at 305. m) and 181 Pa-s (at 3.05 m). In contrast, the corresponding peak pressures associated with these LD50 impulses varied markedly, 5.58 Mpa (at 52 m), 2.31 Mpa (at 305. m) and 1.21 Mpa (at 3.05 m) for carp tested at 3.05 m depths.

Keevin (1995) compared mortality of bluegill (Lepomis macrochirus) exposed to a 2 kg charge of T-100 detonated at 2 m depth with various measurements of the pressure waveform. He demonstrated that there was a significant correlation ($P > 0.05$) between all values of impulse and energy flux density and mortality, with the exception of impulse calculated as 50 (Table 6.2). However, Keevin exposed the bluegill to explosive pressures at only one depth.

Table 6.2.- Spearman correlation matrix of number of dead (n=25) versus waveforms. Spearman correlations larger than 0.619 are significant at $p < 0.05$. (Modified from Keevin (1995))

Waveform	**Shot 1**	**Shot 2**
Peak pressure	0.903	0.651
Impulse (first positive wave)	0.9	0.806
Impulse (calculated by the greatest difference of peak pressure to pressure low)	0.878	0.892
Impulse (5e)	-0.195	-0.554
Impulse 6.7e	-0.805	-0.843
Energy Flux Density	0.878	0.892

The rapid oscillation in the pressure waveform between a high overpressure and underpressure associated with detonation of high explosives is most probably responsible for fish mortality. This oscillation in waveform is responsible for the rapid contraction and overextension of the swimbladder resulting in internal damage and mortality. Any waveform value that provides a good predictor of mortality over a wide range of conditions (i.e., organism depth, explosive size, explosion depth) would be a suitable measure. Currently, it appears that impulse provides the best measurement for shallow shots and energy flux density provides the best measurement for deep water shots. However, this is an area that needs further evaluation.

EXPLOSIVE PRESSURE RELATED ORGAN DAMAGE

Investigators have found the swimbladder to be the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). The swimbladder, a gas-containing organ is subject to rapid contraction and overextension in response to the explosive shock waveform (Wiley et al. 1981). Gas-containing organs have also been implicated as a causative factor of internal damage and mortality in other vertebrate species exposed to underwater explosions. Sailors exposed to depth charges and torpedo explosions, while escaping their sinking ships during World War II, suffered damage to gas-containing organs (Cameron et al. 1944; Ecklund 1943; Gage 1945; Palma and Uldall 1943; Yaguda 1945). The lungs, stomach, and intestines were ruptured or hemorrhaged, while other organs were relatively unaffected. Similar results have been observed in underwater explosions tests with other mammalian species (Richmond et al. 1973).

Because the swimbladder was burst outward, some investigators have suggested that negative phase (relative to ambient) of the pressure wave is responsible for damage to the swimbladder (Anonymous 1948; Hubbs and Rechnitzer 1952; Wiley et al. 1981). For example, postmortem observation of striped bass (Roccus saxatilis) and trout (Cynoscion regalis) found "the edges of holes in the swim bladder were turned outward and that blood from broken vessels in the wall of the bladder had been blown into the abdominal cavity" (Anonymous 1948).

Laboratory tests have demonstrated that small negative pressures can injure swimbladders. Tsvetkov et al. (1972) applied pressure of 1-6 atmospheres (101.4-608.4 kPa) above the surface of water containing fish in a closed container over a period of 2-5 min. After the pressure was applied, fish were allowed to adapt until they reached neutral buoyancy. Pressure was then released at rates of 0.1-6.0 atm/s (10.1-608.4 kPa/s). One hundred percent mortality of roach (Rutilus rutilus) was observed when the rate of discharge was 3 atm/s (304.1 kPa/s), 40-72% at a rate of 0.1-0.5 atm/s (10.1-50.7 kPa/s), and 10% at a rate of less than 0.1 atm/s (10.1 kPa/s). Rupture to the swimbladder walls was observed at their weakest point in

response to the large increase in volume. Hubbs and Rechnitzer (1952) found that negative pressures of only one atmosphere (101.4 kPa) killed marine fish. Brown (1939) showed that the guppy could not successfully adapt to decompressions of more than about one-half atmosphere (50.7 kPa). Hogan (1941) applied negative pressures of up to one atmosphere (101.4 kPa) to a variety of fish species, for periods of 10 to 30 seconds and found that physoclistous fish suffered hemorrhage in the circulatory system and often died. Muir (19S9) found that young salmon could usually survive decompressions of about one atmosphere (101.4 kPa); but when the pressure was lowered to the vapor pressure so that the water cavitated, mortality was high.

The rate and magnitude of pressure change in laboratory studies, both positive and negative, does not approach those observed in underwater explosions. In addition, laboratory studies do not duplicate the rapid oscillation from positive pressure to negative pressure which result in rapid volume changes in the swim bladder. Underwater explosions should be far more damaging.

Species lacking swimbladders or with small swimbladders are highly resistent to explosive pressures (Aplin 1947; Fitch and Young 1948; Goertner et al. 1994). For example, Aplin (1947) noted that two opal-eye perch (Girella nigricans), 15.24 m from a 9 kg charge of 60% petrogel, were killed and their viscera reduced to a "pulp". However, 4 sculpin (Scorpaena guttata) and a cabezone (Scorpoenicthys marmoratus), which both lack swimbladders, in the same cage were not injured nor was there any damage to their internal organs. Wiley et al. (1981) and Goertner et al. (1994) noted that hogchokers (Trinectes maculatus), which lack swimbladders, were extremely tolerant of underwater explosions, and greatly exceeded the tolerance of any species with swimbladders that they had tested. Goertner et al. (1994) found that hogchokers were not killed beyond a distance of 1 m from a 4.5 kg charge of pentolite. Immediate death appeared to be caused by loss of blood resulting from hemorrhaging in the gills. Goertner et al. (1994) suggest that the lack of hogchoker injuries, except when close to an explosive charge, is probably due to the absence of obvious air cavities. They imply that the observed damage may be caused by the presence of microbubbles. Microbubbles have not been confirmed for fish but are known to occur in humans, where they have a radii of a few micrometers (Lewin and Bjorno 1981). Microbubble response to microsecond pulses of ultrasound has become a concern in the field of diagnostic medicine using ultrasound (Flynn and Church 1988). Investigators have defined a "transient cavity" as one that expands to a critical maximum radius and then collapses violently. The gas temperature and pressure reach extremely high values and a shock wave is generated in the surrounding medium during collapse and rebound. Ayme-Bellegarda (1990) and Holland and Apfel (1990) suggest that a bubble in the presence of a boundary can be more damaging because of the formation of a jet in the collapsing bubble which is directed toward the boundary.

Keevin et al. (In preparation) exposed 25 caged bluegill placed 2 m below the water surface to a 2 kg charge of T-100 explosive detonated at 2 m depth. Pressure waveform values (Table 6.3) can be compared with internal damages (Table 6.4) or mortality (Table 6.5) to determine damaging pressure levels. An abrupt increase in internal damage (ruptured swimbladder, kidney, liver, and spleen damage) occurred at values above approximately 700 kPa peak pressure, 50 Pa-s impulse (first positive wave), and 40 J/m^2 energy flux density. Mortality abruptly increased at approximate values above 500 kPa peak pressure, 40 Pa-s impulse (first positive wave), and 20 J/m^2 energy flux density. The lower threshold values for mortality reflect the mortality scoring system which scores minor injuries as "dead". LD50 values are presented for each pressure waveform measurement are given in Table 6.6.

Table 6.3.-Pressure waveform values resulting from the underwater detonation of a 2kg charge of T-100 at a depth of 2m. Independent duplicate trials are reported. (Keeven et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
Peak Pressure (kPa)[1]	1300.0	860.0	900.0	693.0	572.0	518.0	340.0	368.0	0
Impulse (Pa-s)[2]	98.6	59.1	49.7	56.1	39.2	38.1	23.6	23.1	0
Energy Flux Density (J/m^2)	134.0	63.9	62.8	45.5	28.1	17.7	9.1	8.1	0
SHOT 2									
Peak Pressure (kPa)1	1130.0	861.0	869.0	899.0	383.0	577.0	398.0	410.0	0
Impulse (Pa-s)[2]	113.0	60.6	67.9	55.4	23.8	45.7	28.3	25.8	0
Energy Flux Density (J/m^2)	128.0	69.4	65.0	42.2	19.0	24.6	10.6	10.0	0

[1] Peak pressure for the first positive waveform
[2] Impulse was calculated by integrating the pressure-time curve for the first positive wave.

Table 6.4.- Bluegill damage counts for each distance tested and controls (n=25 at each distance) based on necropsies of fish preserved 1 hr post blast. Bluegill were exposed to a 2 kg charge of T-100 at 2 m. Independent duplicate trials are reported. (Keevin et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
External Damage	9	3	1	0	0	0	0	0	0
Ruptured Swimbladder	22	14	13	9	1	0	0	0	0
Free Blood In Swimbladder	21	24	23	17	2	0	0	0	0
Free Blood In Coelom	12	4	12	6	6	0	0	0	0
Kidney Damage	16	8	8	0	0	0	0	0	0
Liver Damage	13	14	14	0	0	0	0	0	0
Spleen Damage	13	17	19	0	0	0	0	0	0
Heart Damage	1	0	0	0	0	0	0	0	0
Free Blood in Pericardium	2	0	0	0	0	0	0	0	0
Brain Damage	0	0	0	0	0	0	0	0	0
SHOT 2									
External Damage	12	4	5	0	0	0	0	0	0
Ruptured Swimbladder	23	21	19	4	0	0	0	0	0
Free Blood In Swimbladder	21	25	25	16	6	0	0	0	0
Free Blood In Coelom	13	5	7	8	8	3	0	0	0
Kidney Damage	21	12	10	0	0	0	0	0	0
Liver Damage	14	15	17	0	0	0	0	0	0
Spleen Damage	9	11	17	1	0	0	0	0	0
Heart Damage	0	0	0	0	0	0	0	0	0
Free Blood in Pericardium	5	0	0	0	0	0	0	0	0
Brain Damage	0	0	0	0	0	0	0	0	0

Table 6.5.- Percent mortality of bluegill (n=25 at each distance) exposed to a 2 kg charge of T-100 detonated underwater at 2 m depth. Independent duplicate trials are reported. (Keevin et al. (In preparation))

	DISTANCE (Meters) FROM EXPLOSION								
	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	Control
SHOT 1									
Percent Mortality	100.0	88.0	92.0	96.0	36.0	0.0	0.0	0.0	0.0
SHOT 2									
Percent Mortality	96.0	100.0	100.0	80.0	40.0	12.0	0.0	0.0	0.0

Table 6.6.- Bluegill LD50 values resulting from detonation of a 2 kg charge of T-100 at 2 m depth. Independent duplicate trials are reported. Keevin et al. (In preparation)

	LD50	Lower Limit	Upper Limit
SHOT 1			
Distance(m)	38.96	37.95	40.00
Peak Pressure(KPa)	625.80	591.60	661.90
Impulse(Pa-s)[1]	44.09	39.00	49.00
Energy Flux Density(J/m^2)	33.30	29.40	37.60
SHOT 2			
Distance(m)	39.23	38.21	40.28
Peak Pressure(KPa)	583.23	131.00	957.94
Impulse(Pa-s)[1]	49.00	46.30	51.80
Energy Flux Density(J/m^2)	28.00	10.42	56.06

[1]Impulse was calculated by integrating the pressure-time curve for first positive wave.

Necropsy results for bluegill in this study agree with those of other investigators who found the swimbladder to be the most frequently damaged organ (Christian 1973; Faulk and Lawrence 1973; Kearns and Boyd 1965; Linton et al. 1985a; Yelverton et al. 1975). The direction of rupture of bluegill swimbladders could not be determined; probably due to the thin and delicate nature of the swimbladder wall and fixation. Damage to the kidney, liver and spleen was extensive and possibly related to the rapid contraction and expansion of the swim bladder. In bluegill, the swimbladder is in close contact with the kidney located dorsally and the alimentary system ventrally. Table 6.4 shows that at distances where swimbladder ruptures occur, other internal damages also occur (i.e., liver kidney and spleen), and as the rate of swimbladder damage falls so do other injuries.

Ogawa et al.(1978) found that in fish with less well-developed swimbladders, neither the kidneys nor air bladder are injured, indicating that the presence of a swimbladder plays an important role with reference to injuries to other organ systems. Wiley et al. (1981) suggested that susceptibility to injury was related to body rigidity and swimbladder position relative to other organs. For example, oyster toadfish (Opsanus tau), a species which is extremely resistant to damage, have swimbladders that are less adherent to the dorsal body wall and therefore were

less in direct contact with the kidney. Wiley et al. (1981) suggested that the thick walls of their swimbladders reduced the incidence of rupture and the inherent flexibility of their bodies cushioned the internal organs from damage caused by rapid fluctuations in the size of the swimbladders. Incidence of internal hemorrhaging and bruising of the kidneys was much greater in the more rigidly built fish in which the swimbladder was closely adherent to the kidney. Apparently, the rapid expansion and contraction of the swimbladder is also responsible for damage to other organs. Knight (1907) and Fitch and Young (1948) have also suggested that the thickness of the swimbladder may also be an important factor in determining mortality levels, with species having thin swimbladders being most susceptible to blasts.

Teleki and Chamberlain (1978) suggested that physoclistous fish species (swim bladder attached to the circulatory system allowing slow change in bladder pressure) are more sensitive to blast pressures than either physostomus species (swim bladder attached to the esophagus allowing quick release of air) or species with no swimbladder. In their testing program, pumpkinseed (Lepomis gibbosus), white bass (Morone chrysops), and crappie (Pomoxis annularis), all physoclistic, were the most sensitive to blasting than physostomus species i.e., rainbow trout (Salmo gairdneri), white suckers (Catostomus commersoni), and yellow bullheads (Ictalurus natalis). In tests with a number of species, Yelverton et al. (1975) concluded there was little or no difference between the impulse required for 50% mortality for fish having dusted swimbladders and fish having non-ducted swimbladders. Christian (1973) suggested that intuitively he would expect that at the outer limits of the lethal zone a physostomous species might be more capable of adapting to the pressure changes than would a physoclistous species, but that under more severe shock conditions the two types might suffer about equal damage. He also stated that it may not matter in the explosion damage process, since pressure changes occur within microseconds, too rapidly for the normal gas-exchange mechanisms to operate. Baxter et al. (1982) suggested that the small duct of a physostomous species would not pass a significant amount of gas during the transit of shock waves.

External damage appears to be species specific and related to the magnitude of the pressure wave (e.g., charge size and distance from explosion). Linton et al. (1985a) noted that external injury to black drum (Pogonias cromis) exposed to primacord detonations was minor, whereas internal injury was substantial. The only visible external damage was loss of opercular scales. Red drum (Sciaenops ocellatus) exhibited no visible external injuries. The presence of a swimbladder may be a causative factor of some types of external damage. A bright red circle was observed on both sides of bluegill, presumably dermal capillary rupture caused by the rapid expansion and contraction of the swim bladder (Keevin et al. In preparation). After preservation, the circle appeared as an area of pallor or discoloration. Tyler (1960) observed a loss of small patches of scales in the vicinity of the swimbladder from each side of red salmon (Oncorhynchus nerka) exposed to 40-percent gelatin dynamite charges.

EFFECT OF FISH SIZE

There is limited information that fish weight may also influence vulnerability. Yelverton et al. (1975) tested a number of different fish species and found that a higher impulse was required to kill larger fish (body weight) than small fish. This was true both within a species and between species tested. Other factors such as age, general health, water temperature, and reproductive condition may influence mortality.

EFFECTS OF UNDERWATER EXPLOSIONS ON LARVAL FISH AND EGGS

Kostyuchenko (1973) exposed anchovy, blue runner and carucian carp eggs to a 50 g charge of TNT. The TNT charge produced structural abnormalities in the anchovy eggs at a distance of 2 to 20 m from the source, in the blue runner eggs up to 10 m away, and in the crucian carp eggs up to 5 m away. Only 20% of the eggs used in the experiment survived at a distance of 2 m, 58.2% at a distance of 10 m; only at a distance of 20 m were there no sharp differences from the control.

The "Guidelines for the Use of Explosives in Canadian Fisheries Waters" (Wright In press) have a guideline for protecting eggs on spawning beds. "No explosive may be use that produces, or is likely to produce, a peak particle velocity greater than 13 mm-sec^{-1} in a spawning bed during egg incubation." The guidelines provide the following table of set-back distances to achieve the standard (Table 6.7).

There have been no comprehensive studies determining the relationship between underwater pressures and larval fish mortality.

Table 6.7.- Set-back distance (meters) from center of detonation to spawning habitat to achieve 13mm-sec^{-1} standard for all types of substrate. (From Wright (In press))

Explosive Charge Weight (kg)	0.5	1	5	10	25	50	100
Set-back Distance (m)	15	20	45	65	100	143	200

SUBLETHAL INTERNAL DAMAGE TO FISH FROM UNDERWATER EXPLOSIONS

Sverdrup et al. (1994) conducted laboratory studies to determine the effects of underwater explosions on the vascular endothelium and on primary stress hormones of farmed Atlantic salmon (Salmo salar). Acclimated salmon were exposed to a series of 10 underwater explosions over 70 min. each of 2 MPa in pressure amplitude, in a laboratory tank. No mortality occurred immediately or during the subsequent 7 days of observation.

Structurally, the vascular endothelium of the ventral aorta and the coeliaco mesenteric artery revealed signs of injury within the first 30 min after the experimental shock. The endothelial impairment was temporary, persisting throughout the first days while being restored after 1 week.

Functionally, the cholinergic and adrenergic vasoconstrictor responses in the coeliaco mesenteric artery were markedly reduced during the first day after the shock. The loss of structural integrity and the reduced functional response indicated a temporary impairment of the vascular endothelium in response to the underwater explosion.

The primary stress hormones, adrenaline and cortical, were not immediately elevated in plasma, but revealed different patterns of delayed increases. The head kidney content of catecholamines was not altered by the acoustic shock, while the atrial uptake of both catecholamines declined progressively during the 48 h of observation. Plasma chloride was not affected.

UNDERWATER EXPLOSIVE FISH MORTALITY MODELS

Based on predictive equations, the kill radius for an underwater explosion can be calculated prior to commencement of the project. Three such predictive models are available: the energy flux density model (Sakaguchi et al. 1976), the impulse strength model (Baxter et al. 1982; Hill 1978; Munday et al. 1986; Wright 1982; Yelverton et al. 1975), and the dynamical model (Wiley et al. 1981). A user-friendly computer program was developed by COASTLINE Environmental Services Ltd. (1986) that uses the impulse strength model (IBlast) and the energy flux energy flux density model (EBlast) to predict effects for both midwater charges and charges that are drilled and buried in rock substrate. Although there are problems associated with these models (Hempen and Keevin 1995; Keevin 1995), they do give an approximation of the potential fish kill radius of a given explosive charge. O'Keeffe (1984) and Young (1991) provide kill probability contours for various fish sizes and charge weights based on the predicted results obtained by the dynamical model.

Young (1991) developed an equation to estimate safe ranges for fish with swimbladders. He noted that the prediction model was based on experimental data and an injury mechanism related to the response of swimbladder gas to the direct and reflected shock waves. Estimated range of vulnerability based on 90 percent probability of survival at a relatively shallow depth. He indicated that small fish are more vulnerable than large fish and fish near the surface are more vulnerable than deep fish.

Young (1991) suggested that the following fish (with swimbladder) safe range (Table 6.8) be used for preliminary planning purposes. He suggestedthat the equations are technically correct but they do not cover all possible conditions or marine environments.

Table 6.8.- Safety zone range calculations for fish with swimbladders. (From Young 1991)

ENGLISH MEASUREMENTS

$$R_{safe} = 95\ W_f^{-0.13} W^{0.28} d_W^{0.22}$$

R_{safe} = Safe range in feet
W = Weight of explosive in pounds
W_f = Weight of fish in pounds
d_W = Depth of burst in feet

METRIC MEASUREMENTS (Conversions)

$$R_{safe} = 43\ W_f^{-0.13} W^{0.28} d_W^{0.22}$$

R_{safe} = Safe range in feet
W = Weight of explosive in pounds
W_f = Weight of fish in pounds
d_W = Depth of burst in feet

Hill (1978) developed a model to predict lethal ranges for fish based on data in Yelverton et al. (1973). The model has been reproduced in Wright (1982) and has been reproduced here. Hill (1978) indicated that the model will "underestimate lethal ranges if the water depth is shallow (less than five times either the detonation depth or target depth, whichever is greater), and the bottom is rocky. In cases like this, there may be a considerable bottom-reflected shock wave which will increase the impulse at any point. If the charge is to be detonated under thick ice, a positive rather than negative surface-reflected wave may result. Once again, this increases the impulse and, in turn, the lethal range. Under these conditions, the calculated lethal ranges or safe distance should be doubled to ensure a conservative safety margin."

To use Hill's model to calculate lethal ranges or safe distance, the following information is required:

1. typical size (weight) of the fish species likely to be in the area,
2. depth of the target fish,
3. depth of detonation of the charge, and
4. weight of the charge.

To determine the slant range, the following steps are required:

1. From Figure 6.1, determine the impulse (I) corresponding to the assumed damage level.
2. Calculate the scaled impulse by dividing the impulse found in Step 1 by the cube root of the charge weight.

   $(I_{sc} = I/wt^{1/3})$

3. Calculate <u>parameter 'A'</u>, which is derived from the depth of the target fish, the depth of the detonation and the charge weight such that:

   $$A = \frac{\text{target depth (m) x detonation depth (m)}}{\text{charge weight (kg)}^{2/3}}$$

4. From Figure 6.2 find the best-fit curve to the calculated value of 'A' and using this curve, determine the value of the Scaled Range (R_{sc}) corresponding to the <u>Scaled Impulse</u> (I_{SE}) determined in Step 2.
5. Calculate the range (R) in meters by multiplying the Scaled Range by cube root of the charge weight.

   $R(m) = R_{sc} \text{ x charge } wt^{1/3}$

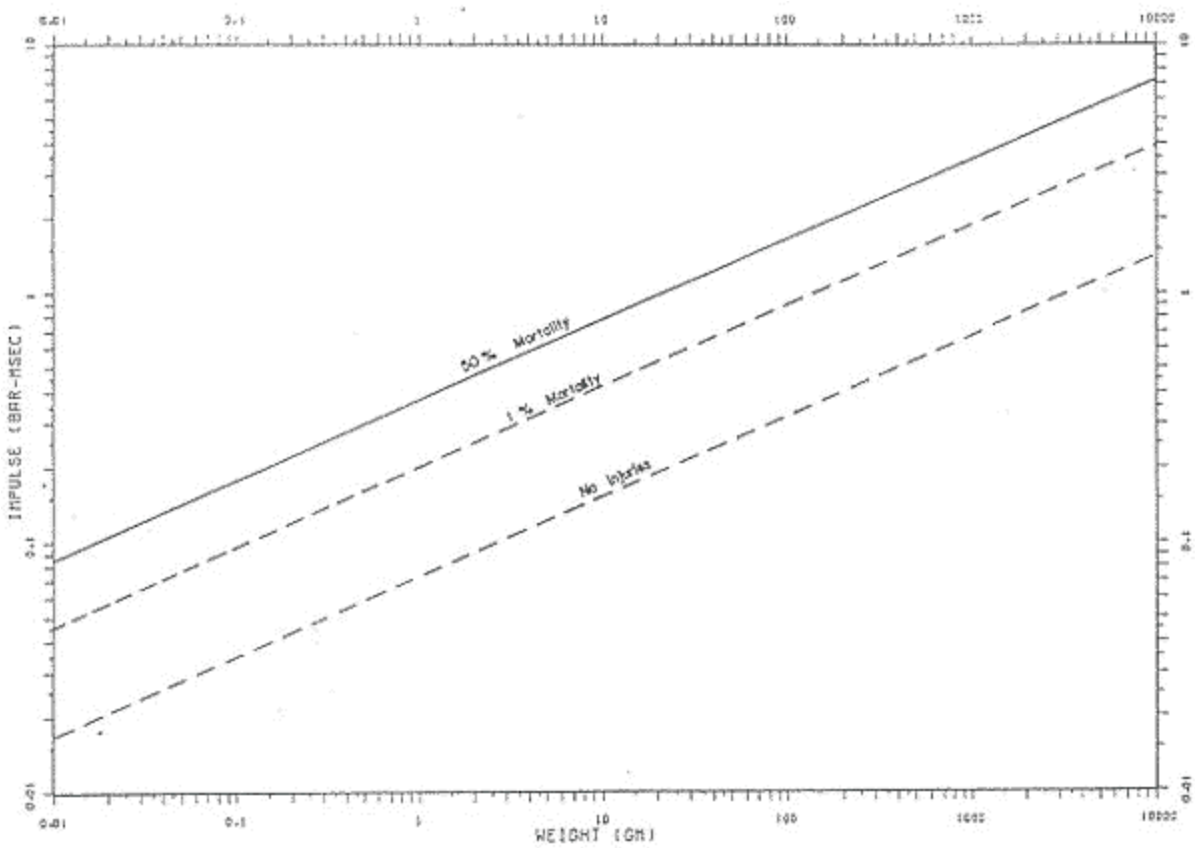

Figure 6.1.-Lethal impulse versus weight for fish (from Hill ; after Yelverton et al. 1975).

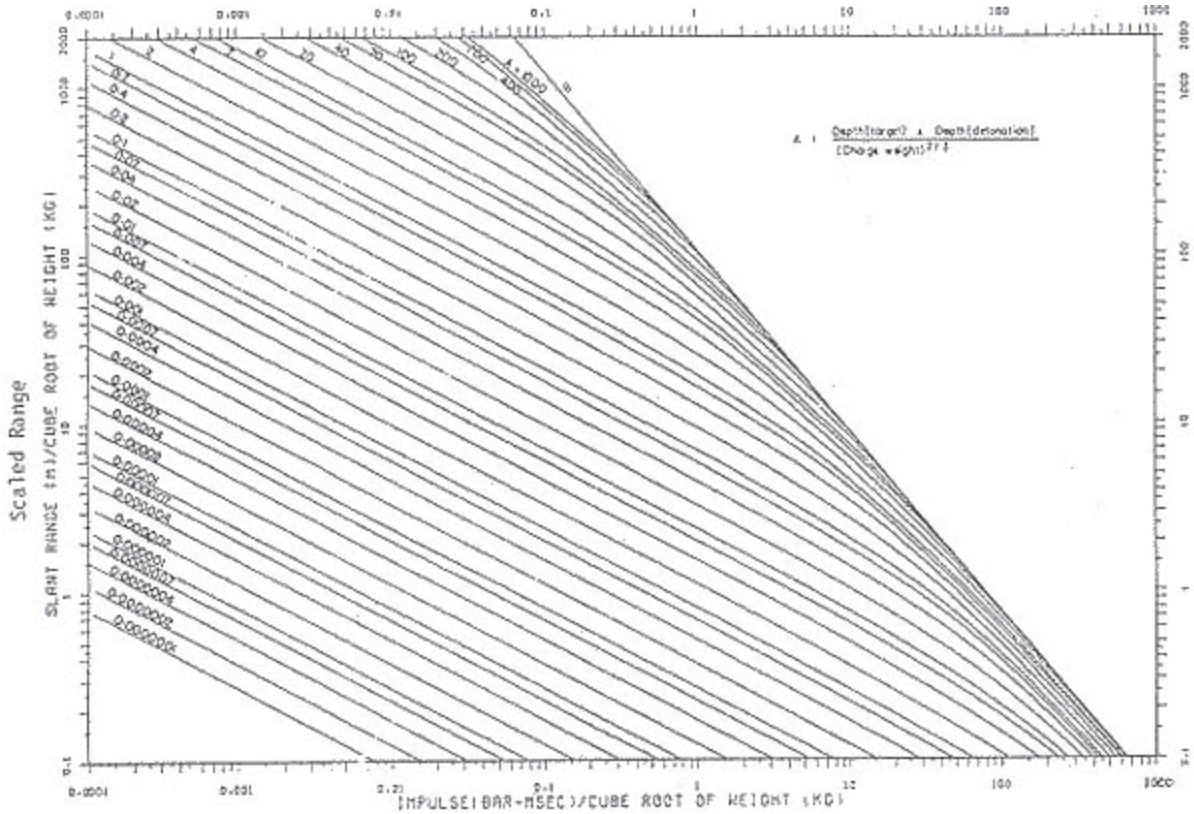

Figure 6.2.-Curves for calculating lethal range from impulse (from Hill 1978 after Yelverton et al. 1975).

EXAMPLE CALCULATION

For instructive purposes Wright (1982) provides the following sample calculation based on Hill's (1978) model.

What is the lethal range (50% mortality) for a 5 kg charge, detonated at a depth of 5 m? The fish in the area are Pacific herring Clupea harengus pallasii weighing 300 g, feeding on zooplankton at depths shallower than 10 m.

Weight of target fish = 300 g
Depth of target fish = 10 m
Depth of detonation = 5 m
Weight of charge = 5 kg

1. From Figure 6.1, an impulse of 2.3 bar-msec causes 50% mortality to 300 g fish;
2. The scaled impulse is calculated

$$\frac{\text{impulse}}{(\text{weight of charge})^{1/3}} = \frac{2.3}{5^{1/3}} = 1.35$$

3. Calculate the parameter 'A' using 10 m as the target depth This is a worst case since fish at shallow depth will experience a lower, less damaging impulse:

$$A = \frac{\text{target depth x detonation depth}}{(\text{charge weight})^{2/3}} = \frac{10 \times 5}{5^{2/3}} = 17.1$$

Therefore, we use the curve for A = 20 in Figure 6.2.

4. Using the curve A = 20 in Figure 6.2 the scaled range corresponding to a scaled impulse of 1.35 will be 48.
5. Lethal range is given by:

$$R_1 = \text{scaled range x charge weight}^{1/3}$$
$$= 48 \times 5^{1/3} = 82.1 \text{ m}$$

Thus, 50% of all 300 g Pacific herring at depths of 10 m and at 82.1 m from the explosion will be killed outright.

Table 6.9 lists those factors which potentially influence fish mortality modeling. Development of a precise model would add little to the accuracy of mortality predictions, since fish community structure (species specific mortality), precise fish location in the water column and size would not be known with any accuracy. At best, a "worst case" impact assessment provides a conservative prediction of mortality. As such, the impulse or energy flux density models may be adequate for those purposes.

Table 6.9.- Parameters that can affect fish mortality making precise predictions of mortality difficult (From Keevin (1995)).

Biological Parameters

1. Depth of fish
2. Weight of fish
3. Species specific mortality

Environmental Parameters

1. Air-water roughness
2. Water-bottom roughness
3. Water/bottom acoustic impedance (bottom type)
4. Water temperature

Explosive Parameters

1. Depth of explosive
2. Relative bulk strength of explosive
3. Surface, mid-column, or drillhole shot
4. Pressure reduction from confined shot

Data Acquisition Parameters

1. Accuracy of pressure transducers and recording equipment
2. Pressure wave processing techniques
3. Standardization of pressure waveform calculations

MITIGATION TECHNIQUES TO PROTECT FISH FROM UNDERWATER EXPLOSIONS

Mitigation techniques are described in detail in Chapter 8.

CHAPTER 7

THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS: MARINE MAMMALS

INTRODUCTION

In mammals, gas containing organs (e.g., lungs, intestinal tract) are most affected by underwater detonation of explosives (Cameron, Short and Wakeley 1943; Clark and Ward 1943). Hill (1978) and Ketten (1995) provide the most recent reviews of existing literature.

INJURY AND MORTALITY OF MARINE MAMMALS EXPOSED TO UNDERWATER EXPLOSIONS

The potential for marine mammal mortality has been documented in the scientific literature. Fitch and Young (1948) indicated that on at least three occasions California sea lions (Zalophus californianus) were killed by underwater explosions used in geophysical survey work. California grey whales (Rhachianects glaucus) were seemingly unaffected and were not even frightened from the area. No information was provided on the location of the charge (open water or jet shot), size of the charge, or distance from the charge. Fur seals were reportedly killed by an 11.4 kg dynamite charge exploded 23 m away (H. F. Hanson, in Wright 1982). Reiter (1981) reported without further details that "there was evidence of [fur] seals....killed from concussion in the immediate area of demolition" when a grounded ship was broken up by about 454 kg of explosives.

Sea otter studies done in association with underground nuclear tests have provided data on the susceptibility of marine mammals to shock waves. Wright (1971) reported that sea otters (Enhydra lutris)were injured by pressures of 100 psi (0.69 MPa) and killed outright by 300 psi (2.07 MPa).

Richmond et al. (1973) and Yelverton et al. (1973) conducted a series of tests to assess the effects of underwater explosions on injury using sheep, dogs, and monkeys. Based on the results of their studies, Yelverton et al. (1993) developed underwater-blast criteria for aquatic and marine mammals (Table 7.1). An impulse of 40 psi-msec (275.8 Pa-s) would result in a high incidence of moderately severe immersion-bast injuries including a high probability of eardrum rupture. They suggested at that impulse the animals should recover on their own. An impulse of 20 psi-msec (137.9 Pa-s) would cause slight blast injuries and a high incidence of eardrum rupture. An impulse of 5 psi-msec (34.5 Pa-s) should not cause any injury and can be considered a safe level for mammals.

Richmond et al. (1973) also ran a series of tests with dogs beneath the surface to evaluate eardrum rupture. A probit analysis of the data yielded an impulse of 22.6 psi-msec (155.8 Pa-s) for 50% eardrum rupture. Yelverton and Richmond suggested that impulse (integral pat) in the underwater blast wave was the parameter that governed biological damage and not peak pressure of energy.

Table 7.1. Underwater-blast damage criteria for mammals diving beneath the water surface (From Yelverton et al. 1973).

Impulse		Criteria
psi-msec	kPa-sec	
40	275.8	No mortality. High incidence of moderately severe blast injuries including eardrum rupture. Animals should recover on their own.
20	137.9	High incidence of slight blast injuries including eardrum rupture. Animals would recover on their own.
10	69.0	Low incidence of trivial blast injuries. No eardrum ruptures.
5	34.5	Safe level. No injuries.

Young (1991) developed equations to estimate marine mammal safe ranges based on experiments with land mammals, presumably Richmond et al. (1973) and Yelverton et al. (1973). Injury was related to the response of air cavities, such as the lungs and bubbles in the intestines, to the shock wave. The estimated mammal safe ranges were based on absence of injury. Young (1991) suggested that the following marine mammal safe ranges (Table 7.2) be used for preliminary planning purposes. He suggested that the equations are technically correct but they do not cover all possible conditions or marine environments.

Table 7.2. Marine mammal safety zone range calculations (From Young 1991)

ENGLISH MEASUREMENT

Calf Porpoise, 200-ft d_w	$R_{ep} = 578\ W^{0.28}$
Adult Porpoise, 200-ft d_w	$R_{ap} = 434\ W^{0.28}$
20-ft Whale, 200-ft d_w	$R_w = 327\ W^{0.28}$

R = Range in feet
W = Weight of explosive in pounds
d_w = Depth of burst in feet

METRIC MEASUREMENTS (Conversions)

Calf Porpoise, 61.0-meters d_w	R_{ep} (m) = 220 $W^{0.28}$ (kg)
Adult Porpoise, 61.0-meters d_w	R_{ap} (m) = 165 $W^{0.28}$ (kg)
20-ft Whale, 61.0-meters d_w	R_w (m) = 124 $W^{0.28}$ (kg)

R = Range in meters
W = Weight of explosive in kg
d_w = Depth of burst in meters

Hill (1978) developed a model to predict lethal ranges for marine mammals based on data in Yelverton et al. (1975). The model has been reproduced in Wright (1982) and has been reproduced here. Hill (1978) indicated that the model Will "underestimate lethal ranges if the water depth is shallow (less than five times either the detonation depth or target depth, whichever is greater), and the bottom is rocky. In cases 1lke this, there may be a considerable bottom-reflected shock wave which will increase the impulse at any point. If the charge is to be detonated under thick ice, a positive rather than negative surface-reflected wave may result. Once again, this increases the impulse and, in turn, the lethal range. Under these

conditions, the calculated lethal ranges or safe distance should be doubled to ensure a conservative safety margin."

To use Hill's model to calculate lethal ranges or safe distance, the following information is required:

1. depth of the target mammal;
2. depth of detonation of the charge, and
3. weight of the charge.

To determine the range, the following steps are required:

1. Determine the impulse (I) corresponding to the degree of protection required for mammals from Table 7.1.
2. Calculate the scaled impulse by dividing the impulse found in Step 1 by the cube root of the charge weight.

   $(I_{sc} = I/wt^{1/3})$

3. Calculate <u>parameter 'A'</u>, which is derived from the depth of the target fish or marine mammal, the depth of the detonation and the charge weight such that:

$$A = \frac{\text{target depth (m) x detonation depth (m)}}{(\text{charge weight (kg)})^{2/3}}$$

4. From Figure 7.1 find the best-fit curve to the calculated value of 'A' and using this curve, determine the value of the <u>Scaled Range</u> (R_{sc}) corresponding to the <u>Scaled Impulse</u> (I_{sc}) determined in Step 2.
5. Calculate the range (R) in meters by multiplying the Scaled Range by cube root of the charge weight.

   $R(m) = R_{sc} \times \text{charge } wt^{1/3}$

EXAMPLE CALCULATION

For instructive purposes Hill (1978) provides the following sample calculation.

What is the safe distance from a 5 kg charge detonated at a depth of 5 m for ringed seals? We wish to ensure that no harm is done to these animals by the explosion. Noting that the seals are feeding on small crustacea, and assuming that these are concentrated at depths less than 25 m, we can calculate the safe distance as follows:

1. According to Table 7.1, 0.34 bar-msec is a completely safe impulse level for submerged mammals;
2. The scaled impulse is calculated:

   $0.34/s^{1/3} = 0.2$

3. The quantity 'A' is calculated:

   $A = (5 \times 25)/5^{2/3} = 42.7$

4. Using the curve for A =40 in Figure 7.1, we find that a scaled range of 210 corresponds to a scaled impulse of 0.2. Therefore, the safe distance is given by :

$$R_S = 210 \times 5^{1/3} = 359 \text{ m}$$

Provided the charge is detonated at least 359 m from the seals, there should be no risk of damage.

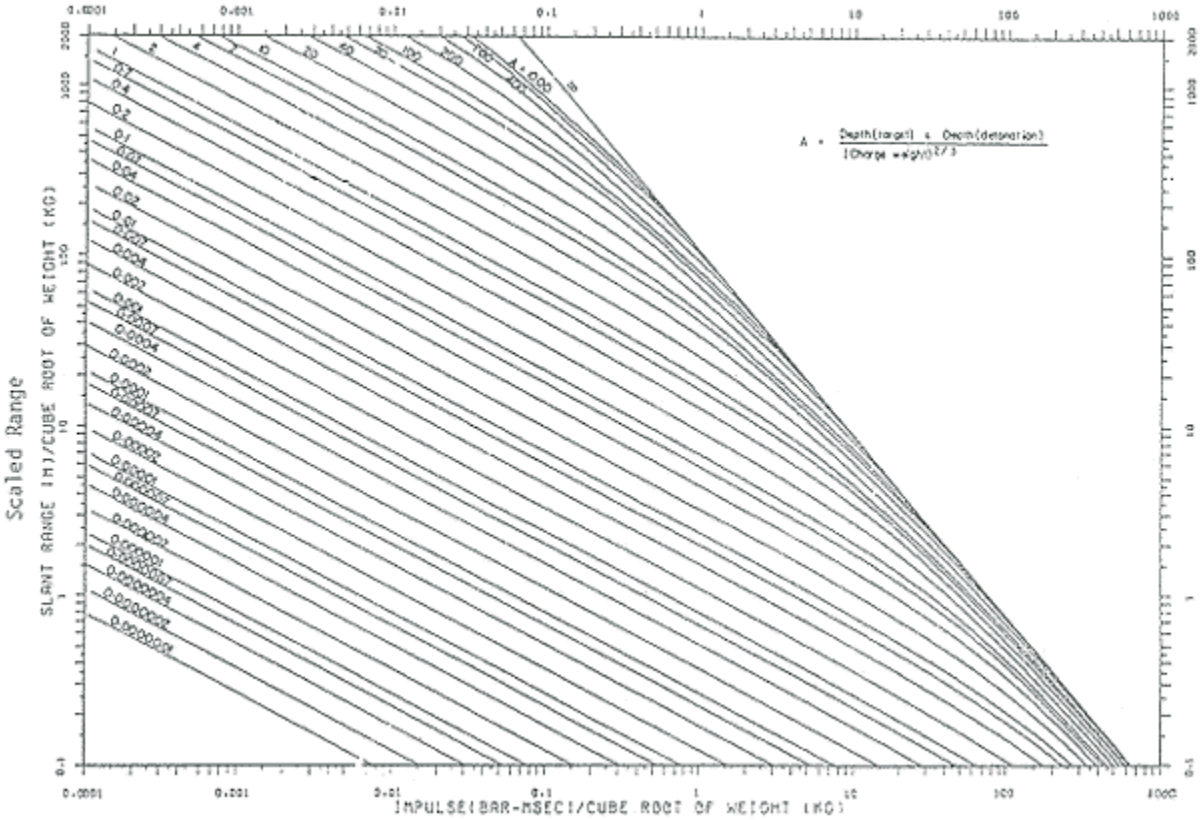

Figure 7.1.-Curves for calculating lethal range from impulse (From Hill 1978 after Yelverton et al. 1975).

Ketten (1995) suggested that for submerged terrestrial mammals, lethal injuries occurred at overpressures > 55 kPa and minimal injury limits coincided with overpressures of 0.5 to 1 kPa. These values seem very conservative when compared with Richmond et al. (1973) and Yelverton et al. (1973). For example, Richmond et al. (1973) found no internal damage in sheep exposed to 612 kPa from a 0.5 lb (225 g) charge of Pentolite at 10 ft (3.0 m) depth on sheep at 1 ft (305 mm) depth, 110 ft (33.5 m) from explosion. In addition, they found no ear damage in dogs with theirs at 1 ft depths (305 mm), exposed to 1.478 kPa from a 1ob (454 g(charge of TNT dtonated at 10 ft (3.0 m) depth, 60 ft (18.3 m) from the subjects.

BEHAVIORAL EFFECTS OF UNDERWATER BLASTING ON MARINE MAMMALS

There is little published information on the behavioral effects of underwater blasting on marine mammals. Todd et al. (1996) found that humpback whales (Megaptera novaeangliae) showed little behavioral reaction to construction detonations in terms of decreased residency, overall movement, or general behavior.

However, they found increased entrapment of humpbacks in fishing gear. Exposure to the construction explosions may have affected the hearing threshold of humpbacks, thus decreasing their ability to use net-produced acoustic cues to avoid net collisions. The probability of an entrapment occurring within 2 days or less of an explosion was 0.38, which was significantly greater than the calculated rate of 0.077 for entrapments occurring outside of a 2-day lag (z test of independent probabilities, $p < 0.0001$).

MITIGATION TECHNIQUES TO PROTECT MARINE MAMMALS FROM UNDERWATER EXPLOSIONS

Mitigation techniques described for fish are also applicable to marine mammals (see Chapter 8). Any attempt to reduce the pressure waveform will reduce the potential kill zone of marine mammals.

As with sea turtles, the simplest method to protect marine mammals from underwater explosions is to avoid periods when they are in the blasting zone. Avoidance of marine mammals can be achieved in two manners. Depending on location, there may be time periods when they are not in the project area due to their life history characteristics (e.g. migration patterns). This can be determined by coordination with the state natural resource agency or National Marine Fisheries Service. Blasting can be planned during time periods of low marine mammal abundance. If marine mammals are potentially in the area during blasting, an aerial survey using a light plane or helicopter can be conducted prior to detonation. If they are observed in the project area, blasting can be halted until they move out of a pre-determined blast zone.

An example of the above strategy is in place for explosive removal of oil and gas structures in state and federal waters of the Gulf of Mexico (Gitschlag 1990). For at least 48 hr prior to detonation, National Marine Fisheries Service observers watch for marine from the surface. Helicopter aerial surveys within a mile radius of the removal site are conducted 30 min prior to and after detonation (Gitschlag and Herczeg 1994). If marine mammals are observed, detonations are delayed until they have left the area.

"Seal bombs" and shell crackers have been used to "scare" marine mammals from the blast zone prior to detonating the large explosion. They have been used in attempts to prevent harbor seals, sea lions and other mammals from feeding on fish (e.g., Mate and Harvey 1987). These pyrotechnic devices expose the animals to sharp noise pulses of varying intensities. Seal bombs explode a few meters below the surface. Shell crackers fired from shotguns and several types of smaller pyrotechnics fired from pistols can explode above, at or below the surface. The general consensus from experience with these devices on the U.S. west coast is that, when first used, they startle the animals and often induce them to move away from feeding areas temporarily. However, the avoidance response wanes when the animals learn that the noise pulses are not harmful. Thereafter, some seals tolerate quite intense underwater sound in order to gain access to food (Mate and Harvey 1987).

There is a potential for marine mammal mortality resulting from the use of "seal bombs" as repelling charges. A similar device killed a human diver when it exploded approximately 0.3 m from his head (Hirsch and Ommaya 1972). Myrick et al. (1990) concluded that one Class-C device will cause injury when detonated within 0.5-0.6 m of a dolphin. They estimate a safe standoff distance of 4 m or more, depending on explosive type and depth.

CHAPTER 8

MITIGATING THE ADVERSE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSIONS ON FISH

INTRODUCTION

Development of effective mitigation strategies requires two components: a working knowledge of explosives and their impacts; and information on current mitigation techniques related to explosives, well grounded in practice theory. However, this is difficult because information about explosives and mitigative measures is often not widely accessible (reports, symposium proceedings, obscure scientific publications). The purpose of this chapter is to review natural resource agency mitigation policies; compare recommendations to available scientific literature on underwater explosive effects; and, develop a series of generic mitigation recommendations which will be useful to both natural resource planners and the blaster in developing strategies to reduce adverse effects of explosive use in aquatic ecosystems. This review is based on a recent publication by Keevin (In press) reviewing state natural resource agency mitigation policies.

A questionnaire was sent to fish and wildlife agency directors in each state to determine current agency policies on the use of explosives for legitimate purposes within waters under their jurisdiction (Keevin In press). Natural resource agencies were asked the following question concerning mitigation requirements within their state:

> "Does your agency require a person/company to apply mitigative techniques to reduce the potential for mortality to aquatic life during underwater blasting? If so, what mitigative techniques are required?"

In addition, the Canadian Department of Fisheries and Oceans' draft national guidelines, "Guidelines for the Use of Explosives in Canadian Fisheries Waters", were also reviewed since they provide mitigation recommendations for the use of explosives underwater.

Seventeen mitigation measures sere identified and are summarized in Table 8.1. They fall into three general categories: 1) review of the explosive design and provide mitigation recommendations based on that design; 2) evaluation of the potential impact and mitigative recommendations based on biological considerations; and, 3) evaluation of potential impact and require physical measures (e.g., bubble curtains, physical barriers, etc.) to minimize impacts. Each mitigation recommendation is reviewed based on existing literature and/or the physics of explosions. Although the mitigation recommendations were developed for fish, they are applicable to any organisms (e.g., marine mammals, sea turtles, etc.). However, specific mitigation recommendations are provided for non-fish species within their respective chapters.

Table 8.1.- Summary of State Natural Resource Agency Responses. (From Keevin (In press))

	AL	AK	AZ	AR	CA	CO	CT	DE	FL	GA
BLASTING DESIGN										
Agency Review	--	Y	--	--	--	--	--	--	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	Y	--	--	Y	--	--	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	Y	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	Y	--	--	--	--	--	--	--	--
Observers	Y	Y	--	Y	Y	--	Y	--	--	--
Compensation	Y	--	--	--	--	--	--	--	--	--
Sampling	--	--	--	--	Y	--	--	--	--	--
Seasonal Restrict	--	Y	--	--	--	--	Y	--	--	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	N	--	--	--	--	--	--	--	--
Noise	--		--	Y	--	--	--	--	--	--
Bubble Curtain	--	N	--	--	--	--	--	--	--	--
Physical Barriers	--	--	--	--	--	--	Y	--	--	--

	HI	ID	IL	IN	IA	KS	KY	LA	ME	MD
BLASTING DESIGN										
Agency Review	Y	--	--	--	--	--	--	--	--	Y
Charge Type	Y	--	--	--	--	--	--	--	--	--
Charge Weight	Y	--	--	--	--	--	--	Y	--	Y
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	Y
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	Y	--	--	Y	--	--	--	Y	Y	Y
Compensation	--	--	--	Y	--	--	Y	Y	--	Y
Sampling	--	--	--	--	--	--	--	--	--	Y
Seasonal Restrict	Y	--	Y	Y	--	--	--	Y	Y	Y
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	Y	--	--	--	--	--	--	--
Noise	--	--	Y	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	--	--	--	--
Physical Barriers	--	--	---	Y	--	--	--	--	--	--

	MA	MI	MN	MS	MO	MT	NE	NV	NH	NJ
BLASTING DESIGN										
Agency Review	Y	--	--	Y	--	--	--	--	--	--
Charge Type	Y	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	--	Y	--	--	--	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	Y	--	--	--	--	--	--	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	--	--	Y	Y	--	--	--	--	Y
Compensation	--	--	--	--	--	--	--	--	--	--
Sampling	Y	--	--	--	--	--	--	--	--	--
Seasonal Restrict	--	Y	--	--	Y	--	--	--	Y	Y
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	--	--	--	--	--	--	--	Y
Noise	--	--	--	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	--	--	--	Y
Physical Barriers	--	--	--	--	--	--	--	--	--	--

NM		NY	NC	ND	OH	OK	OR	PA	RI	SC
BLASTING DESIGN										
Agency Review	--	--	--	Y	--	--	Y	Y	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	--	--	--	--	--	--	Y	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	Y	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	--	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	--	--	Y	Y	--	Y	--	--	--
Compensation	--	--	Y	Y	Y	Y	Y	Y	--	--
Sampling	--	--	--	--	--	--	Y	--	--	--
Seasonal Restrict	--	Y	Y	--	--	--	Y	Y	Y	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	--	--	--	--	--	--	Y	--
Noise	--	--	--	--	--	--	--	--	Y	--
Bubble Curtain	--	--	--	--	--	--	Y	--	--	--
Physical Barriers	--	Y	--	--	--	--	--	--	--	--

	SD	TN	TX	UT	VT	VA	WA	WV	WI	WY
BLASTING DESIGN										
Agency Review	--	--	--	--	--	--	--	--	--	--
Charge Type	--	--	--	--	--	--	--	--	--	--
Charge Weight	--	--	Y	--	--	--	Y	--	--	--
Shaped Charges	--	--	--	--	--	--	--	--	--	--
Delays	--	--	--	--	--	--	Y	--	--	--
Decking	--	--	--	--	--	--	--	--	--	--
Stemming	--	--	Y	--	--	--	--	--	--	--
BIOLOGICAL CRITERIA										
Mortality Models	--	--	--	--	--	--	--	--	--	--
Observers	--	Y	Y	--	--	Y	Y	Y	Y	--
Compensation	--	--	Y	Y	--	--	Y	Y	Y	--
Sampling	--	Y	--	--	Y	--	Y	--	--	--
Seasonal Restrict	--	--	Y	--	Y	Y	Y	Y	Y	--
PHYSICAL MITIGATION FEATURES										
Repelling Charges	--	--	N	--	--	--	Y	--	--	--
Noise	--	--	Y	--	--	--	--	--	--	--
Bubble Curtain	--	--	--	--	--	--	Y	--	--	--
Physical Barriers	--	--	Y	--	--	--	--	--	--	--

DEVELOPMENT OF MITIGATIVE STRATEGIES: THE BLASTING DESIGN

Agency Review of Blasting Design. Eight states responded that the blaster was required to submit a detailed blasting design for agency review prior to approval. The Canadian Department of Fisheries and Oceans also requires detailed blasting design information as a permit requirement.

Review prior to implementation of a project can be very effective in reducing impacts. The first step in the review process should be to determine if there is a need for use of explosives. Obviously, the best way to mitigate impacts of explosives is to avoid or minimize their use. The Oregon Department of Fish and Wildlife's blasting permit application requests information on alternatives to in-water blasting and for an analysis of their practicability. In a harbor project, the Massachusetts Department of Environmental Protection required the use of a mechanical breaker until there was a loss of efficiency, before blasting rock. Likewise, for seismic programs, the Mississippi Department of Environmental Quality indicated that although there was no specific language in their rules and regulations prohibiting the use of explosives as an energy source, "... the Commission would not look fondly on issuing a permit of that nature, especially since less invasive energy sources are currently available."

The second step in the review process should be a thorough review of the explosive design. A good explosive design (i.e., size of charges, use of shaped charges, stemming, decking, etc.) can help reduce adverse impacts to the aquatic environment. For example, a blasting cap, or cap and primer, is preferable from an environmental protection perspective over detonating cord to initiate an underwater explosive. This is because a blasting cap adds little to the magnitude of an explosion while detonating cord has an associated kill radius that extends along the cord from the firing mechanism to the explosive being detonated. Metzer and Shafland (1986) found that five species of experimental fish stationed within 7 m of a single strand of detonating cord (10.63 g PENTA/m) were killed instantly upon detonation. Use of detonating cord rather than a blasting cap (and possibly a primer charge) produces a cylinder of mortality with a 14 m diameter.

In conclusion, an agency requirement to provide detailed blast design information and to have a pre-project review meeting with the blasting company can be an extremely effective mitigation tool. Regulatory agencies can hamper the progress of initially approved programs. Projects can be delayed or contractual issues may arise, if regulatory agencies require approval of individual shots. Should the evaluation be slowed or the shot not be approved, the-blaster is revising the program outside of contractual obligations. Regulators offer the greatest aid when they provide operational review to some established limit, which may be revised, as the work demands through a specified procedure. The purpose of the regulation should be to remain within bounds of a reproducible, objective, environmental test.

Charge Type. Two respondents make recommendations concerning the type of explosive. The Massachusetts Department of Environmental Management required "the use of low-velocity explosives" in a dredging project at Cohasset Harbor. The rational for this approach is "probably" based on research (Baldwin 1954; Ferguson 1962; Fry and Cox 1953; Hubbs and Rechnitzer 1952) which indicated that black powder, a low detonation velocity explosive, had little effect on fish. Detonation velocity (DV) is the rate at which a blasting agent ignites. It ranges from about 1,650 to 7,650 m/s for products used commercially today (Dick et al. 1993a). Hubbs and Rechnitzer (1952) found that in marine fish species tested, the lethal threshold peak pressure from dynamite (DV = approximately 17,000 m/s) explosions varied from 276 to 483 kPa. Peak pressures from slow burning black powder (DV = 1,709 m/s), producing pressures as high as 855 to 1,103 kPa, did not kill caged fishes. Based on the findings of Hubbs and Rechnitzer (1952), Teleki and Chamberlain (1978) concluded that the lethality of an explosive is directly related to its detonation velocity. They suggested that the more rapid the detonation velocity the more abrupt was the resultant hydraulic pressure gradient and the more difficulty fish had adjusting to the pressure changes. They felt that a knowledge of the detonation velocity is critical to a true understanding of the impact of blasting on fish.

Use of black powder or gunpowder, widely used in early seismic exploration studies, has been largely discontinued due to hazardous handling properties and poor quality of seismographic records (Lipton et al. 1985b). Black powder produces a pressure waveform that is unlike other commercially available high explosives currently in use. It has a slow rise time, low amplitude, and long frequency when compared to high explosives which have an abrupt rise time, high amplitude, and short frequency. Keevin (1995) compared mortality of bluegill (Loomis macrochirus) exposed to three high-explosives types (T-100 Two Component, Pellite, and Apex 260) spanning the range of detonation velocities within commercially available explosives. Using equivalent weights of explosives, there was no significant difference in mortality curves based on distance from the explosive charge. This suggests that detonation velocity of commercially available explosives, recognizing that black powder deflagrates, is not an important factor in fish mortality.

The use of a linear charge, rather than a point-source explosive, during seismic exploration, may reduce fish mortality. Faulk and Lawrence (1973) and Mobil Oil (1984) found that the lethal range for linear-format explosives (e.g., detonating cords) is less than that of point source detonations for similar charge strength. Imperial Chemical Industries Ltd. (1968) reported that a 30 m length of "Aquaflex" containing 0.68 kg of explosive detonated 9 m below the water surface will produce a seismic record comparable in quality to that secured from a conventional 23 kg charge. Munday et al. (1986) suggested that the question that remains to be answered is how the relative lethality of the shock waves from linear explosives differs from point source detonations. They indicate the need for research involving the exposure of caged fish at different distances from linear charges. Munday et al (1986) note that measurement and analysis of the waveform "signature" generated by particular explosives should be an essential component of any such studies.

Canadian guidelines require that: "No explosive may be used that produces, or is likely to produce, an instantaneous pressure change greater than 100 kPa at a distance greater than 10 meters from the point of detonation." In order to meet this requirement, both the type of explosive and charge weight would have to be carefully evaluated. In an underwater blasting project for a natural gas utility crossing the Nipigon and Winnipeg rivers, McAnuff et al. (1994) chose an explosive product that was resistant to sympathetic detonation to comply with this guideline. Depth of the blast hole collar, and the length and gradation of stemming, also had to be carefully chosen.

Charge Weight. Nine respondents made recommendations concerning the charge weight of explosive. Reducing the charge size will reduce the amount of energy released into the water column. Blasters generally use developed experience, general formulae, or commercial computer programs to determine charge weight to accomplish a particular task. However, these procedures do not directly provide information specific to local conditions (e.g., local geology, rock hardness, concrete reinforcement, structural integrity). A limited testing program can often be employed to determine the minimum charge size to accomplish the required work, thereby minimizing environmental effects.

Doubling the explosive charge weight does not double the pressure. For deep shots, the peak pressure is approximately proportional to the cube root of explosive weight (Cole 1948). At 4 m distance, a 1 kg charge of TNT should produce 10.9 MPa peak pressure. A 2 kg shot, given the 1 kg charge pressure, scales to 14.2 MPa for the same 4 m distance. It would be necessary to increase the charge weight to 8 kg to produce a peak pressure of 23.9 MPa.

Shaped Charges. The term "shaped charge" refers to surface placement of explosives which have a preferred volumetric geometry or are formed with a lined or unlined cavity in the end opposite the initiation point. The detonating explosive progressively shatters the liner, focusing it into a directional high-velocity jet of particles. This jet has tremendous penetrating ability. Shaped charges can provide a fairly precise cutting tool in demolition work that can be used to weaken or destroy key structural points (Skinner et al. 1973). No respondents recommended use of shaped charges as a mitigation technique. Testing has not been conducted to determine if shaped charges produce less pressure impact to the environment. However, if blast energy is focused in such a way that the explosive is doing more "work", then less shock energy may be transmitted to the water column as compared to other surficially placed explosives. Also, shaped charges are used to do precise work which may reduce the total weight of explosives employed when compared to other explosive techniques.

Delays. Large explosive charges can be broken into a series of smaller charges by use of timing delays. For example, demolition of a bridge pier requires drilling numerous shot holes that are then filled with explosives. Shot holes can be detonated simultaneously or in succession, with a time interval between detonation of each shot hole or groups of shot holes. The greater the weight of explosives shot instantaneously, the greater the intensity of the shock wave and the greater the area of effect (Tansey 1980).

Delay blasting caps or series delays can be used to achieve delay periods between successive detonation of shot holes. Blasting caps with different delay periods are available; delay periods range from 25 msec (cap #1) to 1,125 msec (cap #20). During detonation, all caps are initiated simultaneously, but the larger the cap number, the longer it takes a filament inside the cap to burn before the charge is initiated. The use of delay caps effectively reduces each detonation to a series of small explosions. In the case where electric initiation is prohibited, series delays may be used, series delays detain the propagation of the ignited or detonated medium. Resulting blast overpressure levels are directly related to the

size of the charge for delay, rather than the summation of charges detonated in all holes (Munday et al. 1986).

There has been no field testing to determine the effectiveness of this technique in reducing aquatic mortality. However, if the pressure wave can be broken into a series of smaller waves that fish internal organs can dynamically respond to as a single event, then the technique should be effective in reducing mortality. Ogawa et al. (1976) conducted a laboratory experiment on the response time of fish to pressure. They reported that fish response time, measured as recovery from deformation, was on the order of 100 msec. In a pressure pulse repetition experiment, no increase in injuries was observed for pulse periods less than 100 msec. However, if it rose above 100 msec, the effect of pressure pulse repetitions on injuries could be detected. Limited field testing (Anonymous 1948) also suggests the importance of producing a repetitive pressure pulse that fish respond to as a single event. Explosions fired in succession extended the immediate lethal range and killed more fish. Based on what has been well researched, the effectiveness of delays in sequence and defining the minimum delay period that provides maximum protection, requires further examination.

Four states responded that delays were recommended as a mitigative technique. Canadian guidelines require the preparation of a mitigation plan that should include the following measure: "if multiple charges are required, time-delay detonation initiators (blasting caps) should be used to reduce the overall detonation to a series of discrete explosions." The Alberta Forestry, Lands and Wildlife Fisheries Habitat Protection Guideline No. 15 recommends "a minimum delay of 25 msec must be used, but a delay of 50 msec between successive charges is recommended; they also state that: "In underwater blasting, confined charges should be used."

Decking. Explosive charges can be "decked" within a bore hole. In this procedure, two or three charges are included in one hole separated by a non-explosive material. A longer delay is used for the lower charge than for the upper charge, causing the upper charge to detonate first, followed by the lower charge. In effect, decking produces results similar to time delays. As a result, overpressure levels are lower than if both charges were combined as a single shot (Munday et al. 1986). The effectiveness of this procedure in reducing environmental effects has not been evaluated; however, lower overpressures should reduce the kill radius.

No state fish and wildlife agency indicated that decking charges was a recommended mitigation procedure. Canadian guidelines require the preparation of a mitigation plan that should include the following measure: "if possible, large charges should be subdivided into a series of smaller charges (a procedure known as decking) using time-delay detonation initiators (blasting caps) to reduce the overall detonation to a series of smaller discrete detonations or explosions."

Stemming. Stemming is the use of a selected material, usually angular gravel or crushed stone, to fill a drill hole above the explosive. Stemming is commonly used by the blasting industry to contain the explosive force and increase the amount of work done on the surrounding strata (Konya and Davis 1978; Moxon et al. 1993). This technique decreases the amount of gas energy that is lost out of the drill hole and thus reduces the impact to the aquatic environment. Brinkmann (1990) has shown that approximately 50% of the explosive energy is lost if unrestricted venting is allowed to occur through the blasthole collar. Susanszky (1977) found, in a series of tests in the Danube River, that absolute values of pressures were decreased by an order of magnitude by using soil for stemming.

Konya and Davis (1978) conducted a series scaled down tests of a variety of stemming materials in a ballistic mortar with a long, roughened bore to simulate the collar of a blast hole. They found that highly spherical sand (wet or dry)

ejected even when loaded to the full bore length (1 m), whereas very angular limestone of similar grain size held at the same powder charge with as little as nine inches of stemming. They concluded that angularity appears to be the single most influential variable in maintaining the stemming material in the blast hole. Gordon and Niles (1990) noted that mud and drill cuttings were poor stemming materials and that angular material was the best materials since it arched and locked into the borehole wall when subjected to detonation pressure. They recommended that the optimum crushed rock particle size should be approximately 1/12 of the borehole diameter.

Two respondents indicated that stemming was recommended to reduce impacts. For example, a permit applicant conducting seismic testing in West Galveston Bay, Texas, proposed placing charges in shot holes and allowing approximately 30 days to pass before detonation to allow the shot hole walls to slough thus "packing" the holes. In response to the proposal, the Texas Parks and Wildlife Department indicated that "... continued loss of fisheries resources could require the packing of shotholes with small gravel or other appropriate material to reduce the changes of pressure." Canadian guidelines for use of explosives in fisheries waters provide for the possible use of stemming as a mitigation feature. "[T]he hole must be back-filled (stemmed) with sand or gravel to the level of the substrate/water interface or the hole collapsed to confine the force of the explosion to the formation being fractured."

DEVELOPMENT OF MITIGATIVE STRATEGIES: BIOLOGICAL CRITERIA

Individual Project Review. Although the question was not specifically asked, most states indicated that each proposed explosive-use project was evaluated on an individual basis. This represents a reasonable approach for evaluating the explosive use design, the existing fishery resources in the blast area, and the magnitude of impact. The agency can review existing fishery data for the blast area, or require a survey if none is available. This allows the agency to make rational decisions based on the quality of fishery (e.g., anadramous fish migrations, larval fish drift, endangered species). This approach also allows flexibility in developing mitigation plans based on the potential impact of each individual project.

Predictive Mortality Equations. An underwater explosion represents a single point of disturbance to the aquatic environment; thus, the mortality zone is generally restricted. A reactionary approach, one requiring stringent mandatory mitigative techniques without a preliminary assessment of impacts, would not be in the best interests of the blaster or the regulatory agency. Such an approach would not benefit the aquatic resources that a regulatory agency is required to protect. Based on predictive equations, the kill radius for an underwater explosion can be calculated prior to commencement of the project. Three such predictive models are available: the energy flux density model (Sakaguchi et al. 1976), the impulse strength model (Baxter et al. 1982; Hill 1978; Munday et al. 1986; Wright 1982; Yelverton et al. 1975), and the dynamical model (Wiley et al. 1981). A user-friendly computer program was developed by COASTLINE Environmental Services Ltd. (1986) that uses the impulse strength model (IBlast) and the energy flux density model (EBlast) to predict effects for both midwater charges and charges that are drilled and buried in rock substrate. Although there are problems associated with these models (Hempen and Keevin 1995; Keevin 1995), they do give an approximation of the potential fish kill radius of a given explosive charge. O'Keeffe (1984) and Young (1991) provide kill probability contours for various fish sizes and charge weights based on the predicted results obtained by the dynamical model.

Two factors need to be considered when estimating total fish mortality using mortality models. Midwater and open water models were developed using open water shot data, so they may be useful in evaluating open water seismic charges but will

overestimate mortality for shots confined within solid media (e.g., demolition shots). Physoclistous fish species (swim bladder attached to the circulatory system allowing slow change in bladder pressure) may be more sensitive to blast pressures than either physostomus species (swim bladder attached to the esophagus allowing quick release of air) or species with no airbladders (Teleki and Chamberlain 1978).

Explosives in open water, that are not contained completely by rigid structures, will produce both higher amplitude and higher frequency shock waves, than contained detonations. Thus, the use of blasting in structure demolition, when the explosives are enclosed within the structure being razed, should result in lower fish mortality than the same explosive detonated in open water. For example, "burning" a steel beam underwater with perimeter charges to sever it would cause higher mortality than the severance of a concrete pier using an explosive of the same weight and detonation velocity placed within the pier by drilling and stemming. The greater the shock energy is transmitted away from the water column through solid media, the lowering the capacity of the water-borne shock wave to cause mortality.

No state fish and wildlife agency currently uses fish mortality models in their pre-project assessment of impacts nor require applicants to submit potential fish kill radius data based on mathematical models. Alaska has used a fish mortality model as a predictive tool to protect marine diving mammals. Nevertheless, this simple planning procedure could give the natural resource agency valuable information concerning the potential magnitude of impact from the use of underwater explosives.

The Canadian guidelines for use of explosives in fisheries waters require the preparation of an environmental impact assessment which includes "the theoretical lethal range of the explosives to be used" based on equations provided in the guidelines. These calculations are made to determine if the explosive charge weight is likely to exceed guideline standards, an instantaneous pressure change greater than 100 kPa at a distance greater than 10 meters from the point of detonation.

The Alaska Department of Fish and Game has used IBlast (COASTLINE Environmental Services Ltd. 1986), in conjunction with mammalian injury data provided in Wright (1982) to set standards for maximum allowable impulse strengths to protect diving mammals during explosive channel excavation within St. George Harbor. They suggested an upper limit of 69 kPa/ms as measured at the mid-water-column depth 150 meters horizontal from the charge.

Observers. Twenty-two states and Canadian guidelines require pre-notification so that an agency representative may be present to assess blast impacts. As a result, the resource agency can better evaluate the magnitude of the impact. If fish mortality is considered excessive, an agency has the option of either halting blasting, requiring significant blasting revisions, requiring the use of mitigative techniques, or requiring monetary compensation for any fish killed. The Missouri Department of Conservation has successfully employed this technique on three recent projects, a lock and dam demolition project, removal of rock outcroppings considered hazardous to navigation, and intake channel construction. However, conservation agents did not find what they considered significant mortality levels from blasting on these Missouri projects.

Many agencies suggested that if high numbers of fish are killed, the applicant would be required to cease blasting or to provide appropriate mitigation. For example, in a project involving bedrock removal in the Potomac River using controlled blasting techniques, the Maryland Department of Natural Resources granted a permit with the condition that the applicant contact the agency "at least 24 hours prior to any day that blasting will be conducted so that an observer may be present." In addition, they noted that if "it is determined that excessive numbers of fish are being killed, the applicant may be required to stop blasting

and/or provide appropriate mitigation for fishery losses."

Compensation of Fishery Losses. Sixteen agencies have either required, or have provisions for, monetary compensation of fish losses based on replacement values developed by the American Fisheries Society (1982, 1992, 1993). Sometimes adjustments to replacement values are made to reflect unique circumstances or to include marine species. Monetary value may be based on: actual counts of dead fish; mathematical mortality models projecting fish kill levels; or actual testing programs. As part of their permitting authority, the Texas Parks and Wildlife Department (TPWD) required the applicant fund a testing program to gather mortality data to project possible impacts from a proposed 3-D seismographic survey in West Galveston Bay. It involved a series of tests using methods proposed for the survey. Using the test data, they projected what would be the total fish kill if the geophysical survey was carried to completion. A monetary value was then assigned using TPWD Guidelines. American Fisheries Society (1982) replacement values were supplemented with added recreational values for any sport fishes killed.

TPWD recognized society's need to conduct such survey work, by making provisions to allow a certain acceptable level of fish mortality without compensation. As an environmental cost of performing geophysical surveys for new oil and gas reserves, ten pounds of fish per 18 acres of surveyed area were deducted from the total projected fish kill. The total weight allowed (2,543 kg) for the entire area affected by the survey was distributed over each species and size class based on their proportion of the total kill weight.

If monetary compensation is based on counts of dead fish found floating at the surface, an agency must recognize that observed numbers do not represent the total fish kill. Incidental observations indicate that many dead fish do not surface (Brown and Smith 1972; Coker and Hollis 1950; Ferguson 1962; Fitch and Young 1948; Indrambarya 1949; Kearns and Boyd 1965; Knight 1907). The proportion of "floaters" to the actual number of fish killed has never been documented. For this reason, resource agencies should use a conservative approach and increase the monetary compensation by a predetermined factor (i.e., possibly 2 or 3 times the observed mortality). This approach would allow the contractor to continue work while the loss to the fishery resource is compensated.

Pre-Blast Sampling Surveys To Detect Fish Presence. Seven respondents recommended or required use of sonar surveys or other sampling techniques to establish presence of fish in the blast area prior to detonation. Monitoring allows detection of migratory populations near the blast site, thereby decreasing the potential risk of higher fish kills.

The Washington Department of Fisheries required the Seattle Engineering Department to contract for hydroacoustic surveys before bridge pier demolition in the Duwamish River to locate salmon in or around the project site. Results were then used to determine whether or not demolition could proceed (Gaia Northwest, Inc. 1990).

It appears that pre-blast surveys have limited value. Munday et al. (1986) showed that fish kill number could not be predicted consistently from pre-blast sonar surveys. Use of purse seining also proved to be only marginally effective in sampling resident populations even when fish schools were found by echo location. Kearns and Boyd (1965) reported that sonar surveys predicted fish kills only 36% of the time in seismic refraction studies off Vancouver Island. Purse seining was used to measure fish presence near a blasting operation in a shallow marine embayment, False Creek, B.C. (Nix and Chapman 1983). Although seine catches reflected week-to-week and month-to-month changes in fish presence, seining success was not closely correlated with fish kills resulting from single detonations. Munday et al. (1986) concluded that monitoring resident fish populations by both sonar surveys and purse seining is not a very reliable method for predicting mortalities from underwater

detonations even if the lethal range can be predetermined. Use of monitoring can identify day-to-day changes in resident fish presence, but precise constraints of monitoring techniques restrict their usefulness within the predicted lethal zone. On-site sampling, particularly hydroacoustic surveys, are useful in identifying periods of major fish migrations, periods when explosive use may need to be restricted by the natural resource agency.

Seasonal Restrictions on Blasting. Twenty-three respondents consider use of time limits during review of blasting proposals. Natural resource agencies are in the best position to know when potentially sensitive time periods occur in the life history of species of concern. Sensitive periods can include those associated with mass migrations, high larval fish abundance, and fish spawning. An agent can review the blast proposal and, based on the magnitude of the program, determine if time limitations are warranted.

The Oregon Department of Fish and Wildlife applies permit conditions that include restrictions on timing of in-water blasting "to prevent injury to fish and wildlife and their habitat, fish eggs or other aquatic life, as well as commercial and recreational fisheries....". The Department has developed guidelines outlining preferred work periods for each waterway, by region. This information is available to the blaster as part of Oregon Administrative Rules for In-Water Blasting Permits. There are provisions to allow the local fishery biologist latitude when a species of concern is not in the area during a proposed blasting period or if a species is present and not adequately protected by the timing guidelines.

Canadian guidelines for the use of explosives in fisheries waters require that "the project should be undertaken at the time of least biological activity or biological sensitivity. Proponents should consult with DFO Regional/Area Authorities to determine the appropriate timing."

DEVELOPMENT OF MITIGATIVE STRATEGIES: USE OF PHYSICAL MITIGATION FEATURES

Repelling Charges. Repelling charges are small explosive charges detonated to "scare" fish from the blasting zone just prior to detonation of a major explosive charge. For example, a demolition contractor, removing a reinforced concrete bridge pier with explosives, would first detonate a series of small repelling charges (e.g., 0.11-0.22 kg explosive charge, explosive boosters) encircling the pier, wait a predetermined time period, and then detonate the demolition charge. It is assumed that noise or pressure from the small charge will drive fish from the immediate area thereby reducing impacts from the much larger and potentially more-damaging main blast. The blasting industry recommends firing a "warning shot" to frighten fish out of an area before seismic exploration work is begun (Anonymous 1978). Blasting companies have used this technique in a "good faith effort" to mitigate potential damages to aquatic resources. It is quick, inexpensive, and does not require use of more sophisticated techniques.

Illinois, New Jersey, Rhode Island, and Washington, recommended use of repelling charges as a mitigation feature. Two respondents indicated that use of repelling charges was not acceptable. The Alaska Department of Fish and Game considered repelling charges to be ineffective and "potentially harmful to piscivorous fishes, marine mammals, and birds which are attracted to feed on fish that are stunned or wounded by the repelling charge." In response to an applicant's proposal to remove pilings from Pine Island Bayou and the Neches River, the Texas Parks and Wildlife Department recommended: "Do not attempt to scare fish away from the site by small charges of explosive. Use of boats or similar noisy operations may be employed."

Canadian guidelines require the preparation of a mitigation plan and suggests that the proponent should consider "detonation of small scaring charges, consisting of

detonator caps or short lengths of detonating cord, set off one minute before the main charge to scare fish away from the site." In response to the Canadian guidelines, McAnuff et al. (1994) detonated a submerged length of primacord or a blasting cap, both upstream and downstream of the blast zone, 30 to 60 seconds prior to the main blast during a gas utility crossing project on the Nipigon and Winnipeg rivers. They noted that on at least one occasion the "scare blast" contributed to fish mortality. In addition, the primacord or cap positioned on the upstream side of the blast tended to be carried downstream toward the main blast due to the strong currents in the river which could have resulted in a cutoff or an unplanned detonation of the main blast.

Incidental observations during blasting operations indicate that explosions are not effective in "scaring" fish from the blasting zone (Aplin 1947; Ferguson 1962; Fitch and Young 1948; Nix and Chapman 1985; Ross et al. 1985). For example, Ross et al. (1985) made three observations on the response of American sand lance (Ammodytes americanus) schools to the detonation of two parallel 25 m lengths of Aquaflex, an explosive cord. The sand lance were observed for a period of 30 s to 120 s before a blast and from 30 s to 60 s after. Observations were of large schools (1000's) swimming against the current. Movements up and down in the water column were observed in response to current surges, with the sand lance hugging the bottom. In response to a blast, all members of the school under observation altered course for approximately 1 to 2 s, before resuming their original orientation and movement patterns. There was no flight response.

A radio telemetry study of largemouth bass (Micropterus salmoides), channel catfish (Ictalurus punctatus), and flathead catfish (Pylodictis olivaris) also found that small charges were ineffective in moving fish (Keevin et al. 1997). Movement distances were used to estimate the proportions of fish which would theoretically move out of computed kill zones associated with detonation of large charges of high explosives. Table 8.2 gives the number of individuals that would have moved out of the kill zone based on their measured movement during repelling charge trials compared with theoretical mortality zones for a range of charge sizes that were calculated using IBLAST (COASTLINE Environmental Services Ltd. 1986). Largemouth bass (n=15) showed little response to repelling charges and none would have moved out of the kill zone calculated for any explosive size. Only two of six flathead catfish tested would have moved to a safe zone based on the kill radius calculated for the smallest theoretical blast weight. This charge size is smaller than would be used for demolition work, for example.

Table 8.2.- Movement of radio-tagged fish from kill zones based on their response at 5 min to repelling charges (see Table 8.3). Predicted kill zones are based on LD0% mortality for a range of charge weights. (From Keevin et al. (1997))

	Expected LD0% Mortality[1]				
Charge weight-explosive (kg)	4.5	11	23	34	45
Predicted mortality range (m)	31	37	42	45	47
	Number moving out of kill zone				
Largemouth bass (N=15)	0	0	0	0	0
Channel catfish (N=7)	2	2	2	2	1
Flathead catfish (N=6)	2	1	1	1	1

[1]Calculated using IBlast (Coastline Environmental Services Ltd. 1986)

Only one flathead catfish would have moved from the kill zone produced by a demolition blast. Two of seven channel catfish tested moved out of the kill zone. Study results are consistent with published observations of the response of fish schools to underwater explosions. Table 8.3 provides information on the species, weight, and habitat type during testing, and distance moved away from the 680 g repelling charge for each individual tested.

Fish mortality from repelling charges, a concern expressed by some natural resource agencies (Keevin, In press), has been documented by field observations (Nix and Chapman 1985; McAnuff et al. 1994). Draft "Guidelines for the Use of Explosives in Canadian Fisheries Waters" (Wright 1992) required the preparation of a mitigation plan and suggested that the proponent should consider "detonation of small scaring charges, consisting of detonator caps or short lengths of detonating cord, set off one minute before the main charge to scare fish away from the site." In response to conditions (based on draft Canadian guidelines) placed on a blasting project by the Ontario Ministry of Natural Resources, McAnuff et al. (1994) detonated a submerged length of primacord or a blasting cap, both upstream and downstream of the blast zone, 30 to 60 seconds prior to the main blast during a gas utility crossing project on the Nipigon and Winnipeg rivers. They noted that on at least one occasion the "scare blast" contributed to fish mortality. In addition, the primacord or cap positioned on the upstream side of the blast tended to be carried downstream toward the main blast due to the strong currents in the river which could have resulted in a cutoff or an unplanned detonation of the main blast. A final version of the Canadian guidelines (Wright, In press) no longer contain recommendations for the use of repelling charges.

Noise. Commercial fishermen have used noise to move fish into nets. Four respondents indicated that noise propagation was used or recommended as a mitigation technique. For example, during a rock removal project on the Arkansas River, the Arkansas Game and Fish Commission recommended that noise be used to repel fish from the blast area. The contractor employed a siren device to scare fish from the work area.

Table 8.3.- Weight (kg) and length (cm) of test fish, distance moved (m) in response to repelling charge, and habitat type of fish prior to testing. (From Keevin et al. (1997))

Largemouth bass

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.600	1.0	38.6	0	Brushpile
48.510	1.3	43.2	6	cover
48.750	1.4	38.9	6	cover
49.790	0.9	39.4	3	cover
48.060	1.0	40.1	3	cover
48.580	1.0	38.1	0	open water
48.450	1.4	43.9	9	open water
49.270	1.3	42.2	9	open water
49.660	1.0	38.6	23	open water
49.460	1.4	45.0	18	open water, reeds
49.170	1.2	41.9	0	open water,cattails
49.130	1.4	44.5	0	shoreline, brush pile
49.700	1.0	40.1	0	shoreline, brush pile
49.100	1.4	42.9	0	open water, shallow
49.640	1.2	41.7	0	open water

Channel catfish

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.060	2.2	57.4	9	open water
49.750	1.2	47.0	46	open water
49.150	2.4	62.5	0	open water
49.080	2.0	59.2	0	open water
48.200	1.1	49.8	66	open water
49.342	1.6	53.9	30	open water
49.040	2.2	57.6	23	open water

Flathead catfish

Fish #	Weight (kg)	Length (cm)	Distance Moved (m)	Habitat Type
49.442	1.6	49.4	23	shoreline
49.520	1.6	52.8	0	shoreline, cover
49.540	2.6	61.0	0	shoreline, cover
49.482	1.9	53.3	0	open water
48.625	1.7	50.0	36	open water
49.723	2.7	99.7	55	open water

Studies testing the effectiveness of a constant noise source to repel fish from a blasting area have focused on clupeids and salmonids. Dunning et al. (1992) found

that during daylight alewife (Alosa pseudoharengus) schooled and avoided: pulsed tones (500 ms pulses, 1,000 ms apart) of 110 and 125 kHz at or above 175 dB; a continuous tone of 125 kHz at 172 dB; and, pulsed broadband sound between 117 and 133 kHz at or above 157 dB. However, pulsed broadband sound at 163 dB was most effective. In contrast, alewives did not react as strongly to the broadband sound at night. At the Pickering Nuclear Generating Station on Lake Ontario, Haymes and Patrick (1986) used pneumatic poppers emitting low-frequency, high-intensity broadband sound, of frequencies between 20 and 1,000 Hz. They found this sound reduced by up to 99% the number of alewives entering an experimental structure. The effectiveness of pulsed, high-intensity broadband sound on species other than alewife is not known.

Knudsen et al. (1994) found that 10 Hz sound was an effective deterrent for downstream migrating Atlantic salmon smolt (Salmo salar) in a small river. In contrast, 150 Hz sound had no repelling effects. It is not known if fish can be moved a large enough distance from an explosive detonation to be out of the potential kill radius. This is an area which requires additional study. If effective, use of noise would be a low cost, "good faith" effort by the blaster to reduce impacts.

Bubble Curtain. A bubble curtain, also called an air curtain or air screen, is created by injecting compressed air into the water column. Bubble curtains are walls of bubbles rising from a bottom-resting bubbler manifold supplied with compressed air. Bubbler manifolds are typically constructed using rows of parallel pipes with small holes drilled along their length. The pipes are supplied with air from one or more distribution headers that equalize pressure to each pipe. Bubble curtains are effective in reducing pressures across the air bubble curtain (Strange 1963). Research has shown that a small fractional volume of air bubbles in water increases the compressability several orders of magnitude above that in bubble-free water, thereby greatly reducing the velocity and increasing attenuation of acoustic waves (Domenico 1982a). As a result, bubble curtains have been routinely used by demolition engineers to protect underwater structures from damage by underwater explosive shock waves (Domenico 1982b). Guidelines for such use are given in Langefors and Kihlstrom (1978).

Alaska, New Jersey, Oregon, and Washington require the use of bubble curtains or recommend it as a mitigative strategy. Canadian guidelines require the preparation of a mitigation plan and suggests that the proponent should consider "deployment of bubble curtains/air curtains to disrupt the shock wave." The Alaskan Department of Fish and Game indicated that: "Bubble curtains have been specified in the past but their ability to mitigate impacts to aquatic life is questionable and their use has been discontinued." The question of the bubble curtain's effectiveness in reducing mortality arose during the explosive removal of oil rig legs in Kachemak Bay during 1976. Mortality was observed outside the bubble curtain. However, the without bubble curtain condition was not tested and mortality would possibly have been much greater without the bubble curtain in operation. Design of the bubble curtain must be appropriate for the conditions to achieve effective mitigation.

Keevin et al. (In press) conducted small-scale, shallow-water field trials evaluating the effectiveness of an air bubble curtain in reducing explosive pressures and the associated fish kill radius of underwater explosions resulting from the detonation of a 2 kg high-explosive charge. One test limitation was that the bubble curtain did not completely enclose the water-column shot. The bubble curtain produced considerable reductions in peak pressure, impulse, and energy flux density and significant reductions in fish mortality (Table 8.4). Peak pressure reductions ranged from 99.4-87.5%. Impulse, calculated by integrating the first positive wave, showed reductions ranging from 89.8-80.7%. Energy flux density reductions ranged from 99.8-89.7% (Table 8.5). A significant reduction ($p < 0.05$) in bluegill (Lepomis macrochirus) mortality was observed when the bubble curtain

was in operation (Table 8.6). Mortality fell from 100%, without the bubble curtain, to 0% with the bubble curtain in operation, at all distances tested.

An air bubble curtain was found to be extremely effective in reducing fish mortality during explosive demolition of Locks and Dam 26 on the Mississippi River (Keevin et al. 1997). Mortality was lowered despite a large underwater explosion (886 kg total weight of 21-54 kg charges/delay), moderate water depth (10.1-11.6 m at the bubble curtain) and high current velocities (approximately 0.6 m/s). A significant reduction ($p < 0.05$) in mortality at 120 hr. at all distances tested, was found for bluegill with the bubble curtain in operation when compared to the without bubble curtain condition (Table 8.7). Total mortality (100%) was observed to 80.8 m from the blast without the bubble curtain. Mortality was observed at all nine distances tested and was still 58% at 117.4 m, the farthest distance tested. With the bubble curtain in operation, 19% mortality was observed at 19.8 m from the explosion. There was no explosion related mortality past 19.8 m, comparing the mortality at each distance with control mortality, when the bubble curtain was operating.

Table 8.4.- Pressure waveform values resulting from underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. Independent duplicate trials are reported. (From Keevin et al. (In press))

	Without Air Bubble Curtain				With Air Bubble Curtain				Control
	DISTANCE (Meters) FROM EXPLOSION								
	6.5	9.0	11.5	14.0	6.5	9.0	11.5	14.0	Control
SHOT 1									
Peak Pressure(kPa)	32,600	3,970	2,240	2,180	The 207 kPa peak pressure trigger setting on the oscilloscope was not exceeded on the 6.5 m transducer.				0
Impulse(Pa-s)[1]	1,230	384	279	207					0
Impulse (Pa-s)[2]	1,630	601	509	398					0
Energy Flux Density (J/m^2)	15,000	491	280	226					0
SHOT 2									
Peak Pressure(kPa)	21,700	4,630	2,610	2,170	302.0	224.00	234.00	272.0	0
Impulse(Pa-s)[1]	990	357	249	175	93.9	36.60	31.00	33.7	0
Impulse (Pa-s)[2]	1,100	512	404	314	164.0	39.00	48.10	46.1	0
(J/m^2)	6,000	346	226	115	11.1	7.62	9.79	11.9	0

[1]Impulse was calculated by integrating the pressure-time curve for first positive wave.
[2]Impulse calculated by the greatest difference of peak pressure to pressure low. Is the greatest strength of expansion which has the potential of worst air-filled organ damage.

Table 8.5.- Percent reduction in pressure waveform values with the air bubble curtain in operation. Value were calculated using pressure waveform data in Table 1 from the underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. (Modified from Keevin et al. (In press))

	DISTANCE (Meters) FROM EXPLOSION			
	6.5	9.0	11.5	14.0
SHOT 1[1]				
Peak Pressure(kPa)	99.4	94.8	91.0	87.5
SHOT 2				
Peak Pressure(kPa)	98.6	95.2	91.0	87.5
Impulse(Pa-s)[2]	85.1	89.7	87.6	80.7
Energy Flux Density (J/m^2)	99.8	97.8	95.7	89.7

[1]A value of 207 kPa was used as the peak pressure value for the air bubble curtain in operation. The oscilloscope was set to trigger at 207 kPa. However, this value was not exceeded. Since actual pressure waveforms were not available for shot 1, it was not possible to calculate impulse or energy flux density.

[2]Impulse was calculated by integrating the pressure-time curve for first positive wave.

Table 8.6.- Bluegill mortality based on live/dead counts (n=50 at each distance tested) resulting from underwater detonation of a 2 kg charge of T-100 at 1.25 m depth without and with the use of a bubble curtain. Independent duplicate trials are reported. (From Keevin et al. (In press))

	Without Air Bubble Curtain				With Air Bubble Curtain				Control
	DISTANCE (Meters) FROM EXPLOSION								
	6.5	9.0	11.5	14.0	6.5	9.0	11.5	14.0	--
SHOT 1									
Number Tested	50	50	50	50	50	50	50	50	50
96 hr Mortality	50	50	50	50	0	0	0	0	0
96 hr + Internal Damage Mortality	50	50	50	50	0	0	0	0	0
SHOT 2									
Number Tested	50	50	50	50	50	50	50	50	50
96 hr Mortality	50	50	50	50	0	0	0	0	0
96 hr + Internal Damage Mortality	50	50	50	50	0	0	0	0	0

Table 8.7.- Percent bluegill mortality based on live/dead counts (n=80 at each distance tested) resulting from the explosive demolition of dam piers at Locks and Dam 26 without and with the use of a bubble curtain. (From Keevin et al. (In press))

Distance From Blast		Percent Mortality[1]	
Feet	Meters	Without Bubble Curtain	With Bubble Curtain
65	19.8	100	19
105	32.0	100	6
145	44.2	100	7
185	56.4	100	1
225	68.6	100	3
265	80.8	100	3
305	93.0	78	0
345	105.2	70	3
385	117.4	58	0
Control	---	15	5

[1]Percentages were rounded to the nearest whole number.

Practical considerations should be taken into account when considering the use of a bubble curtain including: location, size and type of the explosive charge; physical water conditions; the quality of the fishery; fish species targeted for protection; and, presence of endangered species and potential number of fish exposed. Placement of a bubble curtain may not be warranted. A benefit/cost analysis should be conducted considering potential for fish mortality and cost of construction, placement and operation of a bubble curtain. Under certain situations, environmental damage may be minimal and it may be more realistic to accept the level of mortality as a societal cost or to mitigate by testing and control, monetary compensation, replacement stocking, or by other means, rather than using a bubble curtain.

McAnuff and Borren (1989) reviewed agency mitigation requirements for underwater blasting in commercial fishing waters at a dock facility near Port Dover, Ontario. A number of practical objections to bubble curtain use were considered to be all but prohibitive including: difficulties involved in supplying compressed air in sufficient quantities to provide a bubble curtain to surround the minimum area required for a viable blast; moving the bubble curtain system to a new location after every blasting operation; and, use during inclement weather. The probable costs of bubble curtain use were considered to be extremely high. It was agreed by Ministry of Natural Resources representatives that bubble curtain use would not be considered mandatory until a fish mortality rate of 50% was attained at fish cages placed at a radius of approximately 800 m from the blasting operation.

Physical Barriers. Physical barriers include any solid barrier that contains or reduces the explosive pressure wave. There is no comprehensive published information on the effectiveness of either full or partial physical barriers in mitigating impacts to aquatic life; however, any solid barriers that prevents or reduces transmission of an explosive pressure wave would probably be effective. Four agencies have recommended physical barriers to reduce the impacts of underwater explosions. In response to a permit request to demolish a bridge using explosives, the Indiana Department of Natural Resources recommended that: "Piers must be enclosed in steel sheeting before any blasting take place".

The Connecticut Department of Environmental Protection placed seasonal permit

restrictions on explosive bridge pier removal including: prohibiting underwater blasting (April 1-July 15), requiring a dewatered cofferdam system (July 16-March 31), and requiring cofferdams that have not been dewatered (November 15-February 28) in order to protect the shortnose sturgeon (Acipenser brevirostrum), a Federally endangered species. Use of the cofferdam was successful in reducing peak pressures below the 100 psi (690 kPa) maximum limit imposed by the National Marine Fisheries Service (Anonymous 1994).

In response to a plan to remove pilings in Pine Island Bayou and the Neches River, the Texas Parks and Wildlife Department recommended that the applicant: "Contain the pressure wave as much as possible. Investigate the use of 'blast blankets' around/upon the explosives to minimize and contain the pressure waves..."

MITIGATION RECOMMENDATIONS

Evaluation of project impacts and development of effective mitigation strategies requires three components: 1. a working knowledge of explosives and explosives engineering; 2. a thorough understanding of the environmental effects of underwater explosions; and, 3. information on current mitigation techniques related to explosives, well grounded in practice and theory. Rarely does the natural resource agency have personnel experienced in explosives engineering and it is equally unlikely that a blasting company would have biological expertise. It is even more unlikely that either group would have information on mitigation techniques. In addition, it is difficult to quickly obtain information concerning the environmental effects of underwater explosives use and mitigative measures. The majority of literature on these subjects is in obscure publications (corporate and government reports, symposium proceedings, and obscure international journals).

The blaster will probably have to work more closely with natural resource agencies to reduce potential impacts. The alternative to working in a cooperative manner with the permitting agency(ies) may be not to work at all. The following recommendations would foster communication between the natural resource agency and the blaster. The key to better communications is information acquisition and exchange between both parties.

1. Provide the regulatory agencies a detailed blasting plan.
2. Schedule meeting between the regulatory agency and blaster. If there are concerns during review of detailed blast plan, require a meeting to review the proposal. Work cooperatively to reduce impacts.

Keevin and Hempen (1995) developed a three tiered mitigation planning process that requires a cooperative spirit between the blaster and natural resource agencies. This approach relies heavily on the exchange of information outlined above.

Based on the preceding review of mitigation techniques, the following measures are recommended to reduce the adverse effects of underwater explosive use.

Blast Design Parameter.

1. Evaluate the need to use explosives. If practical alternatives are available and not excessively expensive, require their use.
2. Plan the blasting program to minimize the total weight of explosive charges per shot and the number of shots for the project.
3. Use angular stemming material of sufficient length in drill holes to reduce energy dispersal to the aquatic environment.
4. Subdivide the charge, using detonating caps with delays or delay connectors with detonating cord, to reduce total pressure. Avoid the use of submerged

detonation cord.
5. Use decking when possible in lengthy drill holes to reduce total pressure.
6. For seismic exploration use non-explosive sources when possible or use linear charges for open water shots or buried charges.
7. Use shaped charges to focus the blast energy when submerged surface charges are necessary, reducing energy released to the aquatic environment during demolition.

Biological Parameters

1. Evaluate the quality of the fishery resource, based on existing information. If there have been no previous surveys of the blast area, and there is reason for environmental concern, require or conduct a survey. Based on the quality of fishery resources, make a decision concerning the magnitude of potential impacts.
2. Require or conduct mathematical mortality modeling to determine potential fishery impacts. Based on predicted impacts, make rational decisions concerning compensation or use of other mitigation techniques.
3. If applicable, limit season of explosive use to avoid major migration periods, spawning seasons, spawning beds, or larval drift.
4. If there is a concern with migrating fish, use sampling techniques (e.g., hydroacoustics) to avoid impacting large congregations.
5. Use non-explosive noise techniques to move fish from the immediate blast zone.
6. Require the presence of an agency observer, with authority to halt blasting or require use of mitigation techniques, if mortality is excessive based on pre-determined mortality levels.
7. If mortality is excessive, based on pre-determined mortality levels or observation, require significant blasting revisions (that allow the work to proceed but lowers mortality), or compensation.
8. If fish mortality is excessive, based on observation or mathematical modeling, or if species of special concern are present (e.g., endangered species), require the use of properly designed bubble curtains or physical barriers.

A TIERED MITIGATION PLANNING PROCESS

Keevin and Hempen (1995) developed a tiered mitigation approach based on: 1) the blasting design; 2) biological criteria; and, 3) use of physical mitigation features. Each tier requires progressively more mitigation measures to avoid impacts to aquatic resources. The tiered mitigation planning process will require a cooperative spirit between the blaster and natural resource agencies.

TIER I MITIGATION PLANNING

Tier 1 planning involves the development of a blasting design by the explosive engineer which attempts to reduce or limit the amount of explosives being utilized. It also involves an assessment of potential environmental effects, based on the existing aquatic resources in the blast area (this may involve survey work) and mathematical mortality modeling by natural resource personnel. An initial coordinated effort is required between the blaster and the natural resource agency.

Blast Design Parameters

1. Evaluate the need to use explosives. If practical alternatives are available, use non-explosive techniques.
2. Plan the blasting program to minimize the weight of explosive charges per delay and the number of days of explosive exposure.

Biological Parameters

1. Evaluate the quality of the fishery resource, based on existing information. If there have been no previous resource surveys of the blast area and there is reason for environmental concern, require or conduct the survey. Based on quality of fishery resources, make a decision concerning magnitude of potential impacts.
2. Conduct mathematical mortality modeling to determine potential fishery impacts (Hempen and Keevin 1995). Based on predicted impacts, make rational decision concerning compensation or use of other mitigation techniques.

TIER II MITIGATION PLANNING

Should the development of an explosive design and environmental assessment of potential impacts result in a determination that "important" aquatic resources are risk, then Tier II planning should be implemented. Tier II blast design mitigation measures involve the use of delays, stemming, decking, et cetera to reduce water borne shock waves entering the aquatic environment. Many of these types of features would be part of good explosives design to reduce peak overpressure or ground vibration. Biological parameters include such measures as seasonal blasting limits to avoid spawning fish, large migrations, or periods of larval drift.

Blast Design Parameters

1. Use adequate lengths of angular stemming material in drill holes to reduce energy dispersal to the aquatic environment.
2. Subdivide the explosives deployment using delays to reduce total pressure. Carefully consider detonating cord in the firing system, as greater mortality could result.
3. When possible use decking in drill holes to reduce total pressure.
4. For seismic exploration require non-explosive sources when possible. If this is not possible use linear charges for open water shots or buried charges.
5. Use shaped charges for surficial charges to focus the blast energy, reducing energy released to the aquatic environment during demolition.

Biological Parameters

1. Recommend presence of an agency observer with authority to resolve revised blast parameters or to halt blasting or to require use of mitigation techniques, if mortality is excessive based on pre-determined mortality levels.
2. If applicable, limit season of explosive use to avoid major migration periods, spawning seasons, spawning beds, or larval drift.
3. If there is a concern with migrating fish, use sampling techniques (e.g. hydroacoustics) to avoid impacting large congregations.
4. Use non-explosive scare techniques to move fish from the immediate blast zone.

TIER III MITIGATION PLANNING

Should there still be environmental concerns after Tier I and II planning efforts, Tier III measures can be employed. If important commercial or sport species are being impacted, there is always the option of monetary compensation for fish losses based on replacement values developed by the American Fisheries Society (1992, 1993). Threatened and endangered species can present special problems with regulatory permitting requirements. Bubble curtains or other physical barriers can be used to avoid mortality of these species (Hempen 1993).

1. If mortality is excessive, based on pre-determined mortality levels or observation, state or federal fish and wildlife agencies can require compensation.
2. If fish mortality is excessive, based on observation or mathematical modeling, or if species of special concern are present (e.g. endangered species) require the use of bubble curtains or other barriers.

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NOLTR 72-211

GUIDE-LINES FOR EVALUATING THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSION TESTS

By
George A Young

AD
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13 FEBRUARY 1973

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NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

20061031473

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NOLTR 72-211

GUIDE-LINES FOR EVALUATING THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSION TESTS

Prepared by:
George A. Young

ABSTRACT: The environmental effects of conventional underwater explosions are described and quantitative estimates provided where possible. These effects include noise, the deposit of chemical products in the sea and atmosphere, cratering and other bottom disturbances, and the killing of fish and other sea life. The long term effects on the environment are minimal. Nevertheless, knowledge of these is needed to avoid unnecessary harm and to fulfill legal and administrative requirements, including the preparation of Environmental Impact Statements. Also, explosion effects knowledge can be utilized during the planning stages to avert unnecessary delays or interference with essential military test programs.

EXPLOSIONS RESEARCH DEPARTMENT
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WHITE OAK, SILVER SPRING, MARYLAND

NOLTR 72-211 13 February 1973

Guide-Lines for Evaluating the Environmental Effects of Underwater Explosion Tests

It is essential that the Navy continue to test the underwater effectiveness of new explosives and of weapons. However, in addition to the various administrative procedures established in the past for the conduct of test programs, a legal requirement now exists to assess the probable environmental impact of any such proposed activity during the planning stage. This report has been prepared to summarize information useful for evaluating the environmental and ecological consequences of underwater explosion tests and to provide guidance for the planning of such tests with minimal adverse effect.

It should be stressed that there is not always a clear distinction between a possibly undesirable effect on the environment and an effect that is immediately hazardous to personnel conducting an underwater explosion field test. This report is not directed toward the problems of safety in explosion testing and should not be used for that purpose.

The preparation of this report was supported by the Naval Ordnance Systems Command under Task ORD-0332-004/092-1/UF 554-301 titled "Environmental Effects of Explosive Testing."

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I

GENERAL REQUIREMENTS FOR TESTING

1.1 INTRODUCTION

Underwater explosion testing for military purposes generally falls within the following categories: (a) testing of new explosives, (b) phenomenology studies, and (c) the measurement of damage to a target. In all three cases, the tests may be concerned directly with conventional explosives and weapons or with the modeling of nuclear explosion effects by the use of chemical explosives. Explosive weights range from one pound to many tons; but, for underwater testing in deep water, a weight of ten tons is a practical upper limit.

In most cases, the tests are conducted in ocean areas or in seas that are open to the public and are used for recreational purposes and for fishing. They are therefore highly visible and are subject to public scrutiny and criticism. Most of the complaints that have been recorded are in regard to possible effects on commercial or game fish, although other environmental effects occur that could be considered objectionable. The majority of people with expert knowledge of underwater explosion phenomena believe that the effects of any test on the environment are localized and short-lived and cause no irreversible changes in the general ecology of a natural body of water. Longer-range effects are minimal and can be estimated on the basis of existing information, but these estimates are qualitative because most of the previous work has been directed toward the prediction of the early-time, close-in phenomena of military interest.

The aspect of this problem of major concern to the Navy at the present time is not the direct effect of explosions on the environment, but the lack of knowledge of the facts by the public and by many government officials. Because of the heightened concern about environmental effects during the 1970's, a tendency exists to be overly critical about projects that conceivably have undesirable effects. Certain major technological developments have been halted or delayed by environmental arguments during recent years; for example, the SST, the Alaskan Pipeline, and many nuclear power plants. The burden of proof is placed on the builder or developer, who is forced, in many cases, to develop quantitative predictions on the basis of extremely limited knowledge. In the case of underwater explosions, too, certain programs have been delayed or cancelled; and a need exists to assemble a body of factual information regarding known or potential environmental effects in order to avert the possibility of future curtailment of activities.

The purpose of this report is to summarize the existing relevant phenomenological information, to document the efforts currently in progress to avoid or minimize harmful environmental effects, to summarize administrative and policy guide-lines, and to recommend future procedures. Pertinent case-histories will be cited. The recommendations will apply not only to large-scale testing, but to possible ways of increasing current knowledge of effects on the environment.

Certain alternatives are available to the conduct of large-scale tests in the open sea or in areas such as the Chesapeake Bay that are heavily used for recreational and other purposes. These include the use of saline lakes such as the Great Salt Lake and Mono Lake; the use of a lake or beach on a military reservation; the use of an artificial pond or a quarry; or the use of water that is highly polluted. Small-scale model tests in a laboratory facility are also useful in some cases. Each approach has favorable and undesirable features; these are listed in Appendix C.

1.2 ENVIRONMENTAL REQUIREMENTS

1.2.1 Weather. The primary weather requirement for explosive testing at sea is a low wind speed. This is not simply because of the wind alone, but because of the roughening of the sea surface that accompanies it. A convenient way to estimate this effect is to utilize the Beaufort Scale, which has been used to classify wind effects at sea since early in the nineteenth century. As a result of long experience, tables have been prepared listing the nature of the surface waves, and other effects of the wind, over the entire range of speeds expected to occur in a maritime environment. The lower wind speed portion of the Beaufort Scale is presented in Table 1.1. In addition, a set of definitions of the sea state has been developed independently of the Beaufort Scale. The boundaries of these do not coincide, but average values of the sea state code are included in the table for guidance.

It is obvious that explosive tests cannot be conducted at a Beaufort number of 6 or more. Whether operations can proceed at lower wind speeds depends on the nature of the tests. If all operations are conducted from ships, it may be possible to work in relatively rough water; however, if boats, rafts, or floats must be launched and maneuvered or towed at sea, difficulties will be encountered. Some problems will occur at a Beaufort number of 3; and as a general rule, a Beaufort number of 4 is an upper limit for the use of small boats at sea for explosive testing. At these wind speeds, white caps are frequent and the surface becomes rough and turbulent.

The lower end of the Beaufort Scale shown in Table 1.1 is useful as a guide for any large body of water. It has less validity in a river; and in this case, currents may be more important. Local conditions should be studied prior to the planning of explosion tests in a river, as these can vary considerably within a distance of a few miles.

The reasons for the desirability of smooth water are the following: personnel can work faster and more safely; explosives and gages remain stationary; support cables hang in a straight line; near-surface explosion phenomena are better defined; the data are more reliable and exhibit less scatter; and personnel are less likely to become sick.

Ideally, all tests should be conducted in calm water, but this is impossible because such a condition rarely occurs for more than a few hours at sea. However, statistics on wind-speed frequencies can sometimes be utilized to select firing sites where the probability of hampering wind speeds is low. Unfortunately, these statistics generally omit an important factor, the diurnal variation of the wind. For example, if calm periods consistently occur only during the hours of darkness, a site may be of little value for explosion testing. In addition, wind statistics

TABLE 1.1

BEAUFORT SCALE AND SEA STATE CODE

Beaufort Number	Nomenclature	Wind Speed (knots)	Description of Sea	Average Sea State
0	Calm	0 - 1	Sea like a mirror.	1
1	Light Air	1 - 3	Ripples with the appearance of scales are formed, but without foam crests.	1
2	Slight Breeze	4 - 6	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break.	1
3	Gentle Breeze	7 - 10	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered whitecaps.	2
4	Moderate Breeze	11 - 16	Small waves, becoming longer; fairly frequent whitecaps.	3
5	Fresh Breeze	17 - 21	Moderate waves, taking a more pronounced moderately long form; many whitecaps are formed. (Chance of some spray.)	4
6	Strong Breeze	22 - 27	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray.)	5
7	Moderate Gale	28 - 33	Sea heaps up and white foam from breaking waves begins to blow in streaks along the direction of the wind.	6

Source: Haynes, 1947

from offshore positions are not always available. On a practical basis, it is often more useful to consult local fishermen or boat operators when planning a test, rather than to utilize limited meteorological data. In any event, daily weather forecasts should be obtained during the conduct of an experimental program to obtain advance warning of frontal passages or storms.

Tests can be conducted in light rain, although this is undesirable from a safety standpoint. Explosion tests should not be conducted in a thunderstorm.

1.2.2 Oceanography. A study of oceanographic factors is essential prior to the selection of a test site. In particular, it is important to avoid regions of rough water. Local wind conditions are not sufficient for a decision, as long swells can travel hundreds of miles from a storm at sea and can subsequently appear in regions where the air is calm. It is a good practice to utilize the National Weather Service forecasts of waves and sea state on a daily basis, as well as the weather forecasts.

Special problems may arise in an area such as the Gulf of Mexico, where surface roughness may persist over a broad area for some time after the passage of a hurricane or other type of weather disturbance. It is essential, also, to avoid currents such as the Yucatan Current and Florida Current (Nowlin, 1971).

The Gulf Stream can be particularly troublesome along the Atlantic Coast because it achieves speeds up to 3 knots and it does not remain in a fixed location (Fuglister, 1963). Currents are also a problem in estuaries and at their mouths.

1.2.3 Water Depth. If a test is conducted for the study of explosion effects in water up to 10 feet deep, a location in a lake, pond, or sheltered harbor is more suitable than a firing site on an exposed coast line. In the latter case, the actual depth may vary considerably as a result of tidal action, and the wave problem may be more severe than at sea. However, an offshore shallow site may be advantageous if water depths up to 100 feet are needed.

In such shallow water, it is generally possible to anchor test equipment to the bottom and to achieve better accuracy in the placement of explosives and gages. In some cases, it may be possible to utilize an offshore platform as a base, for example the platforms in the Gulf of Mexico near Panama City, Florida. Stage 1 is 11 miles offshore in water 95 feet deep, and Stage 2 is 1.6 miles offshore where the water depth is 60 feet (Tolbert and Austin, 1959).* It should be noted that extensive areas of relatively shallow water exist in the Gulf of Mexico; however, because of the presence of escarpments, deep water may often be found within a few miles of a relatively shallow test site (Ewing, et al, 1960).

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* It was learned recently that these platforms have become havens for game fish, consequently, explosive testing in their proximity may not be permitted.

II

EXPLOSION EFFECTS

2.1 NOISE

The propagation of noise is an undesirable feature in extensive explosion test programs because it is an annoyance to the community. No potential physiological hazard exists, as in the case of the high-level continuous noise generated by many manufacturing activities, or by proximity to gunfire or aircraft; however, noise in itself is considered to be a form of pollution and an invasion of personal rights. The problem is of no concern in tests at sea, but it can be important in inland waters when explosions are relatively shallow and residential areas are within a few miles of the firing site.

The level of explosion sound heard at a distance is strongly dependent upon atmospheric conditions. For example, sound was audible at a distance of 400 miles from a land explosion of 5000 kilograms in Europe during 1925, while locations closer to the source reported no sound (Gutenberg, 1951). Such anomalies had been reported previously in regard to the audibility of gunfire.

The reason for the occasionally distant propagation of sound waves is the refraction of sound in the atmosphere. In the case of large explosions and nuclear tests, refraction occurs in the stratosphere; but when small explosions occur, the sound may be channeled by refraction in a shallow surface duct. In this case, the intensity decreases slowly with distance and zones of exceptional audibility may occur. On rare occasions, this effect could cause window breakage.

It is essential, therefore, to avoid firing on days when the atmospheric temperature near the ground either increases with height or is constant. This type of condition can be presumed always to accompany a fog. It is common during the early morning hours, particularly in the absence of wind.

Reed (1964) has provided some useful criteria, based on experience at the Nevada Test Site. He has stated that large windows may be broken by explosion shock waves with a 0.03 psi overpressure and that sonic booms may break windows at an overpressure of 0.015 psi. Reed also stated that noise may be startling at 0.002 psi.

In the case of underwater testing, the most noise would be generated by an explosion just beneath the surface. The air blast phenomena are complex, but only maximum pressure values are needed for purposes of estimation. Figure 2.1 shows air blast peak pressure as a function of distance for relatively shallow explosions. The highest values may occur at a reduced depth, $d/W^{1/3}$, of 0.20 $ft/lb^{1/3}$ *. The curves represent HBX-1 values, as the best available data are

* Cube root scaling is used in studies of shock wave effects. In this case, all depths and other space dimensions are reduced by dividing by the cube root of the charge weight.

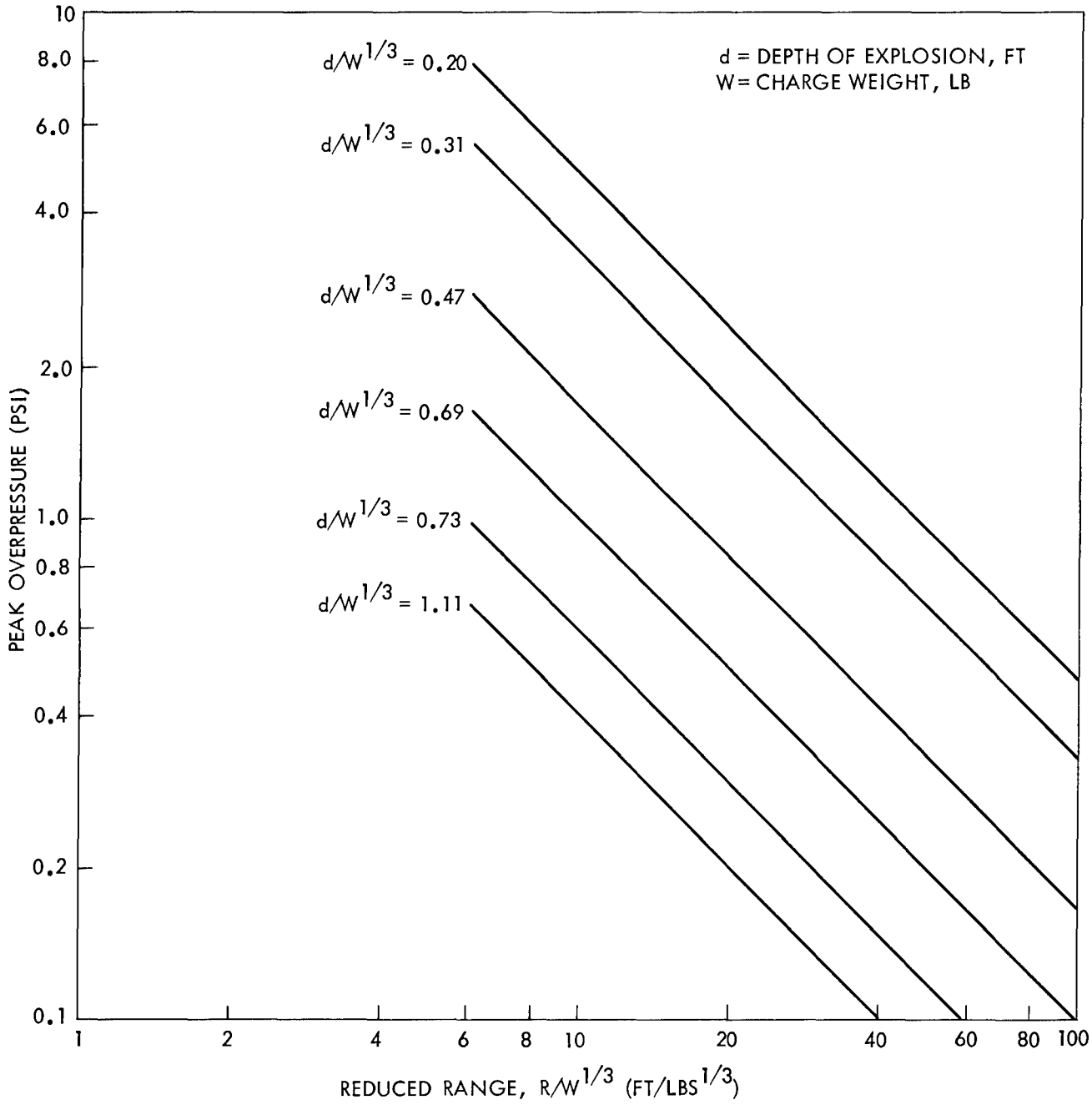

FIG. 2.1 AIR BLAST PRESSURES FROM UNDERWATER HBX-1 EXPLOSIONS

from this explosive. The ranges are slightly larger than would be expected for TNT, but the actual difference should not exceed 10 percent.

The curve for the shallowest depth has been extrapolated to greater ranges for several charge weights in Figure 2.2 to provide some guidance concerning the distances at which sound may be audible. As indicated in the figure, it has been assumed that the threshold of possible slight damage occurs at 0.01 psi and that sound is audible at all pressures above 0.001 psi. Approximate sound levels in decibels are included in the figure.

The following equation may be used to estimate the maximum range of audibility for underwater explosions:

$$R_a = 7.9\ W^{1/3} \quad , \tag{2.1}$$

where:

R_a = range of audibility, nautical miles ,

W = charge weight, lb .

Figure 2.2 and Equation 2.1 are valid only in good weather in the absence of wind and low level temperature inversions in the atmosphere. Deeper explosions represent less of a problem, and it is probably reasonable to disregard noise considerations if explosions are at a reduced depth of 2.0 ft/lb$^{1/3}$ or at greater depths.

2.2 THERMAL EFFECTS

The heating of water by conventional underwater explosions was discussed thoroughly by Young (1971). It was shown that any appreciable heating that might occur would be limited to a relatively thin shell surrounding the explosive charge for a period of only milliseconds after the time of detonation. The rapid turbulent mixing that occurs subsequently will soon reduce any temperature excess to a negligible amount, e.g., with 15-lb charges; this takes place in about two minutes. Figure 2.3 provides an example of temperature records obtained after a Pentolite explosion with this charge weight. Even with a weight of 10,000 pounds, it is doubtful that any temperature anomaly could be detected in the water after a period of one-half hour.

This result should be equally valid in regard to atmospheric heating by very shallow and by surface bursts.

2.3 CHEMICAL POLLUTION

2.3.1 Explosion Products. In this section, only the chemical products of a bare explosive charge will be discussed. If a mine or torpedo is detonated, fragments of metal will doubtless be deposited on the bottom*, and traces of materials from the case and the fuzing mechanism may gradually go into solution. The latter is doubtless an effect of minor significance.

The explosives most commonly used underwater are organic nitrated compounds with a chemical formula of the type (C-H-N-O), such as TNT, Tetryl, RDX, and PETN (Cole, 1948). The products of these explosives are probably better known than the products of newer explosives containing aluminum, nitrates, perchlorates, and other substances.

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* If an explosive is less than 15 charge radii deep, the fragments may cover a considerable area.

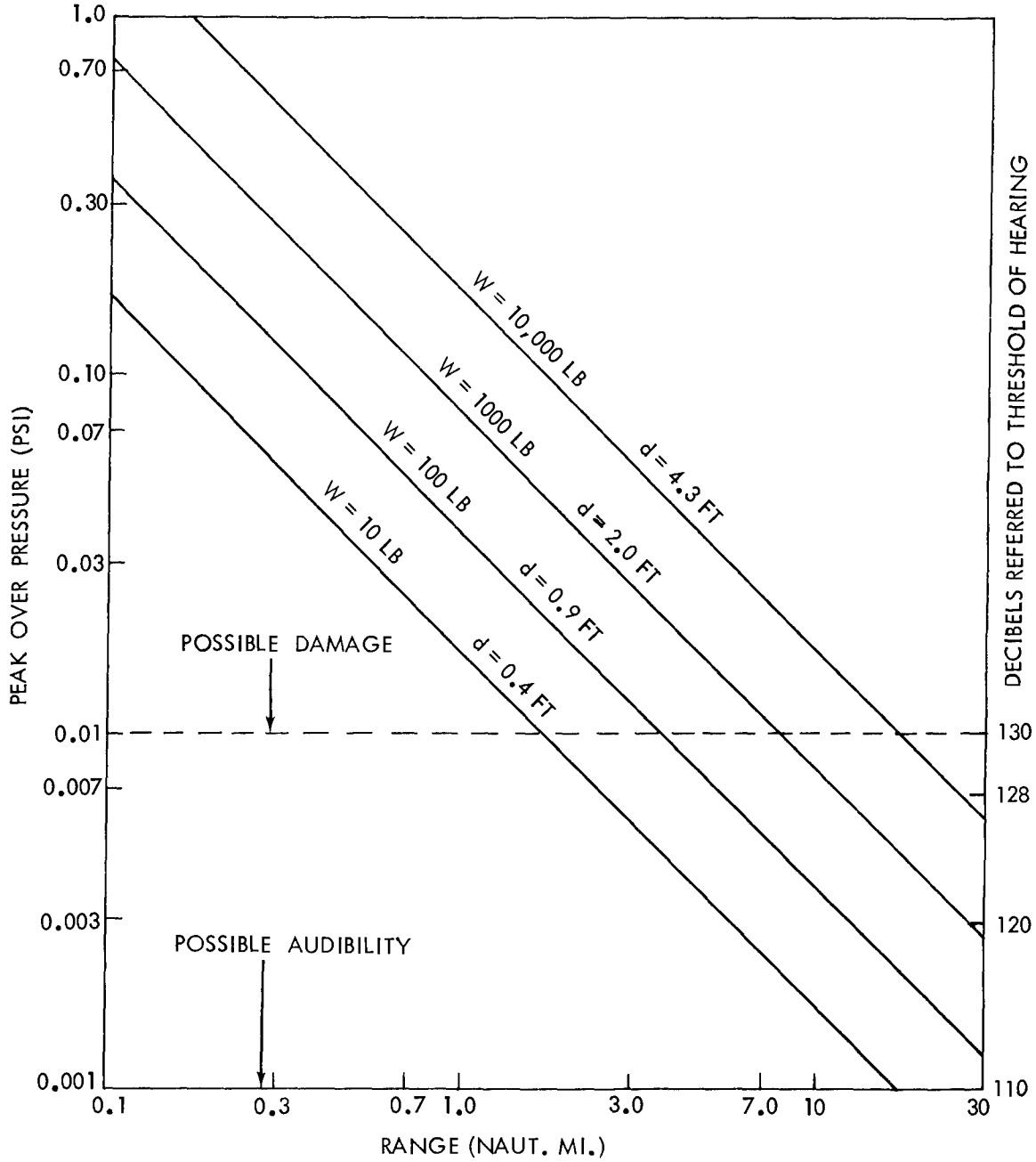

FIG. 2.2 RANGES OF AUDIBILITY FOR SHALLOW UNDERWATER EXPLOSIONS

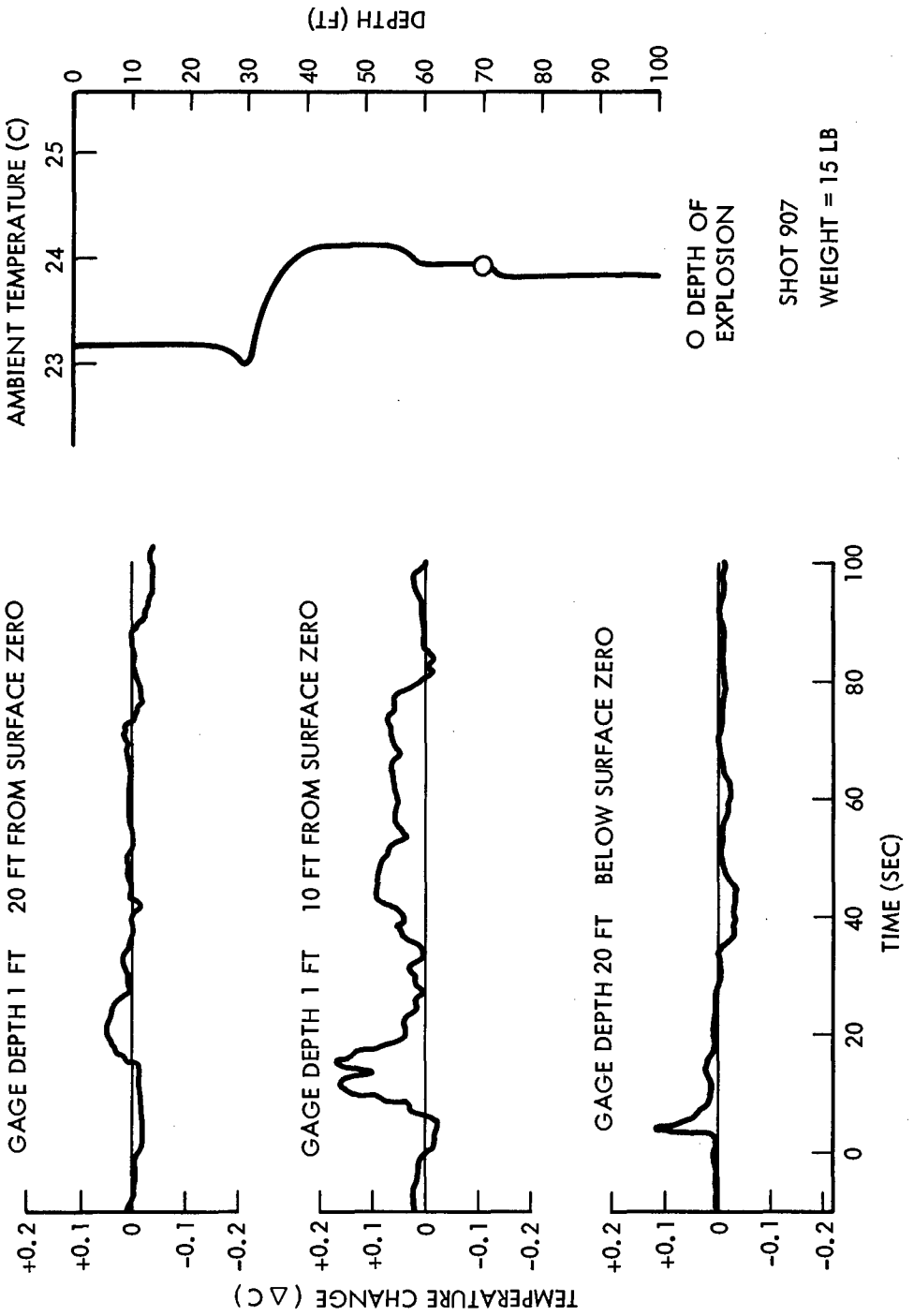

FIG. 2.3 TEMPERATURE CHANGES PRODUCED BY A PENTOLITE EXPLOSION IN FREE WATER

Ornellas, et al, (1966) and Ornellas (1968) investigated the products of detonation of PETN ($C_5H_8N_4O_{12}$), TNT ($C_7H_5N_3O_6$), HMX ($C_4H_8N_8O_8$), NM (CH_3NO_2), and FEFO ($C_5H_6N_4F_2O_{10}$). As the latter two are not used in Navy programs, they will not be considered here. Ornellas analyzed the products of the explosives in a calorimeter and compared the results with calculations based on different theoretical approaches for confined and unconfined charges. The products are listed in Table 2.1A as given in his publications. It should be noted that the C-H-N-O compositions utilized were selected to provide a wide range of oxygen balance, therefore, the quantities of products listed represent the range of amounts to be expected from this type of explosive. In brief, an explosive such as TNT is oxygen-deficient and it forms relatively large amounts of carbon and hydrogen, while PETN, an oxygen-rich explosive, produces less hydrogen and no carbon.

The compositions of other C-H-N-O explosives were reported by Kamlet and Jacobs (1968). This publication and a paper by Kamlet and Ablard (1968) present discussions of the detonation properties and chemical products of explosives. It should be noted that some authors believe that nitric oxide is an explosion product, though a minor one.

Table 2.1B presents the same data as in Table 2.1A in terms of percentage by weight. This form might be more useful for quickly estimating the total amount of a particular substance deposited in the environment by a test with an explosive charge of a known weight.

It seems reasonable to assume that the products of an underwater explosion will be the same as those of a confined charge and that an unconfined charge is representative of a surface burst.* It is not clear where the transition will actually take place; however, it seems likely that explosives at a depth of two or more charge radii will behave like confined charges.

To properly evaluate the ultimate disposition of explosion products in the marine environment it is necessary to treat them in at least three categories: gases, insoluble solids (particulates), and soluble solids. The gases, of course, are soluble in water; but most of the gaseous products will escape to the atmosphere unless an explosion is exceptionally deep. Initially, the products are contained in a large spherical bubble that pulsates and migrates toward the surface (see Section 2.3.3.2); and the gaseous composition of the bubble is of particular interest for evaluating the rate of solution.

The gases formed by the three explosives considered thus far are listed in terms of percentage by volume in Table 2.2. These values may be readily converted to partial pressure, as in Table 2.3 of Section 2.3.2.1. Water vapor and hydrogen cyanide are treated as gases here, although they partially or completely condense to the liquid state at some later time.

It may be noted that the majority of the products of these explosives are found in the natural environment and are harmless to man and to marine life. This is not necessarily true for carbon monoxide (CO) and hydrogen cyanide (HCN). However, both are rapidly diluted to low levels of concentration, as will be shown in Sections 2.3.3.1 and 2.3.3.2.

* In this report, an explosion is considered to be a surface burst if at least half the charge is exposed to the air.

TABLE 2.1A

DETONATION PRODUCTS OF CONFINED AND UNCONFINED EXPLOSIONS
(values in moles/mole)

Product		Explosive					
		PETN		HMX		TNT	
Name	Symbol	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined
Carbon Dioxide	CO_2	3.32	3.50	1.92	1.44	1.25	0.063
Carbon Monoxide	CO	1.61	1.56	1.06	2.65	1.98	5.89
Carbon	C	—	—	0.97	—	3.65	1.01
Nitrogen	N_2	1.95	2.00	3.68	4.01	1.32	1.36
Water	H_2O	3.68	3.45	3.18	2.50	1.60	0.17
Hydrogen	H_2	0.34	0.51	0.30	1.53	0.46	2.31
Ammonia	NH_3	0.056	<0.0002	0.395	—	0.162	0.022
Methane	CH_4	0.004	<0.0002	0.039	—	0.099	0.0092
Hydrogen Cyanide	HCN	—	—	0.008	0.0006	0.020	0.024
Ethane	C_2H_6	—	—	0.001	—	0.004	—

Sources: Ornellas, Carpenter, and Gunn, 1966
Ornellas, 1968

TABLE 2.1B

DETONATION PRODUCTS OF CONFINED AND UNCONFINED EXPLOSIONS
(values in percentage by weight)

Product		Explosive					
		PETN		HMX		TNT	
Name	Symbol	Confined	Unconfined	Confined	Unconfined	Confined	Unconfined
Carbon Dioxide	CO_2	46.22	48.72	28.53	21.40	24.22	1.22
Carbon Monoxide	CO	14.26	13.82	10.02	25.06	24.42	72.64
Carbon	C	—	—	3.93	—	19.30	5.34
Nitrogen	N_2	17.28	17.72	34.81	37.93	16.28	16.78
Water	H_2O	20.97	19.66	19.34	15.21	12.69	1.35
Hydrogen	H_2	0.22	0.32	0.20	1.04	0.41	2.05
Ammonia	NH_3	0.30	—	3.42	—	1.21	0.16
Methane	CH_4	0.02	—	0.21	—	0.70	0.06
Hydrogen Cyanide	HCN	—	—	0.07	0.01	0.24	0.28
Ethane	C_2H_6	—	—	0.01	—	0.05	—

TABLE 2.2

GASEOUS PRODUCTS OF CONFINED EXPLOSIONS
(values in percentage by volume)

Product		Explosive		
Name	Symbol	PETN	HMX	TNT
Carbon Dioxide	CO_2	30.283	17.819	18.124
Carbon Monoxide	CO	14.674	9.834	28.715
Nitrogen	N_2	17.788	34.154	19.139
Water	H_2O	33.555	29.508	22.275
Hydrogen	H_2	3.146	2.727	6.697
Ammonia	NH_3	0.508	5.520	2.339
Methane	CH_4	0.036	0.359	1.438
Hydrogen Cyanide	HCN	——	0.071	0.292
Ethane	C_2H_6	——	0.009	0.054

Many explosive compositions currently in use consist of mixtures of different organic explosives or mixtures of these with aluminum. One product of the latter explosives is aluminum oxide (Al_2O_3), which is formed as a white insoluble powder. A typical percentage of Al_2O_3 by weight for an aluminized explosive would be about 35 percent.

Carbon is always highly visible after a TNT explosion, either as smoke or in a surface pool of blackened water. In the HYDRA IIA Series, conducted by the Naval Radiological Defense Laboratory in 1961 with 10,000-lb charges of HBX-1*, samples of airborne materials included carbon clusters from the explosion and spheroidal aluminum oxide particles, some as large as 250 microns in diameter. Varying amounts of carbon were found in these particles.

Some information is available on a special explosive composition called Lithanol, which was developed to produce an explosion bubble with no permanent gases. The chemical equation for a Lithanol explosion is the following (Murphy, 1963):

$$3(LiClO_4 \cdot 3H_2O) + 8Al \rightarrow 3\ LiCl + 4\ Al_2O_3 + 9H_2O \quad . \qquad (2.2)$$

Lithium chloride is soluble in water; and in a series of tests conducted with large Lithanol charges in the Caribbean Sea during 1967, water samples were taken at the surface after four of the 1400-lb shots for analysis. It was found that the concentration of lithium averaged about 0.192 mg/l during the first 18 minutes and was reduced to background levels (0.187 mg/l) in possibly 30 minutes. The amount of aluminum oxide was not measured, but it was visible in the surface pools.

It should be mentioned that certain compositions used in detonators contain poisonous substances. These include fulminate of mercury ($Hg\ (ONC)_2$), and lead azide ($Pb\ (N_3)_2$). Lead and mercury oxides are formed by the explosion of these compounds. However, the total weight of a detonator charge is generally less than one gram. Detonators containing PETN are more frequently used in Navy test programs.

2.3.2 Background Levels

2.3.2.1 Atmosphere. The major atmospheric gases are nitrogen, oxygen, and argon, and the relative proportions of these three are virtually constant over the entire world. Other gases are found in minute quantities, which tend to vary as a result of industrial pollution, volcanic activity, or biological effects. The most important variable constituents are water vapor and carbon dioxide. The most common gases, and the atmospheric gases possibly formed by conventional explosions are listed in Table 2.3.

Considerable effort has been devoted toward the measurement of the amount of carbon dioxide in the atmosphere during recent years because changes in the concentration of this gas could possibly have long-range effects on the climate (Rasool and Schneider, 1971). The total quantity of the gas in the atmosphere appears to be increasing at the present time; but in addition, numerous variations

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* HBX-1 consists of RDX, TNT, Aluminum, and Wax in the following proportions: 40/38/17/5.

TABLE 2.3

ATMOSPHERIC GASES

Name	Symbol	Volume Percentage	Partial Pressure (atmospheres)
Nitrogen	N_2	78.1	0.781
Oxygen	O_2	20.9	0.209
Argon	A	0.93	0.0093
Water Vapor	H_2O	0 - 3	0 - 0.03
Carbon Dioxide	CO_2	0.0316	3.16×10^{-4}
Methane	CH_4	1.4×10^{-4}	1.4×10^{-6}
Nitrous Oxide	N_2O	5×10^{-5}	5×10^{-7}
Hydrogen	H	5×10^{-5}	5×10^{-7}
Carbon Monoxide	CO	10^{-5}	10^{-7}
Nitric Oxide	NO	None	
Nitrogen Dioxide	NO_2	4.08×10^{-9}	4.08×10^{-11}
Ammonia	NH_3	2.02×10^{-9}	2.02×10^{-11}

Sources: Handbook of Geophysics, 1960
Robinson and Robbins, 1969
Georgii, 1963

have been discovered that can be attributed to natural and manmade causes. These include photosynthesis by plants, venting from soils and rocks, volcanic eruptions, changes in atmospheric pressure, changes in the temperature of sea water, biological activity in sea water, and the burning of fossil fuels. However, for the purposes of this report, an average sea level value of 316 ppm by volume in oceanic regions is sufficiently accurate (Takahashi, 1961; Keeling and Waterman, 1968). The measured values rarely differ from this amount by more than 5 percent.

Relatively little information is available on the concentration of carbon monoxide in the unpolluted atmosphere because of difficulties in measurement. However, relatively clean air sampled in the Arctic and Antarctic regions averages about 0.1 ppm (Robinson and Robbins, 1969).

Ammonia and the oxides of nitrogen are trace gases which play an important role in the formation of aerosol particles in the atmosphere. Of the eight oxides of nitrogen, only N_2O and NO_2 have been detected in the lower atmosphere. These gases and ammonia show considerable variability (Georgii, 1963); the values given in Table 2.3 represent approximate background levels.

The atmosphere also contains solid particles, and the natural atmospheric aerosol has two major parts (Handbook of Geophysics, 1960). Over the oceans, at positions remote from sources of pollution, the marine aerosol consists primarily of particles of sea salt with essentially the same chemical constituents as sea water (see Section 2.3.2.2). The particle radii range from about 0.1 to 30 microns. Continental air contains dust and mineral particles from soils, with the same range of sizes, and it also contains particles less than 0.1 micron in radius, which originate mainly from various kinds of smoke.

As the major constituent of the latter is probably carbon, this part of the atmospheric aerosol might resemble the airborne particulate matter produced by an explosion in the air or at a very shallow position in water. The total aerosol concentration in continental air ranges from 50 micrograms per cubic meter in unpolluted regions to 1000 micrograms per cubic meter over large cities.

The natural atmospheric aerosol is an essential part of the planetary water cycle, as the particulates serve as condensation nuclei for the water vapor in the air. These droplets grow to raindrop size and fall to the surface. In this manner, the sea salts in the marine aerosol may be deposited on land in rainfall to ultimately flow back to the sea.

It is interesting to note that the primary mechanism for the transport of sea salt across the sea-air interface is the bursting of small bubbles. These are formed by the entrainment of air in breaking waves and by the impact of raindrops. The bubble diameters range from about 0.1 to 5 mm (Monahan and Zietlow, 1969). It has been estimated that from 2 to 5% of the ocean is covered by breaking waves at all times and that a bursting rate of possibly 30 bubbles/cm^2 sec can be found in these regions (Blanchard, 1963).

When a rising bubble reaches the surface, a thin film possibly 2 microns thick, is pushed up. This immediately disintegrates to form from 10 to 100 droplets with diameters of 1 to 20 microns (Moore and Mason, 1954). These droplets evaporate and the sea salt residue remains airborne. Immediately following this, the bottom of the bubble rises into the air in the form of a jet, which breaks up

into possibly five drops with diameters about one-tenth the bubble diameter. As these are relatively large, they usually fall back into the sea without evaporating appreciably. However, their impact may eject tiny droplets to the air. This process has been described in publications such as Blanchard (1963) and Garrett (1967).

It is important to point out that bacteria, surface films, and other contaminants in sea water are also ejected to the air by this natural bubbling process (Garrett, 1967; Blanchard, 1971).

2.3.2.2 Sea Water. Every natural element on earth doubtless exists in sea water, although some are found in extremely low concentrations and a few have not been detected and measured as yet. For example, Horne (1970) presented a table listing the measured concentrations of 74 elements in the sea. The major constituents exist in virtually constant ratios to each other in all parts of the world. The chemicals in the sea are in various forms, e.g., dissolved solids and gases, gases entrapped in bubbles, electrolytes and non-electrolytes, colloids, and solid particles. Some are organic and some inorganic, and many of the former play an important part in life processes. The various cycles and chemical processes that occur are quite complex and will not be discussed here; however, Horne's 1970 publication is a useful reference for the interested reader, as it contains a summary of current knowledge and an extensive bibliography.

Table 2.4 is a list of the chemical elements in sea water (in non-gaseous form) that are also likely to be found in conventional explosives. The table gives representative average values for the oceans, though local variations can be expected for the less common elements. For example, 72 samples of sea water in the Gulf of Mexico had an average content of 2.0 micrograms/liter of particulate aluminum, and the measurements ranged from 0.2 to 10.2 micrograms/liter in value (Feely, 1971). The average concentration was therefore lower than indicated in Table 2.4. It seems likely that semi-enclosed bodies of water, such as the Gulf of Mexico, would be more likely to exhibit such minor deviations in composition that the open oceans.

Table 2.5 lists gases found in solution in sea water. The concentration varies with temperature and salinity. In the case of carbon dioxide, the concentration of dissolved gas in sea water is about 0.3 ml/l. However, CO_2 reacts with water to form carbonic acid (H_2CO_3). This acid then singly and doubly ionizes to form bicarbonate and carbonate ions. The total CO_2 in the carbonate system in sea water is therefore about 45 ml/l, which means that only 0.7% is in physical solution (Kanwisher, 1963a).

The concentrations of hydrocarbons such as methane and ethane in sea water vary because of chemical and biological processes, and in some regions these gases leak from the bottom sediments and go into solution. This is believed to occur in the western part of the Gulf of Mexico, where average concentrations of 38.1×10^{-5} ml/l of methane and 6.03×10^{-6} ml/l of ethane were measured (Frank, et al, 1970).

When a mixture of two or more gases is in contact with water, the solubility of each gas is the same as if it were present at its own partial pressure.

TABLE 2.4

EXPLOSIVE CONSTITUENTS FOUND IN NATURAL SEA WATER

(Non-Gaseous)

Name	Symbol	Concentration (mg/l)
Hydrogen	H	108,000
Lithium	Li	0.17
Carbon	C	28*
Nitrogen	N	0.5
Oxygen	O	857,000
Aluminum	Al	0.01
Mercury	Hg	0.00003
Lead	Pb	0.00003

* In compounds

SOURCE: Horne (1970)

TABLE 2.5

GASES DISSOLVED IN SEA WATER

Name	Symbol	Concentration (ml/l)	Temperature (C)	Salinity (0/00)
Nitrogen	N_2	11.4	10	36.13
		9.61	20	36.13
Oxygen	O_2	6.33	10	36.13
		5.16	20	36.13
Carbon Dioxide	CO_2	0.320	10	36.13
		0.214	24	36.13
Carbon Monoxide	CO	23.0×10^{-6}	10	36.13
		19.4×10^{-6}	20	36.13
Methane	CH_4	5.7×10^{-5}		
Ethane	C_2H_6	1.1×10^{-6}		

SOURCES: Sverdrup, et al (1946)
Lamontagne, et al (1972)
Green and Carritt (1967)
Douglas (1965)
Douglas (1967)
Riley and Skirrow (1965)

Therefore, air does not dissolve in sea water as a whole, but each gas dissolves in proportion to its solubility and partial pressure. Water in contact with the atmosphere tends to reach equilibrium (i.e., the water is just saturated), and the concentration of the solution of the gas is expressed in the form of Henry's law (Sverdrup, et al, 1946):

$$C_s = \alpha P \quad , \tag{2.3}$$

where:

C_s = concentration of the gas in the water, ml/l,
α = solubility coefficient, ml/l-atmos.,
P = partial pressure of the gas, atmos.

Table 2.6 presents some solubility coefficients for use with Equation 2.3. It should be noted that the values of α are dependent on temperature, salinity, and pressure; and it is necessary to use tables (e.g., Dorsey, 1940; Douglas, 1965; Green and Carritt, 1967; and Douglas, 1967) when accurate calculations are needed. The values of P for average atmospheric conditions are given in Table 2.3. However, actual values of atmospheric pressure, including the pressure of water vapor, are needed to provide accurate results when in situ studies are conducted.

The assumption that the gases in sea water are in equilibrium with the gases in the atmosphere is probably a good first approximation and is valid when long-period averages are studied. However, oxygen and carbon dioxide are affected by chemical and biological activities, and minor deviations in the concentrations of all gases doubtless occur as a result of normal pressure and temperature changes in the atmosphere and the oceans. Consequently, at a given time or place, the gases in solution may not be in equilibrium, and a flux will take place across the air-sea interface.

The mechanism of transport of gases across this boundary has been described in publications by Kanwisher (1963a; 1963b) and Davies (1963). It is generally assumed that the gas exchange is controlled by the rate of diffusion through a thin, relatively unstirred, surface layer. This layer varies from about 10 to 200 microns in thickness, and the air above and the water below are considered to be well mixed and to have uniform concentrations of gas. The concept of a thin surface layer is also used in studies of heat transfer across the air-sea interface (e.g., Ewing and McAlister, 1960; Saunders, 1967; Wu, 1971).

The model used for gas exchange is sketched in Figure 2.4. It should be stressed that this approach is useful only near the surface, as the structure of the atmosphere and oceans becomes more complex at greater distances. The rate of flux across the surface is given by:

$$\frac{dq}{dt} = A\ D\ \frac{\partial C}{\partial z} \quad , \tag{2.4}$$

where:

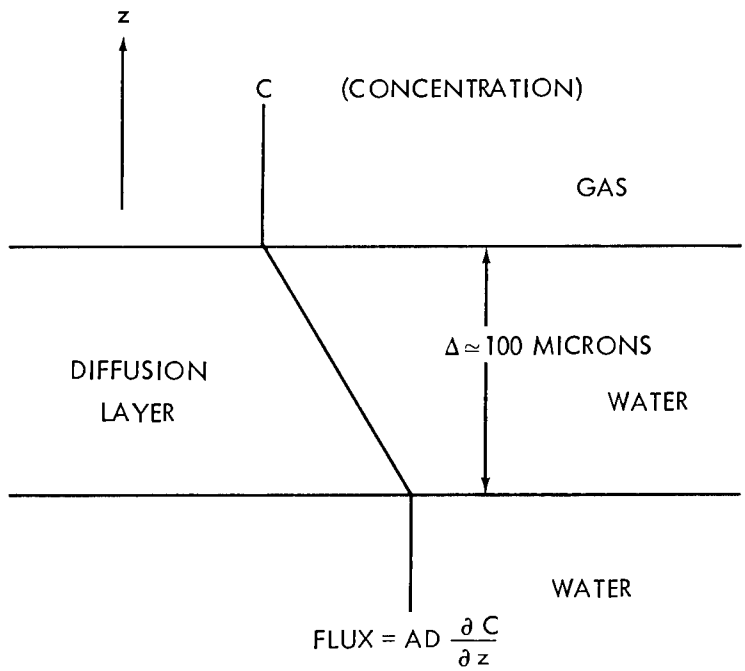
q = quantity of gas, ml,
t = time, sec,
A = area of surface, cm^2,
D = diffusivity of gas in water, cm^2/sec,
C = concentration of gas, ml/l,
z = direction perpendicular to the interface, cm.

TABLE 2.6

SOLUBILITY COEFFICIENTS FOR USE IN HENRY'S LAW

Name	Symbol	Solubility Coefficient α (ml/l-atmos)	Temperature (C)	Salinity (0/00)
Nitrogen	N_2	14.6	10	36.13
		12.3	20	36.13
Oxygen	O_2	30.3	10	36.13
		24.7	20	36.13
Carbon Dioxide	CO_2	1012	10	36.13
		677	24	36.13
Carbon Monoxide	CO	23.0	10	36.13
		19.4	20	36.13
Methane	CH_4	40.7		

SOURCES: Douglas (1965)
Douglas (1967)
Green and Carritt (1967)
Riley and Skirrow (1965)
Lamontagne, et al, (1972)



GAS	D FOR GAS IN WATER * (cm^2/sec)
O_2	2.0×10^{-5}
N_2	2.0×10^{-5}
CO_2	1.6×10^{-5}
H_2	4.5×10^{-5}
NH_3	1.1×10^{-5}

* SOURCES: DORSEY (1940)
LE BLOND (1969)

FIG. 2.4 GAS-WATER INTERFACE MODEL

Utilizing a linear gradient of concentration in the diffusion layer (Figure 2.4), and assuming that the concentration of gas in the water is given by Equation 2.3 and that no gas is present above the interface, the relation reduces to the following form:

$$\frac{dq}{dt} = \frac{A\ D\ \alpha\ P}{\Delta} \quad , \qquad (2.5)$$

where:

Δ = film thickness, cm,
P = partial pressure of the gas in the water, atmos.

If gas is present above the interface, the relation is:

$$\frac{dq}{dt} = \frac{A\ D\ \alpha\ (P - P_o)}{\Delta} \quad , \qquad (2.6)$$

where:

P_o = pressure of the gas, atmos.

The values of the diffusivity of gases in water are all of the order of 10^{-5} cm^2/sec. Typical values are included in Figure 2.4. The diffusivity of the gases in air is about 10^4 times as great, which provides the justification for assuming a complete mixing in the lowest level of the atmosphere.

As shown in Table 2.6, the solubility of gases varies considerably, and CO_2 will dissolve faster than the other gases under consideration. The film thickness also varies, and it becomes effectively thinner in the presence of wind and turbulence, which leads to more rapid transport across the interface.

An additional complication occurs in the case of carbon dioxide, as the exchange rate of this gas depends on the pH. When the wind speed is low and the water is quiescent, an enhancement of the transfer rate occurs if the solution pH is greater than 6.0 (Hoover and Berkshire, 1969). However, the importance of this in the open ocean has yet to be evaluated.

The oceans also contain suspended matter, which varies widely in quantity. Along the Atlantic Coast, the amount exceeds 1.0 mg/l within a few kilometers of shore (Manheim, et al, 1970). On a world-wide basis, the average value for inorganic matter is probably less than 0.1 mg/l. Much of this debris consists of soot, fly ash, and processed cellulose, rather than mineral particles. The sources include refuse from ships as well as sewage and the discharge from rivers and estuaries.

2.3.2.3 Inland Waters. As inland waters include lakes, rivers, bays, and estuaries, an almost infinite range of possible levels of chemical content is possible. In many cases, this is a result of man-made pollution; however, in a clean estuarine system, almost pure sea water may be found at the mouth while fresh water enters at the sources. Various degrees of mixing occur at intermediate points and some density stratification usually exists.

In an estuary, the amounts of background constituents at a given location can be estimated by the use of a simple mixing model and a knowledge of the composition of the fresh water and sea water inputs (Warner, 1972). This approach is useful for identifying polluting substances, if a water sample contains a chemical that is not accounted for by the model.

Sverdrup, et al (1946), listed the compositions of dissolved solids in the Mississippi, Columbia, and Colorado Rivers. These showed considerable variation, and each river in the world is probably unique in regard to chemical content. The same is doubtless true of lakes.

Certain lakes, such as the Great Salt Lake in Utah and Mono Lake, California, require special consideration. For example, at Mono Lake, the percentage by weight of dissolved chemicals is about double that of sea water, and the specific gravity is about 1.05. The water is very corrosive. The bottom is covered with deposits of organic material, silt, and sand to a depth of 12 feet.

Chemical pollutants in the bottom mud are not necessarily the same as in the water. For example, heavy metals have been found in Potomac River mud from Washington, D. C. to points 100 miles downstream (Profile, 1971). The concentrations during August 1970 were greatly in excess of any reported for sea water, with peak levels of over 60 ppm for cadmium and copper, near 50 ppm for nickel, about 2800 ppm for zinc, 1700 ppm for manganese, about 80 ppm for lead and chromium, and 25 ppm for cobalt.

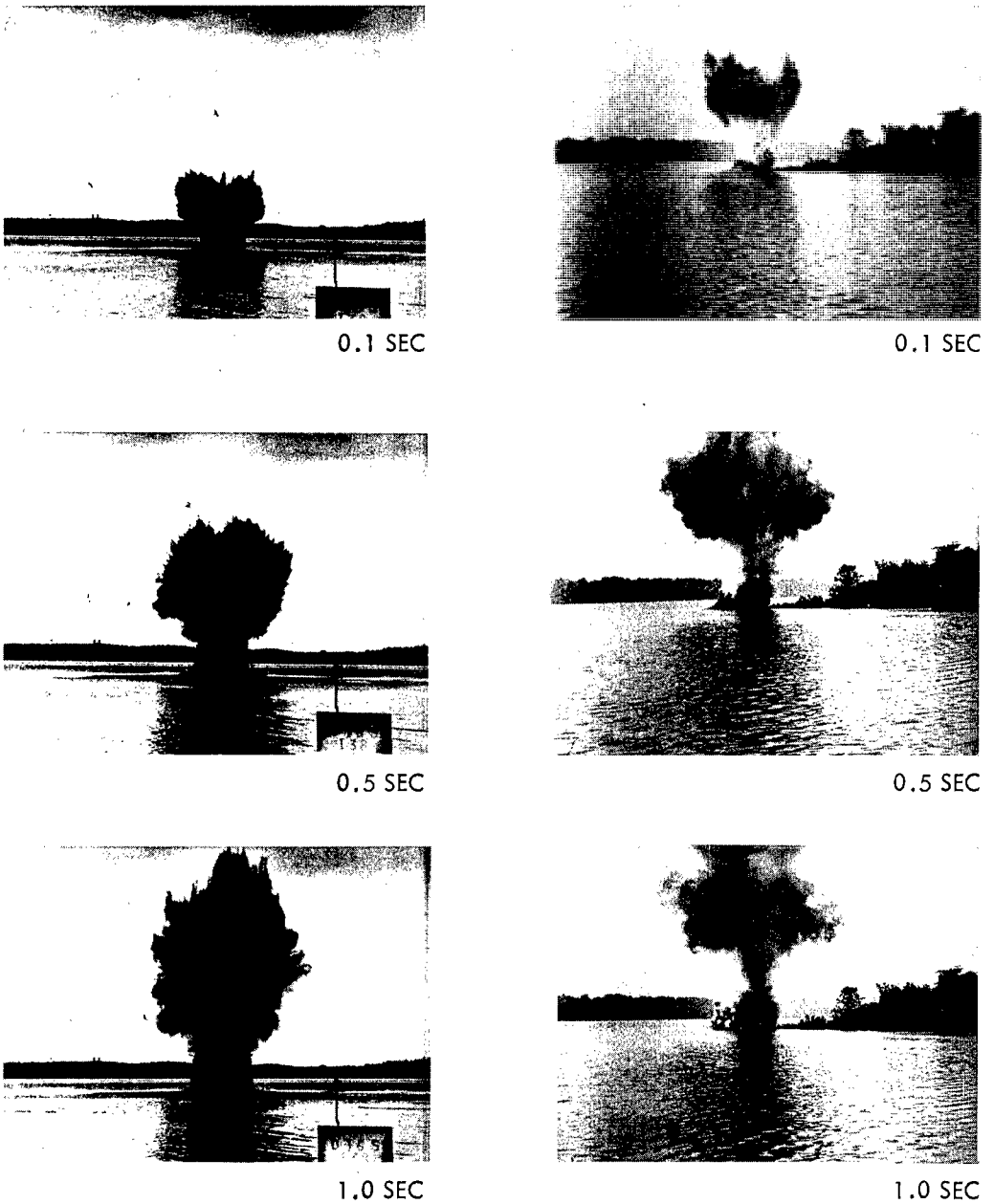
In the Chesapeake Bay, sediment samples near Annapolis showed the following concentrations of metals: lead (60-11 ppm), copper (54-18 ppm), cobalt (355-16 ppm), nickel (58-27 ppm), and vanadium (135-70 ppm). The highest concentrations were observed at the surface of the sediments. The nearby Patuxent River was found to be relatively unpolluted (Pyzik and Sommer, 1972). The chemical composition of the Bay waters was investigated by Newcombe, et al (1939), who found fairly complex variations with season and geographical location. This is to be expected because of the many major tributaries and drainage basins in the estuary system.

If explosion tests are conducted in a location where the background levels of possibly harmful chemicals in the water and sediment are not known, it may be advisable to analyze samples prior to testing. If this is not done, it is possible that future investigators would attribute the presence of metals or other solids to the explosions.

2.3.3 Transfer and Dilution Mechanisms

2.3.3.1 Atmosphere. As indicated in Section 2.3.1, explosion products may be gaseous or solid, and the latter may be soluble or insoluble in water. In the case of a water surface burst, virtually all of the products become airborne and a black smoke cloud is clearly visible from explosives such as TNT (see Figure 2.5). A surface burst also produces a cavity in the water, and spray from the edge of the cavity is ejected into the air, thereby entraining some of the solid products. Consequently, a relatively small pool of blackened water remains at the surface.

Water surface bursts of conventional explosives have received only limited attention. To provide an estimate of atmospheric pollution, the most conservative



A. $d = 0$ $d/A_1 = 0$ WEIGHT = 100 LB B. $d = 20$ FT $d/A_1 = 0.11$

FIG. 2.5 SURFACE AND VERY SHALLOW EXPLOSIONS

procedure is the assumption that all the products become airborne. In the case of an air burst, if the gases expand to atmospheric pressure without mixing with air, their volume should be about 27 W cubic feet, according to theoretical studies (Brode, 1959; Groves, 1963). However, this value seems unrealistically small, probably because of the neglect of atmospheric mixing.

Explosions just beneath the surface form a smoke crown with a radius equal to about 11.3 $W^{1/3}$ feet (Milligan and Young, 1954). As the crown is roughly spherical, its volume is approximately equal to 6000 W cubic feet. This may be utilized as the initial volume containing the explosion products, air, and water for both surface and very shallow bursts. The gases and a portion of the solids can be expected to remain airborne. Table 2.7 provides an estimate of the concentrations of gases in the crown, if all of the products are contained within the smoke crown at the time of its formation. The values in the table are therefore an upper limit.

The density of a smoke crown is not known, but is assumed to be negligibly different from that of the atmosphere for calculation purposes.

Hydrogen cyanide is of special interest because it is poisonous in low concentrations. The threshold limit value for HCN vapor is a concentration of 10 parts per million (Steere, 1971). This is the condition to which nearly all workers may be repeatedly exposed daily without adverse effect. As the initial concentration in the smoke crown is 5.30 ppm, no harmful effects can be anticipated.

In the case of carbon monoxide, the threshold limit value in air is 50 ppm. This is lower than the smoke crown value; but as indicated above, it represents a concentration to which exposure is permissible for a period of eight hours. Concentrations of 400-500 ppm can be inhaled for one hour without appreciable effect (Braker and Mossman, 1970).

The gases in the smoke crown are rapidly diluted by turbulent mixing; and as a rough guide, it may be assumed that the maximum concentration decreases with distance to the 1.50 power (Slade, 1968). A person 100 meters from an explosion would therefore be exposed to a possible CO concentration of only about 0.5 ppm, if he is directly downwind.

Ammonia is an irritant, but the concentration in the smoke crown is below the level that will cause irritation of the eyes, nose, throat, and lungs (Braker and Mossman, 1970). Oxides of nitrogen are possibly formed in trace amounts by explosions, but these would also be at a concentration well below those needed for the initiation of symptoms.

Even if the effects considered here are additive, the combined effect is of no concern to individuals directly downwind of an underwater explosion.

Significant changes take place in surface effects when the explosion depth is increased, although the gaseous products are ejected to the air even by relatively deep explosions. In this case, the products form a spherical bubble that undergoes a series of oscillations while it migrates toward the surface (Cole, 1948). Products are transferred from the bubble to the ambient water by various means, but the arrival of the bubble at the surface results in the ejection of most of the gases. The surface manifestations decrease in size and energy with increasing depth of burst for a given charge weight.

TABLE 2.7

TNT PRODUCTS IN A SMOKE CROWN

Product		Concentration (ppm by volume)		
Name	Symbol	Crown	Atmosphere	T.L.V.*
Carbon Dioxide	CO_2	329	316	5000
Carbon Monoxide	CO	522	0.1	50
Nitrogen	N_2	348	781,000	——
Water	H_2O	405	20,000	——
Hydrogen	H_2	122	0.5	——
Ammonia	NH_3	42.5	0.00002	50
Methane	CH_4	26.2	1.4	——
Hydrogen Cyanide	HCN	5.30	——	10
Ethane	C_2H_6	0.98	——	——

* Threshold Limit Value

It is convenient and practical to employ the calculated maximum radius of the bubble (A_1) during its first expansion as a characteristic length for scaling and prediction purposes. This method is not rigorous, and A_1 is fictitious at shallow depths; however, this approach is sufficiently accurate for current purposes. More extensive discussions of explosion scaling are available in publications by Cole (1948), Snay (1961), and Young, (1965).

The maximum bubble radius for a TNT explosion is given by the following equation (Cole, 1948):

$$A_1 = 12.6 \frac{W^{1/3}}{Z^{1/3}} \quad , \qquad (2.7)$$

where:

A_1 = maximum radius of the explosion bubble during its first oscillation, ft

Z = hydrostatic pressure at the depth of explosion, ft of water (usually taken as d + 33 ft, with d = depth of explosion in ft).

Geometric scaling of the explosion bubble is given simply by the ratio of the explosion depth, d, to A_1. Figure 2.6 has been taken form a report by Young (1971) to show the expected surface phenomena of explosions at different values of d/A_1. The following description has been condensed from material presented in that report.

In the very shallow category ($d/A_1 < 0.20$), a roughly spherical black smoke crown is formed above an almost perfectly cylindrical white column (Figure 2.5). A central jet then emerges above the crown and rises to a height of about ten times the column diameter, carrying a portion of the smoke with it. The water and solids drop back to the surface to form a roughly circular pool, but some finer particles and droplets are carried downwind, leaving a light deposit on the surface.

At slightly greater depths ($0.20 < d/A_1 < 1.0$), the smoke crown disappears and a tall cylindrical column of water and spray can be seen, to be followed rapidly by radial plumes that emerge at the base (Figure 2.7A). It would be expected that all of the gaseous explosion products would enter the atmosphere at these depths but that only a small percentage of solids would become airborne, possibly as a result of the evaporation of small droplets.

Between reduced depths (d/A_1) of 1.0 and 4.0, the plume phenomena become more complex because the explosion bubble can complete one or more oscillations as it migrates upward (see Section 2.3.3.2). In some cases, the plumes are predominantly radial (Figure 2.7B), while in others they resemble the vertical plumes in Figure 2.7A. Within this range, possibly 90% of the product gases escape to the atmosphere while virtually all of the solids remain in the water. The mechanisms of transfer include the emergence of the explosion bubble, small-scale bubbling at the surface, and possibly diffusion across the surface.

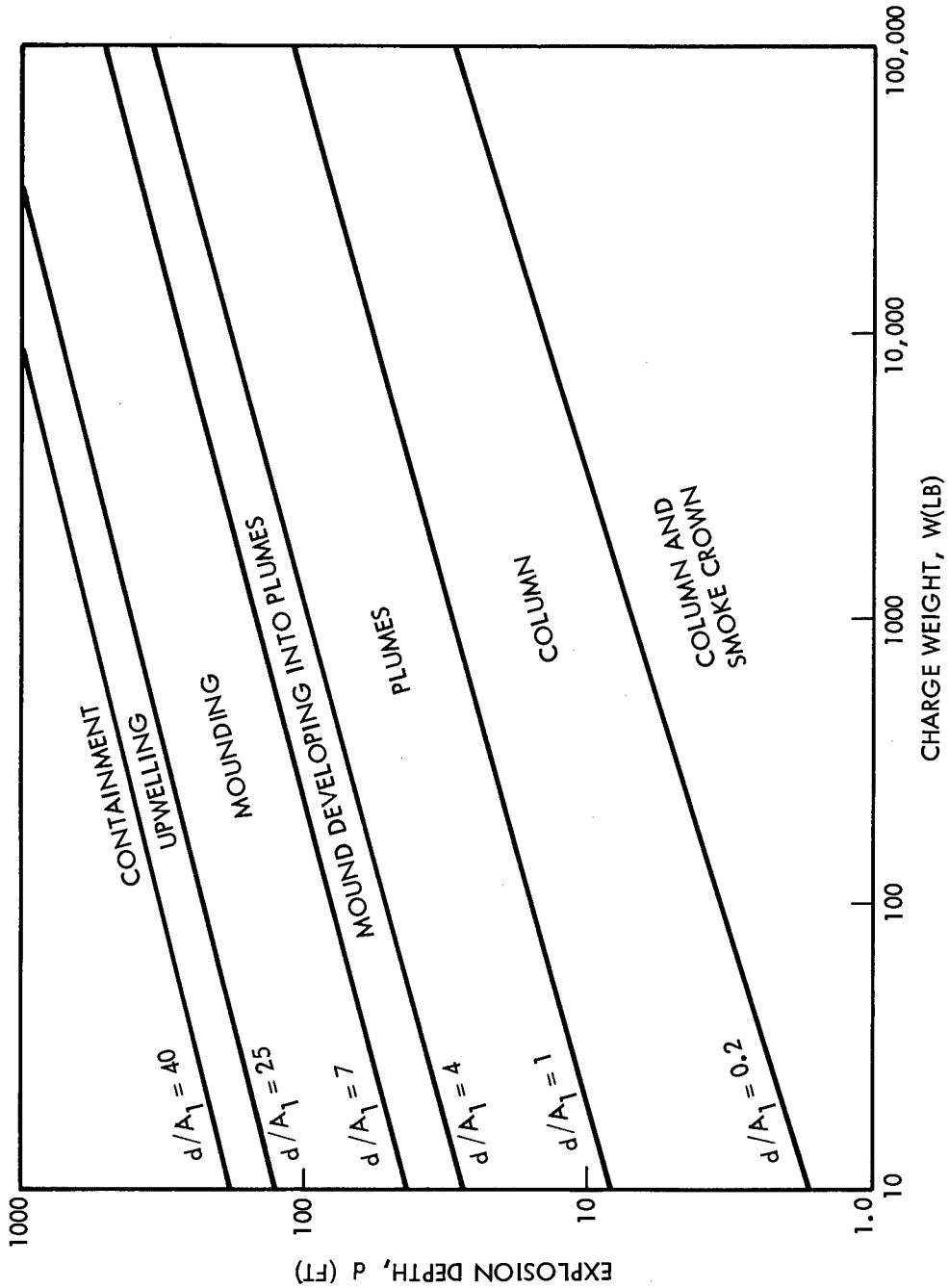
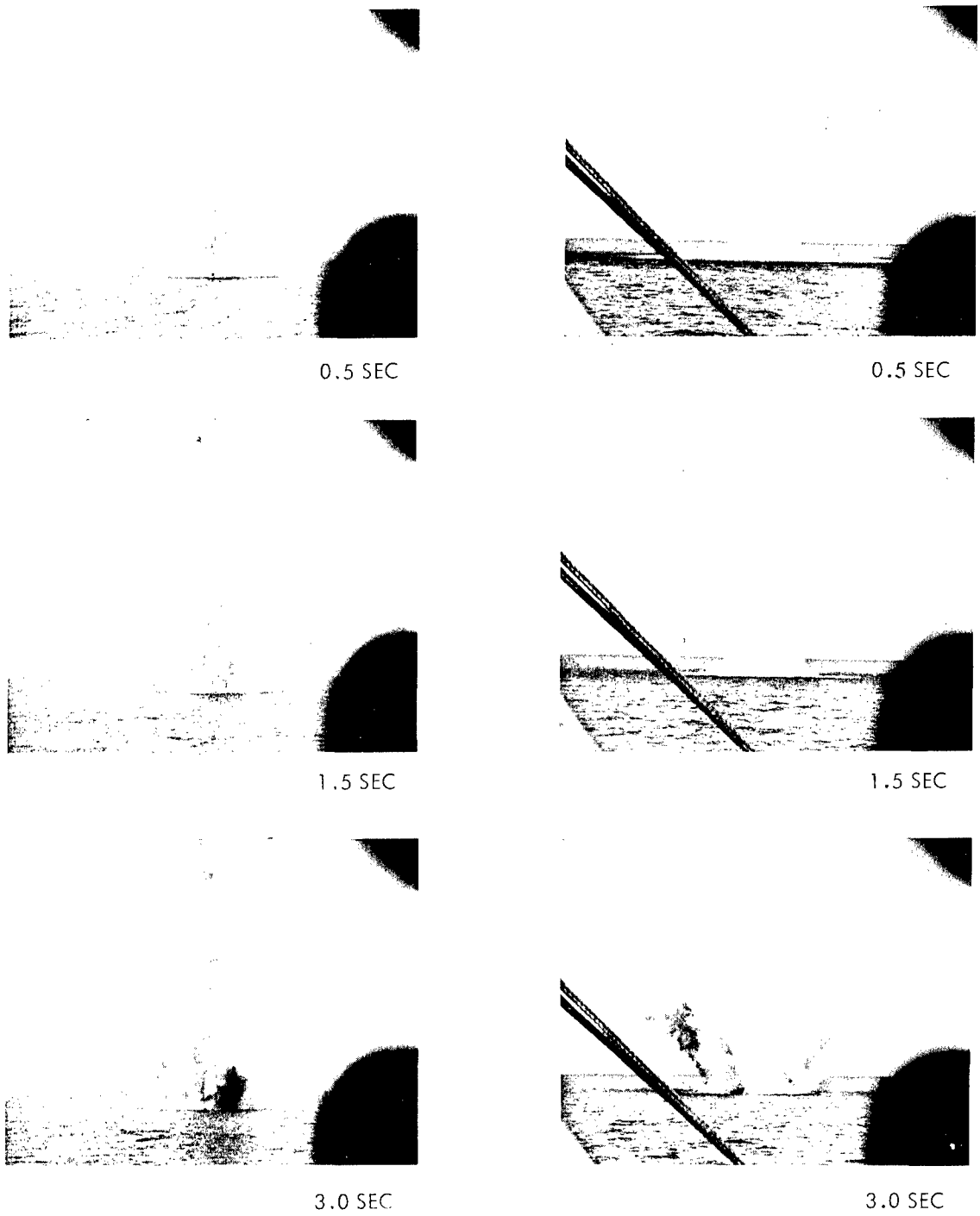


FIG. 2.6 SURFACE EFFECTS OF CONVENTIONAL FREE-WATER EXPLOSIONS



A. d = 10 FT d/A_1 = 0.41 WEIGHT = 300 LB B. d = 45 FT d/A_1 = 2.27

FIG. 2.7 PLUME PHENOMENA OF SHALLOW AND DEEP EXPLOSIONS

Figure 2.8 illustrates the phenomena to be expected between reduced depths (d/A_1) of 4.0 and 7.0. When the bubble emerges, a rough mound of water rises above the surface and then erupts into a large number of plumes. More than half of the gaseous explosion products should be expelled to the atmosphere.

At greater depths ($7.0 < d/A_1 < 25$), only a smooth hemispherical mound appears (Figure 2.9). This subsides rapidly and spreads out laterally to form a surface pool. However, in this region, it is also expected that more than half of the gaseous products will be expelled.

When explosions occur at reduced depths (d/A_1) between 25 and 40, no elevation or depression of the surface occurs, but a rising current of water and explosion products spreads out radially at the surface. This process is called upwelling. At reduced depths in excess of 40, no visible surface phenomena are expected and the products should be contained, though the possibility remains that tiny undissolved gas bubbles could float to the surface after a considerable period of time. This should be a negligible effect for environmental considerations.

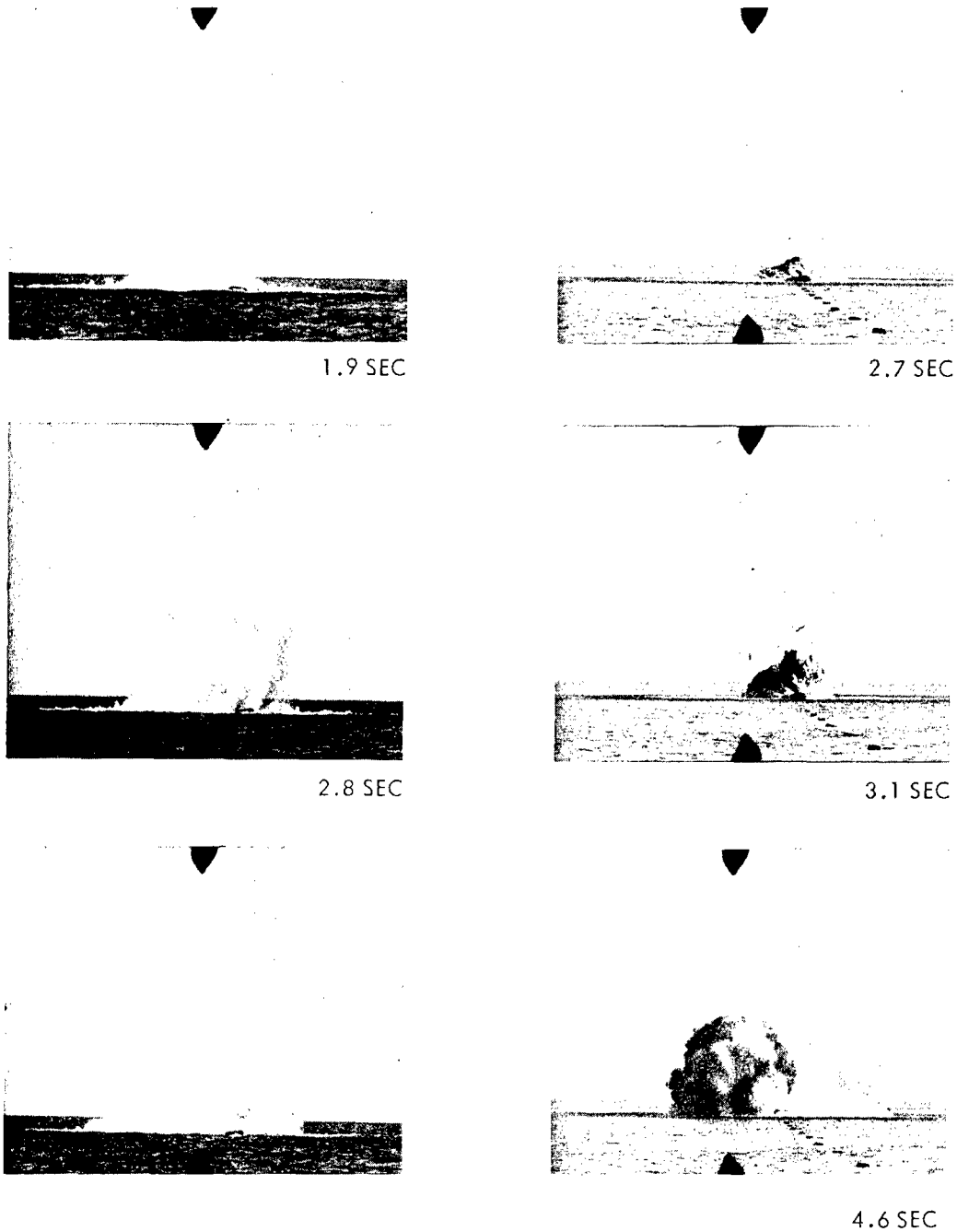
Figure 2.10 is presented to provide some guidance concerning the vertical extent of the plume phenomena. It seems likely that all explosion products injected into the air would remain beneath the heights shown in the figure until carried downwind and acted upon by atmospheric diffusion mechanisms.

Figure 2.11 was prepared on the basis of very limited information to provide estimates of the disposition of gaseous material after an underwater explosion. This information can be used to roughly estimate the atmospheric concentration.

2.3.3.2 Sea Water. The explosion phenomena that occur beneath the water surface cannot be observed directly in field tests with relatively large charges. However, a limited amount of underwater photography of small explosions (6 lb) at sea has been accomplished, and hundreds of experiments with gram-size charges have been photographed in tanks. By combining the model studies with related observations of surface effects, a good understanding of the sub-surface bubble behavior has been achieved.

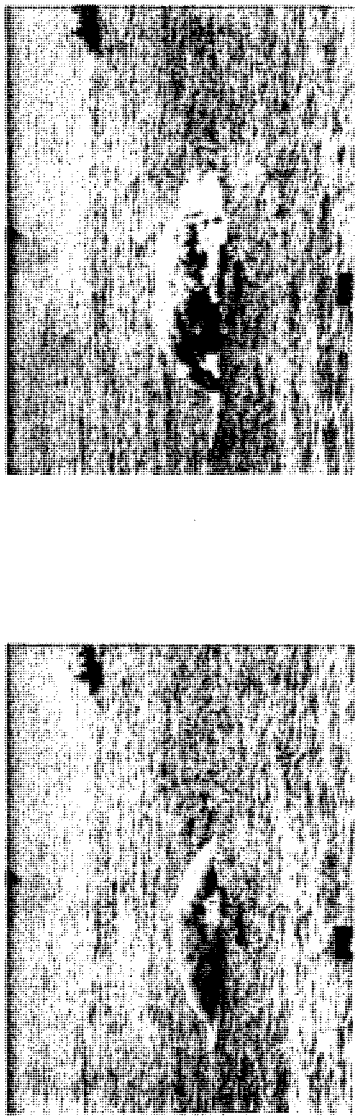
As indicated previously, the products of a deep explosion in water expand to form a spherical bubble. When fully expanded, the internal pressure is lower than the hydrostatic pressure at the depth of burst. The bubble then collapses to a minimum size, whereupon it re-expands almost as though a weak second explosion has occurred. This first collapse of the bubble results in an appreciable loss of energy, a certain amount of turbulent mixing with the surrounding water, and probably the generation of small bubbles.

During the subsequent migration of the main bubble, the pulsations gradually become weaker, and the bubble develops an internal circulation. It resembles a spherical vortex at this stage. Eventually, the circulation stops, and the bubble acquires a hemispherical shape. It gradually erodes at the rear while the leading edge remains smooth. Explosion products are probably deposited in the turbulent wake of the bubble until it disintegrates into a cloud of tiny bubbles. In some cases, relatively large bubbles move out of the cloud and reach the surface first. In the deepest shots on record, the vortex becomes unstable and breaks up into a cloud of bubbles after migrating a relatively short distance. Some of these effects are shown in the photographs in Figures 2.12 and 2.13. The higher tank acceleration in Figure 2.13 resulted in a greater scaled depth of explosion.



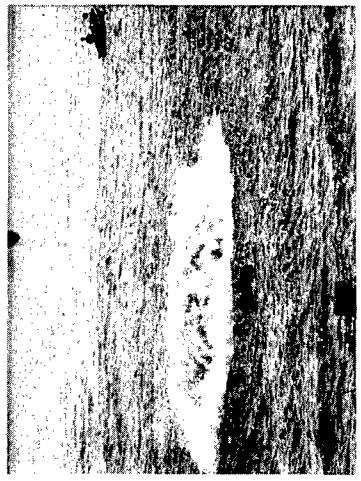
A. d = 80 FT d/A_1 = 4.57 WEIGHT = 300 LB B. d = 100 FT d/A_1 = 6.06

FIG. 2.8 MOUND AND PLUME FORMATION BY VERY DEEP EXPLOSIONS



6.5 SEC

7.1 SEC



7.5 SEC

9.4 SEC

d = 100 FT d/A_1 = 8.85 WEIGHT = 50 LB

FIG. 2.9 MOUND DEVELOPMENT AFTER A VERY DEEP EXPLOSION

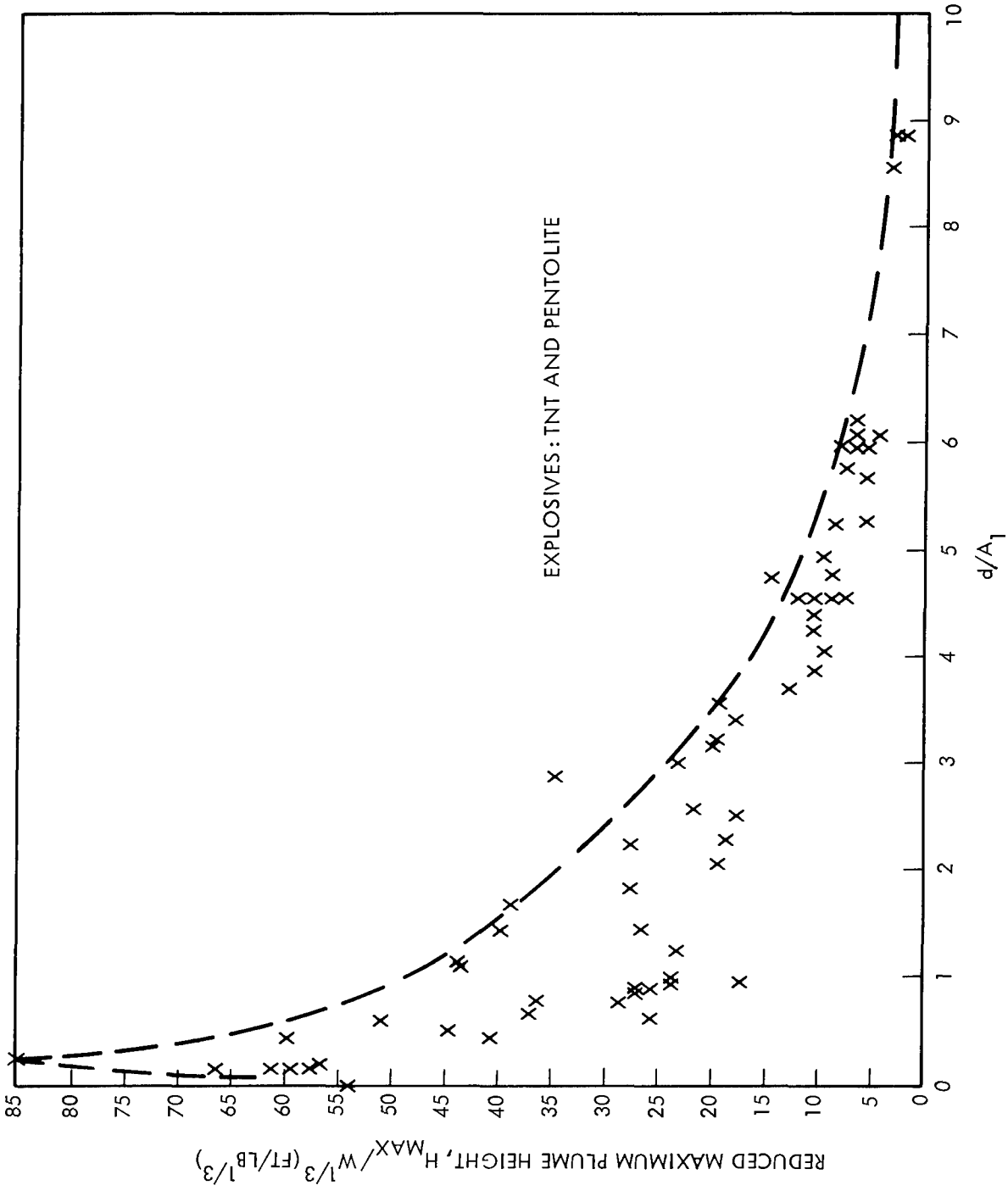


FIG. 2.10 PLUME HEIGHTS

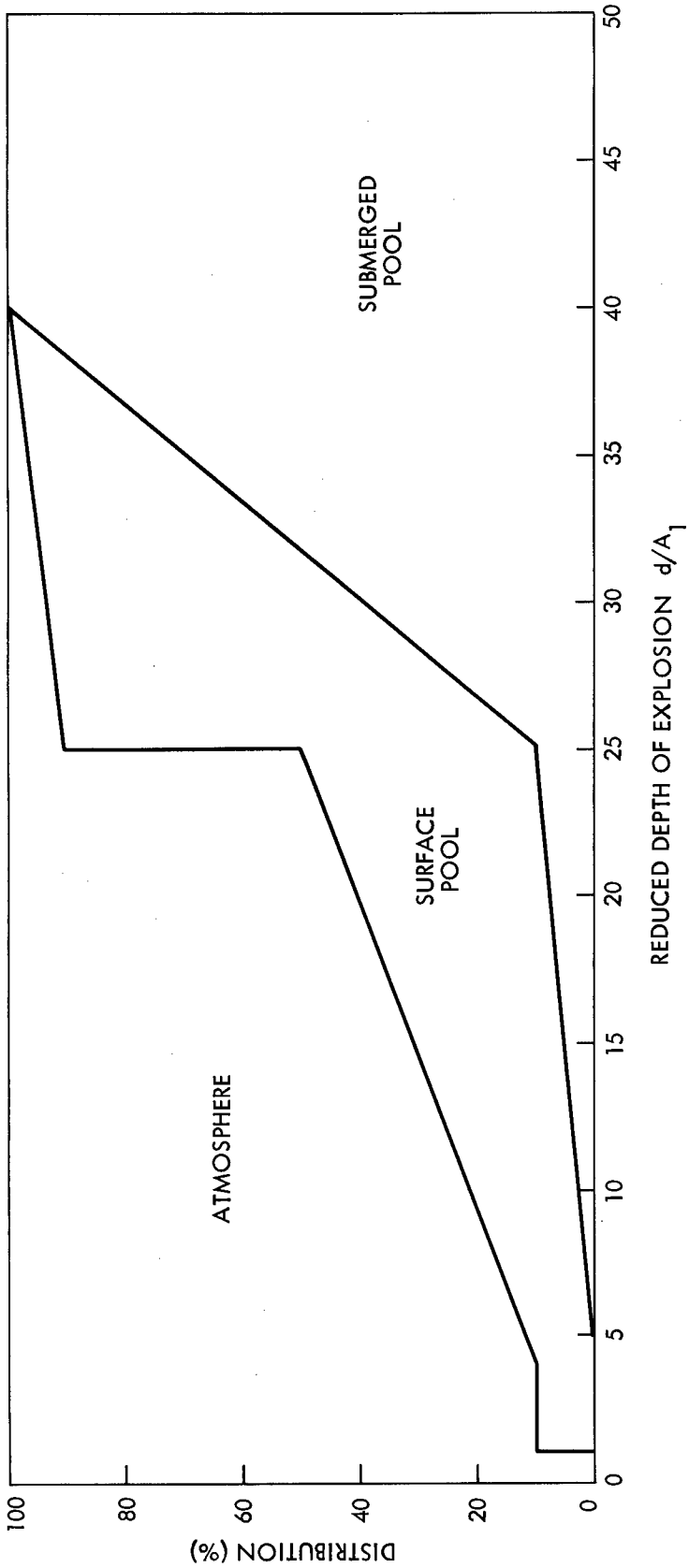


FIG. 2.11 ESTIMATED DISTRIBUTION OF PRODUCT GASES FROM UNDERWATER EXPLOSIONS

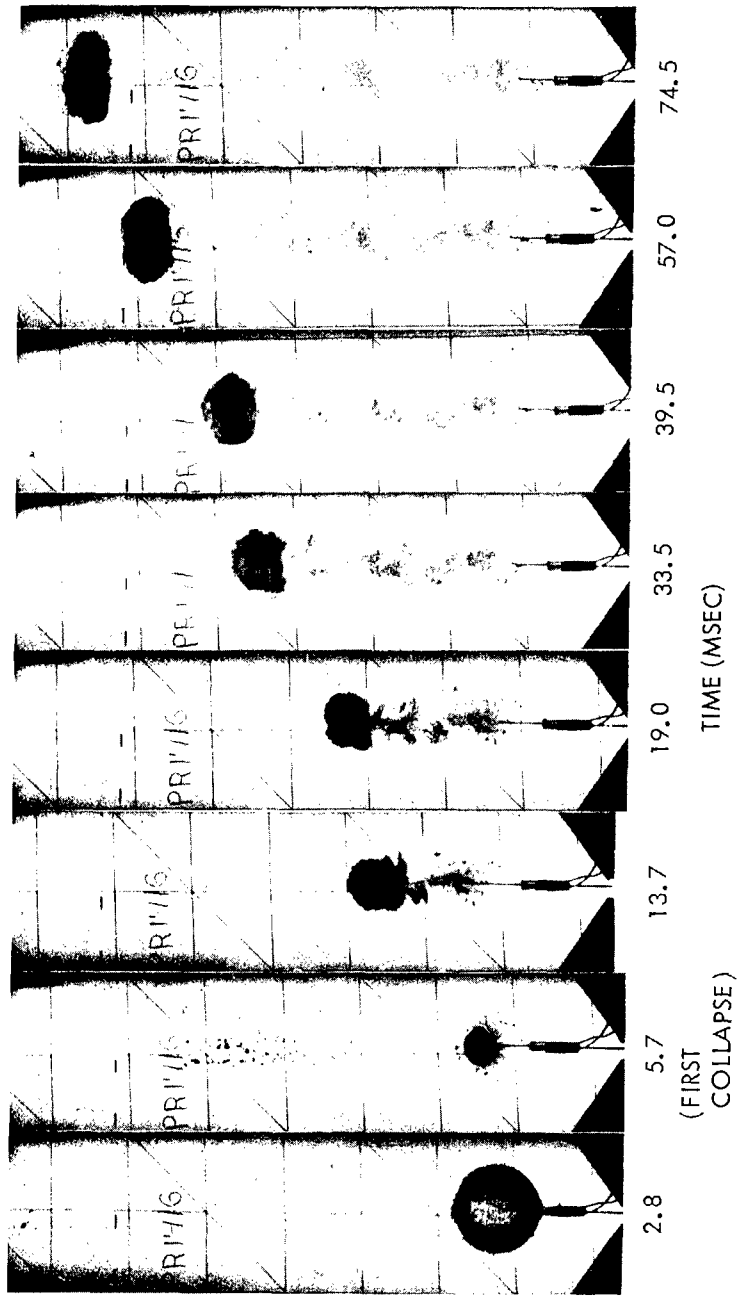


FIG. 2.12 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1416
(ACCELERATION = 48 g's)

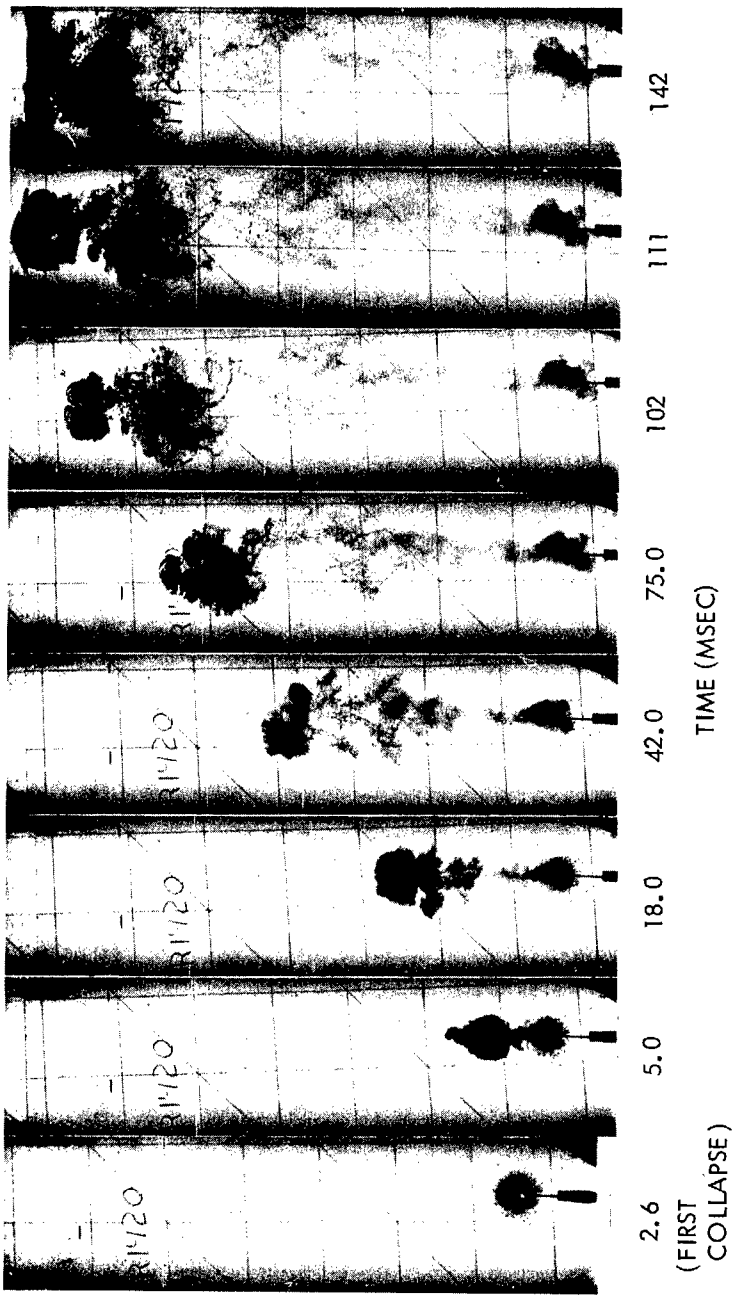


FIG. 2.13 BUBBLE MIGRATION IN ACCELERATED TANK EXPERIMENT - SHOT 1420
(ACCELERATION = 112 g's)

If a bubble reaches the surface while it is pulsating, spectacular plume development may be observed (e.g., Figures 2.7B and 2.8). If a passive hemispherical bubble emerges, a mound is formed (Figure 2.9), while, if the bubble disintegrates into a swarm of tiny bubbles, only an upwelling is observed at the surface. If the explosion is at an excessive depth ($d/A_1 > 40$), these bubbles are not seen. In all cases except the latter, a surface pool is formed. The mechanisms differ, as the pool is formed by the emergence of the bubble and the spillover of the plumes in relatively shallow shots, and by an upwelling current in deeper cases. It also seems likely that material reaches the surface in the wake of the rising large bubbles.

While a bubble is rising, gases will diffuse across the boundary, just as in the case of the air-sea interface. A surface layer should exist on each bubble interface; however, this layer will be effectively thin because the bubbles are moving upward and the surface may be rough because of turbulence. Other factors involved are the effects of surface tension on very small bubbles and the fact that a bubble will expand when it moves into a region of lower hydrostatic pressure (Le Blond, 1969). It is also known that a bubble swarm, or cloud, will rise faster than individual bubbles and that the rate of diffusion may be affected by the presence of other bubbles (Gal-Or and Hoelscher, 1966). In addition, impurities on a bubble surface will affect the rate of solution.

To provide a preliminary estimate, most of these factors may be ignored and a simple model utilized, as sketched in Figure 2.14. The gases dissolved in the medium may be assumed to be in equilibrium with the atmosphere (Table 2.5); the gases in the bubble are those listed in Table 2.2. Because of differing rates of solution, the bubble composition will change while the bubble migrates toward the surface.

The behavior of bubbles of different gas mixtures has been investigated by Wyman, et al (1952). In the case of air bubbles dissolving at high hydrostatic pressure, for example, it was shown that the bubbles gradually became richer in nitrogen because the solubility of oxygen is about double the solubility of nitrogen.

Consider, for simplicity, a passive bubble of a single gas dissolving in water. The rate of change in bubble radius is given by the following equation (Wyman, et al, 1952):

$$\frac{dr}{dt} = -\frac{RTD\alpha}{\Delta}\left(\frac{P_B - P}{P_B}\right) , \qquad (2.8)$$

where*:

r = bubble radius, cm,

R = universal gas constant, cm^3-atmos./mole deg,

T = absolute temperature, K,

D = diffusivity of gas in water, cm^2/sec,

α = solubility coefficient, moles/cm^3-atmos,*

P_B = pressure in the bubble, atmos,

P = partial pressure of gas in the water, atmos,

Δ = thickness of the diffusion layer, cm.

* The units used here for α differ from those in Table 2.6 and Equations 2.3, 2.5, and 2.6.

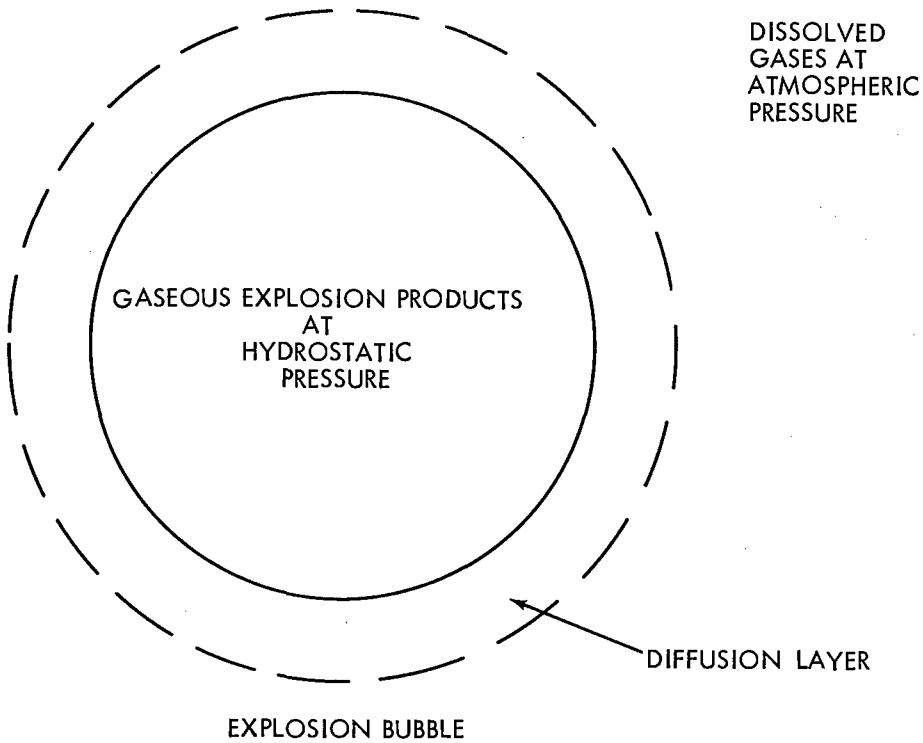


FIG. 2.14 BUBBLE DIFFUSION MODEL

At a depth of 200 meters, P_B = 21 atmospheres. If the gas under consideration is oxygen, P = 0.209 atmosphere, $\alpha = 4.41 \times 10^{-6}$ moles/cm^3-atmos, $D = 2.0 \times 10^{-5}$ cm^2/sec, R = 82.05 cm^3-atmos/mole deg, T may be taken as 293 K and d estimated to be 0.02 cm. In this case $dr/dt = -1.05 \times 10^{-4}$ cm/sec.

If a bubble contains pure carbon dioxide, and $P = 3.16 \times 10^{-4}$ atmosphere, $\alpha = 60.8 \times 10^{-6}$ moles/cm^3-atmos, $D = 1.6 \times 10^{-5}$ cm^2/sec, and T = 297 K, then dr/dt is equal to -1.18×10^{-3} cm/sec, which is a relatively rapid rate of shrinkage by molecular diffusion.

It is evident from the order of magnitude of these results that an explosion bubble that remains intact will dissolve relatively slowly and will change only slightly before reaching the surface. The times of arrival of bubbles of constant volume that originate at a depth of 200 meters are given in Figure 2.15, which also shows calculated bubble migration velocities. The velocities of pulsating explosion bubbles are averages and are shown in relation to the maximum radius A_1.

Data for the rate of disappearance of air bubbles in water were published by Wyman, et al (1952); these may be used as a rough guide to the possible behavior of bubbles of explosion gases. The data showed that air bubbles with an initial radius of about 0.2 cm persist about 40 minutes at a depth of 200 meters and about 50 minutes at a depth of 10 meters. These values are consistent with those calculated from Equation 2.7.

It is clear that only very small bubbles can dissolve while migrating to the surface, even from relatively deep explosions. It therefore seems likely that even the explosions at the "containment" depths would eventually leak some gases to the atmosphere, but this would certainly be at a slow rate and would be difficult to detect.

A simplified model of the surface pool was developed by Young (1971) to estimate the physical extent at the time of stabilization, i.e., after the kinetic energy has been dissipated and the pool is at rest. The following equations can be used for this purpose:

$$R_{max} = 59\ W^{1/3} \quad , \tag{2.9}$$

$$h_{max} = 1.6\ W^{1/3} \quad , \tag{2.10}$$

$$V_{max} = 18{,}000\ W \quad , \tag{2.11}$$

$$t_{max} = 5\ W^{1/3} \quad , \tag{2.12}$$

where:

R_{max} = radius of the surface pool at stabilization, ft,

h_{max} = depth of the surface pool at stabilization, ft,

V_{max} = volume of the surface pool at stabilization, ft^3,

t_{max} = time of pool stabilization, min.

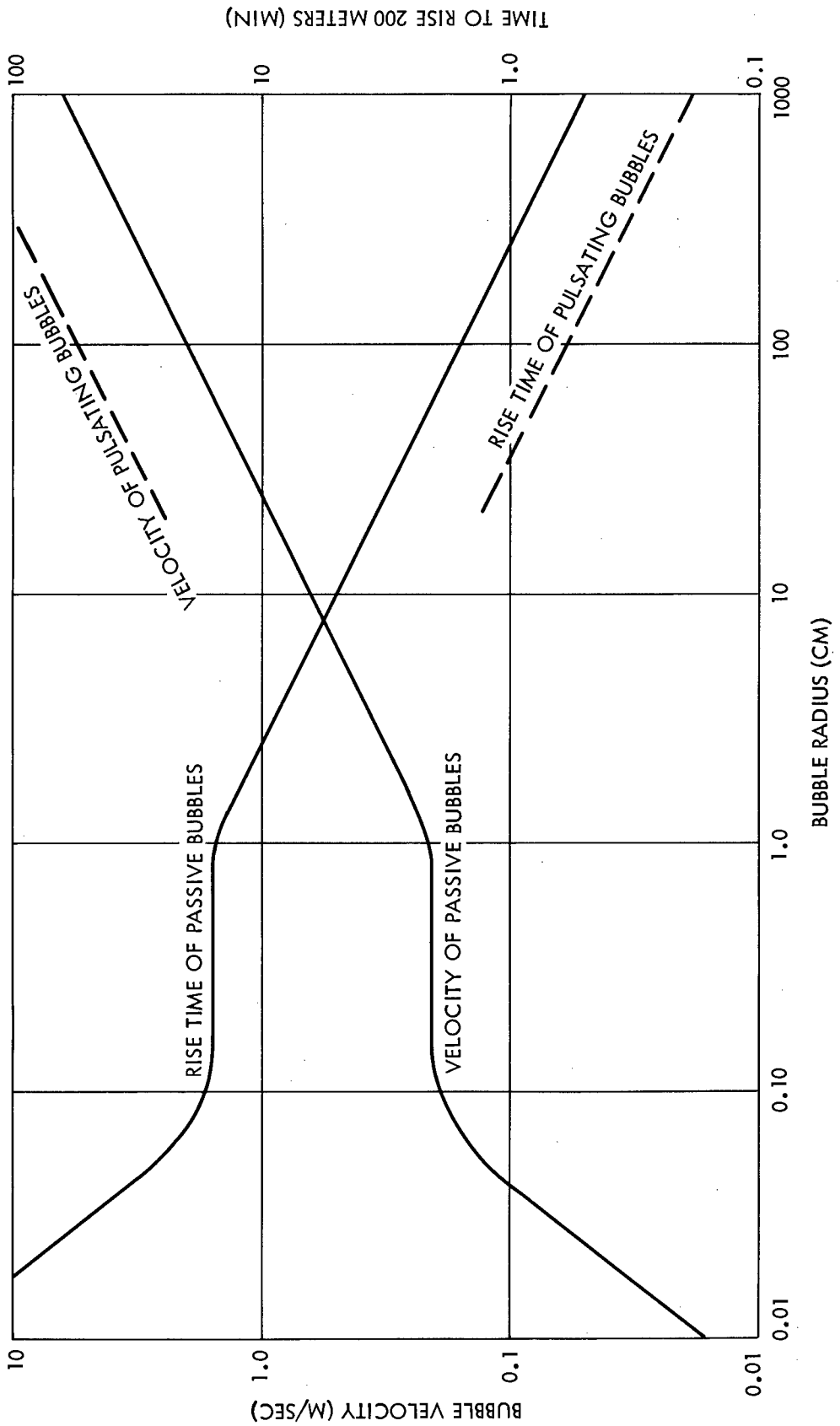


FIG. 2.15 MIGRATION OF BUBBLES

Explosion products remaining in the water should be either in the surface pool or in a submerged vertical cylinder extending from the depth of burst to the surface with a diameter equal to $2A_1$. Figure 2.11 gave the estimated distribution of gaseous products and Figure 2.16 provides an estimate of the distribution of solids.

These values are unverified, and for environmental studies in which it is more important to demonstrate the absence of a hazard than to determine the exact nature of a phenomenon, it is simpler and more effective to take a limiting situation, i.e., a "worst case", and assume that all of the products remain in the surface pool.

As an example, consider the hydrogen cyanide produced by a TNT explosion. The weight of HCN may be taken as kW lb, where k is a coefficient obtained from Table 2.1B by dividing percentages by 100 (k = .0024 in this case). Taking the volume of the pool from Equation 2.11, the concentration in the pool becomes

$$C_o = \frac{kW}{18{,}000W} \quad , \qquad (2.13)$$

where:

C_o = concentration in surface pool, lb/ft^3.

For comparison with oceanographic data, Equation 2.13 may be expressed as follows:

$$C_p = 0.889\ k \quad , \qquad (2.14)$$

where:

C_p = concentration in surface pool, mg/l.

In this example, the result is a concentration of HCN of 2.13×10^{-3} milligrams/liter. The concentrations of all the products of a TNT explosion are shown in Table 2.8, based on the assumption that all remain in the surface pool. This is particularly unrealistic for the gases, and all values are doubtless higher than would be observed. The table also includes average sea water background values.

After the kinetic energy of the surface and underwater pools has been expended, the pools appear to stop expanding. However, a slow growth continues as a result of small-scale oceanic turbulence, and at the same time the pools may be distorted by large-scale irregularities and transported by currents. This process has been described in detail in publications by Okubo (1962), and Pritchard, et al (1971).

Several theoretical solutions have been obtained for the diffusion of substances introduced instantaneously at a point in the sea. These have been summarized by Okubo (1962) and by Smith (1967). The theories may be utilized if detailed calculations are needed for the spread of the products of a conventional explosion; however, for the purposes of this report, only some approximate estimates of the significant effects are needed. For simplicity, a radially symmetric two-dimensional horizontal diffusion process will be assumed to take

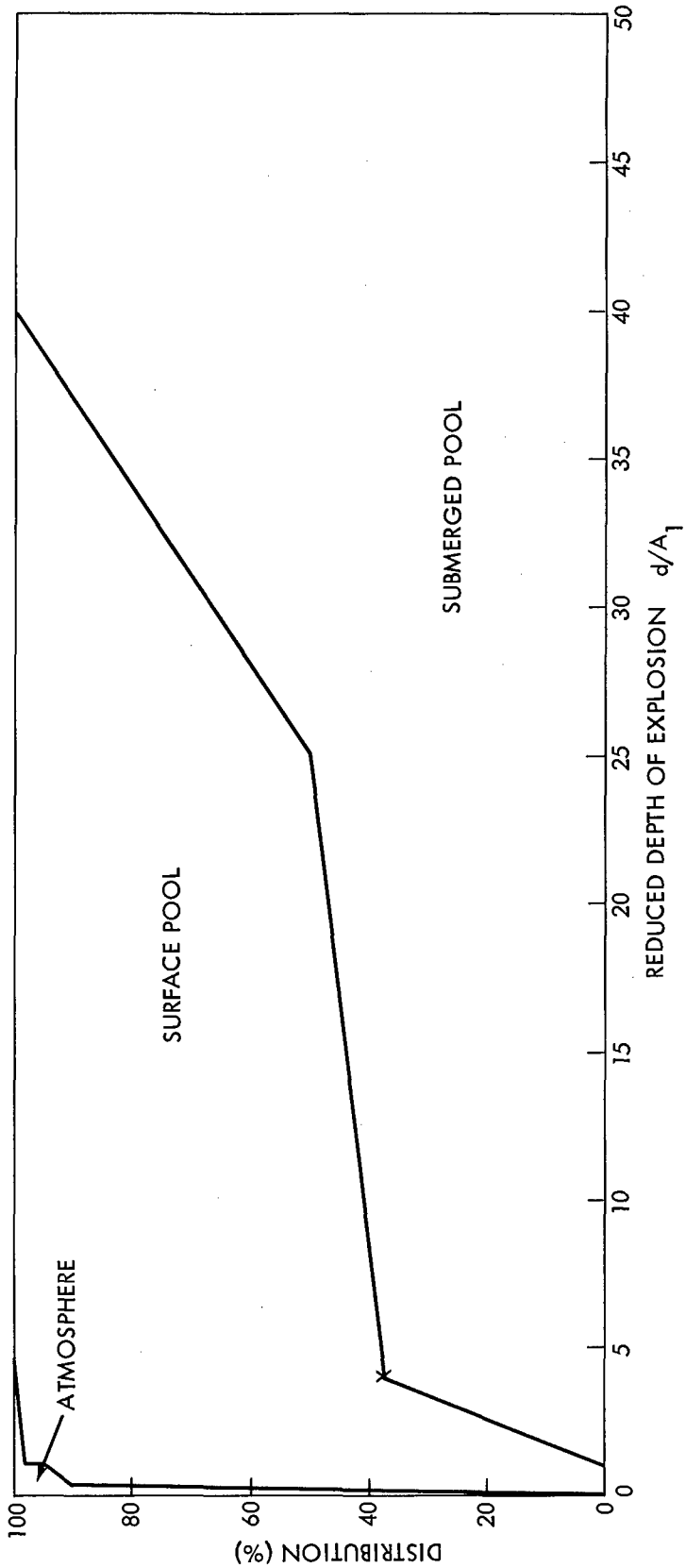


FIG. 2.16 ESTIMATED DISTRIBUTION OF SOLID PRODUCTS OF UNDERWATER EXPLOSIONS

TABLE 2.8

TNT PRODUCTS IN A SURFACE POOL

Product		Concentration (mg/l)	
Name	Symbol	Pool	Ocean
Carbon Dioxide	CO_2	0.215	0.631
Carbon Monoxide	CO	0.217	28.8×10^{-6}
Carbon	C	0.172	28
Nitrogen	N_2	0.145	14.3
Water	H_2O	0.113	—
Hydrogen	H_2	3.64×10^{-3}	—
Ammonia	NH_3	1.08×10^{-2}	—
Methane	CH_4	6.22×10^{-3}	40.9×10^{-6}
Hydrogen Cyanide	HCN	2.13×10^{-3}	—
Ethane	C_2H_6	4.44×10^{-4}	1.49×10^{-6}

place. The most conservative* theoretical models indicate that the maximum concentration over a long time period decreases with the square of the time. On this basis, the concentrations given in Table 2.8 may be reduced by the time squared to provide a rough estimate of long period effects. The values obtained will represent an upper limit.

The radius of the pool is also a significant parameter, but this becomes difficult to define and to measure at late times because of mixing at the edge. If the pool extent is defined as the radius at which a particular level of concentration is detected, this value will increase with time and then decrease as a result of dilution. However, as the horizontal variance** of the pool increases in proportion to $t^{2.54}$ (Pritchard, et al, 1971) it may be assumed that the radius increases roughly as $t^{1.27}$.

Strictly speaking, the concentration in a pool will always exceed background levels, because the explosion products are added to the constituents already in sea water. However, when the added substances become an order of magnitude below the background levels, it would seem realistic to consider them then to be a part of the environment. In most cases this occurs prior to the time of pool stabilization (see Table 2.8).

The possible hazardous levels of substances such as these in regard to marine organisms have not been well documented, but some estimates have been given for CO_2, NH_3, and HCN (FWPCA, 1968). The Federal Water Pollution Control Administration recommends that the free carbon dioxide concentration should not exceed 25 mg/l and offers evidence that the pH of the water has an important effect on the toxicity of cyanide and ammonia. Some undesirable effects were noted at hydrogen cyanide concentrations of about 0.3 mg/l and it was found that 2.5 mg/l of ammonia is acutely toxic. These values are well in excess of those calculated for the surface pool. Also, as indicated previously, the values given in Table 2.8 are doubtless unrealistically high.

2.3.3.3 Inland Waters. The explosion phenomena, up to the time of stabilization of the pools, are the same in inland waters as in the open sea. However, as indicated in Section 2.3.2.3, the background levels of dissolved substances can be substantially different. In addition, the transport and diffusion of surface and submerged pools will be controlled by local conditions. It is necessary, therefore, to study these in advance if predictions of the concentration of explosion products at relatively late times are needed.

In a typical estuary, three water layers may often be distinguished (Pritchard, et al, 1971). The surface layer has a low but roughly constant salinity, and the bottom layer has a higher salinity. In the intermediate layer, salinity increases rapidly with depth. The surface layer has a net motion seaward, while the bottom layer flows toward the head of the estuary. In addition,

---

* In this case, a conservative model is one that gives a high value of concentration, or pool size, at a given time.

** The mean squared value of the horizontal distance of explosion product parcels from the center of the pool.

a tidal oscillation is added to the circulation pattern, and vertical transfer across the intermediate layer may occur. The fate of a pool of explosion products in an estuary therefore is influenced by a variety of factors, including the initial depth of formation and the local currents and tides.

Currents and diffusion processes are also complex in the Great Lakes, where pronounced seasonal and diurnal variations have been found (e.g., Murthy, 1972; Csanady, 1972). In some locations, the currents can shift drastically in a few hours.

In a small pond, an accumulation of solid explosion products may occur over a period of time. This can be estimated from the weights of the charges and the rate of firing.

2.3.4 Bottom Effects

The most obvious effect of explosions on the seabed is cratering, and there is probably no doubt that benthic sea life in the cratered region will be destroyed. As a rule of thumb, the bottom is probably disturbed over twice the width of the crater. Figure 2.17 has been extracted from a report by Young (1971) to indicate the width and depth of craters on clay or sand bottoms. At greater scaled depths of explosion, experimental data are limited, but the following equation may be used to estimate crater width. This equation is based on the assumption that the crater radius is equal to the explosion bubble radius when the water is relatively deep.

$$C_w = 29 \frac{W^{1/3}}{Z^{1/3}} \quad , \qquad d/W^{1/3} > 1.0, \tag{2.15}$$

where:

C_w = crater width, ft.

Crater effects are temporary on sand or mud bottoms, but a crater in clay may persist for a period of years. The restoration of benthic life probably takes up to a year in the vicinity of a crater.

The effects of a yielding bottom on an explosion bubble have not been investigated, but is is known that the bubble from a very deep explosion on a rigid bottom tends to pulsate at the bottom before it floats upward. An example of this type of behavior in a small-scale model test is shown in Figure 2.18.

It may be assumed as a rough guide that a pulsating bubble will remain at the bottom when the explosion depth exceeds the following:

$$d_b = 30W^{1/4} \quad , \tag{2.16}$$

where:

d_b = depth at which the bubble pulsates at the bottom, ft.

When the oscillations are completed, the remaining gas doubtless rises toward the surface, possibly as a cloud of small bubbles. It seems likely that a portion

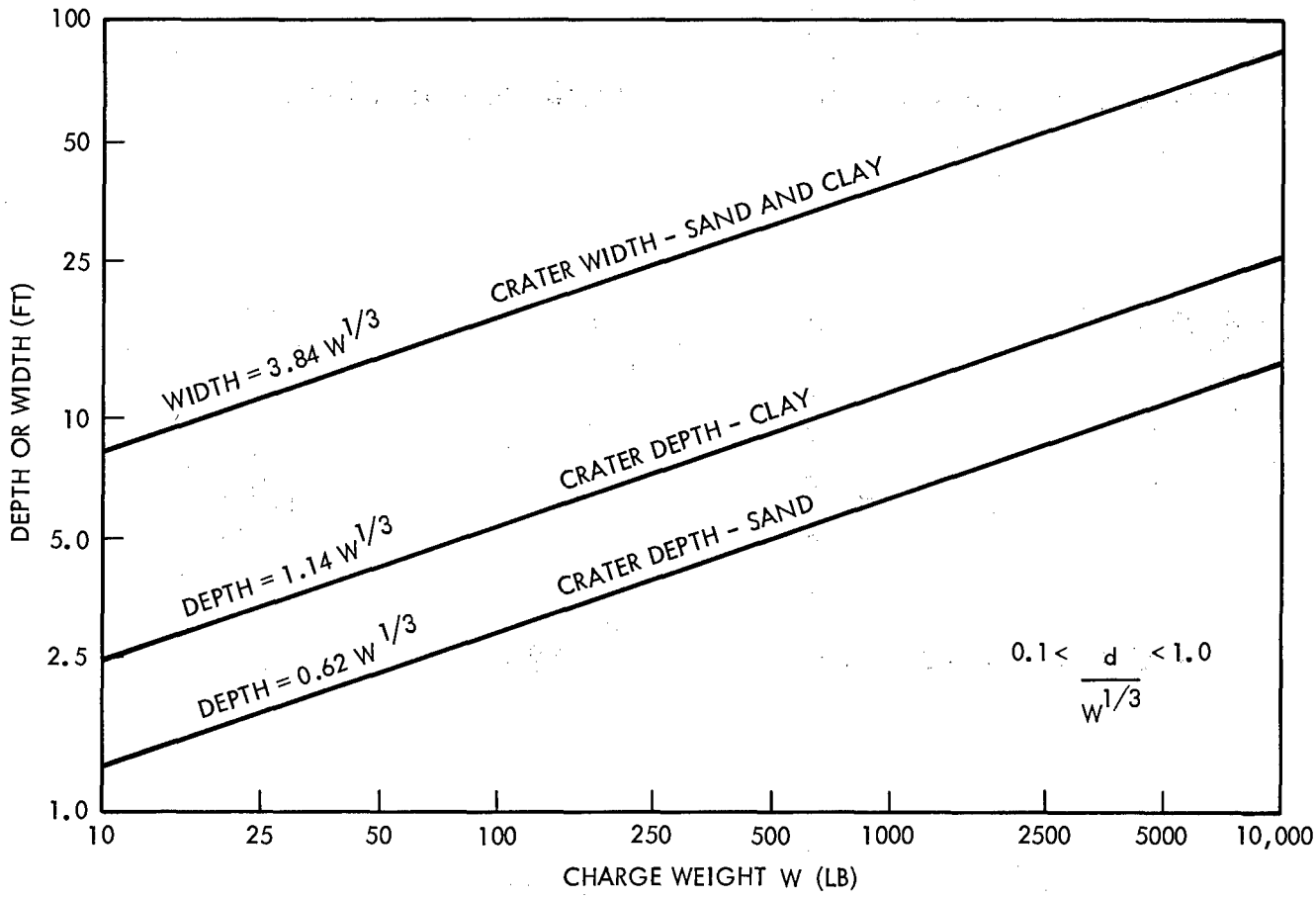
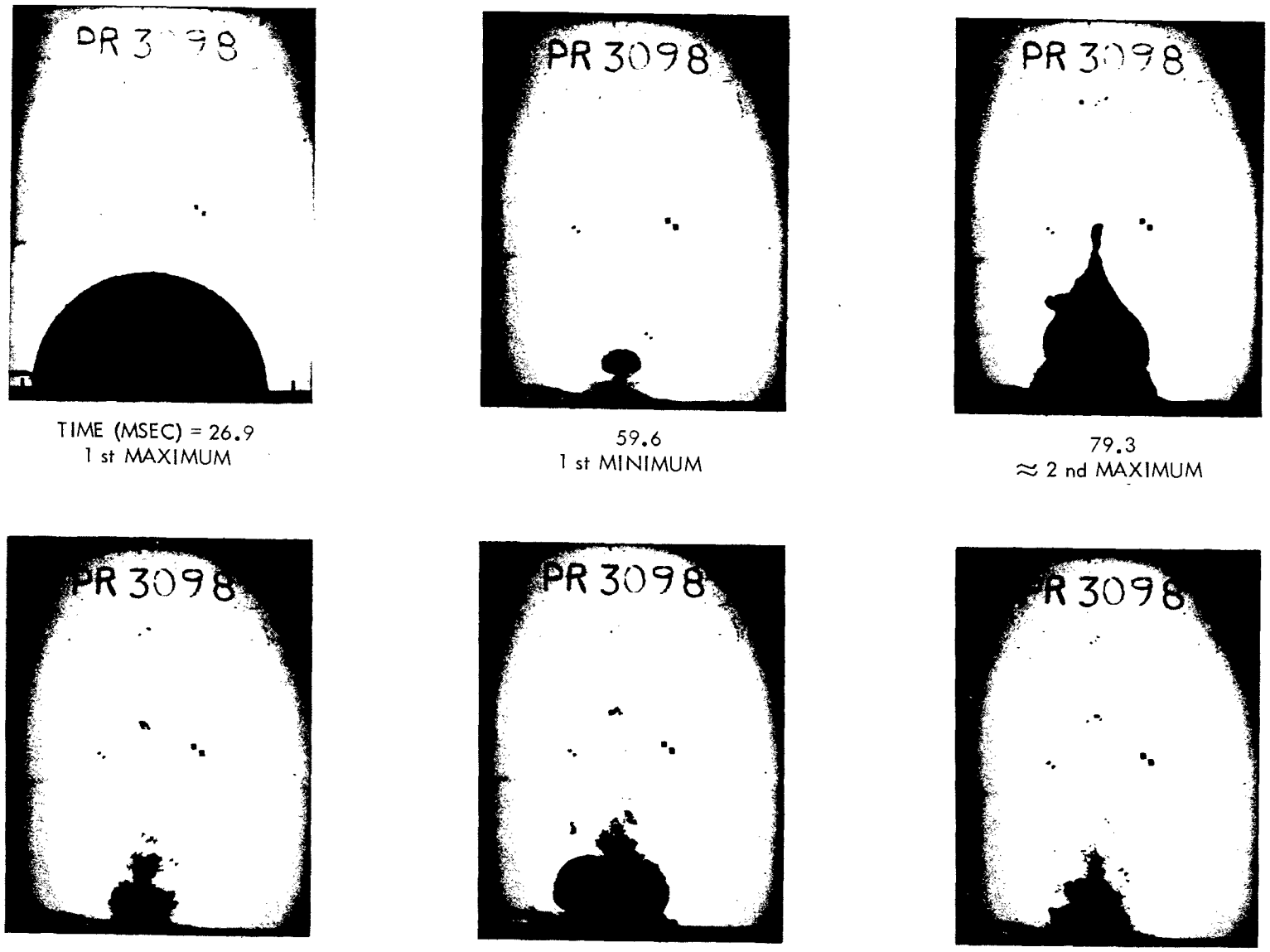


FIG. 2.17 UNDERWATER CRATER WIDTHS AND DEPTHS



TIME (MSEC) = 26.9
1 st MAXIMUM

59.6
1 st MINIMUM

79.3
≈ 2 nd MAXIMUM

100.7
≈ 2 nd MINIMUM

120.7
≈ 3 rd MAXIMUM

139.7
≈ 3 rd MINIMUM

FIG. 2.18 BUBBLE PULSATING ON THE BOTTOM IN VACUUM TANK EXPERIMENT

of the solid products will remain in the crater and some of the finer bottom particles will be carried upward with the bubbles. It also seems likely that a turbidity cloud of disturbed bottom material will remain in the vicinity of the burst for some period of time. A secondary effect of interest is that an explosion on the bottom could possibly release a cloud of natural gases, such as methane, from the bottom sediments.

This problem has received little attention, but some guidance can be provided on the basis of existing relevant information. The amount of bottom material dislodged should be equal to the crater volume, as shown in Figure 2.19. At greater depths, the following equation may be utilized to provide an estimate:

$$C_v = 2360 \frac{W}{Z} \quad , \quad d/W^{1/3} > 1.0, \qquad (2.17)$$

where:

C_v = volume of crater, ft^3.

This volume is an upper limit to the material that remains suspended for a significant period of time, as in certain types of bottom, such as clay, large clumps may be ejected. These ejecta fall back immediately.

As marine sediments are frequently classified by the size distribution of their particles, a knowledge of the sediment type can be used to provide an estimate as to whether a turbidity cloud and appreciable upward transport will occur. In Table 2.9, the size classifications are given; and as a general rule, particles larger than 1 mm in diameter can be expected to settle too rapidly to form a persistent cloud. However, particle size alone is not a sufficient criterion, as clay can have considerable cohesive strength. Turbidity clouds are therefore most likely over silt bottoms, or bottoms where the percentage of silt and clay is greater than fifty percent (Athearn, 1967).

As the properties of sediments and sediment clouds are not well understood, the values in Table 2.9 are only a rough guide. For example, a suspended particle will fall more slowly in turbulent water than in still water (Murray, 1970), but a dense cloud of sediment might settle at a faster rate than an individual particle (Young, 1965). However, in the latter case, the cloud would then spread out laterally.

On a practical basis, the presence of a deep cloud of sediment is probably of no concern. However, when explosions occur in shallow water, the displaced bottom material is clearly visible to observers and could result in complaints if it persists and is carried from the area by currents. In the case of TNT tests, for example, this material would be mixed with the carbon in the surface pool. Some downwind deposit would also occur from airborne material. It seems likely, however, that no bottom material would become airborne with explosion depths in excess of $1.0\ W^{1/3}$ feet.

The possibility exists that the bottom mud might be contaminated and that these contaminants would be dislodged and redistributed by an explosion. However, this is probably a localized effect of only limited concern.

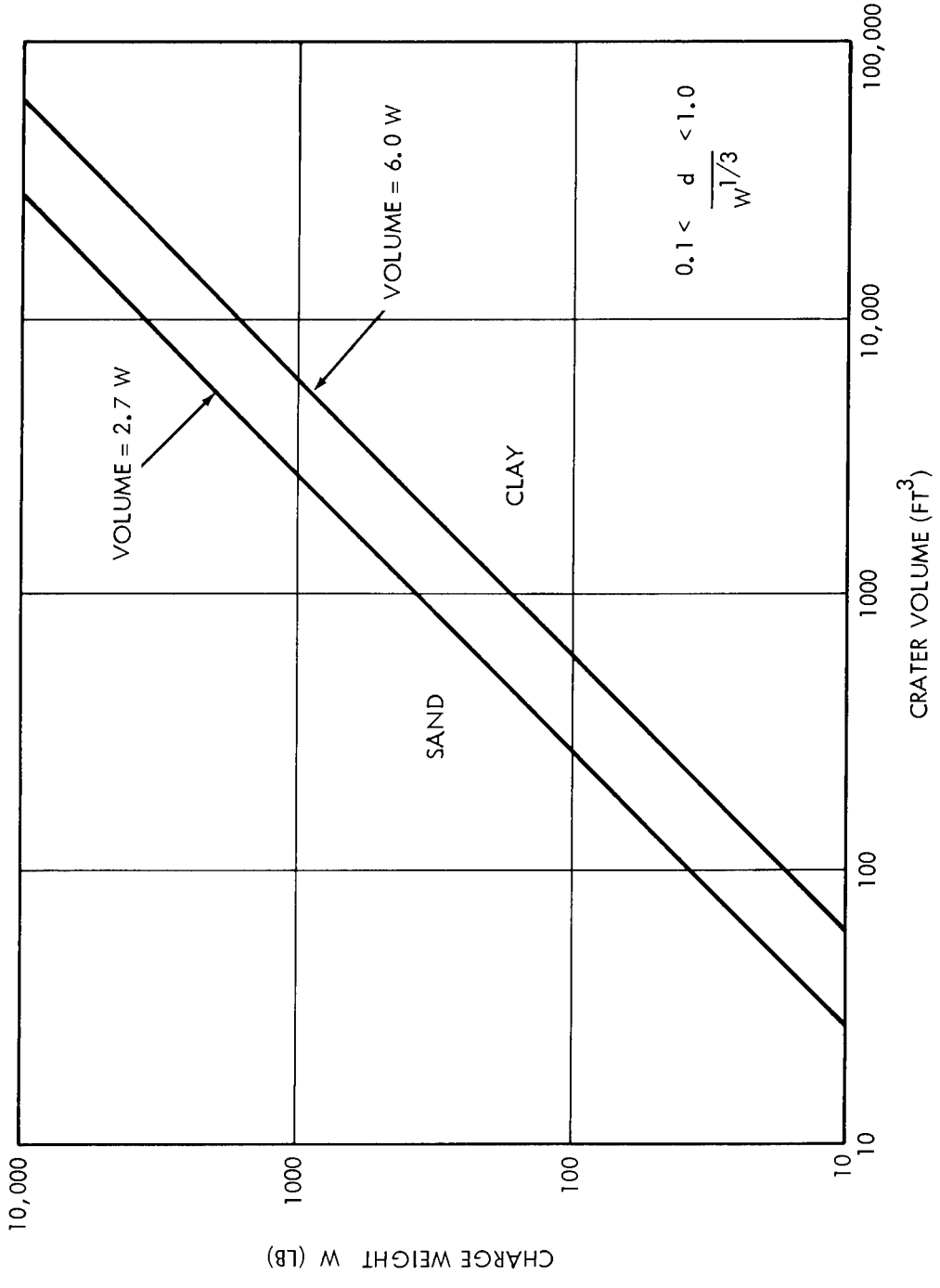


FIG. 2.19 CRATER VOLUMES

TABLE 2.9

PARTICLE SIZES IN MARINE SEDIMENTS

Category	Particle Diameter Range (mm)
Clay	0.000125 - 0.00195
Silt	0.00391 - 0.0312
Very Fine Sand	0.0625 - 0.125
Fine Sand	0.125 - 0.250
Medium Sand	0.250 - 0.500
Coarse Sand	0.50 - 1.0
Very Coarse Sand	1.0 - 2.0
Granules	2 - 4
Pebbles	4 - 64
Cobbles	64 - 256
Boulders	256 -

SOURCE: Sverdrup, et al (1946)

If an explosion takes place on or near a sloping bottom, consideration should be given to the possibility of initiating a turbidity current. This current is formed by a suspension of sedimentary particles that flows along the seabed because the bulk density of the mixture exceeds that of clear sea water. The motion starts on a sloping bottom, and the current then moves downslope and fans out a considerable distance across the sea floor because of its inertia and its low viscosity. Sand and silt are gradually deposited on the bottom as the current slows down and stops. The best documented example is the current that broke twelve telegraph cables on the seabed immediately after the 1929 Grand Banks earthquake (Heezen and Ewing, 1952). The epicentral area was on the continental slope, about 6000 feet deep, and the current evidently moved down the slope at a high velocity and halted somewhere on the ocean floor over 400 miles away at a depth of 17,000 feet. Cables on the Grand Banks were not disturbed.

Mud slides or slumps can also occur on sloping bottoms. These have a high density and can contain large particles or boulders in some cases. In general, they will come to an immediate stop when they reach the bottom of a slope (Kuenen, 1956).

An avalanche is a density flow on land that is similar in many respects to an underwater turbidity current. Explosives are commonly employed to check the stability of snow, and in some cases, to start an avalanche when it reaches a dangerous state (Forest Service, 1961). If the snow is stable, the explosive charge produces a crater, indicating that no avalanche hazard exists.

A similar condition possibly exists on the seabed; although some experiments conducted with explosives in unstable sediments in the Scripps Submarine Canyon off La Jolla, California produced craters instead of turbidity currents (Dill, 1966). It seems possible that the explosives were not placed in the positions needed to trigger a density current or that the sediments were not sufficiently unstable. As this general subject is not well understood, the generation of a current, or a slump, should be considered as a possible environmental effect of an explosion on a sloping bottom. This situation should be avoided, if at all possible, in Navy testing.

2.3.5 Sub-Bottom Effects

When an explosion occurs with a relatively slight burial of the charge, i.e., less than about 0.2 $ft/lb^{1/3}$, the effects will be similar to those of bottom shots. However, when charges are buried deeply in the bottom, the deposit of solid products within or on the bottom should be almost complete. As long as cratering occurs, gases will escape, though it is unlikely that a single large coherent bubble will be formed. Crater radius increases with depth of burial, to a value about double the radius of a bottom explosion crater when the reduced depth, below the bottom, is about 1.0 $ft/lb^{1/3}$. Containment within the bottom will possibly occur at a reduced depth of 5.0 $ft/lb^{1/3}$. As this problem has been given almost no attention in the past, these values are highly speculative.

A sub-bottom explosion will generate pressure and shear waves that will be partially reflected from the seabed and will be transmitted, in part, to the water. This complex problem has not been investigated except for studies related

to the possible environmental effects of deep underground nuclear tests in the Aleutians (Kirkwood and Fuller, 1971). The shock wave entering the water on the Cannikin test was estimated to produce an overpressure of about 100 psi at the seabed in most areas. Biological effects, if any, were probably limited to benthic organisms.

The possibility exists that a sub-bottom explosion in the vicinity of a sloping bottom could trigger a turbidity current in unstable sediments. This explosion geometry may be more effective for this purpose than a charge resting on the bottom (see Section 2.3.4).

2.4 FISH

2.4.1 Mechanisms of Injury

The research conducted on the mechanisms of fish-kill by underwater explosions has been relatively limited, although it is generally accepted that fish with swim bladders are more vulnerable than other species and that rupture of the swim bladder is a prime cause of death.

Much of the available data is statistical and is based on the observation of dead fish floating after an explosion test (see Section 5.1); however, in a few cases, specimens were placed in cages at known distances from charges fired for the specific purpose of observing the effects on marine life. Experiments of this type were reported by the Chesapeake Biological Laboratory in 1948. Oysters, crabs, trout, rock (striped bass), croaker, spot and menhaden were studied.

The results were somewhat erratic, possibly because the number of specimens varied considerably during the tests. In cases where fish were placed a given distance from a charge on only one test, the results have less significance than if fish were placed the same distance from several shots of the same type. Figure 2.20 shows some of the results reported when more than ten specimens were exposed at the same distance from charges weighing from 28 to 32 pounds. The percentage of deaths includes those killed outright and specimens that died from injuries. The results are consistent with those of Hubbs, et al (1960), who reported a lethal range of about 500 feet with 25-lb charges of commercial explosives for sardines and anchovies. In these tests, also, there was considerable unexplained variation in the results.

Bottom dwellers are affected less than fish because of a different physiology and because the shock wave decreases rapidly along the bottom when explosions take place on the bottom (e.g., Hubbs and Rechnitzer, 1952). Effects on benthic life will be discussed in Section 2.4.4.

It has been assumed, in many investigations of fish lethality, that the radii of certain levels of injury and deaths are related directly to the peak pressure in the shock wave. However, this could never be demonstrated clearly because of the limited quantity of data and the fact that many tests were conducted in the vicinity of the bottom or the water surface. The shocks were therefore complex in structure as a result of the interaction of direct and reflected waves (shock waves reflected from the surface become tension waves and reflections from the bottom are positive; however, the strength of the latter is strongly dependent on the bottom material).

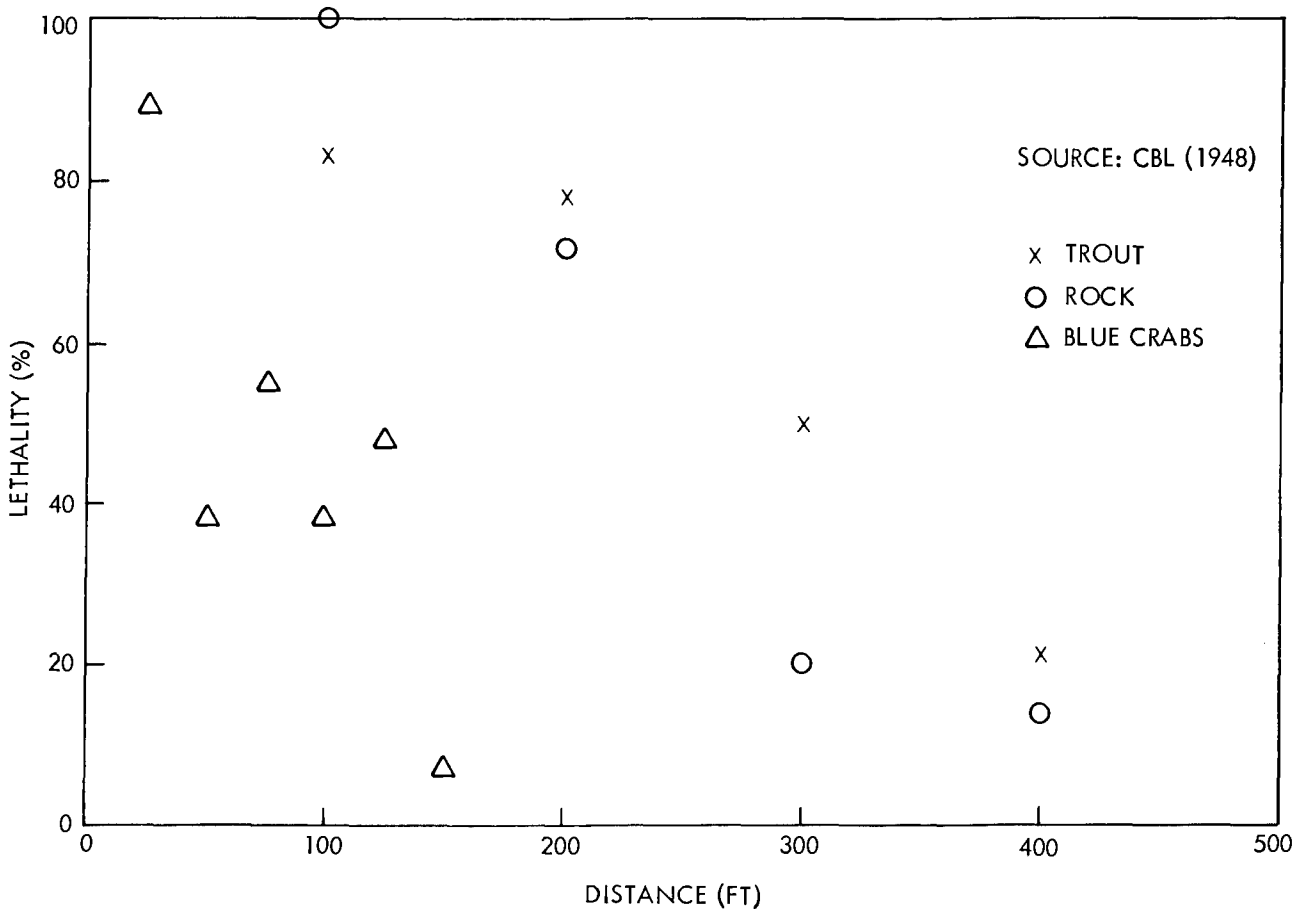


FIG. 2.20 LETHALITY DATA FOR MARINE LIFE FOR EXPLOSIVES WEIGHING 28 TO 32 POUNDS

The various contradictions in the data, plus experimental evidence and improved understanding of physiological processes lend support to the hypothesis that fish lethality is actually related to the negative pressures occurring in the water after the direct wave has been reflected from the surface. These negative pressures are found in an extensive region where the water is cavitated and in a zone beneath this region. The lateral extent of the region may not vary appreciably when different weight charges are used (Gaspin and Price, 1972).

Close-in fish will doubtless be killed directly by the strong shock wave, but in a relatively small volume of water. These fish have been observed to sink, rather than float to the surface.

Until a satisfactory theory of fish lethality is developed, statistical data on the weight or numbers of fish killed in experimental programs can be used for estimating the possible effect of planned tests. Such data for a single test have little value, but in some cases the number of tests was large enough to provide reliable averages for certain locations or seasons.

For example, Aplin (1947) reported observations of the fish killed in a series of 46 shots fired off the Southern California Coast in the Santa Barbara-Ventura Area during geophysical survey programs in 1946. Fitch and Young (1948) also collected data on fish killed as a result of geophysical survey work in the same general area during 1947. They published data for a total of 1296 shots. In both cases, the average charge weights were well under 100 pounds. No efforts were made to minimize the number of fish killed.

Coker and Hollis published data from larger (250 to 1200 lb) charges in 1950. Their data were obtained from 21 HBX-1 explosion tests conducted in the Chesapeake Bay during the summer of 1948. Most of the charges were fired near mid-depth in 150 feet of water. In this series, also, no effort was made to avoid fish-kill. In addition, statistical data are available on a continuous basis from 1958 for underwater explosion test programs conducted in the Chesapeake Bay and Patuxent River near Solomons, Maryland with techniques developed to keep fish-kill at a minimum level (see Section 5.1).

Most of the published values are in pounds of fish, rather than number, and this value is probably more meaningful in regard to market value. When the pounds of fish killed are reduced in terms of the weight of explosive, the ratios are fairly consistent. The data are presented in this form in Figure 2.21.

Because of the many variables involved, Figure 2.21 can be used only as a rough guide to possible fish mortality. However, it does show that fish-kill can be reduced in controlled programs. It is probably reasonable to assume that the average fish-kill can be held well below one-half pound per pound of explosive when precautions are taken (see Sections 5.1 and 6.2.1). This result would not apply to a single explosion, but to a series of tests in regions where the fish population is similar to that in the Chesapeake Bay.

Investigators of fish-kill have consistently reported that fish return to an area after explosions have occurred, i.e., there is no irreversible effect on fish population. In confined regions, such as submarine canyons, repopulation may require a few months after a period of testing (Hubbs and Rechnitzer, 1952).

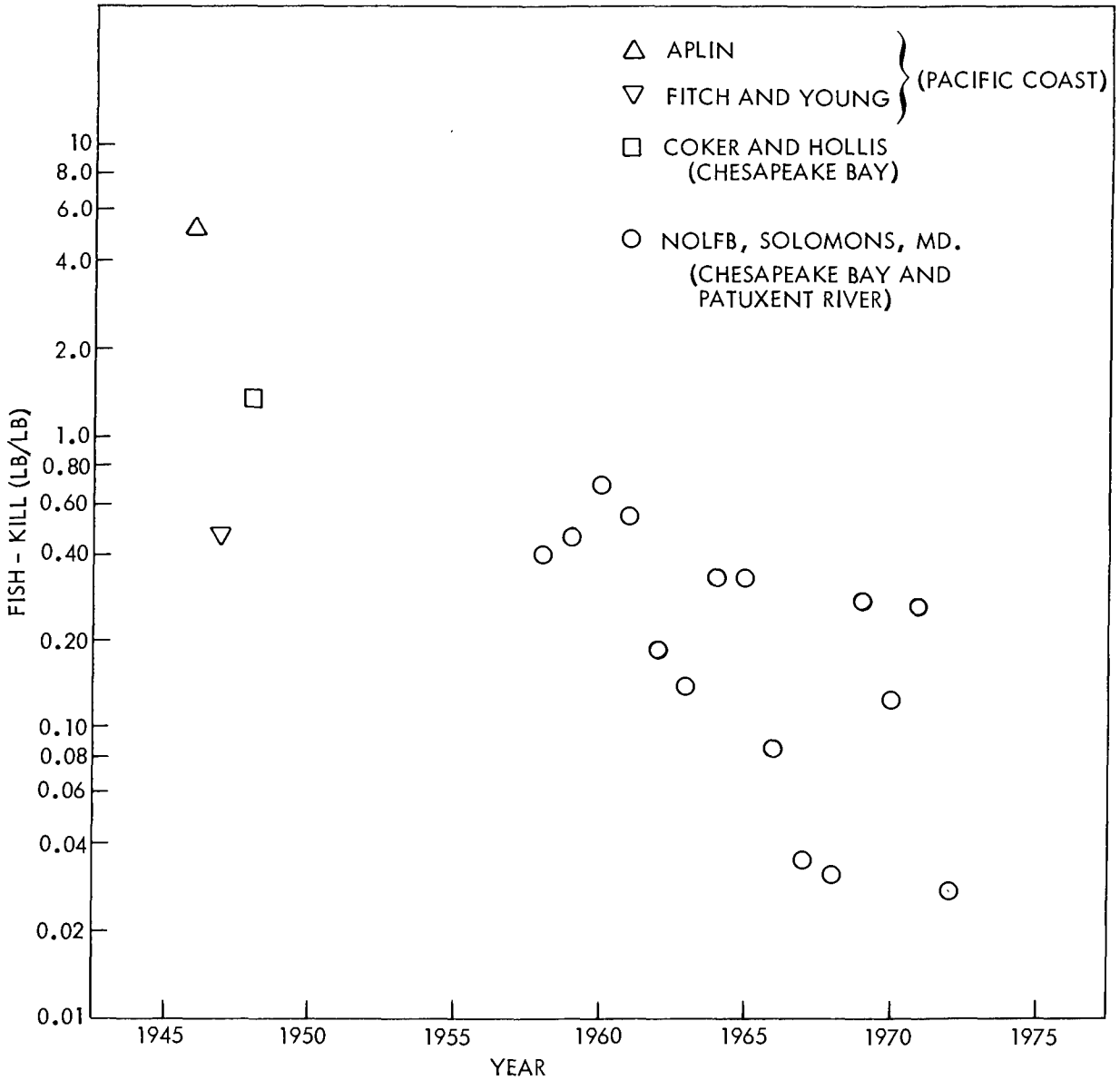


FIG. 2.21 STATISTICAL DATA ON FISH MORTALITY IN UNDERWATER EXPLOSION TESTS

2.4.2 Season

The seasonal trends in the availability of fish in the oceans and inland waters are well known to commercial fishermen and to sportsmen. These variations are probably more pronounced in inland waters than in the open sea. For example, the seasonal effects in the Chesapeake Bay and its tributaries are used as a guide for the scheduling of explosion tests (Section 5.1).

The most important fish in the Bay is the striped bass, which winters in water deeper than 40 feet because the cold waters retain a high oxygen content. Explosion tests are not conducted in the deep waters during the winter months for this reason, but tests in the same locations during the summer have a negligible effect on marketable fish.

Another seasonal influence to be considered is the local tourist season. For example, the busy season in the Florida Panhandle is during the summer months, while the main influx of tourists in south Florida occurs during the winter. The scheduling of tests during these periods is to be avoided, both from the point of view of safety and because of the possible objections of local Chambers of Commerce (see Section 5.5).

As it is beyond the scope of this report to cover all seasonal effects on fisheries, these should be investigated locally prior to the planning of tests.

2.4.3 Location and Depth of Burst

Most of the known commercial fishing grounds of the world are on the continental shelves and the banks of the oceans, generally in water less than 200 meters deep. The distribution of fish in other parts of the oceans is not well known, and the depths at which fish are found vary with the time of day and with other factors. For example, Backus, et al (1970), reported the results of about 290 midwater trawl hauls made to a depth of 1,000 meters in the equatorial and western North Atlantic Ocean from 1961 to 1968. The number of fish collected per hour in night-time collections in the North Atlantic Ocean showed maxima between depths of about 50 and 100 meters.

However, daytime hauls shallower than 200 meters caught little or nothing, partly because most mesopelagic species lie at greater depths by day. Many species migrate at sunset to depths shallower than 300 meters.

The possibility exists, then, that relatively deep explosions at sea could kill relatively large numbers of fish if measures are not taken to prevent this.

2.4.4 Bottom Explosions

There are probably benthic animals at all depths in the oceans, although the number decreases with increasing depth and is small at depths in excess of 2,000 meters (Wigley and Emery, 1967). The commercially important life, such as lobsters, crabs, oysters, and clams, is most prevalent in depths less than about 200 feet. Most of these are highly resistant to shock. For example, Aplin (1947) reported that lobsters showed no signs of injury from 20-lb charges fired at 50- and 55-foot distances.

In studies reported by the Chesapeake Biological Laboratory (1948), only 2% of oysters were killed at once and 5% died of injuries within 100 feet of 30-lb TNT charges and 200 feet of 300-lb TNT charges.

These results are mainly empirical, and no theory has been developed to provide a better understanding. However, it is evident that these benthic organisms are much more resistant to shock than fish with swim bladders. An additional contributing factor in some cases is the rapid attenuation of the underwater shock wave in shallow water and the even faster attenuation along the seabed.

2.5 SEA MAMMALS

Current information concerning the possible effects of explosions on sea mammals is extremely limited; however, the probability of killing a sea mammal in a test program is slight. The danger exists mainly on the Pacific coast, from California to Alaska. Operation Wigwam, for example, was conducted in a relatively barren area about 600 miles off the California coast, and there was some concern about the possibility of a whale encountering the submerged cables. There seems to be no doubt that the public concern over the inadvertent killing of a mammal would be greater than that usually expressed over fish-kills. This is evidenced by legislation to protect porpoises, seals, whales, and sea otters.

The possible effects of the Cannikin Underground Nuclear Detonation on all sea life, including sea otters, harbor seals, and sea lions were estimated prior to the test by Kirkwood and Fuller (1971). In their report, it was estimated that an overpressure of 100 psi or more could possibly rupture the eardrums of sea otters, leading to eventual death. In the case of a TNT explosion in free water, the range at which the 100 psi pressure contour is found is given by the following equation:

$$R_{100} = 116\ W^{1/3} \quad , \qquad (2.18)$$

where:

R_{100} = range of 100 psi overpressure level in free water, ft.

Kirkwood and Fuller made the following statement in regard to larger mammals: "It should be noted that studies on the relationship between body size (weight) and the response of an animal to atmospheric overpressure pulses suggest that as body size increases the tolerance to pressure pulses increases. Thus, animals such as harbor seals and sea lions, which are several times as large as sea otters, should be relatively less vulnerable to underwater overpressure pulses."

III

ADMINISTRATIVE REQUIREMENTS

3.1 REGULATIONS

3.1.1 Federal

Basic Federal laws, documents, and regulations pertaining to environmental effects in general include the following:

A. Public Law 91-190, "National Environmental Policy Act of 1969," January 1, 1970.

Section 102 (2) (C) requires that a detailed environmental statement be included in "every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment."

B. Executive Order 11507, "Prevention, Control, and Abatement of Air and Water Pollution at Federal Facilities," February 5, 1970, (35 Fed Reg 25, 2573 (1970)).

C. Executive Order 11514, "Protection and Enhancement of Environmental Quality," March 7, 1970 (35 Fed Reg 46, 4247 (1970)).

D. Public Law 91-604, "Clean Air Amendments of 1970," December 31, 1970.

E. Executive Office of the President, Council on Environmental Quality, "Statements on Major Federal Actions Affecting the Environment," April 23, 1971 (36 Fed Reg 79, 7724 (1971)).

Contains guidelines for implementation of P.L. 91-190, i.e., the preparation of environmental statements. These include general guidance for determining when an environmental statement is required.

The Council on Environmental Quality (CEQ) was established to recommend a broad-ranging Federal program against pollution. Their findings are being published in a series of reports, e.g., "Ocean Dumping" and "Toxic Substances."

The Environmental Protection Agency (EPA) is an independent agency with five areas of responsibility: air pollution, water pollution, radiation health and safety, research on solid waste disposal, and control of dangerous toxicants in the environment. The EPA is basically an enforcement agency, but it also is responsible for setting standards, for anti-pollution planning, and for research and monitoring programs.

3.1.2 Department of Defense

Department of Defense Environmental Quality Policy encompasses many topics that are not related to explosion testing. Therefore, only documented items that are relevant in some manner to explosions will be included in this section and the remainder of this chapter. The emphasis will be on underwater tests; however, some aspects of land testing are also of interest.

It is the policy of the DOD that (OSD (H & E), 1972):

"Maximum effort will be made to incorporate environmental pollution preventive measures in the basic design for weapon systems, military materiel, and tests and exercises."

"Department of Defense components will cooperate fully with the Environmental Protection Agency and other Federal agencies, and will comply with such published standards and criteria relating to pollution abatement for Federal agencies as are promulgated by those agencies or by State and local agencies."

Department of Defense Directive Number 6050.1 of 9 August, 1971, establishes the DOD Environmental Policy in detail, stating initially that:

"At the earliest practicable stage in the planning process and in all instances prior to decision, the environmental consequences of any proposed action shall be assessed."

"Whenever an environmental assessment ... indicates ... that the resulting action may significantly affect the quality of the human environment or may be highly controversial with regard to environmental impact, a detailed environmental statement shall be prepared..."

As stated in Attachment 1 to Enclosure 1 of DOD Directive 6050.1, it is impossible to list all activities that would have a significant effect on the quality of the human environment; however, in a particular assessment, all environmental effects must be considered, whether those effects are adverse or beneficial. Examples of factors to be considered, as published in this document, are:

A. Effect on water.

Will the action:

(1) Introduce toxic or hazardous substances or significant amounts of chemicals, organic substances or solid wastes into bodies of water,

(2) Significantly increase sedimentation in a body of water, or

(3) Significantly alter the temperature of a body of water?

Will the action improve the quality of a body of water?

B. Effect on atmosphere.

Will the action result in emissions into the atmosphere of toxic or hazardous substances or significant amounts of other pollutants?

Will the action result in the creation of excessive noise, considering the proximity of and the likely effects of the noise on humans or wildlife?

Will the action tend to reduce the amount of pollution in the atmosphere?

C. Effect on natural resources.

Will the action result in significant destruction of vegetation, wildlife, or marine life?

Will the action enhance the quality of vegetation, wildlife, or marine life?

Will the action significantly affect soil quality?

Will the action result in contamination or deterioration of food or food sources?

D. Other values.

Will the action significantly affect, beneficially or adversely, the health or welfare of man, including aesthetic considerations?

Will the action significantly affect, beneficially or adversely, other forms of life or ecosystems of which they are a part?

These factors all require consideration in the planning of underwater explosion tests, although the response to these questions will be largely negative.

3.1.3 Navy

Figure 3.1 is an abbreviated chart showing the Navy Environmental Protection Organization. A Deputy Under Secretary of the Navy for environmental matters has been established in the Office of the Secretary of the Navy to coordinate Navy and Marine Corps Programs. The Deputy Chief of Naval Operations (Logistics) has the principal responsibility for directing, coordinating, and monitoring the results of this program within the Navy. He also provides the Navy focal point for review of environmental impact statements. He maintains cognizance and purview over the issuance of authorizations and potential environmental effects of all target ship sinkings and deep water dumping operations.

The Chief of Naval Material also has broad responsibilities, including the following, as stated in OPNAVINST 6240.3B of 11 April 1972:

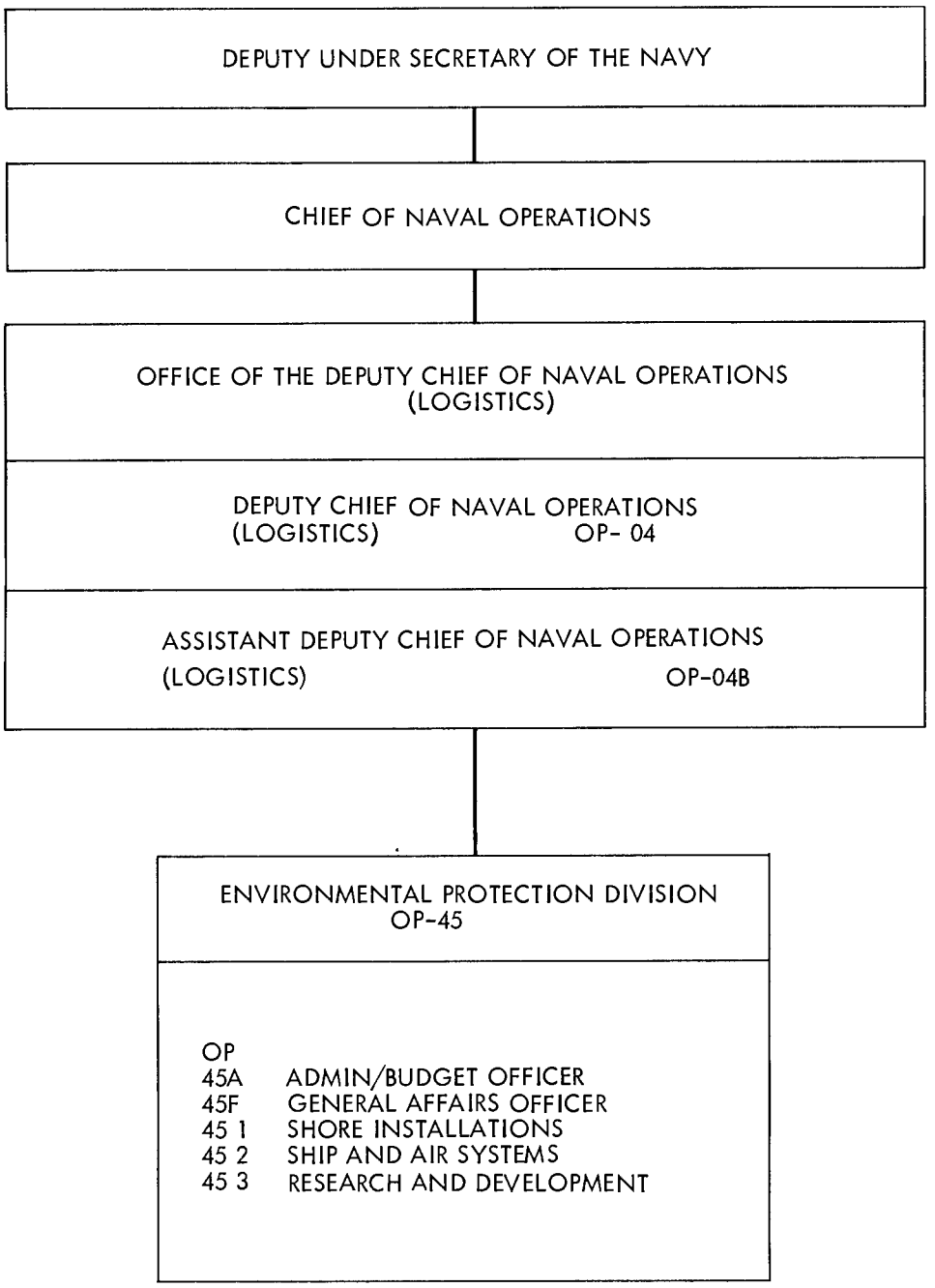


FIG. 3.1 NAVY ENVIRONMENTIAL PROTECTION ORGANIZATION

A. Identify and evaluate on a continuing basis activities and conditions affecting environmental quality, including but not limited to air and water pollution, solid waste management and disposal practices, noise, sources of thermal energy, ionizing and non-ionizing radiation, chemical agents, and biological research materials.

B. Perform research to define and study environmental pollution problems associated with the fulfillment of Naval requirements, including those requirements associated with weapons systems, assuring that consideration is given to the control of environmental pollution through research, development, test and evaluation projects and programs, and the coordination of such research actions with other Navy commands, other Department of Defense components and Federal agencies.

OPNAV INSTRUCTION 6240.2A of 11 December 1970 reiterated the DOD policy requiring the assessment of the probable ecological and environmental consequences of an action at its inception. The list of the types of actions to be assessed included programs for weapons testing and programs for the large scale disposal of conventional ammunition. A five-point environmental impact statement (see Section 3.3) is required if the assessment indicates a significant adverse environmental effect or if the proposed action is likely to controversial. The decision to prepare a statement evidently rests with the originator, however, CNO (OP-45) will assist in the resolution of doubtful cases.

The following procedures for processing environmental impact statements have been extracted from OPNAVINST 6240.2A. (Procedures in regard to legislative proposals and real estate acquisition are not included because of their lack of relevance.)

a. The cognizant Office, Command, or Activity prepares a draft environmental statement and submits six copies to CNO* via the chain of command.

b. CNO coordinates the draft statement with other appropriate Navy components and advises originator of concurrence or non-concurrence.

c. If concurrence applies, CNO submits copies of the statement to OASD (H & E)**.

d. If CNO does not concur with the statement, the draft together with the recommended changes, will be returned to originator.

e. The OASD (H & E), after review and coordination of the statement with other DOD components, advises CNO of concurrence, or recommends changes.

f. Following receipt of OASD (H & E) concurrence or recommendations for revision, CNO directs the originator to resubmit 13 copies of the draft or revised draft statement to CNO. To expedite, the originator, unless otherwise directed, may forward copies directly to CNO with copies to the chain of command.

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* OP-45

** Office of the Assistant Secretary of Defense (Health and Environment)

g. Upon receipt of the draft statements by CNO, CNO submits 10 copies to the Council on Environmental Quality. CNO will concurrently request the originator to solicit the views of other federal agencies having jurisdiction by law or special expertise with any of the environmental problems associated with the proposed action, and to solicit comments from the state and local agencies when the environmental impact of the proposed action is pertinent to those agencies.

h. After review of the comments and views received from federal, state, and local agencies, the originator shall forward 10 copies of the final environmental statement, including 10 copies of all comments received during the review process, to CNO for review and forwarding to the Council on Environmental Quality, and concurrently one copy of same to OASD (H & E).

It is important that draft environmental statements be prepared and circulated for comment and furnished to the CEQ early enough in the review process before an action is taken in order to permit meaningful consideration of the environmental issues involved. To the maximum extent practicable no adminstrative action shall be taken sooner than 90 days after a draft environmental statement has been circulated for comment and furnished to the CEQ, and, except where advance public disclosure will result in significantly increased costs of procurement, made available to the public. Neither shall such administrative action be taken sooner than 30 days after the final text of the environmental statement (together with comments) has been made available to the CEQ and the public. Consequently, the minimum waiting period after submission of the draft statement is 90 days because the 30-day period and 90-day period may run concurrently to the extent that they overlap.

It is interesting to note that Admiral Zumwalt, Chief of Naval Operations, issued Z-gram 114 on 6 July, 1972 to launch a test program of "Ecology Spotreps" (Spot Reports) by Navy ships and aircraft to report environmental hazards found at sea. The reports are designed to provide effective data on such environmental blights as oil spills, air pollution, accumulations of debris and fish kills, and includes observation in all areas on, above, and under the seas. This new Spotrep Test Program considers the collection of specific data on polluting effects in the world's oceans as an essential first step in eventual worldwide control of environmental hazards to the seas.

3.1.4 State

The legal aspects of underwater explosion testing in the Maryland portion of Chesapeake Bay have been well documented. A memorandum prepared by the Office of the Judge Advocate General to state the Navy's legal position in Maryland waters is reproduced in entirety as Appendix A. Certain items, which are believed to have validity in all states, have been extracted and condensed here.

In brief, constitutional authority for ordnance testing involving underwater explosions exists by virtue of the war powers of the United States. The right and power of regulation and control of navigable waters for purposes of national defense exists in peacetime as well as in time of war, for the power to wage war embraces the power to prepare for it. Tests and training involving underwater explosions are directly related to preparing for the defense of the nation.

The State of Maryland has a statute that prohibits placing, throwing, or using explosives in Maryland waters except for bona fide engineering, milling, or mining purposes. This does not bar the Navy from conducting explosive tests because the United States is not subject to the police power of the states. However, the authority of the Navy to conduct underwater tests is limited by the United States Code in that the tests shall not interfere unreasonably with the food fishing industry. If such interference occurs, the United States is subject to liability for resulting damage.

In addition, the State has legal means of halting explosion testing because, prior to the commencement of the tests, a permit must be obtained from the Army Corps of Engineers. If the State can show that the Navy is violating a state law, or is interfering with the food fishing industry, it can move to block the issuance of a permit or have a permit revoked. The Corps must therefore review all requests with this in mind and must consult the concerned agencies before issuing a permit.

3.2 DUMPING

3.2.1 Targets and Debris

There are at least two opposing points of view in regard to the desirability of dumping solid waste materials at sea. Sport fishermen, in general, are in favor of certain types of dumping for the creation of artificial fishing reefs, while many environmentalists oppose ocean dumping of all kinds.

The construction of fishing reefs has become an accepted practice on the Atlantic coast and in the Gulf of Mexico, and research in this field is being supported by the National Oceanic and Atmospheric Administration (Stone, 1971). The reason for this effort is that most of the continental shelf is relatively smooth and sandy and is lacking in natural reefs and rock outcrops that could provide a habitat for encrusting organisms such as barnacles, hydroids, corals, and mussels, and also become protective areas, food sources, or spawning grounds for fish.

Artificial reefs can, in some cases, be more effective than natural reefs in attracting fish. Sunken ships are known to serve as artificial reefs, but materials such as concrete blocks, building rubble, automobile bodies, and scrap tires have been used successfully (Stone, 1971). The materials must, of course, be non-toxic solid wastes.

In some cases, obsolete ships may be deliberately sunk for this purpose (e.g., Ocean Industry, 1968; Burchard, 1972), and during 1972, target vessels employed in a Navy damage study were purposely sunk at a location near Key West, Florida, where a fishing reef was desired (see Section 5.2).

At the present time, it is assumed that this approach increases the fish population and is non-polluting. To investigate this further, the Naval Undersea Center has used the CURV to photograph two submarines sunk in 150 and 1,488 feet of water to check for possible changes in the biota (Cooke and Hoyt, 1971). It was found that the submarine at a depth of 150 feet gave every evidence of producing an artificial reef while the deeper submarine showed no evidence of colonization by sea life. Very slow changes are anticipated at this depth.

It is likely that an accidental sinking could cause considerable local pollution as a result of leakage of oil or other substances. However, a ship that is deliberately sunk should be cleaned of pollutants in advance. The water depth should be sufficient to preclude any hazard to navigation.

It is not advisable to dump garbage and other trash at sea when vessels are anchored, even though they may be several miles from land, as the debris from a stationary ship may remain in the vicinity or be carried to shore by the currents. In this regard, OPNAVINST 6240.3B states: "Garbage shall not be thrown overboard within the contiguous zone which is 12 miles from the coastline. All trash and rubbish disposed at sea should be packaged to have negative buoyancy."

It should be pointed out, however, that the latter is not necessarily the most desirable procedure. For example, when ordinary garbage is dumped from a moving vessel, a rapid dispersion occurs in the wake, and the garbage may serve as food for sea animals. In any event, it is biodegradable. On the other hand, packaged waste, if in plastic or metal containers, may persist for centuries.

It is of interest to point out here that the Department of the Navy prepared a Final Environmental Impact Statement on the Use of Target-Ship Hulls in Exercises at Sea in August 1971. The Statement is concerned with the use of ships as targets for conventional air-to-surface and surface-to-surface weapons during fleet exercises for the purposes of combat readiness training and weapons evaluation. Of necessity, these exercises are conducted at locations in excess of 50 nautical miles from any coast line and clear of all shipping lanes. The ships are sunk in water with a depth of at least 6,000 feet.

It was concluded that damage to marine life is minimal, but that contamination from petroleum products in the hulls could be a problem. However, the target ship tanks and lines are flushed with water, leaving a possible residue of four to five hundred gallons, at a cost between $1500 and $2000. Removal of the remainder would cost about $22,000 and require about three weeks of additional preparation. The latter was not recommended, as it was felt that the few hundred gallons of residual fuel would be released slowly and would not constitute an adverse environmental effect on a long term basis.

The basic argument against the deliberate sinking of ships in deep water is that any part of the ocean floor is susceptible to eventual exploitation when the technology reaches the requisite state of development. The ships could then be a nuisance and a possible hazard. However, if deep parts of the ocean with limited marine resources are utilized, this possibility is minimized. An example is the use of the Blake Basin Disposal Site, where the water depth exceeds 16,000 feet, as an explosives dumping area (NAVRECONTECHSUPPCEN, 1971).

The report on Ocean Dumping prepared by the Council on Environmental Quality (CEQ) in 1970 states that: "Current regulatory activities and authorities are not adequate to handle the problem of ocean dumping." The report makes the following recommendations with direct or indirect application to explosive testing at sea or in estuaries:

> High priority should be given to protecting those portions of the marine environment which are biologically most active, namely the estuaries and the shallow, nearshore areas in which many marine organisms breed or spawn.

Ocean dumping of existing sources of solid waste should be stopped as soon as possible.

Ocean disposal of explosive munitions should be terminated as soon as possible.

Use of waste materials to rehabilitate or enhance the marine environment, as opposed to activities primarily aimed at waste disposal, should be conducted under controlled conditions.

The last statement has relevance to the use of target vessels and other materials to create fishing reefs. The report of the CEQ also contains the following remarks, which tend to support this practice: "Construction and demolition debris, less than one percent of all wastes dumped in the ocean, are composed mainly of dense and inert materials. Because of the small amounts dumped and their character, these wastes are not a threat to the marine environment."

3.2.2 Oil

The Navy is particularly concerned with pollution of the sea and inland waters by the accidental or deliberate spilling of oil products (OPNAVINST 6240.3B). Even a relatively small discharge of oil can have serious effects on marine life and waterfowl, can contaminate beaches, and can cause risk of fire. This is relevant to experimental vessels at a test site and to the possible leakage of oil from a target vessel, either afloat or submerged.

The current presidential goal is to terminate all intentional discharges of oil and oily wastes into the oceans by 1975 if possible. Facilities aboard ships to hold oily wastes and sludges will be matched by facilities ashore to receive, process, and dispose of such wastes. At present, it is the policy of the United States that there should be no discharges of oil into or upon the navigable waters of the United States, adjoining shorelines, or into or upon the waters of the contiguous zone. The discharge of oil in harmful quantities in these waters is prohibited.

A National Contingency Plan has been prepared by the Council on Environmental Quality for coordinating the response to a spill of oil or other hazardous material. In the case of an accidental oil spill during a Navy explosion test program, an On-Scene Commander would be designated to take charge of oil containment and countermeasures, cleanup and disposal of the pollutants, and the restoration of the environment to its previous condition. The latter is relevant mainly to the contamination of a beach or shore-line.

3.2.3 Explosives

Millions of tons of unexploded ordnance have accumulated on the seabed during the past 100 years (Busby, et al, 1968). Most of the weapons dropped during wartime combat operations are in relatively shallow water, but obsolete ordnance that has been deliberately dumped at sea is usually in water at least 6,000 feet deep.

The CHASE program consisted of at least 16 shiploads of obsolete and unserviceable munitions that were sunk at disposal sites in the Atlantic and Pacific. Of these, 12 exploded, either deliberately or accidentally, while sinking; and the remainder went to the bottom intact. At the present time, all deep water dumping of obsolete munitions has been suspended pending a study of all alternative methods of disposal, particularly methods that will have a minimal impact on the environment.

However, if explosive dumping takes place at sea, detonation is preferable to sinking, because a controlled explosion is not hazardous to human life, while a sunken ship loaded with explosives is a hazard for an indefinite period of time. In addition, a depth of explosion can be selected that will minimize undesirable environmental effects.

The fragments and debris from five exploded CHASE ships covered areas of the seabed averaging about 500 meters in diameter (Spiess and Sanders, 1971). Photographs showed many benthic organisms in the debris fields, with no evidence of irreversible damage.

3.3 ENVIRONMENTAL IMPACT STATEMENT

An environmental impact statement should include a description of the proposed action and tell why it must be accomplished. In addition, a detailed schedule is needed. The following five essential items belong in the body of the statement, as set forth in OPNAV INSTRUCTION 6240.2A of 11 December 1970:

a. Predictions of the probable total impact of the proposed action on the environment. This shall include commentary of the direct impact on some part of the environment such as the clearing of the forests or the pollution of air or water resources, as well as the more threatening danger associated with changes in existing eco-systems. Indirect or secondary significant consequences for the environment should be included for the analysis. Likewise, any benefits to the environment resulting from the proposed action shall be mentioned.

b. A statement of any adverse environmental effects which cannot be avoided should the proposal be implemented. This would include an evaluation of the extent to which aesthetically or culturally valuable surroundings, human health, high standards of living, and other of life's amenities would be sacrificed.

c. A list of carefully developed alternatives to the proposed action that might avoid some or all of the adverse environmental effects. Include with these alternatives economic, technical, and operational considerations, as well as their environmental impact.

d. A detailed description of the relationship between local short-term uses of the environment and the maintenance and enhancement of long-term productivity. For this exposition, assessment of the action's cumulative and long-term effects is required. Short-term uses are to be construed as those not affecting succeeding generations.

e. An inventory of all irreversible and irretrievable commitments of natural resources which would be involved if the proposed action should be implemented. This section should identify the extent to which the action curtails beneficial uses of the environment.

Environmental impact statements should be comprehensive and precise, and should contain thorough documentation when this is available. As the statements must be made available to the public when possible, it should be assumed that they will receive careful scrutiny. In addition, environmental action groups, special interest associations, governmental agencies, and Congressional Committees may be expected to use the environmental impact statements as a source of information.

The environmental statement should be accompanied by a summary sheet that must provide the following information:

A. Indicate whether the statement is draft or final.

B. Give the name of the action and indicate whether it is an administrative or legislative action.

C. Provide a brief description of the action and indicate what geographical region (States and counties) is particularly affected.

D. Summarize the environmental impact and adverse environmental effects.

E. List alternatives considered.

F. (For draft statements) List all Federal, State, and local agencies from which comments have been requested.

G. (For final statements) List all Federal, State, and local agencies and other sources from which written comments have been received.

H. Provide the dates the draft statement and final statement were made available to the CEQ and the public.

IV

EXPERIMENTAL MEASUREMENTS

4.1 MONITORING A TEST

4.1.1 Fish Counts

Although it has become a standard Navy procedure to take all feasible measures to prevent the killing of fish in underwater explosion testing, this is sometimes unavoidable and dead fish are observed at the surface. In some cases, the number and species of fish killed are estimated visually. However, a preferable method is to net the dead fish and remove them from the site to avoid the possibility of the carcasses drifting to shore. The dead fish should be sorted and counted or weighed.

As game fish killed by an explosion remain edible, they can be cooked and eaten. On the other hand, if large numbers of trash fish are killed, they may be ground up for use as bait or dropped back in the sea as food for other species. In terms of ecology, the latter is probably the best procedure.

Fish counts of this nature should not be expected to provide biological effects information, though a visual estimate of the lethal range can be made. The actual location and number of fish killed will depend on the pre-shot fish distribution, which will doubtless not be uniform.

4.1.2 Water Sampling

Various techniques have been developed by oceanographers for sampling the waters of the seas at various depths. These include, for example, the Nansen bottle, the Niskin bottle, and the Van Dorn Sampler. However, sampling of the sub-surface water affected by an explosion would require accurate placement and control of sampling devices and would also involve an appreciable number of stations to insure success. Even so, it would be necessary to employ a sensitive tracer to provide assurance that a sample was, in reality, affected by the explosion.

For monitoring purposes, the simplest and least expensive technique is to use a fluorescent dye tracer and then sample the surface pool by traversing it with a small boat. A container of fluorescein dye, mixed with water, can be attached to the supporting cable directly above the charge. A ratio of one lb of dye to 100 lb of explosive should provide visibility for at least one-half hour. The sampling containers can be one-liter plastic bottles, providing that the bottles can be sealed tightly, preferably with O-rings. The times and locations of sampling should be recorded for a total time of one-half hour.

Water samples can be analyzed for virtually any constituent by currently available techniques, such as the use of a mass spectrometer. The data can be extrapolated by diffusion theory, such as described in Section 2.3.3.2, to estimate concentrations at late times. An alternate approach is to measure the concentration of dye with a fluorometer, either in situ or in sampling bottles, as the concentration of dye is proportional to the concentration of explosion products. However, this method is less precise than the direct measurement of explosion products.

Dye concentration can also be determined from an aerial photographic negative with a photodensitometer (Ichiye and Plutchak, 1966). This method has the advantage of providing data for the entire surface pool at selected times.

As fluorescein dye is used as a distress signal by downed pilots, local Naval Air Stations should be notified in advance if it is to be used in an explosion test. It should be noted that the dye dissolves to a low concentration within minutes and that it is harmless to man and to sea life. Although it has the property of high visibility at low concentrations, it will not color a submerged object and leaves no mark.

Fluorescent dyes are used frequently by oceanographers for the study of diffusion processes and as tracers for sewage and other pollutants. They do not have the undesirable features of radioactive tracers, which have been used in the past, because extremely low concentrations of radioactive materials are detectable.

The dye most frequently used by oceanographers is rhodamine, a red fluorescent dye (e.g., Katz, et al, 1965). However, when this was used in underwater explosion tests, the dye remained visible for only a few minutes. This was possibly a result of a partial decomposition of the dye by the heat of explosion. Other dyes have also been tested, but none proved to be as satisfactory as fluorescein.

4.1.3 Temperature Measurement

As theory and experimental data both indicate clearly that temperature changes produced in water by explosions are entirely negligible after a few minutes have elapsed, there seems to be no justification for attempting to measure this effect for the purpose of monitoring a test. However, if a need does exist, two approaches are feasible. One is simply to traverse the pool (made visible by a fluorescein dye tracer) with a small boat, utilizing a thermistor at the end of a probe held at the bow. The thermistor should be at least one foot deep. A battery-powered chart recorder may be operated in the boat. An accurate, fast-responding system is needed, as temperature changes of only a few tenths of a degree should be anticipated.

An alternate approach is the use of infra-red equipment in a low-flying aircraft to scan the surface pool. Many such devices are available commercially, and this technique is now commonly employed in studies of thermal pollution and other environmental effects (e.g., Burnett and White, 1970).

4.2 ACQUISITION OF BASIC DATA

It must be recognized that efforts to monitor a Navy test, or to acquire environmental data from a series designed for a different purpose, will produce

only qualitative results. It would probably not be feasible to expend the effort to acquire extensive quantitative data as an adjunct to such tests. In some cases it would hamper and delay progress toward the primary objective; in others it would provide data that is unique because of the test configuration* and is therefore limited in its usefulness.

As a general rule, it is extremely difficult to collect accurate data on the environmental effects of underwater explosions. When done properly this entails the careful underwater placement of sensitive sensors and sampling devices in a three-dimensional array. The measured effects will be highly variable in space and time and will often be difficult to distinguish from natural events. The records will be difficult to interpret unless underwater photography and dye tracers are employed.

Underwater photography is not feasible unless relatively small explosive charges are used. In any case, above-surface photography is a primary source of data, and extensive coverage is essential. This must be handled in such a manner that accurate timing and length scale markers are recorded on the films.

The number of fish killed in most underwater tests is highly subject to chance and cannot be used for prediction purposes except on a statistical basis. Data useful for evaluating biological effects can only be acquired in controlled tests with fish placed in cages at selected positions and detailed pressure-time records obtained at the same locations. Other specimens should be placed in the same type of cages at the same depths for the same periods of time, as controls, to evaluate possible effects of confinement.

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* An example of this type might be an explosive charge fired a few feet from a very large target, possibly injecting gaseous products into the target.

V

CASE HISTORIES

5.1 NAVAL ORDNANCE LABORATORY FIELD BRANCH - SOLOMONS, MD.

Explosive tests of underwater ordnance have been conducted near Solomons, Md., since 1944 (Green and Davidson, 1969). These include tests with mines, torpedoes, depth charges, and other explosive actuated devices, as well as research on the phenomenology of new or special explosives. Four explosive firing sites are in use; three in the Patuxent River and one in the Chesapeake Bay. The locations of these are shown in Figure 5.1.

Procedures have been developed over a period of years to minimize the harmful effects of the explosions on fish and other marine life. These methods have been evolved in cooperation with the State of Maryland Department of Natural Resources and the Chesapeake Biological Laboratory at Solomons. The latter is a branch of the Natural Resources Institute of the University of Maryland. In brief, the procedures are the following:

A. Firing is not permitted during certain months and at certain depths where high concentrations of fish are expected. Oyster bars are avoided.

B. The State of Maryland (Department of Natural Resources) is notified by telephone and telegram prior to each test.

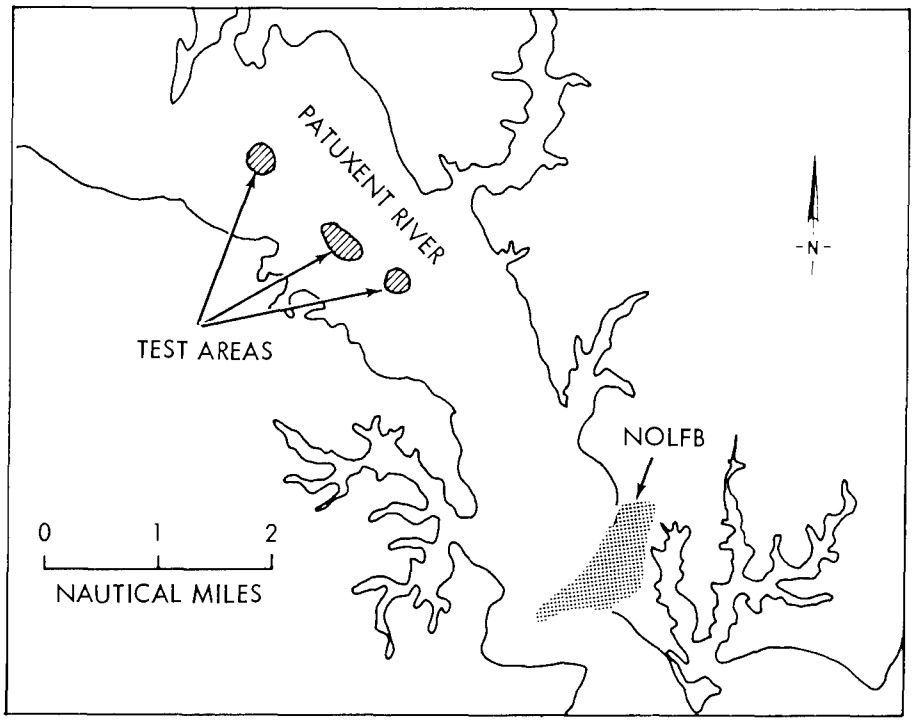
C. Observers from the State of Maryland are invited to all tests.

D. Fish-finders (special fathometers) are utilized to detect fish in the vicinity of the site. If appreciable numbers are observed, the test is delayed.

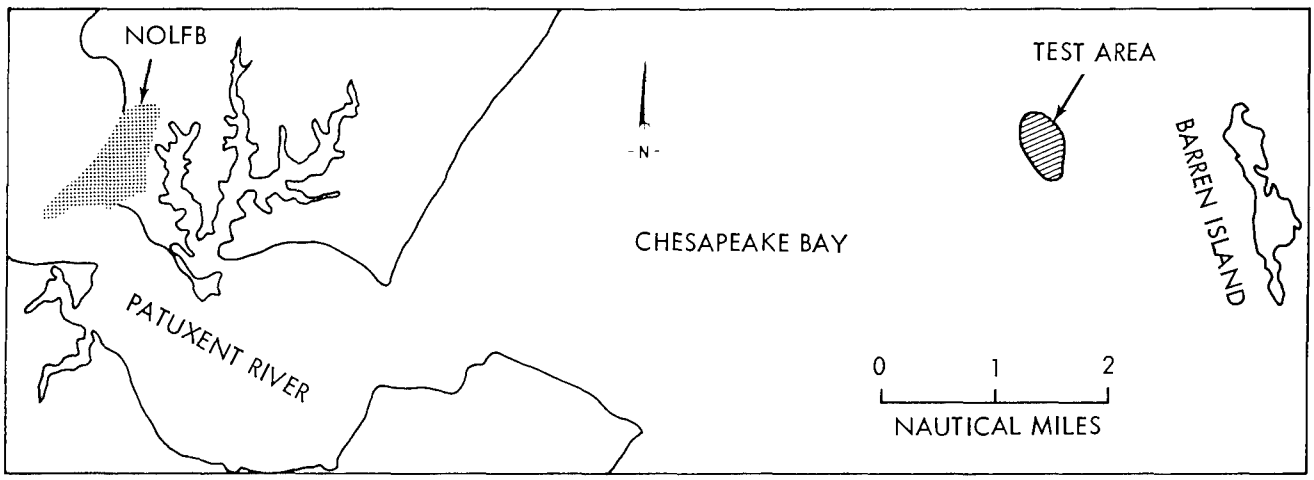
E. Dead fish are netted after each shot and estimates of the weight and species are made.

F. The dead fish are sometimes ground and are dropped as food for crabs or other fish.

The firing programs are geared to the ecology of the river and bay with a view toward the elimination of any harmful or irreversible effects. No firing is done in areas known to be favored habitats of fish. In general, firing is permitted in the Patuxent River during the entire year in water depths down to 40 feet. Firing is permitted at all depths from April through November. No firing is permitted at the Chesapeake Bay site during December, January, and February; and, in some years, during March. The reasons for these requirements are given in Table 5.1, as developed by the Chesapeake Biological Laboratory. In special circumstances the rules may be modified. For example, no firing was permitted in the Patuxent River during the latter part of 1972 because of the harmful effects of abnormally heavy rainfall on oyster production.



A. PATUXENT RIVER SITES



B. CHESAPEAKE BAY SITE

FIG. 5.1 EXPLOSIVE TEST AREAS USED BY NOLFB, SOLOMONS, MD.

TABLE 5.1

ESTIMATED EFFECTS OF UNDERWATER EXPLOSION TESTS ON MARINE LIFE IN THE PATUXENT RIVER AND CHESAPEAKE BAY

Degree of Damage to fish*	Types of Fish in Designated Areas	
	Chesapeake Bay Depths Greater than 40 feet	Tributary Rivers Depths Greater than 40 feet
1. Maximum probable damage December, January, February	Maximal concentration of striped bass occurs near the bottom in deep water. There is a high probability that large kills of striped bass will result. Some white perch and juveniles of other species will be killed.	Maximal concentration of white perch occurs near the bottom in deep water. There is a high probability that large kills of white perch will result. Some striped bass will be killed.
2. Heavy probable damage November and March	Since striped bass and large white perch are migrating into deep oxygen-rich water in late fall and early spring, large kills may result among striped bass; few white perch will be killed.	Some striped bass concentrate in deep water of lower estuaries and most white perch concentrate in the same areas. Large numbers of white perch and some striped bass will be killed.
3. Moderate probable damage April, May, September, October	Migratory fishes, including striped bass, shad, river herrings, white perch, etc., will appear in kills. Schooling surface fish may be killed.	Same as open Bay.
4. Least probable damage June, July, August	Since most fish do not frequent deep oxygen-poor waters, few marketable fish will be killed. Menhaden will be killed in large numbers. Schooling near-surface striped bass and other species may be killed at times.	Same as open Bay.

* Assuming no efforts are made to avoid fish-kill.

SOURCE: ltr from L. Eugene Cronin, Director of Maryland State Board of Natural Resources to Commander, NOL, 10 January 1957.

Statistical data on the weights of explosive fired and on the weight of fish killed are available on a regular basis from 1958. These values provide guidance concerning the average effects of an extensive controlled firing program. The data are summarized in Table 5.2.

It is interesting to note that personnel of the Chesapeake Biological Laboratory and the U. S. Fish and Wildlife Service observed the results of 21 HBX-1 explosion tests in the deep water firing site in the Bay during the summer of 1948 (Coker and Hollis, 1950). This was prior to the initiation of the measures taken to minimize the killing of fish in the Bay. The total number of fish killed was 32,658, with a total weight of 18,822 pounds. This resulted in an average of 1.36 pounds of fish per pound of explosive, a value much higher than recorded since 1958 (see Section 2.4.1).

It should be pointed out that the Patuxent River and Chesapeake Bay are utilized heavily by sports and commercial fishermen. They have been sources of complaints when an occasional heavy kill occurred. Complaints have also been received from residents on the river when dead fish drifted on shore. The latter situation is now prevented by the netting of dead fish after each test.

In regard to long range effects in the Patuxent River, the following statement was published by Tiller and Coker in 1955: "Examination of records of the commercial fishery of the Patuxent River for the period 1944-1953 show trends which follow generally the pattern of the Chesapeake Bay fishery. No decline has occurred which has not been evident in other areas supporting similar fisheries, and in which no explosive test programs have been conducted."

The available evidence, i.e., the statistical data and the results of a special study, indicate that the fish-kill by explosive testing in the Chesapeake Bay and the Patuxent River is negligible. In relative terms, the ratio of fish killed to the commercial catch is well below one percent.

In addition, it may be more significant that massive fish kills occur in the Chesapeake Bay estuary system as a result of natural causes and pollution. For example, 38 fish kills were recorded during 1971, including two herring mortalities on the Susquehanna River resulting from low water and a depletion of dissolved oxygen. The official estimate was over 1,250,000 fish (Holden, 1972). The total killed during the one year period was 16 million fish. The number of fish killed, even in extensive uncontrolled explosive test programs, is trivial compared to quantities of this magnitude.

However, when massive natural fish kills do occur in the vicinity of explosive test sites, it is essential that State authorities be notified promptly so that the cause can be determined. If this is not done, the possibility exists that uninformed observers will attribute the deaths to explosive testing.

5.2 CNO PROJECT D/S 580 - GULF OF MEXICO

CNO Project D/S 580 was a series of underwater explosion damage tests that are of special interest because the planned location was changed several times as a result of environmental considerations. The problem of major concern in this regard was the disposal of two target vessels, a destroyer and a cruiser.

TABLE 5.2

FISH MORTALITY DATA FROM NOLFB, SOLOMONS, MD

Year	Explosives Fired		Fish Killed			Average Mortality Relative to Explosions	
	Total Weight	No. of Shots	Edible	Non-Edible	Total		
	(lb)		(lb)	(lb)	(lb)	lb/shot	lb/lb
1958	19,000	44	613	7,107	7,720	175	.406
1959	9,000	70	247	4,003	4,250	60.7	.472
1960	22,000	65	807	14,553	15,360	236	.698
1961	12,000	195	312	6,218	6,520	33.4	.543
1962	14,000	45	561	2,069	2,630	58.4	.188
1963	13,000	42	291	1,529	1,820	43.3	.140
1964	16,000	82	290	5,070	5,360	65.4	.335
1965	36,000	272	640	11,470	12,110	44.5	.336
1966	34,000	53	556	2,304	2,860	54.0	.084
1967	35,000	178	275	995	1,230	6.91	.035
1968	42,000	209	1200	100	1,300	6.22	.031
1969	27,330	279	991	6,583	7,574	27.1	.277
1970	17,107	151	1036	1,064	2,100	13.9	.123
1971	5,928	143	575	1,001	1,576	11.0	.266
1972	18,505	70	170	337	507	7.24	.027

The test site selected in the early stages of planning was about 12 nautical miles southeast of Key West, Florida, and the tests were scheduled for January 1972. During July 1971, the planned location was changed to a position about 55 nautical miles west of Dry Tortugas as a result of a CNO stipulation that the target ship disposal be accomplished beyond 50 miles of the U. S. coast in water at least 6,000 feet deep. Although the water at the site was only a few hundred feet deep, the location was near the West Florida Escarpment and was within 14 nautical miles of a disposal area with a water depth in excess of 6,000 feet. The schedule was revised as a result of anticipated weather conditions in the new location. The CNO directive was evidently based on the policy established for the disposal of target ship hulls used in exercises at sea (Section 3.2.1).

However, during February 1972, the President of the Greater Key West Chamber of Commerce and the Mayor of Key West both recommended that the plan be modified and a new site be selected where the target ships could be sunk in relatively shallow water to provide artificial fishing reefs for the benefit of sport and commercial fishermen. On 28 March 1972, the Governor and Cabinet of the State of Florida, sitting as the Executive Board of the State Department of Natural Resources, passed a resolution formally requesting that the Navy sink the vessels at a site suitable for an artificial reef. These items are reproduced in Appendix B because of their general interest in regard to this concept.

An environment impact assessment was made by the Navy, showing that no adverse environmental effects were anticipated and that the reef would provide a haven for food and game fish where none existed. The net effect was therefore beneficial.

After considering other possible locations, it was decided to conduct the tests and scuttle the ships about 13 nautical miles east-southeast of Key West, off the American Shoals, at a position near the original site. The tests were conducted successfully and the target ships were sunk during May 1972. The locations were 24° 27.8' N and 81° 33.3' W for the destroyer and 24° 28.8' N and 81° 33.0' W for the cruiser.

The following agencies were apprised of the artificial reef proposal and no objections were made: The Department of Commerce, National Maritime Fisheries Service; The Department of Interior, Bureau of Sports, Fisheries and Wildlife; The Environmental Protection Agency; and the U. S. Army Corps of Engineers. A representative of the EPA inspected the two ships at the Key West Naval Station during April 1972 and determined that the cleanup procedures on the ships and tanks were reasonable and adequate. The U. S. Coast Guard had a patrol craft at the site each day an experiment was conducted in order to insure that vessels remained a safe distance from the targets and to monitor the effects the explosions had on the marine environment.

The damaged targets produced slicks that formed as a result of the bubbling of air to the surface. These bubbles transport fine particles and dissolved substances. However, no oil slicks were observed, and fish kill was observed on only one test, where about 50 red snappers were counted.

5.3 UNDERWATER EXPLOSIONS RESEARCH DIVISION, PORTSMOUTH, VIRGINIA

The Underwater Explosions Research Division (UERD) of the Naval Ship Research and Development Center is located at the Norfolk Naval Shipyard, Portsmouth, Virginia. The UERD conducts an average of 90 to 100 underwater explosion tests per year in the turning basin of the Shipyard, with 80 percent of the tests involving

charges weighing less than 20 pounds. The water is 40 feet deep and the charges are usually 24 feet deep. The authorized limit is 150 pounds.

As the site is near the shipyard, the Elizabeth River shipping channel, and a waterfront industrial area, there is no sport or commercial fishing and little aquatic life. Consequently, there is no concern about environmental effects on marine organisms.

The UERD also uses two test sites in the Chesapeake Bay; the deep channel utilized by NOLFB (see Section 5.1) and Old Plantation Flats, northwest of the town of Cape Charles, Virginia. The tests in the Bay usually involve large charges, with weights ranging up to 15,000 pounds. The average rate is less than one test program per year.

NSRDC informs local, state, and federal authorities of planned experiments in the Chesapeake Bay and invites them to attend or send a representative. The list of those notified includes (Nichols, 1970):

A. Senators (federal),
B. Applicable member of House of Representatives,
C. Regional Director, Bureau of Commercial Fisheries and Wildlife,
D. Director, Bureau of Commercial Fisheries,
E. Virginia Marine Resources Commission (Virginia waters only),
F. Virginia Institute of Marine Science (Virginia waters only),
G. Maryland Department of Chesapeake Bay Affairs (Maryland waters only),
H. Chesapeake Biological Laboratory (Maryland waters only), and
I. Maryland Marine Police (Maryland waters only).

Furthermore, the District Office of the U. S. Army Corps of Engineers and U. S. Coast Guard are notified, and the Coast Guard will subsequently issue a "Notice to Mariners" describing the experiments.

In general, the same procedures are followed as those employed by NOL, i.e., tests are not scheduled during the winter months, a fish finder is used to locate schools of fish in the firing area, the tests are delayed until the fish disperse, and dead fish are removed from the water. The test sites are far enough from shore to preclude effects on beaches or residential areas.

5.4 WEST COAST SHOCK FACILITY

The West Coast Shock Facility is located at the San Francisco Naval Shipyard at Hunter's Point. The underwater explosion tests conducted at this location are similar to those done at Norfolk Naval Shipyard and include charges weighing up to 60 pounds.

Tests are made against the Large Floating Shock Platform (LFSP) in a slip, and the policy is to sweep out the slip with nets before firing a charge. California State Fish and Game personnel are invited to witness all of the tests.

When operations are conducted off the end of the slip with 300-pound charges, sonar is used on a small boat to check for the presence of fish and the tests are delayed if schools of fish are present.

5.5 PANAMA CITY, FLORIDA

Various underwater explosion test programs have been conducted near the Naval Coastal Systems Laboratory at Panama City, Florida, in the waters of St. Andrew Bay and the Gulf of Mexico. The bottom of the Gulf is smooth and consists of hard sand, with a very gradual slope. The depth is 100 feet at a distance of about 12 nautical miles from shore. The water is clear enough for underwater photography.

As the tourist season extends from Memorial Day to Labor Day, explosive testing must usually be scheduled before or after these dates. During 1969, the Naval Ordnance Laboratory was permitted to fire in the Gulf during September and October after approval was given by the local Chamber of Commerce. However, it is now necessary for the Coastal Systems Laboratory to obtain clearance from the Florida Department of Natural Resources before scheduling a program.

The Waterways Experiment Station in Vicksburg, Mississippi, had planned an explosion test series in the Gulf during May 1971, but this was postponed for a review of possible environmental hazards. Permission was granted to conduct the tests during April 1972.

June is the best month for operations in the Gulf near Panama City. In the time period when explosion tests are permissible, May is probably the best month, followed by April, September, and October (Tolbert and Austin, 1959). This assessment is based on the number of days that small boats can operate, which is a result of a combination of meteorological and oceanographic factors.

5.6 MONO LAKE, CALIFORNIA

Mono Lake, California, has been used several times for multi-ton underwater explosion test programs because of its remote location, its accessibility, and the absence of fish and most wildlife. Because of the high salinity of the water, only brine shrimp can survive in the lake. These are seined, quick frozen, and marketed as fish food. In addition, there are several gull rookeries on the islands in the lake.

The most recent test program in Mono Lake was conducted by the Naval Ordnance Laboratory during 1969. Permission was granted by the California Fish and Game Commission on the condition that all possible care be taken to avoid disturbing the shrimp beds or the gull rookeries. In addition, a representative of the Commission was notified prior to each test so that he could witness each firing (Pittman, 1971).

During the test program, the rookeries were not affected, but large numbers of shrimp were killed. Complaints from the harvesters indicated that the quality of the product was degraded by large quantities of bottom scum and dead shrimp. However, ten days after the last shot, the harvesting company stated that the catch was back to normal except in the area where the firings had occurred. In this area, the shrimp concentration had increased. The explanation given was that the explosions had disturbed the bottom and sent large numbers of the eggs to the surface. The warmer water caused earlier hatching, thus increasing the concentration of shrimp.

This result, and the formation of artificial fishing reefs, provide examples of possible beneficial effects of explosion testing.

VI

RECOMMENDATIONS

6.1 PROPOSED CHECK LIST FOR AN ENVIRONMENTAL ASSESSMENT

The Geological Survey (Leopold, et al, 1971) has developed a matrix to be used as an aid in the preparation of Environmental Impact Statements. The matrix serves the purpose of insuring that all relevant items are considered and it also provides a means of evaluating the magnitude and importance of each proposed action.

As a less elaborate approach is adequate for underwater explosion testing, a simple check list has been prepared for the preparation of a complete Environmental Assessment or Impact Statement. The magnitude of most effects can be estimated from material in this report, but the importance of these will vary with the location of the site. However, it is expected that a site will be selected on the expectation of minimal environmental effects.

The following is the proposed Environmental Impact Check List.

ENVIRONMENTAL IMPACT CHECK LIST

A. Existing Characteristics of the Environment (Test Site)

Water - Salinity
Temperature
Currents
Sea State
Pollutants

Seabed - Depth
Composition
Slope

Atmosphere - Composition (Pollutants)
Wind Direction and Speed

Sea Life - Fish
Benthic Life
Sea Mammals
Plants

Recreational Activities - Boating
Fishing
Swimming
Beaches

Commercial Activities - Shipping
Fishing
Oil or Gas Wells

B. Effects on the Environment

Physical Effects (Magnitude and Duration)

Atmosphere - Noise
Smoke Cloud
Gases

Water - Heating
Solid Products
Gaseous Products

Beach - Deposit of Solid Products
Deposit of Bottom Material

Seabed - Cratering
Sediment Clouds
Turbidity Currents
Mud Slides

Biological Effects - Fish
Benthic Life
Sea Mammals
Plants

Dumping - Experimental Debris
Trash
Garbage
Targets
Explosives
Oil

C. Alternatives

Other Sites
Saline Lake
Quarry
Pond
Lake on Military Reservation
Beach on Military Reservation
Polluted Water
Tank

6.2 GENERAL COMMENTS

6.2.1 Recommended Research

Data are limited on all of the long-range environmental effects of underwater explosions, and such data should be acquired where possible. One feasible approach

is to sample the bottom and the water in locations where testing has continued over a period of years. These samples may be compared with samples acquired in similar nearby regions where no testing has occurred. The populations of marine organisms can also be compared in these areas. It would also be of interest to determine the geographic extent of the measurable effects of continued testing at a site.

Knowledge of the physical effects of bottom explosions is also relatively limited. This includes such effects as cratering in different soils in deep water, the displacement of bottom material, and the formation of sediment clouds and turbidity currents.

The highest priority, however, should be given to studies of the effects of explosions on marine life. This effort can be divided into two major problem areas; the biological effects on different species and methods of dispersing fish from an explosion test site.

The study of biological effects requires the placement of cages of various specimens of fish and benthic organisms at selected positions in the water and the recording of accurate shock wave pressure-time histories at each location. A sufficient number of specimens and tests is required to obtain meaningful statistical results. In addition, caged specimens should be placed in a natural environment as controls.

Even with an improved understanding of effects on biota, however, a requirement to minimize harm to marine life will always exist. It would therefore be highly desirable to develop a simple means of dispersing fish from an explosion test site prior to the firing of each shot.

The following methods have been suggested for attracting fish or driving them away; either approach is possible during a test program, but the use of certain dispersing equipment in the vicinity of the explosive or experimental gages may be unsafe or may interfere with the recording equipment.

Attraction

Radio Broadcasts (Wyatt, J. L., 1965)
Pulsed Electric Currents (Elliott, 1970; Crowther, 1969; Patten and Gillaspie, 1966)
Underwater Sound (Maniwa, 1970)
Underwater Structures (Roedel, 1971)
Lights (Roedel, 1971)

Dispersion or Barrier

Pulsed Electric Currents (Elliott, 1970; Crowther, 1969; Patten and Gillaspie, 1966)
Air Bubble Curtain (Kupfer and Gordon, 1966)
Radio Broadcasts (Washington Post, 1972)
Nets (Section 5.4)
Chemicals (Wisby, 1952)

6.2.2 Recommended Procedures for the Conduct of a Test

The following are recommended in addition to the normal administrative procedures required prior to the conduct of explosion tests at sea:

A. Select a site compatible with the objectives of the test, but where possible undesirable effects on the environment are minimized. Select a site remote from public view, if possible.

B. Estimate the magnitudes of all environmental effects. (Prepare an Environmental Assessment.)

C. Discuss the plans informally in advance with local Naval personnel, Chambers of Commerce, and State and local officials in order to establish good working relationships and to anticipate possible objections or complaints. It is seldom possible for an outsider to judge the reaction of local residents to a proposed test.

D. Invite State and local Fish and Game personnel to observe the tests and inspect the area before and after each explosion.

E. Utilize methods to detect and disperse fish at the test site, and postpone firing if schools of fish remain in the vicinity.

F. Scoop up all dead fish.

G. Dump no trash, garbage, or debris of any kind.

REFERENCES

Aplin, J. A., 1947: The Effect of Explosives on Marine Life, California Fish and Game, Vol. 33, No. 1, pp 23-27

Athearn, W. D., 1967: Estimation of Relative Grain Size from Sediment Clouds, pp 173-176, in Deep-Sea Photography, The Johns Hopkins Press, Baltimore

Backus, R. H., et al, 1970: The Distribution of Mesopelagic Fishes in the Equatorial and Western North Atlantic Ocean, Journal of Marine Research, Vol. 28, No. 2, pp 179-201

Blanchard, D. C., 1963: The Electrification of the Atmosphere by Particles from Bubbles in the Sea, Progress in Oceanography, Vol. I, pp 73-202, The MacMillan Co., New York

Blanchard, D. C., 1971: The Oceanic Production of Volatile Cloud Nuclei, Journal of the Atmospheric Sciences, Vol. 28, No. 5, pp 811-812

Braker, W. and Mossman, A. L., 1970: Effects of Exposure to Toxic Gases - First Aid and Medical Treatment, Matheson Gas Products, East Rutherford, New Jersey

Brode, H. L., 1959: Blast Wave from a Spherical Charge, The Physics of Fluids, Vol. 2, No. 2, pp 217-229

Burchard, H., 1972: Old Navy Boats Scuttled to Aid Marine Life, The Washington Post, April 24, p C1.

Burnett, E. S., and White, P. G., 1970: Water Pollution - The Role of Remote Sensing, Journal of Remote Sensing, Vol. 1, No. 3, pp 9-13

Busby, R. F., Hunt, L. M., and Rainnie, W. O., 1968: Hazards of the Deep, Part 2, Ocean Industry, Vol. 3, No. 8, pp 32-39

Chesapeake Biological Laboratory, 1948: Effects of Underwater Explosions on Oysters, Crabs, and Fish, CBL Publication No. 70, Solomons Island, Md.

Coker, C. M., and Hollis, E. H., 1950: Fish Mortality Caused by a Series of Heavy Explosions in Chesapeake Bay, Journal of Wildlife Management, Vol. 14, No. 4, pp 435-444

Cole, R. H., 1948: Underwater Explosions, Princeton University Press, Princeton, New Jersey

Cooke, T. S., and Hoyt, J. W., 1971: Ocean Pollution by Sunken Ships, NUC Symposium on Environmental Preservation, 20-21 May 1970, NUCTP 215, pp 119-123

Council on Environmental Quality, 1970: Ocean Dumping - A National Policy, U. S. Government Printing Office, Washington, D. C.

Crowther, H. E., 1969: Hardware Research - Key to Improved Fishing, Under Sea Technology, Vol. 10, No. 1, pp 54-55, 61

Csanady, G. T., 1972: The Coastal Boundary Layer in Lake Ontario. Part I: The Spring Regime, Journal of Physical Oceanography, Vol. 2, No. 1, pp 41-53

Czul, E. C., Carey, E. W., and Heemstra, F. W., 1971: Second Post - Dump Survey of the CHASE X Disposal Site, NRL Memorandum Report 2319, Naval Research Laboratory

Davies, J. T., 1963: Mass-Transfer and Interfacial Phenomena, Advances in Chemical Engineering, Vol. 4, pp 1-50, Academic Press, New York

Dill, R. F., 1966: The Effects of Explosive Loading on the Strength of Sea-Floor Sands, Third U. S. Navy Symposium on Military Oceanography, Navy Electronics Lab., pp 197-206

Dorsey, N. E., 1940: Properties of Ordinary Water-Substance, Reinhold Publishing Corp., New York, N. Y.

Douglas, E., 1965: Solubilities of Argon and Nitrogen in Sea Water, Journal of Physical Chemistry, Vol. 69, No. 8, pp 2608-2610

Douglas, E., 1967: Carbon Monoxide Solubilities in Sea Water, Journal of Physical Chemistry, Vol. 71, No. 6, pp 1931-1933

Elliott, F. E., 1970: On the Status of Electric Fishing, MTS Journal, Vol. 4, No. 1, pp 58-60

Ewing, G., and McAlister, E. D., 1960: On the Thermal Boundary Layer of the Ocean, Science, Vol. 131, No. 3410, pp 1374-1376

Ewing, J., Antoine, J., and Ewing, M., 1960: Geophysical Measurements in the Western Caribbean Sea and in the Gulf of Mexico, Journal of Geophysical Research, Vol. 65, No. 12, pp 4087-4104

Feely, R. A., 1971: The Distribution of Particulate Aluminum in the Gulf of Mexico, M. S. Thesis, College of Geosciences, Texas A & M University, College Station

Fitch, J. E., and Young, P. H., 1948: Use and Effect of Explosives in California Coastal Waters, California Fish and Game, Vol. 34, No. 2, pp 53-70

Frank, D. J., et al, 1970: Methane, Ethane, and Propane Concentrations in Gulf of Mexico, The American Association of Petroleum Geologists Bulletin, Vol. 54, No. 10, Part I, pp 1933-1938

Fuglister, F. C., 1963: Gulf Stream '60, Progress in Oceanography, Vol. I, pp 265-373, The MacMillan Co., New York

FWPCA, 1968: Water Quality Criteria, Report of the National Technical Advisory Committee to the Secretary of the Interior, U. S. Government Printing Office, Washington, D. C.

Gal-Or, B., and Hoelscher, H. E., 1966: A Mathematical Treatment of the Effect of Partical Size Distribution on Mass Transfer in Dispersions, A. I. Ch. E. Journal, Vol. 12, No. 3, pp 499-508

Garrett, W. D., 1967: Stabilization of Air Bubbles at the Air-Sea Interface by Surface-Active Material, Deep-Sea Research, Vol. 14, pp 661-672

Gaspin, J. B., and Price, R. S., 1972: The Underpressure Field from Explosions in Water as Modified by Cavitation, NOLTR 72-103, Naval Ordnance Laboratory, White Oak

Georgii, H., 1963: Oxides of Nitrogen and Ammonia in the Atmosphere, Journal of Geophysical Research, Vol. 68, No. 13, pp 3963-3970

Green, E. J., and Carritt, D. E., 1967: New Tables for Oxygen Saturation of Seawater, Journal of Marine Research, Vol. 25, No. 2, pp 140-147

Green, J. J., and Davidson, G. M., 1969: Explosive Tests of Underwater Ordnance by the Naval Ordnance Laboratory in Maryland Tidal Waters, NOLTR 69-33, Naval Ordnance Laboratory, White Oak

Groves, G. V., 1963: Initial Expansion to Ambient Pressure of Chemical Explosive Releases in the Upper Atmosphere, Journal of Geophysical Research, Vol. 68, No. 10, pp 3033-3047

Gutenberg, B., 1951: Sound Propagation in the Atmosphere, pp 366-375, Compendium of Meteorology, American Meteorological Society, Boston

Handbook of Geophysics, 1960: United States Air Force, Published by the MacMillan Company, New York

Haynes, B. C., 1947: Techniques of Observing the Weather, John Wiley & Sons, Inc., New York

Holden, B., 1972: A Matter of Life and Death, Maryland Conservationist, Vol. 48, No. 1, pp 23-27

Hoover, T. E., and Berkshire, D. C., 1969: Effects of Hydration on Carbon Dioxide Exchange across an Air-Water Interface, Journal of Geophysical Research, Vol. 74, No. 2, pp 456-464

Horne, R. A., 1970: Sea Water, Advances in Hydroscience, Vol. 6, pp 107-140, Academic Press, New York

Hubbs, C. L., and Rechnitzer, A. B., 1952: Report on Experiments Designed to Determine Effects of Underwater Explosions on Fish Life, California Fish and Game, Vol. 38, No. 3, pp 333-366

Hubbs, C. L., Shultz, E. P., and Wisner, R. L., 1960: Preliminary Report on Investigations of the Effects on Caged Fishes of Underwater Nitro-Carbonitrate Explosions, University of California, Scripps Institute of Oceanography

Ichiye, T., and Plutchak, N. B., 1966: Photodensitometric Measurement of Dye Concentration in the Ocean, Limnology and Oceanography, Vol. 11, No. 3, pp 364-370

Kamlet, M. J., and Ablard, J. E., 1968: Chemistry of Detonations. II. Buffered Equilibria, Journal of Chemical Physics, Vol. 48, No. 1, pp 36-42

Kamlet, M. J., and Jacobs, S. J., 1968: Chemistry of Detonations. I. A Simple Method for Calculating Detonation Properties of C-H-N-O Explosives, Journal of Chemical Physics, Vol. 48, No. 1, pp 23-35

Kanwisher, J., 1963a: Effect of Wind on CO_2 Exchange Across the Sea Surface, Journal of Geophysical Research, Vol. 68, No. 13, pp 3921-3927

Kanwisher, J., 1963b: On the Exchange of Gases Between the Atmosphere and the Sea, Deep-Sea Research, Vol. 10, pp 195-207

Katz, B., Gerard, R., and Costin, M., 1965: Response of Dye Tracers to Sea Surface Conditions, Journal of Geophysical Research, Vol. 70, No. 22, pp 5505-5513

Keeling, C. D., and Waterman, L. S., 1968: Carbon Dioxide in Surface Ocean Waters, 3 Measurements on Lusiad Expedition 1962-1963, Journal of Geophysical Research, Vol. 73, No. 14, pp 4529-4541

Kirkwood, J. B., and Fuller, R. G., 1971: Bioenvironmental Effects Predictions for the Proposed Cannikin Underground Nuclear Detonation at Amchitka Island, Alaska, BMI-171-141, Battelle Columbus Laboratories, Ohio

Kupfer, G. A., and Gordon, W. G., 1966: An Evaluation of the Air-Bubble Curtain as a Barrier to Alewives, Commercial Fisheries Review, Vol. 28, No. 9, pp 1-8

Lamontagne, R. A., Swinnerton, J. W., and Linnenbom, V. J., 1972: Comparison of C_1-C_3 Hydrocarbons in Various Ocean Environments, Fifty-third Annual Meeting of the American Geophysical Union, Washington, D. C.

LeBlond, P. H., 1969: Gas Diffusion from Ascending Gas Bubbles, Journal of Fluid Mechanics, Vol. 35, Part 4, pp 711-719

Leopold, L. B., Clarke, F. E., Hanshaw, B. B., and Balsley, J. R., 1971: A Procedure for Evaluating Environmental Impact, Geological Survey Circular 645

Li, P., et al, 1965: Unsteady State Mass Transfer from Gas Bubbles - Liquid Phase Resistance, A. I. Ch. E. Journal, Vol. 11, No. 4, pp 581-587

Manheim, F. T., Meade, R. H., and Bond, G. C., 1970: Suspended Matter in Surface Waters of the Atlantic Continental Margin from Cape Cod to the Florida Keys, Science, Vol. 167, No. 3917, pp 371-376

Maniwa, Y., 1970: Recorded Sound Lures Fish, Ocean Industry, Vol. 5, No. 1, pp 47-49

Milligan, M. L., and Young, G. A., 1954: The Scaling of Base Surge Phenomena of Shallow Underwater Explosions, NAVORD Report 2987, Naval Ordnance Laboratory, White Oak, Md.

Monahan, E. C., and Zietlow, C. R., 1969: Laboratory Comparisons of Fresh-Water and Salt-Water Shitecaps, Journal of Geophysical Research, Vol. 74, No. 28, pp 6961-6966

Moore, D. J. and Mason, B. J., 1954: The Concentration, Size Distribution, and Production Rate of Large Salt Nuclei Over the Oceans, Quarterly Journal of the Royal Meteorological Society, Vol. 80, pp 583-590

Murphy, M. F., 1963: Two Explosives Generating Condensible Products, NOLTR 63-12, Naval Ordnance Laboratory, White Oak, Md.

Murray, S. P., 1970: Settling Velocities and Vertical Diffusion of Particles in Turbulent Water, Journal of Geophysical Research, Vol. 75, No. 9, pp 1647-1654

Murthy, C. R., 1972: Complex Diffusion Processes in Coastal Currents of a Lake, Journal of Physical Oceanography, Vol. 2, No. 1, pp 80-90

NAVRECONTECHSUPPCEN, 1971: Photographic Survey, Blake Basin Disposal Site, Naval Reconnaissance and Technical Support Center, Report 107/71

Newcombe, C. L., Horne, W., and Shepherd, B. B., 1939: Studies on the Physics and Chemistry of Estuarine Waters in Chesapeake Bay, Journal of Marine Research, Vol. II, No. 2, pp 87-116

Nichols, T. B., 1970: Underwater Explosion Tests in the Chesapeake Bay - A Review of the Problems, Policy, and a Prognosis, Naval Ship Research and Development Center, UERD, Portsmouth, Virginia

Nowlin, W. D., Jr., 1971: Water Masses and General Circulation of the Gulf of Mexico, Oceanology International, Vol. 6, No. 2, pp 28-33

Ocean Industry, 1968: Old Yacht Sunk to Provide Site for Fish Study, Vol. 3, No. 6, pp 35-36

Ornellas, D. L., Carpenter, J. H., and Gunn, S. R., 1966: Detonation Calorimeter and Results Obtained with PETN, The Review of Scientific Instruments, Vol. 37, No. 7, pp 907-912

Ornellas, D. L., 1968: The Heat and Products of Detonation of HMX, TNT, NM, and FEFO, Journal of Physical Chemistry, Vol. 72, No. 7, pp 2390-2394

OSD (H&E), 1972: Department of Defense Environmental Quality Program, Status - 1 January 1972, Office of the Deputy Assistant Secretary of Defense for Environmental Quality

Okubo, A., 1962: Horizontal Diffusion from an Instantaneous Point-Source Due to Oceanic Turbulence, Chesapeake Bay Institute Technical Report 32, The John Hopkins University

Patten, B. G., and Gillaspie, C. C., 1966: The Bureau of Commercial Fisheries Type IV Electrofishing Shocker--Its Characteristics and Operation, Special Scientific Report, Fisheries No. 529, Washington, D. C.

Pittman, J. F., 1971: Environmental Effects of Explosive Testing, NOLTN* Naval Ordnance Laboratory, White Oak, Maryland

Pritchard, D. W., et al, 1971: Physical Processes of Water Movement and Mixing, Chapter 4 of Radioactivity in the Marine Environment, pp 90-136, National Academy of Sciences, Washington, D. C.

Profile, 1971: NOS Monitors Mattawoman Creek, Vol. 28, No. 2, pp 1, 5, Naval Ordnance Station, Indian Head, Maryland

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*NOL Technical Notes are not distributed outside the Laboratory. For additional information, contact the Air Ground Explosions Division of the Naval Ordnance Laboratory.

Pyzik, A. J., and Sommer, S. E., 1972: Geochemical Profiles of Chesapeake Bay Sediments, Upper Cretaceous to Recent, Fifty-third Annual Meeting of the American Geophysical Union, Washington, D. C.

Rasool, S. I., and Schneider, S. H., 1971: Atmospheric Carbon Dioxide and Aerosols: Effects of Large Increases on Global Climate, Science, Vol. 173, pp 138-141

Reed, J. W., 1964: Air Blast from Cratering Explosions, pp 169-180, Engineering with Nuclear Explosives, Third Plowshare Symposium, TID-7695, U. S. Atomic Energy Commission

Reed, J. W., 1972: Air Blast Overpressure Decay at Long Ranges, Journal of Geophysical Research, Vol. 77, No. 9, pp 1623-1629

Riley, J. P., and Skirrow, G., 1965: Chemical Oceanography, Vol. 1, Appendix V, Academic Press, New York

Robinson, E., and Robbins, R. C., 1969: Atmospheric CO Concentrations on the Greenland Ice Cap, Journal of Geophysical Research, Vol. 74, No. 8, pp 1968-1973

Roedel, P. M., 1971: Improving Methods of Locating and Catching Fish, Under Sea Technology, Vol. 12, No. 1, pp 23-24

Saunders, P. M., 1967: The Temperature at the Ocean-Air Interface, Journal of the Atmospheric Sciences, Vol. 24, No. 3, pp 269-273

Slade, D. H., Editor, 1968: Meteorology and Atomic Energy, U. S. Atomic Energy Commission, Oak Ridge, Tennessee

Smith, D. R., 1967: Comparison of Theoretical Ocean Diffusion Models, USNRDL-TR-67-50, Naval Radiological Defense Laboratory, San Francisco, California

Snay, H. G., 1961: The Scaling of Underwater Explosion Phenomena, NOLTR 61-46, Naval Ordnance Laboratory, White Oak, Md.

Spiess, F. N., and Sanders, S. M., 1971: Survey of CHASE Disposal Area (NITNATOW), SIO Reference 71-33, Scripps Institution of Oceanography, San Diego, California

Steere, N. V., 1971: Handbook of Laboratory Safety, The Chemical Rubber Co., Cleveland, Ohio

Stone, R. B., 1971: Recent Developments in Artificial Reef Technology, MTS Journal, Vol. 5, No. 6, pp 33-34

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., 1946: The Oceans, Prentice-Hall, Inc., New York

Takahashi, T., 1961: Carbon Dioxide in the Atmosphere and in Atlantic Ocean Water, Journal of Geophysical Research, Vol. 66, No. 2, pp 477-494

Taylor, G. I., and Davies, R. M., 1944: The Rate of Rise of Large Volumes of Gas in Water, Reprinted in Underwater Explosion Research, Vol. II, The Gas Globe, Office of Naval Research, 1950, pp 415-429. Also see Proc. Royal Soc., A, Vol. 200, 1950, pp 375-390

Tiller, R. E., and Coker, C. M., 1955: Effects of Naval Ordnance Tests on the Patuxent River Fishery, Special Scientific Report, Fisheries No. 143, U. S. Dept. of the Interior, Fish and Wildlife Service

Tolbert, W. H., and Austin, G. B., 1959: On the Nearshore Marine Environment of the Gulf of Mexico at Panama City, Florida, Technical Paper No. TP 161, Navy Mine Defense Laboratory, Panama City

Warner, T. B., 1972: Mixing Model Prediction of Fluoride Distribution in Chesapeake Bay, Journal of Geophysical Research, Vol. 77, No. 15, pp 2728-2732

Washington Post, 1972: Vepco Uses Serenade to Discourage Fish, 31 July 1972

Wigley, R. L., and Emery, K. O., 1967: Benthic Animals, particularly Hyalinoecia and Ophiomusium, in Sea-Bottom Photographs from the Continental Slope, pp 235-249, in Deep-Sea Photography, The Johns Hopkins Press, Baltimore

Wisby, J. W., 1952: Olfactory Responses of Fishes as Related to Parent Stream Behavior, Ph.D. Dissertation, University of Wisconsin

Wu, J., 1971: An Estimation of Oceanic Thermal-Sublayer Thickness, Journal of Physical Oceanography, Vol. 1, No. 4, pp 284-286

Wyatt, J. L., 1965: Fish Herder, Patent No. 3,177,465

Wyman, J., Jr., et al, 1952: On the Stability of Gas Bubbles in Sea Water, Journal of Marine Research, Vol. 11, No. 1, pp 47-62

Young, G. A., 1965: The Physics of the Base Surge, NOLTR 64-103, Naval Ordnance Laboratory, White Oak, Md.

Young, G. A., 1971: The Physical Effects of Conventional Explosions on the Ocean Environment, NOLTR 71-120, Naval Ordnance Laboratory, White Oak, Md.

APPENDIX A

MEMORANDUM OF LAW ON AUTHORITY OF THE NAVY WITH RESPECT TO ITS USE OF THE MARYLAND PART OF CHESAPEAKE BAY FOR TESTS AND TRAINING INVOLVING UNDERWATER EXPLOSIONS *

January 2, 1970

I. Question Presented

1. Concern over the oyster population of Chesapeake Bay and the possible threat posed to it by underwater explosions conducted by the Navy in Chesapeake Bay resulted in an inquiry from the State of Maryland concerning the authority of the Navy to conduct these explosions. For purposes of this memorandum, this question is presented: Does the Navy have authority to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay?

II. Legal Authorities and Discussion

A. Constitutional Authority of the United States to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

2. Constitutional authority for gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay exists by virtue of the war powers of the United States. Under the Constitution the United States has a right in and power of regulation and control of navigable waters for purposes of national defense, as well as for purposes of commerce and navigation. This right and power was recognized by the Supreme Court in Ashwander v. Tennessee Valley Authority (297 U.S. 288 (1936)). Addressing itself to the question of whether constitutional authority existed for the construction of Wilson Dam, the Court concluded that such authority existed by virtue of the war powers of the United States as well as by virtue of the commerce powers. The dam was constructed for the purposes of national defense and the improvement of navigation "in the exercise of the constitutional functions of the Federal government." (297 U.S. at 330.) The Court took judicial notice of the international situation existing at the time that the act authorizing the construction of the dam was passed by Congress, observing that "it cannot be successfully disputed that the Wilson Dam and its auxiliary plants, including the hydro-electric power plant, are, and were intended to be, adapted for the purposes of national defense." (297 U.S. at 327). In summary, from Ashwander it may be concluded that the United States has, under the war powers of the Constitution, a right in and power of regulation and control of navigable waters for purposes of national defense; furthermore, this right and power exists in peacetime as well as in time of war, for the power to wage war embraces the power to prepare for it. (See Constitution of the United States of America--Analysis & Interpretation 346 (1964 ed).)

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* Prepared at the request of the Chief of Naval Operations. Submitted as enclosure (1) to Judge Advocate General ltr JAG:131.6 JHS:skr Ser 34 to CNO, dated 5 January 1970.

3. Although Ashwander does not specify the degree of control of and activity in and on the navigable waters by the United States which the war powers authorize, its holding that Congress may, for the purposes of national defense, authorize the permanent impounding of water in a navigable stream for use in the production of electric power (in peacetime) argues that the degree of control of and activity in and on the navigable waters which the war powers authorize is broad. It may reasonably be construed as including the reasonable use of navigable waters, e.g., Chesapeake Bay, for tests and training involving underwater explosions, such training and testing being directly related to preparing for the defense of the nation.

B. Effect of the Submerged Lands Act on the Authority of the United States to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

4. By virtue of the Submerged Lands Act of 1953, the United States has quit-claimed to the several states all right, title, and interest, "if any it has," to the lands beneath and natural resources within their boundaries. (43 USC 1311; People v. Hecher, 4 Cal. Rptr. 334 (Cal. App. 1960).) Specific provision is made in the Submerged Lands Act, however, that paramount to but exclusive of the states' proprietary rights of ownership, management, leasing, use, and development are the United States' "navigational servitude and rights in and powers of regulation and control" of the lands beneath and waters of navigable waters "for the constitutional purposes of commerce, navigation, national defense, and international affairs." (43 USC 1314.) Thus Congress, by virtue of the Submerged Lands Act, has in no way limited the United States' right in and power of regulation and control of navigable waters for the purposes of national defense; rather, it has specifically retained such right and power to the fullest extent provided for in the Constitution.

C. Statutory Authority for Navy Tests and Training Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

5. By virtue of section 5012, title 10, United States Code, the Navy is authorized to "develop aircraft, weapons, tactics, technique, organization, and equipment of naval combat and service elements." (10 USC 5012(c).) Implicit in this authorization is the authority to conduct gunnery training and ordnance testing involving underwater explosions, for such training and testing are clearly necessary in order to develop weapons, tactics, technique, and equipment of naval combat. Such training and testing are, of course, conducted with funds appropriated by Congress, which funds, when appropriated for research, development, test, and evaluation, are appropriated pursuant to authorization legislation. (See e.g., "Legal Basis for 1969 Navy Budget Estimates by Appropriation;" see also sec. 201, Pub. Law 90-500, 82 Stat. 849, as amended.)

6. Gunnery training and ordnance testing involving underwater explosions are expressly contemplated in section 3, title 33, United States Code, which provides, inter alia, that:

> "In the interest of the national defense, and for the better protection of life and property . . . the Secretary of the Army is authorized and empowered to prescribe such regulations as he may deem best for the use and navigation of any portion or area of the navigable waters of the

United States . . . endangered or likely to be endangered by Artillery fire in target practice or otherwise, or by the proving operations . . . at any Government ordnance proving ground . . . ."

Although this provision does not confer authority upon the Navy to conduct gunnery training and ordnance testing involving underwater explosions, nor does it confer such authority upon the Secretary of the Army which authority may be delegated to the Navy, its clear import is that authority to conduct gunnery training and ordnance testing involving underwater explosions does exist. Pursuant to the authority conferred by it upon the Secretary of the Army detailed danger zone regulations have been promulgated which, inter alia, include areas of Chesapeake Bay used by the Navy for gunnery training and ordnance testing involving underwater explosions. (33 CFR 204.32, .36, .42, .46, .50, .51A.)

D. Implication of Maryland's Consent to Installation of a Calibration Range in the Mouth of the Potomac River.

7. Article I, section 8, clause 17 of the U. S. Constitution provides, inter alia, that Congress "shall have power to . . . exercise like authority [exclusive legislation in all cases whatsoever] over all places purchased by the consent of the legislature of the state in which the same shall be, for the erection of forts, magazines, arsenals, dock yards, and other needful buildings." This provision does not require state consent in order for the Federal Government to make a purchase; rather, it requires state consent in order for Congress to exercise exclusive legislative authority over an area purchased. (Paul v. United States, 371 U.S. 245 (1963).)

8. Article 96 of the Annotated Code of Maryland (1957) contains numerous provisions wherein the state of Maryland has consented to federal purchases. Among them is a provision whereby the state consents to the installation of a calibration range in the mouth of the Potomac River. (Sec 40.) As the foregoing indicates, this provision exists to confer upon Congress exclusive legislative authority over the area of the calibration range, not to authorize the purchase of land for the range, nor to authorize the installation of the range itself. It in no way indicates that Maryland's consent is necessary in order for the Navy to conduct underwater explosions in the Maryland part of Chesapeake Bay. In point of fact, consent is unnecessary, for the explosions are conducted by the Navy pursuant to statutory authorization, which authorization is pursuant to the war powers of the United States.

E. Effect of Maryland Statute Prohibiting Underwater Explosions.

9. Article 66C, section 247 of the Annotated Code of Maryland (1957) prohibits placing, throwing, or using explosives in Maryland waters except for bona fide engineering, milling, or mining purposes. This provision does not bar the Navy from conducting tests and training involving underwater explosions in the Maryland part of Chesapeake Bay. Under the Supremacy Clause of the Constitution, the United States, in the exercise of its constitutional functions, is not subject to the police power of the several states. (Ohio v. Thomas, 173 U.S. 276, 283 (1899).)

F. Limitations on Authority of Navy to Conduct Gunnery Training and Ordnance Testing Involving Underwater Explosions in the Maryland Part of Chesapeake Bay.

10. No provision specifically limits the authority conferred upon the Navy to conduct gunnery training and ordnance testing involving underwater explosions. However, section 3, title 33, United States Code, places the following limitation upon the authority of the Secretary of the Army to prescribe danger zone regulations:

> "(T)he authority conferred shall be so exercised as not unreasonably to interfere with or restrict the food fishing industry, and the regulations prescribed in pursuance hereof shall provide for the use of such waters by food fishermen operating under permits granted by the Department of the Army."

11. This provision is in accord with the declaration of policy set forth in section 742(a), title 16, United States Code, which states, inter alia, that:

> "The Congress declares that the fish, shellfish, and wildlife resources of the Nation make a material contribution to our national economy and food supply, as well as a material contribution to the health, recreation, and well-being of our citizens . . . that the fishing industries strengthen the defense of the United States . . . that the training and sport afforded by fish and wildlife resources strengthen the national defense by contributing to the general health and physical fitness of millions of citizens.. . . The Congress further declares that the fishing industry, in its several branches, can prosper and thus fulfill its proper function in national life only if certain fundamental needs are satisfied by means that are consistent with the public interest and in accord with constitutional functions of governments. Among these are:
>
> (1) Freedom of enterprise -- freedom to develop new areas, methods, products, and markets in accordance with sound economic principles as well as freedom from unreasonable administrative or legal restrictions that unreasonably conflict with or ignore economic needs."

12. Claims relating to loss of property rights by viture of the danger zone regulations promulgated for Chesapeake Bay have been considered in at least two Court of Claims cases. (Jackson v. United States, 103 F. Supp 1019 (Ct. Cl. 1952); Todd v. United States, 292 F. 2d 841 (Ct. Cl. 1961).) In Todd v. United States, a congressional reference case involving claims for the value of fishing nets and equipment and property rights in certain fishing locations in Chesapeake Bay allegedly taken by the Secretary of War (without just compensation) by his declaration of danger zone regulations, the Court of Claims held that the claims, although barred by limitations, were legitimate. The particular regulations established restricted and prohibited areas for military purposes arising out of the activities of the Patuxent Naval Air Station. The regulations reduced the number of nets the plaintiffs could fish, limited the hours they could fish, and made their operation inherently dangerous by reason of the location of the nets within the gunnery range. By virtue of Maryland law, the plaintiffs had a property right in the fishing grounds. The court found that there had been an

actual taking of private property for public use without just compensation. The government "permanently deprived plaintiffs of property from which they earned their living and which they had the right to sell or devise. It had a value, and defendent is equitably, and but for the statute of limitations would legally be, required to pay for appropriating it." (292 F.2d at 845.)

13. According to the court, the Secretary's authority to issue regulations in the interest of national defense and protection of life and property on navigable waters was specifically restricted by section 3 of title 33 to such as would not unreasonably interfere with the food fishing industry. "Defendent's actions here were an unreasonable interference." (292 F.2d at 845-46.) Thus the court did not question the constitutional authority for the danger zone regulations, or for the activities necessitating the regulations. It appears to have recognized a federal right to regulate navigable waters for the purpose of national defense. It did conclude that the Secretary's authority to issue danger zone regulations was expressly restricted by Congress. Liability, it would seem, resulted because the Secretary acted beyond the scope of authority conferred upon him by Congress.

14. From the foregoing authorities it appears that the Navy, when conducting gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, must not unreasonably interfere with or restrict the food fishing industry, its authority to train and test being no greater than the Secretary of the Army's authority to prescribe navigation regulations related to this training and testing. Where the Navy, in conducting gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, unreasonably interferes with or restricts the food fishing industry, it may, as a consequence, subject the United States to liability for any property "taken".

15. The limits of "reasonableness" in this context are impossible to define. In the final analysis, the decision as to when and to what extent to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay is one of policy. Weighed against the needs of the Navy in preparing to meet its mission must be the adverse public reaction, the resulting acrimony, and the real damage to food fishing.

G. Possible Acquisition of Easement by Prescription.

16. In view of the extended period of time during which the armed forces have conducted underwater explosions in Chesapeake Bay, the United States may have acquired by prescription against the State of Maryland an easement in Chesapeake Bay for the continued conduct of these activities. Having concluded that these activities are authorized by the war powers of the Constitution, it is not necessary to discuss the question of a possible easement.

III. Conclusion.

17. From the foregoing, it is concluded that the Navy has authority to conduct gunnery training and ordnance testing involving underwater explosions in the Maryland part of Chesapeake Bay, such authority being limited only to the extent that training and testing involving underwater explosions which unreasonably interfere with or restrict the food fishing industry may subject the United States to liability for resulting damage.

APPENDIX B

CORRESPONDENCE RELATING TO DISPOSAL OF TARGET VESSELS AS FISHING REEFS NEAR KEY WEST, FLORIDA

Item 1 Letter from the Greater Key West Chamber of Commerce to Rear Admiral John H. Maurer, USN, of 22 February 1972.

Item 2 Letter from the Mayor of Key West to Rear Admiral John H. Maurer, USN, of 23 February 1972.

Item 3 Letter from the State of Florida Department of Natural Resources to Rear Admiral John H. Maurer, USN, of 28 March 1972, with enclosure.

The Greater Key West
CHAMBER OF COMMERCE

402 Wall Street, Old Mallory Square, Key West, Florida 33040

February 22, 1972

Rear Admiral John H. Maurer, USN
Commander Key West Force
Key West, Florida 33040

Dear Admiral Maurer:

As we both are aware, one of the outstanding attractions of Key West is sport fishing, and one of its sustaining industries is commercial fisheries. The economy of the City is therefore greatly dependent on our visitors and the basic income from our fishermen. Obviously only good fishing can keep this resource healthy.

The most lucrative areas for fishing are found around the many wrecks and sunken hulks of ships in the vicinity of Key West. These sunken ships provide a favorable environment for the development of large populations of some of the most popular fish. Unfortunately, the locations of many of the sunken hulks are either unknown or are too remotely located in relation to Key West to be available to the fishermen.

It has come to my attention that the U. S. Navy sometimes deliberately sinks obsolete or unusable ships in the deep waters of the ocean. A more practical disposition of these ships would appear to be to sink them in the vicinity of the Keys in water of from 250 to 400 feet of depth where they could be available to the public as ideal fishing spots. The locations could be chosen so that they could pose no hazard to navigation or damage to the ecology of the area.

Should you agree with the above, I would recommend that the matter be studied by the Navy and if feasible that consideration be given to disposing of one or two obsolete ship hulls in relatively shallow water near Key West.

Sincerely yours,

W. B. Hannum, Jr.
President

Mayor
Charles McCoy

City of
KEY WEST

Key West, Florida
Office of the
MAYOR

23 February 1972

Rear Admiral John H. Maurer
Commander Key West Force
Naval Station
Key West, Florida 33040

Dear Admiral Maurer:

I am aware of the efforts by the Greater Key West Chamber of Commerce to induce the Navy to help improve the fishing conditions of the Key West area by sinking obsolete ships in certain selected locations. Such action, if approved, should greatly enhance both the sport fishing and commercial fishing potentials of Key West.

Additionally, the fine relations which already exist between the Navy and the citizens of Key West would be further improved by an action of this type on the part of the Navy.

I heartily endorse the idea and wish to add my support to its early implementation.

Sincerely yours,

Charles McCoy
Mayor

STATE OF FLORIDA

DEPARTMENT OF NATURAL RESOURCES

Larson Building / Tallahassee 32304 / Telephone 224-7141

RANDOLPH HODGES
Executive Director

March 28, 1972

Admiral John Maurer
United States Navy
Key West, Florida

Dear Admiral Maurer:

Enclosed is a resolution that was adopted today by the Governor and Cabinet, sitting as the Executive Board of the Department of Natural Resources. This resolution requests the placing of the two cruisers near the American Shoals to be used as an artificial fishing reef.

Your cooperation is greatly appreciated and the staff of this Department and other state agencies involved stand ready to lend all possible assistance.

Sincerely,

Randolph Hodges
Executive Director

RH/ia

Enclosure

RESOLUTION

WHEREAS, it has been brought to the attention of the Department of Natural Resources that the United States Navy proposes to dispose of two 900-foot cruisers by sinking them in 6,000 feet of water 75 miles west of Key West, Florida, in the Gulf of Mexico, on May 1, 1972, and

WHEREAS, several local salt water fishing organizations have previously expressed a desire for the State to install fishing reefs to improve fishing in Florida waters, and

WHEREAS, the State of Florida Department of Natural Resources is desirous of obtaining the said vessels to be used as an artificial reef along the natural reef line off American Shoals for the benefit of the fishermen of the State,

NOW, THEREFORE, BE IT RESOLVED, that the Governor and Cabinet, in a regularly scheduled meeting in Tallahassee, Florida, do formally request that the United States Navy remove all potential pollutants from the aforesaid vessels and that said vessels be sunk near the reef line off American Shoals in State waters at a site selected by the Department of Natural Resources, in cooperation with the Board of Trustees of the Internal Improvement Trust Fund and the Department of Pollution Control, as agreed to by the United States Navy.

DONE AND ADOPTED ON THIS THE 28th day of March A. D., 1972.

Reubin O'D. Askew
GOVERNOR AND CHAIRMAN

APPENDIX C

ALTERNATIVES TO TESTING AT SEA

Method	Advantages	Disadvantages
Saline Lake	Usually no Biota except brine shrimp No charge weight limitation	Corrosive effect of water No ship targets Depth limitation
Quarry or pond	No fish kill Water effects confined	Limited charge weight No ship targets Depth limitation
Laboratory tank	No environmental effects Sub-surface photography Low cost rate	No realistic targets Possible surface tension effect
Lake or beach on military reservation	No public complaints, except possibly for noise	No ship targets Depth limitation
Polluted water	No harmful effects on marine environment	Health hazard Possible effects on shore facilities

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Ornellas, et al, (1966) and Ornellas (1968) investigated the products of detonation of PETN ($C_5H_8N_4O_{12}$), TNT ($C_7H_5N_3O_6$), HMX ($C_4H_8N_8O_8$), NM (CH_3NO_2), and FEFO ($C_5H_6N_4F_2O_{10}$). As the latter two are not used in Navy programs, they will not be considered here. Ornellas analyzed the products of the explosives in a calorimeter and compared the results with calculations based on different theoretical approaches for confined and unconfined charges. The products are listed in Table 2.1A as given in his publications. It should be noted that the C-H-N-O compositions utilized were selected to provide a wide range of oxygen balance, therefore, the quantities of products listed represent the range of amounts to be expected from this type of explosive. In brief, an explosive such as TNT is oxygen-deficient and it forms relatively large amounts of carbon and hydrogen, while PETN, an oxygen-rich explosive, produces less hydrogen and no carbon.

The compositions of other C-H-N-O explosives were reported by Kamlet and Jacobs (1968). This publication and a paper by Kamlet and Ablard (1968) present discussions of the detonation properties and chemical products of explosives. It should be noted that some authors believe that nitric oxide is an explosion product, though a minor one.

Table 2.1B presents the same data as in Table 2.1A in terms of percentage by weight. This form might be more useful for quickly estimating the total amount of a particular substance deposited in the environment by a test with an explosive charge of a known weight.

It seems reasonable to assume that the products of an underwater explosion will be the same as those of a confined charge and that an unconfined charge is representative of a surface burst.* It is not clear where the transition will actually take place; however, it seems likely that explosives at a depth of two or more charge radii will behave like confined charges.

To properly evaluate the ultimate disposition of explosion products in the marine environment it is necessary to treat them in at least three categories: gases, insoluble solids (particulates), and soluble solids. The gases, of course, are soluble in water; but most of the gaseous products will escape to the atmosphere unless an explosion is exceptionally deep. Initially, the products are contained in a large spherical bubble that pulsates and migrates toward the surface (see Section 2.3.3.2); and the gaseous composition of the bubble is of particular interest for evaluating the rate of solution.

The gases formed by the three explosives considered thus far are listed in terms of percentage by volume in Table 2.2. These values may be readily converted to partial pressure, as in Table 2.3 of Section 2.3.2.1. Water vapor and hydrogen cyanide are treated as gases here, although they partially or completely condense to the liquid state at some later time.

It may be noted that the majority of the products of these explosives are found in the natural environment and are harmless to man and to marine life. This is not necessarily true for carbon monoxide (CO) and hydrogen cyanide (HCN). However, both are rapidly diluted to low levels of concentration, as will be shown in Sections 2.3.3.1 and 2.3.3.2.

* In this report, an explosion is considered to be a surface burst if at least half the charge is exposed to the air.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Ordnance Laboratory White Oak, Silver Spring, Maryland 20910	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

GUIDE-LINES FOR EVALUATING THE ENVIRONMENTAL EFFECTS OF UNDERWATER EXPLOSION TESTS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

George A. Young

6. REPORT DATE 13 February 1973	7a. TOTAL NO. OF PAGES v + 102	7b. NO. OF REFS 108
8a. CONTRACT OR GRANT NO. b. PROJECT NO. ORD-0332-004/092-1/UF 554-301 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NOLTR 72-211 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ordnance Systems Command Washington, D. C. 20360

13. ABSTRACT

The environmental effects of conventional underwater explosions are described and quantitative estimates provided where possible. These effects include noise, the deposit of chemical products in the sea and atmosphere, cratering and other bottom disturbances, and the killing of fish and other sea life. The long term effects on the environment are minimal. Nevertheless, knowledge of these is needed to avoid unnecessary harm and to fulfill legal and administrative requirements, including the preparation of Environmental Impact Statements. Also, explosion effects knowledge can be utilized during the planning stages to avert unnecessary delays or interference with essential military test programs.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Environmental Effects						
Underwater Explosions						
Explosion Products						
Environmental Impact						
Fish-Kill						

Attachment 1

Calumet Harbor Bedrock Investigation by GEI Consultants – FY 2014

DRAFT

Geotechnical
Environmental and
Water Resources
Engineering

Subsurface Investigation Report

Calumet Harbor Bedrock Investigation – FY 2014

W912P6-14-D-0002

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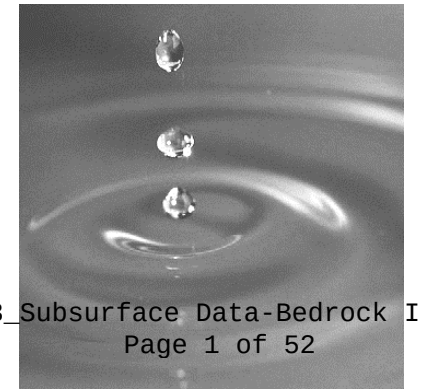

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1. Authorization and Project Background

This report summarizes the results of the Calumet Harbor Bedrock Investigation FY14, outlined in the Scope of Work dated February 27, 2014 and prepared by the US Army Corps of Engineers (USACE), Chicago District. GEI Consultants, Inc. (GEI) was contracted by Strata Earth Services (Strata) to provide field oversight and logging of soil borings, provide geotechnical engineering services and prepare this summary report. Strata holds IDIQ contract No. W912P6-14-D-0002 with the USACE Chicago and Detroit Districts to provide geotechnical services.

The purpose of this project is to investigate the properties of the bedrock in the Calumet Harbor channel over an approximate 15 acre area where the bedrock creates a topographic high. The proposed work consisted of drilling eight borings over water to a depth of 10 feet into bedrock to obtain continuous core samples from the top of the rock surface. The core was logged and photographed, and laboratory samples selected to test the compressive strength properties of the bedrock. As a result of difficult drilling conditions and weather conditions a total of 6 borings were extended to the planned depth. The seventh boring was terminated at the top of the bedrock after wave action and barge movement fractured the coring bit in place. The eighth boring was drilled approximately 1.5 feet into the bedrock using a rock bit, after the coring bit was lost during drilling of the previous boring (CH-7-14).

2. Project Location and Site Conditions

The Calumet Harbor is an artificial harbor on Lake Michigan at the mouth of the Calumet River in South Chicago Illinois. The harbor is built behind a combined timber crib and armor stone breakwater that extends approximately 2 miles into Lake Michigan. The harbor channel is dredged to a depth of 28 feet below the water surface (IGLD 85) and serves as a principal shipping terminal between the Great Lakes and Illinois Waterway.

Coordinates for the proposed boring locations were provided to Strata/GEI in the February 27, 2014 Scope of Work. The drilling location is located approximately 1.25 miles to the east of the mouth of the Calumet River. Figure 1 in Appendix A illustrates the overall location of the site and general location of the proposed borings. Eight boring locations are arranged in a rectangular area, located approximately 1,500 feet west of the breakwall. Figure 2 in Appendix A indicates the proposed boring locations.

Site conditions at the boring locations are the waters of Lake Michigan. To access the drilling locations and provide a working platform on the water, Strata contracted Kindra Lake Towing for tug and barge services. The drill rig was loaded onto a 90-foot barge with a hole through the deck for completion of the borings. This barge was pushed into place with the tug Morgan. Some protection from weather and wave action is afforded by the breakwall, but wind and wave action still adversely impacted drilling activities and the project schedule. A number of attempts were made to mobilize the barge and rig to the projects site only to be cancelled after wave heights resulted in excessive vertical and horizontal movement of the barge platform.

Bedrock beneath the harbor is Silurian-aged dolomite of the Racine Formation. The topographic high that was investigated with this study is likely a former reef structure, one of many in the Chicago area. These structures are up to 1.5 miles in diameter, and because the reefs are erosion resistant, they occur as topographic highs at the bedrock surface. These reefs are evident on land as low hills and as shoals in Lake Michigan (Mikulic and Kluessendorf, 1999).

3. Scope of Work

Strata/GEI's services were completed in general accordance with the Calumet Harbor Bedrock Investigation FY14 Scope of Work (USACE Contract No. W912P6-14-D-0002). The Scope of Work included, but was not limited to, the following tasks:

- Preparation of a Quality Control Plan (QCP) and Accident Prevention Plan (APP) and submitted for review and approval by USACE.
- Mobilize drilling equipment and personnel to complete eight soil borings to depths of approximately 10 feet into bedrock beneath the water and thin layer of overburden.
- Coordinate utility clearance and site access with USACE representatives.
- Established soil boring locations as specified by USACE.
- Drill borings at eight (8) locations to recover bedrock core samples for analysis and testing. Prepare boring logs for each borehole on ENG FORM 1836 at the time of drilling with all pertinent data included. Calculate and record Rock Quality Designation (RQD) values during drilling. Drilling and sampling was conducted in general accordance with ASTM standards.
- Visually inspect the bedrock recovered from the boreholes, including rock type, porosity, core recovery, RQD, hardness, fractures (fracture frequency, fractures per foot), condition and filling of fractures, and other pertinent data.
- Visually classify unconsolidated sediment covering the bedrock, if present.
- Restore the drill site to "original condition" after drilling. Boreholes were grouted with a cement grout following completion.
- Clean, mark, box, and photograph recovered core samples.
- Prepare a stratagraphic log of subsurface conditions encountered at the boring locations.
- Select one representative sample of rock core from each borehole in the upper 5 feet of the borehole (eight total) for laboratory testing.
- Test selected core samples for uniaxial compressive strength in accordance with ASTM D7012, Method C.
- Prepared a subsurface investigation report summarizing the field investigation, rock conditions, boring locations, final boring logs, and laboratory test results.

4. Exploration Procedures

4.1 Drilling Procedures

Drilling was conducted on April 21, 2014, April 23, 2014, and May 31, 2014. This prolonged schedule was the result of adverse weather conditions on the lake which prevented drilling on several attempts.

All boreholes were cored in accordance with the requirements of ASTM D 2113 – *Standard Practice for Rock Core Drilling and Sampling of Rock for Site Investigation.* Rock cores were drilled using a diamond core bit of NX size (54.7 mm ID). Casing was set into the upper portion of the rock, but the depth of the casing into the rock was minimized to obtain as much information as possible from the upper 5 feet. Casing was generally set only in the upper few inches of the bedrock.

Sediment encountered covering the bedrock was sampled using standard split-barrel sampling procedures, in accordance with ASTM D 1586 – *Standard Test Method for Penetration and Split-Barrel Sampling of Soils.*

Following drilling, the borehole in the rock at each location was grouted using a cement grout, and the casing pulled.

4.2 Boring Locations

The drilling location is located approximately 1.25 miles to the east of the mouth of the Calumet River. Figure 1 in Appendix A illustrates the site location. Eight boring locations are arranged in a rectangular area, located approximately 1,500 feet west of the breakwall. Figure 2 in Appendix A indicates the location of the proposed borings. The coordinates provided in the Scope of Work had the Northing and Easting headings reversed. This error was noticed when the coordinates were loaded into the Trimble. The headings of the data table were reversed, and the correct location within the Calumet Harbor was obtained.

During drilling, the tug/barge navigated to the proposed locations using a Trimble GEO-XH GPS unit. Every attempt was made to get set the barge as close as possible to the proposed location. However, due to the movement of the 90 foot long barge and securing the location with the barge spuds, setting on the exact location for each boring was not possible. Table 1 in Appendix B contains the coordinates for the actual drilled locations. The coordinate system used was Projected Coordinate System NAD 1983 State Plane Illinois East FIPS 1201 Feet. Figure 3 in Appendix A illustrates the actual drilled ("as drilled") locations, and Figure 4 in Appendix A illustrates the location of the actual vs. the proposed boring

locations. The offset of actual vs. proposed locations ranged from 5.8 feet to a maximum of 112 feet.

4.3 Depth Measurements

All depths measured during drilling were measured from the level of the water surface at the time of drilling. Water elevation data was obtained from the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Center for Operational Oceanographic Products and Services (CO-OPS) website. NOAA operates a gaging station in Calumet Harbor (Station ID 9087044). The station is located on the north bank of the Calumet River, approximately 3,000 feet west of the mouth of the Calumet River, near the USACE South Slip. Figure 1 in Appendix A illustrates the location of this station.

Water level measurements are collected at 6-minute intervals at the NOAA station. Historic data was obtained via the NOAA NOS CO-OPS website, and the water elevation at the time of drilling was determined. The NOAA water level data is reported in feet, using the 1985 International Great Lakes Datum (IGLD85). Elevation data has been converted to the Low Water Datum (LWD), by subtracting 577.34 feet from the IGLD85 elevation. Elevations using both datum are presented in this report. The water elevation for each boring on Table 1 in Appendix B is an average for the time of drilling at each particular location. In general, water elevation did not vary by more than 0.2 feet during each individual drilling period but did change by over a foot between individual mobilizations. Table 1 in Appendix B contains a summary of the boring elevations, water depths, overburden thickness, top of rock elevation and rock depth data.

During drilling, the depth of water and drilling depths were both measured from the lake water level surface. The drill rods were inserted through the hole in the barge deck, and the depth to the lake bottom measured from the barge deck. The height of the barge deck above the water surface was then measured, and subtracted from the drill rod measurement. Therefore, drilling depths recorded on the boring logs were measured from the water surface.

4.4 Boring Log Procedures

An experienced geologist was present during drilling to inspect the recovered core and interpret the information obtained from the rock core samples. Rock core was examined and logged for rock type, porosity, core recovery, RQD, hardness, fractures (fracture frequency, fractures per foot), condition and filling of fractures, and other pertinent data. Logging of the boreholes was performed in general conformance to ASTM D 5434 – *Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock*. Core boxes were labeled and photographed. Appendix C contains the core photographs.

A separate boring log was prepared for each borehole on USACE ENG FORM 1836 at the time of drilling. The rock core was placed in standard core boxes, cleaned, labeled, and photographed with scale for reference. Empty spaces in the boxes were filled with foam pipe insulation to prevent movement of core. Field data placed into formal boring logs using the gINT program. Completed boring logs are contained in Appendix D.

4.5 Laboratory Testing Procedures

GEI selected eight (8) representative samples of rock core to be tested and submitted the list of proposed samples to USACE for review and approval.

The rock samples were tested for Unconfined Compressive Strength (UCS) per ASTM D 7012, Method C. The samples were tested by AECOM at their geotechnical laboratory in Vernon Hills, Illinois. The results of UCS testing are summarized in Section 5.2.

5. Subsurface Conditions

Subsurface conditions at the drilling locations consisted of a thin layer of sediment overlying dolomite bedrock. The overburden ranged between one inch and 3 feet in thickness, and consisted of clay, sand and gravel. The interface between the overburden and bedrock is generally distinct, with minor weathering of the bedrock surface. Observations at each borehole are described in detail below. Boring logs for each boring are contained in Appendix D, and photographs of the core are contained in Appendix C.

Figure 5 in Appendix A illustrates the location of two cross-section profiles. Figures 6 and 7 (Appendix A) are profiles across the drilled area, using data obtained from the boring logs. Figure 6 is a northeast-southwest profile which includes borings CH-2-14, CH-5-14, and CH-6-14, and Figure 7 is a northwest-southeast profile which includes borings CH-3-14, CH-5-14, and CH-7-14.

5.1 Rock Characteristics

Bedrock consists of Silurian-aged Racine Dolomite. The rock is a gray to cream-colored vuggy dolomite, granular to micritic (aphanitic) in grain size. The rock is non-weathered and fresh. It is of medium hardness, as it can be scratched with a knife. The rock contains abundant vugs and porosity, comprising up to approximately 25% of the rock. These pores range in size from 1 to approximately 20 mm in diameter, and are mostly open. Pores and vugs contain pyrite, solid asphalt bitumen, and occasional calcite crystals. Pyrite is also present in the groundmass of the dolomite rock.

The rock contains abundant fractures, most of which are horizontal in orientation. These horizontal fractures are likely along bedding, and are most probably opened by the drilling and recovery process. Due to drilling on the Lake Michigan surface, the up-and-down motion of the waves caused the drill stem to move as well, thereby occasionally breaking the rock within the core barrel and producing the horizontal fractures. Some fractures at angles between horizontal and vertical also exist, but are a small percentage of overall measured breaks.

The natural fractures are generally fresh, smooth, and tight, with no coatings or fillings. A minority of fractures (both horizontal and non-horizontal) contain a thin coating of clay on the fracture surfaces. Some non-horizontal fractures are present which are closed and cemented with calcite.

5.1.1 Boring CH-1-14

This boring was the second boring drilled on May 31, 2014, and the fourth overall boring drilled. The actual drilled location was approximately 45 feet to the west of the proposed location. The water depth was 29.75 to the top of the sediment, which was 3 feet think. The top of bedrock was 32.75 feet below the water surface (elevation of 546.12 feet IGLD85, or -31.22 feet LWD).

Sediment consists of gray very soft clay with trace sand between 29 and 30.75 feet, medium to stiff clay with little sand between 30.75 and 31.25, and weathered dolomite and clay between 31.25 and 32.25 feet. This boring contained the thickest section of sediment of any of the borings drilled.

Bedrock at this boring is gray vuggy dolomite, becoming cream-colored and less vuggy with depth. The rock was cored as one run between 32 and 42 feet over the course of 30 minutes. Core recovery was 97%, and RQD at 82.9%.

Fractures are generally horizontal partings, with a 45o fracture at 39.75 and another at 42 feet. A vertical fracture was present between 40.5 and 41 feet. Fracture surfaces are generally clean on all fractures.

5.1.2 Boring CH-2-14

Boring CH-2-14 was the first boring to be drilled, completed on April 21, 2014. The actual drilled location is approximately 100 feet south of the proposed location. The water depth was 31 feet (below water surface), and 8 to 12 inches of sediment were present over the bedrock. The sediment was a gray clayey silt with pebbles which resembled a glacial till.

The top of bedrock was at a depth of approximately 32 feet, or an elevation of 545.91 feet IGLD85 (-31.43 feet LWD). A total of 10 feet of core was drilled at this boring in two 5-foot runs (32 to 37 feet, and 37 to 42 feet). Recovery was 98% and 100% for the two runs. Fractures were few in the top 5-foot run, with no more than two fractures per foot. The RQD was 96%. The lower run contained more abundant fractures, as many as 5 per foot, thereby reducing the RQD to 85%. Fractures are horizontal, with the exception of a 45° break between the 35.5 and 36.5-foot depth, and another at approximately 41.25 feet.

The rock is gray vuggy dolomite with pyrite, bitumen, and calcite crystals in the pores. Porosity ranged from 1 to 10 mm in diameter, and comprise up to 25% of the rock. The rock was medium hard, able to be scratched with a knife. Coring was accomplished within 30 minutes, with 10 minutes required for each 5-foot run.

5.1.3 Boring CH-3-14

Boring CH-3-14 was the second boring, completed on April 23, 2014. The actual drilled location was approximately 112 feet southeast of the proposed location. At this location, the barge was set up, but the wave action on the barge prevented drilling until several hours after arriving at the location. During this time, the waves and barge movement bent the spud of the barge. At the completion of the drilling, the spud was raised only approximately 4 feet, at which point it stuck in the spud sleeve of the barge. Drilling was suspended after this boring for repairs to the barge.

The water depth was approximately 30.5 feet to the top of sediment at this location. Only approximately 0.5 feet of sediment were present over the bedrock surface, which was at a depth of 31 feet below the water level, or at an elevation of 547.04 feet IGLD85 (-30.30 feet LWD).

A total of 10 feet of coring was completed at this location, all in a single run between 31 and 41 feet depth. Coring required approximately 13 minutes. Core recovery in this boring was 85%, while the RQD was 74%. The rock was a gray vuggy dolomite, as described above.

This core contained abundant fractures, many of which were likely caused by the movement of the barge during drilling. Two zones, one at a depth of 34 to 34.5 feet, and another between 37 and 39-foot depth contained many fractures, with the rock broken into small pieces and generally poor recovery from these depths. The portions of the core between these two zones contained between 1 and 3 fractures per foot, while the lower portion of the core (39 to 41 feet) did not contain any fractures.

5.1.4 Boring CH-4-14

Boring CH-4-14 was the sixth boring drilled on May 31, 2014, and the eighth boring and final drilled at the site. The location of this boring was approximately 47 feet southeast of the proposed location. Due to damage to the core barrel at boring CH-7-14, no coring was attempted at this location. The depth to the top of the sediment was measured at 31.75 feet below the water surface. Approximately 0.55 feet of sediment were encountered, placing the top of the rock at a depth of 32.03 feet (elevation of 546.57 feet IGLD85, or -30.77 feet LWD). The sediment consisted of very soft gray clay with little sand, underlain by gray silt with trace gravel. The rock was drilled with a rock bit between 32.75 and 33.75 feet. No core was recovered.

5.1.5 Boring CH-5-14

Boring CH-5-14 was the third boring drilled, and the first drilled on May 31, 2014. The actual drilled location was approximately 56 feet southwest of the proposed location. The water depth at this location was 28.6 feet to the top of the sediment. Sediment thickness was

0.4 feet, so the top of bedrock was 29 feet deep, or at an elevation of 549.77 feet IGLD85 (-27.57 feet LWD). The sediment at this location was 2 inches of gravel underlain by 2 inches of clay with fine gravel.

A total of 10 feet or rock was cored at this location, in one run between 29 and 39 feet. The core recovery from this borehole was 82.5%, while the RQD was 72%. Approximately 1.5 feet at the bottom of the run was not recovered. Coring required approximately 25 minutes. The rock was a gray to cream-colored dolomite with bitumen and pyrite on fracture surfaces. The rock is somewhat lighter in color and finer grained then that encountered at CH-2-14 and CH-3-14.

A vertical fracture begins at the bedrock surface (29 feet) and extending to approximately 31 feet. A series of fractures between 31 and 32 feet have broken the core into small pieces and lowered recovery in this zone. A vertical fracture is also present between 32 and 32.5 feet. A 45o fracture is present at approximately 36.5 feet. Below 37 feet the core is broken into small pieces, and there was no recovery for the bottom 1.5 feet of the borehole.

5.1.6 Boring CH-6-14

Boring CH-6-14 was the third boring drilled on May 31, 2014, and the fifth overall boring drilled at the site. The location of the boring was approximately 6 feet from the proposed location. The depth of water at this location was measured at 29.65 feet below the water surface, with approximately 1 inch of sediment over the top of the bedrock. The top of bedrock was approximately 29.75 feet deep (elevation of 549.24 feet IGLD85 or -28.10 feet LWD).

Recovery of core at this boring was 100%, and RQD was 75.6%. Rock consists of gray vuggy dolomite and cream-colored dolomite. Coring required approximately 20 minutes for the 10-foot run between 29.75 and 39.75 feet.

Several vertical, closed fractures are present in this core. These fractures, between 30 and 30.75 feet, 35 and 35.25 feet, 36.25 and 36.5 feet, and 38.5 to 38.75 feet are closed and tight, and contain some solid bitumen. Two inclined fractures are present between 31 and 32 feet, which are also closed and contain bitumen. Horizontal fractures are present along throughout the core.

5.1.7 Boring CH-7-14

This boring was the fifth boring drilled on May 31, 2014, and the seventh overall drilled at the site. The location was approximately 44 feet west of the proposed location. The water at this location was 29.75 feet below the water surface. Approximately 3 inches of sediment were present over the top of the bedrock, which was at 30.00 feet (elevation of 548.96 feet IGLD85 or -28.38 feet LWD).

Coring began at this location at 16:56 and ended at 17:04 when the wind picked up and a large wave moved the barge, picking up the casing from the hole and damaging the core barrel. Attempts to reset and continue coring were not successful, and the borehole was terminated. The run was approximately 8 inches between 30 and 30.67 feet. Recovery was 100%, with RQD at 63%.

The rock is gray vuggy dolomite with bitumen staining.

5.1.8 Boring CH-8-14

Boring CH-8-14 was the fourth boring drilled on May 31, 2014, and the sixth overall boring drilled at the site. The location of the boring was approximately 22 feet to the southeast from the proposed location. The depth of water at this location was measured at 30.5 feet below the water surface, with less than 1 inch of sediment over the top of the bedrock. The top of bedrock was approximately 30.5 feet deep (elevation of 548.38 feet IGLD85 or -28.96 feet LWD).

The rock in this boring is gray to cream-colored vuggy dolomite. Core recovery from this boring was 92%, while the RQD was approximately 60%. Coring required approximately 30 minutes between 30.5 and 40.5 feet. The boring was cored in one run.

A vertical fracture is present in the core from the top (30.5 feet) nearly through the entire depth of the core. The fracture is tight and closed, with a filling of bitumen in the upper portions of the core. Less bitumen is present in the deeper portions of the core. Angled fractures are present at depths of 37, 38, and 39.75 feet. Recovery is compromised in areas where fracture frequency is higher, between 37 and 39 feet in depth.

5.2 Rock Testing Results

Eight representative samples of rock core were selected and tested for Unconfined Compressive Strength (UCS) per ASTM D 7012, Method C. The samples were tested by AECOM at their geotechnical laboratory in Vernon Hills, Illinois. Table 2 in Appendix B contains a summary of the laboratory test results. Measured UCS in the samples ranged between a low of 2,880 pounds per square inch (psi) to a high of 7,755 psi. Appendix E contains a copy of the laboratory testing results.

6. Limitations

This report has been prepared in general accordance with generally accepted geotechnical engineering practices to aid in the evaluation of this site and to assist the owner and architect and/or engineer in the design of this project. No other warranty, either expressed or implied, is made. The scope is limited to the specific project and location described herein, and our description of the project represents our understanding of the significant aspects relevant to the geotechnical characteristics. In the event that any changes in the design or location of the facilities as outlined in this report are planned, we should be informed, so that the changes can be reviewed and conclusions of this report modified, as necessary, in writing by the Geotechnical Engineer. As a check, we recommend that we be authorized to review the project plans and specifications to confirm that recommendations contained in this report have been interpreted in accordance with our intent. Without this review, we will not be responsible for the misinterpretation of our data, analysis, and/or recommendations, nor how these are incorporated into the final design.

The analysis and recommendations submitted in this report are based on data obtained from soil borings performed at locations indicated on the location diagram and from information discussed in this report. This report does not reflect any variations which may occur between borings. In the performance of subsurface explorations, specific information is obtained at specific locations at specific times. However, it is a well-known fact that variations in soil and rock conditions exist on most sites between boring locations, and that seasonal and annual fluctuations in groundwater levels will likely occur. The nature and extent of variations may not become evident until the course of construction. If variations then appear evident, it will be necessary for a re-evaluation of recommendations contained in this report after performing on-site observations during the construction period and noting characteristics of the variations.

The Geotechnical Engineer of record is the professional engineer who authored the geotechnical report. It is recommended that all construction operations dealing with earthwork and foundations be observed by the Geotechnical Engineer of record or the Geotechnical Engineer's appointed representative to confirm that design requirements are fulfilled in the actual construction. For some projects, this may be required by the governing construction regulator.

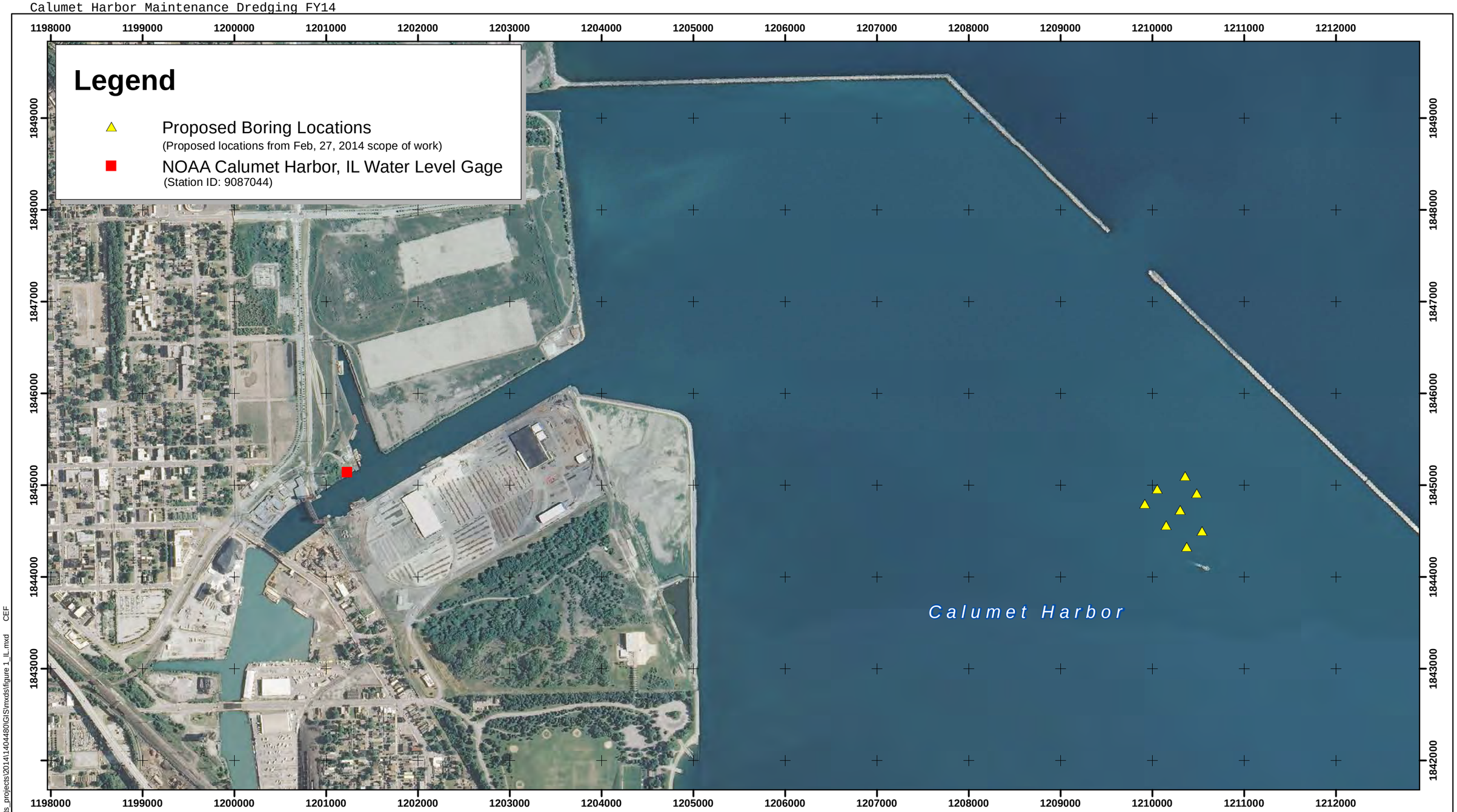
7. References

Mikulic, D. G., and Kluessendorf, J., 1999, The Classic Silurian Reefs of the Chicago Area, ISGS Guidebook 29, Geological Field Trip 4: April 24, 1999, North-Central Section, Geological Society of America 33rd Annual Meeting, Champaign-Urbana, Illinois

Appendix A

Figures

- Figure 1 – Proposed Boring Locations
- Figure 2 – Proposed Boring Locations – Detail
- Figure 3 – As Drilled Boring Locations
- Figure 4 – Boring Location Difference
- Figure 5 – Location of Cross-Section Profiles
- Figure 6 – Cross Section Profile A-A'
- Figure 7 – Cross Section Profile B-B'



0 1,000 2,000 4,000 Feet

1 inch = 1,000 feet

Projected CoordinateSystem: NAD_1983_StatePlane_Illinois_East_FIPS_1201_Feet
Background Imagery: NAIP/Indiana_2012_1m_NC (arcgis on gis.apfo.usda.gov)

N W E S

United States Army Corps of Engineers

Calumet Harbor Bedrock Investigation FY 2014
(W912P6-14-D-0002)

GEI Consultants

1404480

SITE LOCATION DIAGRAM

DATE: JULY 2014

FIGURE 1

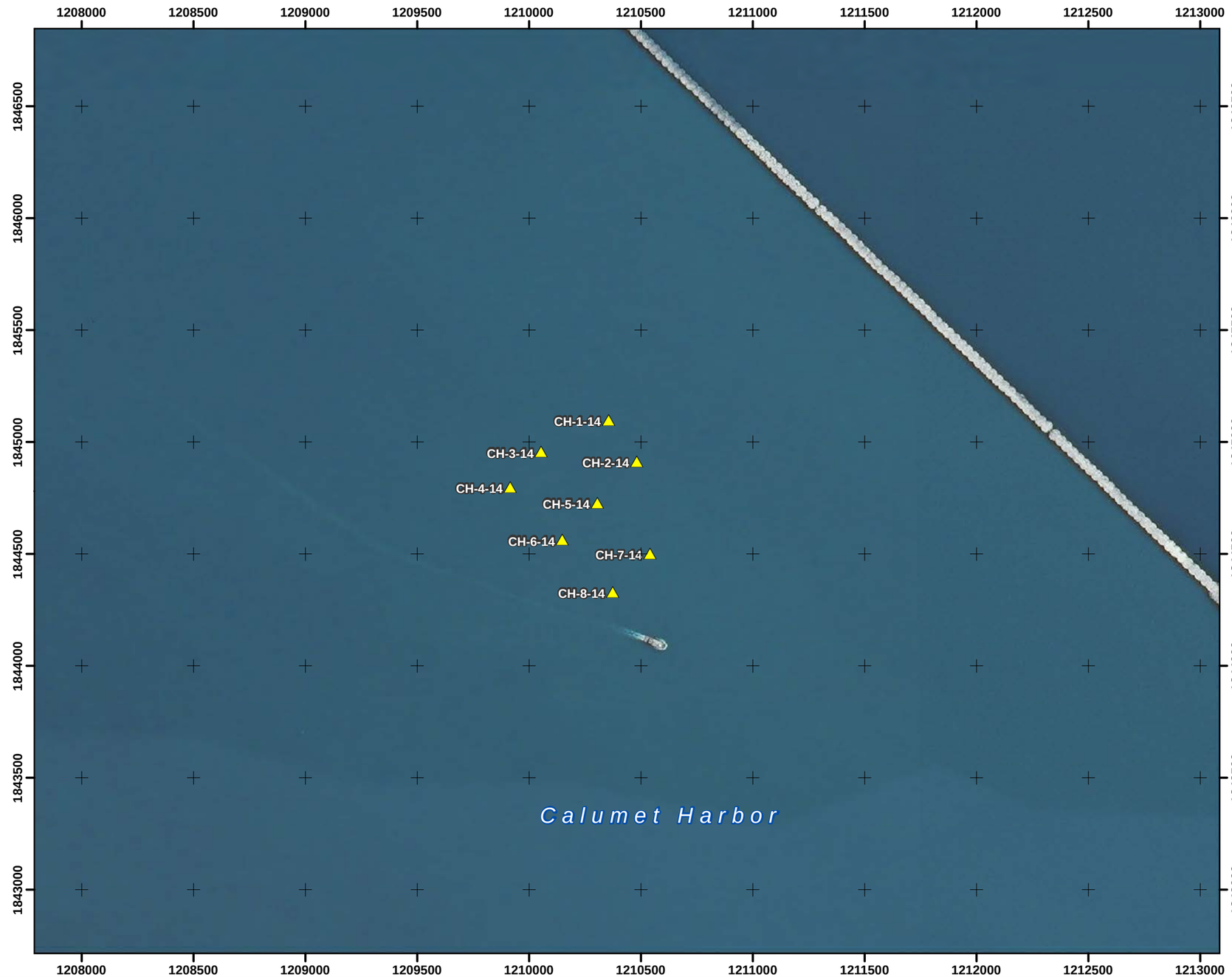
11-JUN-2014 F:\GEI_Consultants_projects\2014\1404480\GIS\mxds\figure 1_IL.mxd CEF

Legend

▲ Proposed Boring Locations

ID	Northing	Easting
CH-1-14	1,845,098	1,210,355
CH-2-14	1,844,914	1,210,482
CH-3-14	1,844,957	1,210,054
CH-4-14	1,844,799	1,209,916
CH-5-14	1,844,729	1,210,305
CH-6-14	1,844,563	1,210,149
CH-7-14	1,844,502	1,210,540
CH-8-14	1,844,330	1,210,373

NOTES: Proposed locations from Feb, 27, 2014 scope of work



0 500 1,000 2,000 Feet

1 inch = 500 feet

Projected CoordinateSystem: NAD_1983_StatePlane_Illinois_East_FIPS_1201_Feet
Background Imagery: NAIP/Indiana_2012_1m_NC (arcgis on gis.apfo.usda.gov)

N W E S

United States Army Corps of Engineers

Calumet Harbor Bedrock Investigation FY 2014
(W912P6-14-D-0002)

GEI Consultants

1404480

PROPOSED BORING LOCATION DIAGRAM

DATE: JULY 2014

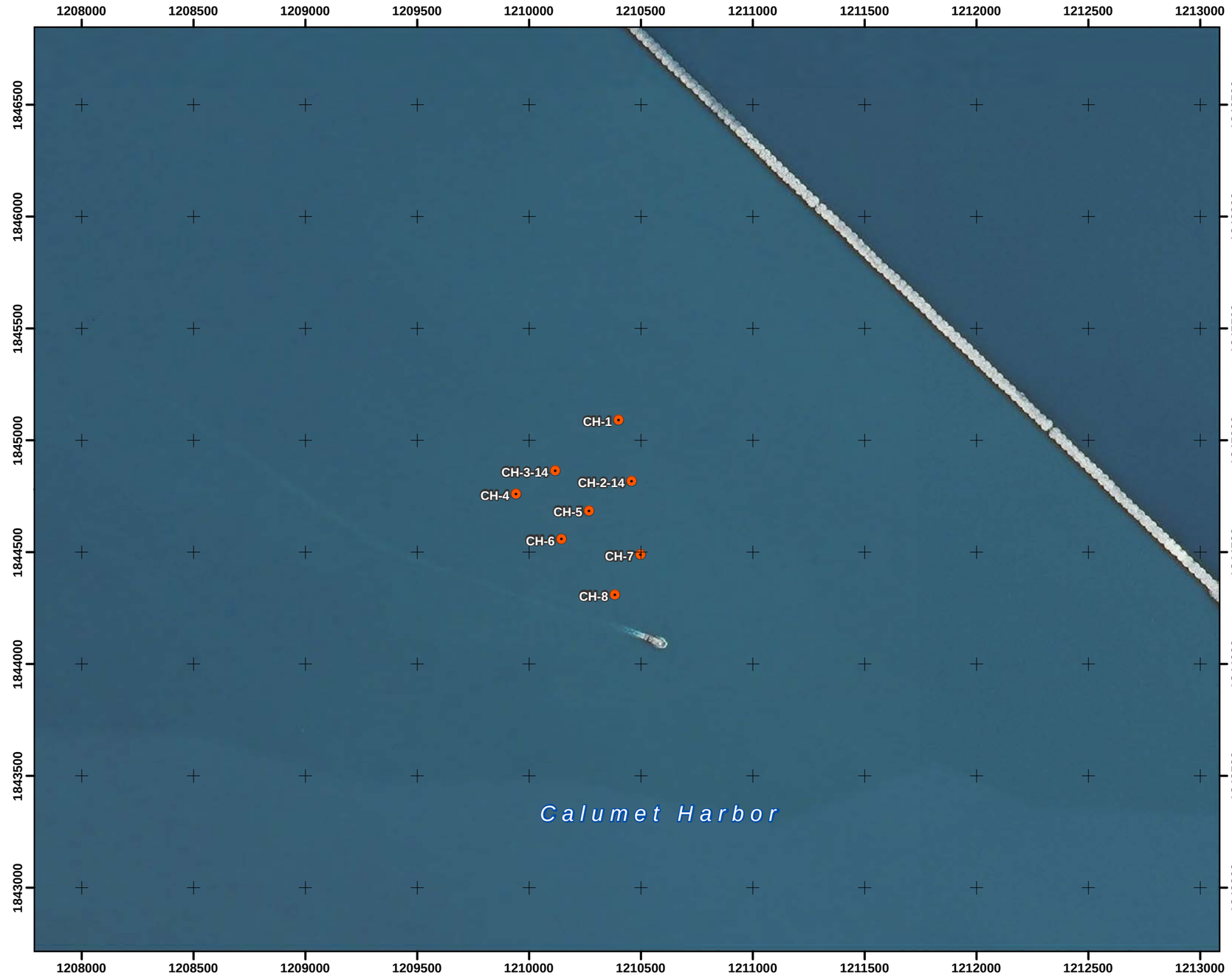
FIGURE 2

11-JUN-2014 F:\GEI_Consultants_projects\2014\1404480\GIS\mxds\Figure 2_IL.mxd CEF

Legend

As Drilled Boring Locations

NOTES: As drilled locations collected using a Trimble Geo-XH GPS Receiver with sub-foot accuracy.



Feet
0 500 1,000 2,000
1 inch = 500 feet

Projected CoordinateSystem: NAD_1983_StatePlane_Illinois_East_FIPS_1201_Feet
Background Imagery: NAIP/Indiana_2012_1m_NC (arcgis on gis.apfo.usda.gov)

United States Army Corps of Engineers

Calumet Harbor Bedrock Investigation FY 2014
(W912P6-14-D-0002)

GEI Consultants

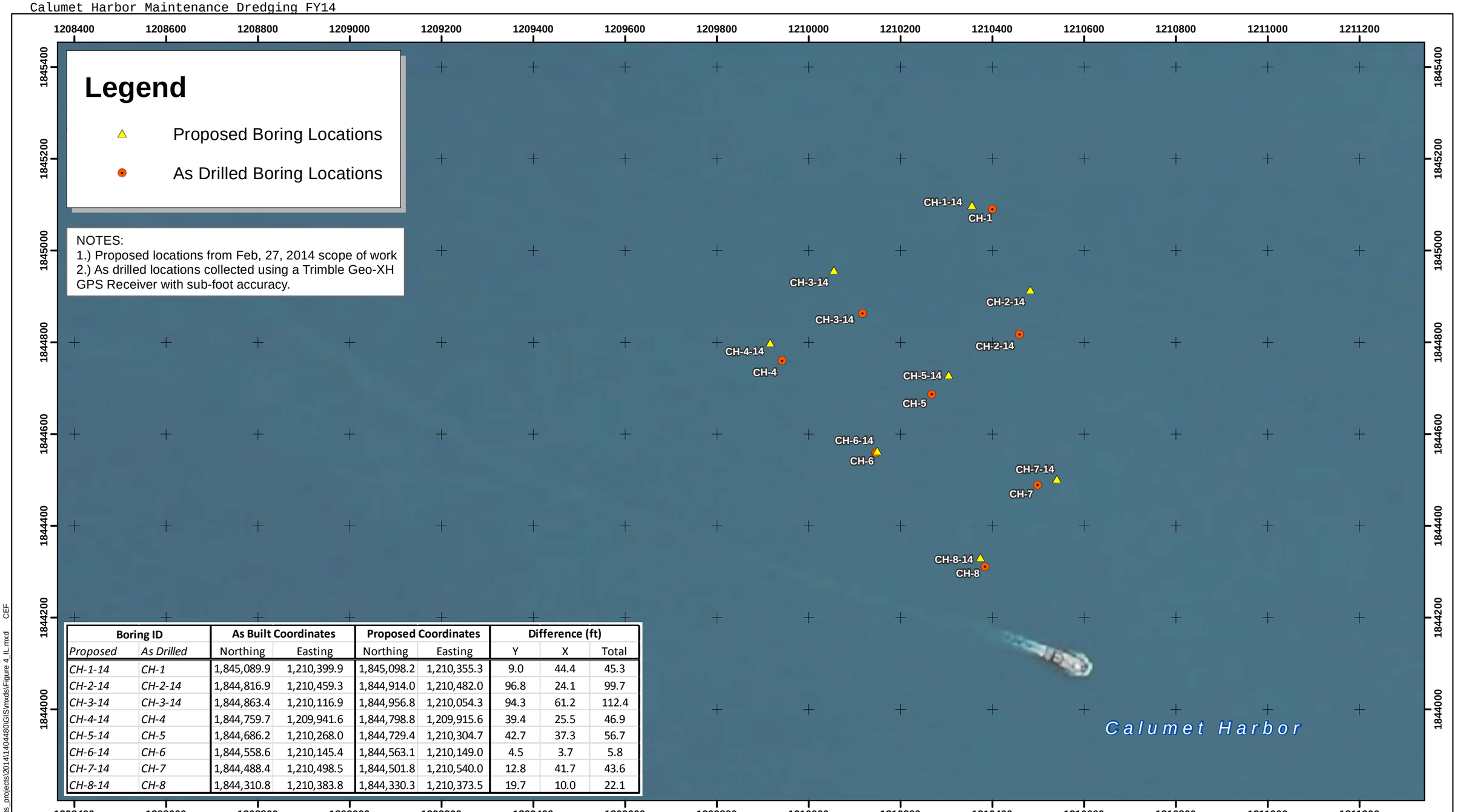
1404480

AS DRILLED BORING LOCATION DIAGRAM

DATE: JULY 2014

FIGURE 3

11-JUN-2014 F:\GEI_Consultants_projects\2014\1404480\GIS\mxds\Figure 3_IL.mxd CEF



Boring ID		As Built Coordinates		Proposed Coordinates		Difference (ft)		
Proposed	*As Drilled*	Northing	Easting	Northing	Easting	Y	X	Total
CH-1-14	*CH-1*	1,845,089.9	1,210,399.9	1,845,098.2	1,210,355.3	9.0	44.4	45.3
CH-2-14	*CH-2-14*	1,844,816.9	1,210,459.3	1,844,914.0	1,210,482.0	96.8	24.1	99.7
CH-3-14	*CH-3-14*	1,844,863.4	1,210,116.9	1,844,956.8	1,210,054.3	94.3	61.2	112.4
CH-4-14	*CH-4*	1,844,759.7	1,209,941.6	1,844,798.8	1,209,915.6	39.4	25.5	46.9
CH-5-14	*CH-5*	1,844,686.2	1,210,268.0	1,844,729.4	1,210,304.7	42.7	37.3	56.7
CH-6-14	*CH-6*	1,844,558.6	1,210,145.4	1,844,563.1	1,210,149.0	4.5	3.7	5.8
CH-7-14	*CH-7*	1,844,488.4	1,210,498.5	1,844,501.8	1,210,540.0	12.8	41.7	43.6
CH-8-14	*CH-8*	1,844,310.8	1,210,383.8	1,844,330.3	1,210,373.5	19.7	10.0	22.1

0 200 400 800 Feet

1 inch = 200 feet

Projected CoordinateSystem: NAD_1983_StatePlane_Illinois_East_FIPS_1201_Feet
Background Imagery: NAIP/Indiana_2012_1m_NC (arcgis on gis.apfo.usda.gov)

United States Army Corps of Engineers

Calumet Harbor Bedrock Investigation FY 2014
(W912P6-14-D-0002)

GEI Consultants

1404480

BORING LOCATION DIFFERENCE DIAGRAM

DATE: JULY 2014

FIGURE 4

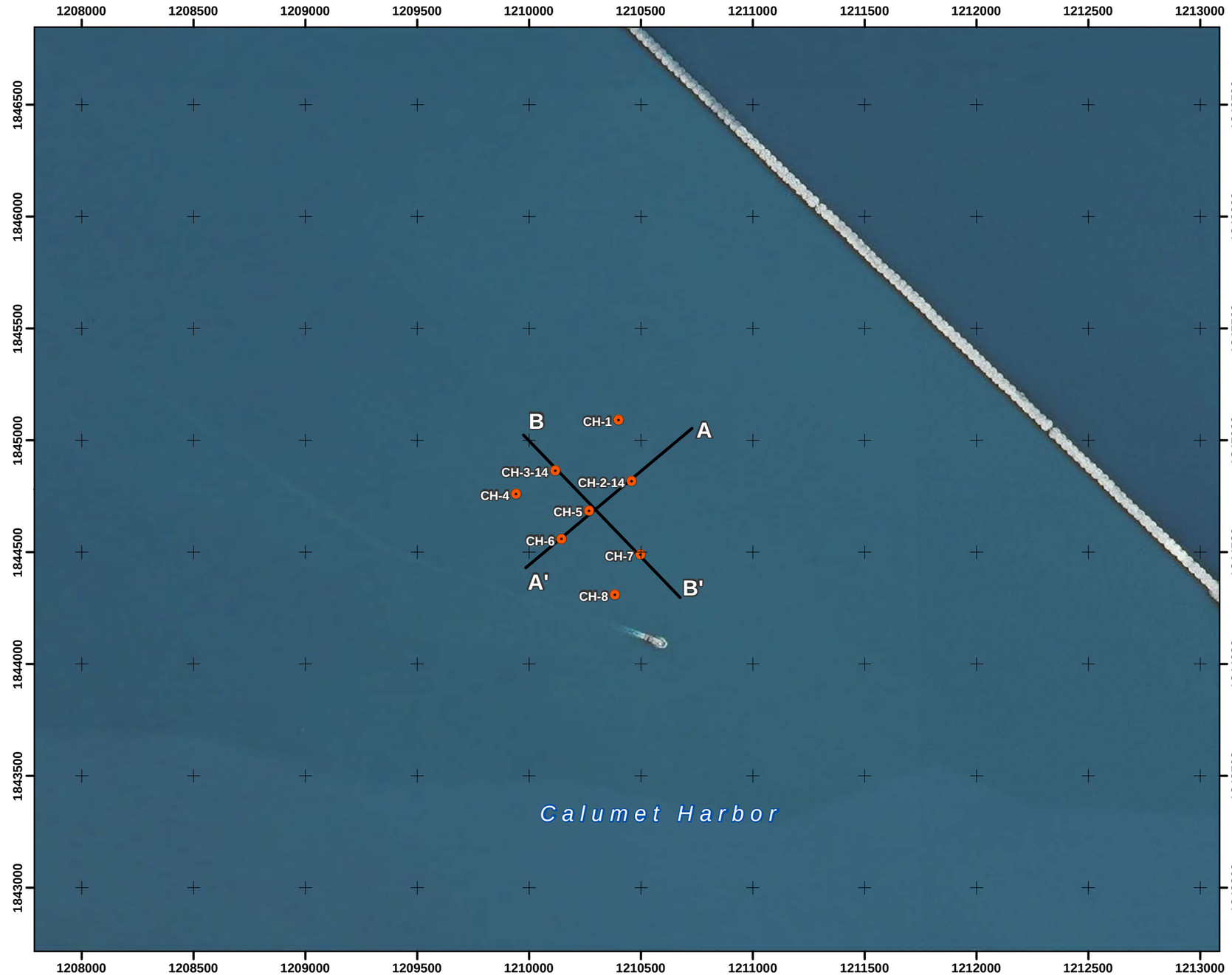
11-JUN-2014 F:\GEI_Consultants_projects\2014\1404480\GIS\mxds\Figure 4_IL.mxd CEF

Legend

As Drilled Boring Locations

A — A' Cross Sections

NOTES: As drilled locations collected using a Trimble Geo-XH GPS Receiver with sub-foot accuracy.

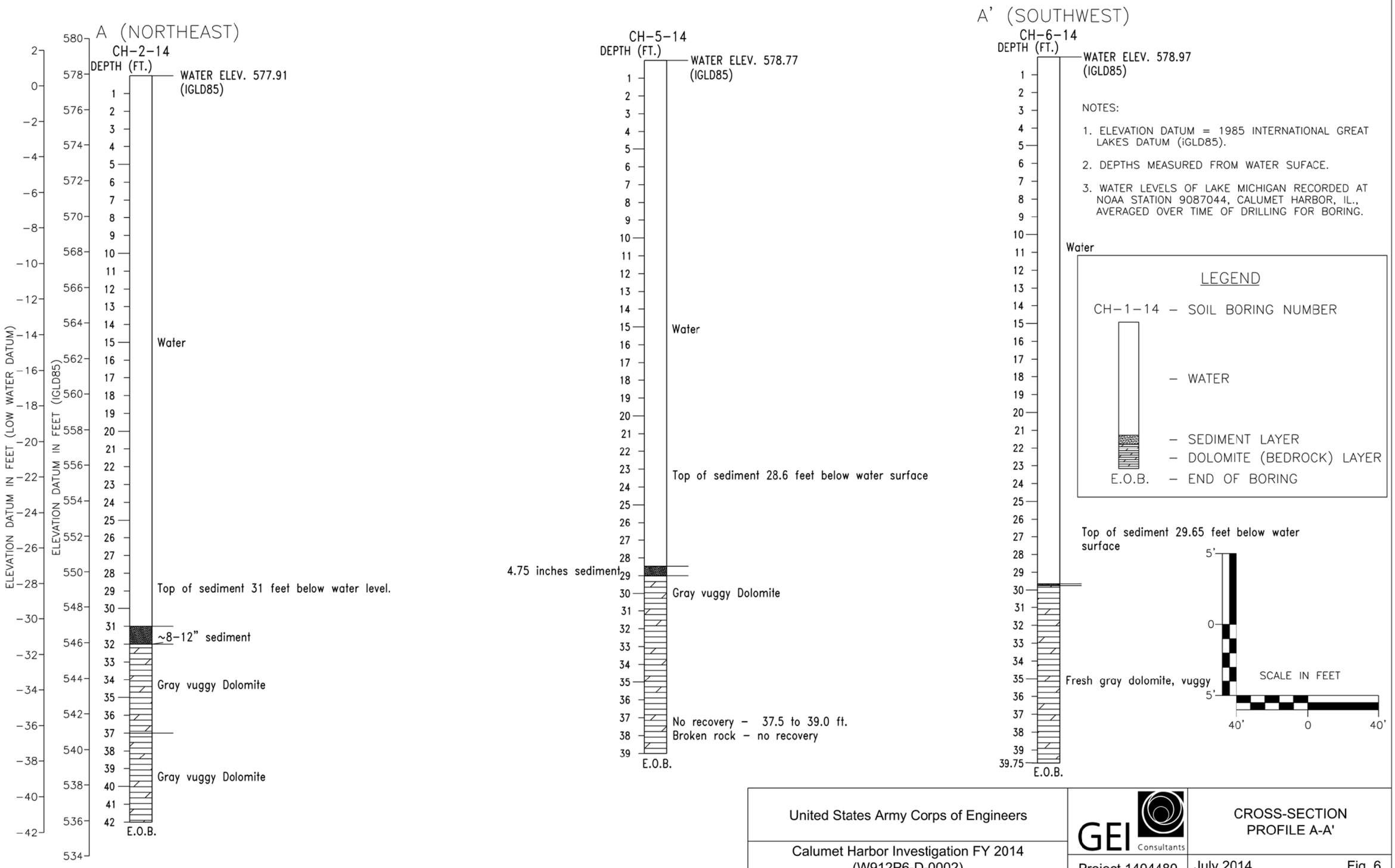


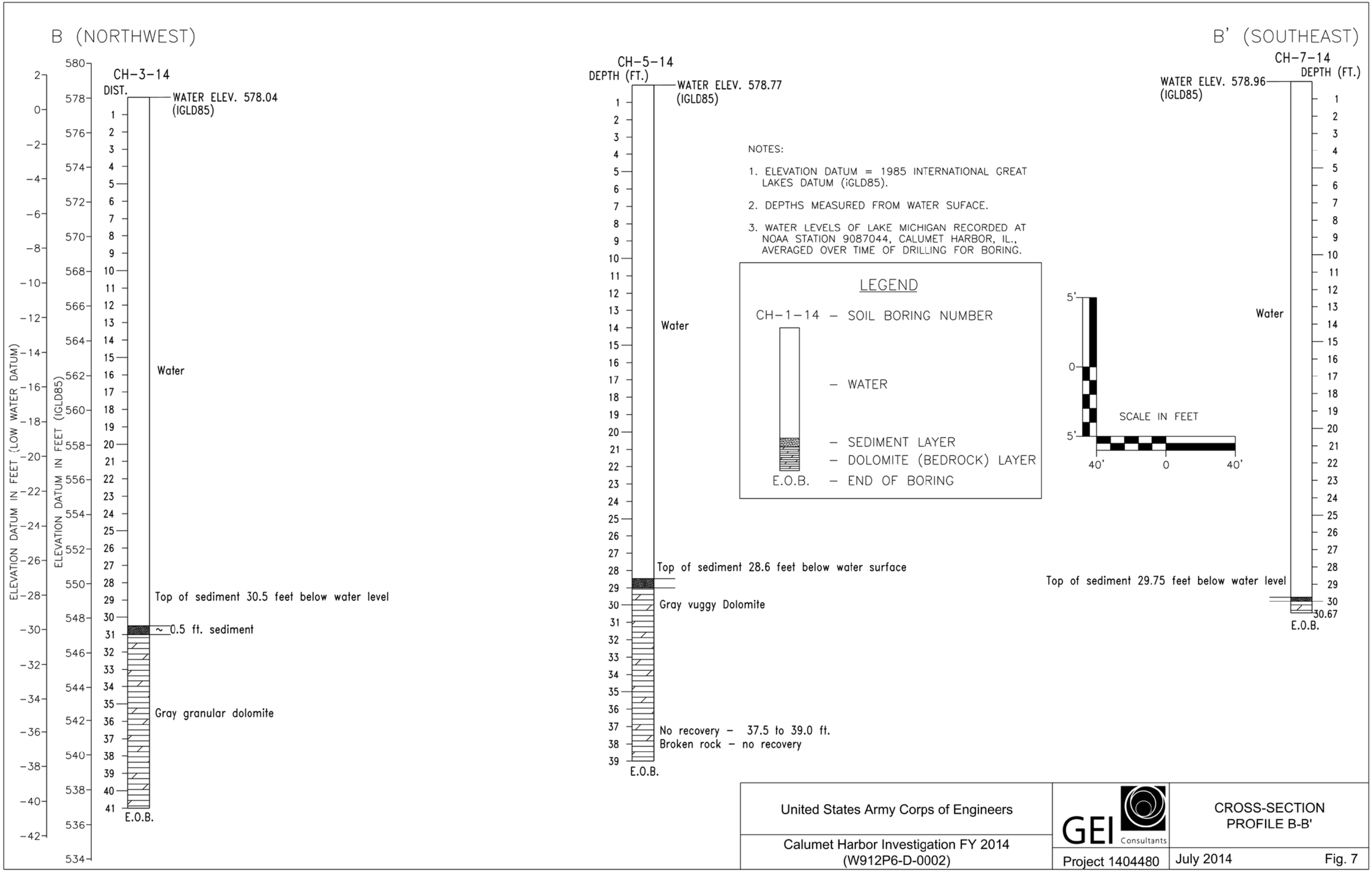
Feet
0 500 1,000 2,000
1 inch = 500 feet

Projected CoordinateSystem: NAD_1983_StatePlane_Illinois_East_FIPS_1201_Feet
Background Imagery: NAIP/Indiana_2012_1m_NC (arcgis on gis.apfo.usda.gov)

United States Army Corps of Engineers	GEI Consultants	LOCATION OF CROSS SECTION PROFILES	
Calumet Harbor Bedrock Investigation FY 2014 (W912P6-14-D-0002)	1404480	DATE: JULY 2014	FIGURE 5

11-JUN-2014 F:\GEI_Consultants_projects\2014\1404480\GIS\mxds\Figure 5_IL.mxd CEF


A (NORTHEAST)
CH-2-14
DEPTH (FT.)
WATER ELEV. 577.91 (IGLD85)
Water
Top of sediment 31 feet below water level.
~8-12" sediment
Gray vuggy Dolomite
Gray vuggy Dolomite
E.O.B.
ELEVATION DATUM IN FEET (LOW WATER DATUM)
ELEVATION DATUM IN FEET (IGLD85)
CH-5-14
DEPTH (FT.)
WATER ELEV. 578.77 (IGLD85)
Water
Top of sediment 28.6 feet below water surface
4.75 inches sediment
Gray vuggy Dolomite
No recovery - 37.5 to 39.0 ft.
Broken rock - no recovery
E.O.B.
A' (SOUTHWEST)
CH-6-14
DEPTH (FT.)
WATER ELEV. 578.97 (IGLD85)
NOTES:
1. ELEVATION DATUM = 1985 INTERNATIONAL GREAT LAKES DATUM (iGLD85).
2. DEPTHS MEASURED FROM WATER SUFACE.
3. WATER LEVELS OF LAKE MICHIGAN RECORDED AT NOAA STATION 9087044, CALUMET HARBOR, IL., AVERAGED OVER TIME OF DRILLING FOR BORING.
Water
LEGEND
CH-1-14 - SOIL BORING NUMBER
- WATER
- SEDIMENT LAYER
- DOLOMITE (BEDROCK) LAYER
E.O.B. - END OF BORING
Top of sediment 29.65 feet below water surface
Fresh gray dolomite, vuggy
SCALE IN FEET
E.O.B.
United States Army Corps of Engineers
Calumet Harbor Investigation FY 2014
(W912P6-D-0002)
GEI Consultants
CROSS-SECTION PROFILE A-A'
Project 1404480
July 2014
Fig. 6


B (NORTHWEST)
B' (SOUTHEAST)
CH-3-14
DIST.
WATER ELEV. 578.04 (IGLD85)
Water
Top of sediment 30.5 feet below water level
~ 0.5 ft. sediment
Gray granular dolomite
E.O.B.
ELEVATION DATUM IN FEET (LOW WATER DATUM)
ELEVATION DATUM IN FEET (IGLD85)
CH-5-14
DEPTH (FT.)
WATER ELEV. 578.77 (IGLD85)
Water
Top of sediment 28.6 feet below water surface
Gray vuggy Dolomite
No recovery - 37.5 to 39.0 ft.
Broken rock - no recovery
E.O.B.
CH-7-14
DEPTH (FT.)
WATER ELEV. 578.96 (IGLD85)
Water
Top of sediment 29.75 feet below water level
30.67
E.O.B.
NOTES:
1. ELEVATION DATUM = 1985 INTERNATIONAL GREAT LAKES DATUM (iGLD85).
2. DEPTHS MEASURED FROM WATER SUFACE.
3. WATER LEVELS OF LAKE MICHIGAN RECORDED AT NOAA STATION 9087044, CALUMET HARBOR, IL., AVERAGED OVER TIME OF DRILLING FOR BORING.
LEGEND
CH-1-14 - SOIL BORING NUMBER
- WATER
- SEDIMENT LAYER
- DOLOMITE (BEDROCK) LAYER
E.O.B. - END OF BORING
SCALE IN FEET
5'
0
40'
United States Army Corps of Engineers
Calumet Harbor Investigation FY 2014
(W912P6-D-0002)
GEI Consultants
Project 1404480
July 2014
CROSS-SECTION PROFILE B-B'
Fig. 7

Appendix B

Tables

- Table 1 – Boring Location, Elevation, and Depth Summary
- Table 2 – Summary of Laboratory Testing Results

TABLE 1
Calumet Harbor Bedrock Investigation - FY2014
Boring Location, Elevation and Depth Summary

Boring No.	Drilled Coordinates[1] Easting	Northing	Date Drilled	Time Drilled[2]	Average Water Level[3] (IGLD85)	Average Water Level (LWD)	Depth of Water (ft)	Overburden Thickness (ft)	Depth to Top of Rock (ft)	Elevation Top of Rock (IGLD85)	Elevation Top of Rock (LWD)	Total Depth Drilled (ft)	Depth Drilled Into Rock (ft)
CH-1-14	1,210,399.9	1,845,089.9	5/31/2014	10:30 - 11:53	578.87	1.53	29.75	3.00	32.75	546.12	-31.22	42.75	10.00
CH-2-14	1,210,459.3	1,844,816.9	4/21/2014	11:20 - 13:55	577.91	0.57	31.00	1.00	32.00	545.91	-31.43	42.00	10.00
CH-3-14	1,210,116.9	1,844,863.4	4/23/2014	12:00 - 13:15	578.04	0.70	30.50	0.50	31.00	547.04	-30.30	41.00	10.00
CH-4-14	1,209,941.6	1,844,759.7	5/31/2014	17:40 - 18:10	578.87	1.53	31.75	0.55	32.30	546.57	-30.77	33.75	1.45
CH-5-14	1,210,268.0	1,844,686.2	5/31/2014	08:15 - 10:00	578.77	1.43	28.60	0.40	29.00	549.77	-27.57	39.00	10.00
CH-6-14	1,210,145.4	1,844,558.6	5/31/2014	12:30 - 13:45	578.97	1.63	29.65	0.08	29.73	549.24	-28.10	39.75	10.00
CH-7-14	1,210,498.5	1,844,488.4	5/31/2014	16:38 - 17:04	578.96	1.62	29.75	0.25	30.00	548.96	-28.38	30.67	0.67
CH-8-14	1,210,383.8	1,844,310.8	5/31/2014	14:15 - 15:10	578.96	1.62	30.50	0.08	30.58	548.38	-28.96	40.50	10.00

Notes:

1 = Projected Coordinate System NAD 1983 State Plane Illinois East FIPS 1201 Feet

2 = All times Central Daylight Time

3 = Water Level of Lake Michigan recorded at NOAA Station 9087044, Calumet Harbor, IL, averaged over time of drilling for boring. Water level elevation in 1985 International Great Lakes Datum (IGLD85)

LWD = Low Water Datum. LWD elevation = IGLD elevation - 577.34

Location data have been corrected to +-6 inches accruacy

TABLE 2
Calumet Harbor Bedrock Investigation - FY2014
Uniaxial Compressive Strength Testing Summary

Boring No.	Depth (feet below water surface)	Elevation (feet) of Sample (IGLD85)	Elevation (feet) of Sample (LWD)	Uniaxial Compressive Strength (psi)
CH-1-14	33.4 to 33.9	545.47 to 544.97	-31.87 to -32.37	2,880
CH-2-14	32.0 to 32.5	545.91 to 545.41	-31.43 to -31.93	7,755
CH-2-14	35.0 to 35.5	543.04 to 542.54	-34.30 to -34.80	3,765
CH-3-14	35.5 to 36.0	543.37 to 542.87	-33.97 to -34.47	3,145
CH-5-14	34.5 to 35.0	544.27 to 543.77	-33.07 to -33.57	6,085
CH-6-14	32.1 to 32.6	546.87 to 546.37	-30.47 to -30.97	6,950
CH-7-14	30.1 to 30.6	548.86 to 548.36	-28.48 to -28.98	3,605
CH-8-14	34.0 to 34.4	544.96 to 545.56	-32.38 to -32.78	5,855

psi = pounds per square inch

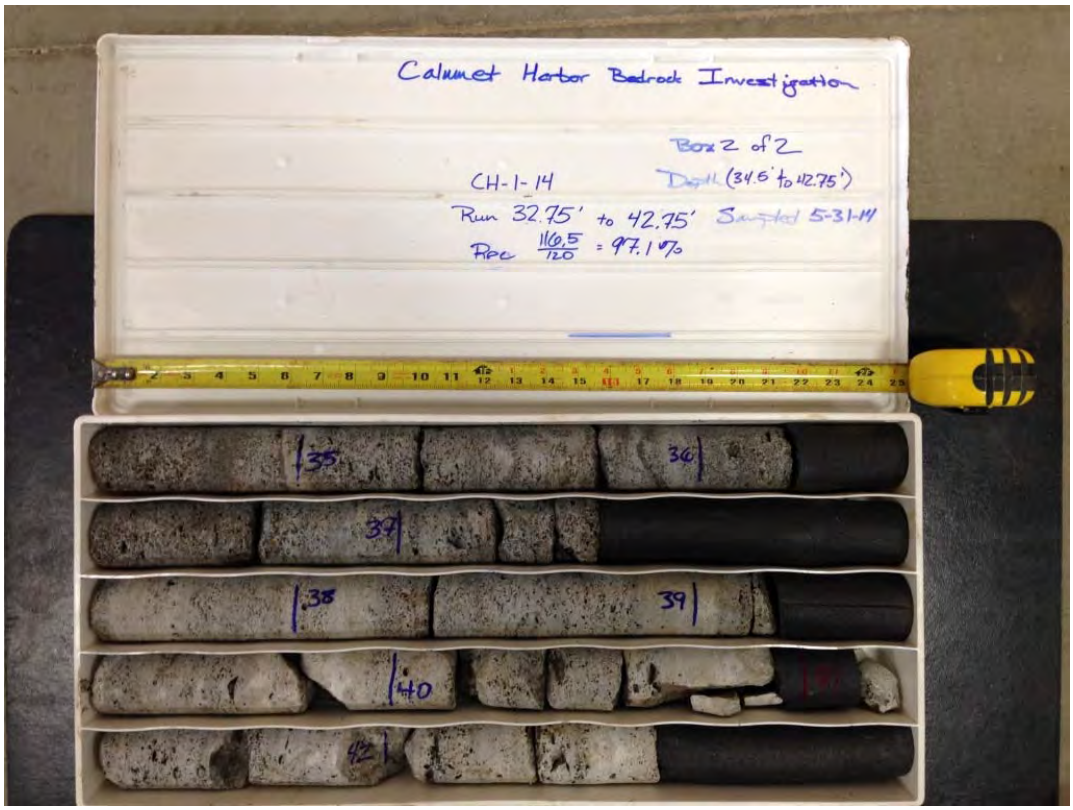
IGLD85 = 1985 International Great Lakes Datum, recorded at NOAA Station 9087044, Calumet Harbor, IL, averaged over time of drilling for boring.

LWD = Low Water Datum. LWD elevation = IGLD elevation - 577.34

Appendix C

Photographs

Boring CH-1-14, Box 1 of 2, 32.75 feet to 34.5 feet depth.



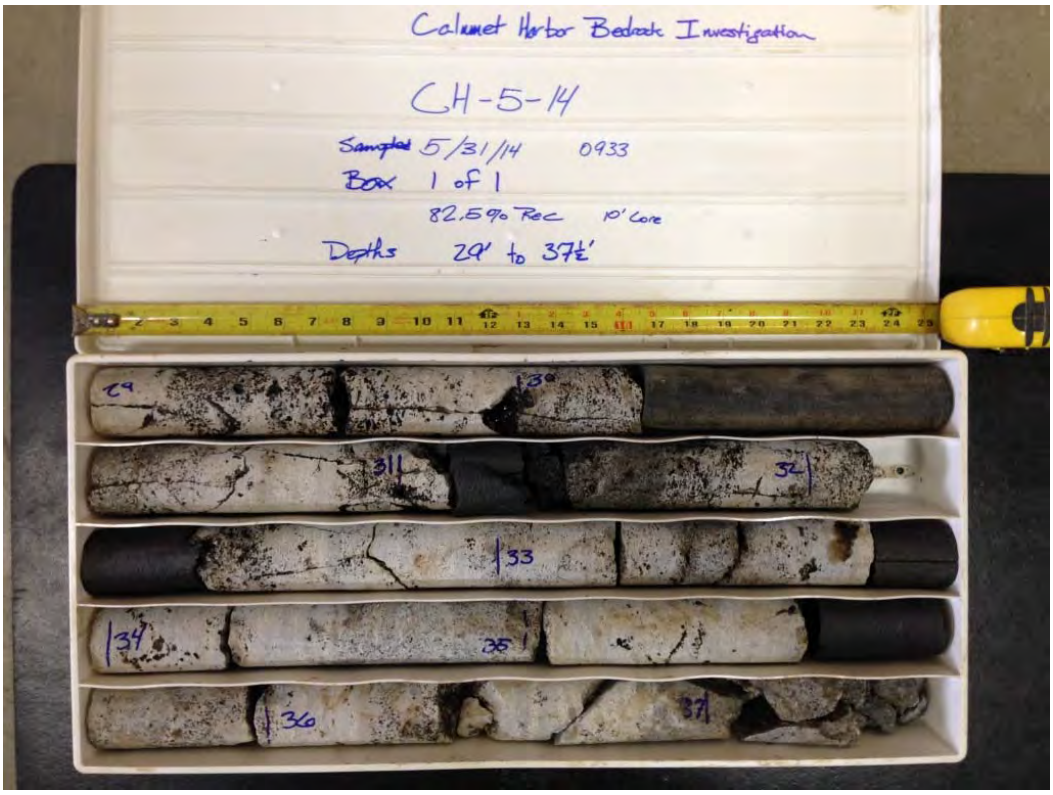
Boring CH-1-14, Box 2 of 2, 34.5 feet to 42.75 feet depth.

Boring CH-2-14, Box 1 of 1, 32 feet to 42 feet depth.

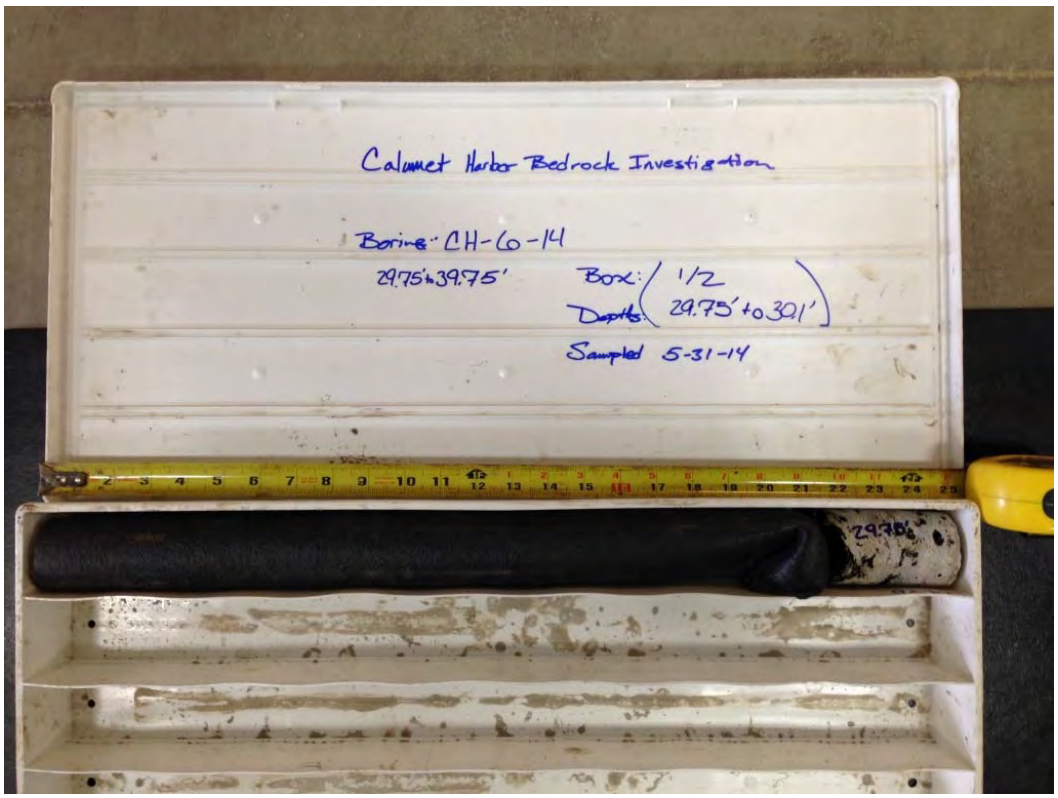
Boring CH-2-14, close-up of core to show vuggy nature of dolomite, with pyrite and bitumen in vugs.

Boring CH-2-14, close-up of core to show vuggy nature of dolomite.

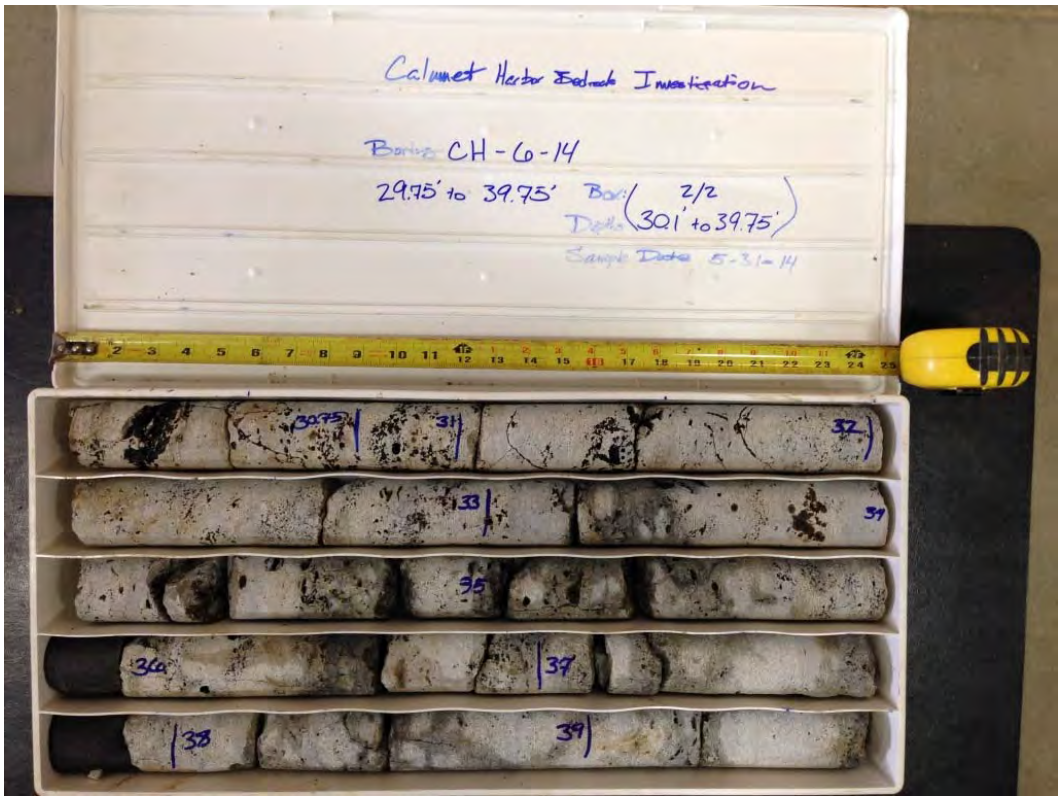
Boring CH-3-14, Box 1 of 1, 31 feet to 41 feet depth.



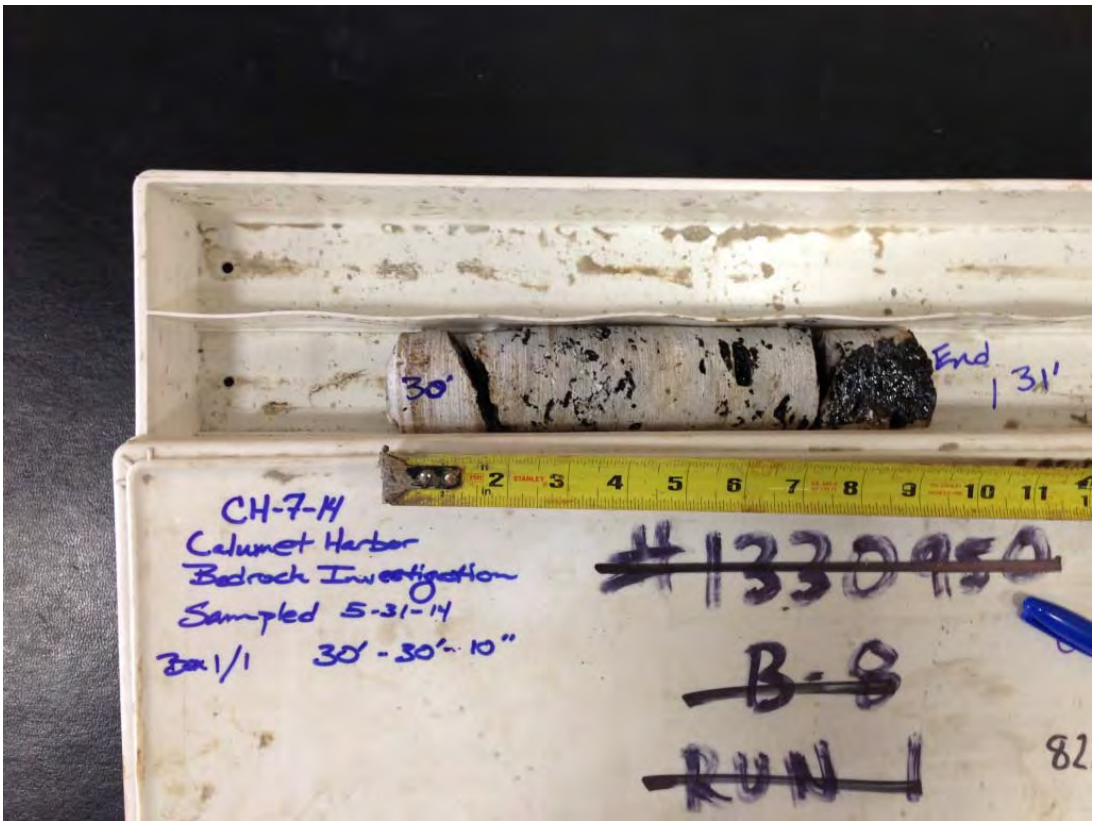
Boring CH-5-14, Box 1 of 1, 29 feet to 37.5 feet depth.



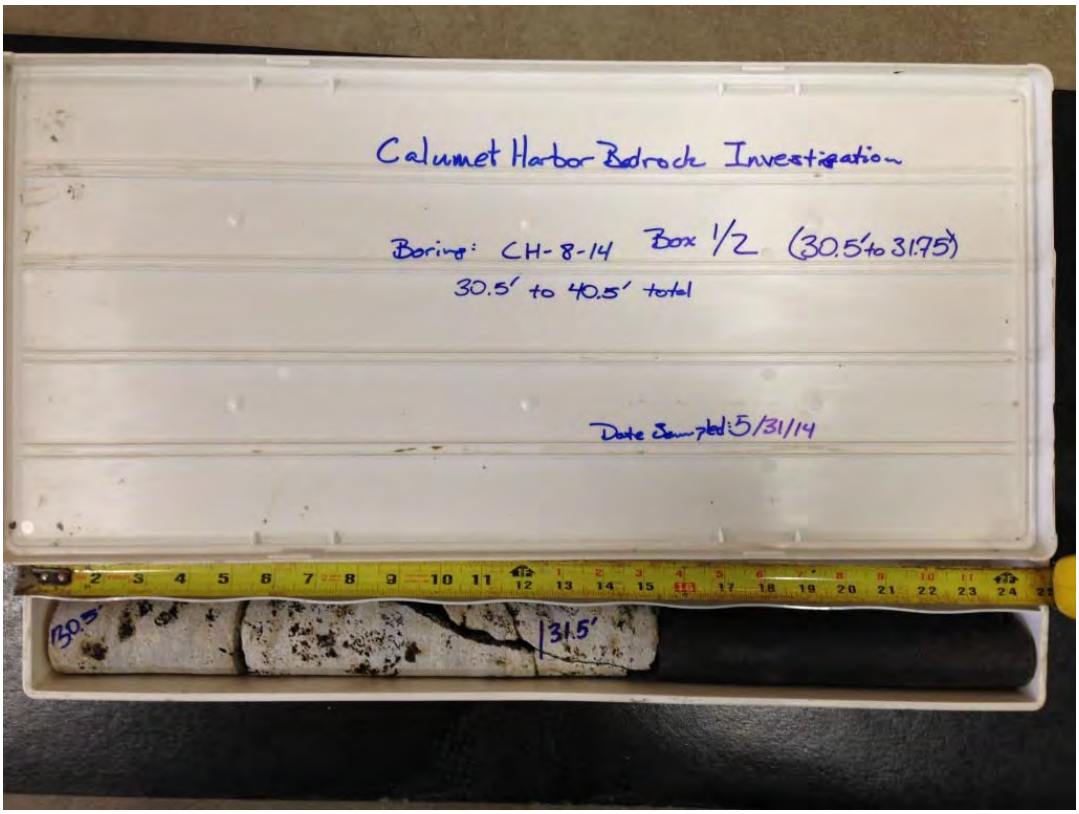
Boring CH-6-14, Box 1 of 2, 29.75 feet to 30.1 feet depth.



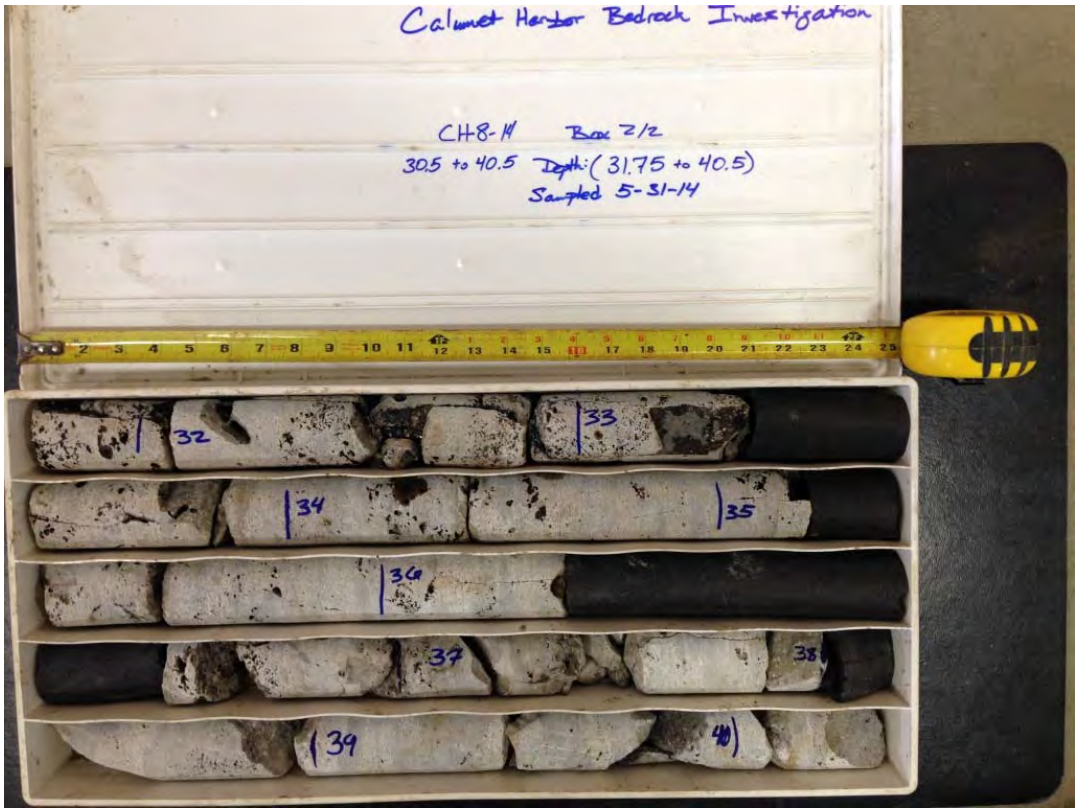
Boring CH-6-14, Box 2 of 2, 30.1 feet to 39.75 feet depth.



Boring CH-7-14, Box 1 of 1, 30 feet to 30.67 feet depth.



Boring CH-8-14, Box 1 of 2, 30.5 feet to 31.75 feet depth.



Boring CH-8-14, Box 2 of 2, 31.75 feet to 40.5 feet depth.

Appendix D

Boring Logs

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,845,089.9 E 1,210,399.9
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-1-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	3.00 ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	42.75 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 3 / UNDISTURBED
14. TOTAL NUMBER CORE BOXES	2
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 5/31/2014 / COMPLETED 5/31/2014
17. ELEVATION TOP OF HOLE	578.9 ft. IGLD85, 1.53 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	97 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1–32		Top of sediment 29.75 feet below water surface **<<Water Depth Approx. 29.75 ft.** 29.00-30.75 - Clay, gray, very soft, trace sand 30.75-31.25 - Clay, little sand, medium to stiff Qp = 1.0 31.25-32.25 - Weathered dolomite and clay			Top of boring measured from water surface
	33–42		Rock at 32.75' Vuggy dolomite, fresh, aphanitic to coarse grained Vugs 1 mm to 1 cm diameter Pyrite in vugs common. Small calcite crystals in vugs common - trace bitumen inclusions Fracture surfaces clean	97	Run #1 32 ft. to 42 ft. RQD = 82.9%	Began coring 11:05 End coring 11:34
	43–45		End of Boring at 42.75 feet below water level			

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE

PROJECT Calumet Harbor Bedrock Investigation

HOLE NO. CH-1-14

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,816.9 E 1,210,459.3
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-2-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 1 ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	42 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 0 / UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES	2
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 4/21/2014 / COMPLETED 4/21/2014
17. ELEVATION TOP OF HOLE	577.9 ft. IGLD85, 0.57 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	100 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1		Top of sediment 31 feet below water level.			Measured from water level, not barge deck
	2		~8-12" sediment			
	3					Top of boring measured from water surface
	4		19 blows for first 6"in spoon			
	5		Clayey silt with pebbles, gray, moist			
	6					
	7					
	8					
	9					
	10					
	11					
	12					
	13					
	14					
	15					
	16					
	17					
	18					
	19					
	20					
	21					
	22					
	23					
	24					
	25					
	26					
	27					
	28					
	29					
	30					
	31		**<<Water Depth Approx. 31.0 ft.**			
	32					
	33		Gray vuggy Dolomite - granular - abundant pyrite in vugs, up to ~10% in rock	98	Run #1	Began coring at 32 ft. below top water
	34		Abundant vugs and pores (to ~25%) ranging in size from 1 mm to 10 mm		32 ft. to 37 ft.	Began @ 13:25 - End @ 13:35
	35		Also black bitumen with pyrite		RQD = 96%	Horizontal fractures likely along bedding - tight but opened during drilling - contain gray clay
	36		Fracture 36.25 to 36.4 feet - smooth, clay covered			
	37					
	38		Same as above - slightly less vugs, but overall larger, some fossil casts as vugs	100	Run #2	Began @ 13:45 - End @ 13:55
	39				37 ft. to 42 ft.	
	40				RQD = 85%	
	41					
	42					
	43		End of Boring at 42.0 feet below water level			
	44					
	45					

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,863.4 E 1,210,116.9
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-3-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 0.5 ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	41 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 0 / UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES	1
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 4/23/2014 / COMPLETED 4/23/2014
17. ELEVATION TOP OF HOLE	578.0 ft. IGLD85, 0.70 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	85 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1–30		Top of sediment 30.5 feet below water level ~ 0.5 ft. sediment Began coring at 31.0 ft. below water surface **<<Water Depth Approx. 30.5 ft.**			Top of boring measured from water surface
	31–40		Gray granular dolomite with pyrite up to 10%. Multiple pores and vugs from 1 mm to 20 mm ~ 25% of rock medium hard (scratched with knife) Fresh, non-weathered Some calcite and Pyrite in pores and vugs, mostly open Fractures generally fresh, no clay or other coatings	85	Run #1 31 ft. to 41 ft. RQD = 74%	Began @ 12:37 - End @ 12:59 32.35 to 32.5 ft - 45° fracture 33.0 to 34.0 ft - Vertical fracture Clean - no filling 34.0 to 34.5 ft - Very fractured, many pieces 37.0 to 39.0 ft - Very fractured, no good pieces
	41–45		End of Boring at 41.0 feet below water level			Decent recovery but poor RQD - much fractured. Boat bobbing as much as 6" during drilling

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Calumet Harbor Bedrock Investigation HOLE NO. CH-3-14

DRILLING LOG

Calumet Harbor Maintenance Dredging FY14

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,759.7 E 1,209,941.6
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-4-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 0.5 ft
8. DEPTH DRILLED INTO ROCK	1.45 ft
9. TOTAL DEPTH OF HOLE	33.75 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 2 / UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES	0
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 5/31/2014 / COMPLETED 5/31/2014
17. ELEVATION TOP OF HOLE	578.9 ft. IGLD85, 1.53 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	0 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1		Top of sediment 31.75 feet below water level			Top of boring measured from water surface
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	10					
	11					
	12					
	13					
	14					
	15					
	16					
	17					
	18					
	19					
	20					
	21					
	22					
	23					
	24					
	25					
	26					
	27					
	28					
	29					
	30		**<<Water Depth Approx. 31.75 ft.**			
	31		Muck: Clay, little sand, gray, very soft (CL)			~ 6 to 8 inch penetration by SPT, about 18" recovered assuming extra 10 to 12 inches is very soft muck
	32		Silt: Silty, hard, trace gravel, gray (ML)			
	33		Top of rock approx. 32.3 ft.			
	34		Augered with rock bit 32.75 to 33.75			
	35		End of Boring at 33.75 feet below water level			No rock cored - lost core bit on previous boring
	36					
	37					
	38					
	39					
	40					
	41					
	42					
	43					
	44					
	45					

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE.

PROJECT Calumet Harbor Bedrock Investigation

HOLE NO. CH-4-14

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,686.2 E 1,210,268.0
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-5-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 0.4 ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	39 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 1 / UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES	1
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 5/31/2014 / COMPLETED 5/31/2014
17. ELEVATION TOP OF HOLE	578.8 ft. IGLD85, 1.43 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	82.5 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1		Top of sediment 28.6 feet below water surface			Top of boring measured from water surface
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	10					
	11					
	12					
	13					
	14					
	15					
	16					
	17					
	18					
	19					
	20					
	21					
	22					
	23					
	24					
	25					
	26		4.75 inches sediment recovered -- 2" gravel, fine, gray			
	27		2.75" clay with fine gravel			
	28		**<<Water Depth Approx. 28.6 ft.**			
	29					
	30		Gray vuggy Dolomite, vugs - 1 to 5 mm in diameter, often with bitumen and pyrite.	83	Run #1	Began @ ~ 09:00 - End @ 09:25
	31		Fracture surface at 29.5 feet, smooth		29 ft. to 39 ft.	
	32		Fracture at 30.25 feet			
	33		Gravel 31.0 to 31.5 - 1", clean with sand and fine sand.		RQD = 72%	
	34		Mechanical break at 33.25 ft.			
	35					
	36					
	37		No recovery - 37.5 to 39.0 ft.			
	38		Broken rock - no recovery			
	39					
	40		End of Boring at 39.0 feet below water level			
	41					
	42					
	43					
	44					
	45					

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Calumet Harbor Bedrock Investigation HOLE NO. CH-5-14

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,558.6 E 1,210,145.4
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-6-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 0.1 or less ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	39.75 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED: 1 UNDISTURBED:
14. TOTAL NUMBER CORE BOXES	2
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED: 5/31/2014 COMPLETED: 5/31/2014
17. ELEVATION TOP OF HOLE	579.0 ft. IGLD85, 1.63 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	100 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1–29		Top of sediment 29.65 feet below water surface **<<Water Depth Approx. 29.65 ft.** **29.65 - 29.73 ft. - 1-inch clayey gravel**			Top of boring measured from water surface ~ 1" weathered layer above competent rock
	30–39		Fresh gray dolomite, vuggy (1 mm to 3 typical). Aphanitic to sand size grains in rock. Occasional vug - 2 cm by 5 to 10 mm high. Vugs frequently filled partially with bitumen recrystalized material, pyrite	100	Run #1 29.73 ft. to 39.75 ft. RQD = 75.6%	Core Began @ 12:40 - End @ ~ 13:12 Fracture surfaces nearly horizontal, some appear to have opened during drilling. Generally clean, fairly smooth Hairline vertical cracks, closed/cemented; not continuous through core
	40–45		End of Boring at 39.75 feet below water level			

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Calumet Harbor Bedrock Investigation HOLE NO. CH-6-14

Calumet Harbor Maintenance Dredging FY14

DRILLING LOG

DIVISION: USACE Chicago District

INSTALLATION:

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,488.4 E 1,210,498.5
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-7-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	0.25 ft
8. DEPTH DRILLED INTO ROCK	0.7 ft
9. TOTAL DEPTH OF HOLE	30.67 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 1 / UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES	N/A
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 5/31/2014 / COMPLETED 5/31/2014
17. ELEVATION TOP OF HOLE	579.0 ft. IGLD85, 1.62 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	N/A %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1		Top of sediment 29.75 feet below water level			Top of boring measured from water surface
	2					Spoon driven about 3" in 3 blows, then refusal on rock
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	10					
	11					
	12					
	13					
	14					
	15					
	16					
	17					
	18					
	19					
	20					
	21					
	22					
	23					
	24					
	25					Began coring at 16:56
	26					
	27					
	28					
	29		**<<Water Depth Approx. 29.75 ft.** Split spoon driven approx. 3": 29.75 - 30.0 ft.			
	30			100	Run #1 30.0 ft. - 30.67 ft. RQD = 63%	
	31		End of Boring at 30.67 feet			
	32					
	33					
	34					Wind picked up at 17:00, large wave picked casing up off bottom, picked barrel/core up off hole. Could not reset.
	35					
	36					Hole was pulled after grinding for several minutes at attempt re-set.
	37					
	38					
	39					
	40					
	41					
	42					
	43					
	44					
	45					

DRILLING LOG

Calumet Harbor Maintenance Dredging FY14
DIVISION USACE Chicago District

INSTALLATION

SHEET 1 OF 1 SHEETS

1. PROJECT	Calumet Harbor Bedrock Investigation
2. LOCATION (Coordinates or Station)	Ill. St. Plane East NAD83 N 1,844,310.8 E 1,210,383.8
3. DRILLING AGENCY	Strata Earth Services
4. HOLE NO. *(As shown on drawing title and file number)*	CH-8-14
5. NAME OF DRILLER	Bill McCarthy
6. DIRECTION OF HOLE	[X] VERTICAL [ ] INCLINED _____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN	~ 0.1 or less ft
8. DEPTH DRILLED INTO ROCK	10 ft
9. TOTAL DEPTH OF HOLE	40.5 ft
10. SIZE AND TYPE OF BIT	NX diamond core
11. DATUM FOR ELEVATION SHOWN *(TBM or MSL)*	Water Level - Calumet Harbor
12. MANUFACTURER'S DESIGNATION OF DRILL	
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 1 / UNDISTURBED
14. TOTAL NUMBER CORE BOXES	2
15. ELEVATION GROUND WATER	NM
16. DATE HOLE	STARTED 5/31/2014 / COMPLETED 5/31/2014
17. ELEVATION TOP OF HOLE	579.0 ft. IGLD85, 1.62 ft. LWD
18. TOTAL CORE RECOVERY FOR BORING	92 %
19. SIGNATURE OF INSPECTOR	

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 weathering, etc., if significant)* g
	1		Top of sediment 30.5 feet below water surface			Top of boring measured from water surface
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	10					
	11					
	12					
	13		Spoon refusal w/0"			
	14					
	15		A few fine gravel pieces retrieved			
	16					
	17					
	18					
	19					
	20					
	21					
	22					
	23					
	24					
	25					
	26					
	27					
	28					
	29					
	30		**<<Water Depth Approx. 30.5 ft.**			
	31		Fresh gray vuggy dolomite - sand-sized grains to fine grained	92	Run #1	Core Began @ 14:35 - End @ ~ 15:02
	32		Some vertical joints/fractures nearly through center of core		30.5 ft. to 40.5 ft.	Vugs 1 mm to 5 mm diameter, typical
	33		Bitumen and pyrite frequently in vugs.			
	34		5 to 10% vugs to 33.5 ft.			
	35		< 5% from 33.5 to 40.5 ft.		RQD = 59.8%	
	36		Fractured surfaces generally clean, more non-horizontal than previous cores.			
	37					
	38					
	39		Estimate 1.5 in. loss at bottom			
	40					
	41		End of Boring at 40.5 feet below water level			
	42					
	43					
	44					
	45					

Appendix E

Laboratory Test Results

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-1-14	Checked By:	BCM	Date:	6/24/2014
Depth:	33.4'-33.9'	Sample ID No.:	NA		
Rock Description:	Limestone Gray				

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1) 0.0003	2) 0.0002	3) 0.0005	in.;	<0.0010	Yes			
Squarness: >0.01 in. gap at 2 in'	No	If Yes, 0.01 in. at		in.					
Sides: Max. Amplitude	1) 0.006	2) 0.007	3) 0.003	in.	< 0.01 in.?	Yes			

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.1165	2) 4.0995	3) 4.1220	Avg.	4.1127	in.		
Diameter (in):	1) 2.015	2) 2.000	3) 2.033	Avg.	2.016	in.	Area (in)^2	3.19

Uniaxial Compressive Strength: **2880** psi Weight: 519.14 grams

L/D: **2.0** Weight: 1.143 lbs.

Load: **9190** lbs. **Unit Weight:** **150.5** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-2-14	Checked By:	BCM	Date:	6/24/2014
Depth:	32.0'-32.5'	Sample ID No.:	NA		
Rock Description:	Limestone Gray				

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1) 0.0005	2) 0.0005	3) 0.0007	in.;	<0.0010	Yes			
Squarness: >0.01 in. gap at 2 in'	No	If Yes, 0.01 in. at		in.					
Sides: Max. Amplitude	1) 0.008	2) 0.005	3) 0.004	in.	< 0.01 in.?	Yes			

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.0454	2) 4.0505	3) 4.0430	Avg.	4.0463	in.		
Diameter (in):	1) 2.009	2) 2.013	3) 2.022	Avg.	2.014	in.	Area (in)^2	3.19

Uniaxial Compressive Strength: **7755** psi Weight: 557.42 grams

L/D: **2.0** Weight: 1.228 lbs.

Load: **24700** lbs. **Unit Weight:** **164.6** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-2-14	Checked By:	BCM	Date:	6/24/2014
Depth:	35.0'-35.5'	Sample ID No.:	NA		
Rock Description:	Limestone Gray				

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1) 0.0001	2) 0.0007	3) 0.0005	in.;	<0.0010	Yes			
Squarness: >0.01 in. gap at 2 in'	No	If Yes, 0.01 in. at		in.					
Sides: Max. Amplitude	1) 0.003	2) 0.004	3) 0.003	in.	< 0.01 in.?	Yes			

Angle of Core Axis to Bedding: 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.0705	2) 4.0490	3) 4.0515	Avg.	4.0570	in.		
Diameter (in):	1) 2.046	2) 2.034	3) 2.052	Avg.	2.044	in.	Area (in)^2	3.28

Uniaxial Compressive Strength: **3765** psi Weight: 554.37 grams

L/D: **2.0** Weight: 1.221 lbs.

Load: **12350** lbs. **Unit Weight:** **158.6** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:	PENDING	Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-5-14	Checked By:	BCM	Date:	6/24/2014
Depth:	34.5'-35.0'	Sample ID No.:	NA		
Rock Description:					

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1) 0.0002	2) 0.0007	3) 0.0005	in.;	<0.0010	Yes		
Squarness: >0.01 in. gap at 2 in'	No	If Yes, 0.01 in. at		in.				
Sides: Max. Amplitude	1) 0.002	2) 0.004	3) 0.004	in.	< 0.01 in.?	Yes		

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.0025	2) 4.0120	3) 4.0080	Avg.	4.0075	in.		
Diameter (in):	1) 2.022	2) 2.023	3) 2.024	Avg.	2.023	in.	Area (in)^2	3.21

Uniaxial Compressive Strength: **6085** psi Weight: 553.23 grams

L/D: **2.0** Weight: 1.219 lbs.

Load: **19550** lbs. **Unit Weight:** **163.5** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-3-14	Checked By:	BCM	Date:	6/24/2014
Depth:	35.5'-36.0'	Sample ID No.:	NA		
Rock Description:					

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1)	0.0006	2)	0.0008	3)	0.0005	in.;	<0.0010	Yes
Squarness: >0.01 in. gap at 2 in'		No		If Yes, 0.01 in. at			in.		
Sides: Max. Amplitude	1	0.006	2)	0.005	3)	0.005	in.	< 0.01 in.?	Yes

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1)	4.0180	2)	4.0445	3)	4.0330	Avg.	4.0318	in.	
Diameter (in):	1)	2.036	2)	2.031	3)	2.030	Avg.	2.032	in.	Area (in)^2 3.24

Uniaxial Compressive Strength: **3145** psi Weight: 528.25 grams

L/D: **2.0** Weight: 1.164 lbs.

Load: **10190** lbs. **Unit Weight:** **153.8** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-6-14	Checked By:	BCM	Date:	6/24/2014
Depth:	32.1'-32.6'	Sample ID No.:	NA		
Rock Description:					

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1)	0.0005	2)	0.0003	3)	0.0004	in.;	<0.0010	Yes
Squarness: >0.01 in. gap at 2 in'		No		If Yes, 0.01 in. at			in.		
Sides: Max. Amplitude	1	0.005	2)	0.002	3)	0.007	in.	< 0.01 in.?	Yes

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1)	4.0115	2)	4.0185	3)	4.0155	Avg.	4.0152	in.	
Diameter (in):	1)	2.035	2)	2.026	3)	2.028	Avg.	2.030	in.	Area (in)^2 3.23

Uniaxial Compressive Strength: **6950** psi Weight: 578.04 grams

L/D: **2.0** Weight: 1.273 lbs.

Load: **22470** lbs. **Unit Weight:** **169.4** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:		Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-7-14	Checked By:	BCM	Date:	6/24/2014
Depth:	30.1'-30.6'	Sample ID No.:	NA		
Rock Description:					

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude	1) 0.0006	2) 0.0008	3) 0.0004	in.;	<0.0010	Yes			
Squarness: >0.01 in. gap at 2 in	No	If Yes, 0.01 in. at	in.						
Sides: Max. Amplitude	1) 0.005	2) 0.007	3) 0.005	in.	< 0.01 in.?	Yes			

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.0675	2) 4.0645	3) 4.0670	Avg.	4.0663	in.		
Diameter (in):	1) 2.026	2) 2.013	3) 2.021	Avg.	2.020	in.	Area (in)^2	3.20

Uniaxial Compressive Strength: **3605** psi Weight: 571.54 grams

L/D: **2.0** Weight: 1.259 lbs.

Load: **11540** lbs. **Unit Weight:** **166.9** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

AECOM

UNIAXIAL COMPRESSIVE STRENGTH
ASTM D 7012
Method C

Laboratory Services Group *750 Corporate Woods Parkway Vernon Hills, Il 60061* *Phone: (847) 793-0306* *Fax: (847) 793-0309*

Project No.:	PENDING	Tested By:	EMR	Date:	6/24/2014
Project Name:	CALUMET HARBOR	Calculated By:	EMR	Date:	6/24/2014
Boring No.	CH-8-14	Checked By:	BCM	Date:	6/24/2014
Depth:	34.0'-34.4	Sample ID No.:	NA		
Rock Description:					

Rock Sample Moisture Condition: [x] As Received [ ] In-Situ [ ] Saturated [ ] Oven Dry

TOLERANCE CHECK

End Flatness: Max. Amplitude 1) 2) 3) in.; <0.0010 Yes

Squarness: >0.01 in. gap at 2 in' No If Yes, 0.01 in. at in.

Sides: Max. Amplitude 1) 2) 3) in. < 0.01 in.? Yes

Angle of Core Axis to Bedding 90 deg Stress or Strain Rate: 0.03 % / min.

Length (in):	1) 4.0450	2) 4.0425	3) 4.0380	Avg.	4.0418	in.			
Diameter (in):	1) 2.025	2) 2.034	3) 2.030	Avg.	2.030	in.	Area $(in)^2$	3.23

Uniaxial Compressive Strength: **5855** psi Weight: 582.05 grams

L/D: **2.0** Weight: 1.282 lbs.

Load: **18930** lbs. **Unit Weight:** **169.4** pcf

YOUNG'S MODULUS		
Et (50% Co)	-	x 10^5 psi
Es (50% Co)	-	

POISSON'S RATIO	
Vt (50% Co)	-
Vs (50% Co)	-

REMARKS:

Before

After

Attachment 2

Narrative from Pilot-Scale Study of Rock Removal
from Calumet Harbor by Luhr Bros Inc. – FY2015

DRAFT

Brandon Beckemeyer
Luhr Bros., INC.
250 W. Sand Bank Rd
Columbia, IL 62236

United States Army Corps of Engineers
Calumet Area Office
906 N. Griffth Blvd
Griffith, IN 46319

Hard Overburden materials and Bedrock Excavation and Removal Revised 7/12/2015

- Summary of Conditions

The work area was in the Calumet Harbor at a depth ranging from -28 LWD to -30 LWD. The material to be removed was a hard bedrock, which can be seen in Figure 3 - 6 and Figures 14 – 19. It is believed to be bedrock. The work area and surrounding areas have little to no sediment on top of the bedrock.

- Means and Methods

Rock removal was performed using two Cat 385 excavators on a 200' x 50' spud barge. One excavator was equipped with a 5.5 CY rock excavation bucket to remove broken rock. The other was equipped with a NPK hydraulic hammer, model GH30, used to fracture and the rock so it can be removed by the excavation bucket. An 850 HP switch boat, the M/V Jay Gene, was used to assist in maneuvering the work barge and material barge. A RTK global positioning system was used to setup the spud barge. Personnel required during operation was one superintendent,

one field engineer, one operator (for the excavator), one operator (for the spud wenches), and the boat crew of one pilot and one deck hand.

- Operations

The hammer was used to break up the rock working a 30' wide by 20' long area. The first day the entire 50' x 50' area was covered with the hammer which had a chisel tip installed taking nine hours to complete. The second day the rock bucket was used to scrape broken material off of the work area. After preforming a survey it was determined that only approximately 0.4' was removed from the work area. Before resuming hammering, the chisel tip was swapped out with a point tip that had a tungsten core. The hardened tip appeared to be penetrating the bedrock deeper and with less difficulty. Unlike the first day where the entire work area was covered we decided to decrease the space between hammer blows attempting to penetrate the bedrock deeper trying to achieve the final grade after this pass. This caused us to only work portions of the work area each day. Figure 24 shows the different areas worked on each set of the barge. The arc shows the approximate arc the excavator could work while swinging side to side on the barge. On the second day areas 1, 7, and 8 were worked. On day three work continued on area 8 and then progressed to area 9, 2, 3, and 4. On day 4 work continued in area 4 and progressed to area 5. Work slowed due to ware on the hardened point and work was stopped on day 4 early due to a mechanical failure. On day 5 the mechanical failure was repaired and the hardened point was switched out for the chisel tip that was used originally being used and areas 5, 6, 10, and 11 were worked. On day 6 the work area was finished by completing area 11 and 12 then excavating the entire work area with the other excavator.

- Rates of Progress

After the 69 hours of work was completed we had removed 58 CY of material from the work area making it an average of 0.84 CY/HR. If the area was increased form the 50ft by 50ft to a 60ft by 60ft the survey showed the removal of 61 CY making it an average of 0.88 CY/HR. There may be more broken material left in the work area that passed through the 6in digging teeth on the bucket which could be up to another 30 CY left in the digging area. From field experience we were able to hammer a 10ft by 30ft area with a new tip in about 2 hours. Once the tip started to wear down the rate slowed to 3 to 5 hours to hammer a 10ft by 30ft area. After talking to the manufacture of the harden tip they requested us to send it back so they could determine if it was faulty. The hardened core inside the tip was determined to be defective and large portions of the core should not have fractured off the core. They did not give and estimated hours of operation that the tip should last but assured us that it was unusual for the hardened core to fracture as we experienced. A breakdown of the hours spent hammering, hours spent excavating, and hours worked each day can be found in the appendix. Hours not spent hammering or excavating were spent traveling to and from the work area, equipment repair, and daily preventative maintenance on the machines.

The entire work area was not able to be taken down to final grad after the six days of work. Figures 25 to 29 show the final survey that was taken on the sixth day with a multibeam sounder. Figures 25 and 26 are maps showing how much cut or fill would be required to reach final grade. The – symbol means that material would have to be removed to achieve final grade and the + symbol means that material was removed below final grade. The median of all the points in a 1x1 area was used in Figure 25 to create the cut fill map and the median of a 5x5 area was used in Figure 26 to create the cut fill map. In Figures 27 to 29 cross-sections were extracted from the

multibeam data. The red line shows the original conditions prior to the hard rock removal. The blue line shows the final grad achieved after the six days of hammering. The green line shows the desired grade for the finished work area. While the desired grade was not achieved over the entire work area it was determined that enough information was collected for the test and more hammering was not necessary.

- Difficulties

The first difficulty encountered was the ability to maintain position over the work area. The bedrock, having no silt on top of it did not give the spuds of the barge anything to penetrate into to hold the barge in place while working. This would cause the barge to slide, which would then move the machine out of the work area. To combat this issue we used the boat to help hold the barge from sliding forward and we used the Cat 385 with the digging bucked to provide extra hold with its bucket being set on the bedrock. We believe if the barge would have had four spuds instead of just two it would have held its position better. It would also been helpful to have a dredge positioning system installed in the excavator so the operator would be able to see and monitor the movement of the barge. This system would also tell the operator the depth of penetration, angle of the implement, and show what areas have been worked. It was also difficult to get started breaking the bedrock. With the bedrock being a solid sheet there was no room for the hammer to expand the rock to allow it to crack and break apart. The bedrock appeared to break apart easier once there was and vertical edged to break off from. Starting in the middle of the work area where there is no relief is difficult and takes a substantial amount of time and effort.

- Other Methods to Consider

An alternative method suggested would be to drill the bedrock before hammering to allow some relief for the bedrock to break. It would use the same theory as drilling and blasting by providing holes for the rock to fracture to but instead of using explosives the hydraulic hammer would be used to fracture the rock.

Appendix

Time Summary of Calumet Rock Removal			
Hours Worked			
Date	Hammering	Digging	Shift Length
4/29/2015	9	0	11
5/1/2015	9	2	12
5/2/2015	10	0	12
5/3/2015	7	0	10
5/4/2015	9	0	12
5/5/2015	6	5	12
Total	50	7	69

Equipment Summery of Calumet Rock Removal						
Equipment Used						
	4/29/2015	5/1/2015	5/2/2015	5/3/2015	5/4/2015	5/5/2015
M/V Jay Gene	X	X	X	X	X	X
L1108	X	X	X	X	X	X
Cat 385 with Hydraulic Hammer	X	X	X	X	X	X
Cullair Air Compressor	X	X	X	X	X	X
Cat 385 with Digging Bucket		X				X
LB151 Survey Boat	X	X	X	X	X	X

Personnel Needed	
Labor Classification	Labor Count
Supervision	1
Engineering	1
Operator per machine	1
Spud Man per barge	1
Mechanic	As Needed

Figure 1 Condition of the hammer after day one

Figure 2 red dot marks the depth needed to reach grade

Figure 3 rock picked up on day two

Figure 4 rock picked up on day two

Figure 5 rock picked up on day two

Figure 6 rock picked up on day two

Figure 7 condition of point after day two (first day used)

Figure 8 condition of point after day two (first day used)

Figure 9 condition of point after day three (second day used)

Figure 10 condition of point after day two (first day used)

Figure 11 condition of point after day three (second day used)

Figure 12 condition of point after day third (second day used)

Figure 13 condition of point after day four (third day used)

Figure 14 rock removed on day six

Figure 15 rock removed on day six

Figure 16 rock removed on day six

Figure 17 rock removed on day six

Figure 18 rock removed on day six

Figure 19 rock removed on day six

Figure 20 condition of tip on day six (after three days of use)

Figure 21 condition of tip on day six (after three days of use)

Model GH30 | Specifications | Media | FAQ | Compatibility

Operating Pressure	2,500 psi	172 bar
Impact Frequency	310 - 390 bpm	310 - 390 bpm
Impact Energy Class ft lbs**	15,000	
Carrier Weight Range (tons)	50 - 93 US tons	45 - 84 Metric tons
Oil Flow	74 - 92 gpm	280 - 350 lpm
Working Weight	13,500 lb	6,125 kg
Tool Diameter	7.2 in	184 mm
Tool Working Length	32 in	815 mm

Figure 22 NPK Hammer Specifications

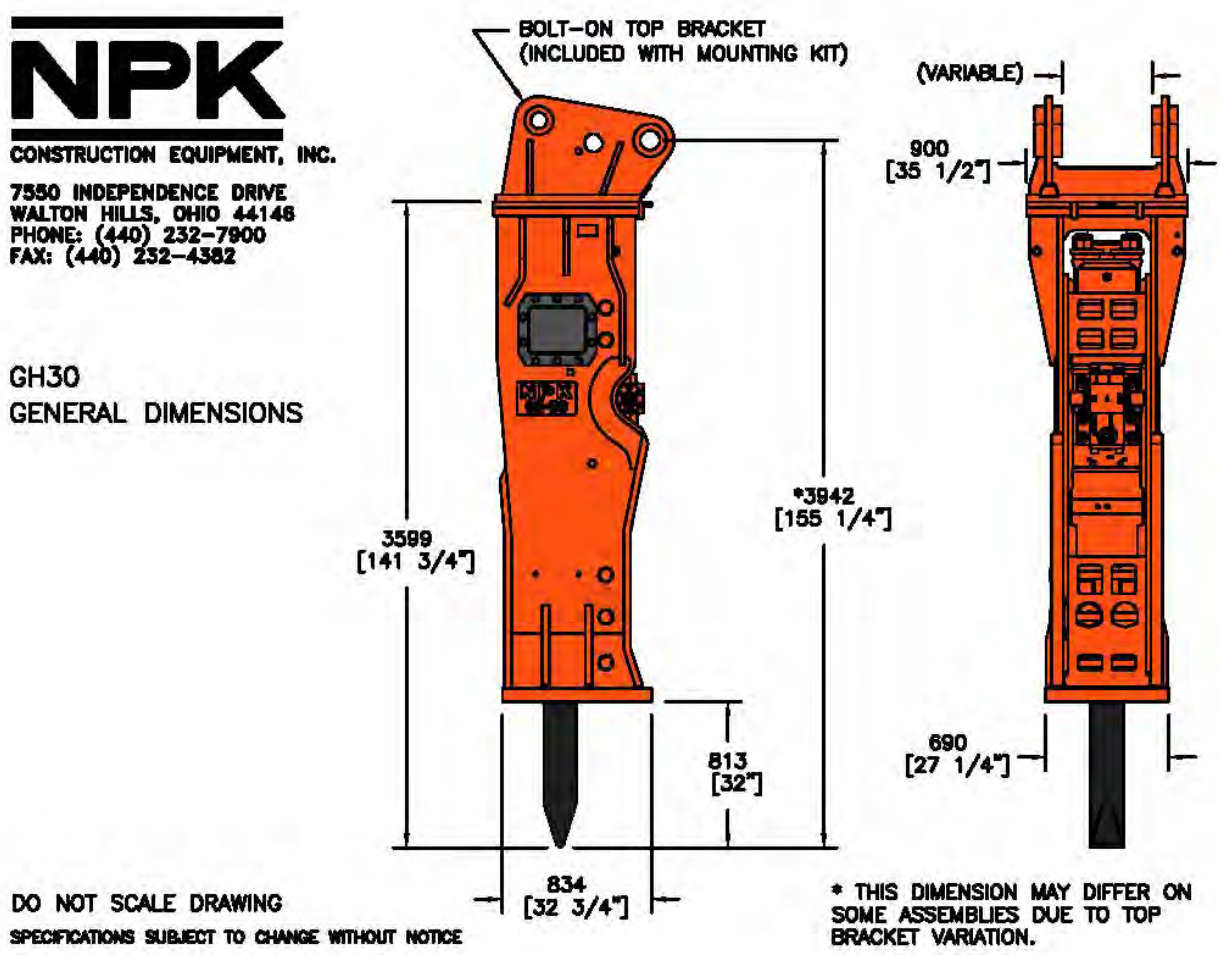


Figure 23 NPK Hammer Diagram

Figure 24 Areas Worked by Hammer on Each Set

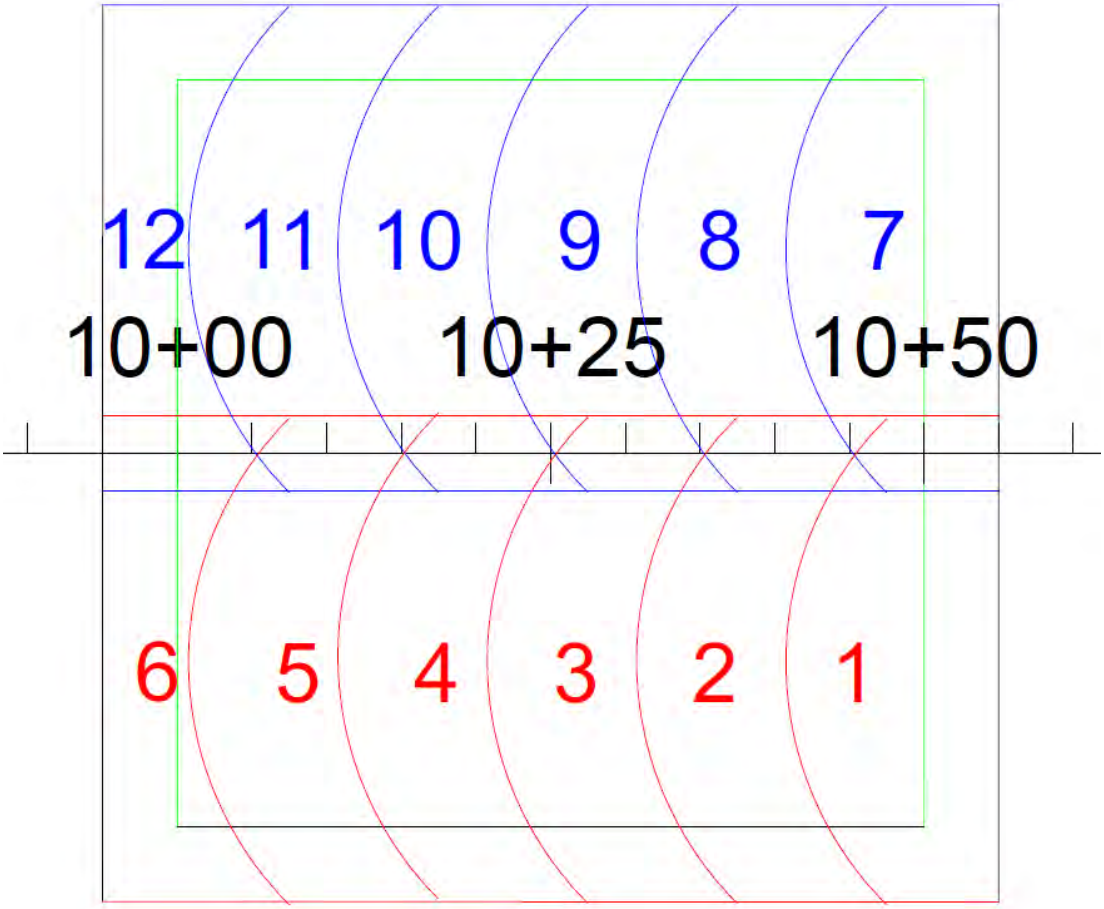


Figure 25 Final Survey; – (cut to desired grade) + (fill to desired grade) green is within 0.5’ of final grade

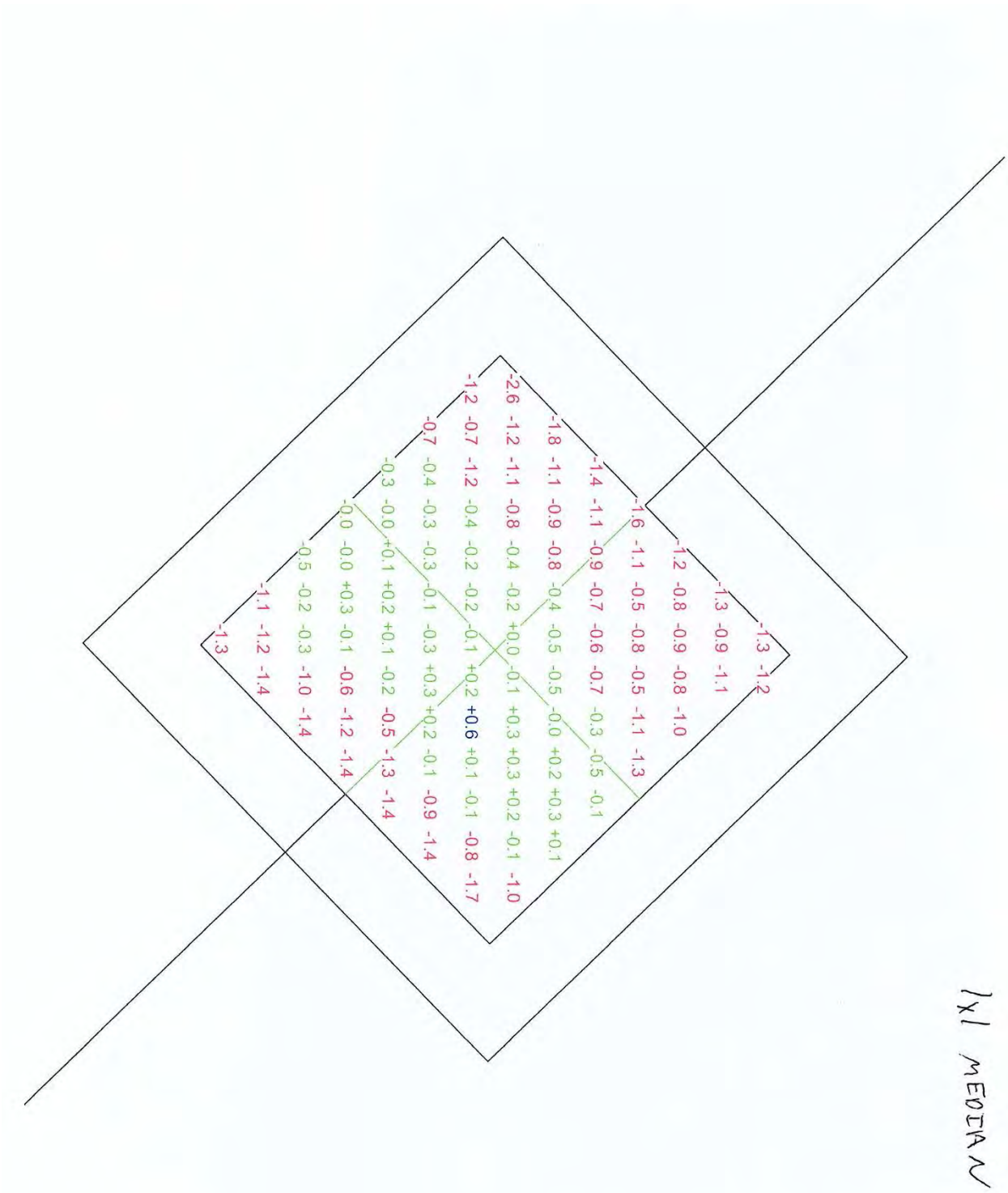


Figure 26 Final Survey; – (cut to desired grade) + (fill to desired grade) green is within 0.5’ of final grade

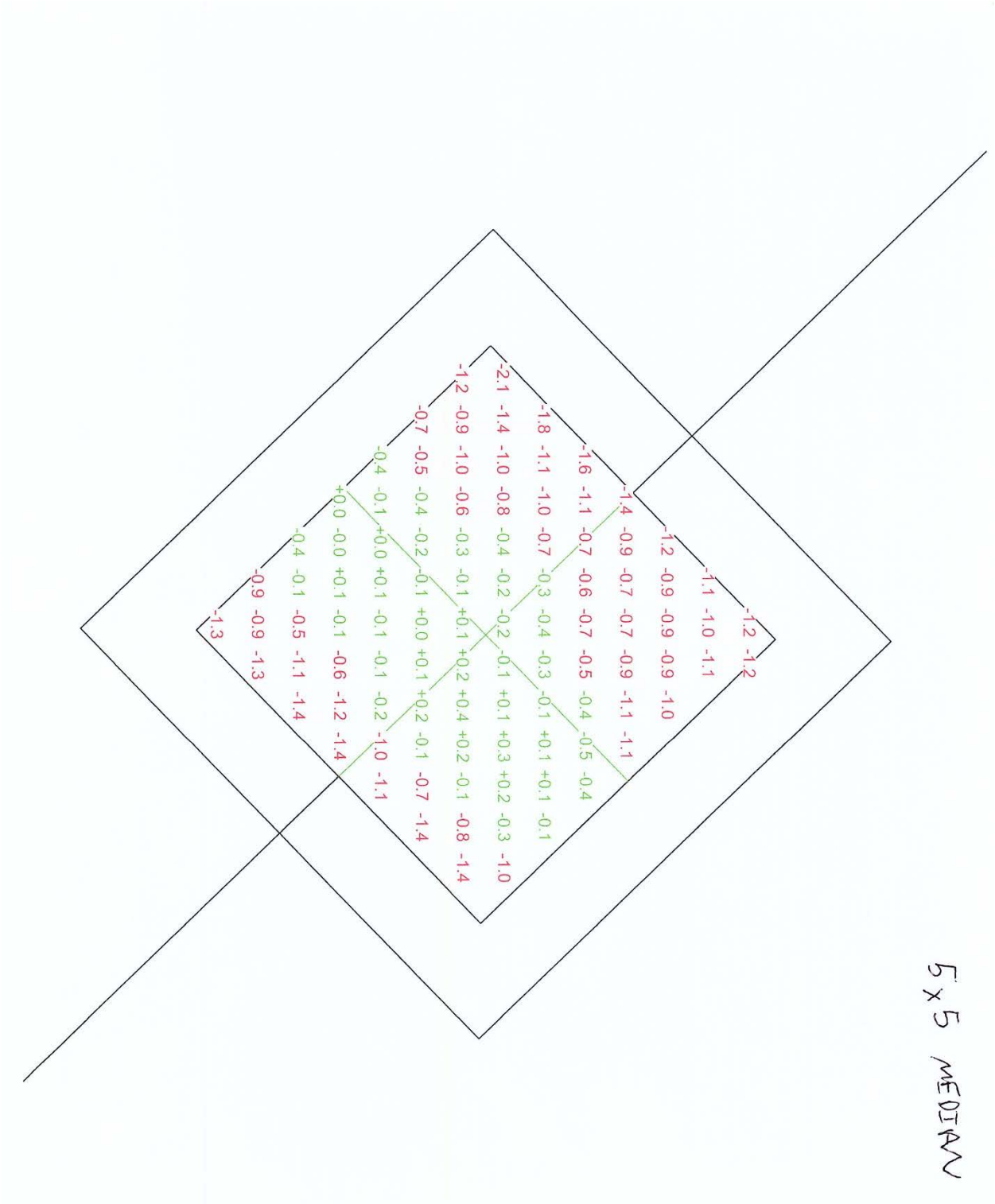


Figure 27 Final Survey; Red – Original, Blue – Final Grade, Green – Desired Grade

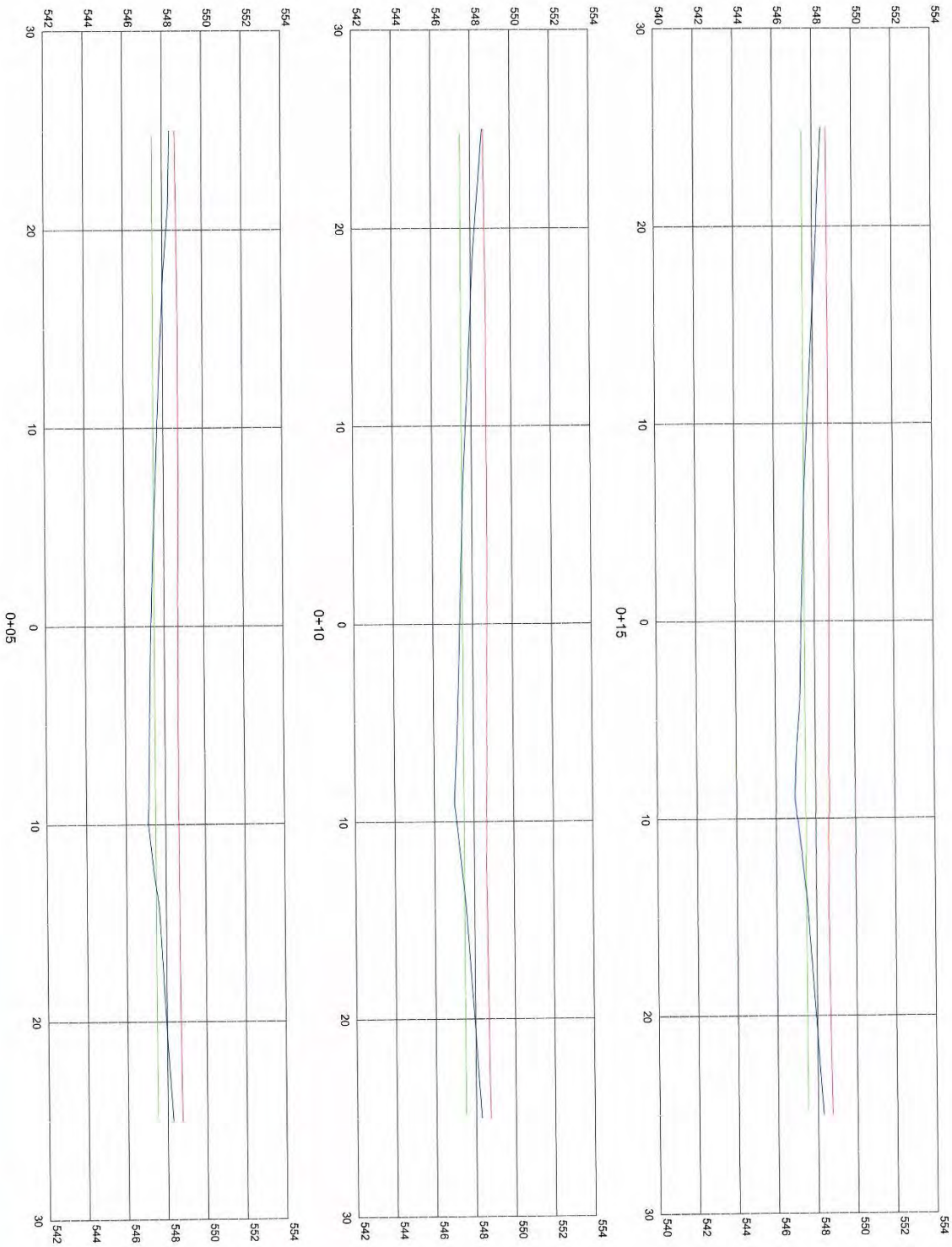


Figure 28 Final Survey; Red – Original, Blue – Final Grade, Green – Desired Grade

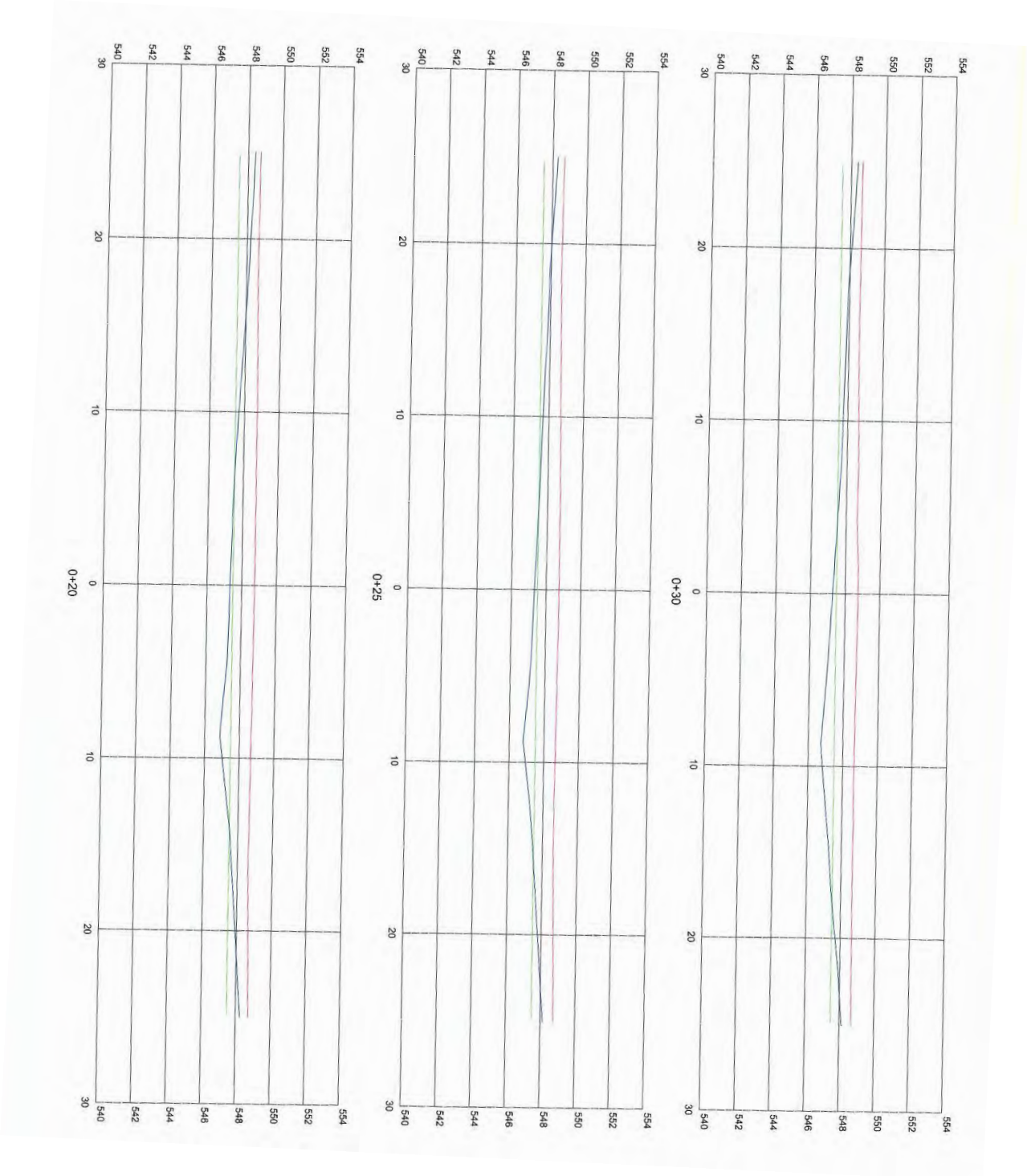
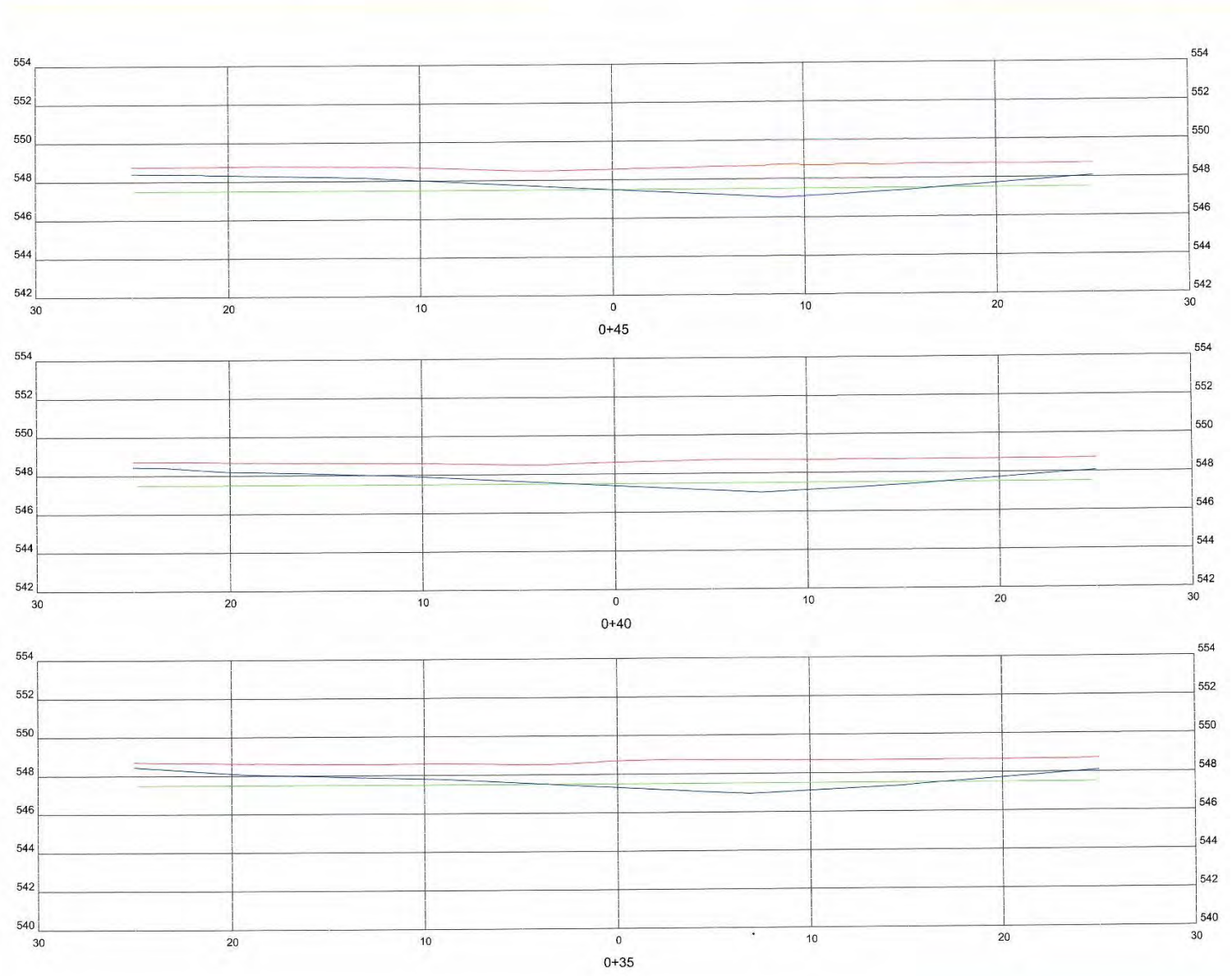



Figure 29 Final Survey; Red – Original, Blue – Final Grade, Green – Desired Grade