Development and Evaluation of a Model to Predict Effects of Buried Underwater Blasting Charges on Fish Populations in Shallow Water Areas.

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April, 1986

Canadian Technical Report of
Fisheries and Aquatic Sciences
No. 1418

Fisheries and Oceans / Pêches et Océans

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

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Canadian Technical Report of Fisheries
and Aquatic Sciences No. 1418

April 1986

DEVELOPMENT AND EVALUATION OF A MODEL TO PREDICT EFFECTS OF BURIED UNDERWATER BLASTING CHARGES ON FISH POPULATIONS IN SHALLOW WATER AREAS

by

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Cat. No. FS 97-6/1418E ISSN 0706-6457

Correct citation for this publication:

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. Can. Tech. Rept. Fish. Aquat. Sci. 1418: x + 49 p.

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ABSTRACT

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A program to monitor the effects of underwater blasting on resident fish populations was undertaken in Vancouver Harbour, British Columbia, in conjunction with a construction project to deepen a ship loading berth. Charges were buried at various depths within conglomerate rock in water depths of 10 to 20 m. An overpressure wave recorder was used to measure shock wave characteristics (i.e. peak pressure and impulse strength) at various distances from the site of charge burial. Variations in overpressure were recorded mid-water, and near the sediment/sea and air/sea interfaces. The effectiveness of air curtains as a mitigative measure in reducing blast effects on fish was evaluated as part of the program. Experiments were also conducted to assess the relative overpressure strengths resulting from the detonation of linear versus point source charges. In situ caged fish were used to compare lethal and sublethal ranges predicted by different effects models.

Results of the study indicated that overpressure waves resulting from buried charge detonations were more complex and longer in duration than those originating from open water detonations. Maximum pressures for buried charges were two orders of magnitude below values predicted by models for mid-water detonations. Mean values for impulse strength (a damage parameter for potential effects on fish) for buried charges were reduced by 20 to 30 times from those predicted by mid-water models. Proximity to air/sea and sediment/sea interfaces resulted in an enhancement of impulse strengths of 2.4 to 5.3 fold respectively at distances less than 50 m. At distances greater than 50 m from the blast site, impulse strengths were consistently lower at the two interfaces compared to values predicted for mid-water. Air curtains were shown to be an effective mitigation measure, and reduced maximum pressure and impulse strength by 53% and 14% respectively. Impulse strengths from linear explosives were on average 41.5% lower than those produced by point source charges for charge sizes capable of producing similar seismic acoustic signals. Caged fish studies with juvenile coho salmon (Oncorhynchus

kisutch) showed that test fish survived impulse strengths 5 times higher than lethal levels predicted lethal by existing models. Our experiments using caged fish suggested that impulse strength was not a good damage parameter for use with buried charges. The uncertainty of predictions increased as the depth of caged fish increased from 1.0 to 6.0.m.

Study recommendations include the need for complete data records incorporating information on blast characteristics and biological effects to further refine existing predictive models. A recommendation for expanding modelling of the potential effects of underwater explosives to include theories based on other damage parameters such as energy flux density is also made. The establishment of a protocol for instrument calibration used to record shock wave characteristics is seen as essential to provide adequate quality assurance for physical data obtained in future research and field monitoring programs. Additional testing of the potential lethal ranges for linear charges under varying conditions is considered necessary to refine mitigative procedures for this type of explosive.

Key words: Underwater explosives, blasting, buried charges, predictive modelling, impulse strength, salmonids, fish effects, marine construction

RÉSUMÉ

Munday, D.R., G.L. Ennis, D.G. Wright, D.C. Jeffries, E.R. McGreer et 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. Can. Tech. Rept. Fish. Aquat. Sci. 1418: x + 49 p.

A l'occasion de travaux visant a approfondir un poste de mouillage dans le port de Vancouver, Colombie-Britannique, un programme a été mis en oeuvre pour étudier les effets du dynamitage sous-marin sur les populations locales de poissons. Des charges explosives ont été enfouies à des profondeurs variant entre 10 et 20 m dans le conglomérat sous-jacent. Un enregistreur d'ondes de surpression a servi à mesurer les caractéristiques de l'onde de choc, telles la pression de pointe et la puissance, à différentes distances du point d'enfouissement des charges. Les variations de la surpression ont été enregistrées sous l'eau, à mi-chemin de la surface et du fond, ainsi qu'à proximité des interfaces eau-sédiments et eau-atmosphère. De plus, l'efficacité de rideaux d'air pour la réduction des effets des explosions sur les poissons a été évaluée. Enfin, des expériences ont été faites en vue de déterminer la surpression relative produite par l'explosion de charges en ligne et de charges ponctuelles. Des poissons mis en cage sur les lieux de l'étude ont permis de comparer les gammes d'effets létaux et sublétaux prévus à l'aide de différents modèles.

L'étude a révélé que l'explosion de charges enfouies produit une surpression plus complexe et de plus longue durée que l'explosion de charges dans l'eau même. Les surpressions maximales produites par l'explosion des charges enfouies étaient inférieures de deux ordres de grandeur à celles prevues par les modèles pour les détonations en pleine eau. D'autre part, la puissance des ondes de choc produites par l'explosion des mêmes charges (paramètre servant à déterminer les effets possibles des explosions sur les poissons) était 20 à 30 fois inférieure à celle prévue par les modèles pour les détonations en pleine eau. A moins de 50 m du point d'explosion, cette puissance bouvait être respectivement 2,4 et 5,3 fois plus élevée à proximité des interfaces eau-atmosphère et eau-sediments qu'à mi-chemin entre la surface et le fond. A plus grande distance du point d'explosion, la puissance de l'onde de choc était constamment inférieure à proximité

des deux interfaces par rapport à la valeur prévue par les modèles pour les détonations en pleine eau. Les rideaux d'air se sont révélés efficaces pour la réduction des effets des explosions: ils ont permis de réduire la pression maximale de 53% et la puissance de l'onde de choc de 14%. En moyenne, pour des charges pouvant produire des signaux acoustiques sismiques comparables, la puissance de l'onde de choc etait 41,5% moins élevée à partir de charges en ligne qu'à partir de charges ponctuelles. Des saumons coho (Oncorhynchus kisutch) juvéniles en cage ont résisté à des explosions d'une puissance cinq fois plus élevée que celle considérée comme létale selon les modèles de prévision existants. Les expériences que nous avons faites avec des poissons en cage portent à croire que la puissance de l'onde de choc n'est pas un paramètre valable pour étudier les effets de l'explosion de charges enfouies. Plus la cage était proche du fond, entre 1 et 6 m de profondeur, plus l'exactitude des prévisions diminuait.

Dans leurs recommandations, les auteurs estiment que pour perfectionner les modèles de prévision, il faut augmenter la masse de données, notamment avec de l'information sur les caractéristiques et les effets biologiques des explosions. Ils ont également recommandé que les modèles de prévision des effets du dynamitage sous-marin incorporent des théories fondées sur d'autres paramètres, comme la densité du flux d'énergie. De plus, l'élaboration d'un protocole d'étalonnage des instruments de mesure des ondes de choc était considérée comme une condition essentielle pour un contrôle adéquat de la qualité des données physiques recueillies au cours des travaux de recherche et de surveillance sur le terrain. Enfin, les auteurs considèrent qu'il faut faire d'autres essais pour définir la gamme des effets létaux des explosions de charges en ligne, dans differentes conditions, en vue d'améliorer les mesures de protection contre ce type de détonations.

Mots clés: explosifs pour travaux sous-marins, dynamitage, charges enfouies, modèles de prévision, puissance, salmonidés, effets sur les poissons, construction en milieu marin.

INTRODUCTION

STUDY BACKGROUND

The present study follows recommendations put forward by D.G. Wright in his policy paper for blasting guidelines for northern waters (Wright, 1982). The paper summarized existing knowledge on the effects of underwater detonations of chemical explosives on aquatic organisms. **Impulse strength**, a time-integral function of pressure generated by underwater shock waves, was acknowledged as the preferred measurement at the time for use in predicting lethal effects on fish. Wright (1982) also recommended that future research efforts concentrate on electronic monitoring to measure changes in impulse strength at increasing distances from explosive charges.

Existing predictive models based on impulse strength (e.g. Yelverton, 1975) have been shown to be most appropriate for predicting lethal ranges for fish exposed to midwater detonations. Assumptions inherent in these models are based on laws of theoretical physics related to spherical spread of a wave form from a point source of energy. These assumptions are not valid when charges are buried, or in shallow water where air/sediment interface effects become important. Violation of these assumptions under different field conditions has resulted in a poor track record for existing models in predicting effects on fish. Field observations of construction-related blasting using buried charges have shown that existing models usually overestimate lethal ranges.

The construction project in Vancouver Harbour at Pacific Elevators Ltd. upon which the present study was based provided an excellent opportunity to investigate effects of buried charges. **COASTLINE Environmental Services Ltd.** was contracted to monitor the biological effects of the blasting program on resident fish populations. From previous field monitoring experience, **COASTLINE** scientists were aware of deficiencies in existing models used to predict effects of blasting on fish, and recognized an opportunity to collect a suitable data base to derive an improved model. By studying the way in which burial of charges affected impulse strength in the water column, improved predictions of effects on fish populations could be made. A limited number of caged fish exposures was conducted to verify the relationship between overpressure and effects on fish as predicted by existing models. The information derived from the monitoring program was used to develop a software program for estimating lethal ranges for both buried and midwater explosive detonations (**COASTLINE Environmental Services Ltd.,** 1986).

SITE DESCRIPTION AND STUDY OBJECTIVES

The study was conducted at Pacific Elevators Ltd., a grain loading terminal on the south shore of Vancouver Harbour (Fig. 1). Dillingham Construction Ltd. was contracted to conduct a blasting program to remove approximately 22,000 m^3 of conglomerate rock in order to deepen a shipping berth. Water depths in the blast area ranged from 10 to 17 m. The 3-month blasting program commenced December 5, 1984, and concluded on March 3, 1985.

Electronic measurement of waterborne shock waves was conducted to determine:

- the effect of depth of charge burial in hard substrate on the strength of overpressure in the water column
- relative overpressure strength in proximity to sediment/sea and air/sea interfaces
- effectiveness of air curtains as a mitigative measure in reducing overpressures generated by buried charges
- relative overpressures produced by linear versus point source charges detonated in open water
- the relationship between impulse strength (a function of overpressure) and fish mortality.

In addition, the effect of the blasting program on resident fish populations was monitored daily using echo location and post-blast observations of fish mortalities, and weekly using purse seining.

SUMMARY OF RELEVANT LITERATURE

The effect of underwater chemical explosives on fish has been the subject of numerous investigations. Several literature reviews have been conducted in an attempt to consolidate existing knowledge in the field with the aim of providing an integrated approach to assessing the effects of explosives on aquatic resources/biota. Falk and Lawrence (1973) provided a review of information on explosive and non-explosive acoustic sources relevant to seismic exploration. Their report provides a good historical perspective of studies on the effects of chemical explosive detonations to fish up to 1973. The authors also reported some of the first observations on the effects of linear versus point source explosives determined through field testing in the Mackenzie River delta.

Hill (1978) provided a broader overview of the effects of underwater shock waves to both fish and marine mammals. This work summarizes the physical characteristics of shock waves, how they propagate, and what the ultimate effects are on various marine organisms. The author also reviewed lethal range prediction models and provided a metric conversion of Yelverton's impulse strength model.

Wright (1982) developed a summary of information on the effects of chemical explosives on fish and marine mammals. The paper discussed the known effects on mammals and fish, and provided a critical review of the most common lethal range estimation models in use up to 1982. The paper by Wright (1982) discussed existing Department of Fisheries & Oceans (DFO) policy related to the use of chemical explosives, and provided the background for subsequent development of DFO policy guidelines for the use of explosives in the Northwest Territories. Yelverton's predictive model which was based on the measurement of impulse strength (Yelverton, 1975) was recommended as the most accurate and readily applicable model for predicting lethal ranges from underwater detonations

In a review published the same year, Baxter (1982) evaluated four data bases on blasting effects developed as the result of previous explosive effects investigations. The author evaluated the degree to which the biological effects observed were correlated to various overpressure wave characteristics, including impulse strength (I), energy flux density (E_{flux}), and maximum or peak pressure (P_{max}) (see Glossary, p. 45). Although the author concluded that the energy flux density model was most suitable for detonations in midwater, he found that impulse strength was more reliable for predicting effects in shallow (near surface) waters to a depth of approximately 3 m. Peak pressure was found not to be a good predictive parameter for fish damage in the case of midwater charges. Additional studies on effects of buried charge detonations on caged fish (e.g. McAnuff and Booren, 1976) have also shown that peak pressure per se is not a good predictive parameter for fish damage.

In a more recent review, Munday (1985) found that the majority of published literature focused on the biological effects of midwater detonations related to seismic surveys in coastal zone areas. Very few studies included direct physical measurement of overpressure waves. In most instances where physical measurements of overpressures were made, only the maximum pressure (P_{max}) was reported. Other than the surveys reviewed by Baxter (1982), a seismic survey at Sable Island (Mobil Oil, 1984) provides the only additional study reviewed in which the overpressure wave characteristics of explosives, in this case linear explosives, were directly related to effects on fish populations. In the Mobil Oil study, Yelverton's impulse strength model was used to predict impact zones. The use of linear charges resulted in an apparent reduction in the size of the zone of effect of 60% to 90% from ranges predicted for a comparable weight of point source charge. Very few published reports described overpressure measurements related to buried charges. Hubbs and Richnitzer (1952) reported the effects on fish resulting from explosive charges "jetted" to various depths in soft sediments. This study provided information on the rate of change in peak pressure with increasing distance from buried charges. The rate of change in peak pressure is the basic principle behind energy flux density models, and this pressure wave characteristic has been directly related to fish mortality (Baxter, 1982). Peak pressure measured in open water normally decays at an exponential rate inversely proportional to distance. The rate of decay for peak pressure in sediments from buried charges (P_{max} = Constant x $R^{-2.26}$) was found to be twice that for open water detonations (P_{max} = Constant x $R^{-1.13}$).

In reviewing the work of Hubbs and co-workers, Baxter (1982) confirmed that the rate of decay or change in P_{max} was greater in the case of buried charges. However, although the rate of decay was greater, absolute values for P_{max} near the explosive source were up to 7 fold higher than peak pressures for the equivalent amount of explosive detonated in midwater. Baxter (1982) concluded that the effect of buried charges would depend on the net result of the two opposing forces.

Sakaguchi et al. (1976) reported on a limited number of field observations with caged fish suspended at various distances from buried charges. No information on the depth of burial was provided. Effects in caged fish were observed up to 100 m from the bore holes. Data from field observations were insufficient for demonstrating correlations between either maximum pressure or energy flux density and damage effects. Additional laboratory testing during this investigation using various types of explosives led the author to conclude that energy flux density was better correlated with effects on fish than was peak pressure. The relationship between impulse strength (i.e., the time-integral function of peak pressure) and observed damage effects was not tested.

The present study is unique in that its objectives were to provide data on impulse strength measurements resulting from charges buried in a hard (solid) substrate in relation to damage effects on fish.

STUDY CONSTRAINTS

The study which follows is the result of research efforts undertaken concurrently with an ongoing construction project. The objectives of the construction project were paramount and researchers were required to conduct investigations in a manner that provided the least interference with construction activities. Drilling, blasting, and dredging activities were carried out in different phases throughout the 3-month period of the construction program. Researchers were dependent on construction personnel for much of the technical information related to charge size and placements. Placements of hydrophones and fish cages were often made difficult due to the periodic movements of the drilling rig and dredging equipment.

DEVELOPMENT OF A PREDICTIVE COMPUTER MODEL

A computer software package (IBLAST) capable of predicting impulse strengths and lethal ranges for fish from buried charges was developed from the data generated in this program. Copies of the IBLAST software and accompanying operator's manual are available from the Department of Fisheries and Oceans, Habitat Management Division, Water Use Unit, 1090 West Pender Street, Vancouver, B.C. V6C 2P1 or Coastline Environmental Services Ltd., B202 - 355 Burrard Street, Vancouver, B.C. V6C 2G6.

METHODS

CHARGE LOADING AND FIRING PROCEDURES

Dillingham Construction Ltd. and VME Associates Ltd. were responsible for designing the blasting program to fracture conglomerate rock from a shallow outcropping in Vancouver Harbour. The study site is shown in Figure 1. The objective of the program was to increase the depth of the shipping berth to 13.7 m below mean low sea level, necessitating the removal of approximately 4.0 m of rock substrate. The substrate to be removed was roughly rectangular in cross section except on the north end where it tapered to depth. A grid pattern was established comprised of 37 transect lines oriented north to south and numbered sequentially east to west on 3 m centres, and 28 rows oriented east to west and numbered sequentially north to south on 2 m centres (Fig. 2). Three drills on 2 m centres were mounted on the drill assembly. The drill assembly was moveable along the drill rig allowing holes to be drilled in series of threes. The drill rig was positioned with a laser-positioning instrument (Spectra-Physica Laser Level GS, Model 945) thereby providing accurate position fixing for drill holes within the grid pattern. The drill rig was anchored in position by retractable cables which were used to move the drill rig from line to line. The cables were tensioned to hold the rig stationary during the drilling operation. The drill rig made two complete passes over the blast area during the course of the overpressure monitoring program. The first pass was from north to south drilling and shooting rows 13 to 28 along lines 1 to 37. The drill rig was rotated

180° prior to a second pass from south to north (line 37 to line 1) for drilling and shooting holes in rows 4 to 12. The number of holes drilled and loaded per detonation varied from 3 to 20 due to a variety of production related constraints.

Explosive charges were oriented in each hole as illustrated in Figure 3. Blasting caps were inserted in primer charges (Pentomex* II) which in turn were inserted into the primary explosive (Hydromex* 210 in the upper 1/2 and Aquamex* in the lower 1/2 of the hole). Blasting caps were used in series from 0 to 20 with increasing series numbers referring to increasing delay periods. Delay periods ranged from 25 msec (cap #1) to 1125 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 into a series of small explosions. Blast overpressure levels produced are the direct result of the size of the charge in each delay, rather than the summation of charges detonated in all holes. More precise control can be exercised during detonation by "decking" charges in each hole. In this procedure, two or three charges are included in one hole separated by a non-explosive material. A higher cap delay number is used for the lower charge compared to the upper charge, causing the upper charge to detonate first, followed by the lower charge. As a result, overpressure levels are lower than if the same two charges were combined as one. All charges detonated in the first pass were initiated as single charges per hole (Recordings 1 to 29). On the second pass, charges were decked with two charges per hole, or in some cases, three charges per hole (Recordings 30-32, 35-50, and 56 inclusive) to mitigate ground vibration near the existing dock.

In the present study, several detonations were made within each bore hole drilled. To facilitate data analysis and interpretation, this report refers to charge numbers in the order in which they were detonated, with charge number one having the shortest delay (and therefore the first to be initiated). Subsequent charges are numbered in sequence according to increasing delay numbers. Charge numbers are related to actual grid locations (Fig. 3) in Appendix 1.

**Canadian Industries Ltd. trade names*

OVERPRESSURE MEASUREMENT

The instrument used to measure and record overpressure levels was a VME-Nitro Consult* Model 3000 Hydrophone Recorder with three recording channels. This instrument employs three pressure-sensitive hydrophones (AMF Geospace Model MP-8D*). Each hydrophone is attached to the surface recorder by approximately 150 m of waterproof cable. The surface recorder receives the pressure signal from the hydrophones and records this input as the deflection of a photo tracer beam on light-sensitive film. Three independent gain settings can be selected for each hydrophone, thereby providing a potential range of pressure measurements from 0 to 8 bars pressure.

The pressure-sensing hydrophones consist of piezoelectric gauges housed in a protective plastic cover. Hydrophones were attached to vertical anchor lines at known depths in the water column. Anchor lines were held near vertical by using large floats in opposition to heavy anchors. Hydrophones were placed at various distances from the explosive charges. In most cases, the hydrophones were located directly in front of the first (initiating) charge in a series of charges, so that the distance of travel (vector distance) for overpressure waves was less for the charge with the smallest cap delay number. This strategy had the effect of increasing the separation of individual blast reports on the recording film.

Hydrophones were placed in position by the sampling vessel, the "Coastline I". A shorebased transit (Sokkisha Model BT 20*) was used to determine the exact position of hydrophones relative to the explosive charges. Accurate survey plans were used to record hydrophone positions and to calculate distances from charges.

Approximately 120 detonations were required for the constructon project. Blast overpressure measurements were determined for 49 detonations from December 5, 1984 to February 4, 1985. In addition, linear and point source explosives were detonated in the water column on seven occasions.

Three hydrophones were used to monitor water overpressure except on the following occasions:

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1. Recordings 23 to 28 - hydrophone 2 not functioning

2. Recording 29 - hydrophones 1 and 2 not functioning

3. Recordings 41 to 43 - hydrophones 1 and 3 not functioning.

In the first two instances, hydrophones malfunctioned due to cable abrasion and subsequent leakage of seawater into the pressure sensor. Three new hydrophones were used for recordings 30 to 56. However, on January 28, 1985, after recording number 40, cables to hydrophones 1 and 3 were severed. These two cables were repaired and all three hydrophones were in use for recordings 44 to 56.

OVERPRESSURE RECORDER CALIBRATION

Calibration of the monitoring equipment was conducted periodically during the study to confirm the similarity of response when all three hydrophones were located at the same position in the water column. Initial tests indicated that the response from the three hydrophones varied by more than ±5%, which was the desired confidence limit for variation in the original study plan. As the shipping berth construction program could not be delayed while calibration adjustments were made, the monitoring unit and hydrophones were calibrated following the field program, and the appropriate correction factors applied to the raw data prior to beginning data analysis.

Calibration of the recording unit was conducted in an aquiescent test tank. Hydrophones were placed in the tank with a separation of 3.7 m between the hydrophone and the acoustic source. The acoustic test source was then rotated around the hydrophone at a constant distance of separation. The test tank is calibrated in such a manner that the pressure levels at the position of the hydrophone are accurately known for given source inputs. The unit is capable of providing calibration pressure levels of 500 millibars. The acoustic test source can also be rotated in relation to the hydrophone, to test response in both horizontal (XY) and vertical (XZ) planes. A "polar" mapping of the hydrophone responses is produced which indicates directional sensitivity.

In addition to tank testing, the electronic characteristics of the amplifiers in the surface recorder were analysed. A gain correction factor was developed for each hydrophone/gain setting combination. These factors were applied to the raw data prior to subsequent waveform analysis.

Following application of the correction factors, statistical tests confirmed that the differences among the three hydrophones when similarly positioned in the water column were not significant (95% confidence level).

MEASUREMENT OF AIR CURTAIN EFFECTIVENESS

Air curtains were used in the construction project to protect concrete pier cribs from the effects of blast overpressure waves. A 7.6 cm diameter pipe approximately 21.5 m long was welded to a steel H beam (78 kg/m). The pipe had 3.1 mm holes drilled on 30 cm centres over its length. Both ends of the pipe were sealed and air was supplied with a 5.1 cm diameter flexible line of 30 to 90 m in length to a "T" junction at the centre of the pipe. Two surface compressors (Joy* 1350 and Gardner-Denver* 1050) supplied air to a 70 m^3 surge tank which in turn supplied air to the curtain at a pressure of 7.74 bars.

The resulting flow of air bubbles created an upwelling with associated water turbidity as the bubbles rose through the 15 to 18 m water column. Air curtains were engaged approximately one minute prior to each blast. Two separate air curtains were used during the study and were moved from crib to crib as the drilling rig moved through the blast area.

The air curtain was long enough to extend approximately 3 m past both ends of a crib. The 3 m extensions provided an opportunity to test the effect of air curtains on overpressure waves generated by the buried charges. Hydrophones were placed on either side of the air curtain at the same depth in the water column at approximately the same distance from the initiating charge. Hydrophones were attached to vertical anchor lines as previously described. The surface floats were secured to the pier crib with tag lines to prevent movement in response to the surface currents generated by the air curtain.

**Registered trade name*

Measurement of air curtain effectiveness was undertaken on 6 occasions: December 21, 1984, and January 3, 4 (2 determinations), and January 9, 1985.

CAGED FISH STUDIES

Caged fish studies were undertaken during the program to test the accuracy of an existing predictive model for lethality versus impulse strength (Yelverton, 1975). Juvenile coho salmon (Oncorhynchus kisutch) were obtained from Capilano Hatchery, North Vancouver, B.C. Fish averaged 10 gm with 10 cm fork lengths and were 1^+ y old pre-smolts. Fish were transported to a laboratory holding facility at the Vancouver Public Aquarium where they were gradually acclimated to a salinity of 27.0 ppt over a one-week period. Fish were held for a minimum of two weeks in the laboratory prior to cage exposure. Three of four sides of the glass aquaria were covered with black polyethylene to reduce disturbance during observation and maintenance. By maintaining low light levels in the laboratory, test fish were generally undisturbed during observation periods. Laboratory light levels were controlled by allowing low levels of diffuse ambient daylight, supplemented with incandescent light supplied by 3 watt bulbs over each of the holding tanks. Lights were on a timer and were regulated to a 12 h light/dark cycle. Seawater was supplied in sufficient quantities to maintain near saturated dissolved oxygen levels and water temperatures of 8.5°C ± 0.5°C. Salinities were monitored daily and varied according to the salinity regime in Vancouver Harbour at the Aquarium intake level (approximately 20 m below sea level). Salinities ranged from 20.0 to 27.5 ppt during the holding period.

Exposure cages for in situ tests with fish were constructed of 6.35 mm opening Vexar* (plastic) mesh (Fig. 4). The mesh was formed into a cylinder of 40 cm diameter and 80 cm length (nominal dimensions) providing a cage volume of approximately 100 L. Access into the cage was through a zippered opening running the length of the cage. An aluminum framework was used to support the mesh cylinder. This framework was constructed so that it did not interfere with direct passage of overpressure waves when the cage was oriented horizontally and side-on to the direction of wave propagation. The alumninum framework was fitted on one end with tubular aluminum brackets which allowed the cage to slide up and down on a vertical anchor line.

**Registered trade name*

Cages were anchored at predetermined distances in front of the initiating charge in a detonation series (Fig. 5). Test exposures were conducted near the surface and midwater column (6.0 m). The location of the cage in the water column was predetermined by the length of the tag lines suspending the cages under the surface floats.

Fish for the cage studies were transported to the exposure site in polyethylene bags placed in 40 L coolers. Bags were inflated with oxygen and sealed prior to transport. One to two hours prior to detonation fish were gently introduced into the exposure cages. A hydrophone was suspended in the centre of the cage and the cage was lowered to depth (Fig. 4). The hydrophone cable was attached to the recorder on the pier which acted as a tag line to keep the cage oriented side-on to the direction of overpressure wave propagation.

During caged fish investigations control fish were maintained and treated in a similar manner to exposed fish. The control fish cage was well outside the range of high overpressure experienced by blast-exposed groups (200 m horizontal distance for control fish as opposed to <30 m for exposed fish).

Within 30 minutes following detonation, test cages were retrieved, initial observations of mortalities made, and test fish returned to the laboratory holding facility. Each test group was maintained in a separate 150 L aquaria.

Observations of fish behaviour and visual manifestations of sublethal damage were made daily for 15 to 21 days following exposure. Surviving fish were sacrificed after the 3-week period and autopsied. For those test groups exhibiting no visual external or internal effects of exposure to overpressure waves, subsamples of 10 to 15 fish were examined. In all other test groups, all fish were examined. Fish were examined externally prior to dissection for examination of internal tissues and organs. Examinations were conducted with a dissecting microscope (Wilde* M5A) using visible damage levels as developed by Hubbs et al. (1960) (Table 1).

**Registered trade name*

SAMPLING OF RESIDENT FISH POPULATIONS

Sampling using a chart recording echo-sounder (Lowrance* Model 1510B) was conducted during the blasting program to determine whether resident fish present in the area prior to detonations were adversely affected by the blasts. A 20° cone angle transducer was used except at times when spurious reflections from objects in the water column were encountered. In this case, an 8° cone angle transducer was used to screen out unwanted signals. Power output was 900 Watts (peak to peak) at a frequency of 200 kilohertz.

The shipping berth and adjacent harbour areas were surveyed following a grid pattern established from siting to shorebased benchmarks. The grid pattern was followed in a similar manner on each survey. This information provided a basis for comparison of fish presence in the blast area on different sampling occasions, and permitted relative comparisons between blasts.

Translation of echo location traces was empirical; the size of the record on the chart determined the size of the school that was sampled. A scaling system was established to describe traces. Observations ranged from a "single fish" which was the smallest trace still discernible through small, medium, and large schools as relative size of the the traces increased. Observations were scaled as follows:

single fish	1/2
small school	1
medium school	2
large school	3

Although this information may be biased in part by the travel of the boat relative to the "school" detected, the size of the trace is still the best estimate of fish presence. "Large" schools were characterized partly by the operator being able to backtrack on the grid system and relocate the school. This is not usually possible in the case of most small and some medium traces. No direct numerical estimate of fish presence can be deduced from echo location records.

**Registered trade name*

Due to the proximity to shore, vessels, pilings, and turbidity from the drilling operation, certain locations on the echo-sounding survey were often not surveyable. The ability to identify both real and "artificial" traces obtained with the echo-sounder was based on previous echo-sounding experience.

Purse seining was conducted throughout the program as a second fish assessment technique. Overall net dimensions were 36.9 m long by 6.2 m deep with a 7.7 m bunt section of 6.35 mm mesh and a 29.2 m leading wing of 19.1 mm mesh. Approximately 6 sets were conducted on each sampling occasion. Sampling was conducted twice weekly for three weeks prior and one week following the commencement of blasting. Numbers of resident fish were found to be low during the initial observation period and consequently purse seining was conducted weekly from the second week of the blasting program until program termination (March 4, 1985).

Observations were made by one observer on the pier and one in a boat following each detonation to record mortalities in resident fish stocks. In the majority of cases, fish that floated to the surface were collected by seagulls before it was possible to determine the size and species. The number of fish killed is an estimate based on the number of fish recovered, the number of fish observed to be moribund in the water, and the number of fish recovered by birds for an approximate 20-minute observation period after each blast. In most cases, these estimates were weighted towards observations of bird activities, as it was seldom possible to recover fish directly before they sank or were picked up by birds. It was also possible to estimate the range of effect by estimating the (horizontal) distance from the site where birds were feeding on blast-affected fish to the location of the blast as evident on the surface by gas bubbles upwelling from the bottom.

Resident fish collected during post-blast observation were examined microscopically to determine the damage level for comparison with results obtained from caged fish experiments.

LINEAR VERSUS POINT SOURCE EXPLOSIVES

As an adjunct to the study of buried charges, an investigation was made of the relative overpressures produced from linear and point source explosives detonated in the water column. The size of charges was small: 65 g of linear explosive (appprox. 2 m of 200 g/ft Primacord*) and 225 g of point source explosive (Pentomex* II primers). The two explosive types were tested in a ratio of approximately 1:4. This parallels the relative amounts of each type of explosive required to produce similar seismic records during geophysical exploration recently conducted in the Beaufort Sea (D.G. Wright, pers. comm.).

Charges were detonated in an area of Vancouver Harbour immediately north (offshore) of the construction blasting area (Fig. 2). Hydrophones were equidistant from both explosive sources as described in Fig. 6. Depth of explosive was maintained at approximately 1.5 to 2.0 m, which is typically the depth at which seismic charges are detonated. Depth of hydrophones varied with measurements taken at 1.5, 2, 10 and 20 m depths. An approximate 130 msec delay period between the detonation of linear and point source charges was used to provide a good temporal separation between the two pressure signatures on the recording film.

In all, 7 comparisons of linear versus point source charges were made. Two (Recordings 33 and 34) were attempted on January 28, 1985, with explosives charges equidistant from the hydrophones at 18 and 28m horizontal distances for trials 1 and 2 respectively. Hydrophones for these trials were positioned 1.5m below the surface. Overpressure recordings were not ideal due to the close proximity of hydrophones to the charges. On February 4, 1985, 5 comparisons were made (Recordings 51 to 55) at a standard separation of 47m between explosive sources and hydrophones. Hydrophone depths were 10m for the first two attempts (Recordings 51 and 52), 20m for the third and fourth attempts (Recordings 53 and 54), and 2m for the fifth attempt (Recording 55).

**Registered trade name*

ANALYSIS OF OVERPRESSURE WAVEFORMS

As previously described, overpressure levels were recorded as traces on light sensitized paper film. Data from the three hydrophones were recorded simultaneously on the same film as separate traces. The gain setting used for each hydrophone was noted for each reading.

Due to the small size of the light beam deflections (12.7 mm = full scale deflection), it was necessary to increase the size of the records before they could be used for computer analysis. The recording film proved to be unstable under intense light so that direct enlargment via photocopying was not possible. A copy table was used on conjunction with a 35 mm camera (50 mm lens) to produce high contrast black-and-white slide reproductions of all overpressure records. One to ten slides were required to record all charge reports for any one recording. A calibration slide of 6.4 mm square grid paper was photographed in a similar manner. This slide was used to determine the magnification factor and to prevent distortion during subsequent slide projection.

Enlarged dot tracings were made for the duration of positive pressure for each charge. Each slide was projected onto a vertical planar surface in a darkened room. Copy paper with a prescribed baseline was aligned with the projected image so that the baseline on the paper was coincident with the ambient (resting) pressure of the waveform. It was then possible to outline the waveform which corresponded to the positive pressure signature for the various charges. Charges for each recording were traced in series on the same copy paper by realigning the paper as the slides for that recording were projected (Fig. 7a).

The enlarged dot traces were converted to numerical (X,Y) coordinates using a Gradicon* digitizer. A computer program (SEABLAST) was developed in BASIC programming language to run on an IBM* PC microcomputer. The program converts the numerical coordinate data to units of milliseconds and bars for X and Y values respectively in the array. Scaling factors used for these conversions are dependent on film speed (time factor) and gain setting/hydrophone combination (pressure factor) used for the initial recording. The following calculations are then made for each charge:

**Registered trade name*

1. Maximum positive pressure.
2. Duration of positive pressure.
3. Impulse strength.

Values for maximum positive pressure and duration of positive pressure are calculated by the direct application of scaling factors to the appropriate vertical (pressure) and horizontal (time) coordinates. Impulse strength is calculated as the area under the pressure-time curve (Fig. 2) via a numerical technique for calculation of the area as irregular polygon. The resultant area of the polygon corresponds to the impulse strengthy in units of bar.msec.

A plotting program was developed to provide a graphic output of the scaled data base as developed through the SEABLAST program. This graphic output was compared with the enlarged dot traces used for input, thereby checking for possible errors during digitizing. The array values are supplied from the scaled data base to a routine driving a Roland* DXY flatbed plotter to produce graphical output. The charge profiles as plotted resemble the original film records, but are scaled accurately in bars and milliseconds. Values for maximum pressure, duration, and impulse strength are printed below each charge profile.

RESULTS

OVERPRESSURE RECORDER CALIBRATION

Independent calibration of the three channels on the overpressure recorder revealed slight differences in response to calibrated voltage input. The response for each channel/gain-setting combination was determined. The voltage output of each hydrophone in response to various pressures was also determined. This information combined with the known response of the recording unit to input voltage from the hydrophones was used to determine scaling factors for the graphic waveform output from the recorder. The following scaling factors for instrument response to pressures above ambient were determined:

**Registered trade name*

	Gain Setting (2.54 cm deflection - units of bars pressure)		
	low	medium	high
Channel 1	0.444	2.219	8.876
Channel 2	0.416	2.081	8.318
Channel 3	0.369	1.850	7.394

Calibration also showed that each channel had an upper limit of deflection after which the response per unit of voltage input did not generate a corresponding linear response in graphic waveform output. These limits of deflection were 2.29 cm, 2.03 cm, and 2.54 cm for channels 1, 2, and 3 respectively. Data derived from deflections beyond these limits were identified in the data base and not used for modelling purposes.

Results of directional sensitivity testing indicated some variation in output signal from the hydrophone depending on the orientation of the hydrophone to the pressure source. A variation up to 21% was observed during polar testing in the horizontal plane for a 100 millibar analog pressure source (at a frequency of 500 Hz) (Fig. 8). In the vertical plane, polar testing showed that the hydrophones were most sensitive to signals originating from directly below the unit. An attenuation of response was also observed in the vertical plane, so that when the source was directly horizontal to the hydrophone, there was an 87% reduction in response relative to the response to the same source originating from below (Fig. 9). In the current study, the deeper the location of the hydrophone in the water column, the greater the attenuation due to these polar response characteristics would be expected.

Polar responses for hydrophones were determined for pulse wave as well as analog wave sound sources. Pulse waves are a square wave of varying duration. The near instantaneous rise to peak pressure plateau observed for pulse waves is analogous to the change in pressure associated with the shock wave from underwater detonations. Polar responses to pulse wave as determined for the horizontal plane showed the hydrophones had a higher directional sensitivity to pulse sound sources than those described for an analog pressure source. In the current study, directional sensitivity in the XY plane was not controlled as the hydrophones were sold by the supplier as being omni-directional. The directionality of the hydrophones was identified as a result of the rigorous calibration exercises performed during our study.

The variation in response for the three hydrophones when placed in the same position in the water column provided a direct measure of the effect of directional orientation. On average, the variation among the three hydrophones used was 12% for the first group of hydrophones (Recordings 1 to 29) and 18% for the second group of hydrophones (Recordings 30 to 56). Hydrophone-to-hydrophone variation was accounted for in the predictive model through application of a "safety factor" to the predicted impulse strength values for buried charges. This safety factor was approximately 4.5 times the predicted impulse strength value and represented the approximate 95% confidence limits for the model.

IMPULSE STRENGTH MEASUREMENTS

Impulse strengths calculated for each charge detonation are provided in Appendix I. The graphic waveforms from which impulse strengths were calculated are included in Appendix II. A description of the recording numbers versus tests performed to obtain impulse strength data is given in Appendix III. In some instances, reports for various charges were too low to be detectable by the recording instrument and no impulse value could be calculated. Reports from charges which exceeded the upper limit of linear response for the recording unit were not included in this analysis.

EFFECT OF AIR CURTAIN MITIGATION ON OVERPRESSURE

Peak pressure across the air curtain was reduced by a mean value of 53% (range 17 to 93%) for the six trials (Table 2). Impulse strength values also showed a decrease across the air curtain during 4 of 6 trials by a mean value of 14% (range 30-73%). In trials 3 and 4 an increase in impulse strength of 140 and 4% respectively was observed (Table 2) due to an increase in duration of the positive phase of the overpressure wave.

CAGED FISH STUDIES

In all four cage structure/overpressure wave trials, average values for peak positive pressure and impulse strength were higher inside the cage than outside (Table 3). Increases ranged from 6 to 36% for peak pressure, and from 2 to 51% for impulse strength.

Results of caged fish exposures are summarized in Table 4. Complete autopsy results are included in Appendix IV. Many of the damage evaluation criteria such as hemorrhaging and "slight" organ damage (see Table 1 for injury level categories) were not apparent or were evident as scar tissue for fish held for 21 days. Fish showing damage (Table 4) would likely have exhibited the damage criteria associated with level 2 or level 3 injury (Table 1) had they been autopsied immediately after exposure. In previous investigations where test fish were autopsied immediately after explosure, level 2 and 3 damaged fish have been considered mortalities for the purposes of calculating percent mortality (Gaspin, 1973, 1975).

Mortality in test fish exposed at depths of 1.0 m occurred within a range of impulse strengths between 1.11 bar.msec (22% mortality) and 3.60 bar.msec (100% mortality). A well defined relationship between impulse strength and mortality was not evident based on the test results. Our data indicated a 50% lethal level at an impulse strength of approximately 3 bar.msec; yet some groups of caged fish exposed at 6.0 m depths survived at higher impulse levels, with one test group showing no effect at an impulse strength of 4.12 bar.msec.

LINEAR VERSUS POINT SOURCE CHARGES

Values of peak pressure for linear charges were 30 to 73% lower than for point source detonations used (Table 3). Similar ratios of peak pressure for the two types of explosives were increased at 1, 10, and 20 m depths. Impulse strengths were found to be 30 to 55% lower for linear as compared to point source charges.

RESIDENT FISH POPULATION MONITORING AND POST BLAST OBSERVATIONS

Results of echo-location and purse seining efforts are illustrated in Figure 10. Figure 10 also shows the post blast fish mortalities for those detonations at which observers were present. Fish presence as determined by echolocation surveys is represented as scaled values. Purse seining successes were calculated as the number of seine attempts yielding fish, divided by the total number of attempts, expressed in percent. "Fish" for these calculations was defined in terms of larger sized fish such as Pacific herring (Clupea harengus pallasii) or surf smelt (Hypomesus pretiosus pretiosus). Smaller fish such as stickleback (Gasterosteus aculeatus) were not included, as this species did not contribute to post blast mortality estimates.

Post-blast mortalities were observed after 22 of the 60 blasts which were monitored during the period of December 5, 1984, to February 4, 1985 (Fig. 10). These data are summarized by number, species, and distance from blast, in Table 6. In resident fish populations mortalities reached 400 to 500 individuals on two occasions (January 11, 1985, and January 15, 1985). Mortalities consisted primarily of herring (Clupea harengus pallasi) and smelt (Hypomesus pretiosus pretiosus). All mortalities were observed within a 50 m horizontal distance from the blast, with most of the large kills occurring within 30 m.

RESULTS OF DATA ANALYSIS

Linear regression analyses were performed to determine which variables were correlated with either maximum pressure, duration, or impulse strength. Several factors (i.e. independent variables in Tables 7a, 7b) were shown to have a functional relationship with maximum pressure, pulse duration, and impulse strength in the present study. Maximum pressure was found to vary inversely with vector range and hole depth. That is, the deeper the charge penetrated into the rock, and the further the point of observation was from the charge, the lower the expected maximum pressure. The R^2 x 100 column in Table 7a indicates the percent of the total variability in the data which is explained by that particular independent variable. In the case of P_{max}, 24.8% of the variability was accounted for by vector range and hole depth. Pulse duration was directly related to recorder depth and charge weight raised to the 2/3 power. However, the "fit" of the data at 7.13% indicated that pulse duration was not a major variable in determining P_{max}.

Impulse strength was also found to be inversely related to vector range and hole depth, with 29.1% of variance accounted for by these two factors (Table 7). Other factors which were identified as important contributors to impulse strength were water depth, charge weight (to the 1/3 power), and collar depth; however, the addition of these three factors only increased the percent of variance accounted for from 29.1 to 31.7%.

Sub-sets of the blast data were subjected to linear regression analysis to identify changes in the relative importance of independent variables at different stages of the blasting program. For blast overpressure measurement to the north of the drilling rig, impulse strength was inversely related to the vector range, and directly related to water depth (Table 7b). Fifty-three percent of the variability in the data was accounted for by these two variables. When a sub-set of this data set using only the first charge in each detonation was tested, impulse strength was again found to be inversely related to vector range, and was positively related to water depth and collar depth. For this data sub-set, these three factors accounted for 72.8% of the total variability.

Data collected on the second pass of the drill rig (when charges were decked) showed that impulse strength was inversely related to vector range and hole depth, and directly related to charge size. The degree of variability explained by these three factors was only 20.4%.

Results of curvilinear regression analysis to compared predicted results from the buried charge and Yelverton models are given in Table 8. Yelverton's model was used to predict impulse strengths at various vector distances for a given charge, and these values were compared to impulse strengths predicted by the buried charge model. A high degree of "goodness of fit" (99.9%) was achieved.

Predictive equations for buried charges are shown for 6 m, surface, mid water, and near bottom depths. The rate for attenuation of impulse strength with distance from the charge is indicated by the power to which $\overset{\perp}{R}_V$ is raised. Attenuation rates were higher for observations near the bottom (2.392) and surface (1.369), compared to mid water depths (0.672). The predictive equations and 95% confidence limits for 6 m depth is plotted in Figure 12. All predictive equations were scaled to account for differences in charge weights.

DISCUSSION

ASSESSMENT OF OVERPRESSURE MONITORING INSTRUMENTATION

A review of the available literature on effects of underwater explosive detonations on aquatic organisms shows that a wide variety of instrumentation and methodologies have been used for determining impulse strength from overpressure measurements. The approach used in most models is the same, whereby a pressure-sensing device (hydrophone) is used to convert pressure from the shock waves into an electrical current which is then transmitted to an amplifying/recording instrument. The data output recorded by the different instrument configurations varies considerably depending on factors such as instrument response time, frequency response, detection capabilities, hydrophone damping, compatible resonance frequencies, polar responses, and other performance characteristics of the instrumentation. This situation makes comparisons of data collected from different studies very difficult. To compare results from one investigation to another, proper calibration of the respective recording systems to known pressure sources must be carried out to allow independent evaluation of instrument performance. Published studies rarely include this information or have actually followed a vigourous calibration sequence.

Response time for the instrument package is one important operating feature. The overpressure waveform for high explosive detonations (Fig. 11) is characterized by a "near instantaneous" rise to peak pressure followed by an exponential decay to the time of arrival of the surface reflected "cut-off" wave (t_c). The rate of initial pressure increase is a function of the high frequency components of the overpressure wave, and detection and recording instruments should have response times of 0.1 millisecond or less. Instrumentation used in the current study had a response time in the order of 0.1 to 0.3

milliseconds, and therefore was not capable of detecting the highest frequency components of the overpressure wave. Instruments with similar response characteristics to those used in the present study have been employed in other investigations of underwater blasting effects (e.g. Mobil Oil, 1984). The faster the instrument response time, the larger the area produced under the pressure-time curve. Improved precision in calculating values for both peak pressure and impulse strength can be attained when instruments with appropriate response times are used.

Improper electronic "coupling" between the hydrophone and the surface recording unit can also be a source of error in overpressure measurments. The hydrophone and associated recorder may be products of different manufacturers, and if proper calibration testing is not performed to ensure that the two components are compatible, the hydrophone output may not accurately indicate the actual overpressure experienced.

Performance characteristics of the hydrophone itself may also be a source of error in overpressure monitoring. One important performance characteristic of the hydrophone unit which should be tested is the "polar response". This term refers to the directional sensitivity of the hydrophone in difference planes and is dependent on the orientation or position of the hydrophone in relation to the pressure source. Ideally, a hydrophone should be "omni-directional", giving a uniform response independent of hydrophone orientation in relation to the blast. Polar response patterns are used to evaluate the directional sensitivity of a hydrophone (see examples, Fig. 9, 10).

Some investigators (Gaspin, 1975, 1976) have circumvented this problem by controlling the orientation of the pressure sensor of the hydrophone. Other investigators have relied on the polar response patterns supplied by the hydrophone manufacturers, which invariably indicate a high degree of omni-directional response. However, independent testing on hydrophones claimed to be omni-directional by the manufacturer has shown that variations in directional sensitivity can be as large as 18% (L. Brocklehurst, pers. comm.). Proper testing of hydrophone directional polarity using a range of frequencies encompassing those produced by the underwater detonations being studied should be included in any calibation exercise for overpressure monitoring instrumentation.

PROBLEMS IN DEFINING IMPULSE STRENGTH

Our review of the published literature revealed that the method employed for calculating impulse strength from overpressure data (i.e. how impulse strength was defined) varied from one investigator to another. Cole (1948) discussed the nature of the pressure-time curve, and suggested one approach to defining a meaningful value for impulse strength for comparing different explosive types. The main problem he identifed was one in establishing an upper time limit for integration of the pressure curve. Cole (1948) noted that, ideally, impulse strength was a measure of a short-lived transient pressure phenomenon. He concluded it was both difficult and undesirable to have relatively long-term pressure responses influence the calculation of impulse strength. This definition presents a problem in calculating impulse strength from some types of blasts, particularly buried charges, which have a proportionately longer positive pressure phase than mid-water detonations. Cole (1948) further emphasized the need to recognize that the selection of the time period for integration (i.e. how impulse strength was calculated) was somewhat arbitrary, and that this fact must be considered when comparing the results of various studies.

Yelverton (1973, 1975) conducted tests on various species of birds, mammals and fish to determine the relationship between impulse strength and biological effects. Because Yelverton's work was conducted in a relatively small test pond (68 m x 46 m x 10 m deep), the elapsed time used for calculating impulse strength was usually less than 0.005 millisecond, which did not include the influence from the incident shock wave, an important wave component experienced in field situations. Yelverton also employed computer techniques to compensate for the inability of the pressure recording instrument used to accurately record the initial rise to peak positive pressure (P_{max}). He extrapolated the pressure curve back to obtain the calculated value of P_{max}, but in so doing,added additional "area" into his calculated impulse strength values.

The work reported by Goertner (1978) used data originally developed during investigations by Gaspin (1973, 1975). These same experimental results were also discussed by Wiley (1981). In all cases, the calculation of impulse strength was based on an integration of the area under the pressure/time curve up to a maximum time, $t = 5\ \Theta$

(J. Gaspin, pers. comm.) (see Glossary, page 45). The instrumentation used had extremely good response time in measuring high frequency signals, and P_{max} was measured directly.

During a recent study of the effects of linear explosives on fish populations near Sable Island, Nova Scotia (Mobil Oil, 1984), Yelverton's impulse strength model was used as the basis for predicting expected lethal ranges. Impulse strength was calculated as the integration of pressure over time for the period of the first positive and negative components of the shock wave. Although not stated in the text, presumably the absolute value of the negative component was used in the summation of positive and negative phases. The rationale for employing this particular approach to calculating impulse strength was not given.

Resolution of a suitable "working definition" for defining impulse strength is required before results from different studies can be adequately compared. At present, the values reported by Yelverton (1973, 1975) are most frequently used as "benchwork" reference values because of their original application to studies involving biological effects.

IMPULSE STRENGTH MEASUREMENTS FOR BURIED CHARGES

It is clear from the foregoing reviews that impulse strength has been determined in a variety of ways and that the calculation of impulse strength depends to a large extent on the characteristics of the instrumentation used in the field measurements. In the present study, we dealt with two constraints in calculating impulse strength.

First, the burial of charges in the substrate produced pressure waveforms which were unique and considerably more complex than the waveforms produced by openwater detonations. This was a result of multiple refractive shock waves travelling through the rock substrate and arriving at the hydrophone at the same time as the direct wave. In addition, multiple charges were detonated with varying time delays which resulted in coincident arrival of reflected waves from previous charges. In part, the characteristics of the overpressure wave from buried charges are the result of the reaction of the rock substrate around the explosive, whereas the openwater waveform is the result of gas bubble expansion and contraction. The complexity of waveforms from buried charges required the use of graphic techniques to define the area under the pressure-time curve used for calculating impulse strength. This procedure may have resulted in overestimation of impulse strength values due to increased time durations for buried charges relative to those reported for midwater charges. Owing to the complexity of the waveforms from buried charges, it was not possible to calculate a time constant (Θ) in the manner used by previous investigators. Therefore, we defined the upper time limit of overpressure integration for calculating impulse strength as the time of arrival of the surface incident (cut-off) wave resulting in negative (below ambient) pressures. The integration is carried out for the duration of positive pressure (T_{pos} ; Fig. 11).

The second limitation imposed on the present study was the frequency response of the available instrumentation used to record overpressure. The instrument used was not capable of detecting overpressure frequencies above 1000 Hz. Because our pressure-time curves for buried charges were complex compared to the predicted waveform for mid-water detonations, our reported peak pressure values were as determined by field measurements without the correction factors applied by Yelverton. Our values for peak pressure and impulse strength, considering this limitation on frequency response, may be lower than would have been calculated had the instrument responded to higher frequency components of the overpressure waves. However, differences in the calculated values for impulse strengths were probably minor. Hill (1978) indicated that overpressure contributions from frequencies outside the 10-200 Hz range were insignificant in relation to the energy of the wave. Variations in the measurement of instantaneous peak pressures may differ significantly depending on the response of the pressure sensing instrument to the high frequency components of the overpressure wave, but this has not been tested.

Yelverton's model is based on experimental data derived by varying the depth of charge, and depth of observation within the confines of a small test tank facility. As such, the model is characterized by predictions which increase in error with ever increasing water depths. The relationship has been established for water depths up to 3 m in open water conditions in the field. Yelverton's model is a function of the change in the relative time of travel for the surface reflected (cut-off) wave relative to the direct pressure wave. As the rate of change of impulse strength in Yelverton's model was established in shallow "depths", the model has a bias towards predicting higher impulse strengths at water depths greater than 3 m.

In summary, the calculation of impulse strength from the unique waveforms for buried charges differs from methods commonly employed by investigators studying mid-water detonations. In many cases, the duration of time over which the impulse strength is integrated for buried charges is longer than would be used for the calculation of impulse strengths for midwater charges. When our methods for calculating impulse strengths for buried charges were applied to mid-water detonations in the present study, values for impulse strength were in agreement with other investigators.

AIR CURTAINS AS MITIGATIVE MEASURES

Our conclusions concerning the relative effectiveness of air curtains as a mitigative measure for blasting effects agree with previous assessments of their effectiveness in reducing maximum pressures from underwater detonations (e.g. McAnuff et al., 1976). Reduction efficiencies of up to 90% have been observed. No information on changes in impulse strengths across air curtains was found in our review of the literature. Reductions in lethality by air curtains are probably greater than predicted by the relative change in impulse strength due to distortions in overpressure waveforms caused by air curtains, and the subsequent effect (i.e. increase) on the calculated values of impulse strength.

A survey of various types of explosive charges has shown that lethality is greatly reduced in the case of low velocity explosives (i.e black powder) which have waveforms of characteristically long duration (Linton et al., 1984). Similarly, lethality has been greatly reduced by the use of air guns even though calculated impulse strength levels are high. In the cases where impulse strength was increased across the air curtain, the increase was due to a longer duration of positive overpressure. This would tend to reduce the damaging effects that these overpressure waves would have on fish as in the case of low velocity explosives and air guns. In this case, impulse strength is not a good damage parameter in predicting effects. The effective reduction in lethality by air curtains is more likely reflected by the relative change in maximum pressure rather than impulse strength.

In the current study, air curtains were used in relatively short lengths to protect pier structures. However, the usefulness as a mitigative measure is limited by the size of compressors required to produce a sufficient flow of air to curtains of sufficient length to be used in the protection of fisheries resources. In the current study, two large compressors were required to supply sufficient air flow for 43 m of air curtain.

LETHAL IMPULSE STRENGTHS - DIFFERENCES IN PREDICTED VERSUS OBSERVED VALUES

Impulse strength levels which resulted in fish mortality in the present study increased with the depth at which the cages were placed over the range from 1 to 6 m. Below a depth of 1 m, the values of impulse stength required to produce mortality in our test fish were higher than lethal values predicted by the Yelverton model. Experimental values for exposure at 1.0 m depth indicated a 50% lethal impulse strength of 2.5-3.0 bar.msec compared to a predicted level of 0.8 bar.msec. This apparent increase in the lethal level threshold for impulse strength measurements may have been the result of several factors including:

1. an increase in the duration of the shock wave caused by charge burial which would yield higher values in calculating impulse strength when pressure was integrated over time;
2. specific differences in sensitivity between species tested in Yelverton's model and the coho salmon used in the present study. Salmonids appear to have a higher resistance to shock damage than other species;
3. differences in the methods used to calculate impulse strength;
4. apparent higher values for impulse strength as an "artifact" of the influence of the cages themselves.

As noted earlier, impulse strength measurements inside the cages used in the present study were higher than measurements directly outside the cage. The cages may effectively change the pressure wave making it more readily detectable by the hydrophone sensors. During calibration, it was determined that the hydrophones were very directionally sensitive to pulse-like signals of short duration and large amplitude. The cage structure may broaden the directional orientation of the passing pressure wave.

The complexity of the overpressure waveforms resulting from buried charges indicates that refracted waves are carried by the bottom strata and can "emerge" to contribute to the resultant overpressure in the water column. Where the refracted waves converge with pressure waves directly from the blast, a higher total impulse strength can reach the fish. These added pressures may not increase the lethality of the resultant pressure wave because waves from impulse strength calculations are not directly related to threshold lethal levels established by Yelverton.

Research on the particular characteristics of the waveforms from buried charges which related to effects on fish are required to resolve this issue. Such studies should involve controlled, experimental exposures of fish to shock waves from various types of buried charges. Calculation of "impulse strength" as related to waveforms from buried charges should be redefined, or a new function derived which can be consistently related to specific levels of mortality in fish. Experimental data of this type are essential as a data base from which to accurately predict effects of buried charges. Attention should be given to the influence of depth of the fish within the water column on mortality.

Ultimately, modelling can be refined through the suggested research approaches to yield more accurate predictions of lethality. If a cause-effect relationship between overpressure waves and damage effects can be identified, then additional mitigation measures may be suggested through the refinement of the blasting activity to avoid the causal element(s). Currently, the model predictions are less accurate than desired. The need for more accurate predictions at this time must be balanced against both the current limitations in identifying fish presence in the blasting area and our limited ability to mitigate damage effects when they are known to occur.

LINEAR EXPLOSIVES AS A SEISMIC ACOUSTIC SOURCE

Transition zone areas are shallow coastal areas which cannot be explored using current shipborne non-explosive techniques (e.g. air guns). Chemical explosives, either linear or point source formulations, have been suggested as the only seismic acoustic energy sources currently available for definition of substrata characteristics in transition zone areas. However, because of the greater lethality to fish of point source explosives, seismic operators have been encouraged by government regulators to use linear explosives wherever possible. The lethality to fish of this explosive configuration has been investigated by several researchers (Falk and Lawrence, 1973; Mobil Oil, 1984). These studies found that the lethal range for linear format explosives is less than that of point source detonations for similar charge strength. Impulse strengths were not measured in concert with mortalities observed in caged fish.

The present investigation represents one of the first published reports of measurements of the relative changes in impulse strength at various distances for both linear and point source explosives. Our data indicated that maximum pressures were lower by an average 45.7%, and impulse strengths by an average 41.5% for linear explosives (0.065 kg) compared to point source explosives (0.225 kg). Differences in charge size would account for some of the observed differences in maximum pressure and impulse strength, but functional scaling relationships developed during previous investigations can be used to compare overpressure wave characteristics for various charge sizes. Predicted values for maximum pressure and impulse strength for linear explosives would have been 34% and 57% respectively less than point source explosives based on charge size alone (Cole, 1948). That average peak pressures were lower than predicted, and impulse strengths higher, can be explained by the finite period of time required for the linear explosives to detonate (0.25 msec). Generally linear explosives are initiated at one end and so the time of detonation is a function of the detonation velocity and the length of the charge. This delay would result in somewhat lower maximum pressures than if the entire explosive volume detonated instantaneously, as is assumed in the theoretical calculations used to derive the predicted values. Since impulse strength is a function of time as well as maximum pressure, the increased pulse duration of the shock wave from the linear explosive would account for the higher than expected impulse strengths observed.

The question which remains to be answered is how the relative lethality of the shock waves from linear explosives differs from point source detonations. As discussed previously, the waveform characteristics of any blast (i.e. the blast "signature") is a critical factor in determining the ultimate lethality of the blast to fish. The situation is analogous to that of the relationship between impulse strength and lethality for high (fast detonation velocity) explosives compared to slower (detonation velocity) explosives. In the latter case, high impulse strength levels generated by large quantities of explosive charges have not caused injury in fish because of the relatively long duration of the shock wave (Hubbs and Rechnitzer, 1952). Additional research involving the exposure of caged fish at various distances from linear charges is required to adequately address this question. Measurement and analysis of the waveform "signature" from the explosives should be an essential component of such studies.

EVALUATION OF BIOLOGICAL MONITORING IN ASSESSING POTENTIAL IMPACTS OF UNDERWATER EXPLOSIONS TO RESIDENT FISH POPULATIONS

Echo sounding and purse seining are common techniques presently used to establish presence of fish in blast areas prior to detonation. In the present study, daily echo locating and weekly or bi-weekly purse seining were used to gather information on fish presence over the study period. This monitoring was intended to identify when migratory populations such as herring, surf smelt, and possibly salmonids occupied shallow water areas in the harbour near the blast site, thereby increasing the potential risk imposed by the blasting operations.

Results of monitoring showed that fish kill was <u>not</u> consistently predicted by pre-blast echo locating in areas surrounding the blast. The same holds true for purse seining which proved to be marginally effective in sampling resident populations even when schools of fish were determined via echo location to be present. In many field situations, echo location and seining are not possible in the immediate area of drilling and blasting due to the presence of mooring cables used to stabilize the drilling rig, etc. Yet, these are the critical areas where most observed fish kills occur. Even when it was possible to get the sampling vessel in close to the charge locations, the suspended sediments and turbulence from the drilling operation, and the proximity to the drilling rig, created spurious records on the echo sounder chart.

Attempts were made to conduct post-blast SCUBA surveys. This proved to be impossible due to the turbidity associated with both the bubble upwelling from the detonation and the air curtains. This turbidity resulted in near zero visibility in bottom waters at the point of entry approximately 50 m from the detonation. Assessment of resident fish presence near the blast area in study sites such as Vancouver Harbour are difficult, especially during complex multi-charge drilling and blasting programs.

Kearns and Boyd (1965) reported that echo location was predicting fish kills only 36% of the time in seismic refraction studies off the West Coast of Vancouver Island. Purse seining was used to measure fish presence near a blasting operation in a shallow marine embayment, False Creek, B.C. (Nix, 1983). Although seine catches reflected week-to-week and month-to-month changes in fish presence, seining success was not directly correlated with mortalities in fish from individual detonations.

Monitoring of resident fish populations by both echo location and purse seining does not appear to provide a high degree of reliability in predicting mortalities from underwater detonations even if the lethal range can be predetermined. The use of this type of monitoring can identify day-to-day changes in resident fish presence in the general proximity of the blast area, but the constraints on both monitoring techniques restrict their application to defining fish presence within the predicted lethal zone. Based on our field experience at a number of coastal blasting sites, we recommend that future blast monitoring concentrate on documenting details of the blast program (e.g. charge sizes, types of explosive, detonation sequence, bore hole characteristics, etc.). This information together with post-blast observations of fish mortalities and possibly in conjunction with blast overpressure wave measurements at each site can be used to develop an improved data base for predicting lethal effects under a variety of operational conditions. Through development of our knowledge of the blast wave characteristics associated with different blasting operations and in turn their relationship to fish mortality, we will ultimately be able to provide better protection for our coastal fisheries resources.

PREDICTIVE MODELLING FOR BURIED CHARGES

The predictive modelling approach used in the current study was one which determined variance from observed measurements, and then identified mathematically cause and effect relationships (independent variables). A number of sources of variance were identified during the study including reporting of operations-related information and variations in polar responses of hydrophones. The following factors were investigated to determine possible relationships with changes in overpressure:

- charge size (W_c) including $W_c^{1/3}$ and $W_c^{2/3}$
- recorder depth
- water depth at charge
- collar depth
- hole depth
- vector range
- position of charge in a detonation series
- proximity to air/sea and sea/bottom interfaces.

Each of the above factors was tested statistically both singly and collectively to determine which factors were related to observed changes in overpressure levels.

Charge size

Charge size (W_c) measured in kilograms was directly related to overpressure levels for mid-water charges. The Law of Similarity of Charges states that an increase in charge size will result in an increase in maximum pressure and impulse strength. The rate of increase will be directly proportional to the rate of change of charge, W_c in the case of maximum pressure, and in $W_c^{1/3}$ for impulse strength. The theoretical relationships which form the basis for the Law of Similarity of Charges have not been tested previously using cylindrical buried charges.

Charge size was related to both duration (as $W_c^{2/3}$) and impulse strength (as $W_c^{1/3}$). The variations in charge size were not large (19.95 $\pm$ 8.29). The program did not provide an adequate test of the relationship between charge size and resultant overpressure due to the relatively small range of charge size used in the blast program monitored in the present study. In order to develop a model which could accommodate different charge sizes, the relationships indicated by the Law of Similarity of Charges were assumed to apply.

Recorder depth

Recorder depth was identified as being directly related to duration of overpressure. This relationship is likely a result of enhancement of the direct overpressure wave by refracted waves with increasing depth. The magnitude of these contributions is discussed under interface effects.

Water depth

The depth of water in which the charge is placed was identified as being directly related to impulse strength levels. The variation in water depth during the study was not large (14.69 $\pm$ 1.75 m). The fact that water depth was significant was likely a result of changes which occurred at the start of the blasting program, when the deeper portions of the site were being drilled and blasted. Initially, the charges were placed closer together than at later stages, which probably resulted in higher overpressures initially in the deeper water areas.

Collar depth

Collar depth (see Fig. 3) was identified as being positively related to impulse strength. This implies that the greater the distance between the sediment surface and the top of the charge, the higher the impulse strength. This is contrary to the relationships which might be expected to occur, and may result from the way in which this factor was determined by the drilling crews. There were inconsistencies between various shift foremen responsible for collecting the drilling log data, which may have resulted in some erroneous collar depth calculations. These inconsistencies arose from variations in measuring the elevation of the sediment surface before versus after drilling the hole. The bottom of the drill spud (outer housing for the drill rod) was used as a reference for the sediment surface. Differences of up to 11 m in recorded collar depths were observed due to subsidence of the drill spud during the drilling process. Baxter (1982) in his review of the work of Hubbs and Rechnitzer (1952) noted that the tamping effect caused by charge burial resulted in higher maximum pressures near the charge than expected for the same charge detonated in mid-water. This same effect may have occurred in the current program due to increased containment of the charge with increased collar depth.

Hole depth

Hole depth or the depth of drill was identified as being inversely related to both peak pressure and impulse strength. It is second to vector range as the most predictive factor for both overpressure characteristics. Much of this dependence may be due to the practice of decking of charges conducted in the second half of the blasting program. In this case, the hole depth was the same for surface and bottom charges. The report from the bottom charge was likely greatly reduced, and therefore would contribute significantly to the inverse relationship identified.

Vector range

Vector range was identified as being inversely related to maximum pressure, duration, and impulse strength. In all cases, it was the most significant factor in determining the resultant overpressure.

Position of charge in a detonation series

It was readily apparent from the data collected in the field that the first or initiating charge in a detonation series most often produced the largest maximum pressure and impulse strength readings. Regression analysis confirmed this relationship. This occurs because of the high degree of confinement of the first charge compared to subsequent charges in a detonation series. Secondary charges are less confined due to fracturing and rock movement resulting from the initial charges.

Construction program changes

Changes in drilling patterns during initial stages of the construction program were identified as a possible influence affecting overpressure. Impulse strengths for Recordings 1 to 11 were consistently higher than mean predicted values. During this initial phase, holes were drilled in 2 x 3 m grid pattern. When it was realized that this drilling pattern resulted in overbreak or excess fracturing, the drill pattern was changed to a 3 x 3 m pattern. The increased volume of rock per unit charge may have dampened overpressures released to the water column.

Observed values for overpressure were generally higher during the second pass of the drill rig than during the first pass. It is significant that dredging activities were keeping pace with the drilling and blasting operations during this time, which was not the case during the first pass. Better clean-up of fallen rock appeared to create an open "blast face" which resulted in higher overpressures being released to the water column. It may also have been important that the pier structures created a greater degree of confinement for refraction on the second pass of the drill rig.

Results of hydrophone placements near the surface and near the bottom compared to mid-water placement showed significant interface effects. Enhancement was observed at both interfaces with the greatest effects observed close to the charge. At a range of 20 m, predicted surface and bottom values exceeded mid-water values by factors of 2.2 and 5.3 respectively. At a range of 50 m, rates of enhancement at the surface and bottom decreased to 1.2 and 1.1 respectively.

Enhancement at the sediment/sea interface is likely a result of the effects of refracted waves added to the direct wave. Because of the different rates of travel of the shockwave in rock versus air (approximately 3X faster in rock), this additive effect would be greatest near the blast when refracted wave arrival and direct wave arrival are in place.

The enhancement observed at the air/water interface is contrary to what might be expected. One would expect that the surface reflected wave (or cut-off wave) would limit the positive pressure wave at the surface before it would limit the positive pressure wave at mid depths. One possible explanation is that of a "shotgun" effect in which the force of the blast is surface-directed by the orientation of the drill holes. In this case, the hydrophone suspended near the surface would receive the greatest overpressure signal. The enhancement observed at the surface could also be explained in part by the polar response patterns of the hydrophones, which showed reduced sensitivity in the vertical plane. Positive reflection of overpressure from the water surface may also have contributed to the enhancement phenomenon. Little is known about the positive surface reflection of overpressure waves, but a positive enhancement effect is possible (Cole, 1948). Experimental field measurements from different types of explosives are required to assess the importance of this phenomenon and its lethal implications.

Modelling approach

Having identified the factors described above which affected changes in impulse strength, the following steps were taken to develop the predicting model:

vector range was selected as the factor which contributed most to the variance associated with impulse strength;

the relationship between impulse strength and vector range was identified through curvilinear regression analysis

the relationship between impulse strength and vector range was scaled to account for differences in charge weight.

The following functional relationship provided by Cole (1948) encompasses these three criteria:

$$\text{Impulse Strength} = a\,(W_c^{1/3})\left(\frac{W_c^{1/3}}{R_v}\right)^x$$

where, a and x are experimentally determined

W_c = charge weight (kg)

R_v = vector range (m)

During the field program, much of the data collected on the second pass (Recordings 30 to 56) were collected with all three hydrophones placed at depths of 6 m at various distances from the charges. This data base was used to generate the curvilinear predictive equation using the function relationship previously described. The majority of observations made during the study program were included within the 95% confidence limits for the predictive equation. Due to the inherent variability within the data base, the confidence intervals on the predictive equation are correspondingly large with the upper confidence limit set at 4.5X the mean predicted value. Even with this large "safety margin" on predicted values, the predictive model at its upper confidence limit represents an approximate reduction in the size of the 50% lethal range of 4.7 fold from that predicted by Yelverton's mid-water model. Until additional experimental data are gathered through future research, the relative contributions of all the factors affecting impulse strength cannot be independently modelled. At present they are inherent within the confidence interval about the predictive equation. As additional data are incorporated into the model developed, the confidence limits for predictions will be improved. The predictive model as defined by the data collected at 6 m depths was found to be predictive of the observed mortalities during the blasting program.

FISHERIES MITIGATIVE MEASURES

Potentials to mitigate the effects of underwater explosive detonations have been compiled from a review of existing literature, discussions with blasting contractors, and through the current investigation of buried charges. The operational characteristics of each blasting program will be different due to the program objects and site-specific considerations. These factors will ultimately determine which mitigative measures are appropriate.

Midwater Blasting

The use of high velocity explosives in midwater applications offers limited opportunities for mitigation. These include:

1. Time blasting operations to avoid periods of high fish presence (e.g., migration periods).

2. Carefully plan blasting program to minimize the size of charge and the total number of charges required.
3. Use of scare tactics (non-explosive) to try and remove fish from the immediate blast area.
4. Subdivide effective charge using detonating caps with built-in delays to reduce the effective charge per delay period.
5. Use of a low velocity explosive if the objectives of the blasting program can still be met.
6. Use of shaped charges to focus the blast energy in such a way as to reduce the energy released to the water column as overpressure during demolition activities.
7. Use of linear explosive (detonating cord) for seismic surveys to lessen the amount of explosive required to produce a comparable acoustic signal for reflective surveys.
8. Use of air curtains wherever practical to effectively decrease the lethality of overpressure waves.

Buried Charges

The use of buried charges offers more possibilities for mitigation compared to the use of midwater charges. Mitigative measures include:

1. Careful planning of blast program to minimize the size of charge.
2. Land use planning to avoid blasting operations in highly productive fish habitats.
3. Time blasting programs to avoid periods of high fish presence.
4. Use of lower detonation velocity explosive products where practical.
5. Use of air curtains wherever practical.
6. Use of alternate mechanical techniques (e.g., weighted clam-shell dredge) to accomplish program objectives.
7. Use of detonating caps with built-in time delays to reduce the effective charge per delay period.
8. Use of a procedure known as "decking the charge" which subdivides the charge in one drill hole into a series of explosions.

9. Use of non-propagating explosives.
10. Use of two caps to detonate each charge to ensure detonation as planned without cap failure.
11. Overdrilling the holes to ensure proper fracturing of the substrate.
12. Leave overburden in place to provide dampening material for subsequent blasts.
13. Use of gravel or similar substrate to stem holes (i.e., filling the holes to the sediment level after the charge is in place).

Charge burial in hard substrate is a form of mitigation in itself. It effectively alters the resultant overpressure both in absolute levels and in its nature. The near instantaneous rise times characteristic resulting from high frequency components of midwater detonations is moderated in favour of lower frequency components. This increases the duration of overpressure in the case of buried charges, which appears to reduce the negative impacts on fish.

CONCLUSIONS

The following conclusions are made as a result of the present study.

1. The performance characteristics of instrumentation used in overpressure monitoring are highly variable. Some instruments now in use do not have the response characteristics required to adequately record overpressure data for determining impulse strength.

2. There presently exists no standard, routine procedure for calibrating overpressure monitoring equipment. The lack of adequate calibration or reporting of same in many previous investigations makes accurate inter-study comparisons difficult.

3. Mean predicted values for impulse strength at vector ranges of 20 to 100 m were 5 to 6 times lower for buried charges than for mid-water charges. A number of factors associated with the drilling, blasting and clean-up operations were related to the impulse strength values observed.

4. Air curtains were shown to be effective in reducing maximum pressures and impulse strength. Impulse strengths were reduced to a lesser degree than peak pressure due to increased durations of the positive (above ambient) pressure wave behind the air curtain. The reduction in fish mortalities observed across the air curtain was most probably related to decreases in peak pressure rather than in impulse strength.

5. Linear explosives generally result in lower values for both maximum pressures and impulse strengths compared to point source charges when used as a seismic acoustic source.

6. Biological monitoring of resident fish populations by echo location and purse seining cannot be used to predict possible risks/effects from underwater explosives detonations to resident fish populations.

7. The predictive model for effects of buried charges developed during the present study is appropriate for operational conditions similar to those experienced during the field program. The accuracy of the model when applied to different charge types, or detonations in different solid substrates and water depths, is unknown and cannot be evaluated without further field data.

8. Each blasting project involving buried charges is different, and more information on the generation of impulse strengths under varied operational conditions is required.

RECOMMENDATIONS FOR FUTURE RESEARCH

The following research needs were identified during the course of the present investigation.

1. A protocol for instrument calibration should be developed designed specifically to assess performance characteristics relevant to studies of the effects of underwater

explosives detonations. The protocol should include evaluation of frequency response range, recording speed, hydrophone polar response (directionality) and instrument response to standard overpressure signals under controlled conditions.

2. A standard system for recording information from underwater explosives detonation programs in Canada should be developed as part of the project approval process. The information should be stored in a computerized system, and data made available to government departments and private industry involved in research and monitoring programs. The recorded information required should include specified details of the operational characteristics of the blasting program, results of overpressure wave measurements, and post-blast biological monitoring data.

3. Research studies are required to investigate the relationships between various characteristics of overpressure waveforms and lethality in fish. The effect of prolonged time responses for positive pressure on the sensitivity of impulse strengths in predicting lethality should be a priority. Other waveform characteristics common to buried charges and linear explosives should be identified, and their relationships to fish lethality tested in suitable field (caged fish) and laboratory studies. As salmonids have been shown to be less sensitive than other species (e.g. Pacific herring) to overpressure effects, several species should be assessed. Consideration should be given to evaluating the relative sensitivities of species from each coast of Canada.

4. As additional "cause-and-effect" relationships are identified, appropriate alternatives for mitigation with respect to different explosive products and blast program designs should be developed.

5. Modifications to existing lethal effects models should be made to improve predictive capabilities in deep water situations. The use of energy flux density as a damage parameter in place of impulse strength for deep waters is recommended. Predictions from the deep water models should be evaluated through results of experimental studies and through the careful monitoring of actual blasting programs.

ACKNOWLEDGMENTS

COASTLINE Environmental Services Ltd. wishes to acknowledge the assistance of P.A. Hiebert, K. Lund and J.-B. Coustalin with field operations, laboratory holding of test fish, and diagnosticsis. R.T. Booren and T.M. Dixon of VME Associates Limited carried out the overpressure monitoring portions of the study.

Special thanks are due L. Brocklehurst of Lab-Core Systems, and J.E. Orme of Alpha Engineering Ltd., for their capable assistance with engineering and electronic components of the study for instrument calibration. The assistance of the Vancouver Public Aquarium in providing research facilities and technical help is gratefully acknowledged.

M. Striken and S. Birtwell of Quantum Research Ltd. performed the statistical analysis of the data, and assisted with modelling and development of the micro-computer software program. Tetrad Computer Applications Ltd. provided digitizing and graphics support. Thanks to L. Borleske for her graphics and word processing support in producing the report.

The authors would like to acknowledge the financial assistance and co-operation provided by Dillingham Construction Ltd., North Vancouver, during field operations. The following Government agencies also provided both financial and technical assistance: Fisheries and Oceans, Canada Oil and Gas Lands Administration - Environmental Protection Branch, and Transport Canada. Major funding was provided through the Unsolicited Proposals Program of the Department of Supply and Services (DSS), Ottawa. The contract was administered by DSS, Science Procurement - Pacific Region, under DSS File No. 03SB.FP501-4-4711.

GLOSSARY

Overpressure wave: The detonation of chemical explosives underwater results in a concussion wave which travels away from the explosive source at the approximate speed of sound in water (1528 m/sec). This wave has as one of its characteristics a rapid increase from ambient pressure to a maximum pressure ($+P_{max}$), followed by an exponential decay. The shock wave will exhibit a negative (below ambient) deflection, especially where the point of observation is near the air/sea interface. In this instance, a reflected surface wave 180° out of phase with the original wave causes a rapid decrease in pressure some time after the arrival of the direct (positive) wave (see Fig. 11). This negative amplitude wave also reaches a maximum (negative) pressure ($-P_{max}$) followed by an exponential return to ambient pressure.

Overpressure: The term "overpressure" refers to a change in pressure from ambient (hydrostatic) pressure.

Duration of positive pressure: The elapsed time (measured in milliseconds) from arrival of the primary overpressure wave resulting in a positive pressure deflection to return to ambient (hydrostatic) pressure. Most often, the positive pressure phase is followed immediately by a negative (below ambient) pressure phase.

Maximum positive pressure (Peak pressure): The largest positive pressure experience (measured in bars pressure) for the duration of positive pressure.

Impulse strength: The time integral of pressure or

$$I(t) = \int_{0}^{t_c} P_{(t)}dt$$

where pressure (P) is in bars and time (t) is in milliseconds; impulse strength has the units bar.msec (see Fig. 11). T_c refers to the cutoff time which is the time of arrival of the surface-reflected wave.

Energy Flux Density: The rate of energy flow through a surface of unit area

$$E(t) = \int_{0}^{\infty} p^2 dt$$

where pressure (P) is in bars and time (t) is in milliseconds; energy flux density has units of Joules/m^2.

Pressure wave time constant (Θ): The time constant or decay constant in some cases is used to define the time period of integration for time related overpressure wave measurements such as impulse strength and energy flux density. For analytical purposes, the overpressure wave decay period (following P_{max}) is described as an exponential decay of the form

$$P = P_m e^{-t/\theta}$$

with Θ being the time constant of exponential decay.

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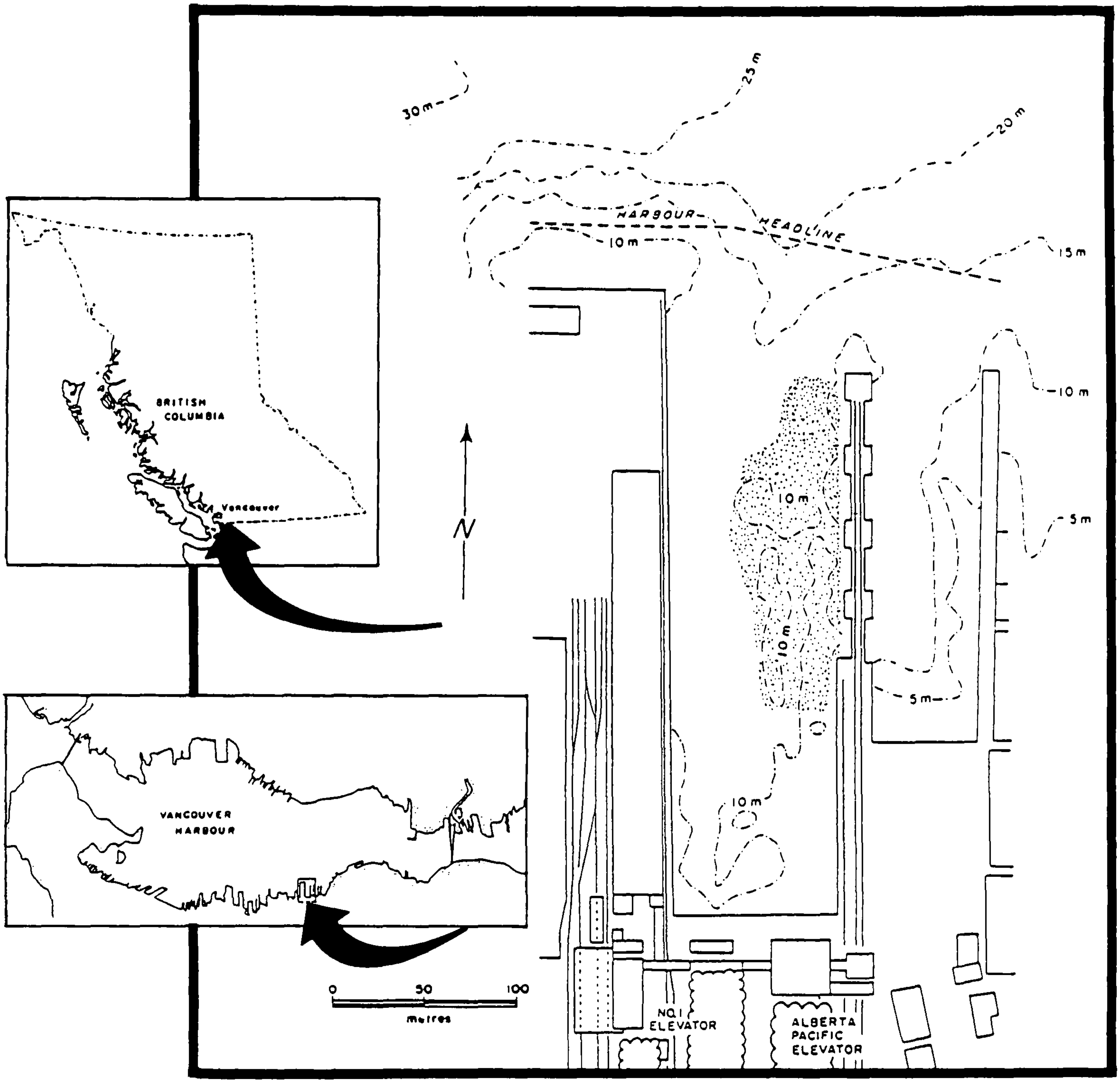


Area of till and rock to be removed by blasting

Fig. 1. Study area at Pacific Terminals Ltd., Vancouver, B.C.

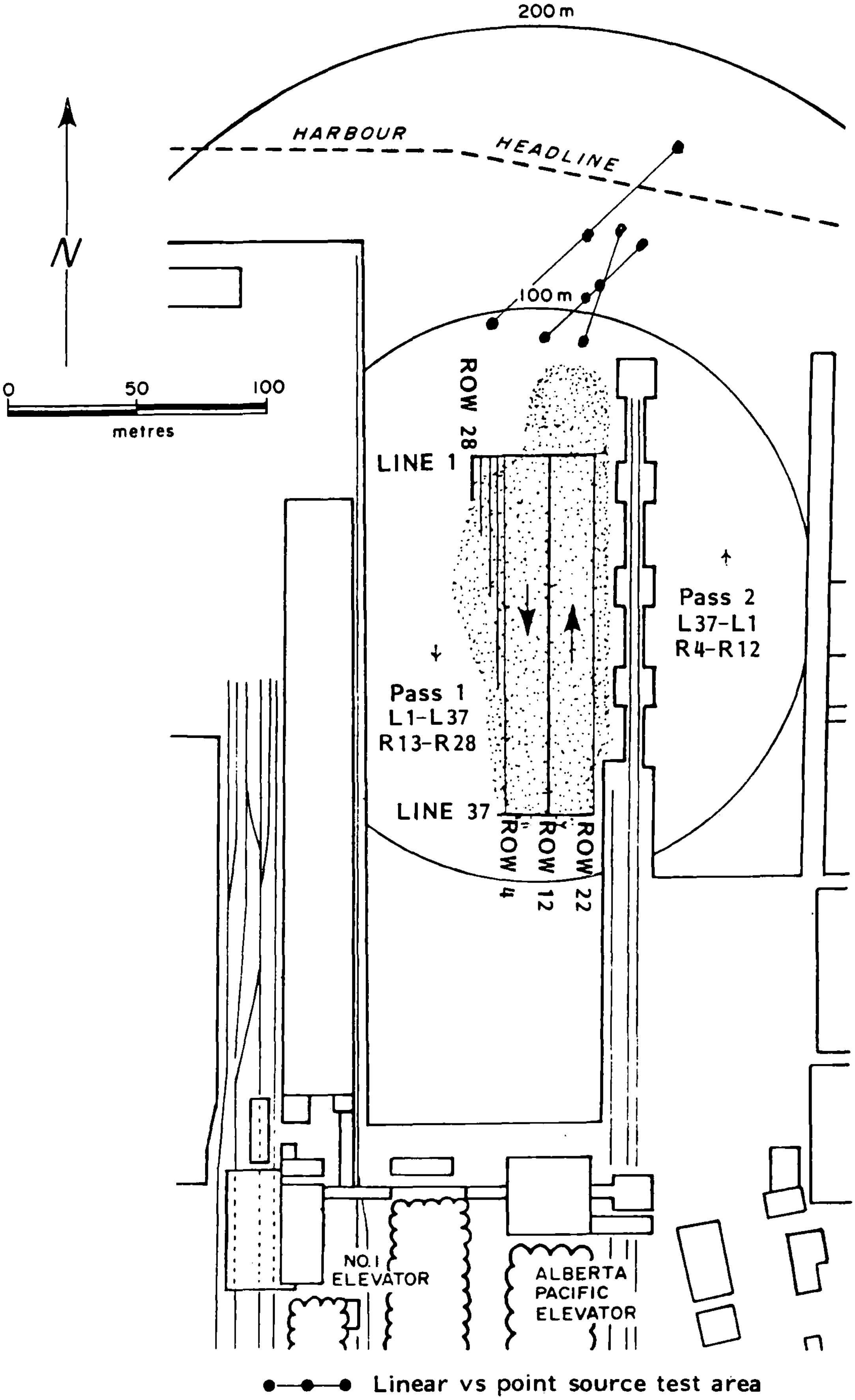


Fig. 2. Grid pattern used for drilling coordinates.

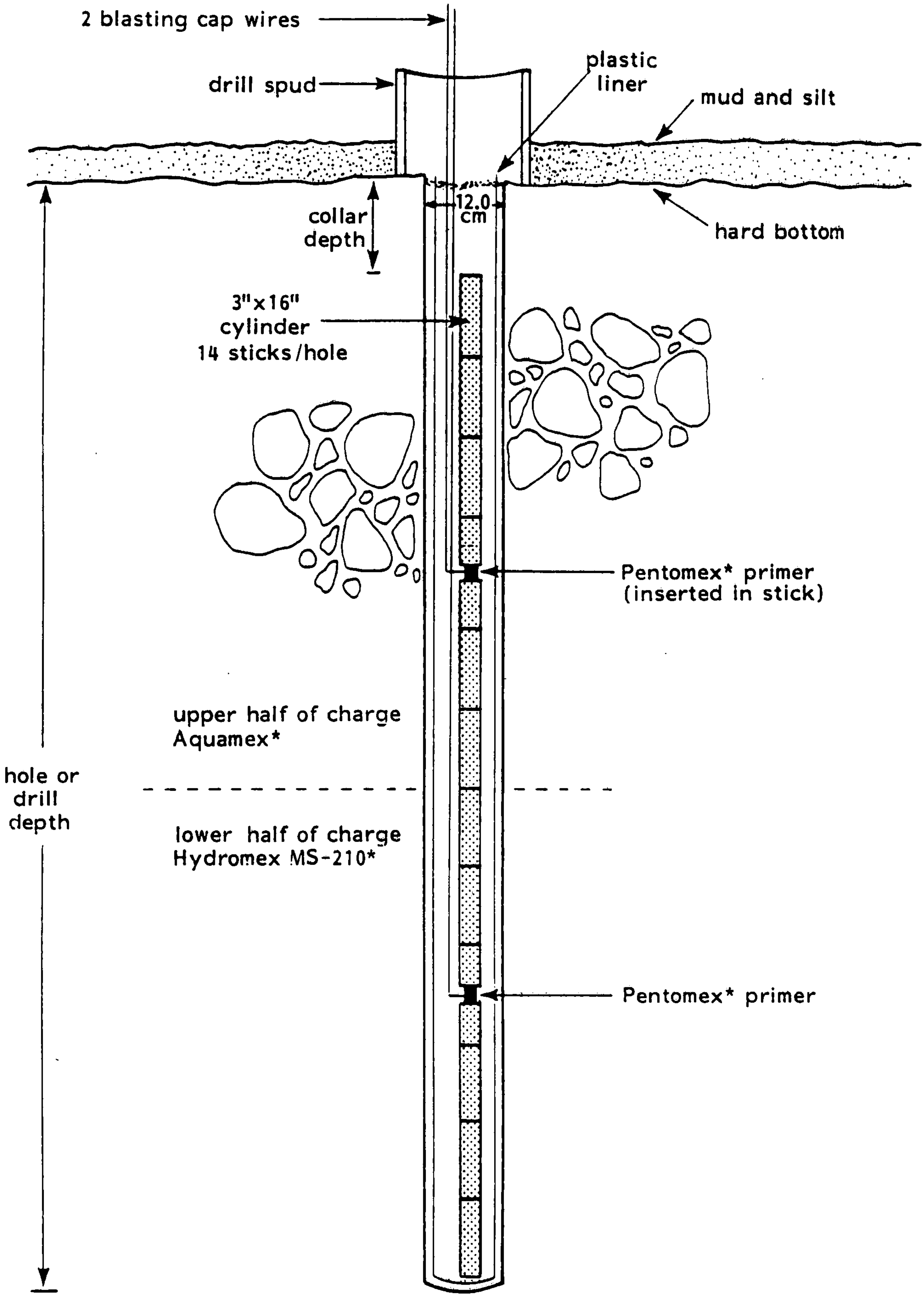


Fig. 3. Orientation of buried charges in drill holes.

*Canadian Industries Ltd. trade names

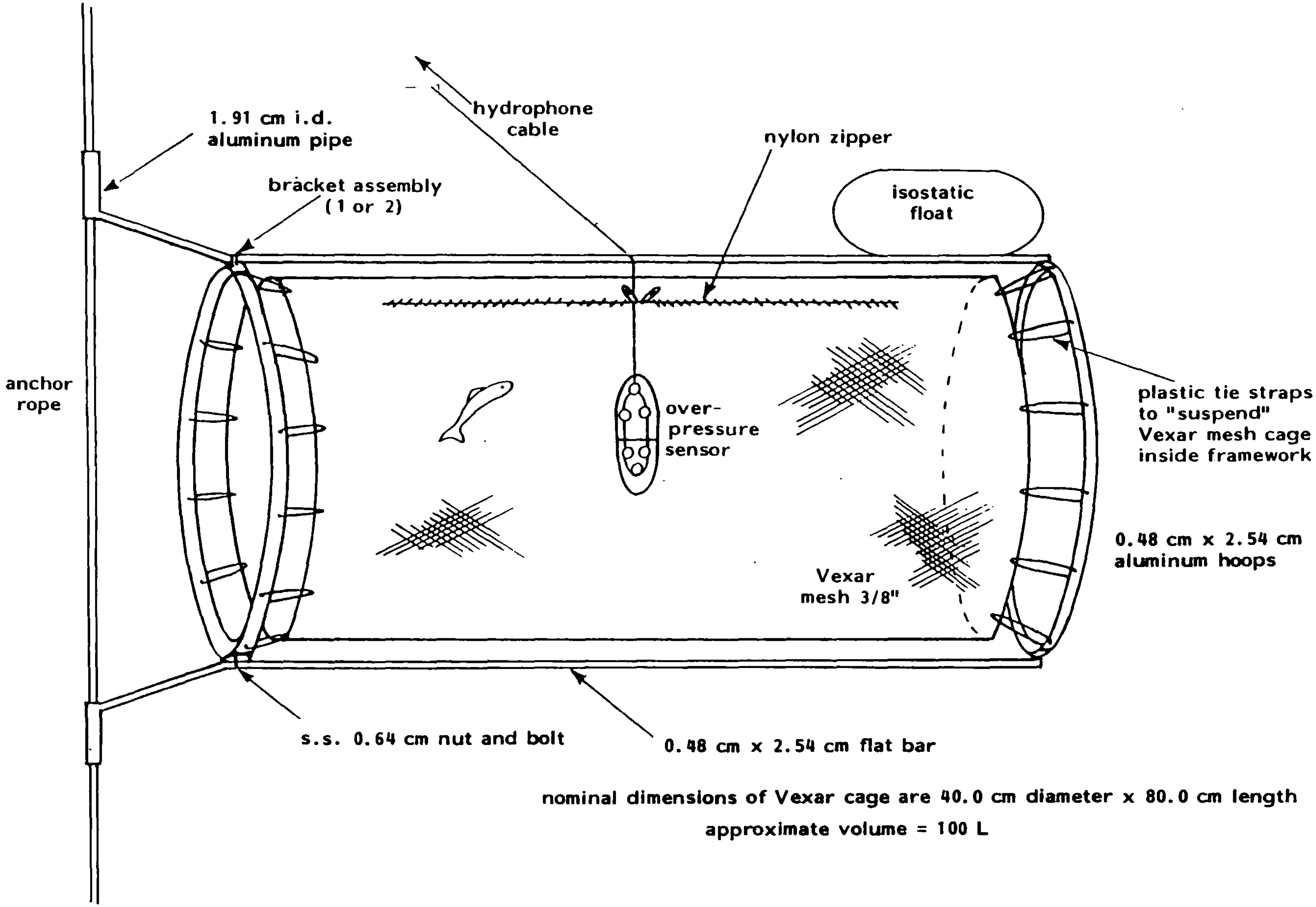
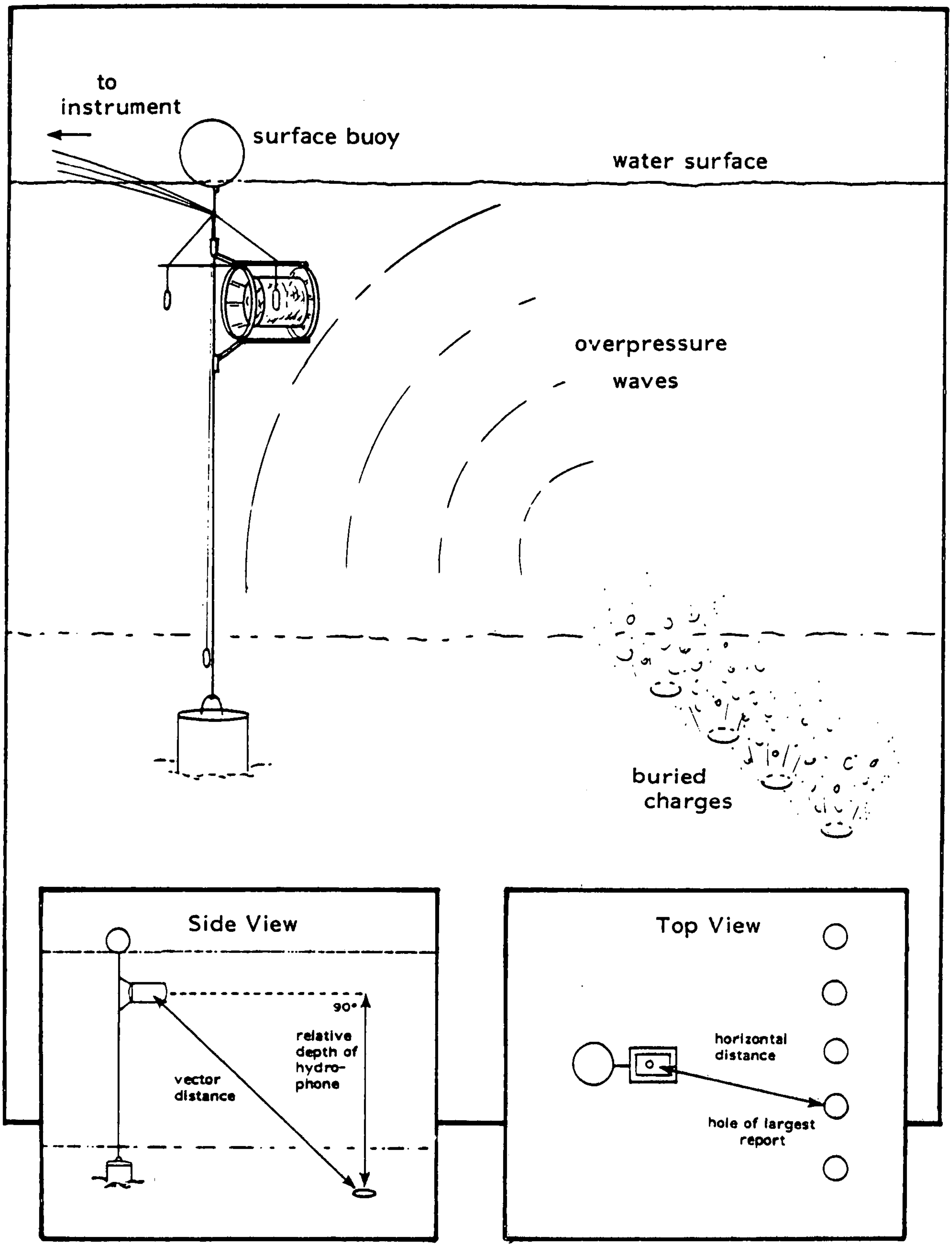


Fig. 4. Exposure cage design showing location of overpressure sensor.



$$\text{Vector Distance (distance from charge to hydrophone)} = \left(\left(\text{Relative Depth of Hydrophone}\right)^2 + \left(\text{Horizontal Distance}\right)^2 \right)^{1/2}$$

Fig. 5. Location of cage and overpressure sensors relative to buried charges.

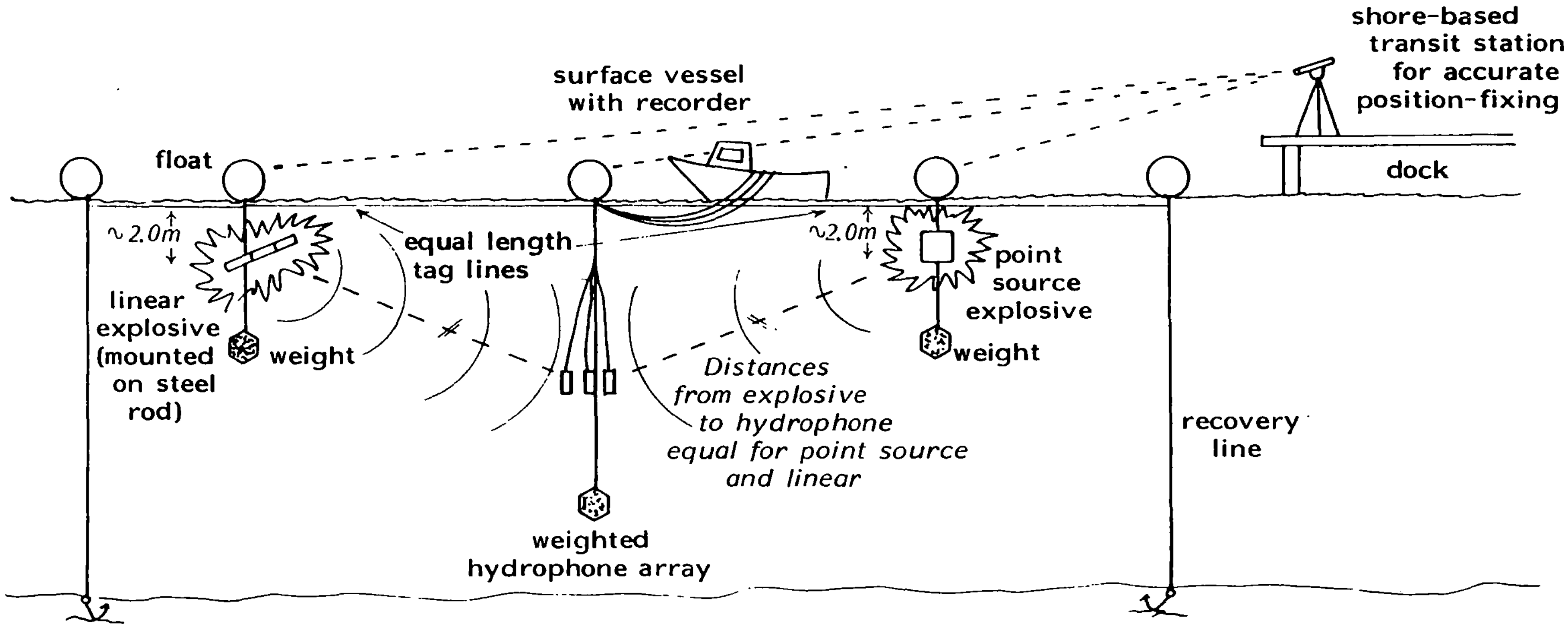
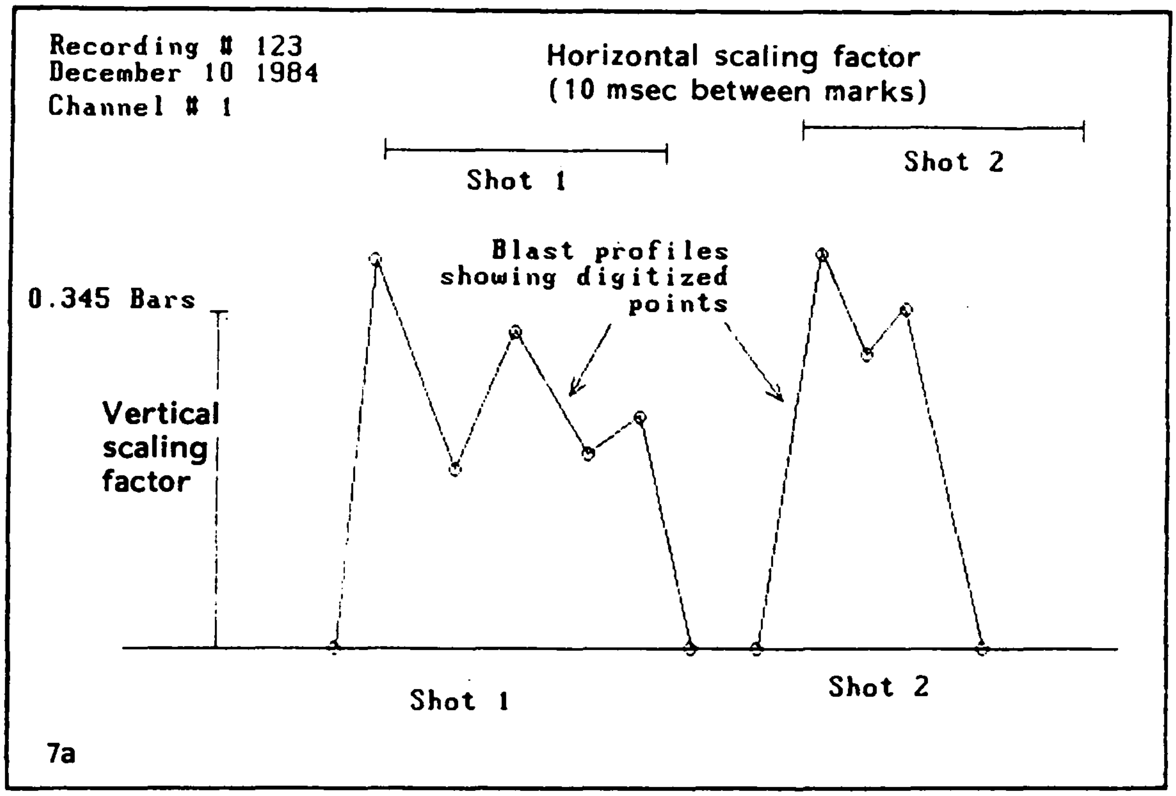


Fig. 6. Experimental design to determine linear vs point source overpressure measurements.



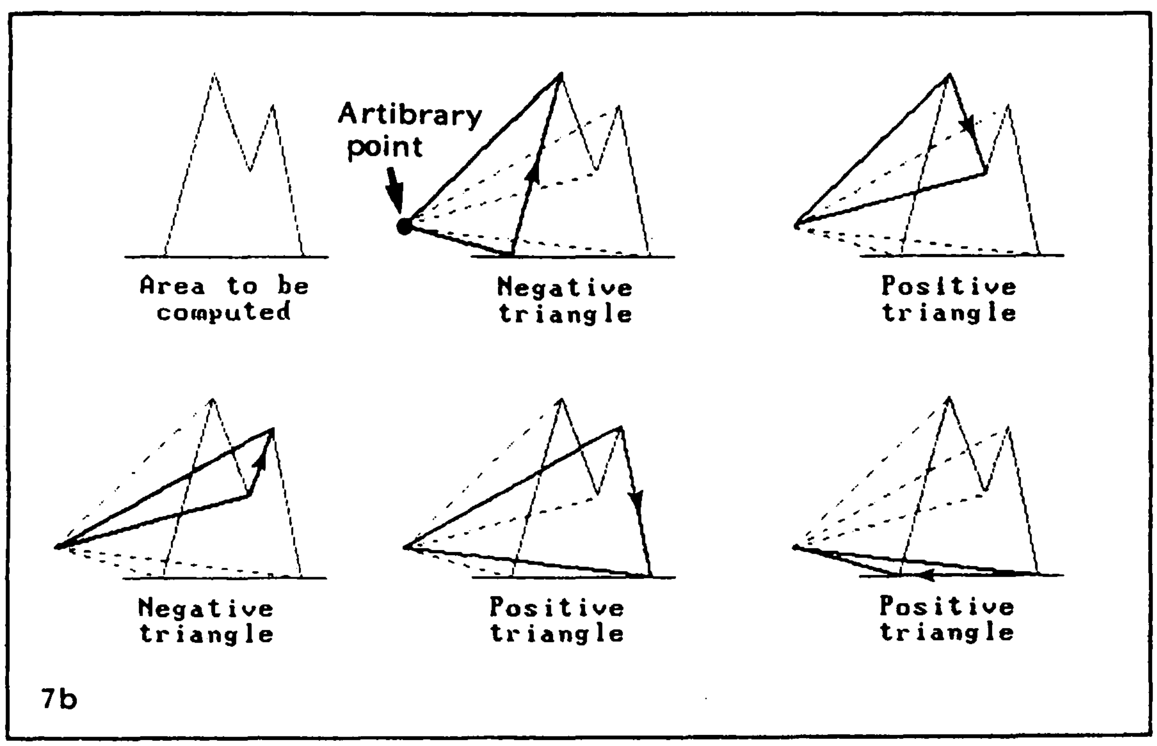


Fig. 7. Methodology used in digitizing data and calculating areas under the pressure/time curve.

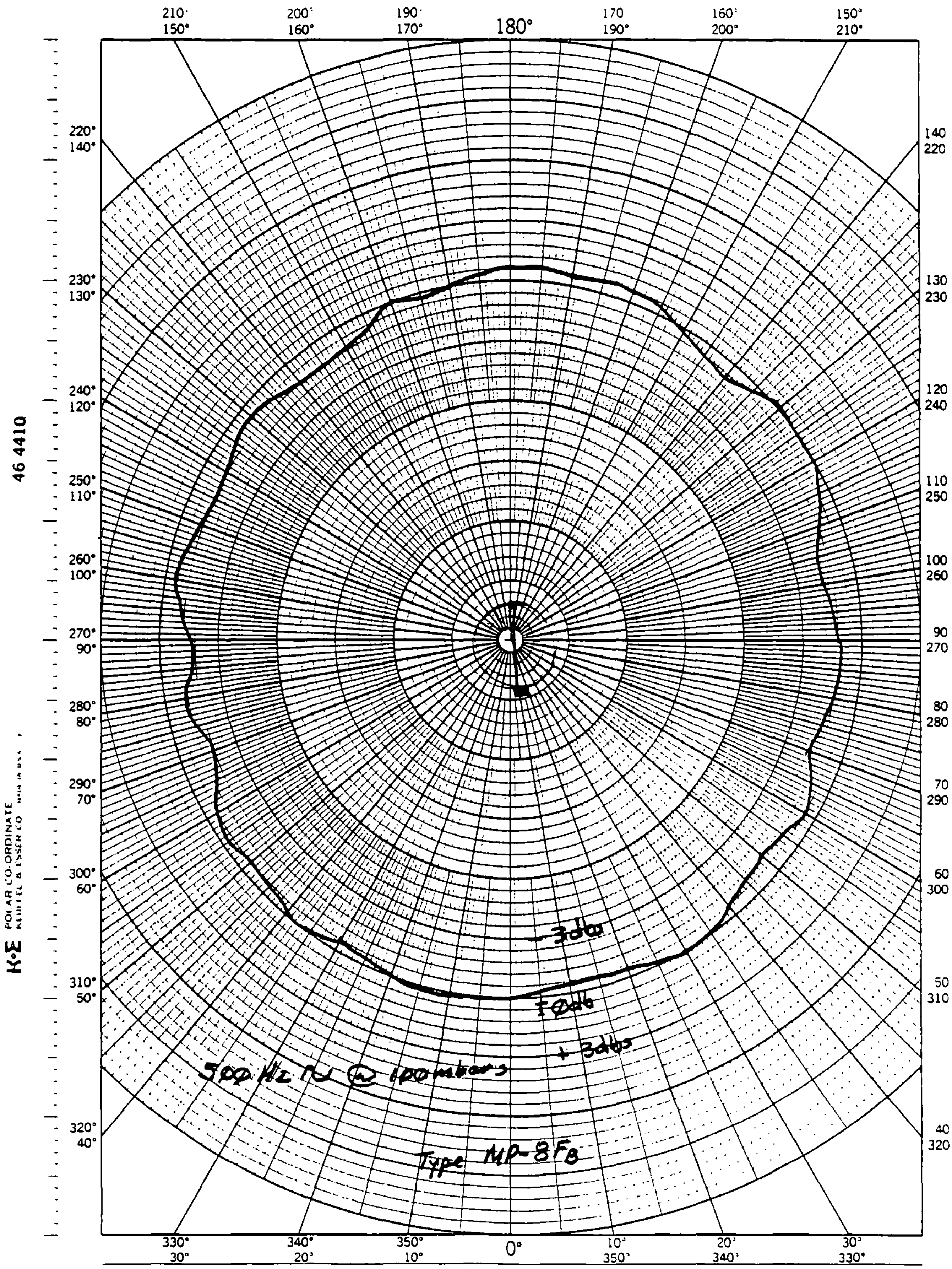


Fig. 8. Polar response pattern in the XY plane for AMF Geospace Hydrophone.

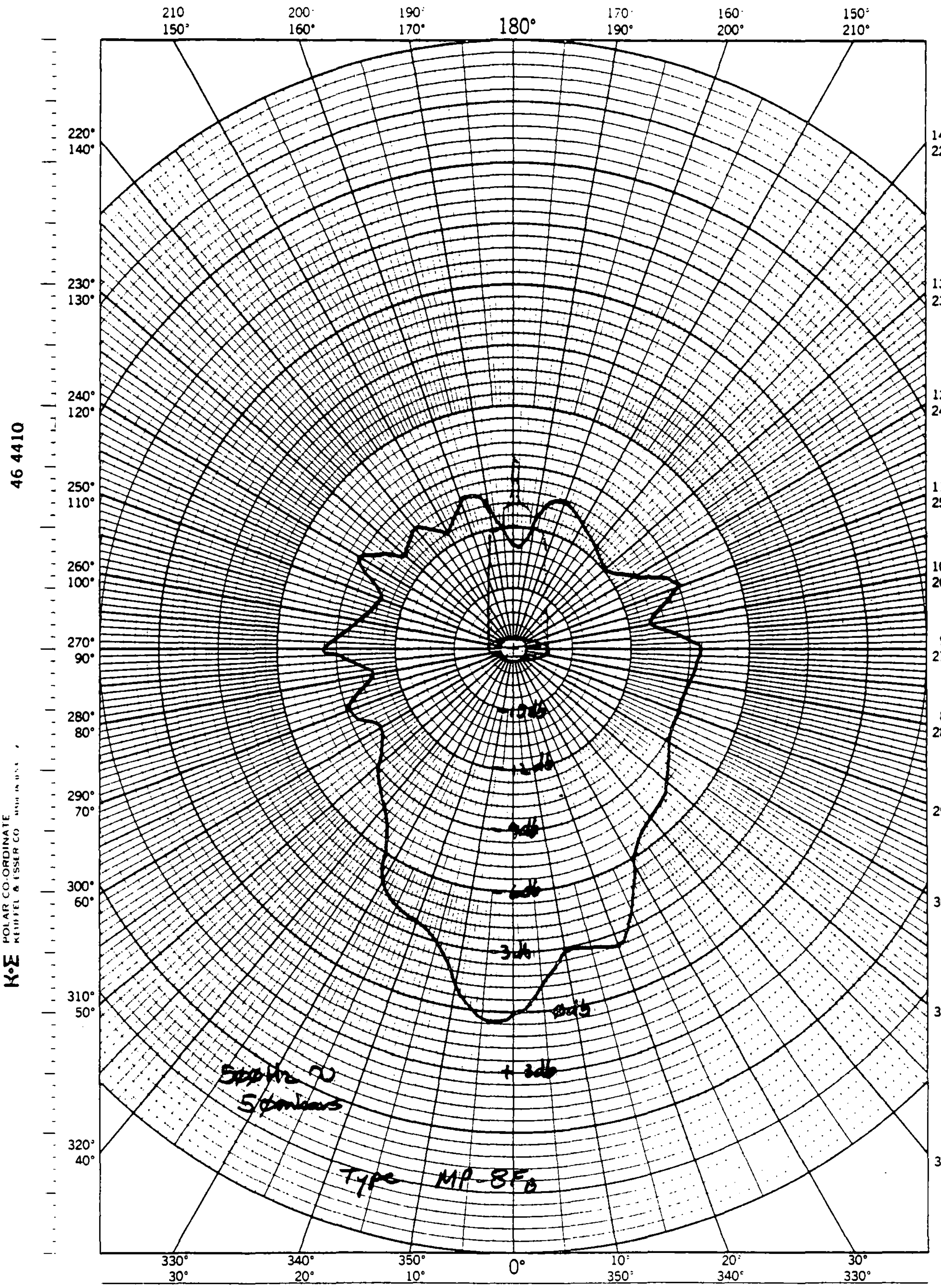


Fig. 9. Polar response pattern in the XZ plane for the AMP Geospace Hydrophone.

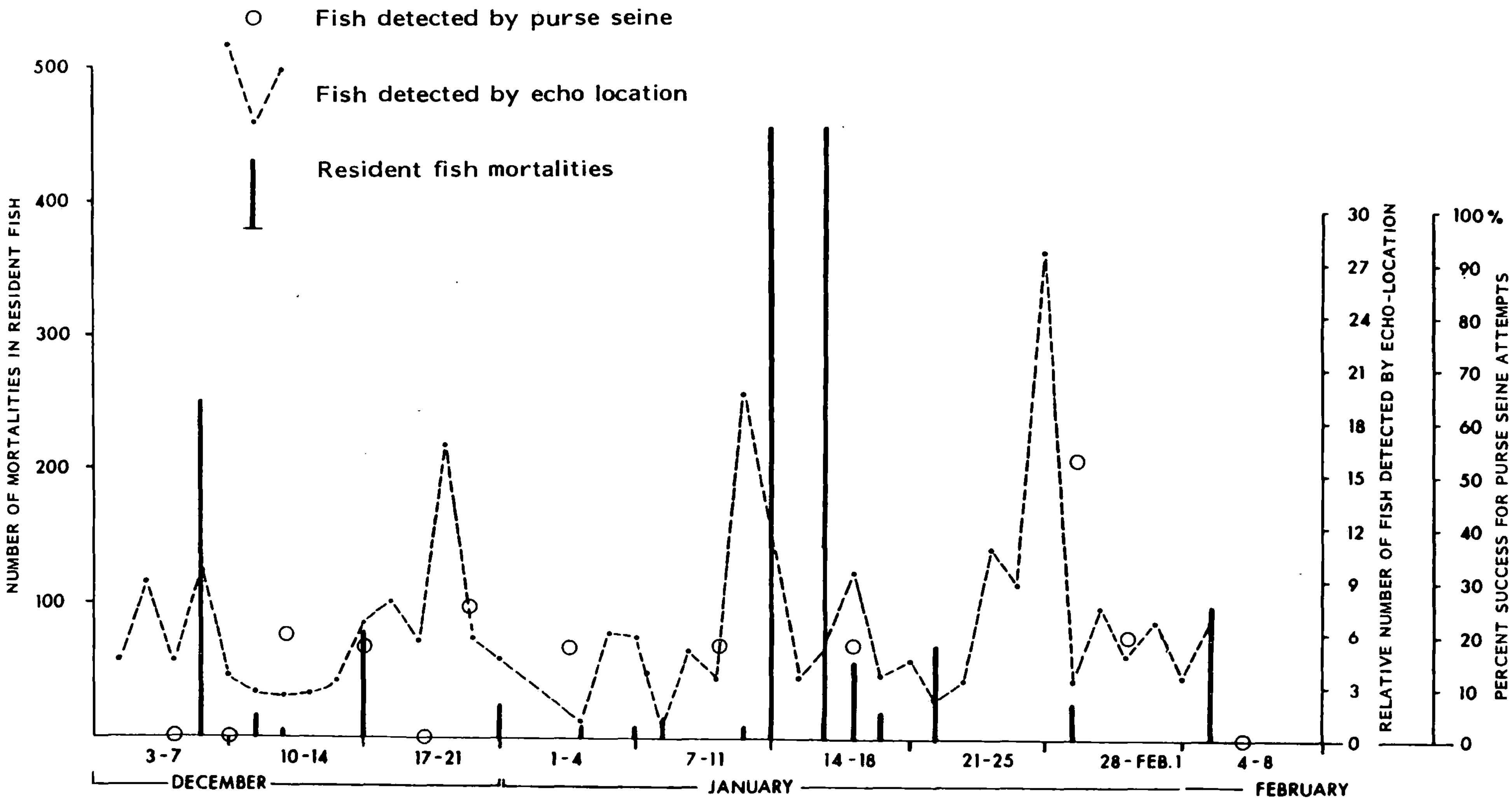


Fig. 10. Results of echo location surveys and purse seine catches used to assess mortalities in resident fish in relation to individual blast events.

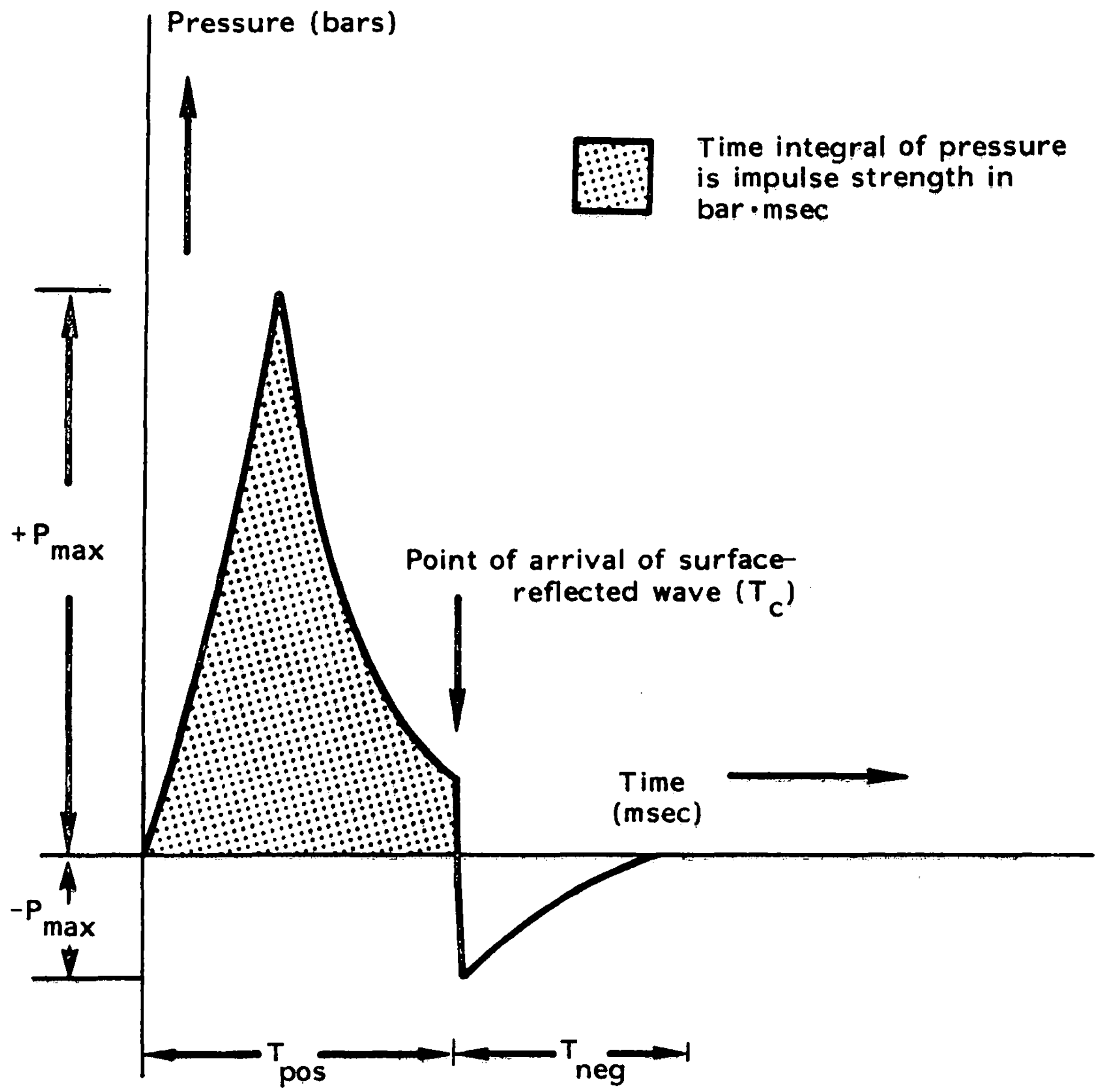


Fig. 11. Simplified overpressure wave showing area integrated to calculate impulse strength.

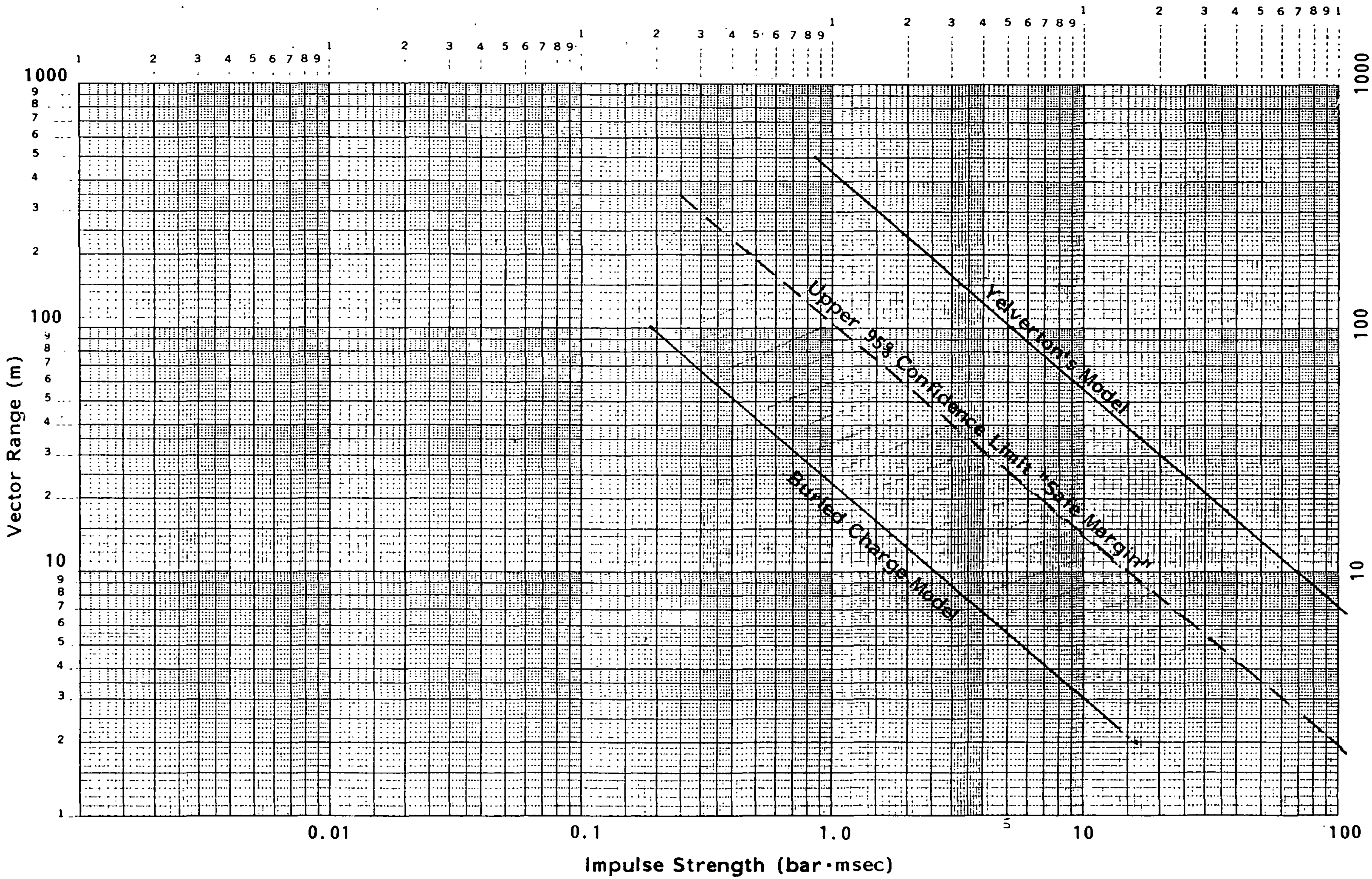


Fig. 12. Curvilinear predictive equiations for buried charges showing upper confidence limit compared to Yelverton's model predictions.

Table 1. Code for evaluating visible fish damage (from Hubbs *et al.*, 1960).

Injury level	
0	No damage
1	Light hemorrhaging in tissues covering kidney
2	Light hemorrhaging throughout body cavity, some kidney damage, but gas bladder intact
3	Severe hemorrhaging throughout body cavity, gross kidney damage, and gas bladder burst
4	Partial breakthrough of body wall, bleeding about anus
5	Ruptured body cavity, internal organs scrambled or lost

Table 2. Relative changes in peak pressure (P_{max}), duration of positive pressure, and impulse strength from underwater blasts due to air curtain mitigation.

Trial Number	Recording Number	Channel Number	Location of Hydrophone in Relation to Air Curtain	Average P_{max} (bars)	Relative Change in Maximum Pressure Across Air Curtain (%)	Average Duration (msec)	Average Impulse Strength (bar·msec)	Relative Change in Impulse Strength Across Air Curtain (%)
1	16	1	in front	0.241		6.489	0.673	
		2	behind	0.192	-20	5.336	0.468	-30
2	18	2	in front	0.192		4.384	0.431	
		3	behind	0.080	-58	4.596	0.190	-56
3	19	2	in front	0.182		4.443	0.343	
		3	behind	0.152	-17	10.865	0.823	+140
4	20	2	in front	0.092		6.314	0.322	
		3	behind	0.043	-53	13.827	0.335	+4
5	25	1	in front	0.253		2.194	0.267	
		3	behind	0.018	-93	1.805	0.071	-73
6	26	1	in front	0.170		5.137	0.456	
		3	behind	0.038	-78	7.292	0.142	-69

Table 3. Effects of exposure cages on maximum pressure (P_{max}) and impulse strength.

Trial Number	Location of Hydrophone in Relation to Fish Cage	Average P_{max} (bars)	Relative Change in P_{max} (%)	Average Impulse Strength (bars•msec)	Relative Change in Impulse (%)
1	inside	0.210		0.478	
	outside	0.192	+9	0.431	+11
2	inside	0.247		0.519	
	outside	0.182	+36	0.343	+51
3	inside	0.113		0.360	
	outside	0.092	+23	0.322	+12
4	inside	0.453		1.179	
	outside	0.429	+6	1.154	+2

Table 4. Percent of fish killed or damaged at various impulse strength levels.

Depth (m)	Maximum Impulse Strength Recorded (bar•msec)	% Mortalities 3 Weeks Post-Exposure (n=25)	% of Remaining Survivors Showing Damage
1.0	0.76	0	0
	1.11	12	10
	3.60	88	100
6.0	0.59	8	0
	0.71	0*	0*
	0.83	0	10
	1.46	12	10
	1.60	12	20
	1.75	0	0
	1.82	8	30
	2.16	0	17
	3.22	4	96
	3.57	4	54
	3.63	0	10
	4.12	0	0

**Held for 3 days only*

Table 5. Maximum positive pressures, impulse strengths and impulse strength reductions at different distances and depths for linear versus point source charges.

Recording Number	Charge Format	Charge Size (g)	Depth of Charges (m)	Depth of Hydrophone (m)	Vector Range (m)	P_{max} (bars)	% Reduction of P_{max} (Linear vs Point Source)	Impulse Strength* (bars·msec)	% Reduction of Impulse Strength* (Linear vs Point Source)
33	point source	225	1.5	1.5	18.0	1.636		0.701	
	linear	65				0.888	46	0.369	47
34	point source	225	1.5	1.5	28.0	1.344		0.695	
	linear	65				0.767	43	0.322	54
51	point source	225	1.5	10.0	47.8	0.803		0.263	
	linear	65				0.559	30	0.179	32
52	point source	225	1.5	10.0	47.8	0.750		0.298	
	linear	65				0.206	73	0.134	55
53	point source	225	1.5	20.0	50.5	0.723		0.328	
	linear	65				0.365	50	0.231	30
54	point source	225	1.5	20.0	50.5	0.711		0.429	
	linear	65				0.485	32	0.297	31
55	point source	225	1.5	1.5	47.0	0.765		0.343	
	linear	65				N.D.	N.D.	N.D.	N.D.

**Average of two or three replicates, depending on readability of records*
***N.D. = no data; amplitude too low for gain setting used*

Table 6. Numbers, species, and distance from blast for resident fish mortalities as determined during post-blast observations.

Date	Number of Mortalities (est.)	Distance from Blast (m)	Species Name	Common Name
December 6, 1984	200-300	10	*Clupea harengus pallasii*	Pacific herring
December 7, 1984	1-5	near blast	Unknown*	
December 10, 1984	15	0-15	Unknown	
December 11, 1984	1-5	0-15	Unknown	
December 14, 1984	30-35	0-15	Unknown	
December 19, 1984	70-80	0-10	Unknown	
December 21, 1984	20-25	10-45	*Clupea harengus pallasii*	Pacific herring
January 3, 1985	8-10	10	Unknown	
January 4, 1985	5-10	15	*Cymatogaster* sp. *Microgadus* sp. *Allosmerus* sp.	Pacific Tomcat
January 7, 1985	10-15	30	*Cymatogaster* sp. *Microgadus proximus*	
January 10, 1985	5-10	5	Unknown	
January 11, 1985	400-500	10	*Hypomesus pretiosus*	Surf smelt
January 15, 1985	400-500	10-20	*Hypomesus pretiosus*	
January 17, 1985	50-60	20-30	*Cymatogaster aggregata*	Shiner perch
January 18, 1985	20	10-20	*Allosmerus elongatus*	Whitebait smelt
January 22, 1985	60-70	50	*Hypomesus* sp. *Clupea* sp.	

Table 6 (continued)

Date	Number of Mortalities (est.)	Distance from Blast (m)	Species Name	Common Name
January 25, 1985	2	-	Unknown	
January 28, 1985	5-10	40	*Clupea* sp.	
	15-25	30	*Clupea* sp. *Hypomesus* sp.	
	15-25	30	*Hypomesus* sp. *Cymatogaster* sp. *Autorhyochus* sp. *Spirinchus* sp.	 Tube-snout Longfin smelt
January 31, 1985	3	Not determined	Unknown	
February 4, 1985	80-100	32 & 50	*Hypomesus* sp.	

* *"Unknown" refers to those fish species which were consumed by diving birds before they could be collected for identification.*

Table 7a. Linear regression equations indicating relative importance of independent variables related to maximum pressure, duration, and impulse strength for underwater blast data.

Dependent Variable	Independent Variable[1]	Coefficient	Normal[2] Coefficient	Partial R^2 X 100	Constant	Standard Error	R^2 X 100
Maximum Pressure	Vector Range	-0.0135	-0.558	17.27			
	Hole Depth	-0.1734	-0.279	4.34	2.194	0.668	24.80
Duration	Recorder Depth	0.1428	0.180	0.79			
	Charge Size$^{2/3}$	0.1948	0.166	0.68	1.746	2.38	7.13
Impulse Strength	Vector Range	-0.0178	-0.592	17.39			
	Hole Depth	-0.3256	-0.379	7.12	3.338	0.806	29.09
- final equation	Vector Range	-0.0190	-0.633	18.47			
	Hole Depth	-0.2522	-0.293	2.01			
	Water Depth	0.1008	0.184	0.80			
	Charge Size$^{1/3}$	0.2417	0.104	0.63			
	Collar Depth	0.2229	0.095	0.49	0.672	0.793	31.73

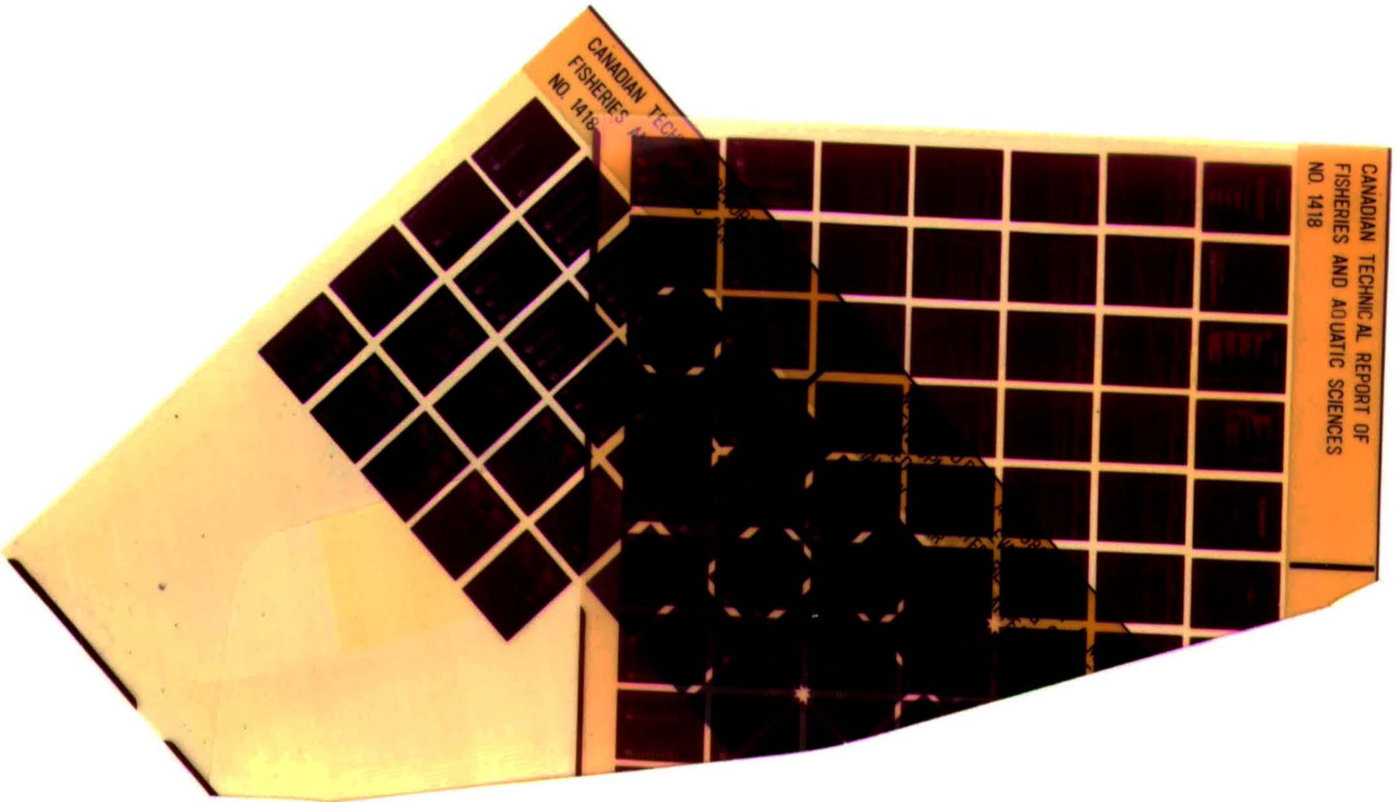
[1] Independent variables are listed in order of acceptance into the equation.
[2] Normal Coefficient = SD_x X Coeff. of x / SD_y

Table 7b. Linear regression equations indicating relative importance of independent variables related to impulse strength under operational conditions.

Dependent Variable	Operational Condition Characteristics	Independent Variable	Coefficent	Normal² Coefficient	Partial R^2 x 100	Constant	Standard Error	R^2 x 100
Impulse strength	-Variable water depth	Vector range	-0.0219	-0.817	31.21			
		Water depth	0.2494	0.552	14.23	-1.835	0.551	53.30
Impulse strength	-Consistent water depth	Vector range	-0.0155	-0.317	8.42			
		Hole depth	-0.3468	-0.286	4.37			
	-Decked charges	Charge size	0.370	0.228	3.21	2.881	0.989	20.44
Impulse strength	-Variable water depth	Vector range	-0.0385	-0.914	36.24			
		Water depth	0.3617	0.597	14.36	-2.958	0.618	72.84
	-First charge only in a series	Collar depth	0.6829	0.189	1.72			

Table 8. Results of curvilinear analysis.

Data Sub-Set Tested	a	x	R^2 x 100	Predictive Equation
i. Yelverton's Model (6 m)	95.06	1.121	99.88	$I = 95.06(W^{1/3})(\frac{W^{1/3}}{R_v})^{1.121}$
ii. Buried Charges				
Water Surface	4.083	1.369	33.19	$I - 4.083(W^{1/3})(\frac{W^{1/3}}{R_v})^{1.369}$
6 m	3.617	1.135	40.17	$I = 3.617(W^{1/3})(\frac{W^{1/3}}{R_v})^{1.135}$
Bottom (10 m)	69.984	2.392	50.76	$I = 69.984(W^{1/3})(\frac{W^{1/3}}{R_v})^{2.392}$
Point Source	19.231	0.80	77.25	$I = 19.231(W^{1/3})(\frac{W^{1/3}}{R_v})^{0.80}$


CANADIAN TECHNICAL REPORT OF
FISHERIES AND AQUATIC SCIENCES
NO. 1418