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Seismic Exploration: Its Nature and Effect on Fish

by
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ABSTRACT

The nature of seismic exploration in offshore and inland waterbodies of the Northwest Territories, as well as the effects on fish are covered in two parts. In the first part, literature pertaining to the nature and effect of explosive and non-explosive seismic energy sources is presented. The second part is concerned with a study of the effects that seismic energy sources commonly used in the Northwest Territories have on fish. Caged Arctic cisco *(Coregonus autumnalis)* and other small Coregonids were subjected to the energy sources to determine their lethal characteristics. Aquaflex (a linear high explosive) detonated in 165 foot lengths on the bottom in 10 ft of water, killed fish over an area of 36,200 square feet. A 10 pound charge of 60% Geogel (a point high explosive) detonated 10 ft below the surface in 15 feet of water, killed fish over an area of 25,450 square feet. In contrast, a 300 cubic inch Par Air Gun caused no direct fish mortalities.

INTRODUCTION

In recent years, the Northwest Territories have witnessed a tremendous increase in the exploration for oil and gas deposits. The Mackenzie River valley, Mackenzie delta, Hudson's Bay and the Arctic archipelago have felt the greatest impact from this exploration. Since the 1920's dynamite and other high explosives have provided the principle energy source for seismic exploration. However, for economic, technical and political reasons, the last few years have witnessed a rapid increase in the use of alternative energy sources, particularly for marine seismic operations.

Despite a substantial volume of published material on the effect of underwater explosions on marine and aquatic life, there is little predictive information about the effect of explosions under specific conditions. There is also a limited amount of information pertaining to the effects of non-explosive energy sources on marine life. It is for these reasons that the Department of the Environment, Fisheries Service, undertook a study to determine the effects that seismic energy sources, commonly used in the Northwest Territories, have on fish. These were a linear high explosive (Aquaflex), a point high explosive (60% Geogel) and a non-explosive source (Par Air Gun).

The purpose of this report is to: (1) familiarize the reader with the nature of underwater explosions; (2) review the available literature on the effects of seismic energy sources on marine and aquatic life; and (3) present the results from the above-mentioned study.

PART I: LITERATURE REVIEW

GENERAL

The principle of seismic exploration is derived from seismology which is the geophysical science dealing with earthquakes and related phenomena. Through controlled generation of accoustical energy pulses near the surface of the earth's crust, geophysicists are able to locate geological structures which could contain oil and/or gas. When these pulses or vibrations strike a layer of rock or other dense material, they divide into three parts: one part returns to the surface as reflected energy; another travels longitudinally along this layer at a greatly increased speed; and a portion of it also returns to the surface as refracted energy. The remaining part which passes downward divides repeatedly as it hits new dense layers. Accoustical energy, returning to the surface, is transformed by a series of geophones into electrical energy which in turn is recorded by a seismograph. Recordings yield a seismic section which is translated into an accurate picture of rock layers beneath the surface.

The sea, where much of the seismic exploration is carried out, provides a uniform coupler with the underlying bottom. Marine seismic surveys, using explosives, are conducted using two methods with minor variations (Fig. 1). The refraction method utilizes the principle that the speed of the shock wave varies according to the elasticity and specific gravity of the rock. Wave speed indicates the depth and type of rock. In the reflection method shock waves are reflected like an echo when they strike a surface boundary between layers of different elasticity and specific gravity. The depth of the reflecting layer can be determined by measuring the

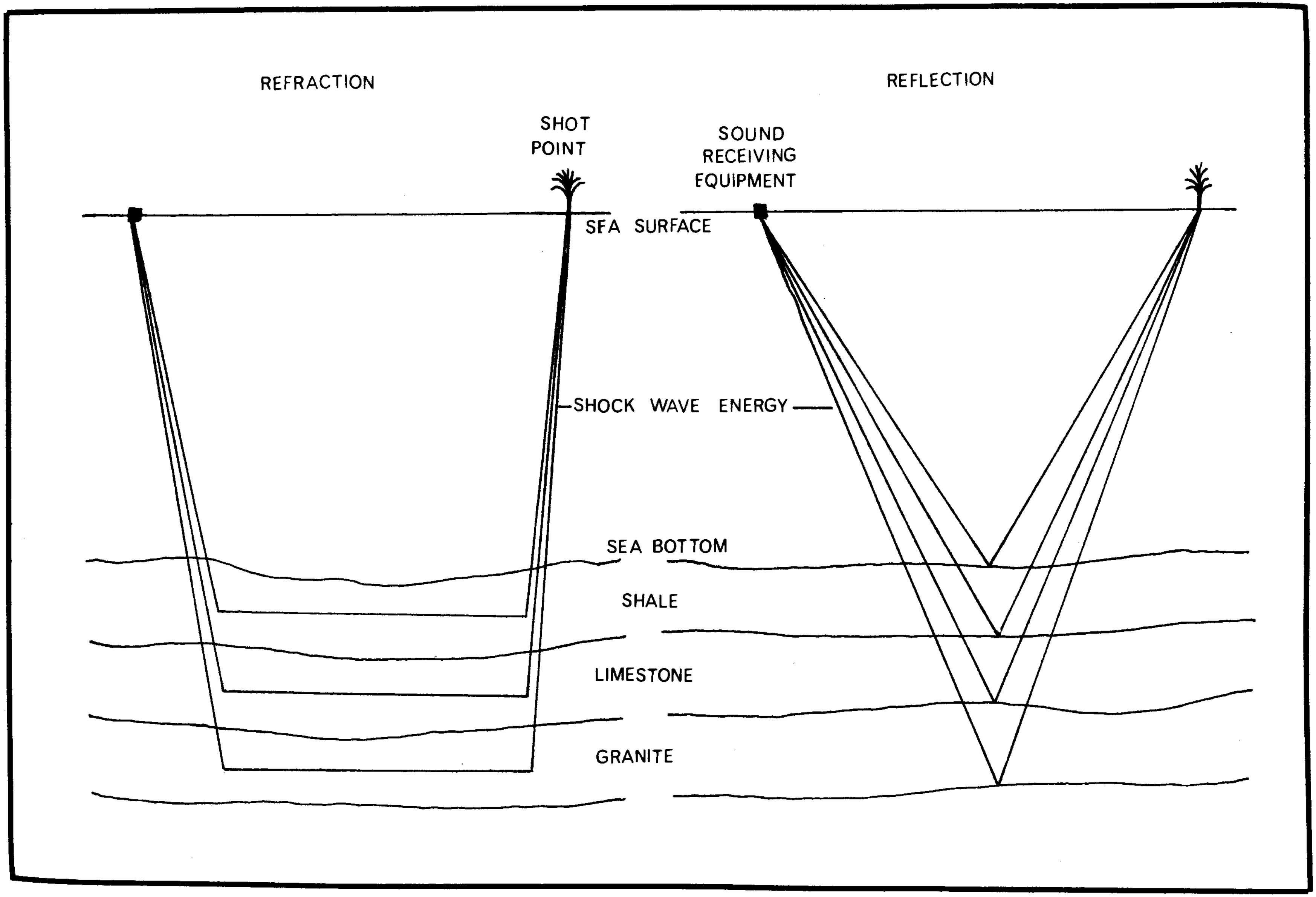

Figure 1: Schematic representation of refraction and reflection shooting.

time taken for the waves to travel to and from the reflecting layer. The energy source is small and relatively closer to the recording instruments for reflection shooting, while it is larger and farther away for refraction shooting.

Two or three co-operating vessels are often employed in refraction and reflection shooting. One vessel moves along a designated course and drops charges at regular intervals, while another vessel lies motionless with all machinery stopped and geophones submerged in the water. Marine seismic surveys may also be carried out by means of a single vessel. This vessel tows a long cable to which the geophones are attached or in which they are incorporated. Charges are dropped at regular intervals and are made to explode at a specified depth and distance behind the geophones.

In many cases seismic exploration methods employing explosives in the Northwest Territories have been modified to meet specific environmental conditions. The methods used for ice-covered water bodies are similar to those for land-based operations. Charges may be detonated in the ice, in the underlying water, on the bottom or beneath the bottom. Multiple charges, laid out in a pattern within the ice, have also been used. Much of the exploration in recent years has been carried out in shallow offshore regions and inland lakes and rivers during ice-free periods. In these regions small shallow draft boats and hovercraft have been used. Charges may be detonated while suspended in the water body, on the bottom or beneath the bottom.

EXPLOSIVE ENERGY SOURCES

There are many different kinds of explosives used for seismic exploration. These may be divided into three groups: low explosive, high explosive and blasting agent. Black or gun powder is an example of a low explosive which burns slowly and produces a slow build-up in pressure of the expanding gases. Its detonation speed is approximately 2,000 ft/sec. However, the use of black powder has generally been discontinued due to poor handling properties and poor quality of the seismographic records. High explosives include many grades of dynamite, Tri-Nitro-Toluene (TNT) and other compounds. All burn immediately and produce a very fast build-up in pressure. The speed of detonation for dynamite ranges from 4,000 to 23,000 ft/sec depending on strength, intensity and grade. Examples of high explosives are Geogel, Loshok, Primacord and Aquaflex. The latter two are detonating fuses which consist of a high explosive charge, Pentaerythritoltetranitrate (PETN), contained within a waterproof covering. When initiated by an electric blasting cap, they detonate at a very high velocity (20,350 ft/sec). Primacord and Aquaflex are defined as line sources whereas blackpowder, TNT, etc. are point sources and are contained within a waterproof cylindrical cartridge.

A blasting agent is not an explosive by itself but can be made to explode by using a primer. Agents are composed of ammonium nitrate and are known as Nitro-Carbo-Nitrate (NCN) explosives. Velocity of detonation ranges from 8,000 to 16,000 ft/sec. An example of a blasting agent is Nitrone SM (Seismic Marine).

NATURE OF UNDERWATER EXPLOSIONS

The essential characteristic of any underwater explosion is the release of a high initial outward acceleration of energy to the surrounding medium. A substantial portion of the total energy released to the water by a seismic source is not radiated immediately in the form of a seismic wave, but is retained and stored temporarily as kinetic energy in the water. At a predictable time later the outward flow of water is reversed, and inward flow converges to produce a secondary seismic pulse called the first bubble pulse.

Detonation within a solid explosive does not take place instantaneously throughout the entire mass, but proceeds as a wave travelling with finite velocity. The disturbance is in the nature of a chain reaction which travels rapidly outward, creating a growing spherical cavity. The travelling gas-solid interface is known as the detonation front. At a very high pressure sea water is not an ideal elastic substance. It behaves somewhat like a spring; the more suddenly compressed, the stiffer it becomes. Thus, the velocity of the outward travelling shock wave is a function of the peak pressure of the wave. As an example, the instantaneous peak pressure for 50 lb of TNT is 1,000,000 pounds per square inch (psi), and the estimated velocity of propagation is 14,000 ft/sec. At a radius of one foot the instantaneous peak pressure in the shock wave is 180,000 psi and the velocity 83,000 ft/sec. At a distance of five feet, the instantaneous peak pressure is 16,000 psi and the velocity of propagation of the shock wave is 54,000 ft/sec. It is estimated that about 30 percent of the original explosive energy is dissipated as heat in the first 10 feet of travel. The peak pressure initially falls off as the -2.9 power of radial distance (R) at the explosive-water interface. As the shock wave travels outward in the surrounding medium and the peak pressure drops from 1,000,000 to 16,000 psi, the rate of decay decreases to $R^{-1.3}$ at R=5 feet. As the peak pressure further diminishes with increasing distance, the decay rate approaches $R^{-1.13}$ and remains at this value until the shock wave eventually degenerates into a low amplitude acoustic wave. Amplitudes, therefore, decrease inversely as the first power of radial distance. If the pulse enters bottom sediments or rocks, it will decay at a faster rate, broaden and change in shape.

All types of underwater seismic energy sources give rise to hydraulic after-flow. The phenomenon is inherent in the nature of the source and in the associated spherical divergence. Afterflow represents temporary storage of kinetic energy not immediately radiated. This energy is ultimately dissipated as bubble oscillation. Because of the momentum stored in the outward afterflow of the surrounding water, the gas bubble continues to expand to the maximum radius. Due to cooling and expansion in volume, the gas pressure falls. For a brief period of time, the water surrounding the gas bubble is, because of its accumulated afterflow momentum, actually moving outward against an inwardly directed pressure gradient. This phenomenon is called overshooting. Eventually expansion is halted and the bubble contraction begins, at first slowly, and then with increasing speed. The collapse is in the nature of an implosion, the result of which is a rapidly increasing inward velocity in the water medium, and rapidly increasing pressure due to compression of the gas bubble. Ultimately, the outward directed pressure gradient brings about contraction. From this time onward, the process is reversed and the bubble expansion begins again. The cycle may be repeated several times with decreasing intensity- a phenomenon called bubble oscillation.

At a given distance from the source, the arrival of the shock wave will cause water pressure to rise almost instantaneously, then decrease exponentially to a negative pressure. At this time, corresponding to the start of the bubble contraction, pressure will increase again, at first slowly, and then with increasing speed to the first bubble pulse peak. Pressure will then decrease again starting the second bubble oscillation cycle. Although the bubble pulse is much lower in peak pressure amplitude than the initial shock wave, it radiates an appreciable amount of seismic energy because of its longer time duration. Since severe bubble oscillations result in poor seismographic records, measures are taken to reduce or eliminate this effect.

When the initial positive pressure pulse from an energy source reaches a free water surface, it is reflected as a pulse of opposite polarity. If the peak value of pressure in the incident positive pulse is less than 1 atmosphere (14.7 psi), the reflected pulse will be the mirror image of the incident pulse and negative in sign. This phenomenon is called rarefaction.

EFFECT OF UNDERWATER EXPLOSIONS ON FISH

Fish may be killed or injured by the effects of underwater explosions in several ways. Damage resulting from pressure changes may range from severe (tearing of muscle tissue, rupture of the abdominal cavity, blood vessels and internal organs, and disruption of the nervous system) to minor (loss of scales and minor blood vessel rupture). The internal organs which are usually affected are the kidney, liver, heart, spleen, gonads and the swimbladder. The most sensitive organ is the swimbladder. Despite a variety of functions in different species, its primary use is that of a hydrostatic organ. Such an organ enables the fish to maintain position and equilibrium in the water by making the density of the fish equal to that of the surrounding water. The swimbladder may be connected to the alimentary canal (physostomatous condition) or closed (physoclistous condition). Control of the volume of gas in the swimbladder is essential to its function as a hydrostatic organ. When a fish swims downward, the external pressure increases and the gas in the bladder is compressed, increasing the density of the fish. When a fish rises in the water, the physical effects reverse.

The power of changing the volume of gas is limited but is greater for those fish possessing an open swimbladder. In any event, when fish possessing such an organ are subjected to a sudden rise or fall in the water column or a rapid pressure change, the effect is usually fatal. The loss of equilibrium and hemorrhaging from a burst swimbladder may cause death either directly or indirectly through an impaired ability to feed and avoid predators. Fish with a swimbladder are usually killed or injured if they are close to an explosion, whereas fish without the organ are not as susceptable (Aplin 1947). Fish possessing an open swimbladder are not as sensitive as those with a closed one since they may partially compensate for the pressure change. Thin-walled swimbladders are usually more subject to damage that those with thicker walls.

Experiments have shown that the effects of pressure on fish fry depends on the species and age, as well as the presence and type of swimbladder. Tests with newly hatched herring and salmon fry revealed that they are apparently not affected by pressure changes (Rasmussen 1967). However, when the same fry reach 3 to 6 months of age, they die within 24 hours if they are exposed to pressures exceeding 2.7 psi. The reason for this change is that in newly hatched herring and salmon fry the swimbladder has not yet developed.

STUDIES ON THE EFFECT OF SEISMIC ENERGY SOURCES ON AQUATIC AND MARINE LIFE

Throughout the past 25 years, many investigators have studied the effects of seismic energy sources on aquatic and marine life. These studies have been prompted through concern expressed by fishermen and enforcement agencies. Following are summaries of findings from several of these investigations.

A series of experiments were conducted by Gowanloch and McDougall (1946) to determine the effects of underwater explosives of dynamite on a shrimp (*Peneus setiferus*), a fish - a croaker (*Micropogon undulatus*) and an oyster (*Ostrea virginica*). Results from these experiments showed that 800 pounds of dynamite did not harm shrimp at a distance greater than 50 feet and croakers at a distance greater than 200 feet. No mortalities attributable to the effect of the explosions occurred with oysters. Tests carried out with lobsters have shown that they are very resistant to pressure. Lobsters placed 50 feet from a 90 pound dynamite source suffered no ill effects (Aplin 1947).

A series of observations and experiments were undertaken by Aplin (1947) to determine the effect on fish and other marine life from the use of 10 to 40 pound charges of 60% Petrogel used in a seismic survey along the Californian coast. Average calculated mortality indicated that about five pounds of fish (anchovies, kingfish, sardines, queenfish and smelt) were killed per pound of explosive expended. For shots within the range of 10 to 40 pounds, there was no apparent increase in the poundage of fish killed. Successive shots in the same area continued to kill fish at a constant rate. In general, the greatest number of fish were killed by shots close to shore. This was presumed to be due to the large density of fish in this area. Further, there was no apparent relation between depth of water or charge size and the weight of fish killed.

Fitch and Young (1948) studied the effects of underwater explosions on fish in Californian coastal waters using high explosives. The weight of explosives used in a single shot varied from 10 to 160 pounds. They noted that in each species of fish there was an inherent resistance to shock pressure. Some fish such as the barracuda, kingfish and queenfish, having a thick-walled swimbladder and a cylindrical body appeared to have much more resistance to pressure changes than did laterally compressed fish with thin-walled swimbladders such as saltwater perch. These investigators found that when explosions were repeated (within 24 hours) in the same area an entirely different group of fishes was killed. The stomach contents revealed that fish killed during the second day were feeding on those killed previously. During this study jetted shots (embedded in the sea bottom) killed an estimated 0.23 pound of fish per pound of explosive and 4.43 pounds of fish per shot. Open water shots killed 0.47 pound of fish per pound of explosive and 31.56 pounds of fish per shot. It was observed from bottom observations that the number of fish that sink is negligible compared to the numbers that float.

Coker and Hollis (1950) observed a series of underwater tests conducted in Chesapeake Bay with 250 to 1,200 pounds of high explosive used for military purposes. After 21 shots the kill was 32,658 fish of 16 different species with Menhaden *(Brevoortia tyrannus)* the most numerous. Neither the number nor the weight of the fish killed was proportional to the weight of explosive used. Normally the lethal radius did not exceed 600 feet and generally was within the radius of 300 feet. Damage inflicted to individual fish was mainly internal including rupture of the swimbladder, vascular system, abdominal cavity and organs. It was believed that fish were not driven away from the test areas as a result of the explosive operations. The extent of fish kill was believed to be governed by two factors: (1) rapid dissipation of the explosive force with distance from the shot point and (2) presence or absence of fish within the restricted lethal range. They also found that surface counts did not account for all the fish affected due to the possibility of sinking fish.

Hubbs and Rechnitzer (1952) reported on experiments designed to determine the effects of underwater explosions on fish. Large charges (50 - 200 lb) of dynamite were found to be very destructive to fish. Considerable areas were depopulated for a few months after such blasts. Charges as small as 10, 5, 2.5 and 1.25 lb often killed fish, even when the explosive had been buried many feet in the bottom sediments. The lethal effects of small charges of dynamitewere in agreement with expectation that peak pressure varies as one-third the power of the charge weight. For charges buried in bottom sediments, the peak pressure varied as the 2.6 power of the distance. The effect of underwater explosions of dynamite was often intensified at the surface, where the positive pressure wave reflected as a rarefacted wave. Fish were very susceptible to the negative pressure pulse. Blackpowder was much less effective than dynamite in producing such reflected waves. Blackpowder explosions proved to be relatively innocuous even up to 45 lbs, where peak pressures as high as 160 psi did not kill fish. There were indications that blackpowder discharges did not drive fish away or prevent them from feeding. They also noted that the lethal range for underwater explosions with dynamite may be greatly extended depending on the shape and nature of the ocean floor, as with submarine canyons.

Fry and Cox (1953) observed the effects of 40 - 90 lb charges of blackpowder on fish life along the Californian coast. After a blast, divers searched the bottom within a radius of 100 feet. No dead or injured fish were found. Clams and tube worms were found, none of which had suffered ill effects.

An investigation was undertaken by Hubbs et al. (1960) to determine the effects of underwater Nitro-Carbo-Nitrate explosives on caged fish. They found that the peak pressure associated with damage to fish varied among species. The horizontal lethal range was estimated to be 150 feet for a 5 pound charge, 350 feet for a 10 pound charge and 500 feet for a 25 pound charge. Vertically below these shots the lethal ranges were 100 to 130 feet, 140 to 200 feet and 200 to 250 feet for the 5, 10 and 25 pound charges, respectively.

An underwater explosion of dynamite was found to be a very effective means of killing adult salmon for tag recoveries (Tyler 1960). Negligible external damage to the fish occurred from the explosions, but there was extensive internal damage. In tests using half-stick charges of 40 percent ammonium gelatin dynamite, a direct relationship was found to exist between water depth and the effective killing range. This range was increased by approximately 15 percent at the 4 and 6 foot depths by doubling the charge strength. It was found that a solid object in the path of the pressure wave reduced the lethal range in that direction.

Ferguson (1961) found blackpowder, detonated with an electric squib, to be relatively inoccuous to yellow perch *(Perca flavescens fluviatalis)*. Nitrone charges, on the other hand, were harmful to perch and other species. Even a one pound charge killed some perch up to 200 feet away. Ferguson noted that fish, held in cages at various distances from the explosion, provided the best measure of charge lethality. There was no apparent difference in the degree of damage between fish in cages at the surface and those at the bottom. The direct distance between the fish and the energy source appeared to be most important. Experiments using blackpowder detonated with Nitrone primers proved to be fatal to fish. Subsequent testing showed that the Nitrone primer was the lethal agent.

The effect of underwater explosions of Nitrone SM on fish populations in British Columbia coastal waters was studied by Kearns and Boyd (1965). Reflection charges ranged from 5 to 25 pound and refraction charges ranged from 10 to 300 pound. Out of 10,676 shots at 9,638 shot points, fish kills were observed at 419 sites. Total surface mortality was estimated to be in excess of 59,300 fish consisting mainly of herring (72.2%) and rockfish (23.8%). Large charges (50 - 300 lb) killed more fish than small charges (5 - 25 lb). By increasing the depth of detonation the potential area of fish kill was increased. Further, in shallow water the horizontal lethal range was greater than that in deeper water.

Paterson and Turner (1968) observed an underwater explosion of 4,000 pounds of NCN explosive in Wentzel Lake, Alberta. Maximum distance from the blast at which dead or injured fish were found was 1,200 feet. Fish killed were burbot *(Lota lota)*, whitefish *(Coregonus clupeaformis)*, trout perch *(Percopsis omiscomaycus)* and cisco *(Coregonus artedii)*.

In 1964, a total of 32 locations in six Northwest Territories and Yukon lakes were subjected to 64 shots of seismic Geogel, ranging from 2.5 to 150 pounds. Thirty-two lethal shots at 21 locations produced an estimated mortality in excess of 19,800 fish. Freshwater smelt and three species of whitefish represented 89 and 7 percent of the total mortality respectively with sticklebacks, pike and grayling comprising the remaining 4 percent. Over 95 percent of the total mortality occurred in 4 lakes as a result of 7 shots. A total of 30 charges out of 64 were larger than 5 pound and 2 out of the 30 greater than 25 pounds. It was estimated that the percentage of the lake area affected by explosions ranged from 0.103 to 28.187 percent (23.23 - 299.76 acres).

During 1966, the Department of Energy, Mines and Resources conducted a seismic survey in the Northwest Territories, Alberta and Saskatchewan, using 1 and 2 T charges of Nitrone SM and Geogel placed on the bottom (Muth 1966). Estimated mortality ranged from 3 to 10,000+ fish consisting primarily of lake cisco, whitefish and lake trout. Estimated lethal radius ranged from 600 to 3,000 feet. Dead or distressed fish appeared at the surface in increasing numbers up to 30 minutes after the explosion. External damage consisted of missing patches of scales, but post-mortem examinations indicated extensive rupture of blood vessels, organs and air bladders. Blast mortality was not confined to any particular age of size of fish although pike appeared to be the least sensitive. Fish mortality was highly variable from lake to lake depending on the proximity of fish to the explosion, pressure differences created by explosions at different depths, the extent of reflected shock waves and sinking fish.

Rasmussen (1967) reported that when dynamite charges were buried in the sea bed fish mortalities occurred all the way to the surface. Often fewer mortalities occurred near the sea bed than at the surface. The deadening effect of the sea bed was evidently not sufficient to eliminate the lethality of the explosion, even where the bottom consisted of mud and sand. It was found, however, that burying the charge at increasing depths in the sea bed led to a general reduction in the lethal effect. Maximum mortality was observed when the 5.5 lb charges were buried less than 30 ft into the sea bed, and little or no mortality occurred at depths greater than 30 ft.

The extent of fish mortality also varied with subterranean features. For example, if a charge was located above a solid stratum the lethal effect was intensified by a large amount of energy being reflected upward. The fact that fish were killed near the surface while those on or near the bottom were not injured was explained in part by the fact that surface and mid-water fish possess swimbladders, whereas bottom fish do not. High fish mortality near the surface was also due in part to the rarefacted or reflex wave, which was especially fatal. Fish killed near the surface in these circumstances usually had their swimbladder burst outward. Further, the shock wave from a charge detonated in the sea bed or near the bottom travels in a well-defined cone, expanding towards the surface. The result is a shallow zone near the bottom in which fish survive, while fish close to the surface are killed.

During polygraphic measurements of bluegill sunfish *(Lepomis machrochirus)* an unusual departure from the normal heart and breathing patterns was noticed during an earthquake (Sparks and Cairns 1972). Results were unusual in that the signals skipped two or three beats. They concluded that fish exhibit a fright response to seismic shock that is similar to that of humans.

A series of caged fish experiments were carried out under ice by Roguski and Nagata (1970). They found that the detonation of 130.5 to 142.5 pounds of high explosive in water depths of 10 to 20 feet had a 100 percent mortality radius of about 300 feet and a maximum lethal radius of approximately 500 feet for juvenile salmon. Larger charges did not extend lethal range under these conditions. There was little difference in effect between charges in water depths of 10 and 20 feet, although a charge at an intermediate depth of 15 feet appeared to have a somewhat shorter lethal range. The blasts caused no measureable excitement movements in a resident northern pike population. Great variation in damage to fish in the same cage was often noted. One salmon often suffered no apparent damage while another might be dead or die later of injuries. It was possible that because of differences in position one fish may have absorbed more of the shock wave.

Numerous studies have been carried out on the effect of underwater explosions to marine and aquatic life, but there are few reports dealing with the effects of non-explosive energy sources. Gaidry (unpub.) found that caged oysters placed in close proximity to an air gun were unharmed. Recently, a series of experiments were conducted by Weaver and Weinhold (1972) to determine if the use of air guns in shallow water was injurious to fish. In these tests, caged coho salmon smolts *(Onchorhynchus kisutch)* were subjected to the firing of 20 to 40 cubic inch air guns at various distances and depths. They concluded that air guns of this size exerted no harmful effects on these fish.

NON-EXPLOSIVE ENERGY SOURCES

In recent years many non-explosive energy sources have been used for seismic exploration. These energy sources have been adopted for a variety of reasons, including the achievement of better seismographic records and the banning of explosives by various governments. Following are general descriptions of some of these energy sources which have gained popularity.

Flexotir

Although the Flexotir system employs a 2 oz explosive charge, it is classified as a non-explosive energy source and may be used with any conventional seismic amplifying and recording source. In use the charge is suspended in the center of a perforated cast iron spherical shell or cage. The shell is approximately two feet in diameter, two inches thick and perforated with 13 holes slightly over two inches in diameter. When the charge is detonated, part of the radiated shock wave passes through the open holes and part through the iron shell. The result is a damping of the bubble oscillation. One or two cages are towed at the end of 50 foot hoses from the stern of the boat. Charges are flushed down the hoses under pressure. Good reflections from marker beds down to 20,000 feet are claimed using two units simultaneously.

Vibroseis

The Vibroseis system functions by the use of continuous energy signals rather than individual pulses. Vibrations are generated hydraulically and are directed toward the sea bed by means of transducers. In operation, four transducers are usually towed behind a vessel at a depth of about 40 feet. The transducers are synchronized with a prerecorded reference signal. The reflected signals are then recorded in the conventional manner.

Hydrosein

This system generates a powerful energy wavefront by means of implosion. It is created by a massive cavitation through the action of a piston in a piston chamber. In standard usage two units are operated synchronously. Since no explosion occurs, nor is air expelled into the water, no secondary or bubble phase is created. The cycle time is approximately 10 seconds between pulses. Firing at depths of 40 feet has provided the best results.

Gas Source Seismic Profiler

This system employs a modular gas source which is used with a continuous marine profile system. Ignition of a mixture of acetylene and oxygen is accomphished by a spark plug within a rubber tube with a stiffened base. Maximum pressure exerted by the tube is about 300 psi. In operation an array of several tubes is towed behind a vessel and ignited simultaneously to produce a wave front propagating perpendicular to the axis of the array.

Dinoseis

This is a gas exploder system which may be used in shallow or deep water. The heart of the system is an expandable chamber in which a mixture of propane and oxygen is ignited. Shock waves result from rapid expansion of the chamber which takes place in about 1/500 of a second. Gases are released through an exhaust valve and indirectly vented to the surface to eliminate bubble pulses. Two models are available which are capable of generating 40,000 and 100,000 ft-lbs of energy.

Flex-O-Gun

The Flex-O-Gun system uses a mixture of oxygen and propane which is ignited by a spark plug in a firing chamber. Shock waves are created through the action of a moveable piston. Flex-O-Gun has a 300 cubic inch capacity and a peak pressure output of 1300 psi. It was developed primarily for use in rivers, lakes and marsh areas. Groups of four or more units, spaced to meet individual requirements, are generally used in water depths from 10 to 30 ft.

Aquapulse

Seismic energy pulses are created through the Aquapulse system by confining the detonation of a mixture of propane and oxygen in an elastic-walled container. The combustion products are vented indirectly to prevent the formation of bubble pulses. Four Aquapulse units are commonly towed in a rectangular array behind a vessel and are fired simultaneously at depths from 35 to 50 feet.

Sparker

Sparker systems operate on the principle that the discharge of stored electrical energy between two electrodes in salt water can be used to generate acoustic energy. High voltage condensers discharge electrical energy into cables towed behind a vessel. Electrode pairs at the end of the cables conduct a high current discharge into the water, creating steam bubbles which in turn generate acoustic pulses. The system is used for continuous profiling, but penetration is limited to 50 feet.

Wire Exploder

The Wire Exploder is a modified sparker with the conversion efficiency of electrical energy into acoustical energy greatly increased. The wire explosion is the phenomenon resulting from the introduction of a very large amount of energy into a fine copper wire. When the wire is exploded under water, an initial shock pulse of high magnitude, followed by an implosion provides an acoustic pulse. The resulting pressure is several times greater in amplitude and time duration than with standard sparkers.

Hydrosonde

Hydrosonde is a continuous seismic profiling system applicable to problems connected with marine engineering surveys and underwater mineral and oil exploration. The technique is similar to echo sounding and employs a repetitive pulsed sound source. Creation of a high energy sound pulse may be achieved by means of a spark, ignition of gases or water displacement. The echos are received by a detector consisting of either one or an array of hydrophones.

Vaporchoc

The Vaporchoc system operates on the principle that steam can be condensed into water with a very high and rapid volume reduction. Once a steam bubble has collapsed and condensed, the medium is not subject to any further pressure which usually causes the bubble effect. During operation steam is injected into the sea in the form of a bubble which grows as long as steam is discharged. As soon as the injection is stopped, the steam condenses and due to the effect of hydrostatic pressure, the bubble collapses completely. All the energy is converted into kinetic energy in the form of the inflowing water. Conventional shooting rate is one shot every 6 to 12 seconds with equal efficiency in shallow or deep water.

Par Air Gun

The Par Air Gun is a well established and widely used marine seismic energy source. It operates by high pressure release of air directly into the surrounding medium. This provides an acoustic output in the useful range of seismic frequencies. Peak pressure output is proportional to operating pressure and roughly proportional to the square root of volume. Several models of air guns are available ranging in volume from 1 to 2000 cubic inches and operating pressures from 200 to 2200 psi. The output power spectrum may be synthesized in several ways: (1) by combining air guns of different chamber sizes in arrays; (2) by using time and/or space diversity in firing an array of guns; (3) by using a wave shape kit to shape the output of an individual gun. Portable air gun systems are versatile and can be usedfrom small boats in shallow water.

Seismojet Air Gun

The Seismojet Air Gun is a portable but powerful pneumatic energy source which is used for shallow and deep water marine exploration. The power output ranges from 3,000 to 8,000 psi at a frequency of 8 cycles per second.

PART II: THE EFFECTS OF SEISMIC ENERGY SOURCES ON FISH IN THE MACKENZIE DELTA AREA, NORTHWEST TERRITORIES

DESCRIPTION OF THE AREAS

Study areas were selected primarily by the operation schedule of co-operating seismic crews. Secondary considerations were the type of water body, water depths and fish availability. Both the line and point high explosive experiments were carried out in Parsons Lake (Fig. 2). This lake is situated east of the Mackenzie delta (69° 57' N; 133° 40' W), and flows into the Eskimo Lakes. Fish species known to inhabit Parsons Lake are Arctic cisco *(Coregonus autumnalis)*, broad whitefish *(C. nasus)* northern pike *(Esox lucius)*, longnose sucker *(Catastomus catastomus)* and ninespine stickleback *(Pungitius pungitius)*.

Air gun experiments were carried out in the Middle Channel of the Mackenzie River delta (68° 41' N; 134° 15' W). Recent investigations by Fisheries Service have shown that the Mackenzie delta channels serve as migration routes for many fish species, particularily anadromous Coregonids (Hatfield et al. 1972). Detailed descriptions of the above areas have been given by Mackay (1963).

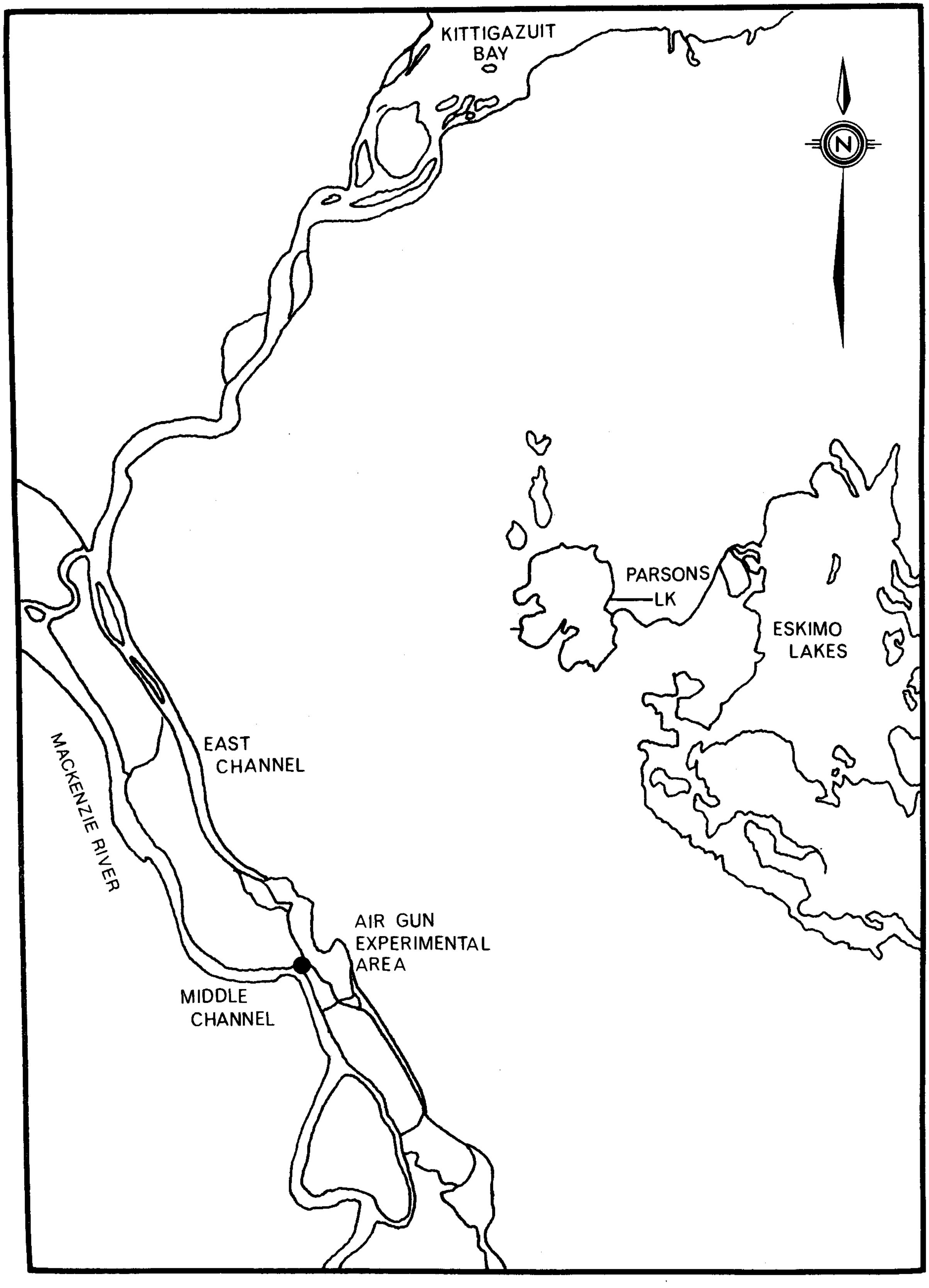

Figure 2: High explosive and Air Gun experimental locations in the Mackenzie River delta area, N.W.T.

MATERIALS AND METHODS

GENERAL

The basic approach taken for all experiments was to subject caged fish to the energy sources under normal shooting conditions. Fish were collected from streams close to the study area using a small-mesh beach seine and transported to the test locations in plastic tubs. Fish were held up to 48 hours before an experiment to allow for recovery from handling stress. One hour before the experiment, fish were placed in cages, positioned around the energy source and allowed to adjust to confinement and hydrostatic pressure.

After each shot, the cages were retrieved and the fish examined. Fish were immediately categorized as being alive, dead or in stress. They were then taken to shore for length measurements and gross external and internal examination. Internal damage was coded according to the area of injury as follows:

0. No apparent damage
1. Swimbladder rupture
2. Kidney damage
3. Internal hemorrhaging
4. Liver damage
5. Rib cage damage
6. Intestinal damage
7. External damage
8. Ovary damage

If internal damage to live or stressed fish was extensive, injuries were assumed to be fatal. An "Estimated Kill" was calculated on the assumption that such fish would certainly die at a later time.

A concept of measuring the lethality of toxic substances, the LC50, was used to predict the lethal range. Normally, the LC50 is the concentration causing 50 percent mortality over a given time period. An LR50 was estimated from a plot of percent dead vs. distance from the charge on log-probit paper. For the purpose of this study the LR50 may be defined as the distance from the energy source where 50 percent mortality occurs.

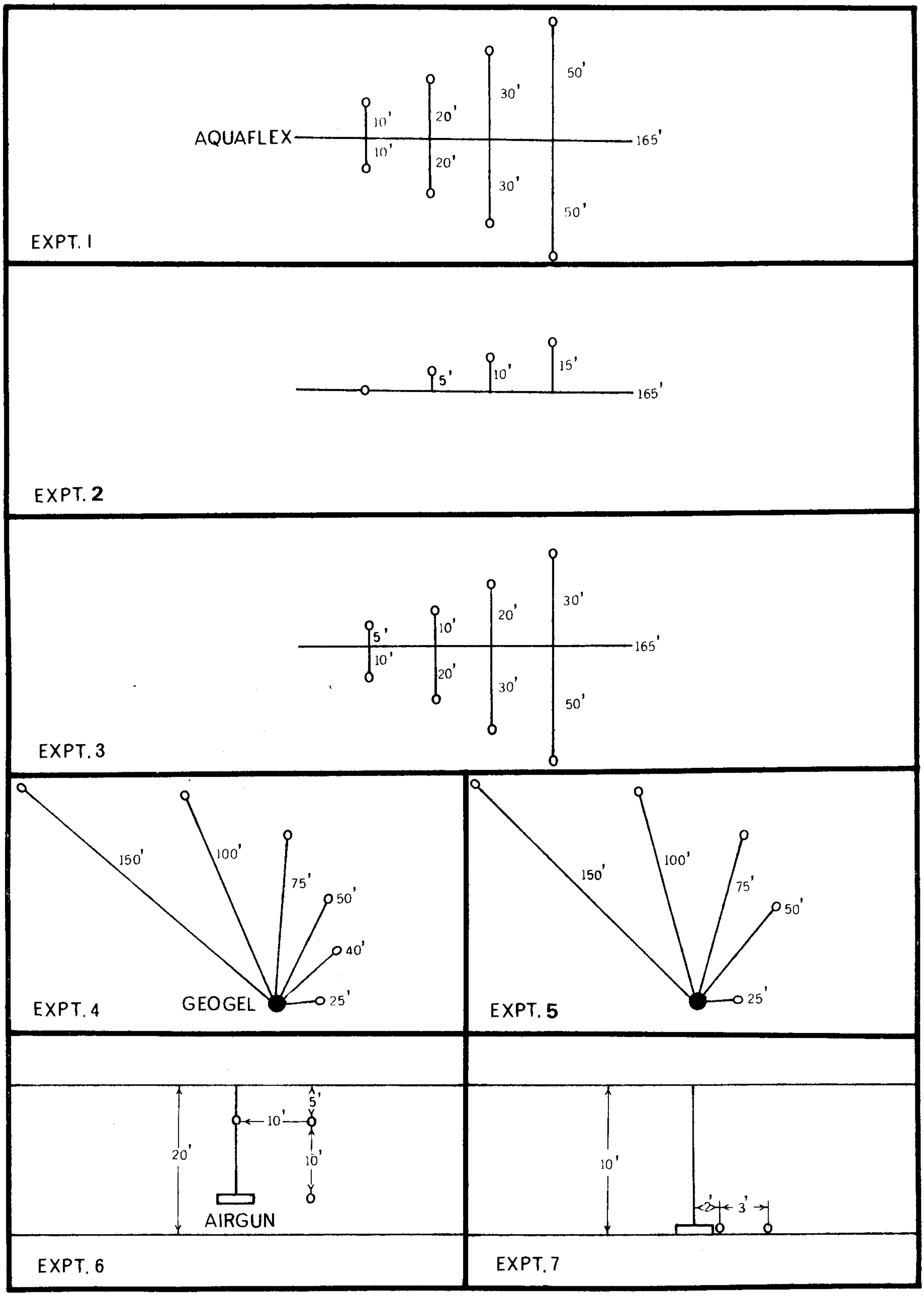

Figure 3: Spacial distribution of fish cages for Aquaflex, Geogel and Air Gun experiments. (Experiments 1-5: surface view; Experiments 6 and 7: side view.)

Aquaflex

Aquaflex, used in the present study had a core weight of 200 grains/ft and was used in 165 ft lengths (4.9 lb). Charges were laid on the bottom of the lake and detonated by an electric blasting cap.

Three caged fish experiments were carried out using Aquaflex. Spacial distributions of the cages for these experiments are shown in figure 3. Experiments 1 and 2 were carried out in 10 feet of water over a soft mud bottom with organic deposits and abundant aquatic vegetation. Experiment 3 was conducted in a water depth of 15 feet over a similar bottom. Cages were cylindrical galvanized minnow traps (.64 cm mesh) measuring 50.8 cm in length and 22.9 cm in diameter. Test fish were Arctic cisco ranging in fork length from 13.5 to 29.0 cm, and were collected from a nearby stream entering Parsons Lake.

Prior to an Aquaflex experiment two buoys were anchored 165 feet apart along the shot line. Cages, with anchors and buoys attached, were then positioned at measured distances perpendicular to the shot line. Aquaflex was laid between the two marker buoys and detonated.

60% Geogel

Geogel used in this study was supplied in 5 lb paper cartridges and was detonated by an electric blasting cap. Each cartridge contained 3 lb of high explosive.

Two experiments were carried out using Geogel. Experiment 4 was carried out in water depths ranging from 5.5 to 7.5 ft over a sandy bottom with aquatic vegetation, while experiment 5 was in a water depth of 15 ft over a mud bottom. Spacial distributions of the cages are shown in figure 3. Cages for the Geogel experiments were constructed of a 0.95 cm steel rod frame covered by 0.64 cm mesh galvanized hardware cloth. Overall dimensions were 45.7 x 45.7 x 91.4 cm. Arctic cisco was used as the test species for these experiments. Prior to an experiment cages, each with three fish, were positioned around the shot point. In experiment 4 the cages were laid on the bottom and their position marked with a buoy. For experiment 5, cages were suspended 10 feet below the surface by means of buoys and anchors. Charge sizes for experiments 4 and 5 were 2.5 and 10 lb, respectively.

Air Gun

The Par Air Gun used in this study was a 300 in^3 gun operated between 2,000 and 2,200 psi. Pressurized air was supplied by two compressors on board the shooting boat. In operation the gun was suspended in the water at the desired depth by means of floats.

Experiments were conducted at two locations. At each site a series of trials were carried out with minnow cages placed at various distances from the gun (Fig. 3). Young coregonids ranging from 7.0 to 10.0 cm in fork length, and collected near the test sites, were used as the test species. Experiments 6 and 7 were carried out in water depths of 20 and 10 ft, respectively over mud bottoms. Prior to an experiment, 4 to 5 fish were placed in a cage which was suspended in the desired position by means of floats. All trials with the air gun were with single firings with the exception of trial 7-3, where caged fish were subjected to a series of 4 shots at 10 to 15 second intervals.

Extraneous Fish Mortalities

In addition to fish kills resulting from experimental shots, surface inspections were also carried out after exploration shots. This was done in order to assess the extent of injury to local fish populations. When the number of fish killed or injured was small, they were counted and the internal organs usually examined. However, when the fish kill was extensive, the surface kill was estimated and a sample was collected for internal examination.

RESULTS

Aquaflex

Results from the three Aquaflex experiments are given in table 1. From the combined results of experiments 1 and 2 it was evident that fish near the surface were more susceptable to injury than those near the bottom. This phenomenon is illustrated in figure 4 by a cross-sectional view of cage placement around the Aquaflex charge. Despite cage placement on both sides of the Aquaflex charge, the results were combined since it may be assumed that the effect would be the same on both sides. The third Aquaflex experiment, conducted in a water depth of 15 ft, revealed an increased lethal range.

The LR50's were found to be 50 and 12.5 ft at depths of 3 and 7 ft, respectively for the combined results of experiments 1 and 2 (Fig. 5). These values were used as reference points to define the lethal zone surrounding the Aquaflex charge (Fig. 4). This zone was extrapolated to the surface at a horizontal distance of 80 ft. The lethal areas at a depth of 7 ft (A), 3 ft (B) and at the surface (C) were calculated to be 6,500, 16,500 and 36,200 ft^2, respectively (Fig. 4). The lethal volume associated with a 165 ft Aquaflex charge detonated on the bottom at a depth of 10 ft was then 185,000 ft^3.

Geogel

Results from the Geogel experiments are given in table 2. No caged fish mortalities occurred in experiment 4 using a 2.5 lb charge of Geogel detonated on the bottom in water depths of 5.5 to 7.5 ft. However, the detonation of a 10 lb charge suspended 10 ft below the surface in 15 ft of water resulted in caged fish mortalities up to 100 ft. The cross-sectional configuration of the cages and their associated mortalities are shown in figure 5. The LR50 for this experiment was found to be 90 feet from the charge in a horizontal direction (Fig. 5). This value was used as a reference point to define the

Table 1. Summary of results from Aquaflex experiments carried out in Parsons Lake.

Experiment	CagCage Depth (ft.)	Distance from Charge		No. of Fish			Type of Injuries	Estimated Kill	
		Horizontal	Direct	At Start	Killed	Under Stress		No.	%
1	3	10	12	2	2	-	1,3,5,6	2	100
	3	20	21	2	2	-	1,2,3,7	2	100
	3	30	31	2	2	-	1,2,5	2	100
	3	50	51	2	0	2	1,3	1	50
	7	10	10	2	0	2	1,3	1	50
	7	20	20	2	0	2	0	0	0
	7	30	30	2	0	2	0	0	0
	7	50	50	2	0	1	0	0	0
2	7	0	3	2	2	0	1,2,3,8	2	100
	7	5	6	2	2	-	1,2	2	100
	7	10	11	2	2	-	1,2	2	100
	7	15	15	2	0	0	0	0	0
3	7	5	0	2	2	-	1,2,3,5,7,8	2	100
	7	10	13	2	2	-	1,2,5,8	2	100
	7	20	22	2	2	-	1,2,5,8	2	100
	7	30	31	2	2	-	1,2,5,8	2	100
	3	10	16	2	2	-	1,2,5,8	2	100
	3	20	23	2	2	-	1,2,8	2	100
	3	30	32	2	2	-	1,2,5,8	2	100
	3	50	51	2	2	-	1,2	2	100

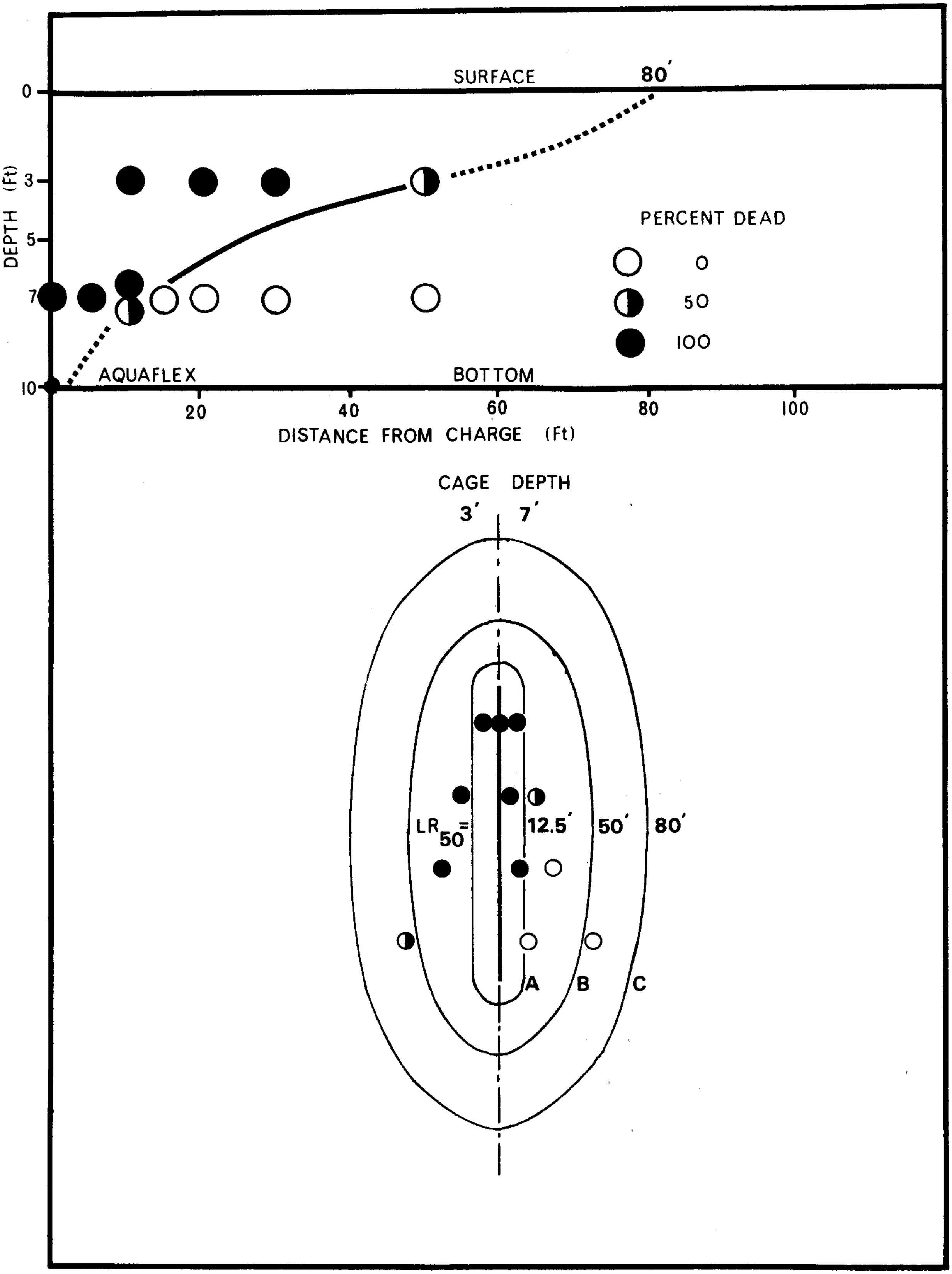

Figure 4. Cross-sectional and surface views of cage placement and respective areas for experiments 1 and 2 using Aquaflex.

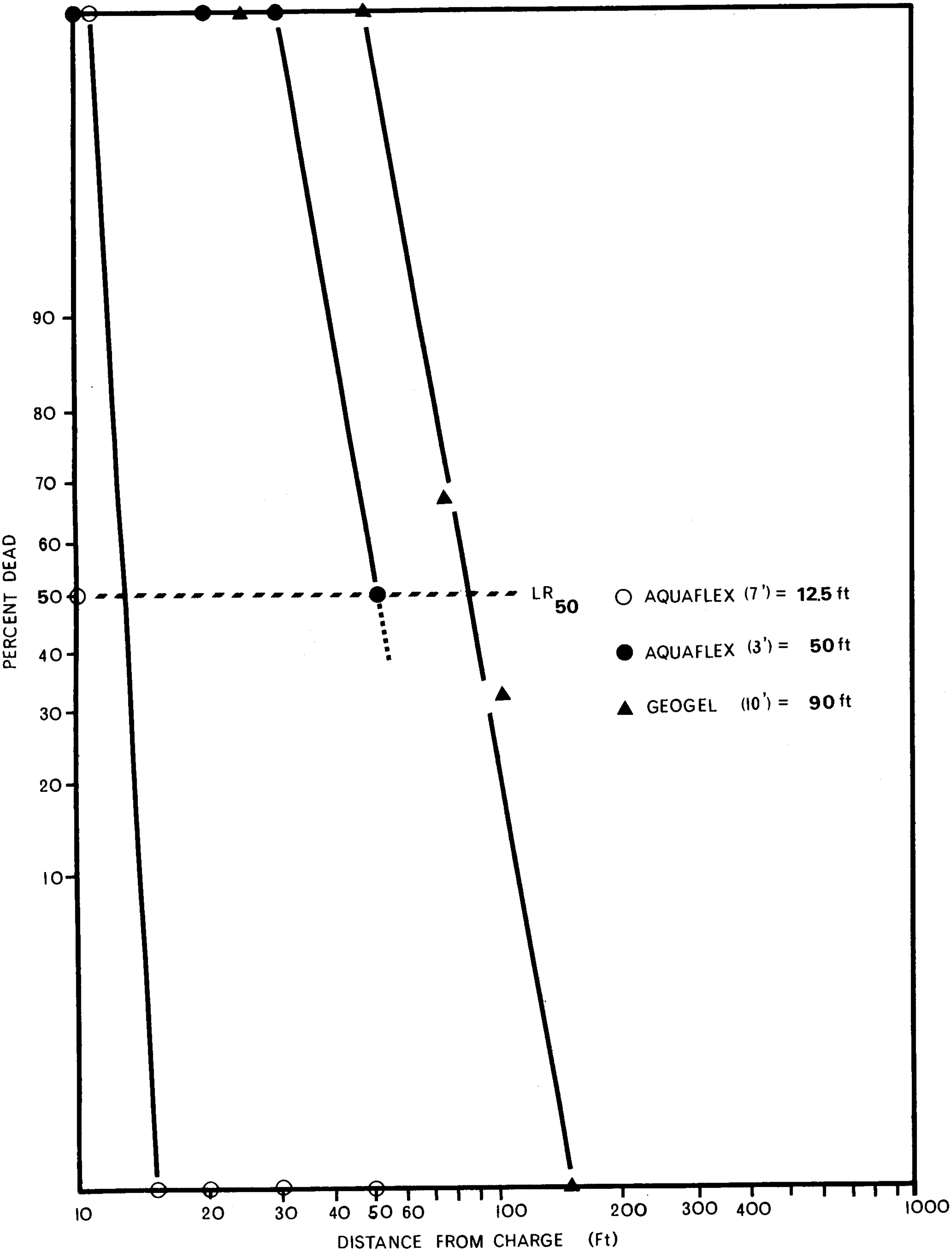

Figure 5. Graphical estimation of the LR50 for Aquaflex and Geogel experiments 1, 2 and 5.

Experiment	Cage Depth (ft.)	Distance from Charge		No. of Fish			Type of Injuries	Estimated Kill	
		Horizontal	Direct	At Start	Killed	In Stress		No.	%
4	7.5	25	25	3	0	0	0	0	0
	7.5	40	40	3	0	0	0	0	0
	7.5	50	50	3	0	0	0	0	0
	7.0	75	75	3	0	0	0	0	0
	6.5	100	100	3	0	0	0	0	0
	5.5	150	150	3	0	0	0	0	0
5	10	25	25	3	3	-	1,2	3	100
	10	50	50	3	0	2	1,2,35	3	100
	10	75	75	3	0	2	1,3	2	67
	10	100	100	3	0	0	1,3	1	33
	10	150	150	3	0	0	3	0	0

Table 2. Summary of results from Geogel experiments carried out in Parsons Lake.

lethal zone surrounding the 10 lb Geogel charge in figure 6. The lethal area (Fig. 6) and volume from a 10 lb Geogel charge detonated at 10 feet in a water depth of 15 ft were 25,500 ft^2 and 380,000 ft^3, respectively.

Air Gun

Results from the Air Gun experiments are summarized in table 3. No actual mortalities were observed during these experiments. Fish used in experiment 6 suffered no apparent damage while two fish from experiment 7 suffered swimbladder damage. Assuming that this damage would lead to eventual death, the lethal radius for a cubic inch Air Gun was estimated to be between 2 and 5 ft. Sequential Air Gun firings at intervals of 10 to 15 seconds had no apparent additional effect on the caged fish.

Extraneous Fish Mortalities

Extraneous fish mortalities resulting from experimental and exploratory shooting in Parsons Lake are summarized in table 4. Coregonids appeared to be most susceptable to underwater explosions considering the presence of other fish species. The area within which deaths occurred did not exceed that defined by the caged fish experiments. Doubling the length of Aquaflex in exploratory shooting doubled the fish kill. Excessive mortalities to local fish populations resulted from the use of a 10 lb charge of Geogel in a water depth of 15 ft. No mortalities were observed during 10 miles of Air Gun shooting along the Mackenzie River in water depths from 5 to 30 ft.

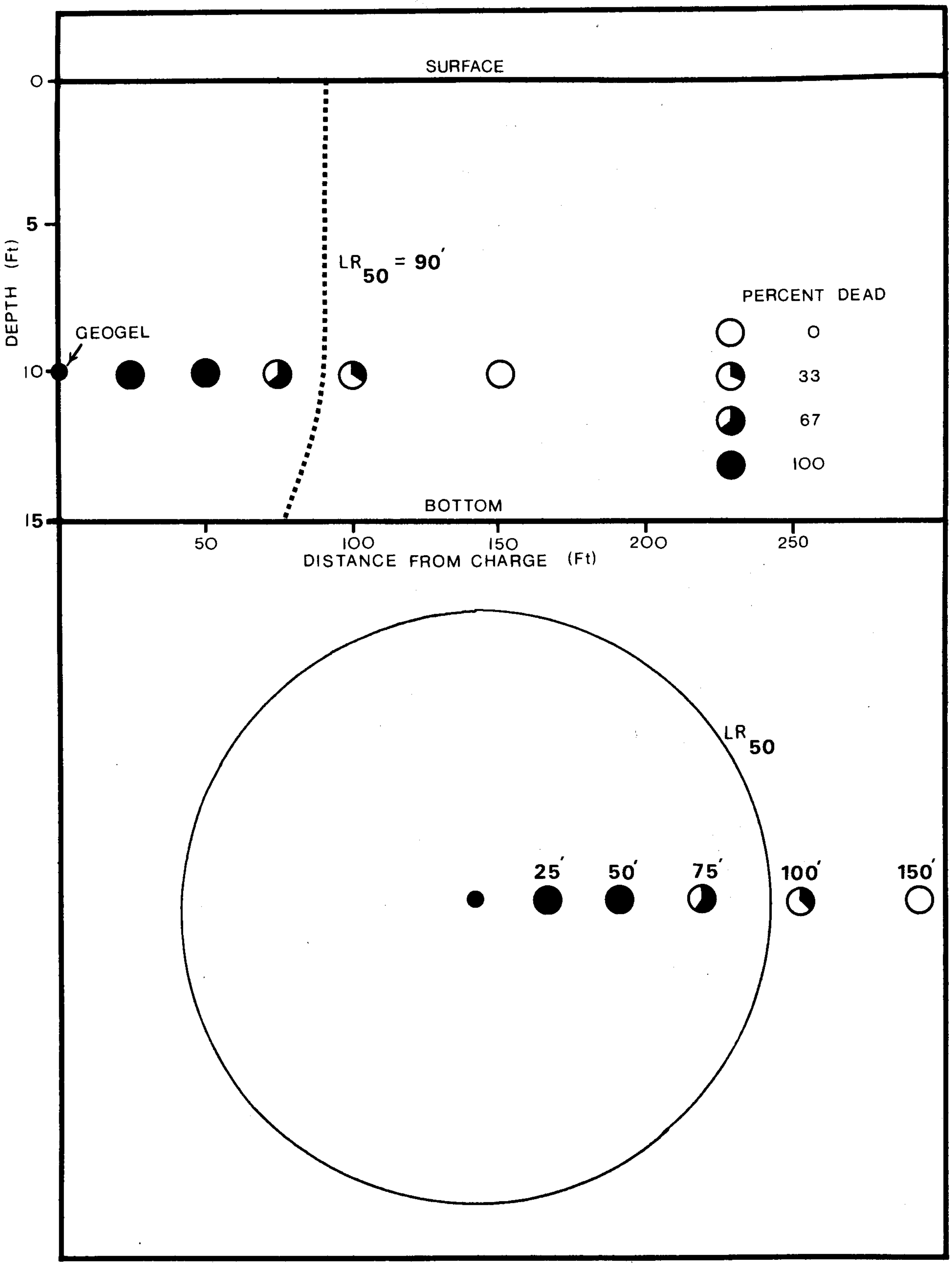

Figure 6. Cross-sectional and surface views of cage placement and respective lethal areas for Geogel experiment 5.

Table 3. Summary of results from Air Gun experiments carried out in the Mackenzie River Delta.

Experiment	Cage Depth (ft.)	Distance from Charge (ft.)		No. of Fish			Injuries	Estimated Kill	
		Horizontal	Direct	At Start	Killed	In Stress		No.	%
6-1	5	0	10	5	0	1	0	0	0
-2	5	10	11	5	0	1	0	0	0
-3	15	10	10	5	0	0	0	0	0
7-1	10	2	2	5	0	0	1	1	20
-2	10	5	5	5	0	1	1	1	20
-3	10	2	2	4	0	0	0	0	0

Energy Source	Charge		Water depth (ft)	No. of fish killed	Species	No. sampled	Injuries	Condition
	Size	Depth (ft)						
Aquaflex	165 ft	15	15	2	*C. nasus*	2	1,2,5	dead
							1,3	dead
Aquaflex	165 ft	15	15	5-10	*C. autumnalis*	0		dead
Aquaflex	2x165 ft	15	15	20-30	*C. autumnalis*	3	1,2	dead
							1,3	stress
							1,3	stress
Geogel	2.5 lb	7	7	2	*C. autumnalis*	2	1,2,3	dead
							1	stress
Geogel	10 lb	10	15	400+	*C. autumnalis*	-		dead
					Immature Coregonids			stress
Geogel	5 lb	15	15	1	*C. nasus*	0	1,3,5	dead

Table 4. Summary of extraneous fish mortalities and injuries resulting from exploratory and experimental shooting in Parsons Lake.

DISCUSSION

The results to date revealed that both Geogel and Aquaflex, detonated in shallow water, were lethal to local fish populations. The lethality of Geogel and other high explosive point energy sources has been demonstrated previously (Hubbs and Rechnitzer 1952; Hubbs et al. 1960). However, comparisons of the lethal range between previous studies and the present are not feasible since experiments were carried out under differing conditions. For example, Hubbs et al. (1960) found the horizontal lethal range for a 10 lb charge detonated near the surface with a water depth of 400 ft to be 350 ft. This is much greater than 90 ft estimated for the present study. The reason for this difference may be attributed to water depth: in shallow water much of the energy is lost through the surface eruption. Tyler (1960) showed that in shallow water the horizontal lethal range was proportional to water depth. Further, Cole (1968) demonstrated that a substantial portion of the energy from a suspended charge may be absorbed by the bottom, depending upon its nature.

There is little information pertaining to the nature and effect of underwater Aquaflex charges. Cole (1948) proposed that the detonation of a line charge would result in an asymmetrical peak pressure zone which would be greater at the end detonated. He assumed that the cumulative effect of successive elements of the explosive may be obtained by simple addition from end to end. Although this could not be demonstrated in the present study, an asymmetrical configuration is a definite possibility. The elliptical shapes of the lethal areas are based on Cole's theory that the shock wave close to a line charge should decay in a cylindrical manner, while at greater distances it should be spherical. Further, Paterson (1968) found that the pressure off the end of an Aquaflex charge was less than that off the side, for a given distance. He showed that the pressure from a 30 ft charge suspended from the surface in 35 ft of water decayed as $R^{-0.6}$ up to R=12 ft. Beyond 12 ft the pressure decreased at a faster rate ($R^{-1.13}$) and approached that of a point charge at 40 to 50 ft. Peak pressures were estimated to be 12,000 psi at 10 ft, 5,800 psi at 30 ft, and 110 psi at 100 ft. Hubbs and Rechnitzer (1952) proposed that shock pressures between 40 and 60 psi were lethal to fish with swimbladders. Since fish from the present study survived at a distance of 100 ft from the Aquaflex charge, peak pressures must have been lower. An explanation for this is that of a modifying influence imposed by the bottom. Cole (1948) showed that for charges placed on the bottom a substantial portion of the energy is reflected off the bottom corresponding to the geometrical reflection path. This phenomenon may explain why fish, in the present study, were killed near the surface, while fish at the same distance from the charge, but near the bottom, were not. These results are comparable to those of Hubbs and Rechnitzer (1952).

It was found that the horizontal lethal range for Aquaflex was substantially increased by an increase in water depth. The explanation for this is that more energy is directed radially from the charge, and less energy is lost in the surface eruption. It is possible that, for a given length of Aquaflex, the horizontal lethal range will not increase beyond a certain water depth. This phenomenon was demonstrated by Tyler (1960).

Lethal surface areas and volumes calculated for the Aquaflex and Geogel charges using the LR50 are modest approximations of the maximum values to be expected. However, due to the rapid dissipation of the shock wave, the lethal area would not extend much further than that calculated by the LR50. The maximum distance where mortality occurs may be expected to be highly variable, depending on fish condition and orientation. The LR50 permits direct comparison between shots using a calculated value rather than one subject to variability and usually estimated.

The lethal areas calculated for the Aquaflex and Geogel shots cannot be compared directly due to their placement in the water column. The lethal surface area for the Aquaflex charge (36,200 ft^2) was greater than that for Geogel (25,450 ft^2). This is believed to result from the fact that the Aquaflex charge is distributed over a greater area. If the maximum lethal surface area is extrapolated to the surface, it would approach that of an acre (43,560 ft^2). The volume affected by the Aquaflex shot (185,000 ft^3) was approximately half that of the Geogel shot (381,750 ft^3). It is expected that from the results of the Aquaflex experiments that if the Geogel were detonated on the bottom the volume affected would be reduced.

In contrast to Aquaflex and Geogel, the 300 in^3 Air Gun proved to be relatively harmless to fish. This is substantiated by Weaver and Weinhold (1972). This non-lethal aspect makes it a very desirable seismic energy source for protection of the fish resource. The findings of a study carried out during 1971 by the Canada Department of Energy, Mines and Resources showed that the use of a 1,000 in^3 Air Gun in northern Hudson's Bay provided at least as good seismic data as that from 50 lb dynamite charges. Since output pressure does not increase linearly with gun volume (Weaver and Weinhold 1972) fish are not expected to be adversely affected. Further, shock waves created by an Air Gun have characteristics similar to those created by low explosives such as blackpowder which are noninjurious to fish.

IMPACT OF EXPLOSIVE ENERGY SOURCES ON THE FISH RESOURCE

Since the discovery of oil and gas at Prudhoe Bay, Alaska, exploration activity in the Northwest Territories has steadily increased from 52 seismic crews operating in 1967, to 206 in 1971, and an estimated 230 in 1972. While these figures apply to both land and offshore operations, it is reasonable to assume that the increase in offshore work has at least kept pace with that on land. Although a comprehensive assessment of offshore seismic activity is beyond the scope of this report, a selection of 61 offshore seismic crews operating between 1970 and 1972 revealed that half of the applicants for offshore work employed an explosive energy source. The remainder used Air Guns, Vaporchoc and Flexotir.

In an attempt to define the magnitude of explosives used in offshore operations during 1972, seven operations were selected as the basis of complete information. The amount of explosives used during these operations totaled 113,000 lb over 950 miles of seismic lines (or 120 lb per mile). The individual charge size, whether single or in a pattern, ranged from 2.5 to 100 lb. Since Aquaflex and Geogel were found to be lethal to fish in shallow water, a potential threat to the fish resource exists through this increased use of explosives. Shallow offshore regions and inland lakes and river systems are likely to feel the greatest impact since they tend to support larger concentrations of fish. These areas are also those commonly used for feeding, migration and breeding purposes.

FUTURE AREAS OF STUDY

Despite a substantial amount of literature pertaining to the effects of seismic energy sources on fish, there remain many questions to be answered. The present study answered a few, but created just as many. Reasons for this are the diversity of seismic energy sources, the different ways in which they are employed and the various conditions under which they may be used. In this regard studies have to be directed to answer questions arising from particualr circumstances. Immediate needs for study are the effect of shooting under ice and buried charges on fish, and the effect of seismic energy sources on marine mammals.

CONCLUSIONS

1. Both Aquaflex and 60% Geogel are extremely lethal to local fish populations in shallow water.
2. The lethal area surrounding an Aquaflex charge, detonated on the bottom, increases from the bottom to the surface of the water body.
3. The lethal area surrounding an Aquaflex charge increases with water depth.
4. A 300 in^3 Air Gun is relatively innocuous to local fish populations in shallow water.

PHOTOGRAPHS

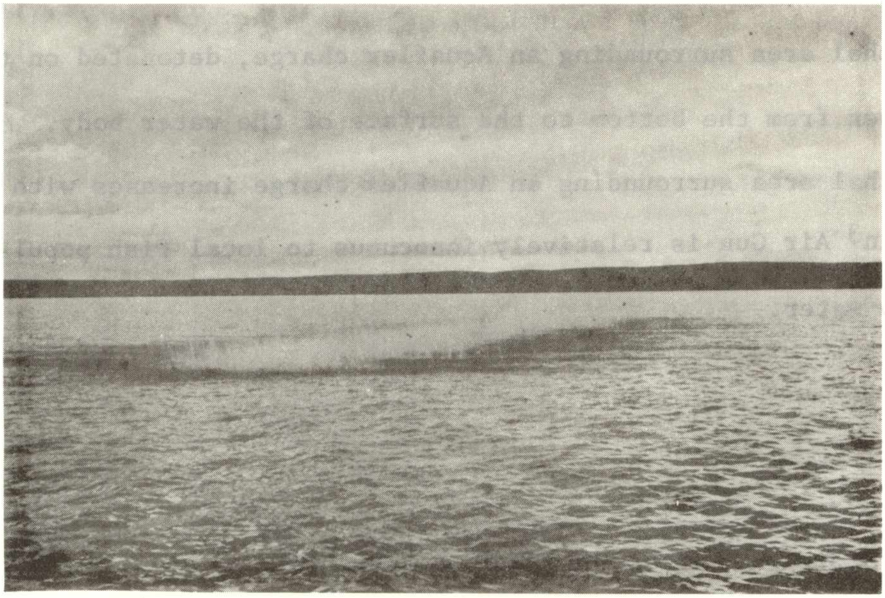

Photo 1. Surface disturbance caused by 165 feet of Aquaflex.

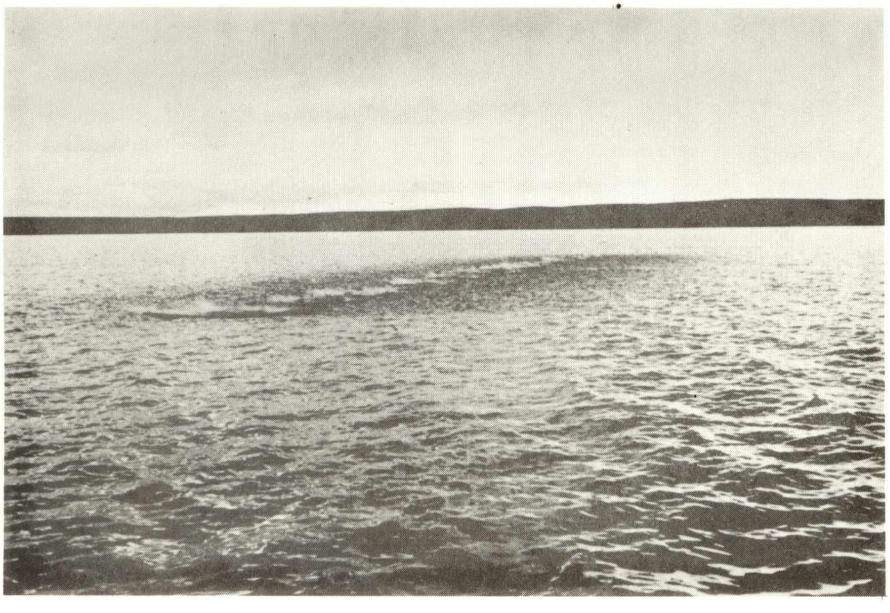

Photo 2. Surface disturbance after detonation of 165 feet of Aquaflex.

Photo 3. Surface dome caused by 2.5 lb of Geogel.

Photo 4. Surface dome caused by 10 lb of Geogel.

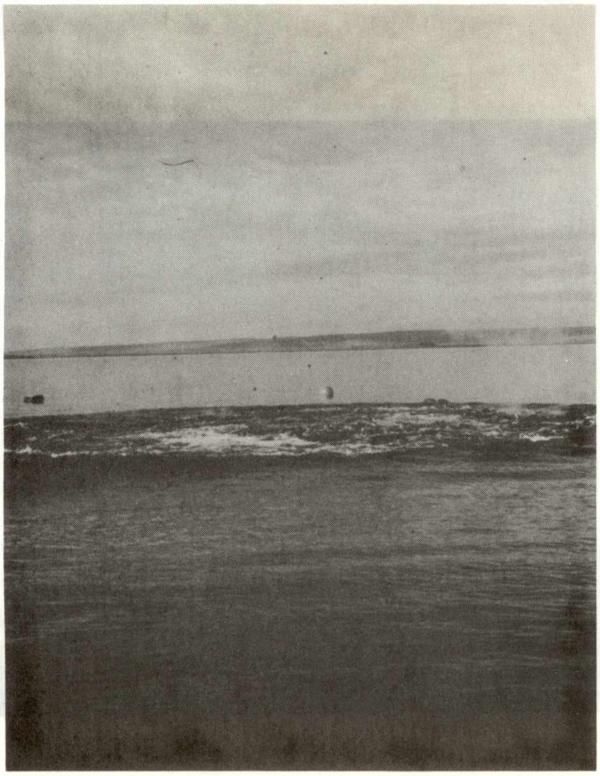

Photo 5. Boil resulting from a 10 lb charge of Geogel.

Photo 6. Surface eruption caused by a 300 cubic inch Air Gun.

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