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Feasibility of Surface Detection of Oil under Ice

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FEASIBILITY OF SURFACE DETECTION OF OIL UNDER ICE

by

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for the

Research and Development Division
Environmental Emergency Branch
Environmental Impact Control Directorate
Environmental Protection Service
Environment Canada

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ABSTRACT

The following sensing modes were addressed to determine the feasibility of their application to the detection of oil in and under ice: radio frequency , acoustic, optical, nuclear and gas sniffer modes. Of the five modes studied, it was determined that the optical and gas sniffer modes would not be applicable for various reasons. Visible radiation would suffer so much attenuation that penetration into the ice would be at best only a few centimeters. Gas sniffer techniques rely on the presence of hydrocarbons in the atmosphere, and it is unlikely that diffusion would occur through an ice cover; even if it did, there would still exist the operational problem of having interference of hydrocarbon emissions from the vehicle used as a means of transportation.

The other three sensing modes were more promising; however, each requires more study before applications can be categorically determined. Radio frequency radiation, while being able to penetrate reasonable depths of ice, is highly attenuated in first-year ice and less so in multi-year ice at frequencies which would give the desired resolution. However, if a clear ice-oil boundary is present (i.e. no oil has migrated into brine channels) it should be possible, at least theoretically, to detect the presence of a layer of oil that is not very much thinner than the wavelength being used. This is because the dielectric constant at an ice-water boundary goes from lower to higher values, whereas at an ice-oil boundary it goes from higher to lower values. Hence, the phase of the reflection in each situation would be 180° out of phase and easily detected in the return signal.

With regard to acoustic techniques, soundwaves penetrate reasonable ice thicknesses at wavelengths which are closely related to the oil thickness in question. The similar acoustic properties of water and oil (especially heavy oils), however, may cause difficulties in distinguishing between the two, and further study is required to establish feasibility.

Nuclear techniques, while providing the required resolution, appear to be fundamentally limited with regard to ice penetration. Expected penetration using current techniques would be approximately 40 cm, and even extensive and costly development might only improve this by a factor of two or three.

From an instrumentation point of view, acoustic or radio frequency techniques would appear to be the most preferable. Instruments for each are potentially light and portable with no safety complications and with relatively low developmental and final

costs. Nuclear detection, with its limitations on depth, additional developmental costs and safety complications, would appear to be the technology of last resort, even though it would provide the best resolution.

It is recommended that experimental studies be undertaken using both radio frequency and acoustic techniques. If it is determined that such techniques are not applicable, then experiments should be carried out with modified nuclear well logs.

RÉSUMÉ

La présente étude porte sur cinq modes de détection et la possibilité de les appliquer aux hydrocarbures présents dans ou sous la glace: fréquences radio-électriques, systèmes acoustiques, systèmes optiques, systèmes nucléaires, et système de "reniflage" des gaz. Deux de ces cinq méthodes sont inutilisables pour diverses raisons. Le rayonnement dans la zone visible serait tellement atténué sous l'effet de la composition de la glace que les ondes ne la pénètueraient que quelques centimètres seulement. D'autre part, le "reniflage" détecte seulement les hydrocarbures présents dans l'atmosphère et même si les hydrocarbures déversés parvenaient à traverser la glace, ce qui est peu probable, on devrait toujours tenir compte des émissions provenant des véhicules de transport.

Les trois autres méthodes ont été jugées relativement applicables mais il conviendrait de les étudier plus à fond pour savoir laquelle est la meilleure. Les fréquences radio-électriques pénètrent des couches assez épaisses de glace mais elles sont fortement atténuées par la glace de l'année, un peu moins par la glace de plusieurs années et ce, même aux fréquences qui permettraient la résolution voulue. Toutefois, s'il existe une limite nette entre la nappe d'hydrocarbures et la glace (c'est-à-dire que les hydrocarbures n'ont pas pénétré dans les crevasses), il devrait être possible, au moins en théorie, de détecter la présence d'une nappe pour autant que cette dernière ne soit pas beaucoup plus mince que la longueur d'onde utilisée. Cette détection est possible du fait que la constante diélectrique augmente lorsqu'on passe de la glace à l'eau, tandis qu'elle diminue lorsqu'on passe de la glace à des hydrocarbures. C'est dire que le signal est déphasé de 180° par rapport au signal initial et qu'il est facile à distinguer dans le signal de retour.

Les signaux acoustiques pénètrent eux aussi assez bien la glace et présentent de plus l'avantage de fonctionner sur des longueurs d'onde qui correspondent mieux à l'épaisseur des nappes à détecter. Toutefois, les propriétés acoustiques semblables de l'eau et des hydrocarbures (surtout les huiles lourdes) peut empêcher de faire facilement la distinction entre les deux et de plus amples recherches sont nécessaires si l'on veut s'assurer qu'il est possible d'appliquer ces méthodes.

Les méthodes nucléaires, malgré leur bon pouvoir de résolution, ne permettent qu'une pénétration limitée de la glace. On pense que les méthodes actuelles ne permettent de détecter les hydrocarbures que lorsque l'épaisseur de la glace est de 40 cm

au plus et même des perfectionnement poussés et coûteux ne pourraient que doubler ou tripler le pouvoir de pénétration.

Du point de vue instrumental, les méthodes fondées sur les ondes acoustiques et les ondes radar nous semblent préférables. Les instruments nécessaires pourraient être légers, portatifs et sûrs sans frais excessifs. La détection nucléaire, étant donné son faible pouvoir de pénétration ainsi que les coûts supplementaires de mise au point et les problèmes de sécurité qu'elle entraînerait, semble constituer notre dernier recours malgré son pouvoir de résolution supérieur.

Nous recommandons que d'autres expériences soient entreprises pour étudier l'utilisation des ondes radar et des ondes acoustiques. Si ces méthodes s'avèrent finalement inutilisables, les recherches devraient alors s'orienter sur la mise au point d'une méthode modifiée de diagraphie nucléaire.

FOREWORD

This study was conducted by NORDCO Limited under contract to the Environmental Emergency Branch of Environment Canada. The study was funded under AMOP, and Mr. M.F. Fingas was scientific authority for the work. The following subconsultants provided major inputs to the study: Dr. J.R. Rossiter, C-CORE; Dr. N.H. Rich, Department of Physics, Memorial University of Newfoundland; Mr. M.P. Bruce-Lockhart, Faculty of Engineering and Applied Science, Memorial University of Newfoundland.

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CONCLUSIONS AND RECOMMENDATIONS

Of the three possible methods being considered, radio frequency, while being able to penetrate reasonable depths of ice, is limited in resolution due to high attenuation at the wavelengths which would give the desired resolution. This is especially true in the case of first-year sea ice which has much higher attenuation characteristics than multi-year or freshwater ice. From discussions in this report, it has been pointed out that oil might collect under ice to varying thicknesses depending on the undersurface relief and in some instances could build up in pockets of considerable thickness. However, any viable technique would be required to detect oil of thickness 1 cm or less, and it has been seen that radio frequency is severely limited in this regard. Nevertheless, oil has been detected under ice using radio frequency (albeit under conditions which are not entirely duplicated in the field) and this is certainly an important beginning.

Acoustical techniques also enable penetration of reasonable ice thicknesses and have the further advantage of operating at wavelengths which are more closely related to the oil thickness in question. However, because of the similarities in water and oil acoustical properties (especially heavy oils), it may be difficult to distinguish between the two. Except for the case of detection of light, highly refined oils by acoustic means, the best hope of detection lies in changes occurring in the brine channel layer due to the presence of oil.

Nuclear techniques, while providing the required resolution, appear to be fundamentally limited with regard to the depth of ice that can be penetrated. Expected depths using current techniques are about 40 cm and even extensive, costly development is likely to improve this only by a factor of two or three.

From an instrumentation point of view, acoustical or radio frequency techniques would appear to be the most preferable, if feasible. Each is potentially light and portable, with no safety complications and with relatively low developmental and final costs. Nuclear detection, with its limitations on depth, additional developmental costs and safety complications, appears to be the technology of last resort even thought it would have the best resolution capability.

It is recommended that studies be undertaken to determine experimentally whether radio frequency and acoustical techniques are capable of detecting oil in or under sea ice to the extent that realistic thicknesses of oil may be detected. Since some experimental work has already been carried out at the Cold Regions Research Engineering

Laboratory (CRREL) using impulse radar for this purpose, it is recommended that close liaison be maintained with that lab to ascertain the results of future experiments and to compare findings. In the initial stages of experimental work it is recommended that freshwater rather than saline ice be used so that a better understanding of subsequent work with saline ice may be obtained. Since the uptake of oil into brine channels will probably have a significant effect on the detection process, this phenomenon will have to be incorporated into the experiment either by careful growth of ice in the laboratory or by field experimentation. Parameters such as frequency bandwidth and wave form should be examined in the study, in as much detail as possible.

If such experiments with radio frequency and acoustical modes are not successful in establishing the feasibility of such methods, then some experiments should be conducted with modified nuclear well logs.

Given the present uncertainties associated with indirect detection methods, it might well be advisable to examine the feasibility of automated mechanical systems, in particular chemical drilling. If remote detection techniques do not prove feasible, an intensive effort to improve mechanical systems could be of considerable benefit. The key to success would be to rethink the problem from the ground up while focusing on the systems aspect. The goal should be a major increase in overall sampling rate rather than simply faster penetration of the ice.

While such an approach could never be competitive with the sensing techniques considered in this study, the payoff could be substantial in the absence of such techniques and should therefore not be discounted at this point.

1 INTRODUCTION

1.1 Purpose of the Study

Petroleum developments in Arctic regions in recent years have prompted several studies concerned with the processes which take place when oil interacts with ice, and with countermeasures for coping with oil spills in cold environments. Oil from a blowout, pipeline break or tanker spill may interact with ice in a variety of ways but, in general, a large proportion of the oil would be trapped in the undulations of the lower ice surface and could be incorporated in a growing ice sheet if a spill were to occur during fall or winter. In the case of first-year ice, the oil would rise to the surface in spring (possibly later in the year in multi-year ice) and could probably be cleaned up by using a variety of techniques, the most expedient of which would be burning. In the stages following a spill and during cleanup, it is clearly necessary to be able to locate and track the oil. Tracking may be done in ice-covered waters by using acceptable ice tracking methods; however, in order to locate the oil under or in a specific floe, it would be necessary to use a small-scale, highly mobile detection method. Such a method, if it were available, could be used in a number of applications: (i) locating specific pockets of oil under ice so that cleanup measures could be undertaken; (ii) locating the oil to replace ice tracking devices or to place ice tracking devices on contaminated areas not previously marked; (iii) verifying the ice tracking systems being used or verifying that a particular area which is being tracked is in fact contaminated with oil; and (iv) locating and mapping spills occurring under river ice. The purpose of this particular work has been to investigatge the feasibility of various techniques to provide such a detection capability.

1.2 Methodology and Background Studies

In this study, a number of possible detection modes have been considered. In the initial stages of the study, a literature search was conducted to determine if such sensing modes had previously been used to detect oil under or in ice. Simultaneously, the search focused on the applicability of these detection modes to measure ice thickness, as this is clearly related to the problem at hand. In addition, contact was made with a number of researchers to determine recent developments in both areas and in the area of oil/ice interaction. With regard to the latter, the resultant effects of oil on the ice characteristics would be of considerable importance to the effectiveness of some of the detection modes.

The following modes of sensing were initially considered for possible use in detection methods:

1. Radio Frequency
2. Acoustic
3. Optical
4. Nuclear
5. Gas Sniffer

Mechanical detection methods, while not being in the same 'sensing' category as the other methods, were also considered because it was felt that such direct methods would avoid many of the uncertainties associated with an indirect detection system. The intention was to compare the predicted performances of the indirect methods with direct sampling by physically penetrating the ice, and these comparisons would then become part of the evaluation process.

From a preliminary consideration of these sensing modes, it was determined that a number showed possibility and these were then evaluated in detail.

During the early stages of the study, it was determined that little work had been published concerning the use of these modes for detecting oil under or in ice. While there has been considerable effort expended to develop sensors for the detection of oil on open water, the application to oil under or in ice has received attention only recently. The possibilities of using a number of sensing modes in ice-infested waters have been discussed by Logan et al.(1975), with a brief treatment of the problems inherent in the use of such modes for the detection of oil under and in ice. A more recent study (C-CORE, 1978), discusses the use of microwave systems for detecting oil in ice-infested waters. The writers are somewhat inconclusive as to the ability of such systems in detecting oil under or in ice cover. Perhaps the most significant work currently under study is that concerning the use of impulse radar to detect oil under ice at the Cold Regions Research Engineering Laboratory (CRREL) in New Hampshire. First results, while being performed under rather ideal conditions in terms of ice undersurface relief characteristics, were somewhat encouraging and further work is planned (Dean, 1979).

There has been relatively little work completed concerning the use of most of the above means of sensing for the application in question; however, this is not true of their application to the measurement of ice thickness. For example, the use of acoustics and radar techniques in ice surveys is well known, and further development is continuing in these areas at a number of centers. Such work is discussed in more detail in a later section.

1.3 Background Review of Oil/Ice Interaction

In order to put the study objectives into perspective and provide an appreciation of the physical phenomena with which a detection technique would have to cope, an overview of the various features of oil/ice interaction is given in the following paragraphs.

From the numerous studies that have been undertaken in the last decade on the behaviour of oil interacting with ice, it is clear that a range of interaction characteristics may be possible depending on such factors as ice conditions, behaviour and type, ambient oceanographic and meteorological conditions and oil types and characteristics. Thus, it is known that the interaction of oil with first-year sea ice will be different than with multi-year ice; likewise the presence of gas in the oil will alter the interaction process, and the effect of winds and currents will also complicate the behaviour.

Laboratory studies have shown that oil which contacts the lower surface of a uniform ice sheet will accumulate under gravitational and surface tension forces to a thickness of approximately 1 cm at equilibrium (Rosenegger; 1975; Malcolm, 1979). However, this thickness may be reduced to as low as 0.2 cm if gas is mixed with the oil (Arctec Canada Limited, 1978). Conversely, the oil thickness may be considerably increased in the case of an oil spill under landfast and pack ice because of the irregular undersurface relief of the ice which causes the oil to form in pools. Landfast ice which forms in areas of low current activity may exhibit lower surface relief variations of 20 to 30 cm when the average ice thickness is 2 m, due to variations in heat flow associated with snow drifts on the surface (Lewis, 1976). Variations in relief associated with snow accumulation may have implications for oil spill tracking and cleanup since it is implied that thicker pools will form in areas of larger snow thicknesses. Further relief variations in the order of 1 to 2 cm may be associated with brine drainage from the ice sheet. In the case of pack ice, the mechanical deformation of the ice causes considerable variation in the undersurface relief, again providing the possibility of having oil accumulate to large thicknesses. In both landfast and pack ice cases, such oil build-up will clearly depend as well on the presence of gas mixed with the oil and on currents. These will tend to increase the area of contact of the oil with the ice thereby decreasing the thickness of the oil layer. A further effect of gas (assuming it is trapped by the ice) will be to cause the oil pool below it to form a level surface at the gas/oil interface. The residence time of gas under a stationary ice cover is not well known. It is felt, however, that the gas might escape through micro cracks in the ice cover which would be impermeable to oil, or possibly cause the ice sheet to deflect sufficiently to produce cracks (Topham, 1977). With pack ice there is the added complication of constant movement under the action of currents and winds, the opening and closing of leads, and the formation of pressure ridges, all of which contribute to the irregularity of the under-ice relief and variation in the volume and thickness of oil constrained beneath the ice.

If oil is spilled under landfast ice during the period of ice growth, the oil layer will become encapsulated as more ice grows beneath it. (Whether this will happen in the dynamic pack zone is not well established). Although the oil initially forms an insulating layer (its conductivity being about 6×10^{-2} times that of ice), this effect becomes reduced as convection occurs in the oil layer. This convective effect (which has implications for possible usage of radiometry methods to detect oil under ice) is possible in layers 2 to 3 cm thick and, in fact, may be so pronounced in layers of thicknesses 10 cm and greater that heat transfer from the water to the ice surface may actually be increased (Lewis, 1976).

If oil is trapped under first-year ice during spring, it will migrate upwards into the brine channels formed in the ice and reach the surface later in the spring as was clearly demonstrated in Balaena Bay during the Beaufort Sea studies (NORCOR, 1975). However, the extension of this phenomenon to oil under multi-year ice is somewhat tenuous. Since multi-year ice is essentially freshwater, the brine having drained out during previous years' thaws, oil trapped in or under it, would be expected to migrate to the surface only over a number of freeze-thaw cycles. Work carried out by Milne et al. (1977) on the porosity of multi-year floes, however, indicates that oil trapped in and under multi-year ice should surface before mid-September if it was spilled under the ice during the previous winter and spring. Results of the Balaena Bay tests showed that oil that had been trapped under the ice during winter had weathered very little by the time it surfaced, indicating that little, if any, of the volatile compounds had escaped through the ice cover. It is possible that any weathering that did occur was due to dissolution into the underlying water.

For the purpose of this study, the migration of oil through the ice is an academic question, (other than the possible escape of volatile components) as the present concern is that of determining the location (and ideally the quantity) of oil to facilitate cleanup measures. This capability, however, can only be developed if there exists a full appreciation of the types of behavior and phenomena that may occur when oil is spilled under ice. Background information has been cited to show the types of behavior that must be considered.

2 A DESCRIPTION AND TECHNICAL EVALUATION OF POSSIBLE DETECTION TECHNIQUES

2.1 Introduction

In the following paragraphs, each of the detection modes listed in the previous section is discussed in detail and evaluated in terms of the expected performance in penetrating an ice layer and detecting oil under or in the ice. In a later section, the techniques which show possibility are considered more closely in terms of developmental and operational characteristics.

2.2 Radio Frequency Mode

This section will outline the feasibility of using electromagnetic (EM) techniques, up to micro-wave frequencies, to detect oil in or under ice. Since significant research is currently in progress in the use of active EM sounders to determine ice thickness, the "state-of-the-art" in this field will be reviewed. (Passive methods are discussed in a later section). Since the detection of oil will depend primarily on changes in electrical properties caused by the addition of oil, these properties are summarized.

Although freshwater ice is highly transparent to radio frequency (RF) waves (Evans, 1965), sea ice is usually highly attenuating (Hoekstra and Cappillino, 1971; Vant et al., 1974; Vant, 1976; Vant et al., 1978). The addition of brine to ice increases the bulk dielectric constant of the ice from 3.2 to 5 or greater. The losses are greatly increased, and the attenuation in dB/m becomes very great above about 1 GHz, as shown in Figure 1. Ice that survives a summer loses much of its brine, and the attenuation in multi-year ice is significantly lower.

The measurements of the electrical properties of sea ice have largely been made in the laboratory and show great variance from sample to sample. This phenomenon is probably related to wide variations in properties from place to place, although the spatial variability has not been conclusively confirmed by in situ studies. In general, however, the values seem to be consistent with field measurements.

The electrical properties of snow are similar to those of a mixture of pure ice and air (Evans, 1965). Hence the dielectric constant depends on the snow density and is usually about 1.5 to 2.5; losses are very low.

The dielectric constant of oil varies between about 2 and 3, depending on the type of oil and the temperature (C-CORE, 1978; Von Hippel, 1954). The attenuation rate is quite low. The data on oils are quite incomplete with few measurements on crude oils

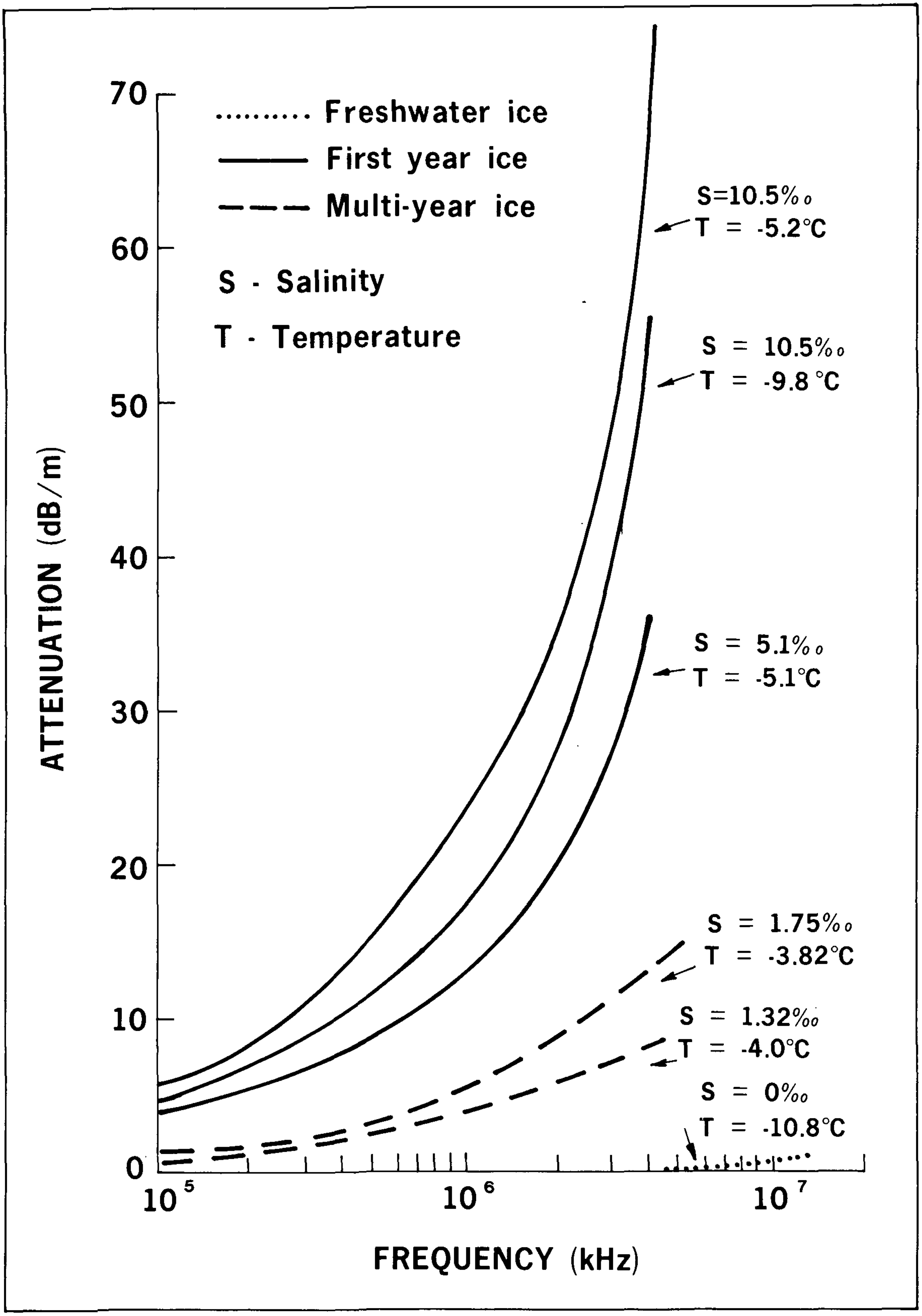

FIGURE 1 EXAMPLES OF ATTENUATION VERSUS FREQUENCY

at low temperatures, or on effects of weathering and oil-water mixtures. It appears that in most respects the electrical properties of oil are not significantly different from those of snow.

The dielectric constant of water at RF is about 80 (Royer, 1973), and the conductivity of sea water makes the losses very great. Hence, it can be assumed that for the frequencies of interest no significant amounts of RF energy will penetrate into sea water.

There are many types of electromagnetic (EM) equipment available using frequencies covering most of the EM spectrum. However, since a signal must pass through the ice twice in order to detect oil, frequencies below about 100 MHz must be used for most types of ice, as indicated in Figure 1. Even at this frequency, the wavelength in ice is approximately 1.5 m, and the resolution would probably be inadequate for detecting thin layers of oil. Use of much lower frequencies, as employed by the geophysical industry for delineating layered strata, would have even poorer resolution (Sinha, 1976).

Considerable effort is being directed toward the development of pulsed EM techniques to estimate the thickness of sea ice. The approaches being developed are designed to operate in the 10 to 500 MHz frequency range and use unconventional methods of improving the time resolution (i.e. thickness resolution).

The most highly developed systems are the impulse radars built by Geophysical Survey Systems, Inc. (GSSI), in Hudson, N.H. They have been used successfully from sleds to measure ice thickness (Campbell and Orange, 1974), and are being used routinely by Arctic operators. Several researchers have also used them successfully from helicopters (Kovacs, 1977; Rossiter et al., 1977). In these systems a broad-band monopulse is transmitted with a centre frequency determined largely by the antenna size. Units have been built with centre frequencies from 80 MHz to about 1 GHz, although lower frequency systems are most often used over sea ice.

Experimental work is being undertaken for Arctic Petroleum Operators Association (APOA) by GSSI and the U.S. Army Cold Regions Research and Engineering Laboratory to determine whether or not impulse radar can detect oil under sea ice (Dean, 1979). Initial tests used a small laboratory model and a very short-pulse time-domain reflectometry unit. Results were ambiguous, but promising enough to warrant further study. More recent work used a tank with dimensions of approximately 2.4 x 2.4 x 1.2 m in which ice up to 60 cm thick was grown using 14-16 parts per thousand NaCl solution.

Number 2 fuel oil was then injected under the ice, and returns were measured using a 700 MHz impulse radar system at the ice surface.

Reports indicate that an oil layer about 10 cm thick could be easily detected although thinner layers could not. Attempts have been made at enhancing the ice-oil reflection using Fourier techniques but the results have proved ambiguous. No studies have been made with fresh water ice so that uncertainty in the properties of the ice itself may preclude a clear understanding of the results. No measurements have been made on aging of the oil after it was injected, although some seepage of oil into the underside of the ice was noticed. It is not clear how applicable the results would be to a real environment, using a lower frequency and considering the natural variation in ice properties. However, these results are promising and indicate that further work is warranted.

The National Research Council (NRC) is developing an ice thickness sounder that transmits a pulse sequence with a pulse repetition frequency (PRF) of 1.28 MHz. In order to measure time delay, the phase of three harmonics of the PRF around 10 MHz is measured. This system is currently in the initial prototype stage and is to be tested for the first time in March 1979. It will probably have too coarse a resolution for the detection of oil and is designed to be used primarily from a helicopter; although, if successful, it may be possible to modify it for surface use.

A third approach, synthetic pulse radar, is being developed by MPB Technologies, Inc., Ste-Anne, P.Q., under contract to the Department of Transport (MPB Technologies, Inc., 1977; Finkelshteyn and Kutev, 1972). This technique is similar to impulse radar except that instead of transmitting a wide-band pulse only five Fourier components are transmitted. These signals are phased so that they form a short pulse when added together. The advantage of this approach is that a significantly better performance figure is theoretically possible, which would allow use over more attenuating ice, or with higher frequencies. Although theoretical work is promising, the system is still in the design and "break-board" stage of development and is not expected to be tested before 1980.

Higher frequency active systems have been tested over sea ice in the past (Chudobiak et al., 1974; Iikuza et al., 1976). Because of the very high attenuation of sea ice with higher frequencies, these approaches were not highly successful. The most promising application for use of EM techniques to detect oil is over multi-year ice or fresh water ice. In these situations the ice is relatively transparent to RF waves of 1 GHz or higher, although any equipment designed to operate at these frequencies would probably not be useful for types of ice, with greater attenuation which are prevalent offshore. (Ramseier et al., 1975).

A major study in ice thickness measurements is planned by C-CORE for March 1979 in the Beaufort Sea, with the following objectives: (i) to improve the performance figure of impulse radar and compare it with the NRC system; (ii) to sound a number of different types of ice in the Beaufort Sea; and, (iii) to measure the physical and electrical properties of the ice in situ. It is hoped that this program, funded by both government and industry, will reduce the number of unknown factors in sounding sea ice using EM techniques.

One of the unknowns in determining the usefulness of EM techniques to detect oil is the actual nature of the ice-oil interface. It is likely that the interaction of oil with ice will depend very greatly on the exact nature of both the ice and the oil. Experiments with first year ice have shown that oil will penetrate into the ice from below via the brine drainage channels (Wolfe and Hoult; 1976; Lewis 1976; NORCOR, 1975). Hence the ice-oil interface is likely to be one of grading properties rather than an abrupt discontinuity, and this fact would decrease the reflection at this interface. In relatively warm sea ice, such as that found in the Labrador Sea, it is likely that oil would percolate to the air-ice surface, and no interface would exist (Martin, 1976). On the other hand, fresh water ice would likely resist penetration of oil, and a clear ice-oil interface would be present.

If a clear ice-oil boundary is present, then it should be possible, at least theoretically, to unequivocally detect the presence of a layer of oil that is not very much thinner than the wavelength being used. This is because the dielectric constant at an ice-water boundary goes from lower to higher values, whereas for an ice-oil boundary it goes from higher to lower (Figure 2). Hence, the phase of the reflection in each situation would be opposite and, therefore, easily detected in the return signal.

It may also be possible to detect the presence of oil under ice by indirect inference. For example, Kovacs (1977) noticed significant spatial variation in ice thickness in the Beaufort Sea near Prudhoe Bay. He postulated that oil would fill the troughs where ice was thinner. Since a radar reflection in this situation would come primarily from the horizontal oil-water interface (which would be a good reflector), it might be a practical means of estimating the extent of an under-ice oil spill. Clearly much more work is required on the actual behaviour of oil under ice, and in the variations in ice thickness that occur in practice.

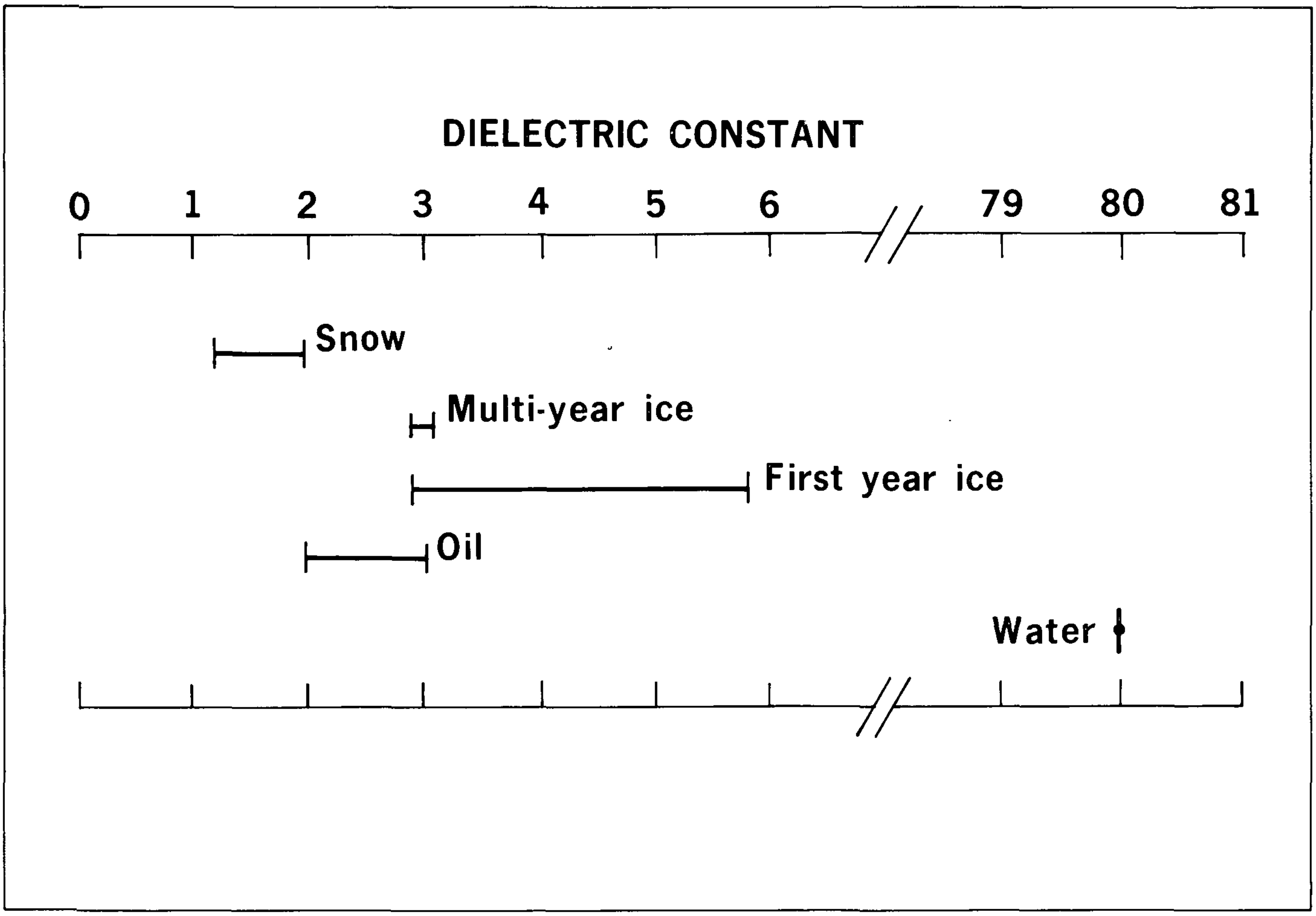

FIGURE 2 VARIATION OF DIELECTRIC CONSTANT: SNOW, ICE, OIL AND WATER

In conclusion, although EM techniques are not, in general, highly promising for the detection of oil under ice, considerable development is currently under way. The equipment is likely to be portable, easily used, and moderately priced. Although it is unlikely that these techniques will be useful for all conditions that would be encountered, it is possible that they would be practical tools for some situations, particularly fresh water ice, multi-year ice, and perhaps for regions in which the ice thickness varies considerably.

2.3 Acoustical Mode

In order to determine the feasibility of applying acoustic techniques to the problem of detecting oil in or under sea ice, a number of the acoustic properties of ice, oil and water were examined. The physical properties of ice (temperature, salinity and crystal structure) greatly influence the speed at which acoustic compressive waves travel through ice. Generalized data on the rate of propagation of acoustic waves as a function of temperature (based on the results of laboratory and field tests conducted by the Arctic and Antarctic Scientific Research Institute) are contained in Figure 3 (Gavrilo and Gusev, 1976). For sea ice, the velocity of compressive waves falls between 3 and 4 x 10^3 $m.s^{-1}$, with the higher values obtained for multi-year ice at low temperatures. This trend of decreasing velocity with higher salinity is also apparent in the Bering Sea ice measurements presented by Bogorodsky et al. (1975) shown in Figure 4.

The velocity of transverse acoustic waves is also presented in Figures 3 and 4. The velocities fall between 1.5 and 2.0 x 10^3 $m.s^{-1}$, considerably lower than values for the compressive wave velocities. For ice of salinity greater than 10 o/oo, shear wave velocity is practically independent of salinity and temperature (for ice of salinity greater than 10 o/oo, shear waves could not be generated).

There is a scarcity of data available in the literature on the acoustic properties of oil. Measurements of the velocity of compressive waves made at atmospheric pressure and 24°C for undiluted and unweathered hydrocarbon samples are reported on by Heigl (1973). These measurements together with impedances and reflection coefficients at 0°C are shown in Table 1. Values of impedance for sea ice, the skeletal ice/oil layer and sea water are taken to be 2.95 x 10^{-6}, 1.80 x 10^{-6} and 1.54 x 10^{-6} respectively (C-CORE, 1978).

Heavy crude oil is virtually identical to water so that the reflection coefficient is zero presumably making it undetectable acoustically. Light oils present some mismatch, but even such a highly refined type as varsol exhibits a coefficient to

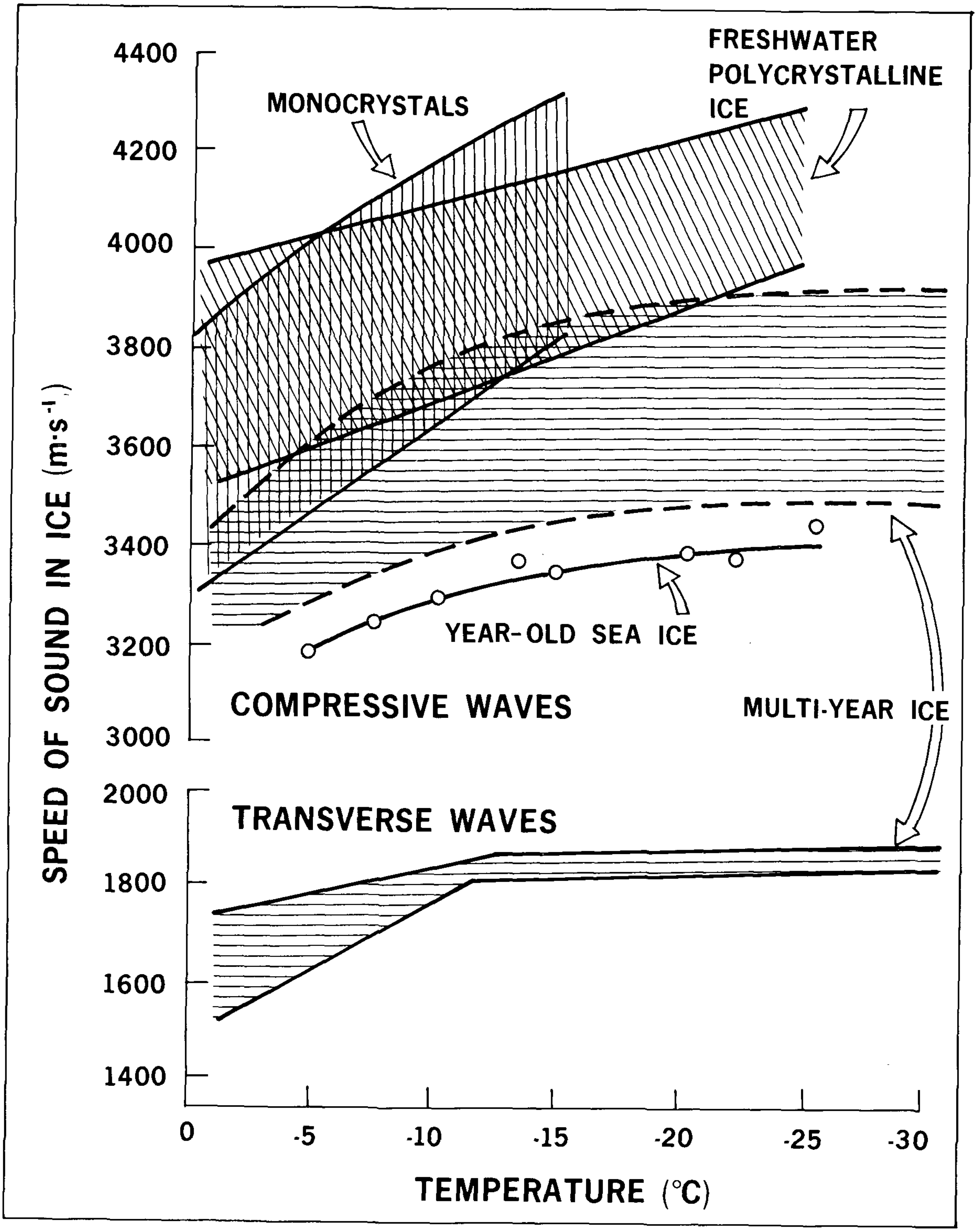

FIGURE 3 GENERALIZED TEMPERATURE DEPENDENCIES OF THE RATES OF PROPOGATION OF COMPRESSIVE AND TRANSVERSE ACOUSTIC WAVES IN ICE
(after Gavrilo and Gusev, 1976)

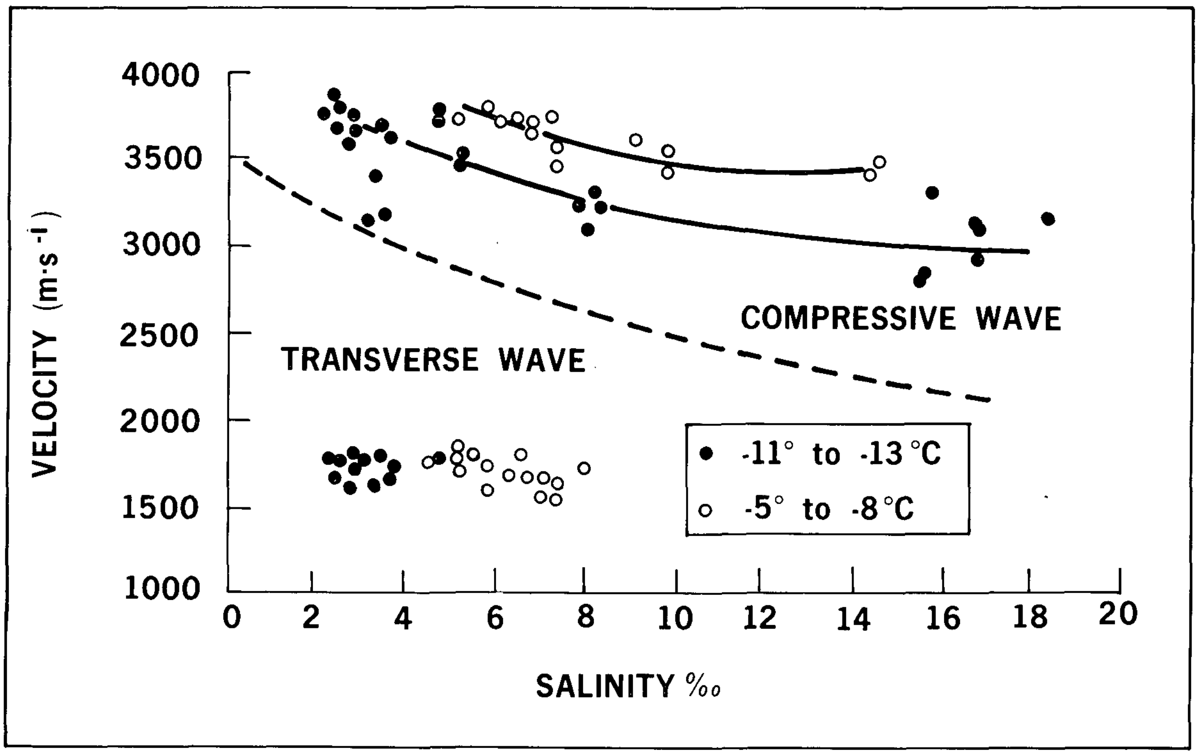

FIGURE 4 VELOCITY VERSUS SALINITY FOR COMPRESSIVE AND TRANSVERSE WAVES
(after Bogorodsky et al., 1975)

TABLE 1 ACOUSTIC PARAMETERS OF VARIOUS OILS
(after Heigl, 1973 and King, 1967, with changes)

Type of Oil	@24°C ρ	@24°C c	@24°C Z	@0°C ρ	@0°C c	@0°C Z	R_{io}	R_{so}	R_{ow}
Marine Bunker	961	1489	1.43	975	1575	1.54	-.31	-.08	0.00
Varsol	808	1299	1.05	824	1385	1.14	-.44	-.22	.15
South Louisiana Crude	844	1489	1.43	860	1442	1.24	-.41	-.18	.11

ρ (rho), (kg/m^3) is the oil density
c (m/sec) is the velocity of sound in oil
Z represents the impedance
R_{io} is ice to oil reflection coefficient @ 0°C
R_{so} is skeletal layer to oil reflection coefficient @ 0°C
R_{ow} is oil to water reflection coefficient @ 0°C

water of only 0.15. Ice to oil coefficients are better but these will be reduced, probably to undetectable levels, by the matching effect caused by oil uptake in the brine channels. Gas pockets, on the other hand, are ideal acoustic targets with reflection coefficients from ice approaching unity. Consequently, gas should be easily detectable acoustically so long as there are sufficient quantities present.

Heavy oils might be detected acoustically if the uptake of oil into brine channels were to alter the physical properties of the ice which might lead to differences in the acoustic properties as well. Because of the differences in oil and water in terms of viscosity, thermal conductivity, etc., the oil/ice layer may be altered mechanically and any resulting anomalies in the normal properties of the ice may be reflected in an acoustic analysis of the interface. This is clearly only speculation at this stage, and experiments would be required to determine whether such changes in acoustic effects would occur.

The attenuation of acoustic compressive waves in natural ice has been investigated by a number of researchers, (Hashimoto et al., 1964; Langleben, 1969; Langleben and Pounder, 1970; Bogorodsky and Gusev, 1973; Gavrilo and Gusev, 1976). A summary of their results is presented in Figure 5. The variety in measurement techniques, direction of sound propagation and the variability in the characteristics and

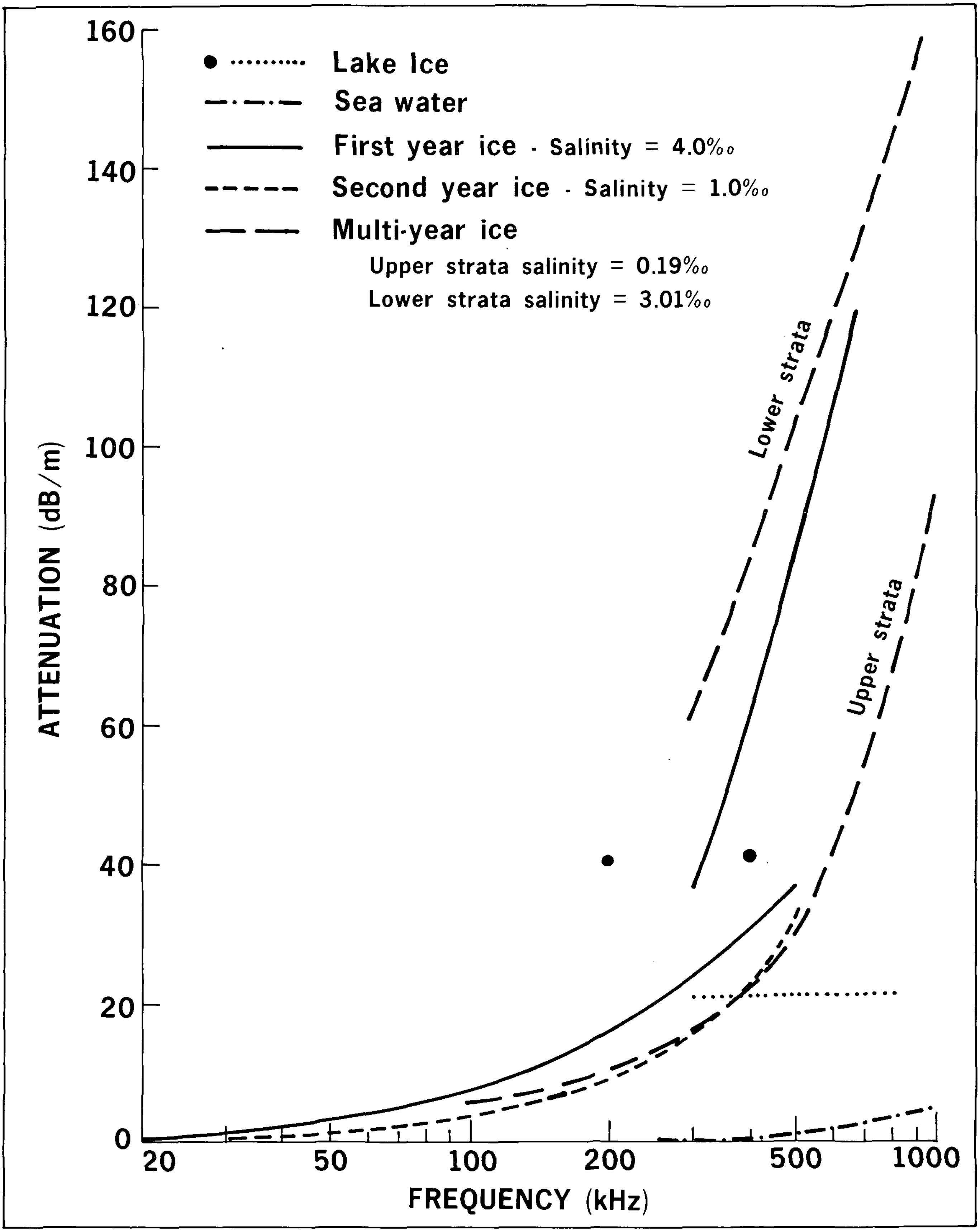

FIGURE 5 ATTENUATION OF ACOUSTIC COMPRESSION WAVES AS A FUNCTION OF FREQUENCY

temperatures of the ice limit direct comparison between the results. However, it can be seen that for frequencies up to several hundred kHz, the attenuation is not high for either freshwater ice or sea ice.

The attenuation of compressive waves in sea water is even lower. At frequencies below 400 kHz, attenuation is less than 1 dB/m (Macphee, 1976). Experimental results indicate that the attenuation in light oils is similar to that of water, whereas the more viscous oils are highly attenuating. This is illustrated in the relative values of attenuation contained in Table 2. These values were calculated for sound path distances of 15 m during a study conducted at BATELLE Columbus Laboratories to evaluate techniques suitable for the detection of oil levels in the tanks of sunken vessels (Fox et al, 1978).

Acoustic techniques have been used successfully for hydrographic surveying carried out through both sea ice and freshwater ice (Kerr, 1977). The attenuation of acoustic compressive waves in ice is low to moderate up to several hundred kHz. However, because of the large acoustic mismatch at the air/ice boundary, it is difficult to couple energy into the ice with non-contact devices which would be desirable for an expedient means of detecting oil under ice. There is a large mismatch in acoustic impedance at either an ice/water or an ice/oil boundary. However, because of small differences in the acoustic impedance of oil and water, it may be difficult to distinguish between these two liquids acoustically.

An important consideration in evaluating the feasibility of acoustic techniques for detecting oil in or under ice is that the acoustic wavelengths which can be used are in the order of centimetres and therefore provide the necessary resolution. The maximum practical frequency is limited by the attenuation and from Figure 5 appears to be approximately 100 kHz which leads to a resolution of about 0.5 cm (assuming that resolution is about 1/3 the wavelength). Discrimination of oil may be further aided by the fact that transverse waves will propagate through the ice but not through either oil or water. Although these waves travel more slowly than compressive waves, it may be possible to uniquely discriminate between them (Caulfield and Liron, 1977).

2.4 Optical Mode

Optical properties of sea ice, although not extensively documented, are well enough known to allow one to essentially rule out any scheme that requires transmission of electromagnetic radiation in the ultra-violet-visible-infrared spectral region down through the ice from the surface and back up through again after interaction with oil at

TABLE 2 ATTENUATION IN FLUIDS AT VARIOUS FREQUENCIES (after Fox et al. 1978).

Fluid	1 kHz	50 kHz	100 kHz	200 kHz	500 kHz	1 MHz
Water	1.24×10^{-4}	3.11×10^{-3}	1.24×10^{-2}	4.97×10^{-2}	3.11×10^{-1}	1.24
20-weight motor oil	5.28×10^{-4}	1.32×10^{-2}	5.27×10^{-2}	2.10×10^{-1}	1.32	6.53
Diesel oil	4.84×10^{-4}	1.21×10^{-2}	4.84×10^{-2}	1.93×10^{-1}	1.21	4.88
Fuel oil	7.58×10^{-3}	1.89×10^{-1}	7.50×10^{-1}	3.03	18.9	75.9
Air	1.71×10^{-1}	4.27	17.1	67.9	426.7	1706.8

the oil-ice interface. Absorption, scattering, or reflection from the oil could be used effectively for detecting the oil if the radiation could reach it, but attenuation will be so severe in the ice itself that prospects are dim for ice thicknesses of more than a few centimetres. Least attenuation through sea ice in the visible range occurs at approximately 500 nm, where it is 0.01 cm^{-1} in first year ice under optimum conditions (Untersteiner, et al., 1974; Roulet et al., 1973; Goodrich, 1970).

The attenuation coefficient α is found from Beer's Law which expresses the intensity I, after passage through distance x, of radiation originally of intensity I_0 as:

$$I(\lambda) = I_0(\lambda) \exp\left[-\alpha(\lambda)x\right]$$

The notation here emphasizes the wavelength (λ) dependence in the expression. It is seen that, at best, passage of light down and back through a one meter thickness of ice would result in a reduction in intensity such that the returning beam would have approximately 15 percent of the intensity of the incident beam at the surface.

One must realize that this figure does not yet include two kinds of effects which will reduce the intensity of the returning beam further, in some conditions by orders of magnitude. First is the fact that realistically one must expect natural ice to show much stronger attenuation. Older ice with bubbles, cavities, brine inclusions, fractures, etc. will suffer severe attenuation through scattering. Thicker ice, or especially ice with snow cover (even though very thin) will show far greater extinction. Attenuation at wavelengths both shorter and longer in the visible and infrared regions is stronger, increasing to either side. Attenuation in the ultraviolet is less well documented than at longer wavelengths (Goodrich, 1970; Onaka & Takahashi, 1968), but it is clear that transmission through sea ice is not sufficient to allow use of ultraviolet excitation of molecular fluorescence or of UV-excited Raman scattering, both of which have been used for detection of oil floating on ice-free water surfaces.

The second kind of effect that will decrease further available signal at the upper surface of the ice is the interaction with oil of the probe radiation which manages to make its way down through the ice. Whether one thinks of absorption followed by fluorescence, of Raman scattering, or selective reflectance, or other processes, all are processes that are less than 100% efficient (often far less, perhaps one photon in 10^6 to 10^8 for Raman scattering, for example). Furthermore, these photons which have resulted from interaction with the oil will subsequently travel in many directions. The emission or scattering may not be isotropic, but neither will it be confined to the backward direction. That is, of the emitted photons, only a small fraction will travel back toward a detector at the surface within a collection angle defined by detector size and distance from oil to detector.

One possibility of a non-spectroscopic, optical technique that does not require penetration of a probe beam through the ice is radiometry in the infrared or microwave spectral regions. The idea would be to detect temperature differences, at the ice-air interface, between regions having oil under the ice and other regions without an oil layer between water and ice. This is based on the fact that the thermal conductivity of oil is about 6×10^{-2} times that of ice; consequently, heat transfer from the ocean water to the colder ice-air surface will be less through vertical paths including oil layers than through ice alone. Presumably a thin air layer at the ice surface could support a temperature gradient such that the ice surface would be cooler over oil than it would be in places where heat flow suffers no impediment from a layer of insulating oil.

Current capability in microwave radiometry techniques can detect temperature differences with approximately 1°K sensitivity (Gjessing, 1978). Whether temperatures differences exceeding this can occur depends on defining the heat transfer processes taking place. Some of the obviously important parameters, in addition to thermal conductivities of oil and ice, are thicknesses of oil and ice layers and the total temperature difference from the ocean water through to the air. The viability of such a technique would be mitigated by the following also:

1) Heat transfer through an oil layer need not be only by conduction. Convective transfer might decrease the expected surface temperature difference, and as

discussed earlier, could possibly increase the heat transfer rate given sufficiently large thicknesses of oil.

2) Radiation reflected from the surface, rather than emitted from it, would interfere. A practical device would necessarily use some means of discrimination.
3) Varying thicknesses of ice alone would cause temperature differences in exactly the same way as expected from oil layers.
4) Different kinds of ice will show varying thermal conductivity depending on age, brine content, and its microscopic structure as determined by its history.
5) Varying thicknesses of snow cover, patches of open water, and time varying wind speed all will complicate interpretation.
6) Emissivity of the ice surface affects the radiated energy too; the flux is not determined by temperature alone. Varying emissivity might be caused by non-uniform salinity, algae content, age of the ice, and snow cover (Apinis and Peake, 1976).
7) Atmospheric absorption of the emitted radiation before it reached detectors might cause difficulties. This is probably a less important objection because "windows" occur in the infrared atmospheric absorption spectrum and the microwave region is not severely affected apart from some well-known regions which could be avoided.

Work by SED Systems Limited, Saskatoon, indicated that it should be theoretically possible to detect oil under ice (Philip A. Lapp Ltd., 1975). This company built and tested an 800 MHz radiometer under contract to Department of Transport (Robar and Wood, 1974) but oil was never used in the testing. Their current thinking is that if oil were injected under a layer of ice that was being monitored, the change would be detected. However, if an unknown piece of ice was monitored, it would be impossible to say whether or not oil was present in or under it.

Based on these considerations, the use of radiometry as a detection technique is speculative, and although infrared and microwave radiometry are well established technically, it would appear that such a method does not warrant further consideration.

2.5 Nuclear Mode

2.5.1 Introduction. In the literature review undertaken for this study, a number of references to nuclear well logging were noted. Logging techniques are used in the petroleum industry to delineate the structure that the borehole penetrates. Since nuclear well logging techniques càn distinguish between fresh and saline water, oil and gas, it was thought that such a method might have application to the detection of oil in or under ice. The application of nuclear techniques in the petroleum industry is described in Hilchie, (1977) and Caldwell, et al. (1977).

In theory, any nuclear particle could be used for detecting the presence of oil since all have some characteristic interaction with carbon or other constituents of oil. However, particles such as mu or pi mesons are hard to produce, especially in a field environment, and the more common charged particles such as protons, electrons (beta rays), alpha particles (a helium nucleus of two protons and two neutrons) all have a high probability of interaction with the electron cloud, and the intensity of any charged particle beam is quickly reduced by absorption or scattering and is severely depth limited.

Of the uncharged particles, the more common of which are neutrons and gamma rays (X-rays are included in the latter), gamma rays interact very well with matter either by ejecting electrons from the target material (photoelectric effect), scattering off the electron but not ejecting it (Compton effect), or producing electron-positron pairs (pair-production). Again these effects reduce the gamma ray beam leading to a reduction in the probability of any interaction between the gamma rays and a hydrocarbon nucleus. Although very intense gamma ray sources are available which might alleviate this attenuation problem, it is not clear that gamma rays will interact differently with ice/water and ice/oil to the degree necessary to differentiate between them.

Neutrons, on the other hand, have little interaction with electrons but have a high probability of interacting with nuclei and therefore would be a better irradiating source. Neutron sources are currently being used in well-logging (as outlined by Caldwell, et al., 1977) and can differentiate between oil and water. Neutrons are used to excite the nuclei of the material surrounding the bore hole and then the gamma ray energy spectrum from the decaying nuclei is measured. The neutron source and gamma ray detectors are located in a carriage that is generally 5 to 9 cm in diameter and 2-3 m long. The rest of the equipment, which includes the power source, winch, etc., is mounted on a truck.

Pulsed neutron sources (as opposed to steady-state sources) with intensities of 3×10^8 neutrons s^{-1} are used in this technique and are generated by accelerating either protons or deuterium and impinging them upon a target with a light nucleus (lithium, tritium or deuterium). While neutron energies up to 30 MeV can be produced with this technique (Gray, 1972), 14 MeV neutrons are currently being used (Hilchie, 1977). This energy is determined by the characteristic reaction used to produce the neutrons.

Measurements indicate that at 14 MeV, ninety percent of the neutrons slow to thermal energies at about 0.025eV and are absorbed within a distance of about 20 cm from the source. The gamma rays subsequently emitted are detected by using a scintillation spectrometer (sodium-iodide crystal type detector) which measures the energy spectrum of the returning gamma rays. The spectrum from excited carbon nuclei has three characteristics peaks at 3.42, 3.93 and 4.44 MeV in an energy region called the carbon window as shown in Figure 6. The spectrum for oxygen shows similar peaks at 5.11, 5.62 and 6.13 MeV. This oxygen window can be used as a normalization for the gamma rays in the carbon window and has implications for the detection of oil under ice using neutron radiation techniques.

2.5.2 Background Theory and Predicted Capability. The probability that a particle will scatter off a given target nucleus is related to a quantity called the cross-section (defined as the effective area presented by the target particle to the bombarding particle) measured in barns (1 barn = 10^{-24} cm^2) and denoted by σ. The cross-section can be roughly related to a characteristic distance called the range of the incident particle by $R = \frac{1}{N\sigma}$ where N is the density of scatters which for neutrons is usually the number of protons in the target material.

The cross-section of neutrons depends on the energy of the incident beam as shown in Figure 7. The equation describing the curve is not accurate for thermal energies (0.025eV) due to special resonance effects of low energy neutrons which increases the cross-section to 80 barns.

The incident neutron beam intensity is attenuated according to

$$I(x) = I_o e^{-x/R}$$

where I_o is initial intensity

$I(x)$ is intensity at some distance x from the source

R is the range of the incident particle.

The present situation in neutron well-logging is described by Caldwell et al. (1977). He presents results from a simulated well-logging field experiment using a water-sand mixture and shows the probability distribution of gamma ray intensity at the detector as a function of distance from a neutron source (Figure 8). The curve may be approximated by the derivative of a Gaussian distribution and can be expressed as:

$$P(x) = Axe^{\frac{-1}{2}\left(\frac{x}{x_o}\right)^2}$$

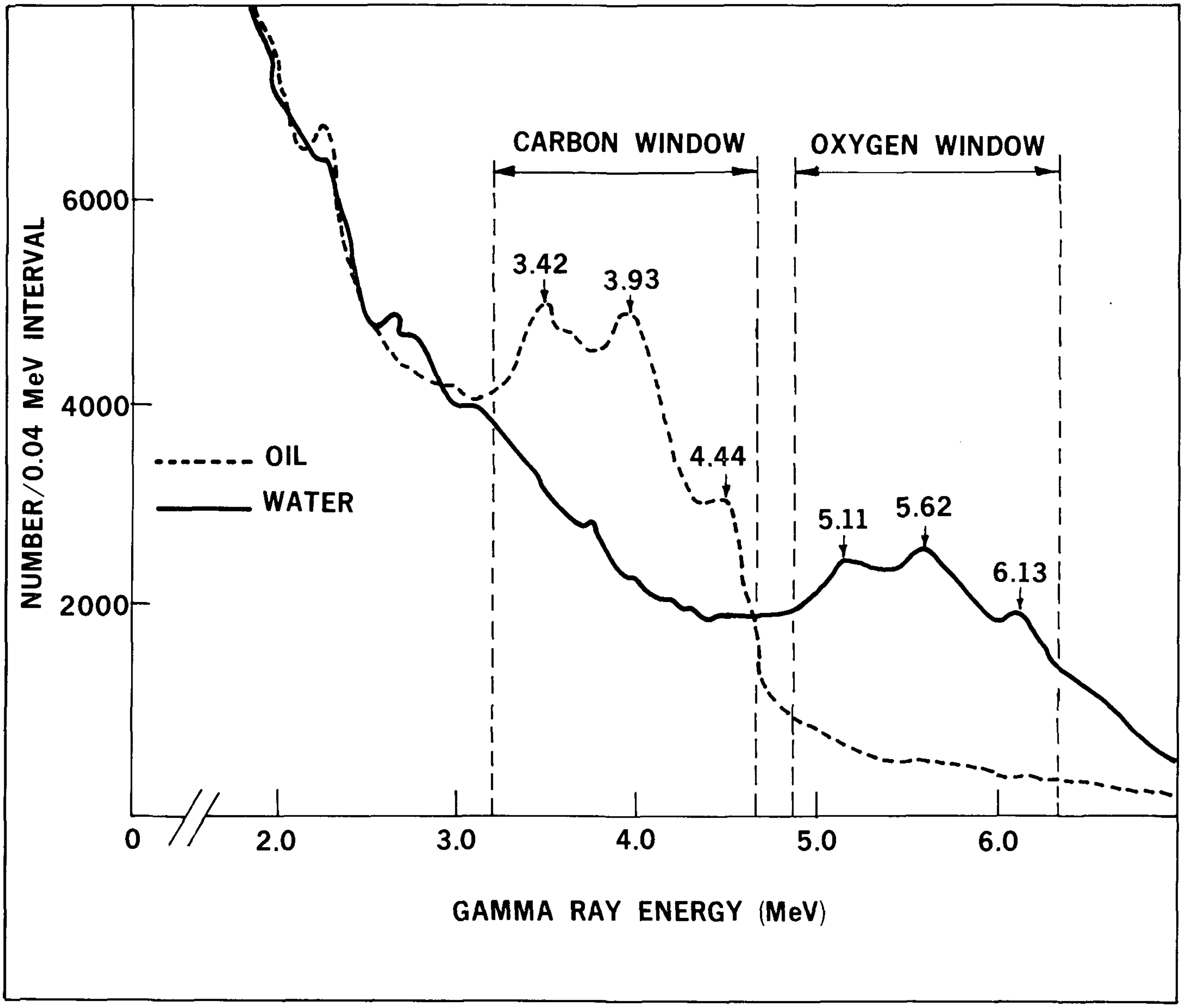

FIGURE 6 CARBON-OXYGEN SPECTRA IN OIL AND WATER (after Hilchie, 1976)

where A is a proportionality constant with units of $(\text{length})^{-1}$

For the well-logging experiment in which the neutron energy was 14MeV, the maximum of the curve, X_o was approximately 12 cm.

The intensity of gamma rays at some depth x, denoted by $I_\gamma(x)$, would be scaled by the neutron intensity (I_n) according to

$$I_\gamma(x) = BI_n P(X)$$

$$= BI_n Axe^{-\frac{1}{2}(\frac{x}{x_o})^2}$$

$$= CI_n xe^{-\frac{1}{2}(\frac{x}{x_o})^2}$$

It has been estimated that the maximum depth from which a gamma ray return can be detected in ice is 40 cm at a neutron energy of 14MeV and intensity of 10^8 $n{\cdot}s^{-1}$ (Mills, 1978). In recent years, it has been proposed to increase neutron intensities to 10^{10} $n{\cdot}s^{-1}$ for uranium logging (Bivens, et al., 1976). Considering this increase of 10^2, the resulting increase in detection depth in ice is estimated from the above equation to be 15 cm for a total depth of 55 cm. A further increase of 15 cm in detection depth can be obtained if the detector sensitivity is increased by 10^2 (Caldwell, et al., 1977). By combining these increases in neutron intensity and detector sensitivity, the detection depth would be increased to 66 cm.

It is also possible to increase the detection depth by increasing the neutron energy and thus neutron penetration depth. The deeper penetration of the neutrons is accompanied by a decrease in cross-section and an increase in range. If the penetration depth and range are assumed to be linearly related, it is possible to determine the effect of increased energy on penetration depth. For 14MeV neutrons, the range is 22 cm as calculated from Figure 7 and the penetration depth is 12 cm from Figure 8. Current neutron techniques may conceivably be extended to neutron energies up to 30MeV which would correspond to a range of 48 cm and a penetration depth of 26 cm. The maximum gamma ray detection depth for a neutron energy of 30MeV is then found to be 94 cm. However, it is known that 14MeV neutrons lose their energy non-linearly so that presumably higher energy neutrons would as well. Consequently, the gain in depth would likely be far less than that predicted by a linear relationship. Moreover, the gamma rays, spreading out isotropically as they do, will arrive at the detector in smaller quantities, thus effectively decreasing the detection depth. If the 10^2 increases in detection

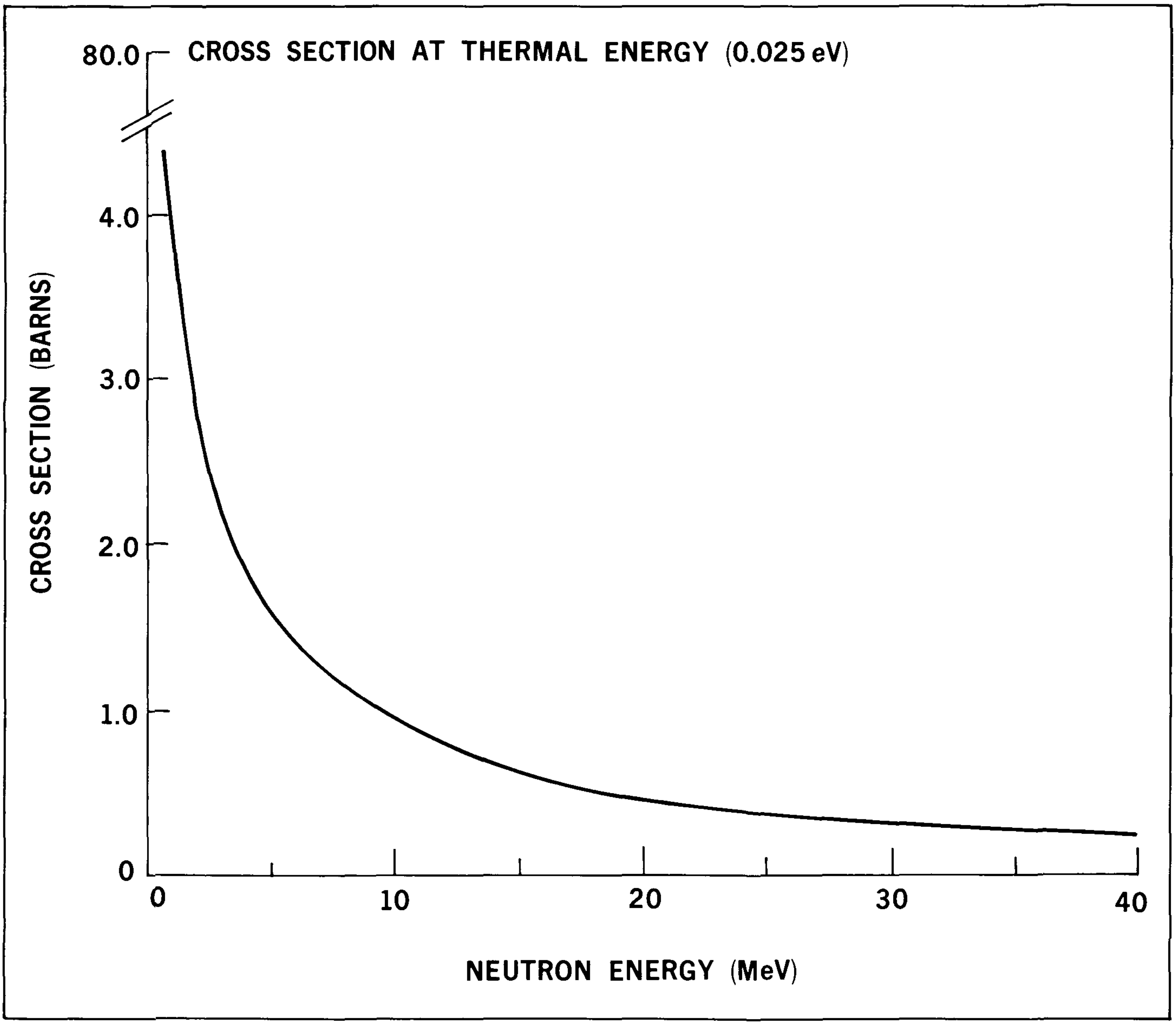

FIGURE 7 CROSS SECTION OF NEUTRONS VERSUS INCIDENT NEUTRON ENERGY

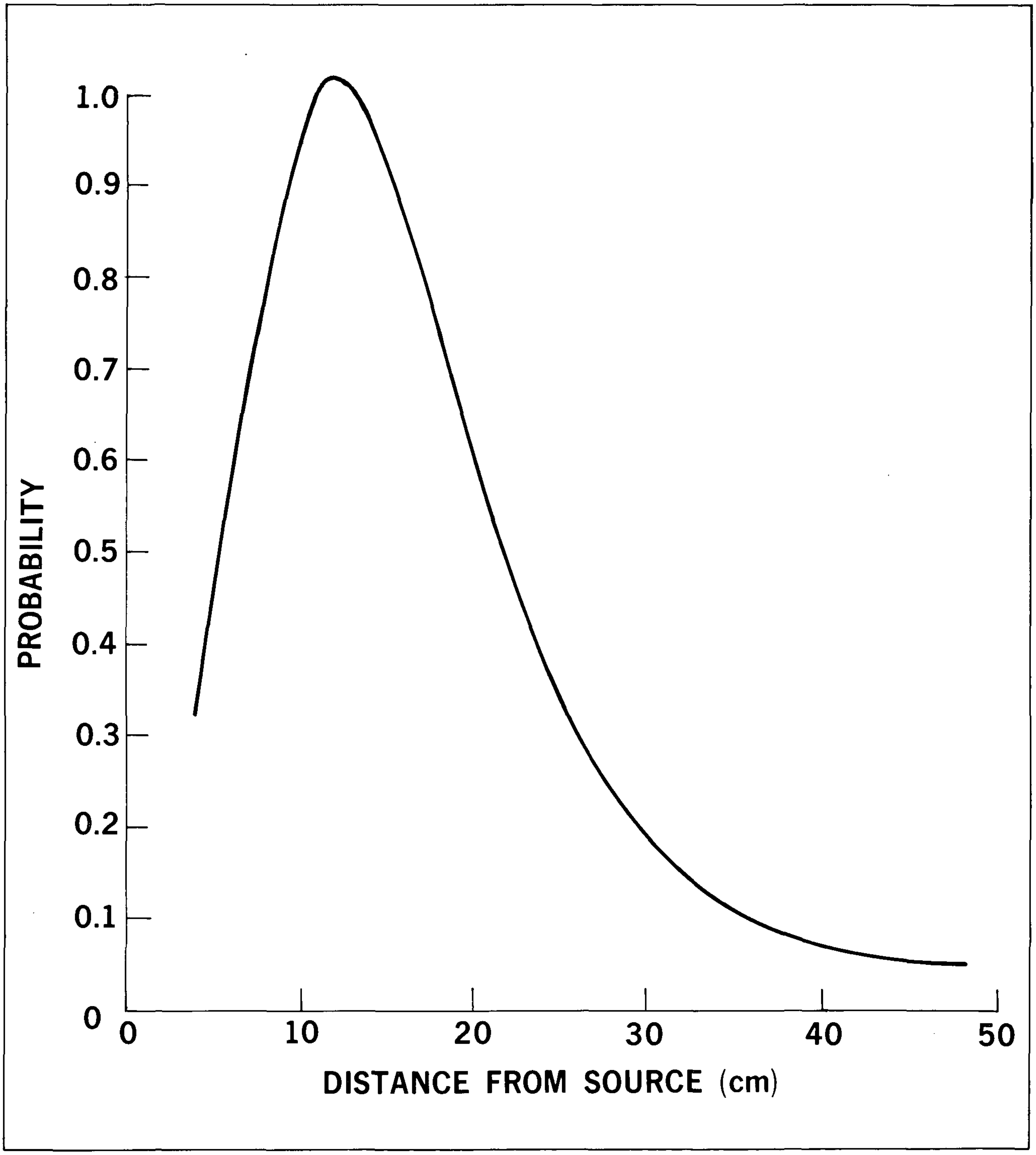

FIGURE 8 PROBABILITY DISTRIBUTION OF GAMMA RAY INTENSITY AT VARIOUS DISTANCES FROM THE NEUTRON SOURCE (after Caldwell, et al., 1977)

sensitivity and neutron intensity and the increase in neutron energy to 30MeV are all considered simultaneously and the assumption of a linear relationship is maintained, the maximum detection depth is calculated to be approximately 150 cm.

However, while an increase in neutron sensitivity of 10^2 may be a matter of basic development and while a similar increase in detector sensitivity may be also quite feasible, a substantial increase in neutron energy must be viewed with some reservation, and certainly a doubling of the present energy would appear to be unrealistic especially in terms of a mobile field operation. The increase to 30 MeV is discussed here simply to show what the upper level of penetration would be theoretically if the energy could be boosted to that level. Thus it appears that whatever depth could be achieved given realistic modifications to existing equipment, it will be fairly shallow (probably less than 1 m) and substantial increases may be possible only with considerable improvements in the equipment.

2.6 Gas Sniffer Mode

If hydrocarbons were to pass from beneath an ice cover to the air above, it might be possible to detect their presence with a gas analyzer (sniffer). Such devices, which operate on the principle of detecting the decrease in energy in the incoming radiation due to the presence of an absorbing target gas, may be used to detect very low concentrations (in the order of a few parts per trillion) of foreign gas in the atmosphere. A gas sniffer could be operated on the ice sheet or be moved along a short distance above the sheet by a helicopter.

The success of such a device in detecting oil under or in ice would be contingent on the diffusion of hydrocarbons through an ice cover. While it is doubtful that any diffusion would occur through solid glare ice, it may be possible for diffusion to occur through micro-cracks in warmer saline ice.

In order to determine whether hydrocarbons would diffuse through an ice cover, some experimental work would have to be conducted. A search of the literature failed to turn up any documentation of such fundamental work. It is expected that if diffusion occurred, the rate of diffusion would decrease with time, as the more volatile components of the oil because of their higher vapor pressures, would be released early in the spill, and the gas sniffer technique would be thus more effective during that time.

The uptake of oil in brine channels has been well documented. Given sufficient time, the oil will surface through these channels and be detected visually. The speed of such a process would depend on whether the ice was first year or multi-year, but even in the latter case, evidence indicates that the oil would surface by early autumn if the spill occurred the previous winter or spring (Milne, et al. 1977). In the case of first year ice, experiments indicate that oil spilled under 1.5 m ice during winter would begin to surface by April (NORCOR, 1975). It is also possible that oil would surface through tidal cracks in the case of landfast ice or gas-induced cracks if gas accompanied the spill. While no experimental work has been documented on the possibility of breakage of the ice cover by gas, Topham (1977) developed an analytical treatment which suggests that this could happen. If such cracks were evident, it is possible that sufficient oil would be visible at the surface to preclude the use of any detecting technique.

The only known related use of a gas sniffer to detect oil in ice conditions is that of NORCOR during the Beaufort Sea studies program during 1975 (NORCOR, 1975). In that work, the device was actually used to detect oil on the ice surface under snow. Some success was attained in that application; however, doubts have been expressed concerning the success of the device when applied to detecting oil under the ice (Brown, 1978). In the experiment referred to here, it was found that the oil that had been trapped under the ice had weathered insignificantly by the time it surfaced in the spring. Any weathering that did occur was probably due to dissolution into the underlying water.

While a gas sniffer would appear to be a plausible technique asssuming some hydrocarbons actually did travel through the ice cover, and is low-weight and available commercially, it does suffer from the disadvantage of not being able to distinguish between hydrocarbons diffusing through an ice cover and ambient hydrocarbon levels of similar or larger concentrations which emanate from fuel used for transport over the ice. Since it is entirely likely that such ambient levels will always exist during the search for spilled oil (whether the mode of travel be snowmobile or helicopter), it would appear that the gas sniffer technique would not be a reliable tool for detection under such circumstances.

2.7 Mechanical Mode

In an attempt to evaluate the performance of mechanical detection modes a survey of ice augers and similar devices was undertaken to ascertain basic operational characteristics such as rate of penetration, weight and mobility. There are several motor driven portable augers on the market and some of these claim to have drilling rates in the order of 1-2 m/min. One particular manual auger is said to have a drilling rate in the order of 5 m/min. Such drilling rates are more applicable to shallow holes from 1-2 m deep and should decrease signficantly for thicker ice. Such augers can usually be handled by one or two people and are relatively inexpensive, with costs in the order of a few hundred dollars.

A novel method of penetrating an ice cover is described by Parsons and Hopkins (1977). The method involves the reaction of ice with such gases as ammonia, hydrogen chloride, sulphur dioxide or volatized ammonium chloride. The gas is contained in a standard tank and is impinged onto the ice through a connecting hose and nozzle. Drilling rates in the order of 2 m/min have been attained using ammonia as the reactant gas. The diameter of the hole drilled in the ice depends upon the size of the nozzle used. During experimental and developmental phases, nozzles ranging from 1-9 mm were used and resulted in hole diameters (due to the effects of gas velocity) up to 30 mm. While the method has the capability of drilling much larger diameter holes, for the purposes of oil detection and in the interest of system efficiency, such small diameter holes would be suitable. The total weight of the system, including a heating unit to maintain vapor pressure, is presently less than 50 kg (for a single tank) but further development could decrease this. A single 7 kg tank of ammonia is estimated to last approximately 2 hours at the flow rates used in the tests.

While this technique is still at an early stage of development, it does pose some intriguing possibilities. For instance, the penetration tube through which the chemicals are pumped might also be used in reverse to sample the fluids lying beneath the ice sheet. It would then be possible to integrate the penetration, sampling and analysis functions into a single automatic operation, thus achieving significantly higher throughputs than with a mechanical augering system of comparable penetration rates. Moreover, the system could be deployed from a vehicular platform, more or less automatically.

While much of this is speculation, it is important to realize that the potential of chemical drilling/sampling may extend well beyond that of simple mechanical augering.

3 DEVELOPMENTAL CONSIDERATIONS FOR THREE CANDIDATE DETECTION MODES

3.1 Introduction

In this section, the three candidate detection modes - radio frequency, acoustic and nuclear -which might possibly be employed to detect oil in and under ice are further examined and compared. Since actual feasibility is a major issue in each case, far more time was spent on examining feasibility in detail from an engineering point of view than had been originally intended. Correspondingly, far less time has been spent on considering full-scale hardware issues. This was not so much a matter of time as the fact that the extreme uncertainty over feasibility, and therefore over the eventual form of any potential instrument, made a detailed consideration speculative at best.

3.2 Resolution, Signal Processing and Multi-Time Analysis Considerations

The resolution of a detection technique is of obvious concern when evaluating the ability of radiation to detect oil in or under ice. In an elementary layered model (snow, ice, oil, water) this is simply the closest possible spacing which can exist between two interfaces that can still be distinguished on the return. It must be emphasized that reflections do not occur from gradual interfaces. Sea ice may have a skeletal layer at the bottom (resulting from oil uptake in brine channels) which would likely act as a very good impedance matcher to either water or oil beneath, not allowing reflections to occur (because effectively there would be no definable interface). Resolution is proportional to the wavelength of the radiation in the layer which is being resolved. The exact proportionality constant depends on a number of signal processing parameters such as the signal-to-noise ratio and the characteristics of the receiving filter, etc., but a reasonable rule-of-thumb estimate is on the order of one-third. That number will be used for comparison purposes, while at the same time recognizing that it may vary by as much as a factor of three or so either way. It should be pointed out that while fine resolution is likely needed to detect thin layers of oil, it also allows smaller impurities in the ice to act as scatters, thereby increasing the reverberation or clutter and degrading the signal-to-noise ratio. This will impair the detection ability of the instrument. It is particularly troublesome in that it is characteristic of the medium and is not improved by increasing the signal strength as reverberation or clutter then increases as well.

As each pulse is emitted and the returns detected, a trace is developed which can be recorded, displayed on an oscilloscope or graphic recorder or digitized as input into a computer. The resulting record is then analyzed always with an eye to identifying some characteristic set of signatures which are able to reveal what is occurring in the region being irradiated. Very sophisticated processing is often applied and can be remarkably successful at consistently detecting features not at all obvious on the original record (at least to the untrained eye). The key is not to understand the physical interaction occurring between the radiant energy and the underlying material, but to analyze and categorize the various kinds of return signatures and attempt to correlate them with the phenomena of interest. Interactions which occur at material interfaces are extremely complex and difficult to predict (although often explainable with hindsight). Work on the acoustic classification of sediments using such sophisticated processing techniques as pulse-to-pulse correlation and analysis of percentage net energy reflected from an interface has been extremely successful (MacIsaac and Dunsiger, 1977). Similar approaches might be applicable to the detection of oil in or under ice.

Even if a detailed signature analysis proves to be generally unsatisfactory because the variations from point to point on the ice undersurface simply override any differences due to oil, multi-time approaches may be useful in particular circumstances. With this technique, surveys are carried out periodically at exactly the same points. Thus while signatures may vary strongly from point to point they should be stable or changing progressively at each point. An abrupt change could then be indicative of oil. The question then would be one of determining how often it would be necessary to sample each point in order to detect such changes (if they were apparent at all).

3.3 Instrument Configurations

3.3.1 Radio Frequency Mode. As pointed out in a previous section, three radars are currently under development in Canada for use in ice thickness measurement. The requirements for an actual "oil-under-ice" radar itself (as opposed to the processing of the radar return) are very similar to those of the ice thickness radar, except that resolution is undoubtedly even more critical.

A functional block diagram of the impulse radar as used by GSSI for ice surveys appears in Figure 9. The radar generates wide band pulses centered at 400 or 80 MHz. The antenna is used both for transmission and reception and the results are displayed on a graphic recorder. If any reliable detection of oil under ice proves to be possible, an analysis box can be easily added to scan for oil signatures and alert the

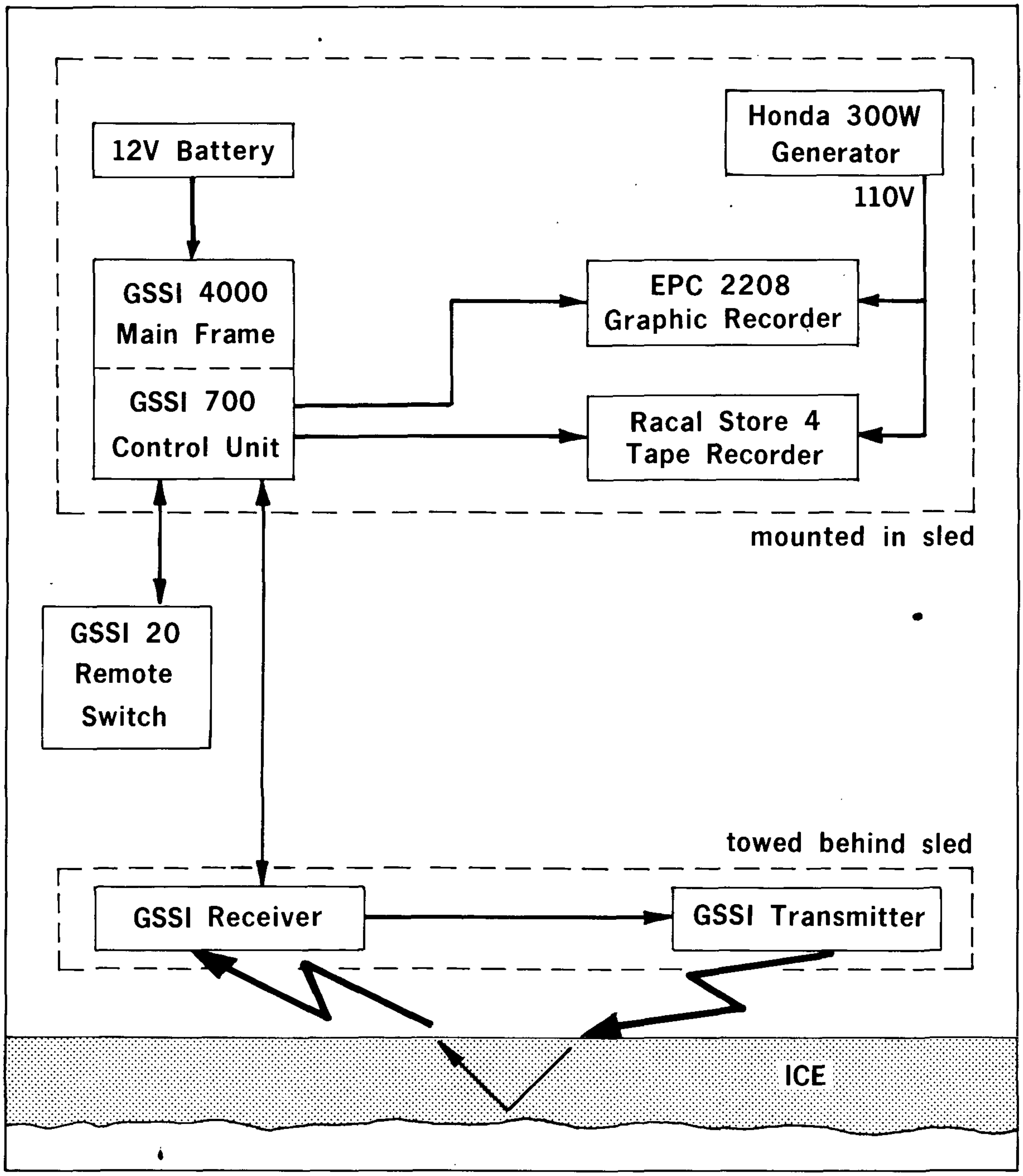

FIGURE 9 FUNCTIONAL SKETCH OF GSSI IMPULSE RADAR SYSTEMS FOR USE ON ICE SURFACES

operator to any potential oil spills. The radar is quite portable, having already been deployed in the field several times.

The price of an operational radar is approximately $30,000. Development costs should be minimal, being dominated essentially by the cost of laboratory experimentation and field trials. Field tests could be incorporated with existing work concerning ice thickness measurement.

3.3.2 Acoustical Mode. It is possible to characterize an acoustic "oil-under-ice" instrument only in very general terms. The difficulty is that the detailed system engineering must wait on the outcome of experiments to determine if the concept is feasible at all, and if feasible, what the parameters should be. The key question is the frequency or range of frequencies that should be used. Transducers designed to operate impulsively do not produce frequencies much above 10 kHz. Higher frequency wide band transducers can be used, but the higher the frequency the narrower the band tends to be; at least in relative terms. Thus resolution, attenuation and transducer characteristics all have to be traded off simultaneously.

Waveform is also an important consideration. Wideband systems are capable of bringing back a lot of information quickly but are generally limited in the amount of energy available in any one band. At the price of much slower operation, far more energy can be brought to bear by slow scanning across the available spectrum (as determined by the transducer).

The generalized block diagram appears in Figure 10. With the possible exception of the signature analyzer and transducer, the technology for each of the blocks is well known to the point of being available off the shelf with perhaps minor modifications. Development of the transducer and analyzer is largely a matter of experiment and design and the ultimate result should not require any unusual manufacturing techniques.

Weight and size do not appear to be a problem as fairly short wavelength radiation will have to be used to achieve the requisite radiation. One operational drawback is the likely requirement that the transducers will have to be in solid contact with the ice. Some work has been done on eliminating this requirement, but at much longer wavelengths where the problem is far less severe.

3.3.3 Nuclear Mode. A block diagram for a possible nuclear detector is shown in Figure 11. The instrument would consist of a neutron source (pulse) and a gamma ray detector. The electrical impulses put out by the detector have heights proportional to the

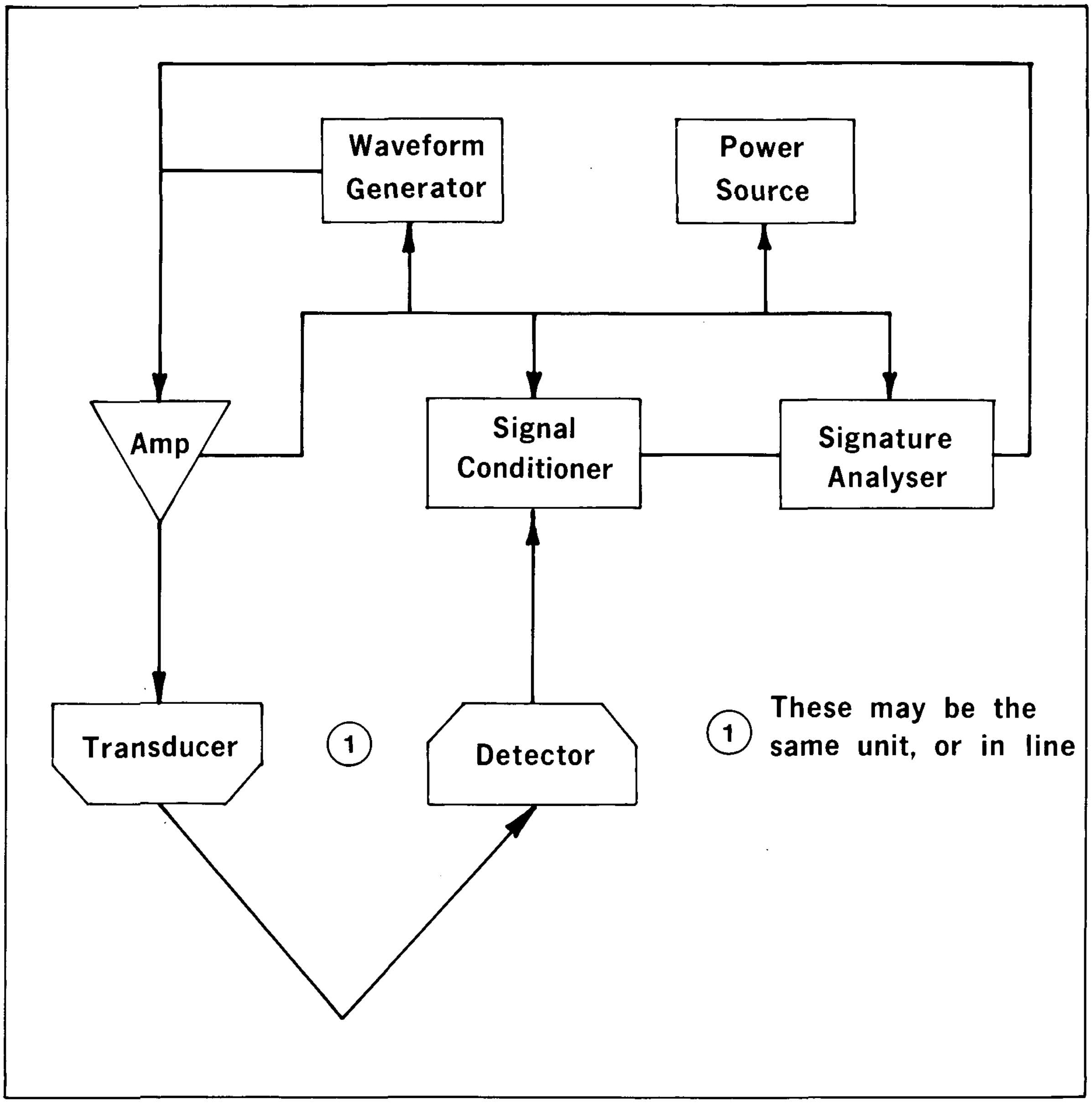

FIGURE 10 BLOCK DIAGRAM FOR ACOUSTIC DETECTOR

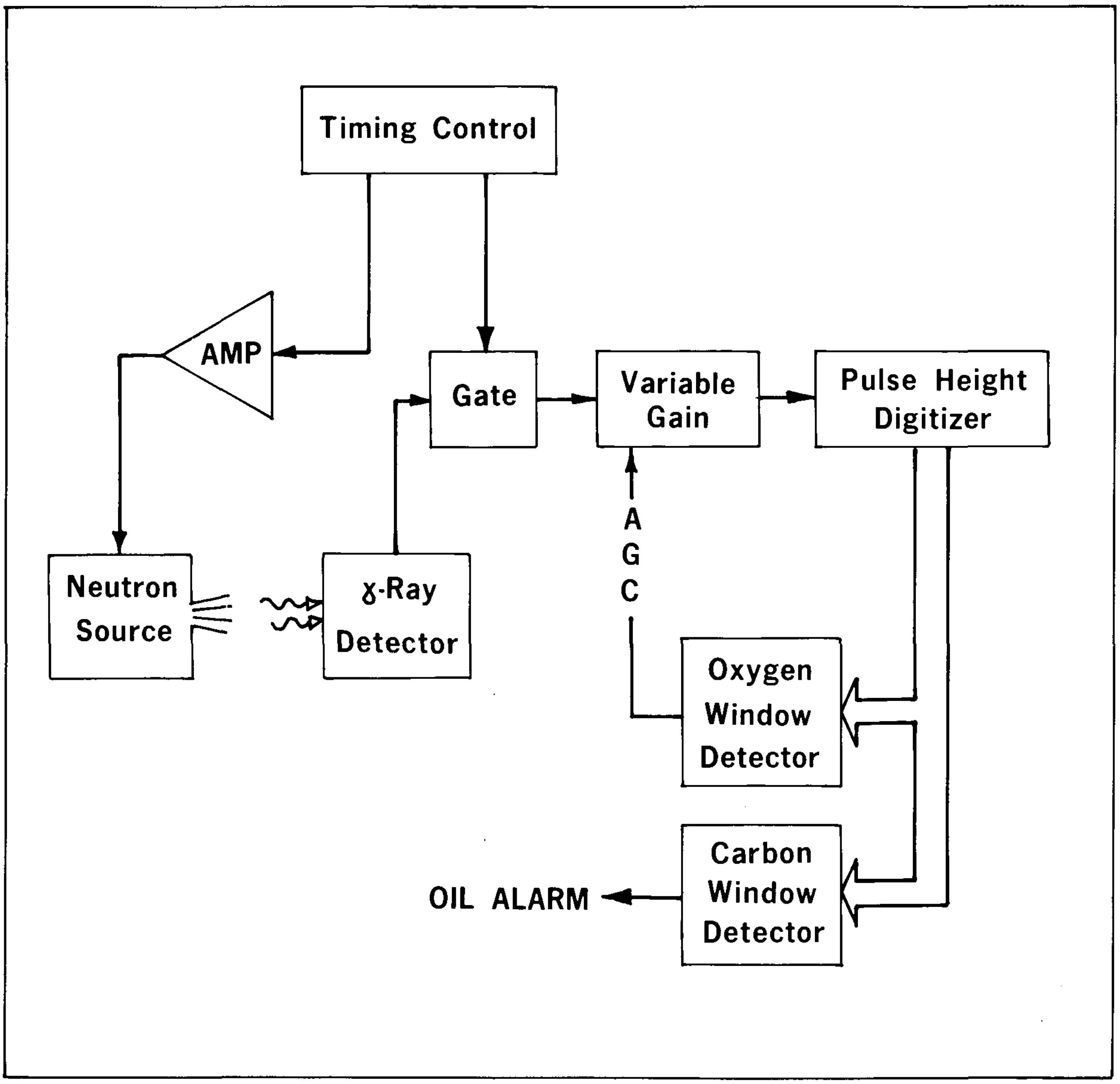

FIGURE 11 BLOCK DIAGRAM FOR NUCLEAR DETECTOR

characteristic energies of the arriving gamma rays. These are then sorted on the basis of height and the number of occurrences of each height range recorded, thus building up a picture of the energy spectrum. Since only that portion of the spectrum in the vicinity of the carbon line is of interest, considerably less memory is required than found in the normal spectrometer. Resolution would probably be improved by also monitoring the oxygen line, strong on account of the constituents of ice, and adjusting the gain automatically to compensate for drifts.

Variable time gating might also help to improve the resolution in the sense that late returns correspond to greater depths so that a band of ice would be examined making any carbon easier to detect. This is limited by random smearing of the depth-arrival time correlation.

An instrument modified for ice use but otherwise in line with existing technology should be portable, at least by helicopter or tracking vehicle. Present day well logs are only a few centimetres in diameter and run up to several meters in length. They are supported by a single truck, but much of that is devoted to equipment for hoisting the device up and down through several thousand meters. It is not clear at this stage what the effect on weight and power would be if the intensity or the energy levels were to be boosted. This requires further investigation.

The sources would have to be redesigned for an operational instrument to make it directional. Cadmium shields are quite effective in stopping neutrons so that the extra shielding required should be quite manageable. Nevertheless, the equipment would have to be certified and there might have to be fail-safe features in case of overturn, high gamma ray returns, etc. Modifications for testing over ice could be accomplished fairly inexpensively. The cost of developing an operational system would be greatly affected by the cost of achieving satisfactory safety standards. It is likely that the cost of advancing the state of the art in terms of greater intensities or energies would be very high indeed. These issues have not been examined in depth because, although this technique would result in the best resolution, the strict limitations on operational penetration make this an approach of last resort.

REFERENCES

1. Adey, A.N., "A Survey of Sea-Ice Thickness Measuring Techniques", Communications Research Centre Report No. 1214, 26, Ottawa, (1970).

2. Albers, Vernon M., Underwater Acoustic Handbook-II, The Pennsylvania State University Press, University Park, Penn. 35, (1965).

3. Apinis, J.J. and W.H. Peake, "Passive Microwave Mapping of Ice Thickness", Electroscience Laboratory, Ohio State University, Columbus, Report 3892-2, 156 (NTIS N 77 10611), (1976).

4. Bivens, H.N., G.W. Smith, D.H. Jensen, E.L. Jacobs and L.G. Rice, "Pulse Neutron Uranium Bore Hole Logging with Epithermal Neutron Die-Away: Exploration for Uranium Ore Deposits." Proceedings IEA Symposium, Vienna, (1978).

5. Bogorodsky, V.V. and A.V. Gusev, "Attenuation of Sound in Ice in the Frequency Range 200-1100 KHz". Sov. Phys. Acoust., 19, (2): 97-100, Sept-Oct. (1973).

6. Bogorodsky, V.V., V.P. Gavrilo, A.V. Gusev, and V.A. Nikitin, "Measurements of the Speed of Ultrasonic Waves in Bering Sea Ice". Sov. Phys. Acoust. 21, (3): 286-287, (1975).

7. Brown, R., NORCOR Research and Engineering, Yellowknife, N.W.T., personal communication, (1978).

8. Caldwell, R.L., W.R. Mills Jr., W.L. Orr, and L.S. Allen, "Nuclear Techniques in Oil and Gas Exploration and Production Nuclear Techniques and Mineral Resources." Proceedings of a panel, International Atomic Energy Agency, Vienna, (1977).

9. Campbell, K.J., and A.S. Orange, "A Continuous Profile of Sea Ice and Freshwater Ice Thickness by Impulse Radar", Polar Rec., 17: 31-41, (1974).

10. Caulfield, D.D. and A. Liron, "A New Solid State Seismometer with Application in P and S Waves" presented at 47th Annual Meeting of Soc. of Exploration Geophysicists, Calgary, Alberta, (1977).

11. Chudobiak, W.J., R.B. Gray, R.O. Gamseier, V. Makios, M. Vant, J.C. Davis and J. Katsube, "Radar Remote Sensors for Ice Thickness and Soil Moisture Measurements", Proc. 2nd Canadian Symposium on Remote Sensing, 2: 417-424, Guelph, April-May, (1974).

12. C-CORE, "Investigation of the Use of Microwave Systems in Detecting and Monitoring Oil Slicks over Ice and Ice-Infested Waters - Phase I, Report, C-CORE Contract Report, Publication 78-18: 408, St. John's, (1978).

13. Dean, A., Cold Regions Research Engineering Laboratory, Hanover, N.H., personal communication, (1979).

14. Evans, S., "Dielectric Properties of Ice and Snow A Review", J. Glacio., 5: 773-792, (1965).

15. Finkelshteyn, M.I., and V.A. Kutev, "Probing of Sea Ice with a Sequence of Video Pulses", Rad. Engs. Elec. Phys., 17: 1680-1684, (1972).

16. Fox, J.R., M.J. Golis and M. Tierney, "Summary Report on An Investigation of Means for Identifying the Contents of Tanks on Sunken Vessels". BATELLE Columbus Laboratories, SUPSALV Report No. 5-77 to U.S. Navy, Naval Sea Systems Command, 64, March (1978).

17. Gavrilo, V.P. and A.V. Gusev, "Use of Acoustic Methods to Analyse Snow and Ice". (In V.V. Gogorodskii, ed. Physical Methods of Studying Ice and Snow, CRREL, 1976) 119-125, (1976).

18. Gjessing D.T., Remote Surveillance by Electromagnetic Waves for Air-Water-Land, Ann Arbor Science Publisher Inc., Ann Arbor, Michigan, (1978).

19. George, K.D., D.L. McKeown and S.W. Young, "Detection of Oil-Water Interfaces", Biennial Review 1975-76, Bedford Institute of Oceanography, Darmouth, (1977).

20. Goodrich, L.E., "Review of Radiation Absoprtion Coefficients for Clear Ice in the Spectral Region 0.3 to 3 Microns". Nat. Res. Council. Canada Tech. Paper 331, (1970).

21. Gray, D.E. ed., American Institute of Physics Handbook. Chapter 8, McGraw-Hill Publishing Co. (1972).

22. Hashimoto, T., Y. Maniwa, O. Omato, and H. Mnoda. "Echo Sounding of Frozen Lake from Surface of Ice". International Hydrographic Review 40, (2): 31-40, (1963).

23. Heigl, J.J., "Oil/Water Interface Detector Laboratory Evaluation". Esso Resources and Engineering Co., Florham Park, N.S. Aug. 73, :94, Final Report on Task II, April 72- April 73, Rep. EE 11 TMR 73, (1973).

24. Hilchie, D.W., Nuclear Well Logging for Petroleum, Nuclear Methods in Exploration and Production, ed. by J.G. Morse, Elsevier Scientific Publishing Co., Amsterdam, 201-213, (1977).

25. Hoekstra, P., and P. Cappillino, "Dielectric Properties of Sea and Sodium Chloride Ice at UHF and Microwave Frequencies", J. Geophys. Res., 76: 4922-4931, (1971).

26. Iikuza, K., H. Oguar, J.L. Yen, V. Nguyen, and J.R. Weedmark, "A Hologram Matrix Radar", Proc I.E.E.E., 64: 1493-1504, (1976).

27. Keer, A.J., "Developments in Through-the-Ice Hydrographic Surveying", International Congress of Surveyors, Stockholm, 13, (1977).

28. King, R.C., Piping Handbook, 5th Edition, McGraw-Hill, New York, (1967).

29. Kovacs, A., 1977, "Sea Ice Thickness Profiling and Under-Sea Oil Entrapment", Proc 9th Ann. Offshore Technology Conf., Houston, 3: 547-554, May 2-5, (1977).

30. Langleben, M.P., "Attenuation of Sound in Sea Ice", 10-500 KHz. J. Glaciol., 8, (54): 399-406, (1969).

31. Langleben, M.P. and E.R. Pounder, "Acoustic Attenuation in Sea Ice Reflection of Sound at the Water-Ice", Interface Report 816, MacDonald Physics Lab., McGill University, :30, (1970).

32. Lapp, P.A. Ltd., "An Investigation of Systems for the Surveillance and Monitoring of Oil Spills in Beaufort Sea", Report for CCRS, Contract 0554-0276, 71 plus appendices, (1975).

33. Leighton, R.B., Principles of Modern Physics, McGraw-Hill Publishing Co., New York, (1959).

34. Lewis, E.L., "Oil in Sea Ice", Pacific Marine Science Rept 76-12, Institute of Ocean Sciences, Patricia Bay, (1976).

35. Logan, W.J., D.E. Thornton and S.L. Ross, "Oil Spill Countermeasures for the Southern Beaufort Sea", Technical Report 31B, (1975).

36. MacIsaac, R.R. and A.D. Dunsiger, "Ocean Sediment Properties Using Acoustic Sensing", 4th International POAC Conference, St. John's, Newfoundland, (1977).

37. Macphee, S.B., "Acoustics and Echo Sounding Instrumentation". Tech. Report. 1976-1. Can Hydrographic Service, Dept. of the Envir. Sept. (1976).

38. Malcolm, J.D., "The Interfacial Tension and Contact Angle of Crude Oil Under Ice", Abstract of paper submitted to POAC 79, Trondhem, Norway, (1979).

39. Martin, S., "A Laboratory Model of the Interaction of Oil and Ice in the Bering Sea", Proc 27th Magka Science Conf., Fairbanks, Aug. 5-7, (1976).

40. Mills, W.R., Mobil Research and Development Corp., Dallas, Texas, private communication, (1978).

41. MPB Technologies, Inc., "Development of Sea Ice Thickness Sensors", MPB Report MPB-121-1-1, to Ministry of Transport, 45, (1977).

42. NORCOR Engineering and Research Limited, "The Interaction of Crude Oil with Arctic Sea Ice", Beaufort Sea Technical Report 27, (1975).

43. Onaka R. and T. Takahasi, "Vacuum UV Absorption Spectra of Liquid Water and Ice", J. Phys. Soc. Japan 24: 548, (1968).

44. Parsons R.C. and R.M. Hopkins, "A Chemical Method for Ice Destruction." POAC Symposium, St. John's, Nfld., (1977).

45. Ramseier, R.O., M.R. Vant, L.D. Aresnault, L. Gray, R.B. Gray, and W.J. Chudobiak, "Distribution of the Ice Thickness in the Beaufort Sea", Beaufort Sea Technical Report 30, Dept. of Environment, Victoria, 98, (1975).

46. Robar, J.D., and H.C. Wood, "Theoretical and Instrumentation Studies in Radio-Frequency Radiometry for Remote Sea Ice Thickness Measurement", Ministry of Transport TDA Report 4P50, (1974).

47. Roulet R., G.A. Maykut, and T.C. Grenfell, "Spectrophotometers for the Measurement of Light in Polar Ice and Snow", Applied Optics 13: 1652, (1973).

48. Rossiter J.R., P. Langhorne, T. Ridings, and A.J. Allen, "Study of Sea Ice Using Impulse Radar", Proc. Fourth Intl. Conf. on Port and Ocean Engineering under Arctic Conditions, St. John's, 556-567, Sept. 26-30, (1977).

49. Royer G.M., "The Dielectric Properties of Ice, Snow and Water at Microwave Frequencies and the Measurement of the Thicknesses of Ice and Snow Layers will Radar", Dept. of Communications, Report 1242, Ottawa, 32, (1973).

50. Sinha, A.K., "A Field Study for Study for Sea-Ice Thickness Determination by Electromagnetic Means:", Geol. Surv. Can. Paper 76-1c: 225-228, (1976).

51. Topham, D.R., "The Defection of an Ice Sheet by a Submerged Gas Source", J. Applied Mech. Trans. ASME, 44: 279-284, (1977).

52. Untersteiner N., G. Maykut, and S. Martin, Washington Univ. Seattle Dept. of Atmospheric Sciences, Annual Report No. 6, Dec. (1974).

53. Vant, M.R., "A Combined Empirical and Theoretical Study of the Dielectric Properties of Sea Ice over the Frequency Range 100 MHz to 40 GHz", Ph. D. thesis, Dept. of Engineering, Carleton University, (reprinted as technical report, Ocean Technology Divn, Envir. Canada), June (1976).

54. Vant, M.R., R.O. Gray, R.O. Ramseier, and V. Makios, "Dielectric Properties of Fresh and Sea Ice at 10 and 35 GHz, J. Appl. Phys. 45: 4712-4717, (1974), (also "Erratum", J. Appl. Phys., 46: 2339, 1975).

55. Vant, M.R., R.O. Ramseier and V. Makios, "The Complex-Dielectric Constant of Sea Ice at Frequencies in the Range 01.-40 GHz, J. Appl. Phys., 49: 1264-1280, (1978).

56. Von Hippel, A.R., Dielectric Materials and Applications, MIT. Press, Cambridge, Mass., 438, (1954).

57. Wolfe, L. And D. Hoult, "Effects of Oil under Sea Ice", J. Glaciol., 13: 473-488, (1974).