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R. O'Neil

AN INVESTIGATION OF SYSTEMS FOR THE SURVEILLANCE AND MONITORING OF OIL SPILLS AT BEAUFORT SEA

Prepared for the Canada Centre for
Remote Sensing under Contract
Serial Number OSS4-0276

August, 1975

Philip A. Lapp Ltd.
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TABLE OF CONTENTS

Page

1015983

APPENDICES (bound separately)

A - REPORT ON OIL/ICE/WATER.... 1015984

APPENDIX B - Evaluation of Radio Methods for Remote Sensing of Oil Spills at Beaufort Sea. 1015985

APPENDIX C - Evaluation of Optical Methods for Remote Sensing of Oil Spills at Beaufort Sea. 1015986

~~APPENDIX C - Probability of VFR and IFR Conditions~~.

~~APPENDIX D - Inventory of Airstrips in the Beaufort~~ Sea Area.

INTRODUCTION

This study was undertaken at the request of the Canada Centre for Remote Sensing, Department of Energy, Mines and Resources as part of the H-series on the Beaufort Sea Project. The broad objective of the H-series is to investigate methodologies for the detection and clean-up of oil which may be released as a result of exploration activities in the Beaufort Sea.

Philip A. Lapp Limited was contracted to undertake the H-2 project within this series. The objective of the H-2 project is "to evaluate and develop a scenario of remote sensing methods and procedures of oil spills in the Beaufort Sea under three separate conditions: a) 100% ice cover (no open water); b) ice infested waters; c) totally ice free water. To accomplish this objective, Philip A. Lapp Limited was requested:

1. to assess specific remote sensing technologies including, but not limited to, multi-spectral scanner, microwave and radar methods.
2. to evaluate the application of these technologies under the following three conditions:
    a) oil under 100% ice cover
    b) oil in ice infested waters
    c) oil in ice free, Arctic waters.
3. to consider the logistical problems of a remote sensing operation in the Beaufort Sea area including,
    a) limitations imposed by the environment.
    b) criteria for evaluating the suitability of types of aircraft.
    c) availability of airstrips to accommodate aircraft equipped with remote sensing instrumentation.

   d) communications systems and alerting procedures.

   e) potential role of the Long Range Patrol Aircraft (LRPA) of the Department of National Defence (DND).

4. to develop realistic scenarios for the application of remote sensing technologies to contingency planning for the Beaufort Sea.

5. to identify and present recommendations for the improvement or development of systems or procedures applicable to the detection and surveillance of potential oil spills in the Beaufort Sea.

This statement of work called for a broad range of disciplines. To meet this requirement, Philip A. Lapp Limited brought together a team of scientists and engineers with backgrounds and broad experience associated with remote sensing technology and with the environment of the Beaufort Sea area. The team consisted of:

1. Philip A. Lapp Limited
   Toronto and Ottawa, Ontario

2. SED Systems Limited
   Saskatoon, Saskatchewan

3. W. R. McNeil and Associates Inc.
   Toronto, Ontario

4. Norcor Engineering and Research Limited
   Yellowknife, N.W.T.

SED Systems Limited were requested to evaluate the use of radio frequency methods. Prior to this project, SED completed several theoretical and instrumentation studies to evaluate radar sounding of sea ice, acoustic sonar for snow depth measurement, and radiometric sensing to determine ocean salinity and the thickness of arctic sea ice cover.

W. R. McNeil and Associates are engaged in a study for the Canada Centre for Inland Waters (CCIW) to investigate the application of remote sensing technologies to water quality monitoring. The extensive background of this company in electro-optics was applied to the consideration of optical techniques for the remote sensing of oil spills in the Beaufort Sea environment.

Norcor Engineering and Research Limited brought to the project direct experience and knowledge of the physics of oil and ice interactions, measurement programs being conducted by Canadian and US agencies and the logistical aspects associated with operations in the arctic environment, particularly in the Beaufort Sea area. Furthermore, Norcor were conducting one of the major studies in the G-series of the Beaufort Sea Project - the interaction of oil with Arctic sea ice.

An initial planning meeting was held in Toronto on January 16, 1975 to develop a schedule and consider the elements of the project in detail.

During the study, several meetings and conversations were held with the scientific authority, or his designate, to report on the progress. An interim report addressing the status of the several concurrent investigations of potential remote sensing technologies was forwarded to the scientific authority in March, 1975. Throughout the study, contact was maintained with other contractors on H series projects to prevent duplication of effort on areas which might juxtapose.

The project team convened again for a workshop held between July 7 and July 10, 1975. At this workshop, each member was asked to present a summary of activities and conclusions for their particular responsibility. With this information, a framework for the final report was drafted, and conclusions and recommended action debated. A draft report was written based on material and discussions from the workshop. This draft report was circulated to participants in the project for their comments. These comments were incorporated to produce the final report.

During the workshop, it became evident that the role of remote sensing in the surveillance and mapping of oil spills in the Beaufort Sea would be limited. As we shall demonstrate, there are several sea/snow/ice/oil states which can occur over significant parts of the year to which no remote sensing technology presently is applicable. Because of this conclusion, we extended the investigation to permit, if possible, the consideration and proposal of a viable and feasible system, incorporating both remote sensing and other technologies, for the surveillance and monitoring of oil spills in the Beaufort Sea.

Therefore the objective of the project was expanded to encompass:

> "the investigation of systems for the surveillance and monitoring of oil spills at the Beaufort Sea".

This investigation included a scientific and technical assessment of the remote sensing instruments including consideration of the hardware specifications, software, operator skills required, data acquisition, data handling and data interpretation, and the interface with command and control operations. Most of this information is not provided for the other technologies; the discussion is limited to introducing them. Therefore specific equipments have not been recommended for the systems proposed. In several cases, there are a variety of equipments available. An assessment of the relative merits of each would be required, including operating characteristics and costs, before specific recommendations could be made. We concluded that such an assessment was outside the scope of this project.

For convenience, the appendices to this report have been bound as a separate document.

2.0 THE CONDITIONS

2.1 The Operational Phases

From December, 1972 to March, 1975, the United States Coast Buard tested an integrated multisensor surveillance system installed on a Grumman Albatross aircraft. The system included side-looking radar, infra-red line scanner, low light level television, and passive microwave imager and was developed to assist in the enforcement of antipollution legislation through the detection, mapping, quantification and classification of oil spills. Because of the array of sensors mounted in the aircraft, the system also was assigned to other Coast Guard missions including ice reconnaissance, and search and rescue. The multisensor approach demonstrated by the U.S. Coast Guard system was considered in this study as a model from which to develop a surveillance and mapping system applicable to operations in the Beaufort Sea.

However, we are not faced with the occurrence of accidental spills or the dumping of oil over thousands of miles of coastline. The location of planned operations in the Beaufort Sea area for 1976 will be known precisely and therefore the location of any potential oil discharge. This significantly reduces the operating theatre to be defined for any proposed system. For the purposes of this report, we have evaluated each system within three operational phases. The first phase covers the initial exploratory drilling program up to two exploratory wells with no planned production. Phase two covers the possible continuation of this exploration program and an expansion in the number of sites. The third phase covers the initiation of the production stage and the expansion to extensive operations in the Beaufort Sea.

OPERATIONAL PHASE 1 - PRELIMINARY EXPLORATION PROGRAM
OPERATIONAL PHASE 2 - EXTENDED EXPLORATION PROGRAM
OPERATIONAL PHASE 3 - PRODUCTION

In all phases, the location of the sites, and therefore the location of potential discharges, will be known. This will be an important factor in considering the surveillance mode of any proposed operating system.

2.2 Possible Oil/Ice/Water States

Another important factor to consider in the assessment of technologies for the detection and mapping of oil spills in the Beaufort Sea is the possible interactions between oil and ice, water and snow. For this report, all ice-water states are grouped into three zones: the shorefast ice zone, the seasonal pack-ice zone and the polar pack-ice zone. The occurrence of open water, snow, and ice openings, including fractures, leads and polynyas are considered within each of these zones.* Norcor Engineering and Research Limited prepared a report for Philip A. Lapp Limited describing the three ice zones and the interaction of oil with the ice/water states within each zone. This report is attached as Appendix A. Due to the extreme variability, as well as the general lack of data for the three ice zones (shorefast, seasonal pack-ice, and polar pack-ice), it is impossible, as noted in the Norcor report, to predict with any degree of certainty,

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* The sea-ice terminology used in this report has been selected to conform to that stated by the World Meteorological Office (W.M.O. No. 259 T.P. 145).

the ice conditions which are likely to prevail at a given time of year for most locations. The descriptions in Appendix A are included solely as an aid to the assessment of remote sensing technologies in conditions which might prevail at any given time in the Beaufort Sea. They are not intended as a definitive statement on the meteorological or oceanographic conditions of the area.

Because it is impossible to predict the ice conditions at a specified time of year with any degree of certainty, we have divided the calendar year into four periods, not necessarily of equal length. These periods represent the time of open water, the freeze up, the period of solid cover, and the melting process. For each of these periods, and each of the three major ice zones (shorefast, seasonal pack, and polar pack), we have summarized the changes that take place in the ice/water states, the changes and normal limits on ice thickness, and comments on features such as ice openings, ridging, and snow cover. This summary is presented in Figure 1 and is used as the base against which the technologies for surveillance and monitoring are assessed.

The descriptions in Figure 1 are not intended to be a definitive statement on the ice climatology of the Beaufort Sea. We recognize that the data from the region is sparse, that many unknowns still exist, and significant variations can occur from one year to the next. For these reasons, we have divorced any time element from the descriptions of the ice/water states; they are presented solely for the purpose of defining the conditions under which a surveillance and monitoring system must operate.

FIGURE 1

DESCRIPTION OF THE ICE ZONES

	SHOREFAST ICE	SEASONAL PACK ICE	POLAR PACK ICE
FREEZE-UP	- slush ice forms in protected areas. - pancake ice on rough seas - ice cover increases to 5/10; thickness to 15 or 20cm. - open water along shear zone.	- ice cover increases to 6/10 or 7/10 - still large sections of open water. - ridging & rafting of new ice - large leads & cracks.	- ice growing to 7/10 and 9/10 - leads constantly opening. - cracks parallel to the movement of the pack. - 1st year ice predominant. - large leads west from Banks.
ICE COVER (9/10 - 10/10)	- ice cover increases to 9/10 and 10/10 - ice thickness grows from approximately 75cm to 165cm. - some ridging and rafting. - often snow covered. - predominantly 1st year ice at shore.	- polar pack intrudes. - ice cover grows to 9/10 & 10/10. - ice thickness increases to about 200cm. - leads less frequent. - Bathurst polynya extends into the area as leads & fractures.	- 10/10 ice cover. - pack moving with the Beaufort Sea anti cyclonic drift. - ice thickness grows to over 200cm.

FIGURE 1 (Page 2)

DESCRIPTION OF THE ICE ZONES

	SHOREFAST ICE	SEASONAL PACK ICE	POLAR PACK ICE
BREAK-UP	- snow cover becomes glazed. - flow leads appear. - ice cover from 10/10 to 3/10; - large areas of open water. - few large floes.	- westerly drift accelerates. - large leads present. - snow cover melting. - melt ponds; 1st year ice thin. - open water. - ice cover decreasing thru 7/10 and 4/10.	- snow cover deteriorates. - 1st year ice softening. - leads common. - melt ponds cover large areas.
OPEN WATER	- may be occasional small floes. - frazil ice may appear late in the period.	- 1st yr. ice gone - groups of floes.	- 2nd year and multi-year ice present. - floes present.

3.0 INTRODUCTION TO THE TECHNOLOGIES

The application of any system to the problem under consideration can be defined in one of two modes - surveillance and monitoring. The surveillance mode defines the role of detection of any oil discharge in the Beaufort Sea. The result from the surveillance mode would be a simple yes/no response to the presence of oil.

The location of any potential oil discharge would be well defined in any of the three operational phases identified previously since the occurrence whether a blowout or seepage would almost certainly occur in the vicinity of the drill site. The surveillance mode would involve checking the known exploration sites in operational phases one and two, plus the production sites which may be introduced in operational phase three.

Three parameters are important in the monitoring mode - areal extent of the discharge, points of concentration, and drift, or tracking. This information is required by the command and control function to direct the crews charged with the clean-up. Knowledge of the areal extent is required for the placing of containment booms and distribution of holding structures; the identification of points of concentration assists in the placing of removal equipment. The oil spill also must be tracked to give early warning of change of direction, particularly if towards the coastline, and any split of the spill into smaller segments.

4.0 CONSIDERATION OF THE TECHNOLOGIES - REMOTE SENSING

For the purpose of this report, remote sensing is defined to encompass all instrumentation for measurement "at a distance". In assessing the application of remote sensing technologies for the surveillance and monitoring of oil discharges in the Beaufort Sea environment, the various systems under consideration were divided into two groups covering the electromagnetic spectrum: passive and active radio frequency methods, and optical methods including photometric, intensified photometer systems and thermal devices.

4.1 Radio Frequency Techniques

A complete assessment of the radio frequency techniques was completed by SED Systems Limited of Saskatoon; the results of their investigation are included with this report as Appendix B. Only a summary of the results will be presented in this section; many of the comments and conclusions are extracted verbatim from the SED report.

4.1.1 Passive Radio Frequency Techniques

After considering all available information on passive microwave detection of oil spills, SED concluded that "radiometric detection, mapping and possibly thickness measurements are possible in open Arctic waters". In the surveillance mode, antenna scanning is possibly near the 20 GHz frequency - the optimum operating frequency to provide a compromise between target contrast, surface resolution, and atmospheric attentuation. The result would be a brightness temperature map of the ocean. Such a map could also prove beneficial in the monitoring mode.

The dielectric properties of oil at microwave frequencies are nearly identical to those of snow. Therefore, with only passive detectors operating in the microwave region, no reliable conclusions can be reached regarding either the detection of surface oil in the presence of snow.

In ice-infested waters, the separation of a change in brightness due to oil on the water compared to a changing fraction of ice in the field of view of the instrument is unlikely. An additional technique would be required to separate first the fractions of ice and water.

To detect oil under an ice canopy, radio frequences must be selected which can penetrate the expected ice thickness. On the other hand, the wavelength must not be too long compared with the scale sizes of the oil pools being sought. Oil in the bottom 4 or 5 centimetres of the ice layer would create a discontinuity in the vertical profile of the dielectric constant and make possible a change in the emission from the region.

No UHF radiometric measurements of this phenomenon in real situations are known, although the technique would appear to be potentially useful since a UHF radiometer should exhibit a brightness temperature decrease of tens of degrees Kelvin. Since the bottom salinity gradient is expected to be most important to the radiation properties of sea ice once oil becomes frozen into the ice and a substantial amount of new sea ice has grown below the oil, little effect is anticipated upon UHF or microwave properties of the ice emission.

4.1.2 Active Radio Frequency Techniques

Three types of instruments were evaluated within this category:

1. Scatterometers
2. Side-Looking Airborne Radar (SLAR)
3. Impulse Radar

Scatterometer - Scatterometers measure the return of a burst of energy radiated from a transmitter and scattered back from the target of interest. The received return signal is proportional to the average scattering coefficient of the target. When the time from transmission to reception of the signal is measured, the instrument is more properly referred to as a radar. Therefore, consideration of scatterometers was deferred to the consideration of radar systems.

Side-Looking Airborne Radar (SLAR) - There are two fundamental types of SLAR instruments: real aperture and synthetic aperture. The real aperture system uses only the forward motion of the aircraft and the along-track beamwidth to provide spatial resolution parallel to the flight direction. The synthetic aperture system utilizes the differing phase relationships between the signals received from target positions ahead of the aircraft and

and those perpendicular to, or behind, the aircraft to obtain fine spatial resolution in both the along-track and cross-track directions. Images are obtained during flight from the computer processed return signals.

Three instruments are currently available outside the military classification. The Motorola APS 94(D) and the Westinghouse PAQ97 are real aperture systems; the Goodyear PAQ102 system is a synthetic aperture system.

In open water, the oil damps the small scale waves and produces an area of diminished radar return (the radar cross section of the waves covered with oil is reduced). The resulting contrast between oil-covered and oil-free sea permits the contaminated regions to be mapped and the extent of the discharge determined.

The SLAR views the surface at an angle to the vertical. Therefore strong reflections from the edges of ice floes are observed. Since SLAR is essentially a surface imaging system, the potential use of this system in observing the effects either of oil under ice or of oil in ice infested waters would appear to be severely limited.

Probing Radars - Probing radars overcome the limited ice penetration of SLAR. While no experimental investigations using probing radars for detecting oil under ice have been reported, two basic approaches are being investigated for sea ice thickness measurement: wide-band frequency modulation of the transmitted signal (FM/CW) and short time duration modulation of the radio energy (pulse and impulse instruments). A commercial FM/CW is available for measuring sea ice thicknesses greater than approximately one meter, although no information has been published regarding its ability to detect oil under ice. It is a contact sensor.

Research is being conducted using a UHF impulse radar (a narrow pulse of DC energy is used to produce wideband transmission) to measure sea ice thickness. The contamination, by oil, of the electrical properties near the ice-water interface would be expected to decrease the bottom surface reflection coefficient. However, the presence of oil may be detected only as a change in bottom reflection from one horizontal position to another on similar ice, or as a change in bottom reflection at the same location at different times.

4.1.3 Conclusions - Radio Frequency Techniques

From the consideration of radio frequency techniques, SED concluded that:*

1. the useable radio frequency range for all-weather, all-day oil spill reconnaissance in the Arctic is from 400 MHz to 40 GHz. Ice penetrating sensors will be restricted to operate between 400 MHz and 3 GHz. Ice or ocean surface scanning sensors should operate below 20 GHz (40 GHz for clear sky operation).

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* extracted from the conclusions from Appendix B - report from SED Systems Limited.

2. No experimental tests have been taken to verify that oil can be detected under sea ice. From theoretical considerations, it appears that UHF (.3 to 3 GHz) impulse radars and radiometers could detect oil spilled under first year sea ice if the oil is observed when it is frozen into the bottom few centimeters of the ice sheet. UHF radiometers should exhibit a brightness temperature decrease of tens of degrees Kelvin under similar conditions. Insufficient data is available to estimate if oil is detectable under multiyear ice. Although there is no evidence to preclude such detection at present, after oil spill has been frozen into or has migrated to the center of the ice sheet, it would be difficult to detect by RF techniques. Although oil under ice may be detected by radio methods it is not certain that actual oil thickness can be determined since radiation of wavelength short enough to be comparable to the oil thickness is strongly attenuated in sea ice.

3. Surface oil in ice free waters can be detected, mapped, and possibly quantitively measured by scanning radiometers at = 20 GHz or by side looking radars (SLR's). Oil spilled on ice infested waters can be easily determined only for small fractional ice cover. Oil cannot be easily identified by type at microwave frequencies.

4. Oil spilled on surface ice will be difficult to detect by microwave remote sensing techniques as it is predicted to impedance match the ice to the air in a manner similar to snow. At frequencies above 20 GHz replacement of surface brine by oil may sufficiently alter ice dielectric properties to create a characteristic surface emissivity change. Experimental measurement would be required to verify this effect.

5. Airborne thickness measurements of sea ice are immediately possible at UHF frequencies. Furthermore, ice structure and typing are also immediately possible using radiometers and dual polarized radars.

6. With the possible exception of side looking radars, microwave sensors suitable for sea ice and oil spill reconnaissance in the Arctic can be carried by light aircraft, helicopters, or surface vehicles such as snowmobiles and trucks. State of the art equipment has been proven to operate satisfactorily in the Arctic environment subject to unusual conditions imposed by handling and storage, cold, and minimal training of operators.

7. A microwave imaging radiometer would be a useful adjunct to a SLAR system since the imager would cover that region below the aircraft, outside the field of view of the SLAR. The imaging radiometer would prove particularly useful during break-up, freeze-up, and open water when conditions were unsuitable for visual or IR observations. The instrument could be mounted on light aircraft*.

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* from further correspondence received from SED Systems Limited. Included after the SED report in Appendix B.

4.2 Optical Techniques

The assessment of remote sensing technologies operating in the optical frequency was conducted by W. R. McNeil and Associates Limited of Toronto; their report is incorporated as Appendix C. As with the investigation of radio frequency techniques, only a summary of the results is presented in this section. Many of the comments and conclusions are extracted verbatim from the appendix.

The optical techniques were considered in three categories: photometric systems, intensified photometric systems, and thermal systems.

4.2.1 Photometric Systems

This class of instrumentation includes a broad category of conventional imaging and non-imaging systems operating in the visible (UV to near-IR). Representative devices include conventional television, multi-channel photometers, multi-spectral scanners, image dissector cameras and multi-band photography. The common characteristic of each of these systems is that they are all passive devices capable of daytime operation only.

The most essential element in any anticipated detection/mapping function for the operational phases in the Beaufort Sea is real time display. Data from conventional multi-spectral scanners are intended for processing at a later time and therefore the output is usually recorded in analog form on magnetic tape. Real time displays can be incorporated with the addition of a method for scan conversion but this invariably leads to a severe loss in image quality.

Multi-spectral systems are available which incorporate image dissectors at the scanner and detection stages. These instruments offer a superior combination of both spectral and spatial characteristics but are limited to one channel registration and therefore are unable to provide thermal information. The image dissector camera can be installed in a small aircraft.

4.2.2 Intensified Photometric Systems

This class of instrumentation includes all types of instruments listed in the previous category but which have in some way been modified for low light level applications (i.e. L^3TV) or by use of some form of artificial illumination as with active systems (i.e. laser fluoresensors).

Intensified Optical Multi-channel Analyzers are non-imaging devices capable of storing up to 500 channels of spectral information over a wide spectral range (200 nm - 1.1u) and at input signal levels comparable to starlight illumination under clear moonless skies. These devices are physically small, require little power, are relatively inexpensive and can incorporate several systems for real time data output (CRT, x-y plotters, paper tape or real time video.

Field experience with low light level imaging systems has demonstrated that they are able to extend the range of useful real time effectiveness of TV reconnaissance systems down to illumination regimes equivalent to "deep twilight". To extend operations to cover all possible degrees of illumination some form of artificial illumination must be introduced. The U.S. Coast Guard recommends a commercial wing-mounted searchlight operating in the continuous wave mode from 28V DC at 60 amperes. The unit weighs less than 50 pounds and, equipped with a variable beamwidth, can operate over a wide range of altitudes.

4.2.3 Thermal Systems

This class includes a broad range of both imaging and non-imaging infra-red sensing devices such as the IR radiometer, IR line scanner and the forward looking IR scanner (FLIR). Most of these systems operate in the 8-14 u region of the spectrum. Some lower resolution systems also operate in the 3-5 u region.

Thermal IR line scanners operate in a very similar manner to multi-spectral scanners except that the incoming radiation is split into both visible and thermal regions. These sensors are not dependent on ambient illumination but cannot penetrate rain or substantial cloud cover. False alarms may be produced from localized thermal structures in the water.

Forward looking infrared thermal imaging systems (FLIR) are passive remote sensing devices; the image can be presented as a TV display. There are FLIR systems available for both aircraft and helicopter operations. The instruments combine quality images with real time display and more extensive coverage with forward looking capability.

4.2.4 Conclusions - Optical Techniques*

It is not possible at present to infer directly the presence of oil under ice using optical techniques. Under some conditions, possibly shorefast ice or snow cover situations, it may be possible to detect oil under ice or snow from thermal imagery. Meteorological and metric considerations will limit the applicability of passive optical techniques.

Ice conditions will severely limit the range of optimum effectiveness of optical techniques for oil on water detection to the open water period (basically the three month Summer period). Even the most sophisticated optical techniques will be ineffective for at least five months of the year. The only exceptions may occur when oil intrudes into ice openings.

During open water and ice infested periods, thermal and intensified optical devices operating at low altitudes will be significantly more effective than conventional photometric instrumentation.

For oil on ice, all optical sensors would be applicable during any period except November or February. The greatest potential would be achieved by combining a thermal and intensified photometric instrument.

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* summarized from the conclusions in Appendix C.

4.3 Application of Remote Sensing Technologies to the Ice Zones

Many of the remote sensing technologies in the optical and radio frequency range have application in both the surveillance and monitoring roles. However, in almost every case the sensor is limited to detection in the presence of open water. Figure 2 summarizes the sensors considered in the assessments with an indication of the operating limitations, the operational status (range from conceptual, through the research and development stages to commercial product), availability (classified to "off-the-shelf" procurement), and practical considerations (comments on cost and complexity). The operating characteristics of the sensors can be applied to the ice/water states identified in Figure 1 to highlight the conditions under which present remote sensing technologies can be applied to the surveillance and mapping of oil discharges in the Beaufort Sea.

Some of the sensors are applicable to the detection of oil, under certain conditions, but not to the mapping of the spill (such as non-imaging sensors in the optical range). In some cases, particularly in open water, there are several remote sensing instruments which could be applied to the roles of surveillance and monitoring. However there are ice/water states, and considerable periods of time during the year, when no remote sensing technology is applicable. This includes remote sensing technologies, or new applications of current systems, in the conceptual stage. Further, the application of remote sensing technologies to the surveillance and monitoring

FIGURE 2

ASSESSMENT OF REMOTE SENSING TECHNOLOGIES

SENSOR	OPERATING LIMITATIONS	OPERATIONAL STATUS	AVAILABILITY	PRACTICAL CONSIDERATIONS
Microwave Radiometers	Detect and map oil on water & under 1st year ice, if oil in bottom cms.	Built for the U.S. Coast Guard	Built to USCG specifications	\$100 - \$200k
SLAR	Detect oil in ice free waters; must be minimum ice	Commercial	Off-the-shelf	High cost; Complex
Impulse Radars	Detect and map oil on water & under 1st year ice, if oil in bottom cms.	Development	No	
Intensified OMA	Non-imaging; usual optical constraints	Development	Off-the-shelf	Reasonable Cost
Laser Flourometer	Non-imaging; power requirements high	Development	18 months	High cost
Image Dissectors	Daytime operation	Commercial	Off-the-shelf	Reasonable cost
MSS	Daytime only	Commercial	Off-the-shelf	Reasonable cost
L^{3}TV	Blooming problems; may require illumination	Commercial	Off-the-shelf	Reasonable cost
Thermal IR Line Scanner	Limited coverage	Commercial	Off-the-shelf	Reasonable cost
FLIR	Power requirements high	Commercial	Off-the-shelf	High cost

roles was considered under ideal environmental conditions. When the physical and operating limitations are applied the actual coverage from the sensors will decrease.

The ability to operate a remote sensing system in the Beaufort Sea will be very dependent on the following conditions:

1. probability of IFR/VFR constraints
2. hours of daylight
3. cloud cover
4. precipitation
5. fog
6. blowing snow

The probability of IFR/VFR constraints would affect the actual flying of the instruments; the probability of any of the other five conditions could affect the operation of any selected instrument. Charts illustrating the comparative probability of flying VFR and IFR missions are presented in Appendix A*. The probability of flying a VFR mission from Inuvik, Cape Parry or Sachs Harbour exceeds 50% for only 5 months of the year, from April through August. The probability of flying IFR missions from Inuvik exceeds 80% over the whole year. From Cape Parry, the probability of IFR varies between 60 and 85 percent; from Sachs Harbour the probability varies between 70 and 95 percent for most of the year but decreases to between 55 and 70 percent from mid-June through August.

Except for the condition of blowing snow, sensors operating in the radio frequency can be considered "all weather sensors". Their operation is not affected by the level of illumination (hours of daylight), cloud cover, precipitation, or presence

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* Prepared by Norcor Engineering and Research Limited.

of fog. If the aircraft can fly the mission, the system will be capable of operating. The same conclusion is not valid for the optical sensors. Their operation is severely limited by level of illumination, cloud cover, fog, precipitation, and blowing snow.

In Appendix C, W. R. McNeil and Associates calculated that the probability of effectiveness of optical and thermal techniques as a function of ambient illumination, cloud cover, precipitation, fog, and blowing snow would be less than 10% from the end of November to the end of April. The probability would rise rapidly after the end of April and exceed 50 percent from the beginning of July to approximately the end of September.

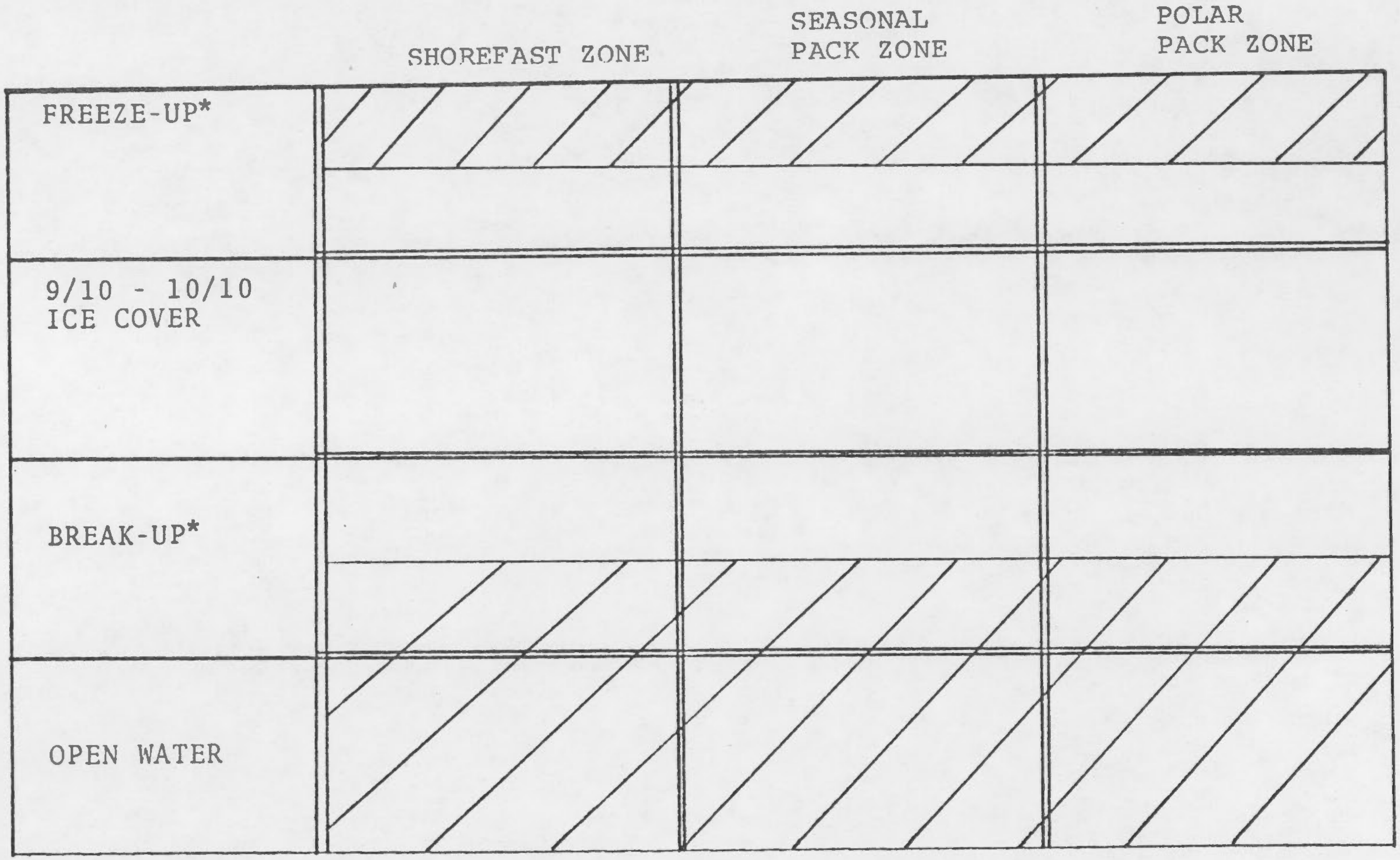
Therefore, the operational role for remote sensing would be severely restricted outside the three month span from July through September (basically the open water case) and it does not appear that any new developments will become operational within the next two or three years. If we consider each ice zone during each period separately, then with the introduction of remote sensing approximately 50 percent still would not be covered in the surveillance role (Figure 3) or the monitoring role (Figure 4). (and 50% of the periods covered in the surveillance role could be done by visual siting from the drill ship).

4.4 Introduction to a Multi-Sensor System

From the preceding discussions, it is obvious that a combination of sensors will be required to satisfy the

FIGURE 3

APPLICATION OF REMOTE SENSING TO THE SURVEILLANCE ROLE

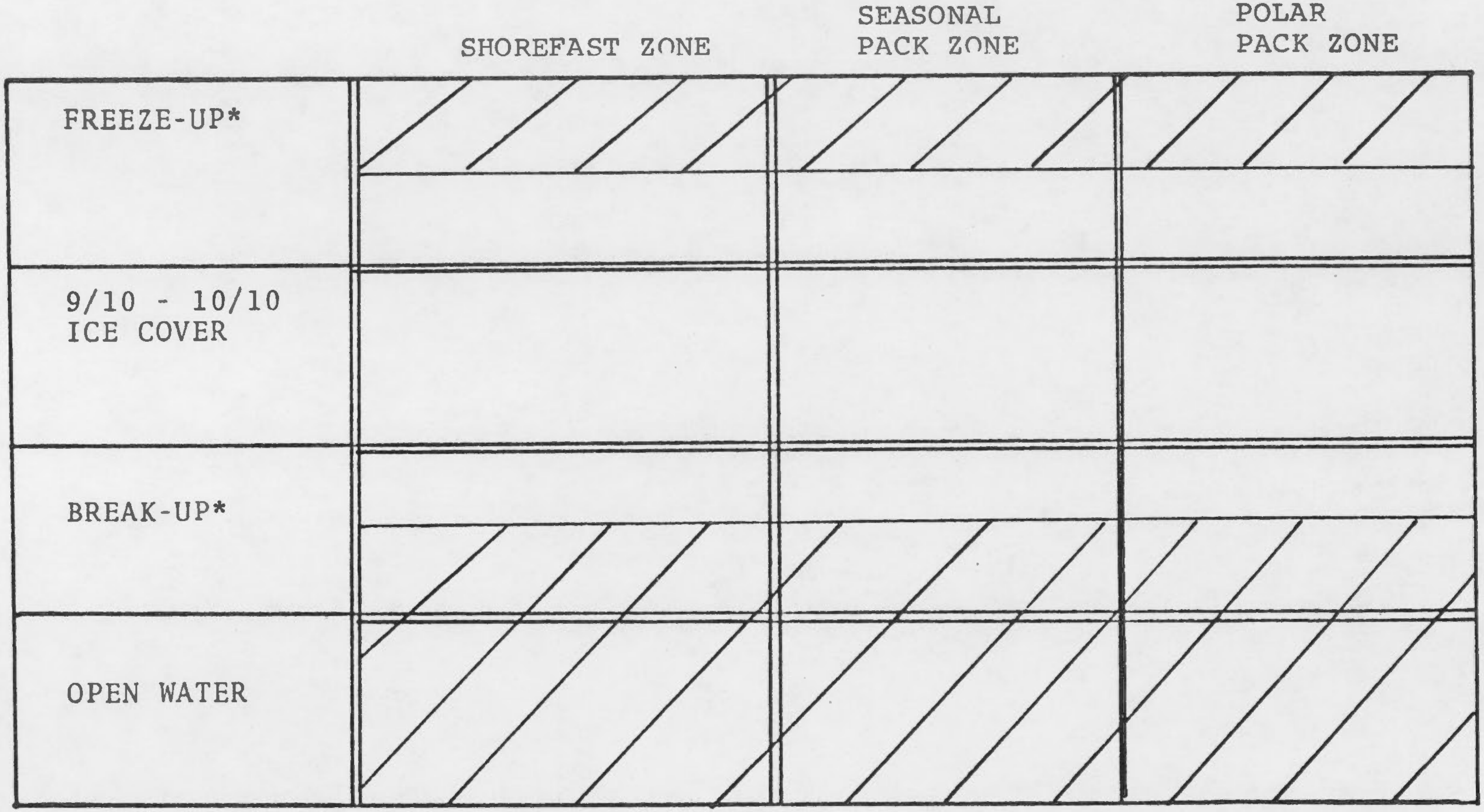


* reduced to 50% because of limited flying conditions for optical system.

▨ – areas and time of year covered by remote sensing.

FIGURE 4

APPLICATION OF REMOTE SENSING TO THE MONITORING ROLE



	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
FREEZE-UP*	▨	▨	▨
9/10 - 10/10 ICE COVER			
BREAK-UP*	▨	▨	▨
OPEN WATER	▨	▨	▨

* reduced to 50% because of limited flying conditions for optical system.

▨ - areas and time of year covered by remote sensing need for a surveillance and mapping system capable of operating throughout the year under all weather conditions and in any ice zone. Except for the criteria imposed by operations in an arctic environment, the multi-sensor approach was the direction followed by the United States Coast Guard in their development of the AOSS system - Airborne Oil Spill Surveillance System.

The AOSS system contained a SLAR, a passive microwave imager, a multi-spectral low light level television, a multi-channel line scanner, a position reference system, and a real processor display console. W. R. McNeil and Associates reviewed the AOSS system in their report (Appendix C) and emphasized the following pertinent conclusions:

1. Static and dynamic "controlled" oil spills were reliably detected and mapped at ranges up to 12 nautical miles.
2. An integrated multi-sensor system is required for effectiveness over a wide range of operating conditions and <u>to reject potential false targets</u>.
3. The system is effective day and night, from clear to dense undercast, for wind speeds up to 26 knots, and wave heights up to 13 feet.

Each of the sensors in the system was selected because of its unique advantages <u>and</u> limitations in terms of sensitivity, resolution, areal coverage, potential false alarms, and dependence on operating conditions. The SLAR system is used primarily because of its long range detection and mapping capabilities, (swaths of 25 nautical miles) and operation during adverse weather conditions. The passive microwave imager is used for the "radar hole" beneath the aircraft. It also serves as a redundant system for the SLAR. Oil film thicknesses also can be approximated for larger spills - a useful parameter for cleanup operations. The sensor is limited by its coarse resolution (180 feet for the prototype).

The line scanner has a resolution of approximately six feet from an altitude of 2500 feet. Thin films are invisible to the thermal IR sensor and therefore it produces a system to check the SLAR which can react to oil as minimal as a monomolecular layer secreted by fish. The low light level television is used for close range, high resolution work.

To cover operations in the Beaufort Sea using such a system, several tests would be required to evaluate the capabilities of the instruments in ice covered periods. One combination could incorporate an imaging radiometer (40 GHz) for detection and measurement in open water and ice coverage data; a UHF radiometer (400 MHz to 2000 MHz) to observe oil under ice soon after a spill, an impulse radar operating between 100 MHz and 1 GHz for detailed mapping of a spill under the ice and perhaps estimate the quantity; a SLAR to detect the presence of oil in ice infested water (if the signal can be separated from the return from large floes); an imaging radiometer to cover the area under the aircraft; a FLIR to assist in detection and mapping, and L^3TV to provide the close range visual.

Unfortunately none of these systems have been tested in the Beaufort Sea environment and certainly not in this configuration! Also, only a large aircraft could carry such a payload and support the power requirements. The AOSS system alone weighs almost 3,000 pounds. Certainly such a system could not be assembled, tested and be ready for operation with two years. Finally, the cost of such a system, easily $1,000,000 for the instruments alone, may not be justified when compared with other technologies.

5.0 CONSIDERATION OF THE TECHNOLOGIES - OTHER

With many of the ice zones and much of the year not covered by remote sensing instrumentation, we turned our attention to the consideration of other technologies which might be applied to the integration of a system capable of satisfying the assigned surveillance and monitoring roles throughout the year. The technologies considered covered a wide range - from submersibles equipped with the latest electronic equipment to men on the ice equipped simply with ice augers. In this section, we shall explore these technologies discussing the role they might play, and, as with the remote sensing instrumentation, assessing the operating limitations, the operational status, the availability, and practical considerations related to the acquisition and operation of the particular instrument. The technologies discussed in this section include:

1. underwater systems
    - submarines
    - submersibles
    - unmanned underwater vehicles
    - remote packages (in situ sensors)
2. acoustical techniques
3. resistivity measurements
4. gas analyzers (sniffers)
5. manual and other techniques (e.g. ice augers)

These technologies are introduced in this report to indicate their potential role in a surveillance and monitoring system. It is not possible to complete a detailed scientific and technical assessment of each, in fact, most of the instruments have never been applied to the task of detecting oil in the Arctic. They are presented here because there is a possibility that they might work. If some can perform the tasks, then in all likelihood a system can be developed to meet the objective:

> "a viable and feasible system for the
> surveillance and monitoring of oil spills
> in the Beaufort Sea"

5.1 Underwater Systems

Underwater systems have the advantage of being almost independent of weather conditions. For this report, we considered five categories of underwater systems ranging from the submarine to remote surveillance packages operating from the ocean floor.

Submarines - Submarines have the advantages of long-range and independence from any tender ship. In fact, it is this independence which differentiates a "submarine" from a "submersible" which cannot operate without some form of tender platform. While submarines equipped with instruments such as side-scan sonar may be able to satisfy the surveillance role in under-ice conditions, they would represent a costly alternative. In addition, the submarine, which would amost certainly be diesel electric, would have to surface to snort and charge the batteries. Since this must be done for two or three hours every day, consideration of a submarine may be excluded.

Submersibles - While submersibles are independent when in the operating mode, their limited range causes them to be dependent on a support vessel for transportation to and from the site. The Pisces I, for example, contains life support for 72 hours; Pisces II, III, IV and V for 200 hours which appears to be the maximum limit for submersibles now operating in the world*.

Submersibles usually can carry an array of electronic equipment including side-scan sonar and low light level television. While it would appear that submersibles have a very limited role, if any at all, in surveillance or monitoring because of the necessity for a support ship (not to mention access through the ice), the operation of Narwal, a submersible designed for Arctic Canadian Continental Shelf Exploration (ACCESS) of Toronto by Perry Oceanographics, should be investigated since the vehicle is designed specifically for operations under arctic ice*.

<u>Unmanned Underwater Vehicles</u> - Unmanned underwater vehicles can be considered in two categories: sea bed vehicles and self-propelled submersibles with at least neutral buoyancy. Sea bed vehicles have been used mainly for bottom profiling, survey work, photography, and salvage work. In 1969, Troika, an unmanned towed sled designed by J. Y. Cousteau, successfully located the wreck of the Caravelle, a ship lost in 7,216 feet of water. With the sea bed rover acting as a base, it is possible to envisage a system composed of a rover and a "daughter" vehicle. The rover would contain the power system, the main propulsion unit, navigation and control systems, and the data transmission or storage equipment. The daughter vehicle would contain the oil detectors. The daughter would be released on a tether to perform a spiral search pattern controlled by the tether release. The information either would be stored

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* Jane's, Ocean Technology, 1974-75", edited by Robert L. Trills, Jane's Yearbooks, London, England, 1975.

on the rover or retransmitted by some form (e.g. cable or underwater transmitter). One concept considered, but then rejected, was the release by the rover of a buoyant aerial capable of penetrating the ice and permitting normal radio frequency transmission. In the final assessment, while they can carry a vast array of instruments, the through-the-ice penetration required for sea bed rovers makes them totally impractical.

However, there are self-propelled unmanned submersibles which may have a role in surveillance and monitoring. Some are extremely cumbersome and can be discounted immediately. These would include vehicles such as the CURV series (Cable-Controlled Underwater Recovery Vehicle) designed for the U.S. Navy to recover ordnance at their underwater test ranges. CURV III, the latest model, measures 6.5 by 15 feet and weighs approximately 4,500 pounds. On the other hand, the unmanned submersible vehicle (U.S.V.) commissioned and used by the United Kingdom Ministry of Defence resembles a large torpedo - 11 feet in length, 13 inches in diameter and weighing 520 pounds. By 1974, 27 of these vehicles had been built for military uses, mainly as targets. Designs have been produced for commercial application incorporating instrument packages such as side-scan sonar, photographic site inspection, magnetometry, physio-chemical analysis, bottom profiling and seismic sonar, and television*.

A vehicle, such as a U.S.V., could be employed for both surveillance and monitoring when the ice cover reaches 10/10. A hole of sufficient size could be augered in

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* Ibid

the ice and the U.S.V. lowered through. In this case, a vehicle, rather than a ship, would act as the support vessel. The U.S.V. then could be directed to the drill site for inspection. If oil discharging from the area was noted, the vehicle could be directed to monitor the areal extent (the U.S.V. can operate to depths of 1,200 feet with a range of 13.5 miles). In addition to these roles, a U.S.V. could be employed for regular inspection of the drill sites over the long winter months.

Remote Packages - For the surveillance of sites in the seasonal pack and polar pack zones, a detection system was envisaged which could be mounted on the ocean floor in the immediate vicinity of any drill site. This system could be installed as the drilling season is drawing to a close and the drill ship is preparing to leave the site. The system would consist of a simple device for detecting the presence of oil (perhaps some form of turbidity meter) transmitting information to a command and control station on the shore. Cable would be an extremely expensive communications link but some type of VLF transmitter to a geophone could be employed. This would transmit a signal at least to the shorefast zone. The receiver on the ocean floor coupled with a retransmitter and an aerial through the ice would provide the final link.

This would be a simple GO/NOGO detector, triggered by the first sign of oil. Once it had been triggered, it would have no further role to play in the monitoring phase.

While conceptual in nature, the equipment necessary to assemble such a system is available and might prove to be the least expensive system considered to this point. Any number of sensors, including a television, for site inspection as well as surveillance, might be incorporated into the package.

5.2 Acoustical Techniques

During the past year, Bannister Pipelines of Edmonton, Alberta tested an echo sounder off Byam Martin Channel for measuring the bottom surface through the ice. In this system being investigated by Bannister, the "jugs", or geophones, are placed in contact with the ice surface (note: it is necessary to sweep the snow away from the ice surface). Though not yet published, the results apparently exhibit close correlation with core samples.

One of the apparent benefits, although not yet investigated, is a profile of the ice. If this profile is altered significantly by the presence of oil, then the acoustical technique could hold great promise for the surveillance and monitoring of oil discharges from above the ice cover. This technique should be pursued to the next stage of assessment.

5.3 Resistivity Measurements

Late in the course of this study, contact was made with Huntec(70) Limited in Toronto. Give ice approximately six feet thick and an ice/oil conductivity contrast of at least two orders of magnitude, the scientists at

Huntec felt that a simple resistivity survey would be capable of mapping the boundaries of puddles to within one or two feet. The method would be based on inductively-coupled resistivity.

The technique was not pursued further but the concept sounds interesting and may prove very worthwhile. The next stage in the investigation of a system based on this technique would be to conduct a technical assessment followed by a field trial if that should show promise. To conduct the technical assessment, information would be required on the electrical conductivity of sea ice and its variation with ice thickness, age, et cetera.

5.4 Gas Analyzers (Sniffers)

Gas analyzers operate on the principal of detecting the decrease in energy in the incoming radiation due to the presence of an absorbing target gas. Barringer Research of Toronto have developed correlation gas analyzers suitable for aircraft mounting. However, because of the low concentrations that would be involved in this particular situation, a system mounted in a fixed wing aircraft does not appear practical.

One alternative would be to lower an instrument near the ice surface from a helicopter. The advantage of this technique is that men and equipment would not have to be transferred onto the ice surface. The instruments also do not rely on any ambient illumination.

Norcor Engineering and Research Limited employed a "sniffer" on the ice surface during their 1974/75 experiments. The system apparently performed very well. A "personal" type of sensor such as this could be considered as an alternative to a system operated from a helicopter. Gas analyzers are available commercially but the particular application we have postulated in this section remains conceptual in nature.

5.5 Manual and Other Techniques

Perhaps the most economical, and certainly the simplest, technique for checking the underside of the ice is to auger a hole through the ice mantle. "A two man crew with a portable power head could auger over 10 holes per hour through ice up to 2 metres thick".*

In the surveillance mode, men and equipment would be transferred to the ice surface in the vicinity of the site. A predetermined search pattern, based on the maximum likelihood of detecting oil from a discharge given the plume characteristics, currents, and under ice profile, would establish the locations for coring. This procedure would be repeated at regular intervals throughout the period of solid ice cover.

If oil is detected in the shorefast zone, then a second search pattern would be put into affect to determine and monitor the extent of the containment

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* Appendix A

under the ice. This monitoring probably would continue until the melting and break-up process begins. Assuming a static condition with a relatively smooth underside to the ice, the absence of currents, a stable lens thickness of 2 cm, and an initial discharge of 2500 barrels a day decreasing linearly to 1000 barrels a day after one month, the entire discharge over 280 days could be contained within a radius of 2850 feet, or about half a mile.

In the seasonal pack and polar pack zones, exact determination of the areal extent and tracking would be difficult because of the ice movement. If oil is found in these regions during the coring, a simple radar reflector, such as a cube or pyramid mounted on a standard, could be imbedded in the ice. These reflectors could be installed over the site at regular intervals. The spill could be tracked using the drift of these reflectors.

An alternative would be a series of beacons, or transponders each with their own internal power source. This would enable any aircraft to "home" on the signal or interrogate the transponder rather than limiting the tracking aircraft to one equipped with suitable radar instrumentation.

5.6 Conclusions - Other Technologies

In this section, we have introduced technologies which might have application to the surveillance or monitoring of oil discharges in the arctic environment. Some of these techniques, while they may produce the desired results, are obviously impractical. A summary of the technologies which should receive further consideration as possible elements in any proposed system is presented in Figure 5.

FIGURE 5

ASSESSMENT OF OTHER TECHNOLOGIES

	OPERATING LIMITATIONS	OPERATIONAL STATUS	AVAILABILITY	PRACTICAL CONSIDERATIONS OR LIMITATIONS
UNMANNED UNDERWATER VEHICLE	to be determined; vehicle available; technical assessment required.	application is conceptual.	to purchaser's specifications	weight (500 lb.)
REMOTE PACKAGE	to be determined; concept only; may operate under extensive ice cover.	conceptual	concept only; components available	no operator required on the site
ACOUSTICAL	to be determined; concept only; operated from on the ice	conceptual	concept only; equipment at R & D stage.	large number of data points required.
RESISTIVITY	to be determined; concept only; operated from on the ice.	conceptual	concept only; equipment available	large number of data points required.
GAS ANALYSER	hand device operates over 1st yr. ice; operation from platform concept only.	use as a "remote" sensor conceptual	commercial	demonstrated success with hand system.
MANUAL AND OTHET TECHNIQUES	environmental conditions for manual operation.	commercial	commercial	relatively inexpensive; demonstrated success.

6.0 A PROPOSED SYSTEM

In proposing a system for the surveillance and monitoring roles, we have considered two stages of development. The first is to propose a system which can be implemented when the exploratory drilling commences and which can cover as much of the year and as many of the ice/water states as possible. While some elements of the proposed system are conceptual in terms of the selected application all involve equipment or components now available commercially. This stage is termed Surveillance (1976) and Monitoring (1976).

The second stage in the development incorporates potential improvements to the initial operating system. In each case, the proposed change requires some level of development. Some changes would require only field testing and evaluation under actual operating conditions; in fact, some of these modifications could be incorporated before the commencement of the drilling program if plans were established to conduct the necessary test and evaluation program over the 1975/76 season. Other changes or modifications to the initial system would require a significant research and development effort and still others would benefit first from a preliminary technical assessment. For the purpose of categorization, this stage is referred to as Surveillance (Beyond 1976) and Monitoring (Beyond 1976).

One of the most important criterion used in the selection of equipments was that they be available to-day and in addition, for any remote sensing instruments, that they be mounted in an aircraft in Canada at the present time. If the sensors are not already mounted then we considered that they must be available as off-the-shelf items and that suitable aircraft can be modified by the time the exploratory drilling program commences.

Some of the remote sensing instruments, such as L^3TV or a passive microwave imaging device, can be mounted on light aircraft. Others, such as SLAR or pulsed laser systems, are either too heavy or require too much power and must be mounted on larger aircraft. It is unlikely that any large aircraft, such as an Electra or Hercules, would be dedicated to the surveillance and monitoring of oil spills in the Beaufort Sea. Therefore for any element of the proposed system which requires remote sensing instrumentation, we have considered two packages - remote sensing package (light) for use with light aircraft and remote sensing package (major) for use only in larger aircraft. The allocation of specific instruments to either of the sensor packages is determined in the particular system and role under consideration.

In some cases, both a primary and secondary system are recommended. This was done for the open water case because the federal government may wish to invoke some check during the drilling season to supplement reports from the industry. Secondary systems are recommended for the period of total ice cover because of the severe environmental conditions which might prevail at that time.

6.1 Surveillance (1976)

The proposed instrumentation for incorporation into a system for undertaking the surveillance role in 1976 is listed in

Figure 6. It should be emphasized that the instruments for the proposed systems labelled (1976) must now be available as off-the-shelf items. During the freeze-up and break-up periods, areas of open water would permit the utilization of thermal IR line scanners and low light level television operated from a light aircraft. These systems could be operated over any of the three ice states. However, the system would not have all weather capability, but our condition that any recommended instrument must be available off-the-shelf precludes the addition at this stage of any microwave system (the thermal IR would be limited only by rain or substantial cloud cover). With the onset of complete ice cover, these techniques would only operate over ice openings-leads, fractures, and polynyas. Becuase of the low probability of VFR conditions during this period, we have added a SLAR to the sensor package thereby upgrading the system to "remote sensing package (major)". For the assessment of remote sensing technologies, we noted that SLAR would not be effective in the presence of ice due to strong reflections from the edges. Since fractures and polynyas can be wide (large fractures can exceed 500 metres in width), the SLAR may have an operational role in this condition, particularly with the thermal IR line scanner and L^3TV as support.

Without question, the operation of remote sensing instruments will be limited during the period of virtually total ice cover. Therefore we have introduced the manual technique of ice coring as a primary system. Crews would be dispatched to the site, or sites, at regular intervals to remove ice cores and check for oil. The coring pattern

FIGURE 6

PROPOSED INSTRUMENTATION FOR A SURVEILLANCE SYSTEM IN 1976

	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
FREEZE-UP	1. Thermal IR Line Scanner & L^{3}TV.	1. Thermal IR Line Scanner & L^{3}TV	1. Thermal IR Line Scanner & L^{3}TV
9/10 - 10/10 ICE COVER	1. Ice Augers & Gas Analyzers 2. SLAR, L^{3}TV, & Thermal IR Line Scanner (over ice openings)	1. Ice Augers & Gas Analyzers 2. SLAR, L^{3}TV, & Thermal IR Line Scanner (over ice openings)	1. Ice Augers & Gas Analyzers 2. SLAR, L^{3}TV, & Thermal IR Line Scanner (over ice openings)
BREAK-UP	1. Thermal IR Line Scanner & L^{3}TV	1. Thermal IR Line Scanner & L^{3}TV	1. Thermal IR Line Scanner & L^{3}TV
OPEN WATER	1. Drilling Team & Observers 2. Occasional flights with SLAR and/or Thermal IR Line Scanner & L^{3}TV	1. Drilling Team & Observers 2. Occasional flights with SLAR and/or Thermal IR Line Scanner & L^{3}TV	1. Drilling Team & Observers 2. Occasional flights with SLAR and/or Thermal IR Line Scanner & L^{3}TV

1. primary system
2. secondary system

would be established as a result of the analysis of expected plume characteristics, currents, and under side profile of the ice.

The SLAR on the remote sensing package also could be used to map the ice surface in the vicinity of the drill site. The output from the SLAR could provide an early warning device for the intrusion of large sails (and therefore correspondingly large keels) near the drill site. If an exceptionally large sail, or floe, passes near the site then the crews could be dispatched to run an additional augering program.

In the open water case, the primary surveillance role would be filled by the crew on the drilling ship. Occasional flights using SLAR, or the remote sensing package from the light aircraft (thermal IR scanner and L^3TV) depending on what systems were available, would provide additional surveillance coverage.

6.2 Surveillance (Beyond 1976)

Beyond 1976, we look forward to improvements, particularly for the 9/10 - 10/10 ice cover period. The proposed instrumentation for the surveillance role beyond 1976 is summarized in Figure 7. The system presented in Figure 7 is considered the "first priority". Some secondary systems are proposed but again these are mainly to provide support during adverse weather conditions or to supplement information supplied by the oil industry. However, the system of "first priority" consists of some elements which require testing or are simply conceptual at this time. None of

FIGURE 7

PROPOSED INSTRUMENTATION FOR A SURVEILLANCE SYSTEM BEYOND 1976

(Equipments of First Priority)

	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
FREEZE-UP	1. in situ sensors	1. in situ sensors	1. in situ sensors
9/10 - 10/10 ICE COVER	1. in situ sensors 2. SLAR, FLIR, Microwave Imaging Radiometer, & L^3TV (over ice openings)	1. in situ sensors 2. SLAR, FLIR, Microwave Imaging Radiometer, & L^3TV (over ice openings)	1. in situ sensors 2. SLAR, FLIR, Microwave Imaging Radiometer, & L^3TV (over ice openings)
BREAK-UP	1. in situ sensors	1. in situ sensors	1. in situ sensors
OPEN WATER	1. Drilling Team & Observers 2. Occasional flights with SLAR, FLIR, L^3TV & Microwave Imaging Radiometer	1. Drilling Team & Observers 2. Occasional flights with SLAR, FLIR, L^3TV, & Microwave Imaging Radiometer	1. Drilling Team & Observers 2. Occasional flights with SLAR, FLIR, L^3TV, & Microwave Imaging Radiometer

1. primary system
2. secondary system

the elements which are "improvements" to the (1976) system can be considered "off-the-shelf" procurement.

Technical assessments or test and evaluation programs may indicate that the changes proposed are not feasible. Therefore, in some instances, elements which might be considered second, or even third, priority have been considered. If these also prove not to be feasible then the appropriate element from the (1976) system should be inserted.

The major change for the surveillance (Beyond 1976) system would be the introduction of in situ sensor packages located on the ocean floor in the vicinity of the drill sites. These packages would form the primary surveillance role for both the 9/10 - 10/10 ice cover period, and the freeze-up and break-up periods.

The sensors in the array would include some form of oil detector and perhaps a television system for visual inspection of the drill site. The packages, which would be placed prior to the drill ship leaving the site, either could transmit continually or respond only to signals from the command and control centre.

The communications link would incorporate a transmitter from the array to an underwater geophone located in the shorefast zone. The required antennas at the drill site could be laid on the ocean floor. The antenna for transmission from the receiving station in the shorefast zone to the command and control centre could be similar to the Arctic Data Buoy designed by the University of Washington.*

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* Jane's, "Ocean Technology, 1974-75", edited by Robert L. Trills, Jane's Yearbooks, London, England, 1975.

These buoys cost approximately $5,000 and are designed to be left unattended for up to two years (eight had been built by early 1974).

For the seasonal pack and polar pack ice zones the second priority system would be the remote package (light) from the 1976) system but with FLIR replacing the thermal IR line scanner, (a combination of FLIR and low light level television), and augmented by a passive microwave imager. This would increase the capability to include all weather coverage.

The microwave radiometer also is recommended for testing in the shorefast zone during the 9/10 - 10/10 ice cover period as a second priority system. In addition, the acoustical and resistivity techniques should be evaluated for possible application in the seasonal pack and polar pack regions. If successful, this would reduce the frequency with which crews must be dispatched to the drill site to conduct a surveillance program. Provided that the in situ sensors remained operable, investigation by the acoustical or resistivity techniques would not be required.

The proposed primary and secondary systems for the open water situation remain unchanged. The proposed secondary system for the 9/10 - 10/10 ice cover would benefit by the addition of a passive microwave imaging radiometer.

For those elements where alternate systems are proposed, the second and third priority elements are summarized below:

FIRST PRIORITY	SECOND PRIORITY
in situ sensors (9/10 - 10/10 ice cover)	acoustical or restivity techniques.
in situ sensors (freeze-up & break-up)	passive microwave imaging radiometer added to the remote sensing package.
in situ sensors (shorefast zone)	passive microwave imaging radiometer added to the remote sensing package.

6.3 Monitoring (1976)

The monitoring program would be put into affect only after the detection of oil from the surveillance program. The purpose of the monitoring program will be to provide the following information to the command and control centre charged with the containment and clean-up operations:

1. areal extent
2. points of concentration
3. tracking

A system proposed for implementation by 1976 to provide these data items is summarized in Figure 8. The system covers the four periods for each of the ice zones.

A sensor combination incorporating a thermal IR line scanner and a low light level television (remote sensing package - light) would be the primary system in all cases except for the 9/10 - 10/10 ice cover. This system would provide information on the areal extent of the spill and points of concentration, and assist in the tracking.

FIGURE 8

PROPOSED INSTRUMENTATION FOR A MONITORING SYSTEM IN 1976

	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
FREEZE-UP	1. Thermal IR Line Scanner & L^3TV	1. Thermal IR Line Scanner & L^3TV	1. Thermal IR Line Scanner & L^3TV
9/10 - 10/10 ICE COVER	1. Ice Augers & Gas Analyzers	1. Radar Reflectors/ Beacons	1. Radar Reflectors/ Beacons
	2. SLAR, Thermal IR Line Scanner, & L^3TV (over ice openings)	2. SLAR, Thermal IR Line Scanner & L^3TV (over ice openings)	2. SLAR, Thermal IR Line Scanner & L^3TV (over ice openings)
BREAK-UP	1. Thermal IR Line Scanner & L^3TV	1. Thermal IR Line Scanner & L^3TV	1. Thermal IR Line Scanner & L^3TV
OPEN WATER	1. SLAR, Thermal IR Line Scanner, & L^3TV	1. SLAR, Thermal IR Line Scanner, & L^3TV	1. SLAR, Thermal IR Line Scanner, & L^3TV

1. primary system
2. secondary system

Because the system does not have all weather capability a SLAR could be incorporated for the open water case (thereby upgrading the system to a remote sensing package - major). Except for the exclusion of the imaging microwave radiometer, this would be similar to the AOSS system. However, the imager has not been considered here because it is not an "off-the-shelf" procurement. It was a prototype built to U.S. Coast Guard specifications. The major system is not considered in the freeze-up or break-up since the effectiveness is questionable.

For the case of 9/10 - 10/10 ice cover in the shorefast zone, a program involving the manual task of dispatching men and equipment to the ice surface and taking core samples would be instituted. The main objective of the program would be to monitor the extent of the discharge under the ice surface in preparation for the clean-up phase. Gas analyzers would be introduced to support and direct the coring program.

Gas Analyzers have not been proposed for the seasonal pack or polar pack regions since their effectiveness over multi-year ice and ice of considerable thickness is unknown. For these regions we have proposed the installation of radar reflectors, or beacons, placed at regular intervals over the drill site. These reflectors, or beacons, would assist in tracking at least one dimension of the extent of the spill. An ice coring program could be introduced to provide some indication of the spread if required.

A sensor package incorporating SLAR, thermal IR line scanner, and L^3TV could be flown over ice openings to investigate possible drift of the spill into leads, fractures or polynyas.

6.4 Monitoring (Beyond 1976)

An improved system for the monitoring role beyond 1976 is proposed in Figure 9. Because the clean-up operation would take place during the open water period, two sensor packages are recommended. The major system, incorporating at least SLAR, microwave imaging radiometer, and FLIR, would provide an overview of the complete spill area and surrounding water and would act as the primary tracking system. The lighter package, incorporating at least FLIR, L^3TV, and an imaging microwave radiometer, would be mounted on a light aircraft, or preferably a helicopter, to provide specific information directly to the clean-up crews on exact areal extent and points of concentration.

If clean-up operations continue into the freeze-up period or commence during break-up, the same remote sensing systems are proposed for these two periods. However, if clean-up operations cease, monitoring activities from only one of the systems would be required.

The proposed system (Beyond 1976) still names the radar reflectors, or beacons, as the first priority system in the seasonal pack and polar pack zones during 9/10 - 10/10 ice cover. These will provide data on areal extent at least in one dimension which should be sufficient information to track the spill. This would be augmented

FIGURE 9

PROPOSED INSTRUMENTATION FOR A MONITORING SYSTEM BEYOND 1976

(Equipments of First Priority)

	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
FREEZE-UP	1. Remote Sensing Package (Major) - SLAR, FLIR & Microwave Imaging Radiometer	1. Remote Sensing Package (Major) - SLAR, FLIR & Microwave Imaging Radiometer	1. Remote Sensing Package (Major) - SLAR, FLIR & Microwave Imaging Radiometer
	& Remote Sensing Package (Light)* - FLIR, L^3TV & Microwave Imaging Radiometer	& Remote Sensing Package (Light)* - FLIR, L^3TV & Microwave Imaging Radiometer	& Remote Sensing Package (Light)* - FLIR, L^3TV & Microwave Imaging Radiometer
9/10 - 10/10 ICE COVER	1. Remote Sensing Package (Light) - FLIR, L^3TV & Microwave Imaging Radiometer	1. Radar Reflectors/ Beacons & Acoustical or Resistivity Techniques	1. Radar Reflectors/ Beacons & Acoustical or Resistivity Techniques
	2. Remote Sensing Package (Major) -SLAR, FLIR & Microwave Imaging Radiometer	2. Remote Sensing Package (Major) - SLAR, FLIR & Microwave Imaging Radiometer	2. Remote Sensing Package (Major) - SLAR, FLIR & Microwave Imaging Radiometer

* either the Major or the Light Remote Sensing Package can be excluded if the clean-up crews are not working in these periods.

1. primary system
2. secondary system

FIGURE 9 (page 2/2)

PROPOSED INSTRUMENTATION FOR A MONITORING SYSTEM BEYOND 1976

(Equipments of First Priority)

	SHOREFAST ZONE	SEASONAL PACK ZONE	POLAR PACK ZONE
BREAK-UP	same as FREEZE-UP	same as FREEZE-UP	same as FREEZE-UP
OPEN WATER	same as FREEZE-UP	same as FREEZE-UP	same as FREEZE-UP

by acoustical or resistivity techniques to map, at regular intervals, the extent of the oil spill in the second dimension. All of this information would be stored and analyzed for use during the clean-up operation. The sensor package incorporating SLAR, microwave imaging radiometer, FLIR, and L^{3}TV would be flown over ice openings as a secondary system to check for oil drifting into leads, fractures, or polynyas. The remote sensing system would be operated over all three ice zones.

The unmanned underwater submersible is proposed as a second priority system in case the evaluation or testing of the acoustical and resistivity techniques indicates that the required information cannot be obtained using these techniques or the submersible can provide additional support by surveying and inspecting the drill site.

The primary system in the shorefast zone would be a microwave radiometer operating between 400 MHz and 2000 MHz. As a second priority system, this could be replaced by, or supported with, an impulse radar operating from 100 MHz up to 1 GHz. These systems would be used to produce detailed maps of the distribution of oil beneath the ice surface. The first and second priority systems may be summarized as follows:

FIRST PRIORITY	SECOND PRIORITY
radar reflectors/ beacons and acoustical or resistivity techniques.	unmanned submersible
microwave radiometer	impulse radar

7.0 IMPLEMENTATION OF THE PROPOSED SYSTEM

Not all of the instruments or technologies identified in the proposed surveillance and monitoring system are currently available for implementation in 1976, particularly the suggested improvements. In some cases, only field testing in the Beaufort Sea environment is required; but, for others, which are only conceptual, several steps must be completed before the instrument or system reaches operational status.

In this section, we present a scenario of how the system might be managed and operated, including commentary on the availability of resources for use in implementing the systems described.

7.1 Operational Considerations

It is not sufficient to limit consideration of an operating system to its elements. Consideration also must be given to the logistical support and management of the operation. For the surveillance and monitoring of oil spills at the Beaufort Sea, we have assumed the existence of a command and control function charged with no less than surveillance of the exploration, and later production, programs and, in the event of an oil spill, the containment and clean-up functions. With this background, we then are concerned with information flow from the command and control centre, in the form of command decisions, and the flow from the surveillance and monitoring system in the form of data and real time imagery, whenever possible.

The surveillance and monitoring program requires logistical support for the instrumentation previously recommended. This support must include:

1. available instrumentation and systems.
2. airstrips
3. aircraft (including modified)
4. communications
5. navigational aids

We have attempted to indicate the availability of the logistical support whenever possible.

Not all the elements of the surveillance and monitoring system are required on the 24 hour clock. Some elements will be required only in case of emergency, others will be required periodically, while still others will be required on a year round basis.

Surveillance (1976) - During the open water period, the surveillance role would be a function for the crew and observers aboard the drilling ship. Occasional flights over the sites with SLAR would provide a secondary system. Because of the cost for a SLAR (between approximately $500,000 and $1,000,000, depending on the instrument) and the aircraft requirements for carrying the instrument, it would be impractical to consider a dedicated system for this role. However, aircraft from the Department of National Defence equipped with SLAR may be tasked for this purpose. At present, DND are flight testing a SLAR aboard an Argus aircraft and have given serious consideration to civilian tasking of the long range patrol aircraft (LRPA). The LRPA would not require airstrips in the area and therefore some thought would have to be given to the communications link between the aircraft and the command and control centre.

The Department of the Environment also are expected to acquire a SLAR in the near future, mounted on a Lockheed Electra. The Electra, with a payload of 26,500 pounds, requires a runway of at least 4,700 feet for takeoff. Runways capable of handling the Electra exist at Inuvik and Cape Parry (Appendix A).*

Surveillance in the freeze-up and break-up periods would be covered with a thermal IR line scanner and low light level television. Both instruments could be mounted on a light aircraft. Inotech which recently assumed responsibility for the airborne operations of the Canada Centre for Remote Sensing operates a C47 (Dakota) and a Falcon. The Dakota carries, among other sensors, a Daedalus IR scanner and low light level television. This aircraft could be tasked with the surveillance role identified for this period. Inotech also flys a Falcon equipped with an RS14 IR scanner but not with L^3TV. The Falcon would be preferred over the Dakota because of its speed and therefore better flight time to the task.

During the period of 9/10 - 10/10 cover, the primary surveillance role would be undertaken by crews transferred to the ice cover at the drill site. These crews would complete a predetermined coring program. They could be moved to the location by helicopters from the wintering drilling ships. Again, the role of a secondary system would be filled by a SLAR but augmented in this case by a thermal IR line scanner and L^3TV. This role could be assigned to the DND LRPA.

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* Data on logistical support in the Beaufort Sea area provided by Norcor Engineering and Research Limited. Incorporated in Appendix A.

Satellite imagery, from NOAA or one of the two ERTS satellites, would be reviewed to indicate the location of leads, fractures or polynyas in the vicinity of the drill site. The aircraft equipped with the sensor package then would be directed to search the ice openings indicated from the satellite imagery. During the flight, the SLAR would survey the ice sheet for the presence of large sails. If there are any in the vicinity they should be tracked and an addition made to the coring program if a sail passes close to a drill site.

Surveillance (Beyond 1976) - The surveillance system would remain unchanged for the open water period. For the other three periods (freeze-up, 9/10 - 10/10 ice cover, and break-up), the primary surveillance system would be an in situ sensor array. This sensor array would be installed on the ocean floor in the vicinity of the drill site shortly before the drill ship leaves the site. The receiver and retransmitter would be installed in the shorefast zone and all communications links checked.

If these packages could not be developed then for the freeze-up and break-up in the seasonal pack and polar pack regions, the system would be similar to the primary system described for the surveillance (1976) role - a thermal IR line scanner and L^3TV.

The Inotech aircraft equipped with these sensors again would be tasked to perform this surveillance role. For surveying the shorefast zone, a UHF radiometer could be added to the sensor package, either mounted on the Dakota or preferably the Falcon.

For the 9/10 - 10/10 ice cover situation, the second priority system would incorporate either acoustical or resistivity techniques. In the shorefast zone this would be a redundant system to a UHF radiometer. As with the ice coring program, crews would be transferred to the ice surface to conduct the acoustical or the resistivity tests. The necessary equipment for this system would be stored and maintained in the Beaufort Sea area.

A sensor package comprising SLAR, thermal IR line scanner and L^3TV would continue to be flown from the LRPA to survey ice openings and search for excessive sails in the pack ice regions.

Monitoring (1976) - The monitoring systems would be put into affect after the presence of oil has been detected. During the open water period the major monitoring system would consist of a sensor package comprising SLAR, a thermal IR scanner and low light level television (L^3TV). The SLAR and L^3TV would be used to map the areal extent of the spill and track the direction of the spill. The thermal IR line scanner would be used to map the concentrations within the spills to assist in the placing of clean-up equipment.

The sensors could be part of the LRPA of DND tasked for civilian use. The aircraft would have to be dedicated to the task of monitoring the spill throughout this period and this could create some problems. One alternative would be to task the Dakota or Falcon from Inotech (formerly located at CCRS). Both of these aircraft could operate from the airstrip at Inuvik (the Falcon requires a paved runway). Using these aircraft would mean that SLAR would not be part of the sensor package. In the AOSS (Airborne Oil Surveillance System) operated by the U.S. Coast Guard, the SLAR is used primarily as the first step in the detection of oil spills because of its significant area coverage. Its main function in the multi-sensor approach advocated in this report is to provide all weather capability. The probability of adverse weather conditions would be least likely at this time of year.

Because of the emergency situation that would be created by the containment and clean-up operations, it might be feasible to consider requesting assistance from the U.S. Coast Guard system, particularly if the LRPA of DND did not have the appropriate sensors mounted at that time. The AOSS tested by the U.S. Coast Guard consists of a SLAR, passive microwave imager, line scanner and L^3TV mounted in a Grumman Albatross. This aircraft has completed the hours on the airframe and the sensor package has been removed. U.S. Coast Guard plans now call for mounting the system into a C-130, or Hercules, aircraft. This aircraft has an exceedingly long range (5,000 miles with maximum fuel load) and the U.S. Coast Guard has considerable experience operating these aircraft from Fairbanks, Alaska. Finally, they do have crews already trained in operating the equipment and interpreting the results.

A third alternative would be to consider the Electra to be acquired by Atmospheric Environmental Services. This aircraft will probably carry a SLAR and possibly most of the other sensors identified in the system. The multi-sensor system would be used in the case of 9/10 - 10/10 ice cover to track the oil spill if it came in contact with fractures, leads or polynyas. In this case it would not be necessary for the aircraft to be dedicated to this task. Flights over the area of interest would be required only when satellite imagery, or surveillance flights of the ice using SLAR, indicated the presence of ice openings. If crews were dispatched to the open water area, lighter aircraft (including helicopters) could be used to provide the definitive information on the location of the spill within the ice opening. The sensor package in this case could be limited to a thermal IR scanner and L^3TV (the aircraft from Inotech might be considered for this role).

The primary monitoring system in the shorefast zone during 9/10 - 10/10 ice cover period would involve crews dispatched at regular intervals to the ice surface to conduct a coring program and map the extent of the spill under the ice surface. The crews could be transferred to the site using the helicopters from the drill ship. Hand-held gas analyzers also could be employed to assist in establishing the coring program.

On the seasonal pack and polar pack ice, the coring program could be more limited. The important element in these areas would be the planting of radar reflectors or beacons over the site at regular intervals during this period of the year. Reconnaissance flights then could be flown to track the reflectors and, by inference, the spill. Several of these reflectors could be stored in the area, ready for immediate use.

During the freeze-up and break-up periods, the monitoring would be undertaken using a thermal IR scanner and L^3TV. Again, the aircraft from Inotech could be tasked with this role. Alternately, a DND aircraft might be assigned the task.

Monitoring (Beyond 1976)

Beyond 1976, the major improvements to the remote sensing packages could be the addition of a microwave imaging radiometer, and a forward looking IR (FLIR).
If field trials proved the instrument reliable, the microwave radiometer could be used to map the spill under the shore-fast zone during 9/10 - 10/10 ice cover (if required, crews occasionally could be sent to the site to check the results using gas analyzers, or coring through the ice).

In the seasonal pack and polar pack regions, the major tracking system would continue to be the placing of radar reflectors or beacons. However, while these were being placed, mapping of the extent of the spill under the ice could be conducted using acoustical or resistivity techniques. This probably would require only limited coring of the ice.

If a scientific and technical assessment of the acoustical or resistivity techniques, or later field trials, demonstrated that these techniques were not feasible then the unmanned underwater submersible might be considered. The submersible which might weigh approximately 500 lbs with full instrument package could be transported to the location by helicopter. An ice hole approximately 2 feet in diameter should be sufficient to lower the submersible into the water. The submersible could be used both to map the extent of the spill and inspect the drill site.

A similar sensor package to that proposed for implementation in 1976, except for the addition of FLIR, and microwave imaging radiomater would be used for tracking oil which might flow into leads, fractures or polynyas.

The final elements to consider adding in the improved monitoring system is a SLAR and a FLIR, to replace the thermal IR line scanner. The SLAR might improve the information on areal extent and tracking of the spill during the freeze-up and break-up periods and certainly could increase the probability of operating the system during poor optical conditions. On the other hand, the system then could not be flown on a light aircraft thereby reducing its versatility. Only a flight test of a SLAR in this capacity could enable a proper decision to be reached.

8.0 RECOMMENDATIONS FOR IMPLEMENTATION

After evaluating several technologies including the supporting logistics and skills required, we concluded that the following instruments could be incorporated into a system to be tasked with the role of surveillance and monitoring of oil spills in the Beaufort Sea upon commencement of the drilling and exploration program:

SURVEILLANCE ROLE (1976)

REMOTE SENSING PACKAGE (Light aircraft)
- thermal IR line scanner
- L^3TV

REMOTE SENSING PACKAGE (Major)
- SLAR
- thermal IR line scanner
- L^3TV

ICE CORING PROGRAM
- ice augers
- gas analyzers

MONITORING ROLE (1976)

REMOTE SENSING PACKAGE (Light aircraft)

- thermal IR line scanner
- L^3TV

REMOTE SENSING PACKAGE (Major)

- SLAR
- thermal IR line scanner
- L^3TV

ICE CORING PROGRAM

- ice augers
- gas analyzers

RADAR REFLECTORS/BEACONS

If improvements or additions to these (1976) systems appear viable following test and evaluation of, or research and development on, alternate instruments then the following systems should be considered for the surveillance and monitoring roles. Where a possible alternative exists, it has been indicated as a second or third priority. In some cases the alternatives are limited and the second or third priority element defaults to the instrumentation proposed for 1976.

SURVEILLANCE ROLE (BEYOND 1976)

FIRST PRIORITY	SECOND PRIORITY		ALTERNATE
IN SITU SENSORS	ACOUSTICAL OR RESISTIVITY TECHNIQUES	- OR -	ICE CORING PROGRAM - ice augers - gas analyzers
	MICROWAVE IMAGING RADIOMETER	- OR -	REMOTE SENSING PACKAGE (Light Aircraft) - thermal IR line scanner - L^3TV
REMOTE SENSING PACKAGE (Major) - SLAR - microwave imaging radiometer - FLIR - L^3TV	REMOTE SENSING PACKAGE (Major) - SLAR - thermal IR line scanner - L^3TV		

MONITORING ROLE (BEYOND 1976)

FIRST PRIORITY	SECOND PRIORITY		ALTERNATE
REMOTE SENSING PACKAGE (MAJOR) - SLAR - microwave imaging radiometer - FLIR - L^3TV	REMOTE SENSING PACKAGE (MAJOR) - SLAR - thermal IR line scanner - L^3TV		-
	ICE CORING PROGRAM - ice augers gas analyzers		-
REMOTE SENSING PACKAGE (Light Aircraft) - microwave imaging radiometer - FLIR - L^3TV	REMOTE SENSING PACKAGE (Light Aircraft) - thermal IR line scanner - L^3TV		-
RADAR REFLECTORS/BEACONS & ACOUSTICAL OR RESISTIVITY TECHNIQUES	UNMANNED SUBMERSIBLE	- OR -	ICE CORING PROGRAM - ice augers - gas analyzers

The following program is proposed in order to implement the above system alternatives in the minimum period of time. We recommend:

1. During the next controlled oil spill under Arctic conditions, the following instruments be field tested and evaluated both independently and operated as a system:
   - SLAR
   - thermal IR line scanner
   - L^3TV

2. A program be instituted during the next period of 9/10 - 10/10 ice cover to place several radar reflectors, beacons or transponders in both the seasonal pack and polar zones during the period of ice cover and to test the ability to track them over the ensuing season.

3. A technical assessment be undertaken of an in situ sensor package, including suitable communications links and constructed from currently available components and equipments. If this assessment demonstrates the feasibility of such a package, an instrument suitable for field operation and testing should be developed and tested.

4. A technical assessment of the application of acoustical and resistivity techniques be undertaken. If this assessment demonstrates the feasibility of either system, then an instrument suitable for field operation and testing should be developed and tested.

5. A forward look IR system (FLIR) be acquired, tested and then introduced into a field testing program as soon as possible.

6. A microwave imaging radiometer be acquired and introduced into a field testing program as soon as possible.

7. *If at any time, the acoustical and resistivity techniques do not appear feasible, consideration should be given to acquiring, modifying (if necessary) and testing an unmanned underwater submersible.*

Having addressed the question of using remote and surface sensing techniques, and the problems of detecting and mapping oil under thick ice, and having considered the problems of flying at all seasons in the Beaufort Sea area and the prospect of maintaining crews on the surface under severe weather conditions, the underwater alternatives start to look increasingly attractive. There the environment is benign and predictable. Instruments and equipment can remain there month after month, year after year undisturbed. While it is appreciated that there is always some dangers from grounding pressure ridge keels in certain locations, we would urge that underwater technology be reviewed seriously for ongoing operations in the Beaufort Sea. Recommendations 3 and 7 above reflect this view, but it is suspected that more than just the oilspill detector and mapping problem would benefit from the underwater approach.

AN INVESTIGATION OF SYSTEMS FOR THE SURVEILLANCE AND MONITORING OF OIL SPILLS AT BEAUFORT SEA

APPENDICES

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TABLE OF CONTENTS

APPENDIX A

Report on Oil/Ice/Water States and Logistical Support in the Beaufort Sea Area

NORCOR
engineering and research limited

REPORT ON THE
REMOTE SENSING OF OIL SPILLS
IN THE BEAUFORT SEA

CANADA CENTRE FOR REMOTE SENSING

TABLE OF CONTENTS

1.0 INTRODUCTION

The following report was prepared for Philip A. Lapp Limited as part of a study of Remote Sensing of Oil Spills in the Beaufort Sea.

The report details the principal oil, ice and water configurations which could develop as a result of an oil spill in the area being proposed for offshore drilling. The emphasis has been placed on factors relating to detection. Research to date has been confined to open water areas and the fast ice zone, and consequently the descriptions for the seasonal and polar packs are somewhat speculative. A section on ice conditions has been included as an aid to interpreting the various configurations. Since conditions are extremely variable, the information should only be used as a general guide.

The final section entitled Operational Considerations includes an analysis of the probability of success for various types of airborne missions staged from three locations around the Beaufort Sea. Information on air strips and associated support facilities in the general area has been summarized.

2.0 SUMMARY OF ICE CONDITIONS

Ice conditions in the area proposed for offshore drilling can be divided into three basic categories; shorefast ice, seasonal pack-ice, and polar pack-ice. Due to the extreme variability as well as the general lack of data for all three zones, it is impossible to predict with any degree of certainty the ice conditions likely to prevail at a given time of the year for most locations. The following summaries are included solely as an aid to interpreting the information on oil in ice configurations, presented in Section 3.0.

The shorefast zone encompasses the band of seasonal ice immediately adjacent to the shore. New ice begins to form about early October and normally reaches a thickness of approximately 2.0m by mid May. The zone typically extends to about the 20m seabed contour by spring (Kovacs, 1974) but can vary considerably depending on the coastal geometry. The sheet tends to be constrained by irregularities in the shoreline, and movement is generally limited during the winter.

Ice first forms in shallow bays and inlets, or areas with reduced salinity, such as the mouths of rivers. Once the temperature of the water is sufficiently depressed, and this depends in part on salinity and circulation, small salt-free ice spinacles and thin platelets begin to form on the surface. These rapidly grow in number until the surface is covered by a sludge or slush. In quiescent seas the layer thickens and hardens into nilas or black ice. More often the slush or grease ice is fragmented by wave action, and the characteristic pancake ice develops. The pancakes tend to dampen movement, and with time thicken and gradually grow together. Depending on atmospheric conditions at the time of freeze-up, isolated remnants of second and multi-year ice can be locked in the sheet.

New ice can grow as much as 10cm in the first 24 hours. Thereafter, the rate decreases appreciably. A reasonable linear correlation has been established between the square of the ice thickness and the cumulative degree days below freezing (Burns, 1974). By late December the sheet is generally in the range of 100cm thick. A maximum ice thickness is achieved by about mid May. This varies considerably between locations and from year to year, but is typically about 2.0m. Variations greater than 0.5m have been observed. Due to the high level of radiation in the spring, melt pools quickly develop, and signs of deterioration are normally evident by early June. Most areas are clear of ice by the middle of July.

The salinity of the ice is dependent on its age, thickness and to some extent its rate of growth. Salinity profiles tend to go through a systematic series of changes as the ice growth progresses. Very high salinities, in excess of 40°/₀₀, have been observed at the top of the sheet. As a rule, the salinity near the top and bottom of the sheet is about 1.0°/₀₀ higher than the average for the sheet, which varies from approximately 10°/₀₀ for a sheet 10cm thick to 5°/₀₀ for a sheet 60cm thick or greater.

As multi-year floes are driven into the fast ice, rafting or hummocking occurs, particularly in the fall when the sheet is thin and least resistant to deformation. The severity and duration of the pressure will determine the size and extent of the resulting ice features. Free floating ridges typically have sail heights of about 3 to 5m. The keel depth is approximately five times greater or 15 to 25m. Much larger sails have been observed on grounded ridges. Leads and cracks open as the pressure is released.

The seasonal pack is essentially a transition zone between the fast ice and the polar pack. It contains both first year and multi-year ice, in various stages of consolidation, depending on the time of year and conditions. The seasonal pack moves primarily in response to motion in the polar pack. Like the polar pack, motion is predominantly in a westerly direction. The mean net long term winter ice velocity is in the order of 2.5 to 3.0cm/sec, or about 2.5km/day (Kovacs, 1974). The width of the seasonal pack varies considerably but can extend up to several hundred kilometers. During the summer, the seasonal pack, driven by offshore winds, tends to hug the polar pack, while in the winter it is forced in against the fast ice. Periodically it will drift away from the fast ice, and large recurring leads open, such as the one off Herschel Island.

It is the most dynamic of the three zones. In the fall, the loose ice in the seasonal pack is progressively compressed against the fast ice. Due to rotation of the pack, slippage occurs in a narrow band at the boundary between the two zones. As the stress intensifies, the ice begins to shear. Shear ridges result, or if the pressure is sufficiently great, massive hummock fields. Since the shear rate is considerably greater in the immediate vicinity of the boundary, both the size and density of ridges is higher in this area, and decreases moving towards the polar pack. The ridges are typically up to 4m high, but sails over 12m have been reported. As a result of the continuous shear action, the new ice, which tends to be the weakest point in the matrix, is often deformed, and open water is common even in the depth of winter.

The polar pack generally lies beyond the continental shelf, but can be driven towards the shore at any time by high winds.

Movement of the pack is anticyclonic, and corresponds to the Pacific gyral. The average drift is about two percent of the wind velocity, and due to the coriolis effect, is inclined at about 30 degrees to the wind direction. The dominant mode of motion is barotropic with a speed surge in the fall (Burns, 1974). During the summer, the prevailing flow is offshore and the pack can reside 300 to 400km out. In the winter, the direction tends to be reversed and the pack moves towards the coast. The degree of penetration of the pack will depend on conditions at the time of invasion. If it occurs near freeze-up, before the fast ice can develop any resistance, as was the case in 1971, the pack can approach within several kilometers of the shore. The principal restriction is generally the depth of water. Once the fast ice has thickened, it tends to hold back the advancing pack.

During the winter, approximately 60 to 70 percent of the area of the polar pack is multi-year ice, 1 to 5 percent open water, and the remainder is first year ice (Kovacs, 1974). There is considerable variation in ice thickness, ranging from thin, first year ice in refrozen leads to multi-year pressure ridges, which can exceed 45m in total thickness. By the end of the winter, undisturbed first year ice is typically about 2.3m thick, while old multi-year floes vary from 2.0 to 4.5m in thickness. The salinity of multi-year ice progressively decreases with time due to leaching. Normally the surface layer is essentially fresh, and the average salinity is less than 2‰.

The density and size of ridges varies considerably between locations and from year to year. A typical density would be in the range of 10 to 20 ridges per kilometer. The average ridge height is about 3m. The ratio of the keel to sail height for free floating multi-year ridges is approximately 3 to 1.

There is little data on the natural depletion rate for firm multi-year ice, but it is generally estimated at between four and seven years.

3.0 OIL-ICE-WATER CONFIGURATIONS

Due to the broad range of ice conditions which can exist in the proposed area, numerous oil, ice, water configurations are possible. The six principal conditions are detailed below. The descriptions are general and oriented towards detection. To date, research has been confined primarily to the open water condition and the fast ice zone. Consequently, the descriptions for the seasonal and polar pack zones are somewhat speculative.

3.1 Oil in Open Water at Freeze-Up

The behavior of oil in open water is reasonably well documented in the literature, and only the dominant considerations are outlined herein. Since performance is very much dependent on the properties of the oil it is impossible to be specific. The spreading of an unconfined oil slick in calm sea is a function of the rate of discharge, the density and viscosity of the oil and surface tension effects. Although there are several theoretical derivations for spreading, they are not directly applicable to a blowout. Firstly, if there is gas involved, the water, particularly in the area of the plume, tends to be very turbulent. Secondly, perfectly calm seas are quite uncommon in an ocean environment. Oil slicks move at approximately 1.5 percent of the wind speed. In most cases this would exceed the natural spreading rate under static conditions.

The stable film thickness for most unweathered, low viscosity crudes is in the range of several microns. There generally is some fractionation across a slick, with the lighter, more volatile components appearing near the edge. Interference patterns created by these thin films can be used to estimate the film thickness. Even at the low temperatures encountered in the Arctic, there can be considerable weathering. Under static conditions, over a 40 percent loss is possible in 30 days at 0°C. With turbulent mixing, the evaporation rate is likely to be somewhat greater. With high winds, water in oil emulsions can develop, but they tend to be unstable for most crudes.

The effect of oil on ice growth will depend to a large extent on the film thickness. For thin films, such as might be encountered in an unconfined open water spill, the oil will likely have a minor effect. The first several layers of crystals will tend to be coated with oil, and not coalesce as readily. Thereafter, the sheet should grow in a normal fashion. Although oil on the surface will greatly reduce the albedo, the effect will be minimal since the level of radiation is low in the fall. In most cases a thick film will have a far greater impact. First, the film will severely limit evaporation. The overall effect will depend in part on the extent of coverage. Secondly, the thermal conductivity of most crudes is in the range of 8 to 10 percent that of new ice, and the oil will serve as an insulating layer. These effects will be partially offset by the fact that the oil will tend to dampen wave action, and thereby produce an environment more condusive to ice growth. The net effect of a thick lens should be to retard ice growth.

Regardless of the thickness of the lens, the ice will grow beneath the oil. Until the area is snow covered, the surface will be discoloured. The oil will continue to evaporate even at very low temperatures. Some of the snow crystals will become oiled, and under certain conditions can be transported by the wind. In the spring, as the snow cover begins to warm, the oil will migrate to the surface, and should be quite visible.

3.2 Oil Under Fast Ice

Oil released in a water column, tends to break into small droplets enroute to the surface. When it strikes the underside of the ice sheet it generally coalesces in lenses or pools. The size of the pool is controlled primarily by the quantity of oil and natural irregularities in the sheet. Since the oil coalesces into sessile drops, the minimum thickness is about 0.5cm for most crudes. The maximum thickness is controlled by variations in ice thickness, and can range from several centimetres in the fall to about 20cm in the late spring. The size of the pools is determined by the frequency and configuration of ice irregularities. Due to the large number of factors influencing ice growth, such as currents and snow cover it is difficult to generalize, but under most conditions the pools will be in the range of about 2 to 20m wide. The extent and percentage of area covered depends on the quantity of oil. As each pocket or cell is filled the oil will overflow into adjacent cells. Moved by currents and turbulence, small droplets can be deposited on the ice a considerable distance from the main oil pools.

Under static conditions a lip of ice quickly forms around each lens and further horizontal movement is blocked. As the temperature of the oil is depressed a new sheet of ice begins to grow on the bottom of the oil lens. Generally, the oil is entrapped in the ice within a matter of days. The oil initially penetrates about 5 to 10 centimetres up into the skeletal layer and the soft ice on the bottom of the old sheet. During the depth of winter further migration is limited. The concentration of oil in the brine channels immediately above the lens is in the range of 1.0 to 3.0 percent by volume. There is a distinct discontinuity in ice properties at an oil lens. The lens acts as a barrier to brine rejection, and high salinities are common above the oil. The ice below the lens resembles a new sheet grown at the surface.

In the spring, as the sheet begins to warm and the brine channels become active, the oil begins to migrate towards the surface. The time and rate at which the oil reaches the surface will depend on temperature and the location of the lens in the sheet. A portion of the oil will remain locked in the ice until the melt actually reaches the lens. Late in the spring, oil released under as much as 2m of ice can reach the surface in less than one hour. While the oil is locked in the ice there is very little weathering or fractionation.

3.3 Oil in the Seasonal Pack

Due to the extreme variability in the seasonal pack, conditions are not readily predictable. The principal factors controlling the behavior of the oil are the extent of open water and the degree of movement. Oil released in open water can be driven into the broken ice on the edge of the seasonal pack by wind and wave action. Since the ice will tend to retard spreading, the film is likely to be somewhat thicker than in open water. As the pack compresses the film will thicken and possibly overflow on lower floes. As well, a number of larger pieces of ice are likely to become oiled due to overturning. As the pack opens and closes the oil will progressively penetrate new channels and very large areas could be contaminated. Some emulsification will likely occur.

Oil released under a relatively solid section of the seasonal pack will initially perform in a similar manner to a release under corresponding conditions in the fast or polar pack zones.

However, due to the general lack of stability in the zone, there is a reasonable probability that some oil will be detectable on the surface quite quickly. This surface oil will tend to enhance the melt, and the remaining oil should be released somewhat faster than for the stable case.

Because the seasonal pack is continuously drifting and there are numerous mechanisms for the transport of oil within the zone, much larger areas are likely to be contaminated than in the shorefast or polar pack zones. The presence of oil on the surface should make detection considerably easier.

3.4 Oil in the Polar Pack Ice

In areas covered by first year ice, which generally represent between 30 to 40 percent of the pack, the oil will perform in a similar fashion to the shorefast zone. The principal difference will occur with the multi-year ice. The multi-year ice tends to be more irregular than first-year ice and therefore much deeper pockets of oil are possible. However, the pack is in continuous motion, and most domes would not be filled in the length of time they are within the area of influence of an oil plume. Even allowing for a drift of several kilometers per day, (and drifts of up to 50 kilometers per day have been reported) at the maximum projected discharge rate for a well in the Beaufort Sea only one barrel will be released per linear metre. At the minimum film thickness of 0.5cm, this would cover a swath 30m wide.

Since multi-year ice is generally thicker than first-year ice, and therefore the thermal gradient is not as steep, the oil will not be incorporated as quickly. As well, since the salinity is considerably less, the rate of migration up the brine channels should be substantially reduced. At present, there is no information on the interaction of crude oil with multi-year ice, but the maximum possible time required for the oil to surface will be the natural depletion rate for the ice, which is estimated at between four and seven years. Judging from the effect of oil on first-year ice, the time should be considerably reduced.

Due to movement in the pack, some of the oiled ice is likely to be broken and overturned. This would probably occur in refrozen leads and other first-year ice, which tends to be the weakest link. This could expose oil on the surface much morequicklythan would be possible by means the natural migration process.

3.5 Oil in Leads, Cracks and Broken Ice

The size and shape of leads varies considerably. They can range from less than a kilometer in length to several hundred kilometers. Oil can reach a lead as a result of a release directly below it, oil flowing along the bottom of an adjacent sheet prior to incorporation, by cracks or fractures cutting through a trapped lens, or by surfaced oil running in during the melt phase. The concentration of oil in a lead will depend on the quantity of oil and the size and shape of the lead. Since leads are continuously opening and closing the film thickness will not be constant. Moreover, with a wide lead, the oil could be herded to one side due to wind action. Emulsification of the oil is possible due to wind and wave action, but it is doubtful if the emulsions will be stable.

In general, the oil should perform in a similar fashion to the open water case, with the exception that films will likely be thicker. Due to lead matrix pumping and wave action, there probably will be some contamination of the surrounding ice sheet. Since refrozen leads tend to be the weakest point in the sheet, there is a distinct possibility that oiled ice will be thrown up in pressure ridges and hummocks.

The effect of oil in the tidal crack system will depend on the tidal range, shoreline configuration and the time of year. During the winter, there normally are obstructions at intervals along the crack, which will restrict spreading. Due to the relative movement between ice on either side of the crack, some oil will be pushed to the surface, and should be visible along the edge of the crack. In the spring, a continuous melt pond develops along the crack, and the oil could spread a considerable distance. Oil in the tidal crack system, particularly in the spring, could pose a major threat due to its close proximity to the shoreline.

3.6 Oil on the Ice Surface

In general, only a limited quantity of oil will reach the surface during the winter, by means of leads and cracks. In the spring, as the sheet begins to warm, activity intensifies in the brine channels. As blockages clear in the channels, the oil begins to migrate upwards. Initially, movement is slow, but rapidly increases once there is a clear passage to the surface. By late in the spring, some of the channels grow to about 1.0cm in diameter. The spreading of the oil on the surface of the ice is usually retarded by snow cover. As the snow warms and begins to drain, the oil spreads more easily on the wetted surface, and much larger areas are affected.

With the decay of the snow pack, oil migrates to the surface, and initially appears as a slight brownish discolouration. This normally occurs first in areas where the cover is thin. The oil reduces the albedo, and the process becomes self-exciting.

Within a matter of days, the albedo can be reduced to about one third that of the surrounding uncontaminated snow. The surface warms rapidly and melt pools grow in size. The added heat enhances the flow of oil to the surface. The process can be temporarily retarded by even a light snowfall, but is quickly reactivated once the oil surfaces again. A limited quantity of oil is locked in the ice, and will not be released until the melt reaches the original level of the lens.

With time, the oil thickens on the melt pools. Due to fluctuations in the water level in the pools, as well as wind action, the surrounding snow becomes oiled, and quickly rots. Once a number of melt pools become interconnected, the wind will tend to herd the oil, and very thick films can result. With continued wave action, some crudes will emulsify. Normally, these emulsions are not stable, however, they breakdown very slowly if deposited on snow. Due to the high levels of radiation, the oil weathers rapidly. For the type of crude likely to be encountered in the Beaufort Sea, about 40 percent will evaporate in 30 days at 0°C. Because the oil absorbs a large portion of the direct solar radiation, the average temperature of a thick oil lens can be as much as 10°C higher than the underlying water. If unrestricted, the ice will clear in oiled areas several weeks sooner than in uncontaminated areas.

The effect of oil released on the surface will depend to a large extent on the nature of the discharge. For a point source the oil will quickly cut a narrow channel through the snow, which is normally not much larger than the oil column. The temperature of the oil and the condition of the snow will determine the extent of spreading. In general, the oil will be confined to the area of the source. Once the snow begins to warm, it will perform in a similar fashion to oil initially contained in the ice sheet, except that it will likely surface somewhat faster. If the oil is sprayed on the snow, most of the small particles will be retained at the surface. During the winter a considerable quantity of oil would likely be carried away in blowing snow. In the spring, when the level of radiation is high, the dark oil particles would cut their way into the snow. New snow cover would terminate the process.

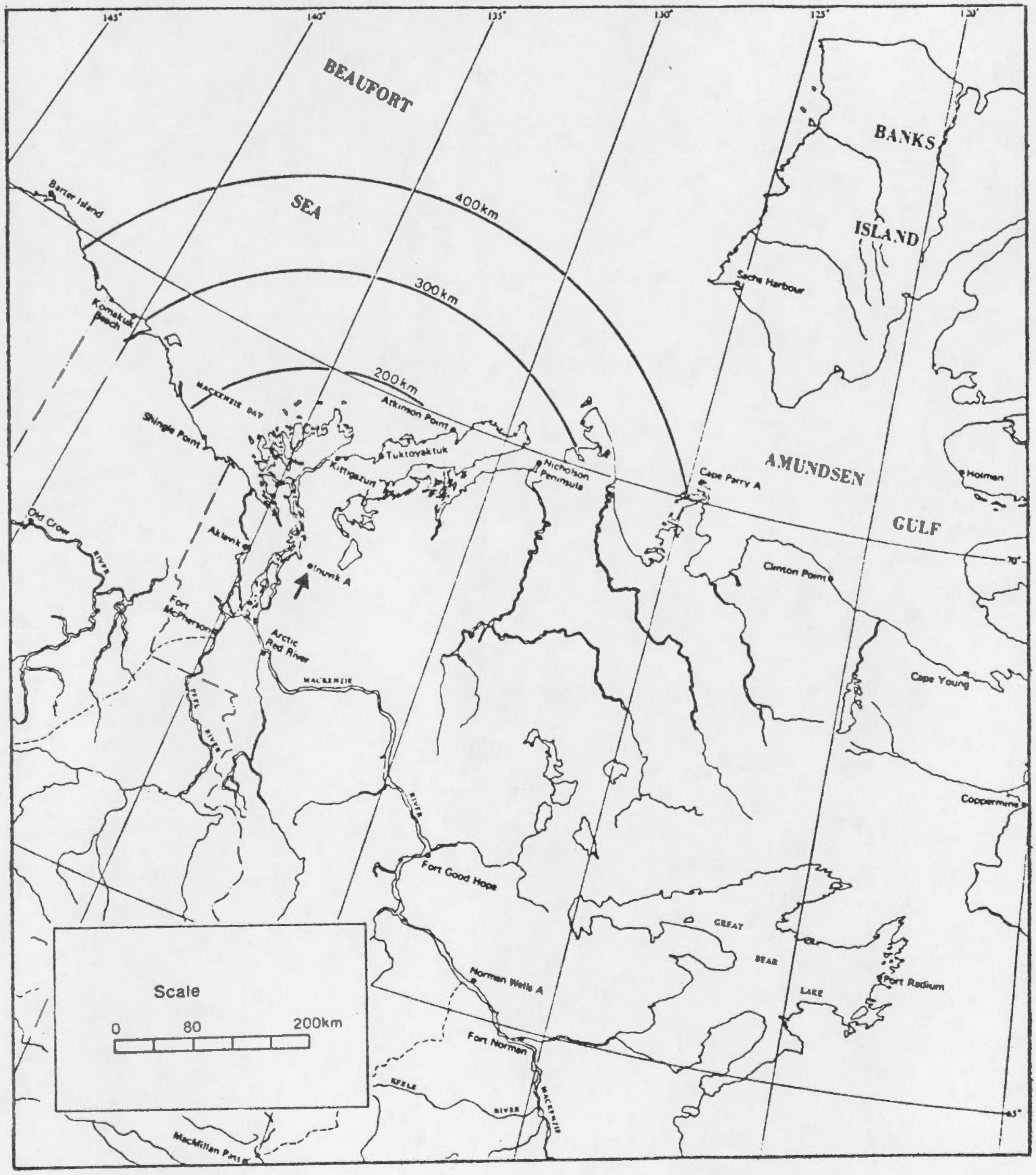
4.0 OPERATIONAL CONSIDERATIONS

4.1 Reliability of an Airborne Operation

There are a number of factors to be considered in determining the probability of success for an airborne mission, including the type of aircraft, conditions at the origin and destination, length of flight, conditions enroute, the size of weather systems, and the location of possible alternates. The matter is further complicated when sensors, having atmospheric limitations are employed. It is impossible to undertake a precise analysis for the Beaufort Sea area. There is virtually no observations for the offshore area. There are limited numbers of stations ringing the shore, but in general the period of record is short, and the conditions are not truly representative. It is therefore necessary to make a number of fundamental assumptions to produce even a rough approximation.

A total of six parameters were examined for Sachs Harbour, Cape Parry and Inuvik. These are the only stations with hourly data summaries for ten years or more. The parameters employed were ceiling height, cloud cover, visibility, wind speed, precipitation and hours of daylight. Since most turbine aircraft will operate to -50°C, temperature was not included. It is not possible with the existing data summaries to determine the frequency with which two or more limiting events occur simultaneously. Consequently, with the exception of hours of daylight, the events were treated as being mutually exclusive, which tends to reduce the probability of success. This is offset, however, by the fact that conditions were only examined at single points. For a mission to be successful, conditions must be favourable at the origin, along the flight path and at the destination simultaneously. Such an analysis is extremely complex, and beyond the scope of this study. For IFR missions,

FIGURE 1. LOCATION PLAN



or short VFR missions, returning to the same airfield, the single point approach is reasonably accurate.

Five different operational classes were established. The first two relate directly to limitations on aircraft flying under Instrument Flight Regulations (IFR) and Visual Flight Regulations (VFR). Since optical sensors, which are affected by atmospheric conditions, could be employed, it was also necessary to examine the probability of maintaining visual contact with the ground from three different altitudes.

An aircraft operating under IFR out of a controlled airspace, is restricted primarily by visibility on take-off and landing. For most airports the minimums are a 500 foot ceiling and visibility of one mile. A cross wind of over 30 mph would also likely curtail or divert a flight. It was assumed that both wind direction and landing strips were randomly oriented, and therefore high winds would only be a limitation 50 percent of the time. Once airborne, the aircraft would only be affected by freezing rain.

An aircraft operating under VFR is restricted in a similar manner on take-off and landing, but also must maintain visual contact with the ground at all times. Due to the lack of lighted features, night VFR is not practiced in the north. As a result, a VFR operation is extremely limited during the winter. A comparison of VFR operations from Inuvik, Cape Parry and Sachs Harbour is shown in Figure 2. The curves are the combined probability of acceptable flying conditions during the hours of daylight. Since the curves do not reflect conditions enroute, they can only be used as a relative comparison of the probability of success for a local mission. Although conditions would appear to be somewhat more favourable in the Inuvik area, the climate tends to be continental, and therefore not truly representative of the Beaufort Sea. It is doubtful if a VFR operation could be employed for anything other than near shore reconnaissance and local support.

For the three levels of reconnaissance considered, the sensor restrictions were combined with those for an IFR operation. Low level reconnaissance was taken as being below 500 feet. Due to the hazard of operating at this level, it was assumed that clear visibility was essential. For rotary wing aircraft with an instrument rating, this would not necessarily be the case, but such machines are not common.

Mid level reconnaissance assumes an operating altitude of over 1000 feet. The combined probability of a ceiling less than 1000 feet and cloud cover greater than 5/10 was added to the limitation on low level reconnaissance. Since high level reconnaissance would be above the cloud cover in most cases, a cover greater than 5/10 was taken as the restriction with no limitation on ceiling.

The average monthly probability of success for the various classes of missions staged from Inuvik, Cape Parry and Sachs Harbour, are shown on Figures 3 to 5 respectively. Although the probability of an IFR mission being successful is better than 60 percent for all locations at any time of the year, optical sensors will be ineffective at high altitudes over 70 percent of the time, and virtually useless during the winter. The optical sensors could be utilized during the summer at altitudes of up to 1000 feet with a success rate of 40 percent or better. However, during October, which is likely to be the critical period for blowouts, optical sensors will be successful less than 20 percent of the time even at low altitudes. It would therefore appear that optical sensors

FIGURE 2 COMPARATIVE PROBABILITY OF FLYING VFR MISSIONS

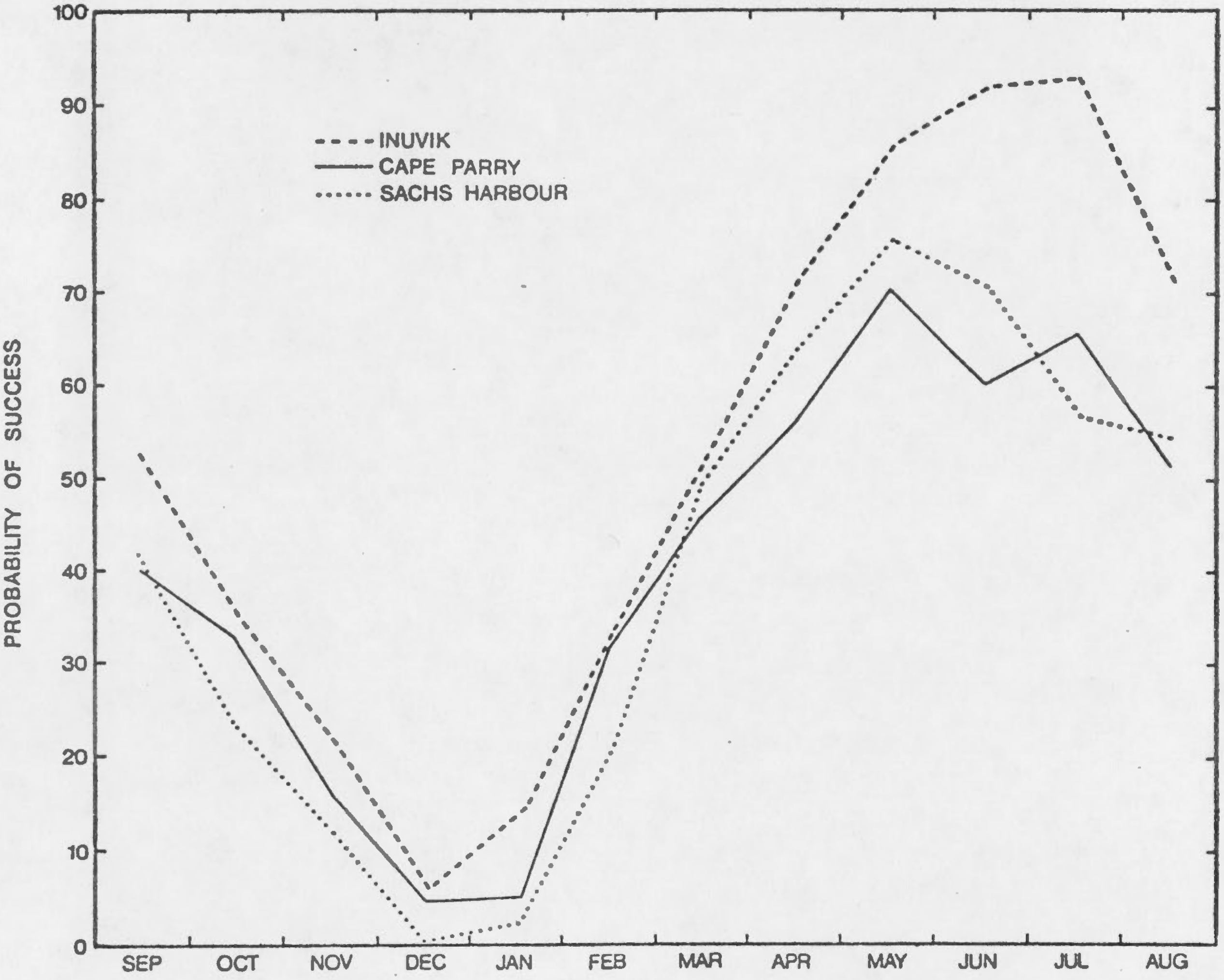


FIGURE 3 MONTHLY PROBABILITY OF SUCCESS OF AIRBORNE MISSIONS FROM INUVIK (From 10 yr. averages)

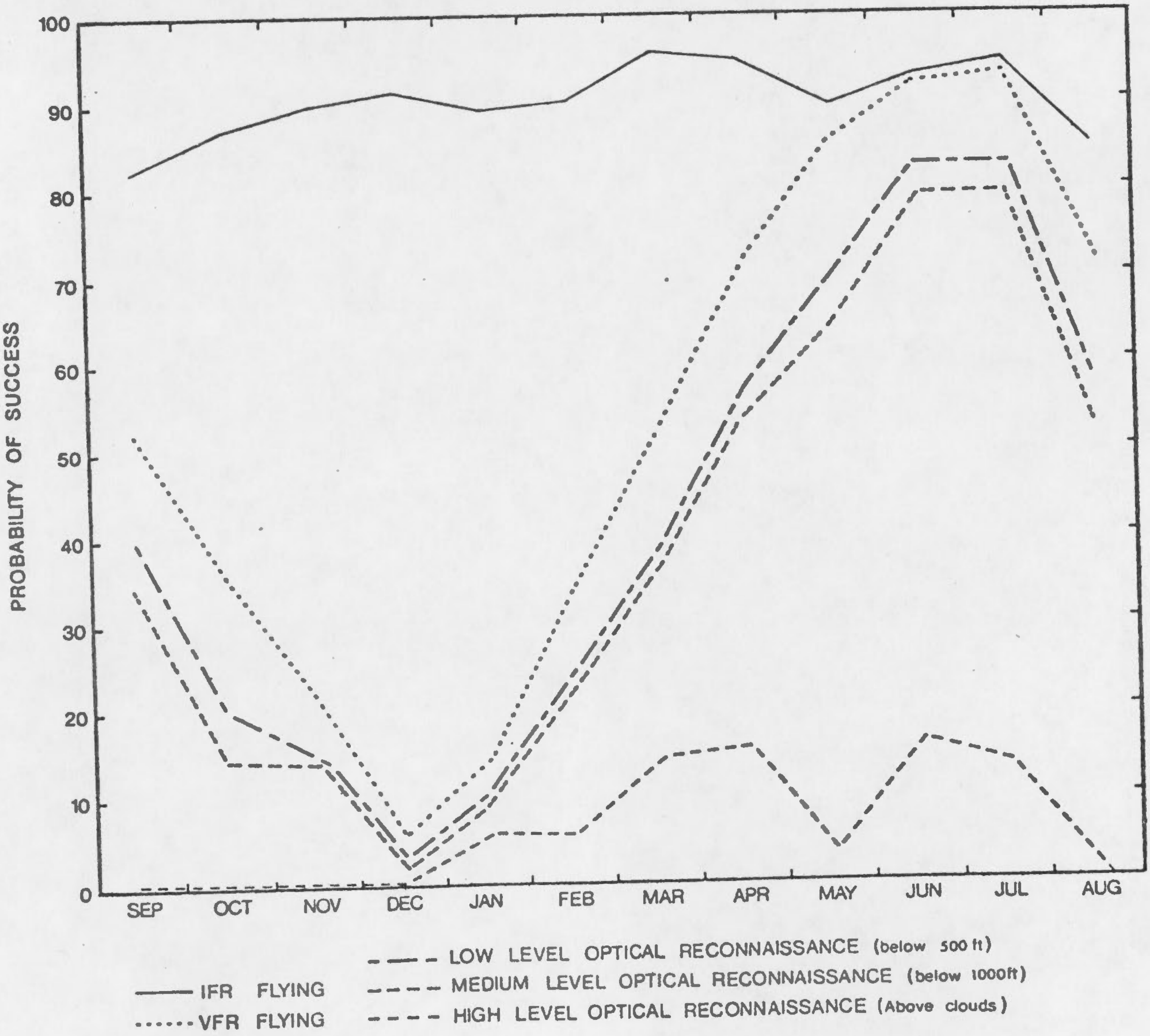


FIGURE 4 MONTHLY PROBABILITY OF SUCCESS OF AIRBORNE MISSIONS FROM CAPE PARRY (From 10yr. averages)

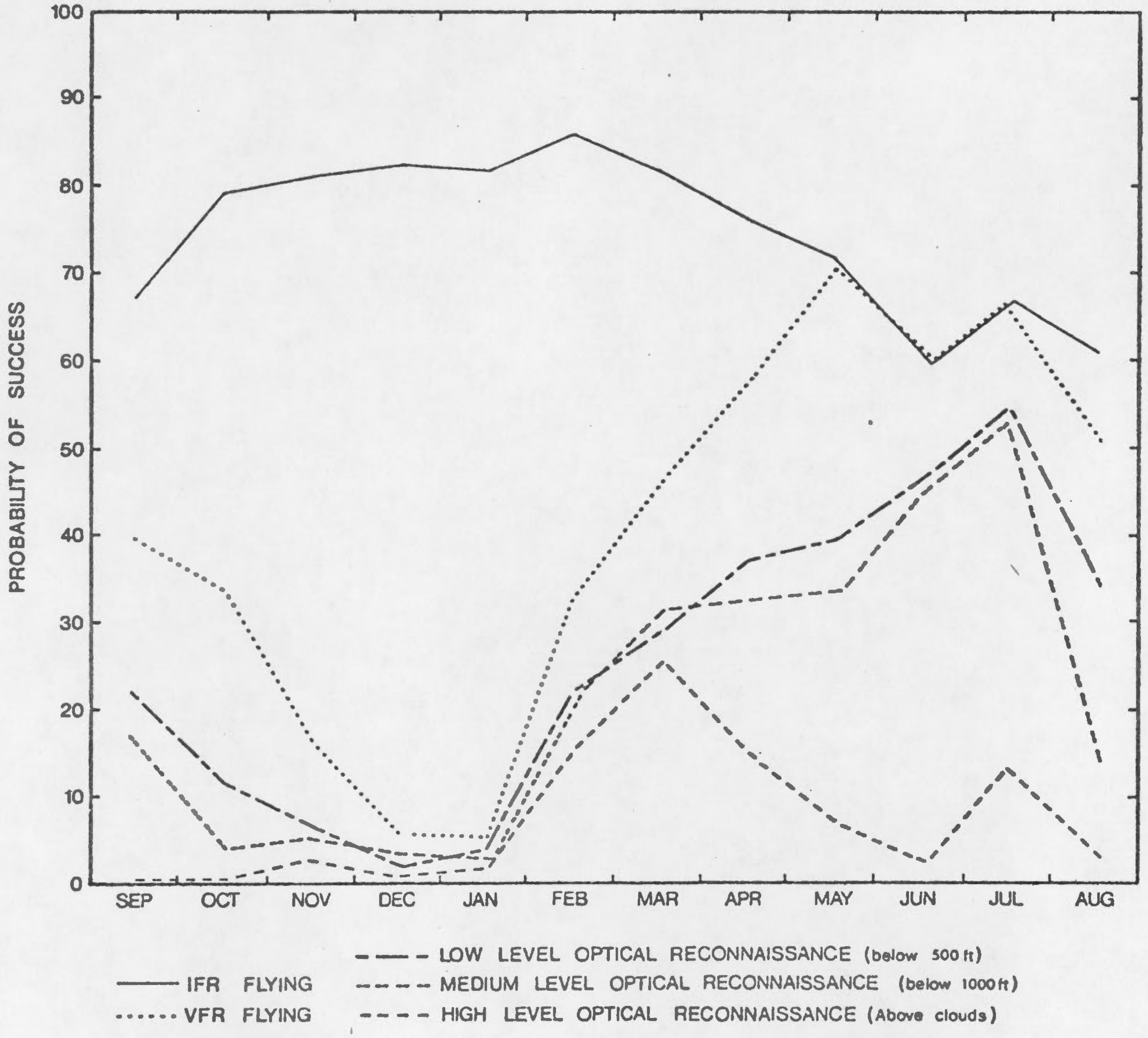
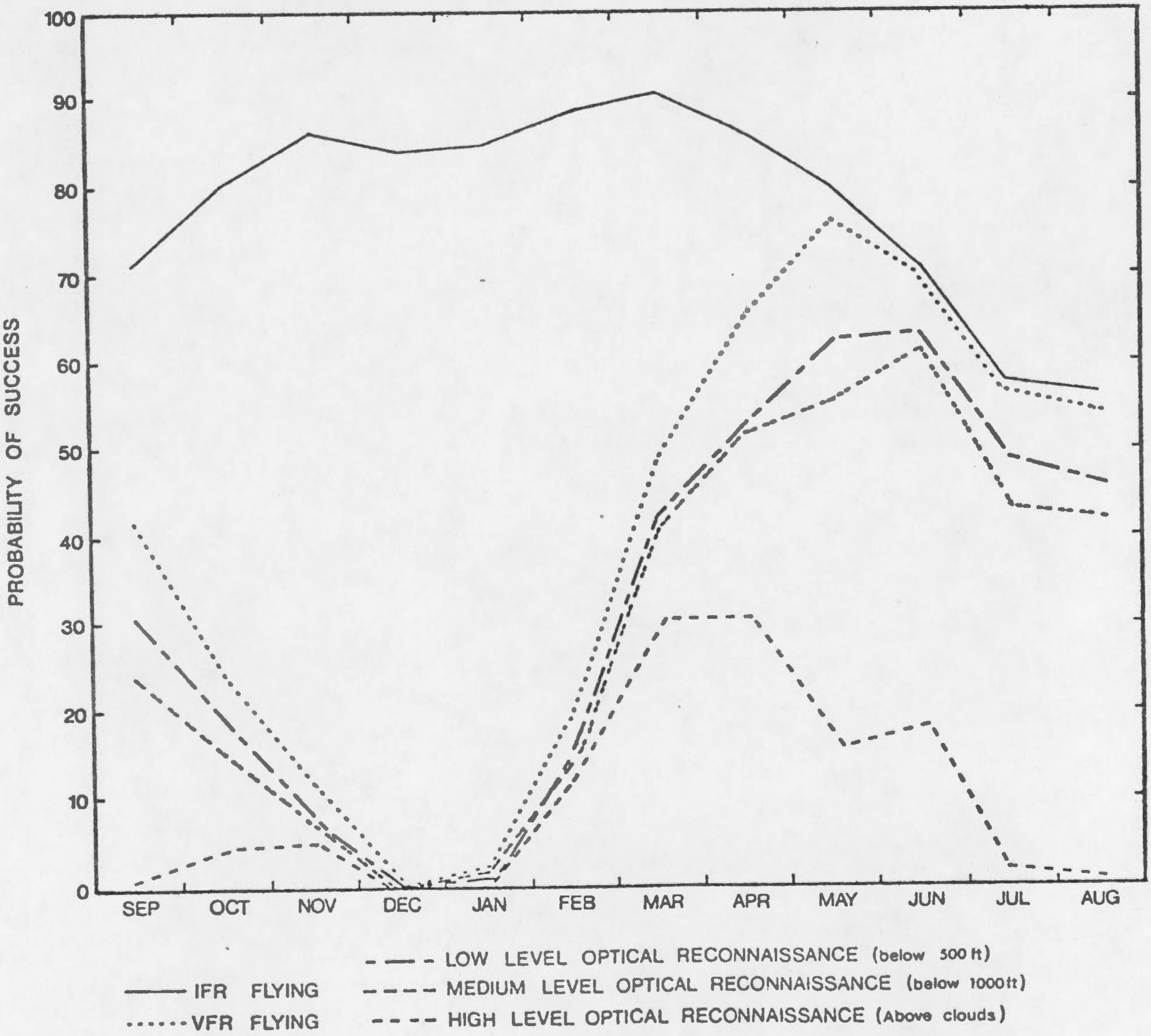


FIGURE 5 MONTHLY PROBABILITY OF SUCCESS
OF AIRBORNE MISSIONS FROM SACHS HARBOUR (From 10yr. averages)



should only be used as a supplementary method of detection.

4.2 Potential Bases and Support Facilities

There are a total of thirteen airfields ringing the proposed study area. Of these, six are public, five are associated with DEWline facilities and two are located at Industry staging areas. The landing strips and associated facilities and services are described in Table 1. There are numerous other fields such as Barter Island, Old Crow, Fort Good Hope, Coppermine and Rae Point, which are outside the normal operating range but could be filed as alternates.

Factors to be considered in selecting a base are the location of offshore activities, the role of remote sensing, the performance of aircraft to be employed, and the availability of support services. All the strips could be used by light aircraft in the event of an emergency or if activities happen to be concentrated in the area. On the basis of existing information, Inuvik would appear to be the best location for a permanent base. Firstly, it has the best airstrip and navigational aids, and is the only location which can accommodate heavy jets. Secondly, there is heated hangar space, a maintenance service, a full range of fuels, accommodation and other necessary support services. Thirdly, the superior communications and more frequent scheduled air service would improve operational reliability. Finally, the cost of a routine operation would be considerably less from Inuvik.

4.3 Surface Operations

Surface crews with suitable transport could prove effective under most conditions. The immediate area of the shear zone is the only location which present a major problem. Although productivity is somewhat reduced during the depth of winter, there are very few conditions which will stop a trained and well equiped crew.

With helicopter or hovercraft support, a field crew could function reasonably effectively during freeze-up and break-up, when heavy fog and cloud cover would severely limit an airborne detection program. A two man crew with a portable power head could auger over ten holes per hour through ice up to 2m thick. The crew could delineate and target oil pools, and thereby reduce the work for cleanup parties.

TABLE 1

SUMMARY OF AIRFIELDS & SUPPORT FACILITIES

LOCATION	STRIP	STATUS	INSTRUMENT LANDING SYSTEM	NON-DIRECTIONAL BEACON	WEATHER	HANGAR SPACE	MAINTENANCE	JP4	100/130	80/87	SCHED. AIR SERVICE	BARGE SERVICE	ACCOMMODATION
Aklavik	2000 x 100 gravel	Public		X				X	X		X	X	X
Bar C	gravel	Private Imp.		X				X	X			X	X
Cape Parry	5000 x 150 gravel	Private DEW		X	X	X		X	X			X	X
Clinton Point	3500 x 100 gravel	Private DEW		X				X	X			X	X
Holman	4000 x 100 gravel	Public		X	X						X	X	
Inuvik	6000 x 150 paved	Public	X	X	X	X	X	X	X	X	X	X	X
Komakuk Beach	3500 x 100 gravel	Private DEW		X				X	X			X	X
Nicholson Penin.	3500 x 100 gravel	Private DEW		X				X	X			X	X
Paulatuk	3200 x 100 sand	Public		X								X	
Sachs Harbour	4000 x 100 gravel	Public		X	X						X	X	
Shingle Point	3800 x 100 gravel	Private DEW		X				X	X			X	X
Swimming Point	1200 x 100 gravel	Private GULF		X				X	X			X	X
Tuktoyaktuk	3500 x 100 gravel	Public		X	X			X	X		X	X	X

NOTE: Prior clearance must be obtained for DEW line and Industry facilities.

APPENDIX B

Evaluation of Radio Methods for Remote Sensing of Oil Spills at Beaufort Sea

EVALUATION OF RADIO METHODS FOR REMOTE SENSING OF OIL SPILLS AT BEAUFORT SEA

DATED: June 30, 1975

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PROPRIETARY INFORMATION

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TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

The development of petroleum sources in the Arctic has introduced new dimensions to the problem of oil spill detection and cleanup. In the Arctic, oil may be spilled over ice, under ice, or in ice free or ice infested waters. Furthermore, the composite ice cover may consist of ice at different stages of growth. Such a variety of configurations, especially in the harsh Arctic environment, compounds the problem of oil spill detection and measurement.

This study addresses the problem of using radio frequency techniques for the remote sensing of oil spills at the Beaufort Sea. Various approachs, using both active and passive microwave and UHF techniques will be evaluated with respect to their applicability to the detection of oil in the Arctic.

For remote sensing applications in the Arctic environment, radio frequency and microwave techniques are particularly desirable due to their all-weather all-day capability. As well, microwave blackbody radiation from ground features is sufficiently intense to eliminate the need for artificial illumination in applications where active sensing is either ineffective or redundant. By measuring the characteristics of this radiation (ie. passive remote sensing) such as polarization, angular dependence and frequency dependence, certain physical properties of the emitting material can be determined .

A variety of programs are now in progress to interpret these passive microwave "signatures" as well as the target return from active remote sensors. A considerable amount of analysis has been completed in the study of the microwave properties of water, oil, and both fresh and sea ice. As many of those studies are still in progress however, only a limited amount of published and confirmed data is available. This is especially true for heterogeneous mixtures of natural materials such as water/ice or oil/ice etc. Thus, in the following discussion of the use of passive and active radio frequency sensing in the Arctic, these available data have been used to anticipate future methods for RF detection of oil spills.

2.0 PASSIVE METHODS

2.1 Description of Passive RF Techniques

The radiation measured by a microwave radiometer comes from several different sources. The directly emitted blackbody radiation of the object or objects in the field of view usually contributes most of the signal energy. The sensor output then is related to the properties of the emitting medium. Other unwanted components of the received energy, such as man made noise, radiation from the sky, the sun, or from nearby natural objects may be reflected from the source into the mainfield of view, or into antenna "sidelobes". Furthermore, the medium between the source and the radiometer receiver may attenuate by absorption or scattering the original source signal, or radiate itself and add to the total received signal at the radiometer. These additional sources of radiation must be included in an analysis of sensors as the frequency range and field of view parameters of the instruments are often limited by the characteristics of the background signal.

The sum of galactic, solar and natural terrestrial radiation, expressed as the effective blackbody temperature for an equivalent radiation power at the receiver is shown in Figure 1, using the data of Penzias (1968) and Paris (1971). At frequencies of 200 MHz and lower, extraterrestrial sources become significantly strong and care must be taken to avoid specular reflections into the main field of view or strong sidelobes from these sources. At the higher frequencies shown in Figure 1, significant attenuation in the atmosphere, especially in heavy cloud or rain is important, and in specific frequency ranges large effects due to spectral resonances in atmospheric gases occur, for example, the water vapour absorption near 22 GHz, and the strong molecular oxygen absorption at approximately 60 GHz. At higher frequencies, many absorption bands from condensation and atmospheric gases occur.

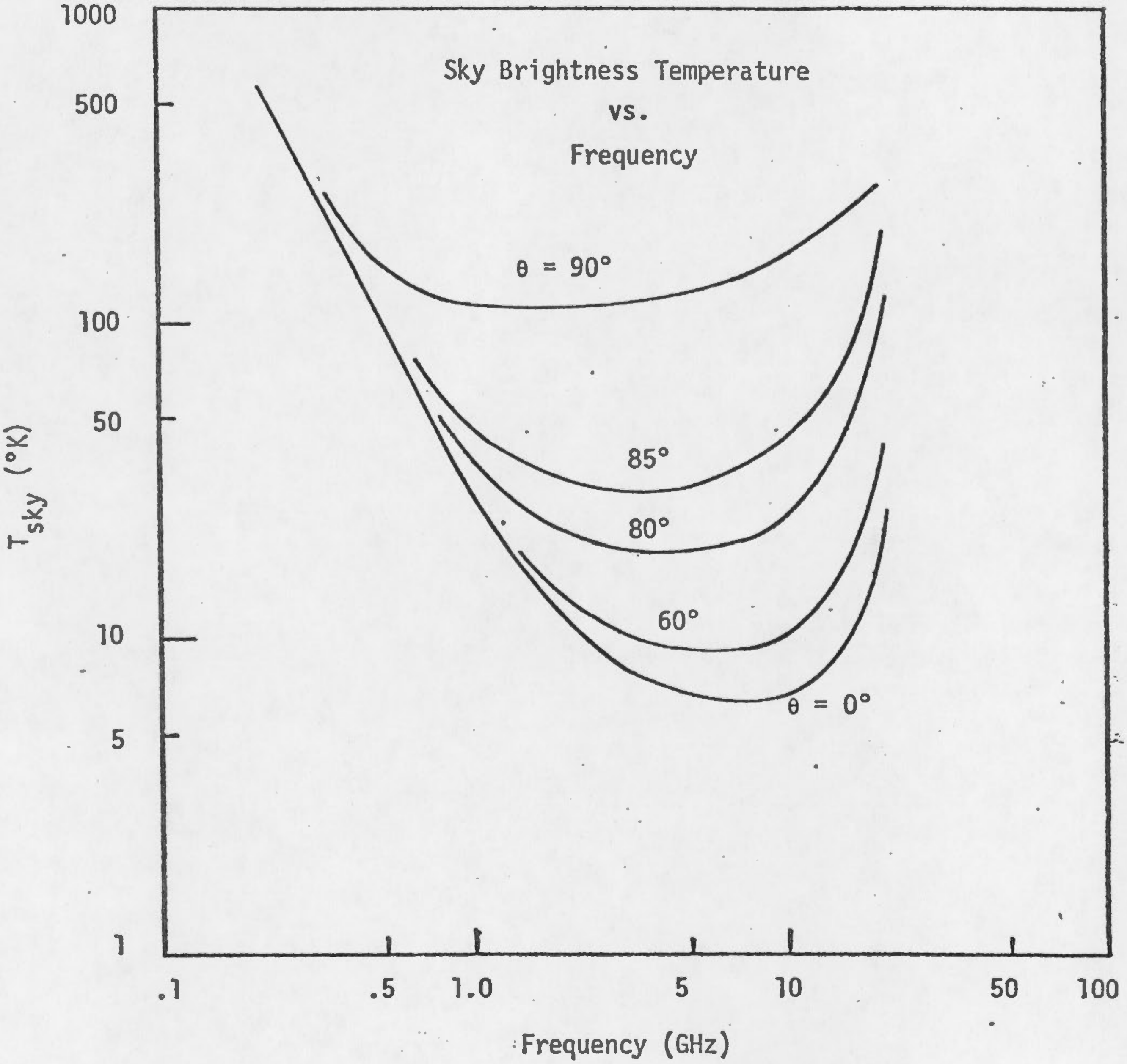

Figure 1. The total sky brightness temperature incident upon the ice surface due to atmospheric, galactic and cosmic sources. Angle of incidence is the parameter.

The transmission of radiation from ground level vertically through the earth's atmosphere is shown in Figure 2 in the presence of ice and water clouds (Moore, 1970).

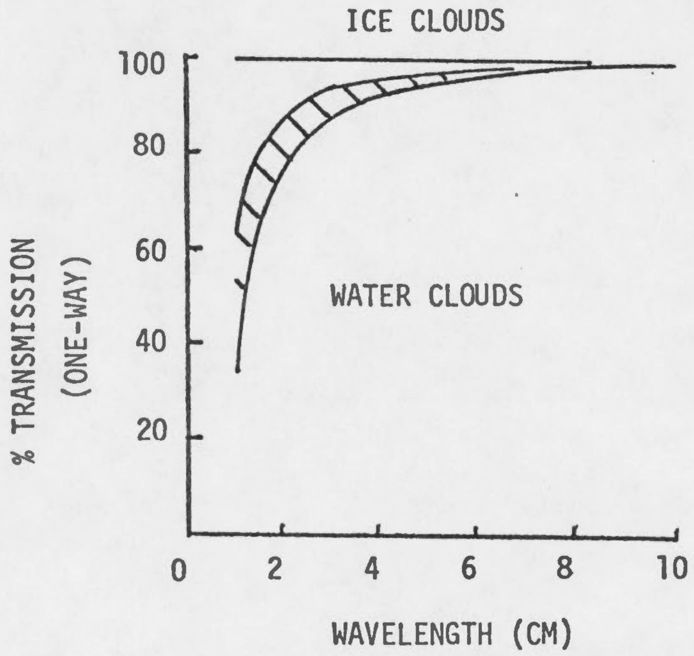

FIGURE 2: The Transmission of Radiation Through the Earth's Atmosphere

No significant attenuation occurs over this path for radiation wavelengths greater than about 10 cm (f $\leq$ 3 GHz). For shorter wavelengths, especially below 3 cm (10 GHz), sever attenuation may be encountered due to water droplets in clouds. The attenuation in ice clouds is less severe.

For remote sensing programs, instruments are generally required to be portable and operational from fixed wing light aircraft, or helicopters. Such requirements also set restrictions on the frequency range available for use, primarily due to the antenna configurations and size for effective spatial resolution on the ground. The ground resolution of a microwave antenna is given approximately by the product of the radiation wavelength and the altitude of the antenna above the ground divided by the linear dimensions of the antenna. Thus, at 3 GHz, for example, an antenna 1. meter wide at an altitude of 100 meters has a ground resolution of about 10 m. Finer spatial resolution can be obtained at shorter wavelengths and with larger antennas. However, for the applications of Artic airborne remote sensing, due to size and weight restrictions all weather microwave radiometers must be utilized to obtain information regarding the average properties of the source at the expense of obtaining high resolution data.

2.2 Oil Spill Detection Using Passive RF

Restrictions on useable frequencies and modes of operation for passive microwave remote sensing are set by the physical properties of the source itself, in this instance mixtures of oil, sea water, sea ice and snow. Sea ice is known to consist of a mixture of pure ice and included brine cells and air bubbles. During the freezing process, brine, derived from sea water, becomes trapped in long, slender, primarily vertical pockets or cells within the ice. The relative concentration of brine and precipitated salts within these cells is a sensitive function of the ice salinity and temperature profile (Assur, 1958). Consequently, the dielectric coefficient of brine in the ice can be as large as 80 + j110 indicating strong absorption of radio frequency energy. For comparison, pure ice with a dielectric constant of 3.5 +j0 is comparatively transparent to microwave energy.

Several investigators have measured large absorption coefficients (Finkel'skteyn et.al., 1970; Ramseier et.al., 1974) and a summary of absorption in ice is shown in Figure 3. The preferential orientation of brine cells in the ice imparts a distinct anisotropy to the electrical properties, and causes absorption to be different for different orientations of the radiation electric vector. For maximum penetration into and emission from sea ice, there is therefore a preferred direction of view and polarization. Minimum absorption occurs for the electric vector aligned perpendicular to the major axis of the brine cells. Robar and Wood (1974b) have modelled the UHF emission from sea ice and indicated that at these frequencies most of the radiation emitted from a sea ice layer originates near the bottom of the ice. In this region, a large gradient in dielectric permittivity exists due to the warm temperature near the water and the consequent large concentration of brine in the ice structure. The profiles of the imaginary part of the ice-brine mixture permittivity, representing dielectric loss, the gradient of this permittivity and the computed brightness temperature contribution per millimeter of ice thickness are shown in Figure 4 for the model of Robar and Wood. The ice thickness is set at 80 cm and a linear temperature gradient through the ice to -10°C at the surface is assumed. To correspond with salinity measurements taken on first year sea ice in Hudson's Bay (Robar and Wood, 1974B) the salinity profile exhibits a maximum at the top and bottom surfaces of the ice sheet, and a salinity increase in the center to represent non-uniformity in the salinity profiles which may be caused for example by rafted ice. The important feature of this calculation is that the contributions to brightness temperature from salinity maxima at the top of the ice and interior to the ice are insignificant compared to the contribution from the bottom salinity maximum where a boundary region exists between the properties of ice and those of sea water.

These emission and propagation features of sea ice are important both in selecting operating frequencies and polarizations, and in understanding the physical basis for any microwave or UHF measurement of oil under, within, or on top of sea ice. In particular, the

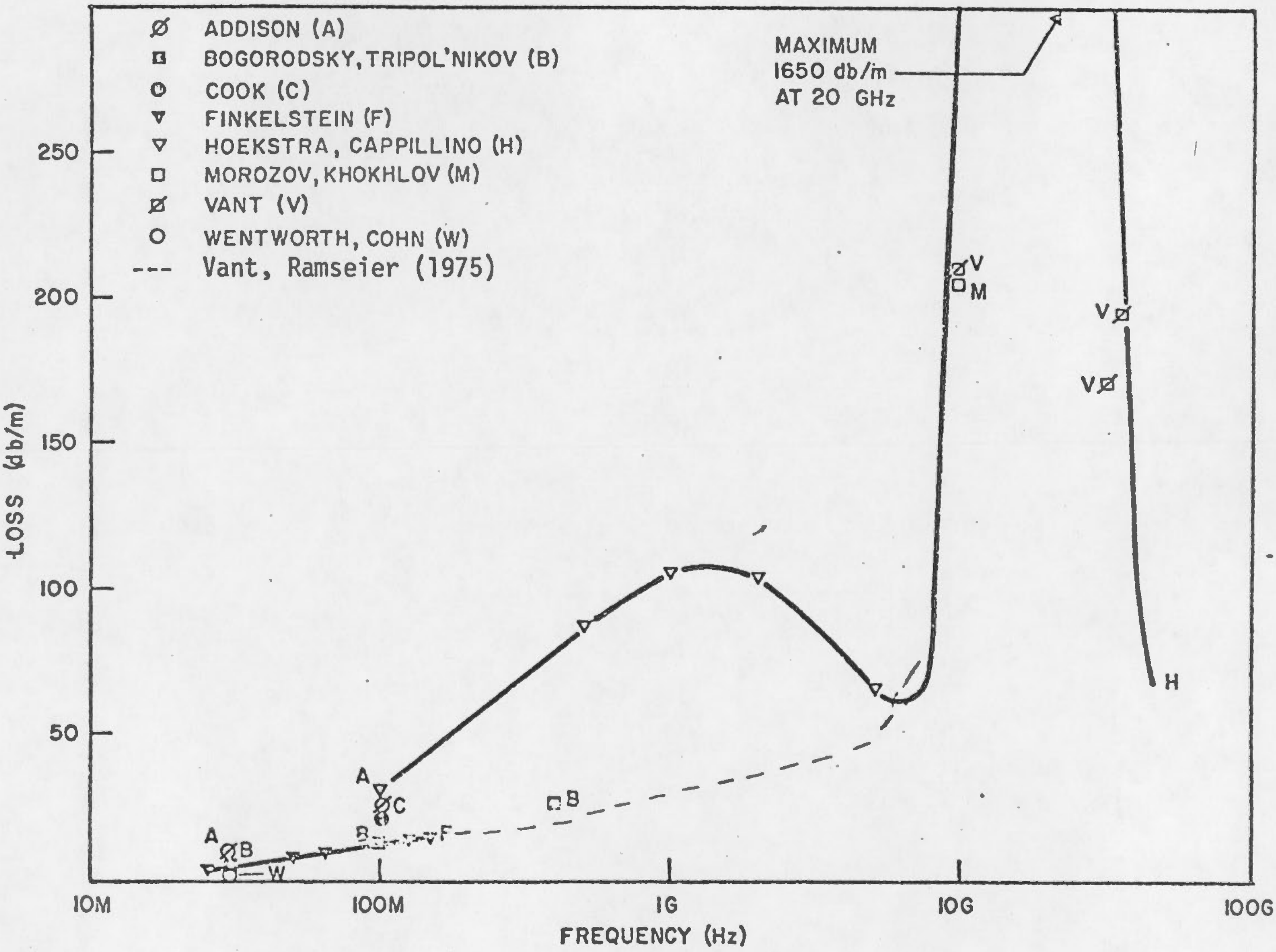

FIGURE 3: Summary of Radiowave Absorption in Sea Ice

following facts are now known: for radiation frequencies where the wavelength is comparable to the linear dimensions of the brine cells, or the air pockets left when brine drains out, large absorption and scattering effects occur which prevent significant penetration of this radiation through ice. Thus at frequencies above a few GHz, radiometers and radars can measure only the near surface of sea ice. Propagation is less attenuated for waves with electric vectors perpendicular to the brine cells, thus vertical rather than off nadir propagation directions are preferred. The ability of radars or radiometers to detect the bottom surface of sea ice depends on a steep gradient in ice dielectric properties occurring near the bottom surface.

Oil spilled under growing ice tends to spread into "lenses" approximately 2 cm. in thickness. However, not all of the bottom of the ice sheet in the area of the spill is uniformly covered (Dickins, 1975 private communication). The immediate effect of this displacement of water by oil is to replace the high permittivity salt water with low permittivity oil (dielectric constant approximately 2.0 + j0). The consequence of this is to reduce the permittivity of the ice mixture and change the gradient in dielectric constant at the ice water interface. Confirmation of the dielectric properties of sea ice has been made from AIDJEX tests from 100 MHz up to 12 GHz (Ramseier, 1975, private communication), however, no measurements at the site of an oil spill have yet been performed. In fact, to this point in time, measurements of oil under ice have not been made by ice penetrating radars or radiometers. Thus, observation of the expected modification of sea ice dielectric properties due to the presence of oil are not available. As the efficacy of spill detection by RF techniques is closely related to such modification of electrical properties, it is important to obtain a confirmation of these effects through experimental measurements.

Since the bottom salinity gradient is expected to be most important to the radiation properties of sea ice, once oil becomes frozen into the ice and a substantial amount of new sea ice has grown below the oil, little effect is anticipated upon UHF or

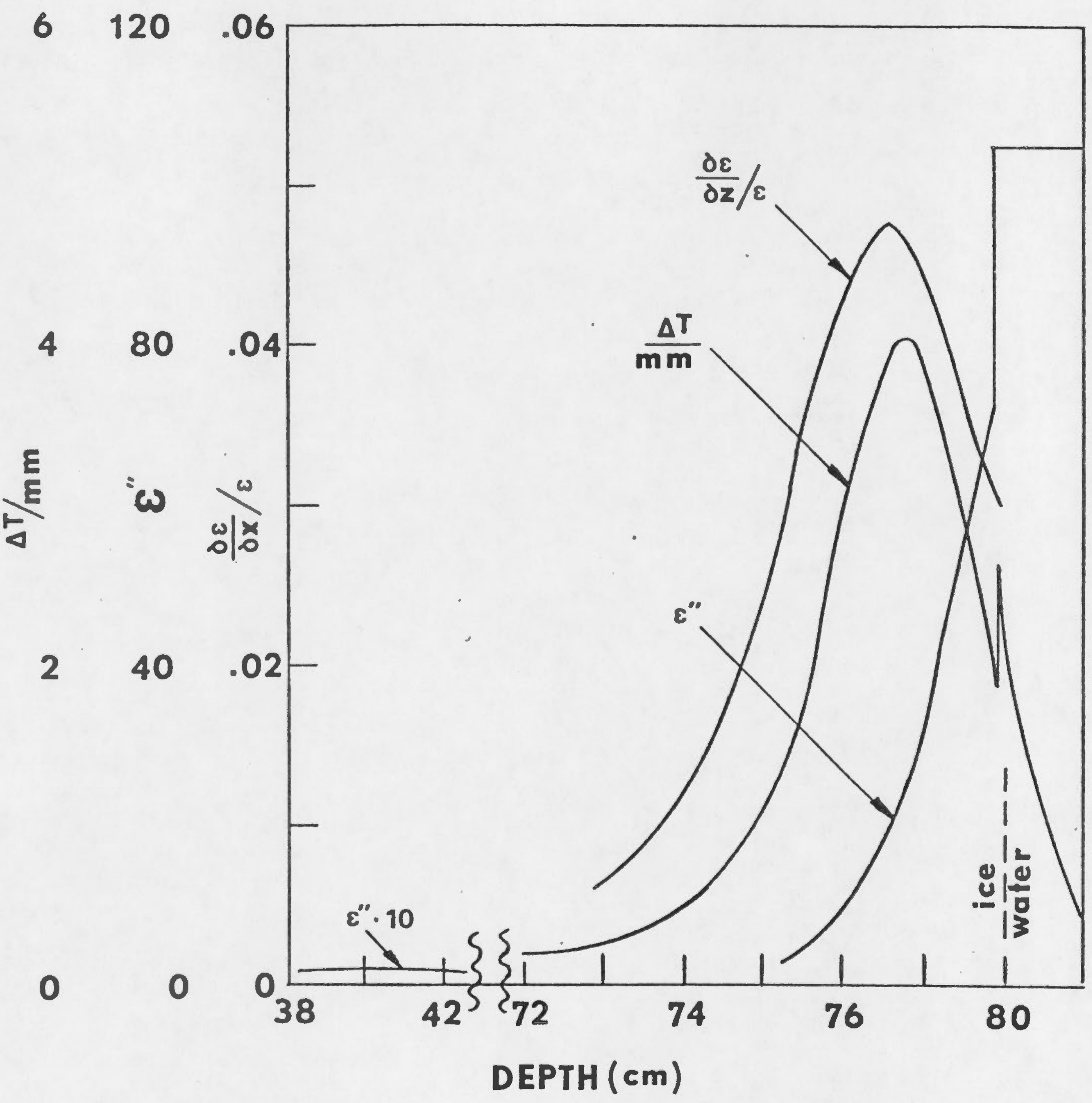

FIGURE 4: Dielectric Properties of Sea Ice near the Lower Water Boundary.

microwave properties of the ice emission. These concepts were tested with computer calculations of the radiation brightness temperature expected from a freezing layer of sea ice using the ice model from Robar and Wood (1974b) based on the theory of Stogryn (1970) and the earlier modelling of Pelletier and Adey (1973).

For frequencies of 400 MHz and 1200 MHz, the sea ice brightness temperature was calculated for a radiometer viewing perpendicular to the ice surface. Two different spill states were assumed in the calculation. Firstly, the brightness temperature was calculated for normal ice growth in the absence of oil. Secondly, it was assumed that an oil spill occurred under 25 cm of new sea ice followed by a continued growth to a thickness of 62 cm. In the latter model the oil was assumed to extend from 25 cm to 35 cm through the ice, being frozen in the ice structure by ice growth. A linear decrease due to the replacement of brine by oil in total ice salinity was assumed to begin at 25 cm with a minimum salinity near 30 cm, approximating total exclusion of salt water at this depth. By 35 cm the bulk salinity had again increased linearly to that assumed for pure sea ice. This modification of ice salinity represents migration of oil into brine cells both above and below the principal oil layer. The results of these calculations are shown in Figures 5 and 6, where the typical predicted brightness temperature variation with increasing ice thickness is evident. These predicted variations of signal with natural sea ice, due to wave interference effects at the top and bottom boundaries of the ice.have been reported from measurements by Basharinov <u>et.al</u>. (1971)

Two significant observations can be made from the foregoing simulation. Firstly, the change in brightness temperature in the presence of oil is between 30 Kelvins at 400 MHz and 100 kelvins at 1200 MHz. With state of the art radiometers having resolutions and accuracies of ≤.5 Kelvins and ≤5 Kelvins respectively, such emissivity changes would be observable soon after a spill occurred. Observable changes in brightness temperature are predicted for oil penetration into the bottom 1 cm of the ice sheet, displacing ≤20% of the brine in the growing ice. These values of brightness

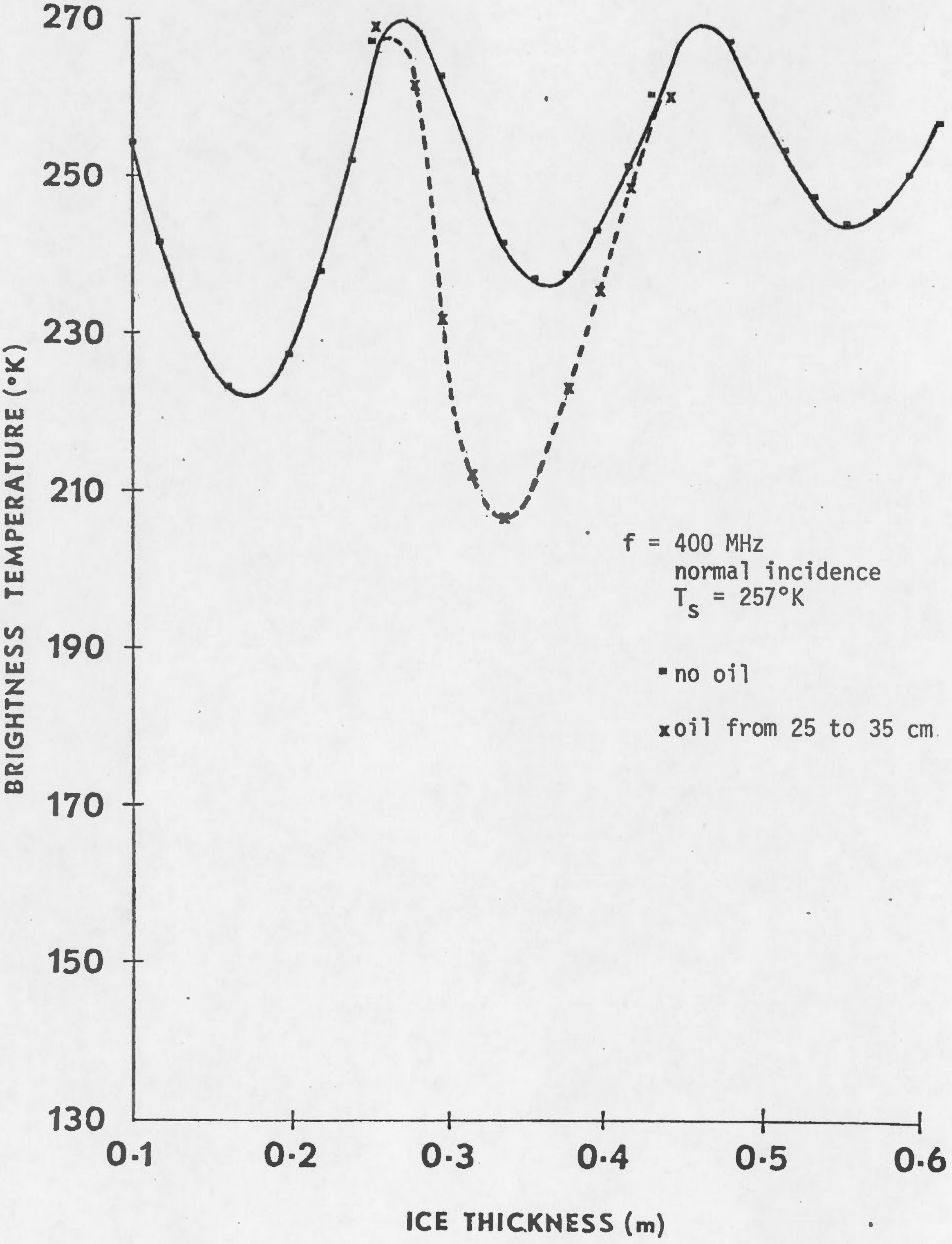

FIGURE 5: The Predicted Brightness Temperature Change with Ice Growth at 400 MHz with and without the Presence of Oil.

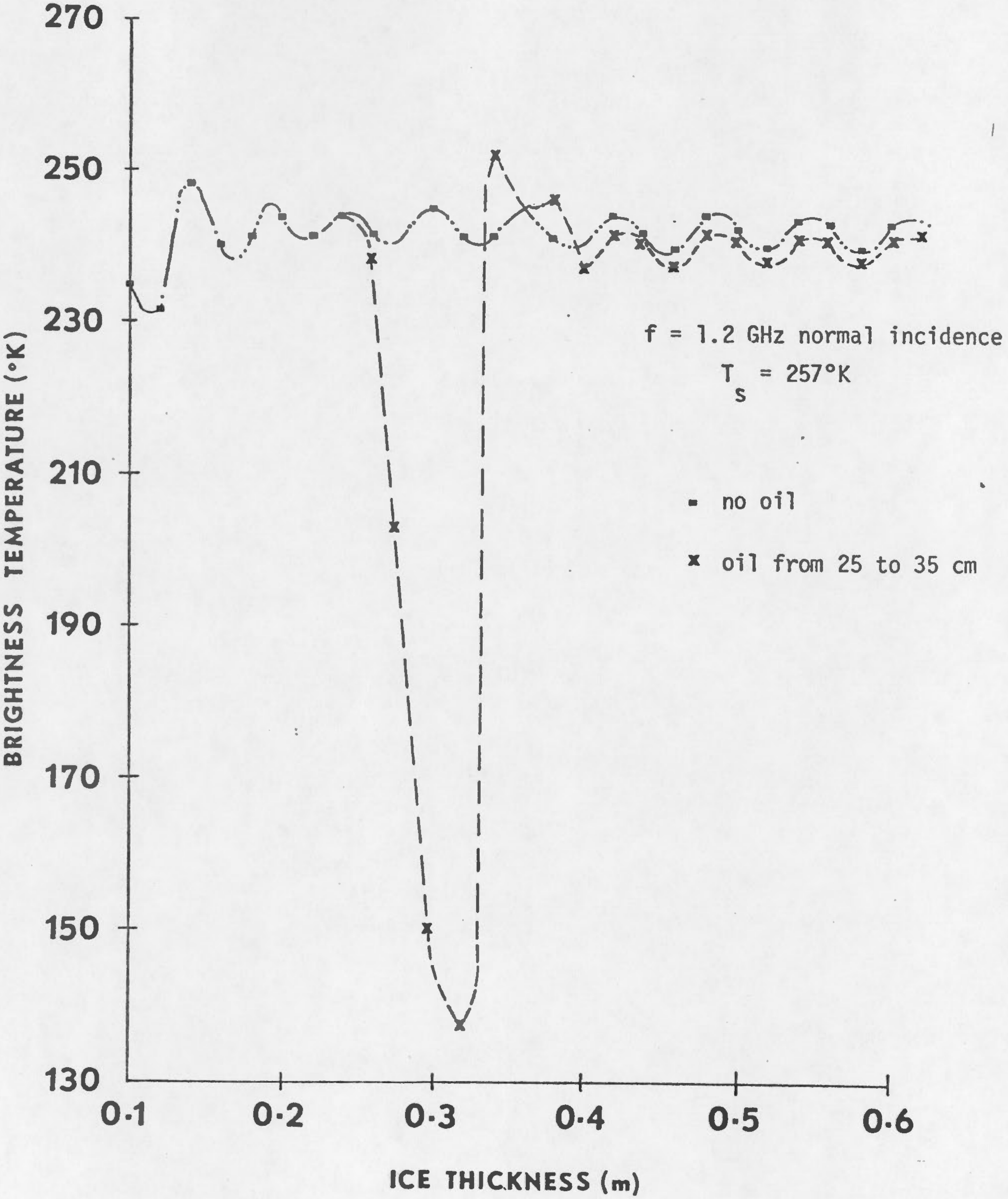

FIGURE 6: The Predicted Brightness Temperature Change with Ice Growth at 1200 MHz with and without the Presence of Oil.

temperature changes do assume that the effect of the oil is spread over the entire field of view of the radiometer. For cases where this is not true, the changes in the brightness temperature would approximately correspond to the fractional spill area in the main antenna beam. Secondly, it is noted that as the oil layer becomes frozen farther into the bulk of the ice, only very small changes in the composite signal are predicted. For example, when the oil is 15 cm from the bottom of the ice, changes $\lesssim .2$ Kelvins at 1200 MHz are predicted. Such temperature offsets would not be sufficient to identify the presence of oil in the ice by radiometric techniques.

When applied to a real case of a spill occurring, for example, under an articicial ice drilling platform in the Arctic (Baudais, et.al., 1974), the large artificial changes in salinity profile such as those found above the natural ice by pumping and freezing of sea water to increase the ice thickness, are not expected to seriously degrade the performance of an instrument capable of observing through natural sea ice. The reason for this is that this enhanced salinity would exist in colder, near surface ice characterized by a small brine volume fraction. The effects of oil on the bottom salinity gradient would still be expected to predominate over the bulk salinity of the ice platform. Diagrams of the artificial ice platform technique also indicate that due to the weight of new ice above the natural ice, a curvature of the natural ice occurs, convex down into the water, and therefore most oil spilled beneath the drilling rig will migrate hundreds of feet away from the rig before stabilizing and interacting with the ice. This feature would influence the positioning of possible monitoring systems in the vicinity of a drilling operation.

For oil on the surface of smooth ice, different spreading characteristics are observed (Chen, 1972; Glaeser and Vance, 1971). For Arctic temperatures, these investigators found that oil did not necessarily spread to a thin layer when spilled onto the surface of ice. In some cases oil was absorbed into the surface. This absorption is particularly strong on multiyear ice where brine drainage has occurred during melt seasons leaving cavities in the ice. The volume fraction of these cavities is significantly large, as Glaeser and Vance (1971) observed absorption of oil in ice to an extent of 25% of the ice volume involved.

Whether oil spilled on the surface of ice can be detected and measured with radio techniques depends again upon the electrical properties of the oil and the ice.

Under normal Arctic conditions where the temperature of the surface of the ice is less than -8 to -10°C, the volume fraction of brine in the ice is small and the dielectric properties near the surface are approximately those of pure ice, ie. permittivity $\varepsilon_{ice} \approx 3.3 + j < 0.02$. Since the permittivity of crude oil is approximately $\varepsilon_{oil} \approx 2. + j0$, and that of air is $\varepsilon_{air} \approx 1. + j0$, the oil will act as an impedance matching medium between the air and the ice for radiation propagating from the ice surface. Furthermore, due to its small dielectric loss, the oil does not absorb any significant amount of microwave energy and mainly through interference effects will its presence modify the natural radiation emitted and reflected by the ice. Coincidentally, the dielectric properties of oil at microwave frequencies are nearly identical to those of snow (Cumming, 1952; Kennedy et.al., 1965). Thus, differentiation between thin layers of snow or oil will be difficult. Although no observations at microwave frequencies of oil on ice have been reported, it appears that in the absence of a separate technique for distinguishing between cold oil and snow, no reliable conclusion regarding the presence or quantity of surface oil can be obtained with microwave remote sensors.

For the situation of an oil spill in ice infested waters, oil on the surface of water will change the surface brightness temperature (Jean et.al., 1971). Although the emissivity of sea water ($\eta \approx .35$) is considerably lower than that of sea ice, independent techniques would be required to determine the fractions of ice and water as well as ice type in a radiometer's field of view. In a reconnaissance mode, separation of a change in brightness temperature due to oil on the water or due to a changing fraction of ice in the field of view is unlikely.

The response of radiometers to oil on open water, however, is more amenable to treatment. This problem has been studied extensively, as its solution may be applied to the detection of oil on oceans and harbour waters in lower latitudes. Two mechanisms are responsible for brightness temperature changes in the presence of oil. Sea water at 0°C has a permittivity of approximately 80 + j120 at a frequency of 400 MHz as compared to 2 + j0 for oil (Robar and Wood, 1974a). Thus, a layer of oil on sea water acts as a matching medium for radiation passing from the water into air. The emissivity and measured brightness temperature of the sea surface are therefore increased (Thomson, 1975; Edgerton et.al., 1970: Meeks et.al, 1971; Hollinger et.al., 1973). A second consequence of an oil spill is the damping of capillary waves and the concomitant reduction of surface emissivity. Experimental studies have suggested that these effects can be separated and the presence of oil can be clearly defined especially in horizontal polarization which tends to give better contrast between oil-covered and oil-free water.

The presence of oil on the water surface also leads to wave interference effects, similar to those observed at visible wavelengths. A further analogy between microwave and optical measurements is valid in that optical interference occurs for particular oil layer thicknesses even for wide angle diffuse illumination of the surface and wide angle measurement (Horstein, 1972). For microwave sensing, maxima and minima in brightness temperature have been observed as oil layer thicknesses changed by quarter wavelengths of the observing radiation. Questionable measurements are reported by Caruso and Oister (1973) and by Jean et.al (1971). The latter compares predicted brightness temperature for changing oil thickness on water with measurements of Aukland et.al., (1969). As shown in Figure 7 at 38 GHz up to 100 Kelvins of brightness temperature change in horizontal polarization are obtained for an oil thickness change from 0.0 mm to 1.4 mm while, in vertical polarization, 15 Kelvins

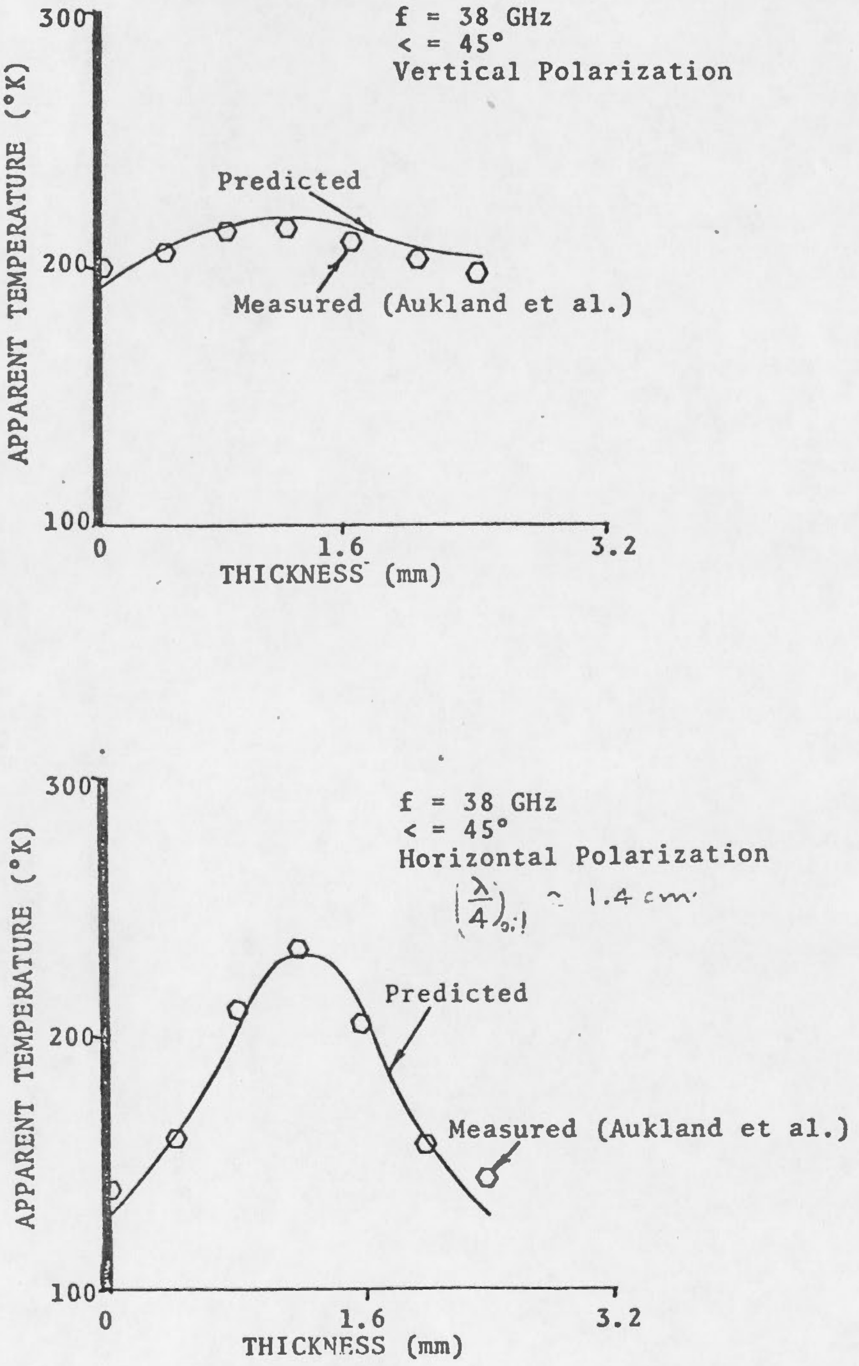

FIGURE 7: Apparent Temperature as a Function of Oil Thickness

are obtained for the same change in oil thickness. Swaby and Forziati (1970) have also reported a correlation between IR scanner data and 19.6 GHz microwave radiometer data over an oil spill where a microwave brightness temperature increase of about 190 Kelvins was observed from oil compared to adjacent open water.

In consideration of the available information on passive microwave detection of oil spills, it appears that radiometric detection mapping and possibly thickness measurements are possible in open Arctic waters. For sensing oil on water the optimum operating frequency would be near 20 GHz to provide a compromise between target contrast, surface resolution, and atmospheric attenuation. Furthermore, in a reconnaissance mode, antenna scanning is possible at this frequency to provide a brightness temperature map of the ocean.

It is evident, however, that a single radiometer frequency or sensing method will not allow for detection of both oil below ice and oil on the water surface. Furthermore, after spill detection by passive microwave remote sensing methods, it will not be possible to determine the type of oil from its brightness temperature signature.

3.0 ACTIVE METHODS

3.1 Description of Active RF Techniques

Active methods of microwave remote sensing include an illumination device operating at the frequency of a receiving instrument. The received energy is that reflected from boundaries between media of different dielectric properties. Since both transmission and reception are involved, more system flexibility (and complexity) are available as compared to passive devices (radiometers).

Perhaps the simplest form of active remote sensor is the scatterometer, in which a burst of energy is radiated from a transmitter and scattered back from the target. The received return signal is proportional to the average scattering coefficient of the target. As with passive radiometers, spatial scanning of the source is possible and an image can be formed by mapping the variation of the scattering coefficient over the viewed area. Certain physical properties of the scattering medium can be extracted from the scattering coefficient for a given frequency, polarization, etc. For example, Rouse (1969) and Parashar et.al., (1974) have been reasonably successful in classifying sea ice into one of four broad thickness categories using dual-polarized scatterometers at two frequencies.

Another active technique is to measure the time from transmission to reception of the signal, and the instrument becomes more properly a radar. Page and Ramseier (1974) clearly describe the types of radar used for snow and ice measurements. These are the imaging radar technique, where an image of a large area is built up from the returns from the various elements of the area of view, and the probing radar, where reflections from adjacent boundaries, for example the top and bottom surfaces of a snow or ice layer are measured and properties such as thickness are derived from the measured time delay. In the former type of radar, properties of the target are inferred from the surface structure identified in the radar image. Reasonably good range resolution can be obtained with this technique, but poor azimuthal resolution is obtained with rotating antennas.

To produce an operational airborne radar, considerable military research and development has resulted in the SLR, or side looking radar. With this instrument, the azimuthal scan function of a ground-based radar is performed by the longitudinal motion of the aircraft, and range perpendicular to the flight direction is determined from the time between transmitting and receiving a signal. There are two fundamental types of SLR instruments, the real aperture and the synthetic aperture SLR. The former type uses only the forward motion of the aircraft and the along-track beamwidth to provide spatial resolution parallel to the flight direction. The latter utilizes differing phase relationships between the signals received from target positions ahead of the aircraft and those perpendicular to, or behind the aircraft position to obtain fine spatial resolution in both along-track and cross-track directions. As the aircraft moves, an image can be obtained from the computer processed return signals.

Presently, three commercial systems are operating outside of military applications (Koopmans, 1975). The Goodyear APQ 102 system operates at 3.1 cm with a synthetic aperture, and a maximum swathwidth of 37 Km can be observed from flying altitudes between 6,000 and 12,500 meters. Ground resolution is 16 meters by 16 meters. The Motorola APS 94 (D) system operates at 2.5 cm wavelength with a real aperture and can measure over a 100 Km swath width with range resolution of 30 meters and along track resolution of 48 meters at near range and 116 meters at far range. Flying altitude is about 3,500 meters. Finally, the Westinghouse system APQ97 uses an 8.6 mm wavelength with a real aperture, maximum swath width of 21 Km and resolutions at 6,000 meters altitude of 11 meters in range, 10 meters in near range azimuth and 22 meters for far range azimuth. For real aperture systems, azimuth resolution degrades with increasing flight altitude. In all cases, aircraft stability is important in producing good imagery and turbulence must be avoided or compensated for. The Motorola system has been used by the Canadian Forces on Argus aircraft and some imagery does exist, although apparently not of the specific area of oil in an ice-water environment.

3.2 Oil Spill Detection Using Active RF Techniques

The SLR is essentially a surface imaging system and the bulk or lower boundary properties of sea ice must be inferred from the top surface scattering coefficients. Some evidence apparently exists that bulk properties of fresh water ice can be measured with SLR's (Page and Ramseier, loc.cit), however, this is unlikely to be true for sea ice with its much larger absorption coefficient.

Since the SLR tends to view more horizontally than vertically, strong reflections from the edges of ice floes are expected, and observed (Page and Ramseier, 1974). Specifically, a strong return was seen from the track of a ship that had passed through ice leaving chunks of floating ice. Due to these observations, the use of SLR systems in observing the effects of oil under ice or on water infested with ice appear to be severely limited.

The SLR is capable, however, of detecting oil slicks in open water where the presence of oil damps the wind-produced capillary waves and produces an area of diminished radar return (Guinard, et.al., 1970). This diminution of radar return is most effective for vertical polarization at wind speeds greater than about 2m/sec. As an example of a SLR used in a reconnaissance mode, the AOSS (Airborne Oil Surveillance System, 1973) is an operational SLR instrument requiring real-time on board computing and is capable of producing almost real time images on film. For searching and mapping of oil spills where rapid action is necessary for successful containment and recovery, real time imagery such as available from AOSS would be invaluable.

Certain limitations of SLR, such as limited ice penetration and high cost and complexity are overcome by probing radars. It should be noted, however, that no experimental investigations of oil under ice has yet been reported for these devices. A probing radar is more applicable than the SLR for the detection of subsurface features due to its ability to accurately measure ranges through the ice from two or more signals closely spaced in time. Such capabilities have recently become possible with technological advancement in radar components, and research prototypes are becoming available for evaluation.

Two basic approaches are being used in probing radars for sea ice measurement. These are wide-band frequency modulation of the transmitted signal (FM/CW) and short time duration modulation of the radio energy (pulse and impulse instruments). A commercial FM/CW system modelled on an aircraft altimeter and operating from 420 to 470 MHz is available from Geophysical Services Inc. Originally used on surface vehicles, it has the ability to measure sea ice thicknesses greater than approximately 1 meter, although no information is published regarding its capability of detecting oil beneath ice.

Impulse radars, using a narrow pulse of DC energy to produce wideband transmission are also in use from surface vehicles (Geophysical Survey Systems Inc.) and experimentally from low flying helicopters

(Gray, private communication, 1975) and aircraft (Bogorodskii and Tripol'nikov, 1974). Active research is in progress studying impulse radar techniques at the Communications Research Center, Ottawa, and experience with an X-band system at 10 GHz, suitable for fresh water ice, is being used to design a UHF impulse radar capable of measuring sea ice (Chudobiak, et.al., 1974).

As in the case of radiometric measurement of sea ice, the contamination by oil of the electrical properties near the ice-water interface is expected to decrease the bottom surface reflection coefficient. That is, a reduced gradient of the dielectric coefficient should reduce the return signal from this region. However, the presence of oil may be detected only as a change in bottom reflection from one horizontal position to another on similar ice, or as a change in the bottom reflection at the same location at different times.

It must be emphasized that at the present time, state of the art active sensors have the proven ability to penetrate first year sea ice. However, there is as yet no measure of the efficacy of such techniques for detection of impurties (ie. oil) imbedded in sea ice.

Ice penetrating radars, like radiometers are likely to have their own special problems associated with pulse discrimination or volume scattering from the bulk of the ice. For example, impulse radars are not likely to discriminate between closely spaced dielectric discontinuities or steep gradients closer than a certain minimum value.

In view of the importance of detecting Arctic oil spills, it is desirable to investigate these RF sensing possibilities by modifying ongoing microwave remote sensing programs to accommodate controlled spills in the test areas.

4.0 SUMMARY OF CONCLUSIONS

The conclusions drawn from the foregoing study on the feasibility of using radio frequency techniques for the remote detection of oil spills in the Arctic are now presented in summary form.

1. The useable radio frequency range for all-weather, all-day oil spill reconnaissance in the Arctic is from 400 MHz to 40 GHz. Ice penetrating sensors will be restricted to operate between 400 MHz and 3 GHz. Ice or ocean surface scanning sensors should operate below 20 GHz (<40 GHz for clear sky operation).

2. No experimental tests have been taken to verify that oil can be detected under sea ice. From theoretical considerations, it appears that UHF (.3 to 3 GHz) impulse radars and radiometers could detect oil spilled under first year sea ice if the oil is observed when it is frozen into the bottom few centimeters of the ice sheet. Impulse radars should respond by decreased signal return when moving from pure to contaminated sea ice. UHF radiometers should exhibit a brightness temperature decrease of tens of Kelvins under similar conditions. Insufficient data is available to estimate if oil is detectable under multiyear ice. Although there is no evidence to preclude such detection at present, after oil spill has been frozen into or has migrated to the center of the ice sheet, it would be difficult to detect by RF techniques. Although oil under ice may be detected by radio methods it is not certain that actual oil thickness can be determined since radiation of wavelength short enough to be comparable to the oil thickness is strongly attenuated in sea ice.

3. Surface oil in ice free waters can be detected, mapped, and possibly quantitively measured by scanning radiometers at ≈ 20 GHz or by side looking radars (SLR's). Oil spilled on ice infested

waters can be easily determined only for small fractional ice cover. Oil cannot be easily identified by type at microwave frequencies.

4. Oil spilled on surface ice will be difficult to detect by microwave remote sensing techniques as it is predicted to impedance match the ice to the air in a manner similar to snow. At frequencies above 20 GHz replacement of surface brine by oil may sufficiently alter ice dielectric properties to create a characteristic surface emissivity change. Experimental measurement would be required to verify this effect.

5. Airborne thickness measurements of sea ice are immediately possible at UHF frequencies. Furthermore, ice structure and typing are also immediately possible using radiometers and dual polarized radars.

6. With the possible exception of side looking radars, microwave sensors suitable for sea ice and oil spill reconnaissance in the Arctic can be carried by light aircraft, helicopters, or surface vehicles such as snowmobiles and trucks. State of the art equipment has been proven to operate satisfactorily in the Arctic environment subject to unusual conditions imposed by handling and storage, cold, and minimal training of operators. From an operational standpoint, it is clear from this discussion that a complementary set of instruments will be necessary to completely satisfy oil surveillance requirements. A likely combination would probably include a 40 GHz imaging radiometer for detecting and measuring oil on open water and providing ice coverage data, a UHF radiometer operating between 400 MHz and 2000 MHz to observe the effect of oil beneath sea ice soon after a spill, and a impulse type radar device operating from 100 MHz to above 1 GHz to do detailed mapping of an under-ice spill site, and perhaps to obtain an estimate of the quantity of oil spilled

if lens thicknesses can be adequately determined. A SLR device may be able to determine the presence of oil on ice infested water if the change in scattering coefficient of the water due to the damping of capillary waves can be determined in the presence of the large scattering effects observed from the edges of ice floes and floating pieces of ice. The contrast between regions covered with oil and those oil-free may be sufficient for this device to determine the slick boundary. In any case, it is clear that more than one instrument will be necessary to cover the range of conditions anticipated in the Arctic, and future tests should be planned to coordinate those instruments which together will be required to provide the necessary information about oil spills.

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August 28, 1975

Mr. Ivor Wm. Thompson
Philip A. Lapp Limited
14A Hazelton Avenue
Toronto, Ontario
M5R 2E2

Dear Ivor:

We received your Draft Report on Remote Sensing of Oil Spills at the Beaufort Sea this week, and have a few suggestions for additions, primarily due to information which we have obtained since our July meeting and the writing of the reports. The principal change in our conclusions would be a greater emphasis upon a microwave imaging radiometer, especially for use in a light aircraft for monitoring of the position and approximate quantity of a known oil spill. This would be especially useful during spring break-up, fall freeze-up, and on open water when conditions were unsuitable for visual or infra red observations, i.e., night time and for fog, cloud, etc.

The microwave imager is also a very useful adjunct to the SLAR radar system since the imager covers that region below the surveillance aircraft of about ±40^{o} from nadir not covered by the SLAR during a pass. In addition, there is some evidence (see enclosure) that the SLAR may have a high false alarm rate for oil spills on open water; especially if any natural wave damping agents such as fish oil are present, even in monomolecular thicknesses. Further, the SLAR has no oil thickness indication at all. This information can be estimated with a microwave imager, but cannot yet be accurately measured. In partially ice-covered areas, while the SLAR receives rather large returns from the edges of floating ice cakes, an imager would be much less sensitive to this source of interference and could be used in partially open water to detect, for example, the presence of oil on an open lead or a melt pond.

In operation, a typical ground resolution of about 30 meters diameter would be imaged at a flight altitude of 800 meters, with a lateral beam scan of ±45° being performed mechanically with a plane antenna, offset on a rotating vertical axis, and repeated at a rate adjusted to the appropriate flight altitude/velocity ratio to give continuous scans. Flight altitudes up to 3,000 meters would be possible, but with proportionately larger footprint sizes.

Parameters for an existing system developed for the United States Coast Guard (Airborne Oil Surveillance System) which could provide a model for an arctic unit are given below:

altitude range	800 m - 3,000 m
frequency	37 GHz
beamwidth	$2^0 \times 2.8^0$
ground resolution	ca. 30 m spot at 800 m alt.
polarization	horizontal
power required	ca. 500 watts
antenna size	about 25 cm x 50 cm, flat, mounted on a vertical rotating shaft to scan
antenna system weight	25 kg
source brightness temp resolution	1.2 Kelvins
antenna rotation rate	max. 35 rev/min to give about 100 separate beam "positions" per second
data rate	for digital smoothing and processing, ten - 10 bit words per beam "position"
data processing	collect above data, average 10 values, co-ordinate shaft encoder position with signal intensity and drive output display device - a small microcomputer
data display	processed data can be stored on magnetic tape or photographic film. Can be presented in real time on a CRT screen in gray-shaded or false-colour presentation for immediate observation with a reasonably inexpensive display system - a few thousand dollars.

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aircraft modifications	- viewing port to allow mounting of antenna - mount a radome of about 60 cm diameter and a wind deflector under aircraft.
operator functions	- set altitude/ground speed input (could be semi-automatic, using altimeter readings and approx. ground speed) - observe CRT display - some training and experience would be required to identify ground features - check on operation of film recorder and/or video tape recording for permanent records.
availability	- units built for USCG by Aerojet Electrosystems - system purchase price unknown, probably > \$100K < \$200K - comparable system could be built in Canada.

Some comparable data for a SLAR system, for example, the APS-94D Motorola unit as used by the USCG are as follows:

altitude range	300 m - 7,000 m
frequency	9.2 GHz
beamwidth	0.87° x 0.9°
ground resolution	30 m lateral range by 20 m/Km of range
polarization	vertical
power output	100 Kw at 3,000 m alt
antenna size	2.5 m in a pod mounted on side of aircraft, yaw stabilized
radar weight	320 kg

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display	- normally hard copy film, 9½" wide - could be visual CRT display
aircraft modification	antenna pad required outside skin, or in a dielectric-covered bay
data requirements	- range divided into 750 intervals - video signal output sampled for 0.2 microsec. intervals - each range interval requires a recursive digital filtering procedure using, e.g., a 768 word memory, a coefficient multiplier and a digital adder
data interpretation	- a greater ground area is observed than with an imager, hence more data interpretation is required - a trained operator-interpretor is necessary
availability	units are available at cost > $1M

A UHF radiometer system such as we have built and are using for our own ice studies has the following characteristics:

altitude range	5 to a few hundred meters
frequency	800 MHz
beamwidth	approx. $15^{\circ} \times 20^{\circ}$
polarization	horizontal and vertical
power required	300 watts
antenna size	about $1m^2$
system weight	about 40 kg
data	normally used time constant is 1 second, one voltage output reading per beam position.

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interpretation	presently requires trained interpretation
aircraft mods	for oil spill monitoring, probably best to fly in a helicopter with antenna underslung for low altitude work over ice within a limited range.

I trust that this will supply you with some useful information for the final report. We continue to collect information and experience, and shall call you if we can contribute further to the project. I have enclosed a copy of the conclusions of an Aerojet study of microwave imagers for oil spill surveillance.

Yours sincerely,

Hugh C Wood

Hugh C. Wood
Research Physicist

HCW/ks

Encls.

COAST GUARD

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PROJECT 714104/A/002

MICROWAVE RADIOMETRIC DETECTION OF OIL SLICKS

PREPARED FOR

UNITED STATES COAST GUARD
APPLIED TECHNOLOGY DIVISION
POLLUTION CONTROL BRANCH
WASHINGTON, D. C.

FINAL REPORT

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Section 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The phenomena influencing microwave emission by oil slicks interact in a complex fashion in the open-ocean environment giving rise to the following experimental observations. Due to the high emission of the thick oil areas contained in slicks, positive brightness temperature anomalies were noted for all oil films measured on calm seas. For all slicks measured on rough seas, the average horizontal polarization signatures were negative. Thus, the additional emission from the thicker portions of the oil slicks were overshadowed by the decrease in ocean emission associated with the reduction of ocean surface roughness. Positive signatures are superimposed on the negative anomalies suggesting that small areas of thick oil were present in the slick area. As predicted by theory, vertical polarization signatures were generally small, and no correlative patterns were established for oil films on rough seas. It should be noted that negative horizontal temperatures can be uniquely associated with oil slicks, since no other phenomenon is known to cause such a signature in the open-ocean environment.

During the field studies, measured brightness temperature anomalies were generally greater than required for the detection of oil slicks. Lowest amplitude signals were of the order of 5°K. A 5°K microwave temperature difference is well within the detection capabilities of passive microwave imaging systems.

The Southern California controlled oil spill experiment, combined with the supporting laboratory and theoretical research concerning the microwave emission characteristics of oil films have yielded the following results:

- Oil slicks on the ocean surface provide unique and readily measurable signatures. Signatures ranging up to 70°K were noted while overflying thick portions of oil slicks. All slicks encountered during the controlled oil spills contained thick portions that were detectable.
- The microwave emission characteristics of oil slicks vary with oil type and film thickness. The mass of oil per unit area is the parameter of most importance.

- The microwave emission characteristics of oil slicks vary with sea state, and provide measureable signatures over a wide range of sea-state conditions. Oil films with an average thickness of one μm were readily detected with 3.2- and 8.1-mm sensors.
- Both theory and measurements demonstrate that horizontally polarized sensors are more responsive to oil films than vertically polarized sensors.
- The microwave brightness temperature signatures of oil slicks increase with sensor frequency (vary inversely with sensor wavelength). However, atmospheric attenuation also increases with frequency. The available atmospheric and oil film signature data indicate that a frequency (wavelength) of about 37 GHz (8.1 mm) is optimal.

These results indicate that imaging microwave radiometers can be employed to detect and map oil slicks. The writers recommend a horizontally polarized, 8.1 mm (37 GHz) imager with a constant viewing angle of 45° and real-time video display for this purpose. This system will provide adverse weather, as well as day and night detection capabilities. Section 8 of this report provides a more complete description of the recommended sensor configuration.

Additional observations concerning the behavior of oil films on the ocean surface may be of interest to the reader and are noted below:

> The oil slicks formed on the ocean surface all exhibited significant point-to-point variations in thickness. Even the slicks formed under near-ideal conditions spread in a non-uniform fashion. For example, point source spills of low viscosity oil on a calm ocean surface exhibited thickness variations exceeding the average calculated thickness (volume of spill divided by total area of slick) by two or more orders of magnitude.
>
> Oil slicks modify sea state by reducing surface roughness, particularly the higher frequency components such as wavelets, small scale waves, breaking waves, etc. Many investigators have considered the physics of sea-state suppression due to oil film, and have developed strong evidence, both theoretical and experimental, that sea-state suppression by an oil film is essentially independent of film thickness. That is, damping due to monomolecular and comparatively thick oil films of interest in oil pollution surveillance give rise to very similar sea-state

> reductions. Experimental data collected during the Southern California controlled oil spills are consistent with this hypothesis.
>
> If this hypothesis is correct, all natural oil films (fish oil, etc.) small legally acceptable man-made spills, etc. will cause similar sea-state suppression, and sensors that rely exclusively on detection of this effect must contend with a potentially large false alarm rate. This relationship should be examined more closely.

Both theory and experimental results indicate that sensor wavelengths of about 8 mm should be employed for pollution-detection systems. Sensors with longer wavelengths are not as responsive to thin oil slicks, and instrumentation and atmospheric absorption limitations are associated with shorter wavelengths.

6.2 RECOMMENDATIONS

The results of this study indicate that a suitably designed passive microwave imaging system will be capable of detecting all significant oil slicks. Although quantitative results regarding precise oil type and thickness cannot be obtained at present, the detection of slicks is of primary importance.

It is recommended that an airborne pollution-detection system, using a passive microwave imager as the primary sensor, be implemented. Such a system would provide adverse weather, as well as day and night detection capabilities. Data from the imager should be presented in real-time on a video display. Complementary sensors such as infrared and ultraviolet instrumentation should also be considered.

APPENDIX C

Evaluation of Optical Methods for Remote Sensing of Oil Spills at Beaufort Sea

AN EVALUATION OF OPTICAL TECHNIQUES FOR REMOTE SENSING OF OIL SPILLS OVER THE BEAUFORT SEA

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

1.1. Study Criteria

There has in recent months been a relatively thorough appraisal of a number of optical and multi-sensor techniques aimed at the remote detection and identification of oil discharges onto water surfaces (Thompson et al, 1974; Edgerton, A. T., et al, 1975). Our objectives in this short study have been very specifically directed at an examination of practical techniques for remote detection of oil slicks over the Beaufort Sea.

The problem as envisaged is one of mapping and monitoring of oil slicks for purposes of containment and clean up. The associated problem of oil species identification is not at this phase as important as the mapping, for clean up purposes, of slicks which might arise from 'blow-outs' or 'seeps' associated with drilling operations in the Beaufort Sea study area. Consequently, fluorescence and Raman techniques, which are generally intended to assist in species identification applications, hold no particular advantages over optical reflectance techniques where detection, monitoring, mapping and thickness determinations are the basic goals.

The optimum solution to mapping of oil under the variety of conditions which can occur in the Beaufort sea must be a multi-sensor approach. In this regard, the complementary roles of the various sensors which might be utilized for these purposes must be examined in each of the six principle oil-ice-water configurations which might occur in the Beaufort Sea. Of these six configurations:

i) Oil in open water
ii) Oil under fast ice
iii) Oil in the seasonal pack
iv) Oil in the polar pack

v) Oil in cracks and broken ice
vi) Oil on the ice surface,

optical techniques can only seriously be considered to be of direct use in i), v) and vi) while thermal applications might be found for configuration ii). Optical remote sensing is not effective for configurations iii) and iv). The remote monitoring of ice conditions iii) and iv) by optical techniques might however be considered as an indirect application of optical methods once oil is located by some other technique.

For optimum use in the monitoring of blowouts, optical techniques must attempt as nearly as possible to be all weather, capable of operation during night and day, and provide real-time spatial display.

1.2 The Multi-Sensor Scenario

This section contains a brief review of the prototype AOSS, Airborne Oil Spill Surveillance system developed by the Aeroject Electrosystems Company for the United States Department of Transportation, U.S. Coast Guard.

The stated purposes of the AOSS system were to assist the U.S. Coast Guard in the detection, mapping, quantification, and classification of oil spills. These purposes were to be accomplished by development of an airborne system capable of the following tasks:

1. ship detection
2. oil slick surveillance
3. slick mapping for both location and size
4. documentation of violators for prosecution.

AOSS was also designed as a multi-mission system intended for other Coast Guard missions including:

1. search and rescue
2. law enforcement

3. ice reconnaissance
4. water temperature mapping
5. aid to navigation
6. flood and hurricane damage assessment.

To assist in accomplishing its objectives, the AOSS multi-sensor array included a side looking radar, a passive microwave imager, a multi-spectral low light level television, a multi-channel line scanner, a position reference system, and a real processor display console.

While the stated purposes of the AOSS system will differ both in kind and in degree to anticipated problems which might arise in the Beaufort Sea, the AOSS multi-sensor experience in oil surveillance will be of direct interest in sensor selection for northern application. Of particular interest to this problem are the AOSS system conclusions on oil surveillance - these are summarized below:

1. Static and dynamic 'controlled' oil spills were reliably detected and mapped at ranges up to 12 nautical miles.

2. The AOSS system routinely documented unreported oily discharges of varying sizes.
3. A multi-sensor evaluation of slicks permits a first-order approximation of volume of the discharge seepage.
4. An integrated multi-sensor system is required for effectiveness over a wide range of operating conditions and to reject potential false targets.
5. The system is effective day and night, from clear to dense undercast, for wind speeds up to 26 knots, and wave heights up to 13 feet.
6. Only gross (i.e. heavy or light) oil spill classification is possible with the present sensor configuration.

The all weather, day/night demonstrated success of the AOSS prototype in remote mapping of oil spills within design objectives should be an encouragement to the remote sensing community. Of particular interest in this study, is the well documented AOSS experience with the two optical/thermal sub-systems (line scanner and L^3TV). Reference to these systems are contained in section 4.0 of this report.

1.3 Beaufort Sea Constraints

There are two problems associated with the application of optical techniques in the Beaufort Sea; (1) It is not presently possible to directly infer the presence of oil under ice using optical techniques. It might, under certain landfast and snow-cover situations, be possible to 'observe' oil under ice or snow from thermal imagery. This results from the fact that the thermal characteristics of ice having an insulating 'pool' or 'lens' of oil beneath it are expected to differ from the thermal characteristics of the surrounding ice. (2) Meteorological and metric considerations (Section 3.0) will limit the applicability of passive optical techniques.

Within the boundaries of these two limiations, our review of the problem indicates to us that some variation of existing optical instrumentation may be optimized for general application to the Beaufort Sea problem. In particular, any system designed for these northern applications should include the following specifications:

1. Capacity for simultaneous registration in at least one thermal and one visible channel.
2. Low level illumination provided by some form of artificial illuminator.

The first specification above would allow a complete range of oil slick mapping, and volume (i.e. thickness approximations) determinations. Careful selection of spectral windows should be made to minimize atmospheric and volume reflectance (i.e. water colour effects). The 600 nm - 1.0 μ region in particular may afford a minimum contribution from volume and atmospheric effects (as compared to the UV). The near-IR, may also extend the 'passive' range of any low light level system as natural night time illumination is two orders of magnitude greater in the near-IR than the UV. (Engstrom, R.W., and Rodgers,L.R., 1971). Finally, non-blooming low light level T.V. systems are optically more efficient in this region of the spectrum. (Edgerton, A.T., et al., 1975, op.cit.)

2.0 OPTICAL TECHNIQUES

2.1 Visible Region

The controlling factor governing the effect upon the apparent reflectance or albedo from substances, such as oil, floating on the water surface, will arise from the incremental energy added to or subtracted from the the background albedo by the floating substance.

The magnitude of the surface contribution to the albedo will be determined by the Fresnel reflectance formula given by (for unpolarized radiation and normal incidence)

$$\rho = \frac{[n - 1]^2}{[n + 1]^2} \qquad (1)$$

where n in Equation (1) is the index of refraction of the oil (assuming oil thickness greater than 1μ). For most oil species, n ranges over values from 1.4 to 1.6. (Fantasia, 1971) depending upon oil API. Simple substitution of these values for n are computed in Table I.

Surface Species	Reflectance (R %)	Contrast Ratio (R_o/R_w)
Water n = 1.34	2.11	1.0
Oil #1 n = 1.4	2.78	1.3
Oil #2 n = 1.5	4.00	1.9
Oil #3 n = 1.6	5.33	2.5

Table I Computed reflectances and contrast ratios for oil and water.

These calculations illustrate how highest contrast ratios will result from highest indices of refraction (under model conditions). These simple calculations ignore the effects of non-normal incidences, spectral effects, interference and polarization effects, cloud cover, haze, water colour, and wind speed (i.e. wave height). Each of these factors may separately and in combination be considered within reasonable models to compute optimum sensor characteristics for optimum contrast.

In certain situations, these factors will in fact combine to actually reduce oil/water contrast to values less than unity (i.e. oil will appear darker than water). An understanding on how such an effect could occur will be appreciated when it is understood that the albedo A generally consists of three reflectance components, a surface term R_s (water or oil), an atmospheric term R_a, and a water colour term R_w. In situations such as regions of high turbidity where the water colour term R_w is large, the blocking effect of an oil slick will actually reduce the net albedo over the slick and yield contrast values less than unity (McNeil, W. R., 1975).

In addition to the reflectance processes just described, oil on the surface can be inferred by judicious application of fluorescence and Raman techniques. Fluorescence phenomena in particular have been extensively investigated in recent years and have shown a ready ability to detect and even classily certain oil species on a day/night basis through wavelength spectral signature and more recently, fluorescent decay spectra analysis (Measures, R. W., 1974).

Raman techniques have not as yet been extensively applied to the problem of remote detection or identification of oils. Raman phenomena are worth investigation and should be presently considered for laboratory trials such as a cataloguing of Raman spectral properties of broad categories of oil species. Existing laboratory Raman spectrometer systems might easily to be configured for analysis of oil samples (Howard-Locke, H., 1975).

Fluorescence and Raman phenomena both require active or artificial illumination for application. The focus of Raman and fluorescent techniques remains spill classification.

2.2 Thermal Region

Thermal processes remain an important key in the remote detection and quantification of surface slicks. The process is due to natural thermal emissions (black body) from all substances, which are remotely 'observable' in atmospheric windows between 3-5 μ and 8-14 μ . Surface oils and water have differing natural emissivities (i.e. 0.993 for water and 0.972 for oil) which account for their differing thermal signatures. Oil in effect will appear 'colder' (i.e. darker) than surrounding waters - the coldest (darkest) IR tones will be associated with the thickest portions of the slick (de Villiers, J. N., 1973). Thin portions of a slick will reach thermal equilbrium with the surrounding and underlying waters and as a result will display no significant thermal contrasts. Thermal techniques, used in conjunction with optical techniques afford an excellent self contained method of mapping the entire spill or slick while simultaneously isolating the thickest portions of the spill - a useful observation where rapid containment is required.

Thermal techniques function both night and day. They are not however all-weather and are subject to similar cloud and haze restrictions as other optical techniques. However because of the longer wavelengths, infrared techniques can more readily penetrate fog and especially haze. Under some conditions, infrared range can be 3 to 6 times the visual range. There is also some theoretical possibility, as yet unconfirmed experimentally, that thermal remote sensing might in certain isolated situations enable remote detection of oil under ice. Wolfe and Hault (1972), in a series of laboratory experiments have found that oil, pocketed beneath ice surfaces will act as an insulator and in effect impede the flow of thermal energy from beneath the ice by reducing the temperature gradient across the ice. For a given ice thickness h_{ice}, the heat flux Q through an ice sheet displaying a temperature gradient ΔT_{ice} will be given by

$$Q = \frac{k_{ice}\Delta T_{ice}}{h_{ice}} \tag{2}$$

where k_{ice} is a constant. For moderate ice thicknesses, oil beneath the surface will act to reduce ΔT_{ice} to small values. Consequently, the oil beneath the surface may radiometrically appear 'colder' than the surrounding areas [smaller Q in Equation (2)]. This phenomena is not as yet known to have been observed but worth discussion.

2.3 Spectral Selection

Several considerations come into play in an optimum selection of spectral characteristics for optical remote sensing of oil slicks.

For visible passive systems, these include the availability of illumination both night and day, atmospheric window, water colour effects and detector sensitivity.

For simple mapping and detection applications utilizing reflectance phenomena in the visible or near-IR, the wavelength region centred near 0.8 μ would appear to be optimum - this region affords good penetration of the atmosphere and yields the highest potential oil/water contrast (by minimizing water colour effects). Physically, for night-time operation (i.e. starlight), the near-IR also offers maximum potential for low light level applications because natural night time illumination is nearly two orders of magnitude greater than in the visible under these conditions (Engstrom, R. W., and Rodgers, L.R., op.cit.). An additional advantage lies in the superior sensitivity of non-blooming low light level systems in this part of the spectrum (Rodgers,R.L.,1973).

In the above applications, detection and mapping constraints were optimized - where additional spectral information is desired, such as will be available with multi-spectral systems, spectral resolutions of the order of 5 nm should be attempted (Grew, G. W.,1973). This is the order of resolution required for sufficient detailing of most reflectance and fluorescent phenomena.

Thermal information is generally available along either the 3-5 μ or 8-14 μ channels. No convincing experimental evidence has as yet been offered to demonstrate any particular physical advantages of either of these channels in there sometimes claimed ability to discriminate between different oil species. The 8-14 μ channel is generally preferable for its superior atmospheric transmission characteristics.

3.0 OPTICAL OPERATIONS AT BEAUFORT SEA

3.1 Sensor Classes

The discussions in this section apply to optical operations of existing airborne and satellite instrumentation over the Beaufort Sea. Optical instrumentation may be grouped or classified in numerous ways. For application to the immediate requirement of providing an effective array of detection/mapping device(s), we recognize three broad classes of electro-optical instrumentation:

1. Thermal: This class includes a broad range of both imaging and non-imaging infra-red sensing devices such as the IR radiometer, IR line scanner and the forward looking IR scanner (FLIR). Most of these systems operate in the 8-14 μ region of the spectrum. Some lower resolution systems also operate in the 3-5 μ region.

2. Photometric: This class of instrumentation includes a broad category of conventional imaging and non-imaging systems operating in the visible (UV to near-IR). Representative devices include conventional television, multi-channel photometers, multi-spectral scanners, image dissector cameras and multi-band photography. The common characteristic of each of these systems is that they are all passive devices capable of daytime operation only.

3. Intensified Photometric: This class of instrumentation will include all types of instruments listed above but which have in some way been modified for low light level applications (i.e. L^3TV) or by use of some form of artificial illumination as with active systems (i.e. laser fluoresensors).

3.2 Meteorological and other Environmental Constraints at Beaufort Sea

This section details the results of a set of probabilistic calculations directed at arriving at a semi-quantitative determination or assessment of the probable effectiveness at Beaufort Sea of each of the three broad sensor classes described above.

To arrive at this assessment, the most recently available ice climatological and meteorological data is used (Burns, B.M., 1973-74).

The climatological and metric parameters which will effect some or all of these downward looking optical remote sensing applications, include the following:

Illumination P_I: Interpreted as the random probability of sufficient natural surface illumination during any period of the year, this quantity is converted directly from 'hours of daylight' data for 70° latitude (Burns, B.M., 1 , op.cit., p.22). This parameter will effect target registration for photometric techniques only. [in probabilistic terms, P_I will be unity on June 21 (i.e. 24 hours of daylight) and zero on December 21 (i.e. 24 hours of darkness)].

Cloud Cover P_C: Cloud cover will impede all high altitude (or satellite) applications of optical techniques. The data utilized are a mean of those listed for Inuvik and Cape Parry (Burns, B.M., op.cit., II, p.185) For 10/10 cloud cover, P_c will be unity; for 0/10 cloud cover, P_c will be zero.

Precipitation (P_p): Precipitation will limit application of all optical techniques through reduction in visibility. Data for Cape Parry is utilized and we assume zero probability for target registration during precipitation periods (snow or rain).

Fog (P_F): Cape Parry data are used (Burns, B. M., op.cit., II, p.189). Fog will affect all high and low altitude techniques.

Blowing Snow (P_S): Cape Parry data (Burns, B.M., op.cit., II, p.190). These data are treated in the same fashion as fog data.

Ice Cover (P_{ice}): Ice cover data are both limited in quantity and highly variable in content. For this assessment, 100% ice cover from mid-November to late April is assumed. From early May through mid-September, or break up, the probability of ice cover within the Beaufort Sea study area is assumed to linearly approach zero. In a similar fashion, the probability of ice cover during freeze-up, (mid September to mid-November), is assumed to linearly approach unity.

The overall probability P_E that an efficient airborne optical sensor will provide positive downlooking registration of a given target (e.g. oil on water) will be a product of the probabilities of the above calculated parameters according to

$$P_E = P_I(1 - P_P)(1 - P_F)(1 - P_S)(1 - P_{ice})(1 - P_C) \qquad (3)$$

The resultant calculations have been segregated into two optically realistic ice/oil/water configurations: 1) oil in open or ice infested waters and, 2) oil on ice. For each of these configurations, four possible sensor case simulations are considered:

Case I: High Altitude Photometric.

This case is intended to simulate a high altitude or satellite application of any Photometric remote sensing device in each of the two stated configurations. For this case Equation (3) is retained without modification.

Case II: Low-Altitude Photometric.

This case is intended to simulate low level light aircraft or helicopter applications utilizing conventional photometric devices. Cloud Cover restrictions would not apply in this case, so that P_c will be zero in Equation (3).

Case III: Low-altitude Intensified Photometric.

This case will simulate any low altitude overflight utilizing an illuminator augmented low light level system, operating under any illumination regime. The parameter P_I is taken as unity and P_C as zero.

Case IV: Low-altitude Thermal:

This final case is intended to simulate the application of a low-altitude thermal IR line-scanner or forward looking IR device.

To account for the oil-under-ice hypothesis outlined in Section 2.0, the two periods , (October-December) and (April-May), representing windows of potential thin ice (or) situations where snow-cover (i.e. on oil) might occur, are represented as having higher detection probabilities in the computed results [Figure (1)]. Otherwise, the thermal constraints for this calculation are considered the same as those for Case III (i.e. $P_I = 1$ and $P_c = 0$).

3.3 Summary

The results for the oil in open or infested water configuration illustrated in Figure (1) and summarized in Table II, represent the general expected range of effectiveness of optical techniques under the 'best' model conditions and are intended only as a semi-quantitative guide in sensor technique assessment. For example, we assume in each case that the sensor is in fact airborne. A more quantitative assessment might include IFR and VFR flying probabilities under each configuration.

In general, as inspection of Figure (1) will verify, ice conditions are seen to severely limit the range of optimum effectiveness of optical tech-

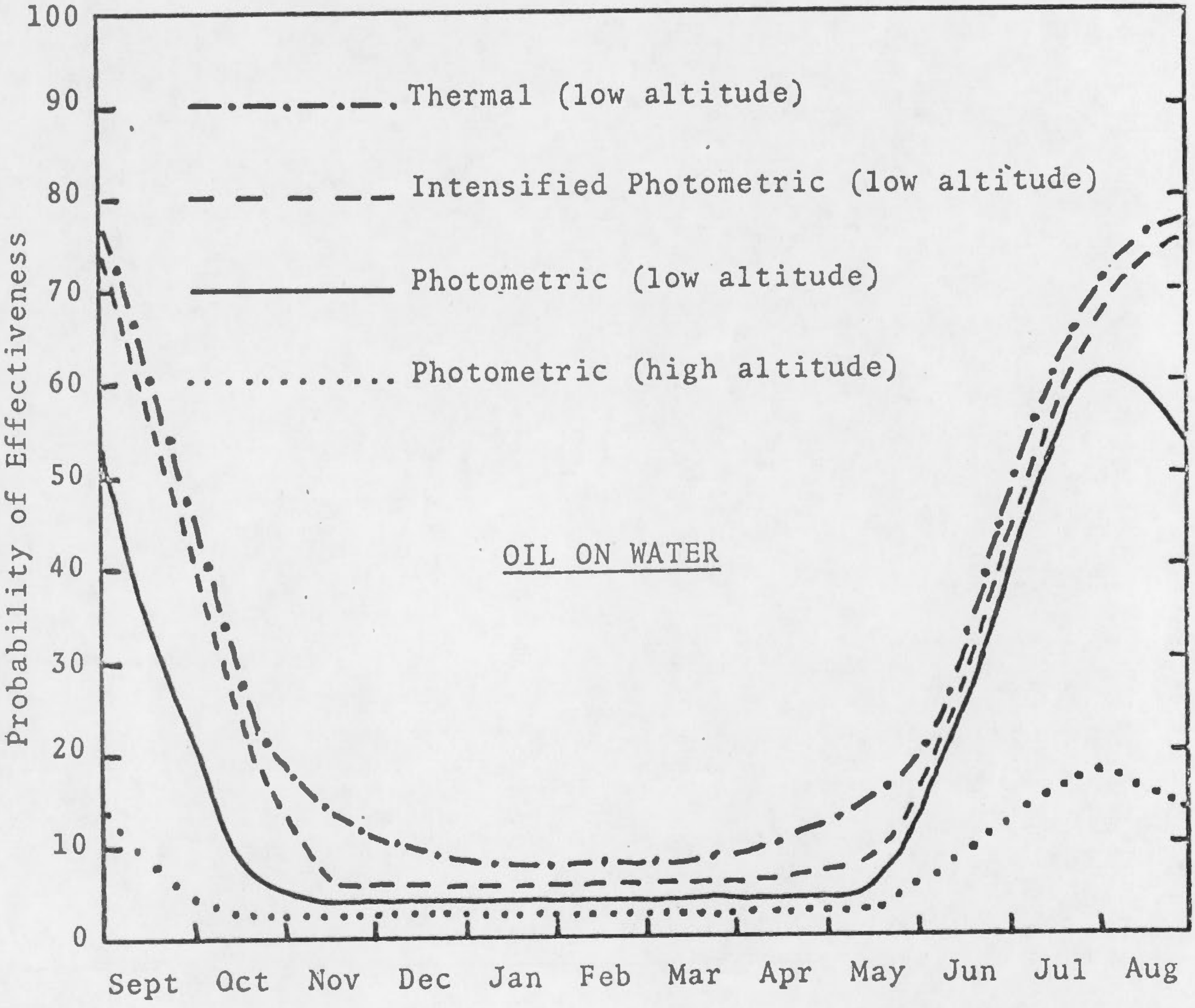

Figure (1) Probability of effectiveness of Optical and Thermal techniques at Beaufort Sea as a function of ambient illumination, cloud cover, precipitation, fog and blowing snow.

	AIRBORNE TECHNIQUES (low altitude)			SATELLITE TECHNIQUES	
PERIOD	THERMAL	INTENSIFIED PHOTOMETRIC	PHOTOMETRIC	THERMAL	PHOTOMETRIC
January	—	—	—	—	—
February	—	—	—	—	—
March	—	—	—	—	—
April	—	—	—	—	—
May	Fair	—	—	—	—
June	Good	Good	Good	Fair	—
July	Good	Good	Good	Fair	Fair
August	Good	Good	Good	Fair	Fair
September	Excellent	Excellent	Good	Fair	—
October	Good	Good	—	Fair	—
November	Fair	—	—	—	—
December	—	—	—	—	—

Table II Summary of probable effectiveness of various sensor classes in Oil on Water detection.

niques for oil on water detection to the three month Summer period.

The most sophistocated optical techniques are seen as ineffective for at least five months of the year. Exceptions will of course occur for oil intrusions into open leads,polynias or in trenches that have been cut in the ice.

During open and ice infested periods, thermal and intensified optical devices operating at low altitudes will be significantly more effective than conventional photometric instrumentation.

The second configuration summary (oil on ice) shows somewhat different results [Fig.(2), Table III]. These calculations show at least a fair probability of success for all four sensor classes over all but the November to February period .

Thermal and intensified techniques, especially when used in tandem, are judged as having excellent potential for effective detection over the entire 12 month period(for low altitude surveillance).

Not shown in these figures but included in the tables are simulation summaries of high altitude (or satellite) thermal and photometric applications of these techniques. For the oil on water configuration (Table II), the calculations indicate only a fair probability of detection effectiveness during the July through October period. For oil on ice (or for ice reconnaissance), such satellite or high altitude techniques indicate a good chance of success over most of the year (Table III).

Intensified Satellite applications of photometric techniques are not as yet operational nor feasible as they presently would require some form of ground illumination of potential targets from orbital altitudes. They are therefore not included for discussion in this summary.

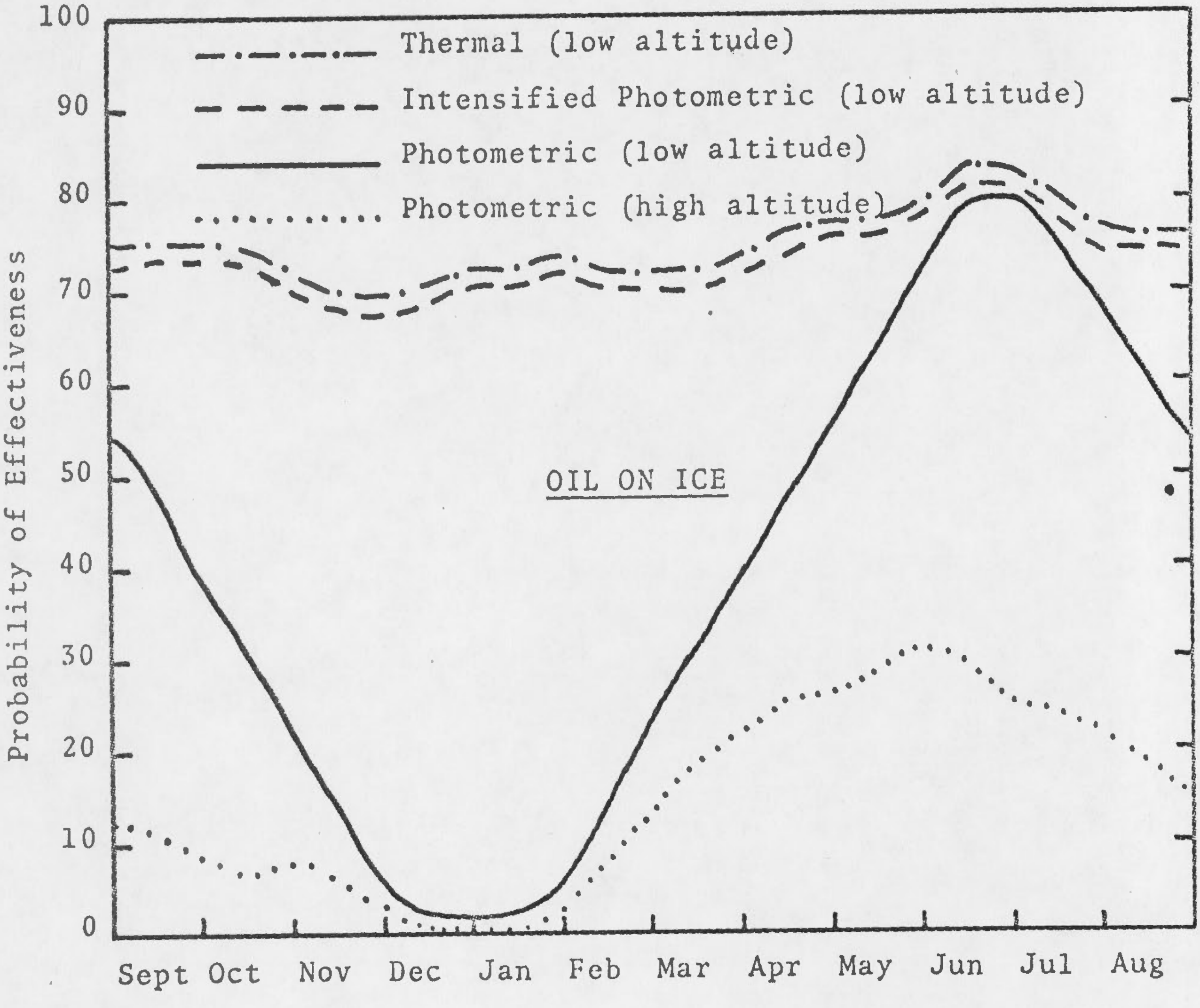

Figure (2) Probability of effectiveness of Optical and Thermal techniques at Beaufort Sea as a function of ambient illumination, cloud cover, precipitation, fog and blowing snow.

PERIOD	AIRBORNE TECHNIQUES (low altitude)			SATELLITE TECHNIQUES	
	THERMAL	INTENSIFIED PHOTOMETRIC	PHOTOMETRIC	THERMAL	PHOTOMETRIC
January	Excellent	Excellent	—	Good	—
February	Excellent	Excellent	Fair	Good	—
March	Excellent	Excellent	Good	Good	Fair
April	Excellent	Excellent	Good	Good	Good
May	Excellent	Excellent	Excellent	Good	Good
June	Excellent	Excellent	Excellent	Good	Good
July	Excellent	Excellent	Excellent	Good	Good
August	Excellent	Excellent	Excellent	Good	Fair
September	Excellent	Excellent	Good	Fair	Fair
October	Excellent	Excellent	Good	Fair	—
November	Excellent	Excellent	Fair	Fair	—
December	Excellent	Excellent	—	Fair	—

Table III Summary of probable effectiveness of various sensor classes in Oil on Ice detection.

4.0 REMOTE SENSING SYSTEMS

Included below is a brief description of several salient features of a variety of optical devices, each of which have under certain situations, some potential for application over the Beaufort Sea.

4.1 Photometric Devices:

4.1.1 Multi-Spectral Devices - Mechanical

Multi-spectral airborne devices exist in numerous configurations. Conceptually these systems may be regarded as consisting of a modular array of three units: a scanning head, a detector-spectrometer, and a data-recorder.

A typical scanning head will consist of a scanning mirror with imaging optics. Scanning heads have been carefully designed for aircraft (and satellite) uses and will generally include some form of roll compensation. For dual or multi-channel registration, the input optics may include a 45^{0} dichroic element, This feature commonly allows simultaneous recording and display in one thermal and at least one visible channel.

The detector-spectrometer module of a typical MSS system will utilize a reflection grating as the dispersing element along with a silicon photodiode detection array. Spectral resolutions of the order of 50 nm in up to 10 visible channels may be specified. Most systems utilize mercury-cadmium-telluride as the basic detection element for the thermal IR channel. (i.e. 8-14 μ).

The most essential element in any anticipated detection/mapping function over the Beaufort Sea, is real time display. Conventional multi-spectral scanners are intended for data-processing at later times, consequently data is usually recorded in analog form on 7 or 14 track magnetic tape.

For real time TV - format display, the scanner output must be followed by some method of scan conversion for TV compatability. This process is often accompanied by a severe loss in image quality.

4.1.2 Multi-Spectral Devices - non-mechanical

This section briefly describes multi-spectral systems which utilize image dissectors at the scanner and detector stages. The image dissector is nothing more than a photomultiplier with a small electronically movable photocathode area which can be operated as a television system. The output from an image dissector is a current whose magnitude is directly proportional to the input irradiance. Unlike storage camera-tubes, the output signal from an image dissector is completely independent of scan rates and previous scan history. Utilizing diffraction gratings or wedge type interference filters, the image dissector camera has a number of advantages which make it suitable for possible daytime use in smaller aircraft:

(1) it has no moving parts;
(2) it is simple and rugged in construction;
(3) it has potential for high real time spatial resolution;
(4) it has high-spectral resolution (i.e. 5 mm or less);
(5) image dissector characteristics are such that platform stability (roll compensation) requirements are low.

The primary disadvantages of the dissector system are the problem of channel registration (one channel only) and the lack of thermal information. However, no known conventional daytime imaging system offers such a superior combination of both spectral and spatial characteristics as these devices.

4.2 Intensified Photometer Systems

4.2.1 Intensified O.M.A.

Intensified Optical Multi-channel Analysers or OMA's are non-imaging devices capable of storage of up to 500 channels of spectral information over a wide spectral range (200 nm - 1.1 μ) and at input signal levels comparable to starlight illumination under clear moonless skies. Spectral resolutions of the order of 0.1 nm are possible with these systems. Commercial devices utilize medium resolution polychromators as the dispersing element. This will be followed by an image intensifier vidicon detector similar in operation principle to the low light level TV device described later.

The signal to be detected is focussed upon a fiber optic face plate with a photocathode deposited upon it. Released photoelectrons are then accellerated to an array of up to 500 silicon diodes from which data is read off by a scanning electron beam. Variable storage modes in these devices allow impressive signal to noise improvements for weak signal applications. Aircraft worthy variations of these systems (Jeffers, S., 1974) could be applied to various remote sensing applications. Some of these would include applications of passive high resolution reflection spectroscopy as well as applications of fluorescence and Raman phenomena using active cw or pulsed lasers as sources. The OMA's are physically small, easily configured for aircraft use and require little power while being relatively inexpensive. Various versions of real time data output are possible (CRT, x-y plotter, paper tape, or real time video).

4.2.2 Laser Fluorosensors

Various versions of primarily experimental cw and pulsed laser fluorosensors have been in operation for several years. However, a potentially commercial second-generation multi-spectral laser fluoro--sensor now under development may be available for field trials early in 1977. This device is expected to provided up to 16 channels of spectral information in real-time. In addition, the system will provide two channels of temporal information for potential application of fluorescent decay spectrum applications. The system, which is being designed with existing multi-sensor systems in mind could provide an effective demonstration of a versatile commercial laser fluorosensor designed for airborne use.

4.2.3 Low Light Level Television (L^3TV)

The basis for operation of low light level television systems is the silicon intensifier target (SIT) tube. The tube uses a photo-cathode as the prime sensor. The photocathode is followed by a silicon diode array (target) to produce gain. Signal is read out on the backface of the target by a scanning beam in a fashion similar to that of conventional vidicon tubes. Overall SIT gain is a function of photoelectron acceleration voltage. A voltage near 10 kV will produce gains of the order of 3000 or low light level image intensification of this order.

'Blooming' of overloaded areas in the resultant TV image has hindered certain applications of the SIT camera. Recently developed 'non-blooming'tubes however utilize the technique of forming a structure in the silicon target array. This structure in effect acts in a passive manner during normal tube operation but 'soaks up' the excess'holes' responsible for the blooming phenomena when the tube is overloaded by optical 'hot' spots.

Field experience with low light level imaging systems has found that they are able to extend the range of useful real time effectiveness of TV reconnaissance systems down to illumination regimes the optical equivalent of 'deep twilight'. This scene illumination is three to four orders of magnitude less than in mid-day (depending on conditions) but three to four orders of magnitude greater than the scene illuminance under starlit or overcast starlit conditions.

To overcome the problem of insufficient scene illuminance under very dark conditions, some form of artificial illuminator will be required for 24 hour application of L^3TV systems. The AOSS program [Section 1.2] in raising this same question, have recommended use of a commercial wing-mounted searchlight illuminator with suitable spectral properties to effectively extend the range of L^3TV to 24 hours at low altitudes (U.S. Coast Guard Report, i, 1973). The recommended illuminator operates in cw mode from 28VDC & 60 A power supplies. The unit weighs less than 50 lbs and equipped with variable beamwidth will operate over a wide range of altitudes.

An optically more efficient illumination approach would to employ some form of laser as the illuminator. For the near-IR spectral range recommended in Section 2.0, a GaAs laser, emitting at 0.84 μ, would serve as the most likely candidate for this application. Utilizing beam expansion optics, such an illuminator would have a nearly unlimited airborne altitude range. For 24 hour application of multi-spectral techniques, some form of tunable dye laser might better serve as a scene illuminator.

Recent trends in low light level imaging technology have been towards the development of all solid state or charge coupled devices (CCD's). Some quarters have suggested that CCD's will completely replace conventional scanning devices for photometric and thermal devices as well.

4.3 Thermal Devices

4.3.1 IR Line Scanner

The basic operating principle of the scanner was outlined in Section 4.1.1. Most IR scanners of interest will use these same basic optics but will split the incoming radiation into its visible and thermal components via a dichroic element inserted at the scanning head.

4.3.2 Forward Looking Infra-Red (FLIR)

Forward looking infrared thermal imaging systems are passive remote sensing devices which operate by scanning in a raster rather than a line mode. The image may be presented as a TV type display. Recently developed FLIR's have been designed for aircraft and helicopter applications. In a typical FLIR system, the sensor looks at the scene ahead of the aircraft. The elevation field of view is covered by the detector array while the scanning action of a rotating or scanning mirror covers the azimuth field of view. Use of fast responce HgCdTe detectors enable elimination of scan conversion steps and permit direct interfacing with TV monitors.

The combination of image quality, real-time display, and coverage (i.e. forward looking capability) show that FLIR is a superior surveillance tool. Cost and secrecy have kept FLIR from the remote sensing community in the past. Both of these factors have fortunately been lessened and versions of this important environmental tool are available for non-military applications.

5.0 CONCLUDING REMARKS

5.1 Multi-Mission Considerations

Selection of optimum electro-optical packages for deployment over the Beaufort Sea must include a consideration of anticipated multi-mission roles for remote sensing aircraft employed in these tasks. In addition to the oil surveillance roles (for detection and mapping purposes) such aircraft might also be involved in the following directly related tasks:

a) ice reconnaissance
b) lead patrol
c) water quality studies

The need for routine and effective ice reconnaissance is clear from any consideration of the disruptive effect that an unheralded incursion of ice flows from the Arctic pack might have upon Beaufort sea drilling operations.

Lead patrol would entail some form of routine reconaissance of open leads. These leads might potentially 'feed' oil from a spill or blow-out deep into the Arctic pack.

Remote sensing roles for water quality in the Beaufort Sea might include remote documentation or simple tracing of 'turbidity' discharges from the Mackenzie river. Such studies, aimed at mapping the eventual destination of the Mackenzie discharge might be extremely useful in the event of an emergency such as a blow-out. The eventual destination of turbid surface waters might parallel that of surface slicks making such documentation very valuable for possible containment scenarios.

5.2 Multi-Sensor Considerations

Any selection of electro-optical instrumentation must also take into consideration the net complement of sensors within what is generally regarded as a multi-sensor problem. An effective remote sensing scenario will include application of several complementary technologies.

In addition to these multi-sensor considerations, optimum selection of electro-optic tools must consider present and future roles of both satellite and in-situ monitoring techniques.

5.3 Recommended Systems

The most versatile real-time day/night detection-mapping technique for monitoring and surveillance for oil slicks in the Beaufort Sea environment will require application of both thermal and visible low light level techniques. The most effective combination of off--the-shelf technologies for present airborne patrol in the Arctic environment would be a synchronous tandem FLIR/L^3TV package augmented with a recommended searchlight illuminator.

Less expensive (and less effective) but still useful techniques would entail integration of off-the-shelf line scanner devices with low light level systems.

Where only a single optical sensor was available, FLIR would be the optimum candidate . This would enable at least 24 hours surveillance over a 12 month period. For cost and maintenance reasons, FLIR may not always be practical. In these cases, a rugged L^3TV camera and searchlight equipped with suitable spectral and polarization filters could serve as and effective alternate.

As a second alternate, a version of the image dissector camera might be considered. While not strictly a low light level device, the combination of characteristics noted in section 4.1.2 would be advantageous under northern conditions. Target illumination would be essential with this camera for night applications. The GaAs laser might provide the best source in this case.

In all the above cases, these systems should be designed for the widest area coverage possible utilizing such developed features as gymbal mounts and zoom lens optics.

For oil species identification and classification as well as for water quality applications where high resolution spectral information would be required, some version of an intensified OMA device could provide this additional spectral information while at the same time serving as a potential detector for future 'add-on' laser-Raman or 'laser-fluorescence' modules.

Equipped with narrow-beam optics such a sensor acting in a passive reflectance mode could be utilized to zero in on small scenes within the FLIR and/or L^3TV fields of view to yield real-time high resolution reflectance spectra of targets of interest.

5.4 Environmental Impact

The statistics of past global experience has shown that the total discharge from accidental and deliberate spills, leaks and offshore operations has amounted to about 0.1 % of total world production on an annual basis (Dealy, J. M., et al, 1974). A thorough consideration of the delicate Arctic ecology, the presence of susceptible life forms and the proximity of wildfowl nesting areas at Beaufort Sea is now under careful scrutiny by a number of other groups. On strictly probabilistic grounds, no matter to what extent and no matter how many safeguards are eventually taken;

inadvertant oil-seepage into this area will eventually occur if resource exploitation of the area is to continue. It is therefore imperative that there be an accelleration in the exchange or cross-feeding of information between the life and physical sciences in order that the potential damage from oil contamination of this area is minimized.

Of special concern, will be the effects that certain toxic substances, known to be present in crude oils (i.e. thiols and certain heavy metals such as nickel and vanadium) could present to Arctic life forms (Pollution Contingency Plan, 1971). Life science expertize could therefore assist in setting acceptable levels for concentrations of these substances for this region.

From the physical sciences, a useful figure of merit which might be of value in various aspects of planning in the region could be some measure of the 'probability of a blow-out or oil seepage' as a function of some measure of drilling activity (i.e. active drilling sites). For example, the extremely high geothermal pressures known to exist in the Beaufort Sea study area may imply higher probabilities of blow-out than at other regions of the globe. This data would also be useful in numerous aspects not only of contingency planning but also in helping to set optimum permissible levels of exploration activity.

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