OIL SPILLS IN COLD CLIMATES;

WITH SPECIAL REFERENCE TO THE TRANSPORTATION AND EXPLORATION OF HYDROCARBONS IN THE KARA SEA

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DECLARATION

In accordance with the University of Cambridge regulations,

I do hereby declare that:

This thesis represents my own original wotk and conforms to accepted standards of citation in those instances in which I have availed myself to the work of others.

This thesis is not now being submitted nor has been submitted in the past for any other degree, diploma, or similar qualification at any other university or similar institution.

This thesis does not exceed the maximum allowable length of 20.000 words, excluding footnotes, tables appendecies, and references.

Jon T. Berg.

Jon Trygve Berg

14 th June 1992

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ABSTRACT

Oil spilled in ice infested waters have frequently been under investigation through the last twenty years. This has been induced by the prospects of large oil reserves offshore both in the American and Russian Arctic. Two oil spill scenarios considering the oil exploration in the Kara Sea have been developed. In this work the fate and behaviour of the oil in ice, environmental conditions in the Kara Sea and the present and past exploration of the region has been summarised. Oil spilled under ice will be encapsulated within the growing ice field for then to be released, without a change in properties, the following season. The movement of the oil will be determined by the motion of the ice. The amount of oil which is contained by the ice and its spreading is determined by the under ice morphology. Oil spilled in open ice will be contained by the ice only to be released when the ice breaks up and melts. No large scale mechanical clean up technology has been developed. Burning might be feasible of newly surfaced or oil contained in leads between floes. However the logistics of such operations will be very expensive and probably not economically feasible. Chemical dispersion might be enhanced due to the thickness of the layer of oil in the broken ice. However, emulsions forms very quickly which decreases the efficiency of the dispersants radically. The scenarios revealed the possibility of spilled oil to be transported out of the Kara Sea and into either the Barents Sea of the polar basin. Possibly to be released into the Barents Sea in the following summer as fresh crude or in the waters surrounding Svalbard after one or two seasons as weathered crude. This emphasises the need for international coordination of the drilling activities in the Kara Sea with respect to possible environmental disasters.

1.0 INTRODUCTION

As petroleum reserves in more temperate and accessible regions become depleted and cold climate technology is expanding, increasing attention is being focused on the Arctic sedimentary basins as future sources of supply of crude oil and natural gas. The discovery of vast hydrocarbon reserves in Western Siberia and Alaska have resulted in increased exploration, the development of conceptual plans for production and transportation facilities, and in a growing awareness by the public, governments and industry of the problems of development of oil and gas fields in an offshore Arctic environment. The first significant flow of oil and gas from Arctic areas came from the Western Siberia basin in the early 1960's (OGJ, 1991i) and around ten years later from the giant Prudhoe Bay oil field in Alaska (Alaskan Update, 1987). Today 18 % of the world oil production comes from the Arctic. About 20% of the total American production, 65.5 % of the former Soviet Union (OGJ, 1992) and 72% of the Russian production (OGJ, 1992) based on 1987 figures from The Stateman's Year Book (Paxton, 1987) and OGJ, Aug 12, 1991. However it was only recently that the first commercial offshore Arctic oil flow started from the giant Entricott field 4 kilometres offshore of Alaska (OGJ, 1987a). There has so far been no production offshore of Siberia; however major developments are expected in the beginning of the 21st century.

The Russian oil industry has always been a major part of the global picture and as early as in 1898 oil production exceeded that of the United States (Yergin, 1991). Russia is still the largest petroleum producer in the world and is second only to Saudi Arabia in export (Chemtech, 1991). After technology is upgraded and political if stability is achieved, the offshore exploration is expected to rise rapidly into the 21st century (Yergin, 1991). Future development will come in the Western Siberian basin but, further into the 21st Century, projected reserves in Eastern Siberia might be offered on the market (ZumBrunnen, 1990). The development of Arctic petroleum reserves requires that world oil and gas prices stabilize and rise, in real terms, over the next several decades (Lanan et al., 1984). Predictions that the former Soviet Union is going to drown the world in petroleum, seem to be totally erroneous, given the present situation (Hydrocarbon Processing, 1984).

The main reason why the offshore development has not naturally followed the onshore development like in the North Sea and in the Gulf of Mexico, is the extreme environmental conditions posed by the Arctic. Sea ice and icebergs, as a result of the intense cold experienced in the Arctic winter, are the single most important factor why there has been no significant offshore development in the Arctic

(Wadhams, 1989). In addition to the extreme ice forces, which dominate the design of Arctic structures, environmental problems concerning oil spills and blowouts are unique to the Arctic. The prospect that incidents such as the Exxon Valdez grounding or the Ixtoc 1 blowout could be repeated in the seasonal ice zone must be considered. This has led to the launching of several research programmes into the fate and behaviour of oil spilled in ice infested waters. Early studies by Lewis (1976) identified a range of new aspects of oil in ice. The most significant achievements was the realisation that oil spilled in ice could move around the Arctic Basin and surface as a fresh spill in the summer and the fact that sea ice will in fact contain the oil in a much smaller area than would be the case in an open water spill.

The increased sophistication and thoroughness of recent environmental impact assessment procedures has resulted in demands for more information about the nature and effects of oil spills which may accompany a proposed development. An important part of any environmental impact assessment is the development of likely scenarios under which oil can be spilled into the environment (Foster, 1980). The scenario provides an opportunity to bring together information about likely spill volumes, oil properties, oil spill process rates (evaporation, spreading, drifting, etc.) and environmental conditions to predict the overall location, properties and impact of the spill (Mackay, 1985). Scenarios building have not been common practice in the former communist states in the analysis of potential environmental impact of oil exploration. However, western standards are more likely to be imposed in the future due to the present political situation in Russia. This scenario study is the first to be undertaken for the oil exploration in the Kara sea.

The research into behaviour of oil and gas in cold and ice infested waters over the last twenty years will be summarised. Also the development of trajectory models and tracking devices to predict the behaviour for a specific spill situation is reviewed. Spill containment and clean-up techniques forms the active part in the oil spill response and is integrated into the scenarios, although very briefly.

In order to establish realistic scenarios this has to be set into a context of the environmental conditions in the Kara Sea. An analysis of the available sea ice data, both drift and extension, for the region will be carried out. This includes the use of remote sensing data collected from 1972 to 1982 (NOCD, 1986), manned stations in the region and drift of ships and buoys. Other significant physical parameters like temperature, salinity and precipitation will also be reviewed. This is to be able to estimate the environmental conditions likely to be experienced by the operator and which is beyond his control. Russian technology and past record of exploration of the Kara Sea also forms an integral part of the scenario study. This to be able to evaluate the performance of the russian personnel and equipment to establish potential hazards.

The environmental problems of the Russian North are severe and the negligence in the past have been unforgivable. This thesis will show that in the case of the offshore drilling in the Kara Sea these problems can easily be exported out of Russia and into other areas. This report will show that such an event could have serious environmental implications not only in the Russian sector but also for the Barents Sea and the Greenland Strait.

2.0 OIL IN ICE

2.1 Oil in the Environment

Hydrocarbons form a natural part of the environment. Whenever organic material is contained under high pressures for long periods, hydrocarbons are formed. They are released by natural processes in relatively small quantities in the biosphere. Natural seeps of oil and gas are well known and produce little damage to the environment. In Alaska alone there have been detected over 30 natural seeps of oil (Becker and Manen, 1989, p21). Several seeps off Baffin Island in Canada are also active (MacLean et al. 1981). The natural seeps account for 22% of the total discharge into the environment (Koons, 1984). It has been shown that in the areas of natural seeps the bacteriological fauna has adapted to the oil enriched environment and developed resistance to the hydrocarbons and even feed on it (Gilfillan et al., 1986 and Walker, 1984, p77). However in high concentrations hydrocarbons can be extremely toxic, and together with its solvent properties possesses a danger to flora and fauna. High concentrations of oil occur solely in connection with human activity. Hydrocarbon production has been the major energy supply to the world throughout the last century. Exploration, production, transportation and storage of oil and gas are the main contributors to hydrocarbons in the environment. The large releases are mainly due to accidents or negligence but a large amount of the chronic and small spills are deliberately spilled into the surroundings. Sources of oil in the environment are shown in Table 1.

Table 1 Input of petroleum into the marine environment.
All numbers in metric tons per annum (mta)

Source	Probable range	Best estimate
Natural Sources	0.025-2.5	0.2
Offshore Production	0.04-0.06	0.05
Transportation	0.95-2.62	1.48
Atmospheric Deposition	0.05-0.5	0.3
Waste waters, Runoff and Ocean Dumping	0.585-3.12	1.18
Total	1.7-8.8	3.2

Modified from Koons (1984) and Neff (1990).

Oil and gas spilled in the High Arctic are likely to come in contact with sea ice and it is important to understand the behaviour of the oil and gas to be able to estimate the damage and apply countermeasures in order to minimize the damage (environmental impact of the oil).

2.2 Potential spill sources

2.2.1 Storage

Oil spilled on top of the ice often originates from mishaps at storage places and tank farms. In most places where oil and gas are being used they are stored at their point of usage. This is usually done in external steel tanks or in larger tanks within rock formations. Usually there are safety measures, like earth barriers, preventing leakages from storage tanks in reaching the environment. In March 1971 an employee at a tankfarm forgot to shut off an oil pump when he left for the evening and it resulted in 167 m^3 of #6 fuel spilled over the ice of Lake Champlain (Lamp, 1973). In June the same year a slush avalanche in Deception Bay, N.W.T., destroyed a tank farm and swept almost 1900 m^3 of oil on to shore fast ice (Ramseier, 1971). In winter 1977, 23 m^3 #2 fuel was spilled from an onshore tank at Nome. The oil went down a slope and penetrated the ice cover of the Snake River (Allen, 1978). In 1979 frost action on pipelines caused the loss of 130 tonnes of diesel fuel from a tank plant close to Sveagruva on Spitsbergen on to the surrounding sea ice. The oil spread out on the snow covered sea-ice covering Van Mijenfjorden (Sendstad, 1979). Oil spilled from storage facilities is likely be applied to the top of the sea ice and flow over it like oil spilled on the ground. A surface blowout of a production vessel or an exploration rig in ice infested waters will spill the oil onto the same level of sea ice. However, there have been no such spills in the history of offshore exploration in the Arctic (U.S. Department of the Interior, 1990).

2.2.2 Transportation

Any ship will have fuel tanks which are potential spill sources. There have been several incidents in which tankers have spilled oil in ice conditions. In February 1970 the tanker Arrow broke in two in Chedabucto Bay and its cargo of 16.000 tonnes of bunker *C* oil started spreading out (Forrester, 1971. McLean, 1973). The largest oilspill in ice was the tanker Othello which in 1970 collided with the tanker Katelysia , spilling 70.000 tonnes of bunker-C into the ice covered Baltic Sea. Little scientific investigation was conducted into this spill (In: Metge and Telford, 1979, p.256). In 1979 the ship

Kurdistan broke in half after a storm and spilled approx 7,900 tonnes of bunker C into the waters of the Cabot Strait in Canada (Reimer, 1980). In Scandinavia the Thunatank 5 spilled 36 to 40 tons of heavy fuel in icy waters (OSIR, 1987). A Crowley Barge Tanker 570 spilled 1.600 barrels (253 m^3) of heating fuel near Flaxman Island on August 20, 1988, apparently after ice ruptured one tank on the barge (U.S. Department of the Interior, 1990). In the Bering Sea, the F/V Milos Reefer grounded on St. Matthew Island in November 1989, spilling at least 5.600 bbl (890 m^3) of its diesel bunker fuel (Akre, 1989 In:U.S. Department of the Interior, 1990). Other spills in cold waters include the Metula spill (Baker 1976) the spill after the grounding of Bahia Paraiso (Baringa and Lindley, 1989, p495) in the southern hemisphere, the spill after the British Mallard, USNS Potomac in Greenland (Pettersen, 1978), and the famous Exxon Valdez spill in Alaska.

2.2.3 Exploration drilling

The only spill above 500 bbl reported in the high Arctic is the release of 2.440 bbl of diesel from the Minuk I-53 artificial island during an intense storm in 1985 (Birtchard and Nancarow, 1986). This was not directly linked to the drilling activities. No subsea blowout has yet occurred but when they arise they are very serious incidents. On June 3, 1979 the Ixtoc-1 exploratory well blew out in the Gulf of Mexico and was not brought under control before 295 days after the blowout. An estimated 530.000 m^3 totally was spilled (Ross et al. 1979). Several investigators and government bodies have considered the possibility of an incident of this kind as a worst case scenario. Investigators who have addressed the problem of a subsea blowout include : Lewis (1976) who considers an oil industry standard blowout from a ruptured drillstring at the seabed. On the same basis have Wadhams (1980) and several other researchers investigated the effects of a hypothetical blowout and the migration of the oil in ice.

2.3 Oil under a solid ice cover

2.3.1 Introduction

In this chapter it will be assumed that the oil is discharged from a point below the ice and that the oil is driven by buoyancy forces up under the ice. The behaviour of the oil is divided up into three phases; primary phase where the oil is still in movement or has just been brought to rest; secondary phase where the oil is being encapsulated within the ice; tertiary phase where the oil is starting vertical motion within the ice.

The actual season the spill occurs under the ice determines the fate of the oil. Most spills are likely to occur during freeze up of the sea at the end of the drilling season. This is when the drilling rig is most likely to have reached oil bearing formations. The spilled oil is then prone to go through all three phases before it is released to the ocean again. However if year round drilling technology is developed, spills in the middle of the winter could be a possibility. The oil is still prone to go through all three phases as the sea-ice is growing through the winter. Spills in the early spring are likely to go through the primary phase of spreading then to jump to the tertiary phase of vertical migration.

2.3.2 Primary phase

The oil mixed with gas will rise from the seabed in a plume predominantly driven by hydrostatic forces. It will impact the sea ice with velocities ranging from 1-3 cm/s to 250 cm/s (Johansen, 1992). Gas "jumping" in the centre of the plume will move fastest and oil droplets on their own will move more slowly. The oil will be broken into droplets ranging in diameter from tens of microns to 2mm (Dickins and Buist, 1981; In Comfort, 1987, p20). A thin water film remains intact between the oil and the ice which is not penetrated or removed by impact as illustrated in Fig. 1. The fact that oil has been seen sliding along under the ice is seen as a confirmation of this (Malcholm and Dutton, 1979, p54). Sessile drop analysis has been applied to various crude oils and have found the contact angle between oil and sea ice to be 180 degrees. This implies that despite contrary belief (McMinn and Golden, 1973) the oil will not "wet" the sea ice but lingers under the ice like mercury drops on a table. This implies that there is very little friction between the oil and the ice and the oil is prone to movement by currants under the ice.

a) Spreading by current;

The spreading of the oil under the ice is governed by the current underneath the ice, the mechanical properties of the spilled oil and the under ice morphology. Migration of oil settled under ice may be conceived as a series of subsequent steps and rest periods, where oil droplets are resuspended by under ice currants, and later trapped under roughness features. Oil from a subsea blowout will tend to be suspended in a turbulent radial flow which causes settling of oil under ice to take place over a prolonged period, and thus tends to increase the under ice area initially infested by oil (Johansen, 1989, p1133).

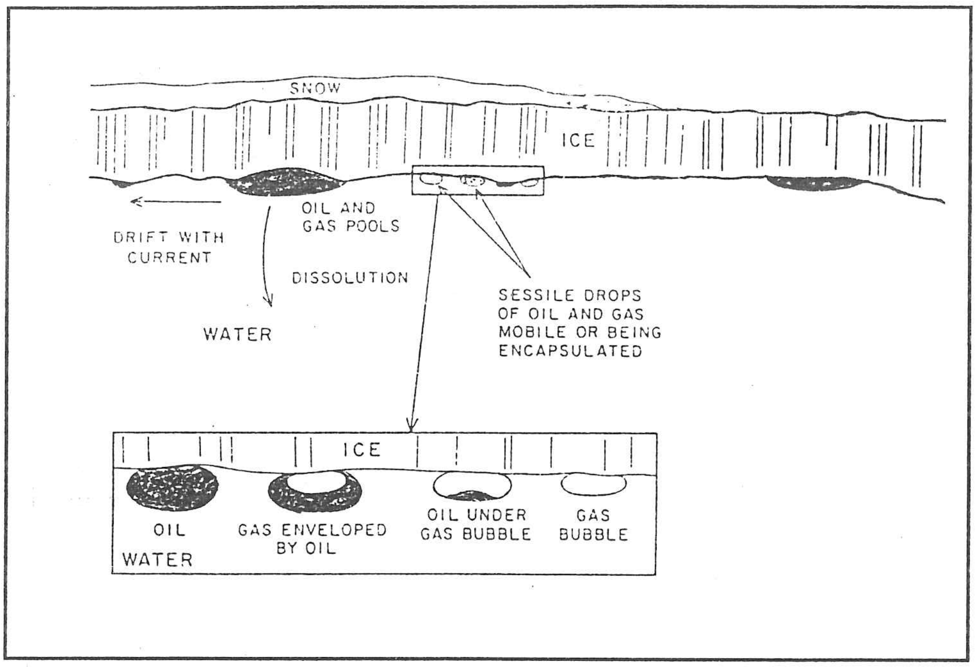


Fig. 1 Oil under ice (modified from Mackay (1985))

Herding of oil in depressions by under-ice currants have been observed in laboratory studies by Malcholm and Cammaert (1981, p929). The herding was dependent upon the geometry of the pocket, the amount of gas present above the oil, the amount of oil and under-ice current. However the slick will have a threshold current velocity which below, due to static friction, the oil will not move. This velocity U_{th} was estimated empirically by Schultz and Cox (1979) to be a function of the viscosity of the oil:

$$u_{th} = 305.79/(88.68-\mu_0) \qquad (1)$$

u_{th} slick velocity is in cm/sec
μ is in poise

Rolling of individual oil droplets are thought to occur at slopes of at least 2° (Lewis 1976, p13). In spill conducted during the Balaena Bay tests showed that the oil flowed along under ice troughs to the nearest dome where it pooled. Little oil was entrapped in the skeletal layer of the ice in the immediate vicinity of the plume (NORCOR, 1975; in Comfort, 1987, p20). During these tests the oil was found to move at about half the current speed. Wotherspoon et al. (1985, p8) developed on the grounds of work done by Cox and Schultz (1981), equations to determine the velocity of the slick as a function either of current in the smooth ice case or density difference, and cavity geometry for the non-smooth ice case. Equations from Wotherspoon et al. (1985) for smooth ice are.

$u_S=0.15u_W-0.60$ $\qquad u_W<18$ cm/sec (2)

$u_S=\quad u_W-15.6$ $\qquad u_W>18$ cm/sec (3)

u_S=Oil slick speed
u_W=Water current

For rough ice:

$u_S=u_W(1-\sqrt{(K/(0.115F_\delta^2 + 1.105))}$ (4)

$K=1+1.96(D_{cavity}/L_{cavity})+2.22\sqrt{(D_{cavity}/L_{cavity})}$
D_{cavity}=Ice roughness height or cavity depth
L_{cavity}=Cavity length
F_δ^2=Densimetric Froude number
$F_\delta^2=S_W/\sqrt{(\text{delta } g\delta)}$ For this case $\delta=\delta_{eq}$
$\delta_{eq}=1.67 - 8.50(p_W-p_o)$

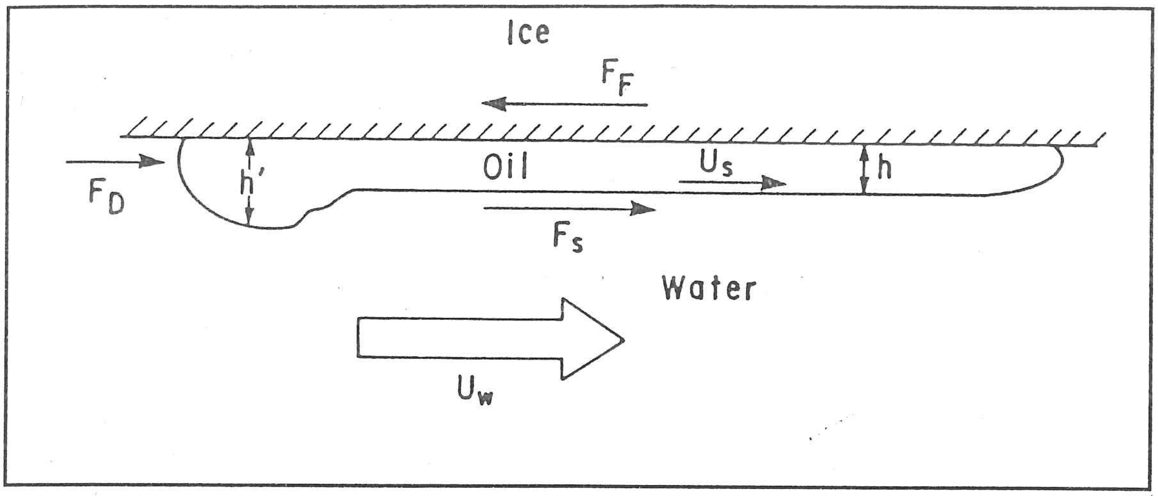
These equations are derived empirically from laboratory studies under fresh water ice and their application to real spills is somewhat uncertain. In the more complex freezing behaviour of saline water the ice forms a skeletal layer in the ice water interface (Lewis, 1976 p4) and one would expect increased friction under such conditions. A theoretical model has been developed by Puskas and McBean (1986) for the estimation of the slick transport under smooth or small scale-roughness ice. By assuming constant velocity, no slip at the oil water interface and equating the friction forces and the shear stress at the oil-water interface, shown in Fig. 2, the following relation was derived:

$u_S=0.0185\ hp_W/\mu_0\ R_l^{-1/5}\ (u_W-2u_S)^2$ (5)

μ_0=viscosity of the oil

They found that equation (5) would underestimate the velocity for oils with high velocity, some slipping for the more viscous oils will occur at the interface. However, in relation to experimental tests equation (5) gives an order of magnitude estimate of the slick velocities.

The transport of oil slicks oriented longitudinally to the direction of the water flow is modelled by the summation of the shear force at the oil-water interface and the oil-ice friction force (as above). Oil slicks oriented transverse to the direction of the water-flow are subjected to an additional form-drag acting as the primary driving force due to the deformation of the slick by the current as shown in Fig. 2 (Puskas et al., 1987).



F_s = shear force current/oil
F_D = drag force (form drag)
F_F = friction force oil/ice

Fig. 2 Forces acting on a sessile drop from Puskas (1985).

b) Fluid Spreading

In the absence of a current or in resting periods during movement like tidal maxima and minima, the oil will spread according to Fay's spreading laws. The oil will be influenced by the gravity and surface tension spreading forces and inertia and viscous retarding forces. In oil spreading on surface waters, Fay's theory indicates that spreading progresses sequentially through the following three phases; gravity-inertia, gravity-viscous and viscous-surface tension. However, when oil is spilled under ice, the spreading force is the buoyancy force, which is the equivalent of gravity in surface water spreading. It can be shown that in many situations, the buoyancy-inertia phase lasts for only a short period and that the buoyancy-viscous phase appears to last for a much longer time, until the spreading is terminated (Yapa et al., 1990, p1470).

In the absence of the formation of water in oil emulsions, the viscosity of spilled oil will be expected to remain constant throughout the spreading phase. Experimental spills with heated oil have shown that the heat transfer from the oil is relatively fast and complete (Greene et al., 1977) when it is spilled from a subsea location under sea ice.

Slick radius:
Hoult et al. (1975) derived a spreading equation by balancing the driving and retarding forces. They

calculated the radius of an oil slick from a continuous blowout as a function of time:

$$R=0.25(g\Delta\ Q^2/h')^{1/6}\ t^{2/3} \qquad (6)$$

R=Radius of oil slick
Q=Flow rate of oil
Δ=difference in gravity of oil and water
h'=half of the root-mean-square roughness of the ice cover

However they have no viscosity term and previous observations have shown that the flow regime under the ice is at least partially laminar (Yapa, 1990, p1469). It is also only defined for the period of continuous spill and not when the flow stops.

A more advanced approach was used by Chen et al. (1976) who derived expressions for oil spreading under ice covers by using the equilibrium conditions between buoyancy and viscous forces. Assuming a water layer to exist between the oil and the ice:

$$R=(cp_w gQ^2/\pi\mu_w^{0.5})^{0.3}\ t^{0.8} \qquad (7)$$

c=a empirically determined coefficient
μ_w=dynamic viscosity of oil

In a recent study Yapa and Chowdhury (1990, p1475) developed a set of new equations to describe the process of oil spreading under sea ice in calm waters. The final slick radius is estimated by:

$$R_f=k_3\ [g(p_w-p_o)/\sigma_n]^{1/4}\ V^{1/2} \qquad (8)$$

σ_n=net interfacial tension
V=Total volume of oil spilled
k_3=empirically determined coefficient.
p_w-p_o=difference in density of water and oil

Their equation agrees closely with laboratory tests under smooth and artificially roughened test ice. These equations can be used for estimating the radius of an oil slick under no current and small scale under-ice roughness. They are however not applicable for areas with pressure ridging, under-ice currants and blowouts which also includes gas. Hence in real life oil spill context they are only applicable for a pure oil (one phase) blowout under smooth fast ice in the absence of currants. A possible scenario could be a pipeline burst close to land. The presence of gas with the oil will have a spreading effect upon the oil. At an oil/gas ratio of 200:1 the oil is assumed to spread over an area 7 times larger that in the absence of gas (Dome Petroleum Limited, 1981: In. Wotherspoon, 1985)

Another approach is to calculate the maximum thickness of an oil layer under the ice. It has bee suggested to model the thickness (H) of a large diameter oil lens by Davy (1957) and Wadhams (1980):

$$H^2 \delta p \, g = 2\sigma(1-\cos\Theta) \quad (9)$$

which gives reasonable numbers of 0.55-0.68 cm when appropriate numbers are inserted. Sandkvist (1989, p1284) estimates the equilibrium thickness to be in the range 3-6 cm, which surely is on the high side. Tests have shown equilibrium thicknesses for several crude oils to be 0.8 cm (Hume et al., 1983, p316)

Schultz and Cox (1979) derived empirically from tests in ARCTEC's ice flume, a relationship between the density of oil and the slick thickness. This formula was based on experimental spills of four different oils under smooth ice. Treating the surface tension of the spills as constant, it was found that, over the range of oil types tested, the slick thickness could be empirically related to the relative oil density according to:

$$\delta = -8.50(p_w - p_o) + 1.67 \quad (10)$$

δ= slick thickness in cm

The equation has no μ term but μ is to a certain extent a function of the density. Additionally it was found that the static thickness also applies to an unaccelerated moving slick. These tests were however under fresh water ice and is therefore likely to be an underestimate of the slick thickness. Once an equilibrium thickness is established, the area of oil contamination can be calculated using the formula A=V/H. This is a crude but effective way of roughly estimating the maximum oil contamination area.

Storage:

In a natural ice field the sea-ice will be deformed by wind and current drag forces. Moving ice pack will develop heavy pressure ridging and this will greatly enhance the ability of the sea-ice to contain oil trapped underneath it. Using the approach of Venkatesh et al. (1990) the volume of storage V_{ui} is related to the horizontal area of an average ice floe A_{fl} and the under ice storage volume per unit area T_{ui} (ie. thickness units):

$$V_{ui} = A_{fl} * T_{ui}$$

The under ice storage volume is derived as a linear function of ice thickness for ice thicknesses >

0.5m. Comfort (1986; In Venkatesh 1990) relates the under ice storage volume to the ice thickness and the standard deviation of the ice thickness;

$$T_{ui} = 0.021 \text{ (Ice thickness)} \qquad (8)$$

For undeformed first-year ice sites, where slush ice keel accumulations do not occur, we have determined potential under-ice oil storage volumes of 10,000 to 32,000 m^3/km^2 (Kovacs et al. 1981). These values compare with the 27,000 m^3/km^2 found by Kovacs (1977) and the values of 25,400 , 36.200 and 47.000 m^3/km^2 found by Barnes et al. (1979). The latter made their under-ice pooling determinations based upon ice depth measurements along each 100-m-long leg of a cross staked out on the ice surface at three fast ice sites. For an area in which the ice had undergone minor pressuring during early fall freeze-up, they found an under-ice relief with a potential oil pooling storage volume of 65.000m^3/km^2.

At sites where slush ice appears to accrete under the fast ice our estimates of the potential volume available for oil pooling in the ice bottom reliefs varied from 23.900 to 57.400 m^3/km^2. How reasonable these values are is uncertain because of a lack of information on the permeability and spatial variation in the slush ice relief.

Kovacs (1979) found that the volume of oil which could pool under a site at *Tigvariak Island* was in the order of 31.000m^3/km^2. While this is a very large quantity, it is, after all, only about three times the amount of oil which could be expected to accumulate under a relatively smooth sea ice bottom.

The magnitude of these figures shows that the sea ice has a considerable ability to store oil originating from an under sea blowout. One might question if the importance of this effect will not "overshadow" the fluid spreading effects by several magnitudes. In any case it emphasises the need for a better understanding of the under-ice morphology.

2.3.3 Secondary phase

When the oil settles under the growing ice sheet it is only a matter of time before it becomes encapsulated within the ice sheet. First an ice lip surrounds the edge of the pool inhibiting the further horizontal motion of the oil. There is a reduction in heat flow to the surface above the oil pool due to the superior insulating properties of oil compared to ice. As a result more heat flows to the surface from that area of the ice/water interface immediately surrounding the pool, which in turn requires an enhanced rate of ice growth and hence the lip (Lewis, 1976, p14). In-situ experiments in the winter of 1979-80 by Dome Petroleum Ltd. (1981a, In: Hume et al., 1983) showed that the oil was encapsulated within 24 to 48 hours. The rate of growth of the ice lip is dependent upon the ice growth rate in the absence of oil and gas, and the ratio of oil and gas. Field data have indicated an ice lip growth rate of at least twice the normal growth rate (Comfort, 1987, p27). In a December, 1980, discharge at McKinley Bay almost all the oil and gas were encapsuled in a 1cm layer of new ice after one day (Dickins and Buist, 1981). In laboratory studies done by Martin (1979, p488) it was observed that the first ice to form beneath the oil resembles the thin horizontal platelets which initially form on the surface of an undisturbed fresh-water lake. In the field, this *c*-axis vertical ice grows to a thickness of about 10mm, after which the ice resumes columnar growth.

Crude oil has approximately 1/14 th of the thermal conductivity of sea ice, and initially temperature profiles show a sharp change in temperature gradient passing through the oil lens (Lewis, 1976, p15). In thicker oil lenses it is possible that an oil lens will enhance rather than reduce the heat exchange between water and surface. If the thickness of the oil lens h is sufficiently small, or on the order of 10mm, then the heat transfer within the layer takes place by conduction. For h greater than 10mm, then the heat transfer takes place by convection. The transfer by convection is much larger that the transfer by conduction alone (Martin, 1979, p486) and can under certain circumstances exceed the heat conduction of the ice alone.

In the period that the oil is encapsuled within the ice it is not exposed to the atmosphere and is not likely to undergo any weathering (Payne and McNabb, 1984). However, during field tests in 1978 at Griper Bay a minor amount of weathering is believed to have occurred while the oil was encapsulated (Comfort and Purves, 1980). In 1982, in McKinley Bay, N.W.T., an experimental spill was conducted to investigate the clean-up of water-in-oil emulsions spilled under first year sea ice. The experiment involved the discharge of 192 litres of a 60% water in oil emulsion beneath the ice at each of two test sites and the discharge of 192 litres of straight crude oil at a third site for comparison. During the time that the oil and emulsion were frozen-in the ice, no significant changes in the physical or chemical properties of the oil were noted. In particular the emulsification did not separate back into its components of oil and water.

Very early laboratory studies by Wolfe and Hoult (1974, p486) showed that the oil will penetrate into the porous layer above the oil lens, however the volume of this oil is negligible.

If encapsuled, early winter oil will sit inside the ice throughout the winter season, gradually being frozen deeper and deeper into the ice sheet. It is believed that the oil inclusion will cause significant changes in the mechanical properties of the ice sheet (Wadhams, 1980, p241). This will make this section of the ice sheet more predisposed to deformation by ridging than other parts of the pack and one might expect heavier ridging in areas of oil contaminated ice.

2.3.4 Tertiary phase

FY ice:

Walker (1975) reports that in spring when the ice temperature approaches the melting point, 70- 90% of the oil from any depth rises, in a period of a week, to the surface of the ice. Observations cited by Martin (1977), and some laboratory work by Purves (1978), suggests oil trapped beneath or within first year ice will begin to flow to the surface when the minimum ice interior temperature reaches -4°C. The flow to the surface accelerates as the ice temperature continues to increase. In spill observations made at a test spill at Balaena Bay, a vertical migration rate of 0.07 cm/s was observed, and the spacing of the areas varied from 0.1 to 0.5 m, which correlates to the typical brine channel spacing. In general, the vertical migration rate, u, is predicted as (Schultz and Cox, 1979, p585):

$$u=(p_w-p_o)\, g\delta d^2/32L\mu_o \qquad (12)$$

p_w-p_o	=water oil density difference
δ	=slick thickness
d	=brine channel diameter
L	=ice thickness
μ_o	=viscosity of the oil

This requires the input of the brine channel diameter d which itself is a function of T. Once on the surface the oil will spread vertically within the ice. Depending on sea state and freezing rate, the to 10cm or more of the sea ice sheet may be composed of ice with a random crystal structure (NORCOR, 1977, p4). Tests have shown that the oil will migrate into this layer. The oil is absorbed laterally in horizontal layers, apparently because of the interaction of melt water from the snow percolating down and oil rising up (Martin, 1979). In a study done by ARCTEC (1977) crude oil and natural gas injected under saline ice found that the presence of gas did not affect the timing of the appearance of oil in spring.

MY ice: Multi year floes will be permeable in the summer as indicated by tests done in the vicinity of Resolute Bay by Milne et al. (1977, p27). The porosity of the ice with respect to connected pores and capillaries ranged between 0.2% and 0.03% in summer.

Tests under 2.5 to 1.9 m multi year ice (at least two years old) shows that 90% of the spilled oil had migrated to the surface after one year (Comfort and Purves, 1982, p30). Other discoveries have shown that oil beneath stationary multi year ice can migrate to the surface, and disperse so widely by natural processes that it is undetectable after five melt periods (Miekle, 1988).

Small studies in multi year ice showed that the oil will migrate horizontally. The test sites still containing oil after one year had experienced a 400% increase in area of contamination over that originally occupied by the initial discharge (Comfort and Purves, 1982, p30).

Oil in multi year ice will migrate upwards in the melt period and be degraded at the surface despite the results from early investigators who found the vertical migration of oil in multi year ice to be insignificant (Martin and Environment Canada In: Schultz and Cox, 1979)

At surface:
Once at the surface the oil, with an albedo of 0.08 to 0.1 as opposed to melting snow with an albedo of 0.6 (Lewis, 1976, p17), will raise the temperature of the ice surface and create melt pools. One may visualize the surface of the ice dotted with black patches where individual oil lenses have reached the surface. Each patch will produce a melt pool as more and more radiation is incident upon them, these pools will extend until they join. Eventually some route to the underlying water will be found and the water and oil in the melt pools will drain towards this centre. The momentum of this flow is sometimes sufficient to carry the oil down through the ice sheet against buoyancy forces but it rises to the surface once again so that this central type of drainage forms a mechanism for oil concentration at certain points.

2.4 Oil in broken ice field

2.4.1 Oil in the shear zone

When the blowout or tanker grounding occurs in the broken ice zone some oil will reach the water surface directly without having to penetrate the ice sheet though a portion will still be trapped in those irregularities of the ice/water interface that are not filled with gas. In this case the oil will follow the general drift pattern of the ice.

The area of oil spilled in open pack ice will be dramatically reduced compared with that of open water. This is observed by several investigators S.L. Ross (1987) and Venkatesh (1990). Venkatesh estimates the equilibrium thickness in slush or brash ice is nearly four times that on cold water which is itself very different from that on warm water. After the Kurdistan the oil was found to contaminate the ice and not to be released into the water before the final decay of the ice (S.L. Ross, 1980).

Laboratory tests done by Metge and Telford (1979) showed that during the interactions between the ice floes, the oiled slush, being more viscous that either oil or slush alone, was squeezed up onto the edges of the floes. This is one of the many mechanisms by which oil can become encapsulated in the ice. A water-in-oil emulsion formed during the tests even though the agitation was rather gentle. In general the effect of entrainment of the semi-solid oil in pack ice is a dispersion of the oil as progressively smaller particles. The trend over the period of observation seems to have been towards finer dispersion and dilution of the oil. This process may have been reversed to some extent during the final melting of the ice when the ice tended to herd or contain small particles. Some reagglomeration may occur, especially with larger blobs (S.L. Ross, 1980)

One of the primary dispersion processes will be the grinding of oil in brash ice as a result of floe impact and differential movement. Ice rubble drifts nearshore and onshore were characterized by an extremely fine oil dispersion (S.L. Ross, 1980, p42)

A secondary process which tended to reduce particle size occurred as the result of solar heating of oil deposits on snow/ice surfaces. Oil was thrown up on floes as spatters or pushed onto floe edges. Once clear of the water, it would warm considerably above ambient temperatures due to solar radiation. The ice supporting the oil would melt. As a result the oil blob would be stretched and spread until surface tension effects intervened to produce micron sized oil particles. This phenomenon was observed both in the field and in the laboratory.

2.4.2 Oil spreading in pack ice

In three experimental spills done by S.L.Ross (1987) it was found that in relatively low ice concentrations up to 6/10 the oil will spread much like Fay's equation would predict with correction for viscosity and ice concentration. It was found that the thicker oil never entered the surface tension phase. In higher ice covers the oil was spreading similarly to oil on snow. This behaviour was found to coincide with the equation developed by Kawamura et al. (1986) for oil on snow. However, the oil spread much faster than it would do over snow. It seems that oil in brash ice spreads according to the modified Fay equation until it saturates the brash ice above the water surface , then ceases spreading, resulting in a final area as predicted by Kawamura et al. (1986).

Brash ice:

The field observations and sampling indicated a distribution of oil particles from approx. 1mm to several centimetres in diameter more or less uniformly distributed throughout the brash. Fig. 3 illustrates the typical oil in ice spreading which were encountered.

Unless crude oil were to surface in an emulsified form it would not interact with the pack ice in the way that was observed with a bunker-C. Unemulsified crude would rise to the water surface rather that being trapped throughout the brash ice as solid particles. Three experimental oil spills in 6/10 dynamic open pack ice to +9/10 pack ice in a state of moderate compression was conducted by S.L. Ross Environmental Research Ltd. (1987). They found that oil spreading was dramatically reduced compared with that of open water, however, Fay's equations with correction factors modelled the spill adequately. No water in oil emulsification was observed. Only minor oiling of floes was observed. In recent laboratory studies by MacNeill and Goodman (1987) the behaviour of oil in leads were investigated. They found that the behaviour of the oil in leads was a function of the rate of closure of the lead: the higher the rate of closure the less oil will be left in between the two sheets. However no "lead-pumping " was observed. This corresponds with findings of S.L Ross (1985) field experiments.

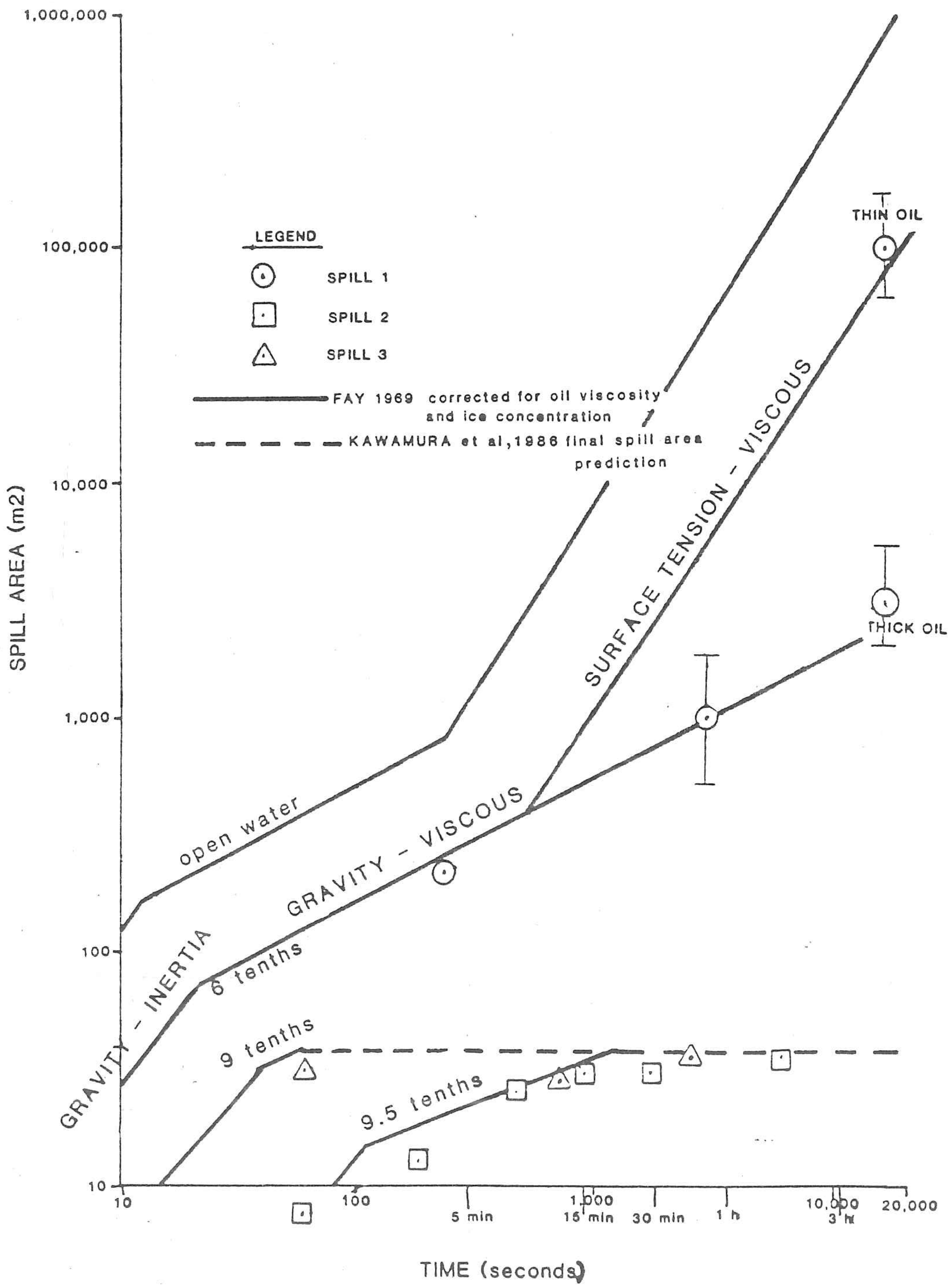


Fig. 3 Oil spreading in pack ice (S.L. Ross, 1987)

3.0 HYDROCARBON COMBAT TECHNOLOGY

3.1 Training and decision making

Training of personnel has received new attention as a major asset in combating oil spills. S.L.Ross (1987) has developed a programme to train oil industry personnel who have countermeasures responsibilities with respect to oil spills. In a spill situation decisions of how to respond have to be made in a very short time. Decision making aids for use of dispersants (Trudel et al., 1987), shoreline clean up (Harper, 1985) and the igniting or extinguishing of well blowouts (S.L. Ross, 1986) have been developed to aid responsible personnel in their efforts.

3.2 Monitoring and surveillance

Once an oil spill has occurred, one of the main concerns is a determination of size, motion and thickness of the spill. This information is essential to optimize spill response and to determine potential impacts on various ecological communities. A major component of any integrated oil spill mitigation package would contain remote sensing, tracking, and predictions of its motion. This information is useful not only for the on-scene commander and his support staff in the technical planning of the response, but it is essential to give adequate public information concerning the spill. While observation, tracking and trajectory predictions are independent, this information is a complementary set of data for a fuller understanding of the oil spill.

3.2.1 Remote sensing

Oil on the water surface is most readily detected by aerial reconnaissance. When weather permits the cheapest and most reliable way of monitoring an oil slick is to observe it from an aircraft (Hume et al., 1983). Recent experimental spills (Buist et al., 1987) have shown excellent results in detecting crude oil from aeroplanes by merely visual aids. However, weather conditions like fog, clouds, rain or if in the Arctic night, will not permit visual inspection. Existing remote sensing techniques were tried out extensively in the Kurdistan incident with little success (Reimer, 1980). Since then several studies have been launched to evaluate the feasibility of using remote sensing for detection of oil in ice infested waters. Esso Resources Canada Ltd. have in a joint undertaking evaluated the use of acoustic and radio-frequency technology to detect oil encapsulated in ice. Radio frequency work ended after a series of theoretical studies showed little or no potential for success (Tunaley and Moorcraft, 1986)(Moorcraft and Tunaley, 1985). Acoustic studies, however, have produced prototype hardware that has performed quite well in field tests (Jones et al., 1986). Several techniques have been tried in the Arctic Marine Oil Spill Program (AMOP). A package consisting of; side-looking radar; an infrared-ultraviolet, dual channel line scanner; a laser fluorosensor; a low light level television; an annotated colour camera and an onboard real time display equipment have been recommended (Meikle, 1988).

3.2.2 Tracking

Due to inaccuracy of remote sensing technology and inherent limitations of such equipment an alternative method is required to track the spill. Initial experiments with a wide variety of drifting buoys, drift cards, plywood sheets and other surface tracking devices have been carried out in Canada to develop a system that follows the track accurately (Fingas and Lea, 1981). Within pack ice the buoys have been found very efficient to track the actual oil. However buoys in non-ice conditions have been found to be influenced more by surface wind than the actual slick (McLaren Plansearch, 1982). A more sophisticated system has been developed by Esso Resources Canada Ltd and Orion. It uses a transmitter-receiver in the buoy and a range bearing tracking system, so that the location of the buoy may be determined from a single land location. Field tests of the system have indicated the effectiveness of this system (Roddis, 1982). These systems are, however, limited by the sight characteristics of the operating frequencies of the equipment.

3.2.3 Oil spill trajectory models

Trajectory models are numerical computer models designed to estimate the likely movement of an oil spill given a set of environmental and technical parameters. Inputs would typically be flowrate and properties of oil, geographical information wind, current and other environmental parameters. Output will normally consist of three components; advection, spreading and state of oil. Advective components are generally physically based and uses a wind drift of 2-4% of the wind speed with a direction of between 0-30° to the right of the wind direction (Northern hemisphere) (Hume, 1983). Spreading is usually according to Fay's spreading laws or modified versions of these (Wotherspoon, 1985)(Comfort, 1987). The state of the oil will be determined by temperature, type of oil and the amount of mechanical energy put into the oil by the wind and sea, collectively called weathering. Stiver and Mackay (1984) and Stiver et al. (1989) have developed equations for the state of spilled oil after exposure to the environment. The equations to estimate the submerged part of the oil are developed by Buist and Potter (1987). These models are also very helpful in developing scenarios and more frequently used in response planning and Environmental Impact Statements (EIS) (US Department of the Interior, 1990).

After initial spreading, as the motion of oil is almost wholly due to its advection by sea ice (Colony, 1986), it is necessary to estimate the motion of individual ice floes. If the spill is not immediately identified and marked with tracking buoys, accumulated knowledge of the ice motion can be used to track the spill. Colony (1986) developed a model based on a Markov process to address the probability of an oil spill being transported to an arbitrary region. Although existing models have many inadequacies, they can provide an approximate, realistic picture of oil spill behaviour which greatly assists the subjective assessment of the severity (Environmental consequences) of a spill. A the moment a state-of-the-art oil spill model is developed by a consortium led by Applied Science Associates, Inc which integrates most of the relevant factors; this, however, is not due for completion before January 1993 (ASA, 1992).

A recent review of the existing trajectory models (Bedford Institute of Oceanography, 1992) found that most models use the same basic principles to predict advection and spreading. The models tend to use some formulation of Mackay's work to predict evaporation, dispersion and emulsification. The models differ in their treatment of input data, grid sizing, transportability to other regions and their capability to predict evaporation, emulsification, oil-in-ice spreading and shoreline impact.

3.3 Chemical dispersants

3.3.1 Introduction

Oil spilled on the sea will float, due to its lower density, as a thin layer on top of the sea. It will spread due to gravity and buoyancy forces until it reaches its equilibrium thickness. Concentrated crude or bunker oil is toxic to a wide range of living organisms and spilled on beaches it is aesthetically unacceptable (Buckle, 1992). The issue of dispersed oil toxicology remains incompletely resolved, however, and some controversy still exists about the desirability of dispersion (Makcay, 1985). Of the 100 dispersants used in Canada over the last 20 years only 8 remain approved (Statoil, 1991). If one looks at the historical use of dispersants, the average efficiency of dispersants averages around 30% (Fingas, 1985). This value is not sufficient to justify the wide use of dispersants as a countermeasure technique. Fingas believes that correct application of dispersants could raise the effectiveness to acceptable values. After the Exxon Valdez, the report to the Secretary of the Interior by MMS concluded that; Dispersants have been found to be routinely ineffective in open-ocean application (U.S Department of the Interior, 1990). However continuous research efforts are being put into the problems of efficiency and toxicity of the dispersants.

Chemical dispersion of the oil is one way of diluting the oil in the water column to increase the process of sinking. A chemical dispersant is a formulation of a mixture of surfactant and solvents which, when applied to the oil from boat or aircraft, either in a neat form or suspension, causes a reduction of the oil-water surface tension and consequently an enhancement of the rate at which oil droplets are sheared from the slick. The complex mechanisms of oil dispersion is described in Fig.4. A large number of factors influence the performance, including dispersant-to-oil volume ratio, temperature, water salinity, turbulence level or sea state, the nature of the oil (especially its viscosity) and the nature of the dispersant-oil mixing process as influenced by oil slick thickness and dispersant droplet size (Mackay and Wells, 1983).

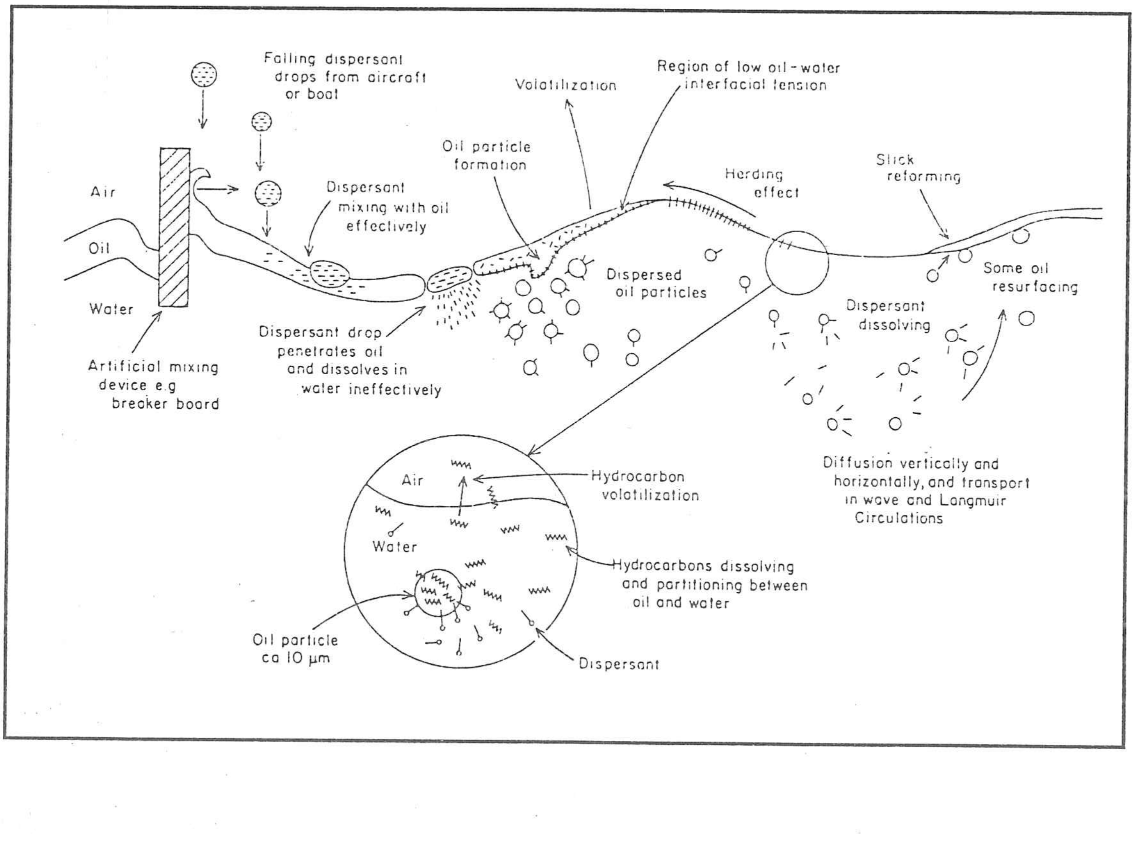


Fig. 4 Physical and chemical phenomena during chemical dispersion of oil spills (Mackay, 1985)

Experiments at IKU, Trondheim, Norway (Daling et al., 1991) have shown that with efficient chemical dispersion formation of oil droplets of the size 1-10μm can be expected. The oil droplets have then reached a size where they do not return to the surface. These droplets are then further broken down in the water column. An important point is that chemically dispersed oil does not sink down into the sediments. Chemical dispersants may be the only practical oil spill countermeasure in many Arctic and Sub-Arctic areas during break-up, the open water period and freeze-up. Remoteness and the danger to field personnel may prevent physical containment and recovery of oil, while the thinness of oil slicks may prevent in-situ burning.

3.3.2 Logistics, and application

Dispersants may be applied by boat or aircraft. Boat application is most appropriate for small spills that can be quickly responded to from shore. Large spills are more appropriately treated by aircraft able to carry large payloads and cover broad areas in short time. This is illustrated in Table 2.

Table 2 Potential dispersant coverage using different application methods

Craft	Dispersant Payload (m^3)	Application Speed (KTS)	Coverage (km^2)	Time (Hrs.)
Boats				
Small Workboat	0.76	10	0.17	2.9
Medium Workboat	7.60	10	1.72	12.5
Large Workboat	38.00	10	8.25	21.7
Aircraft				
Bell 206	0.19	35	0.03	0.02
Pawnee	0.50	80	0.10	0.04
DC-4	9.50	140	2.06	0.14
DC-6	13.30	140	2.75	0.2
Hercules	20.90	140	4.45	0.4

U.S Coast Guard Data (Linsted-Silva 1984)

To apply the chosen dispersant most effectively to the oil slick at the best application rate is crucial for the outcome of the campaign. Early studies conducted by Hildebrand et al (1977) studied the feasibility of dispersant application in the Beaufort Sea. These included application by fixed and rotary wing aircraft, by air cushion and other surface vessels. The study resulted in recommendations of applying the dispersant with planes and helicopters due to their superior response times. Application techniques are critical and difficult to implement (Fingas, 1985). The importance in proper training of pilots is addressed in a training programme launched by SINTEF (1990) in connection with the use of dispersants in the North Sea. It was found that with a minimum of instruction and training effectiveness could be raised significantly. Applying dispersants at the sea-bed in conjunction with a subsea blowout has been shown to be very efficient. Tests by Mackay et al. (1983) showed that the use of dispersants reduced the oil droplet from millimetres to approximately 10 microns. It became apparent from those studies that chemical dispersants can have a profound effect on the behaviour of subsea oil discharges, thus enabling human intervention to substantially modify oil spill behaviour and effects.

3.3.3 Effectiveness

Because dispersant use is an expensive and environmentally dubious oil spill countermeasure, one must know whether chemical dispersants will in fact disperse different types of crude oil, at different stages of weathering and at various temperatures and salinities. Much of the early work was conducted at micro scale level in laboratories by Mackay and co workers (Mackay et al. 1978, Wells and Harris, 1979, Harris and Wells, 1980, Mackay et al. 1980b; Mackay and Wells, 1982). It was attempted to devise a satisfactory method of rating dispersant effectiveness. This work has resulted in the development of the Mackay Nadeau Steelman (MNS) apparatus (Fingas et al., 1986). This apparatus is primarily used to compare existing dispersants and their performance under different environmental conditions. Secondly it can be used by operators under the clean-up of a spill to evaluate whether dispersants are a feasible way of treating the spill.

Dispersants lose effectiveness even more rapidly than mechanical recovery as oil weathers and becomes more viscous. Oils with in-situ viscosities above 2.000 cst usually cannot be dispersed (U.S Departement of Interior, 1990). In the UK the same value is set at 4000 cst (Statoil, 1991,p 79). As an example based on the weathering model of Kirstein and Redding (1988), under average summer conditions a spill of $3500m^3$, such viscosities would be reached by Prudhoe Bay crude about 8 hours after spillage. In the presence of sea ice, the rapid formation of mousse (Payne et al., 1984) could preclude the effective use of dispersants in even shorter period of time. Best use of dispersants obviously occurs when they can be applied immediately after the spill has occurred. The efficiency of various recovery devices versus sea state is shown in Fig. 5.

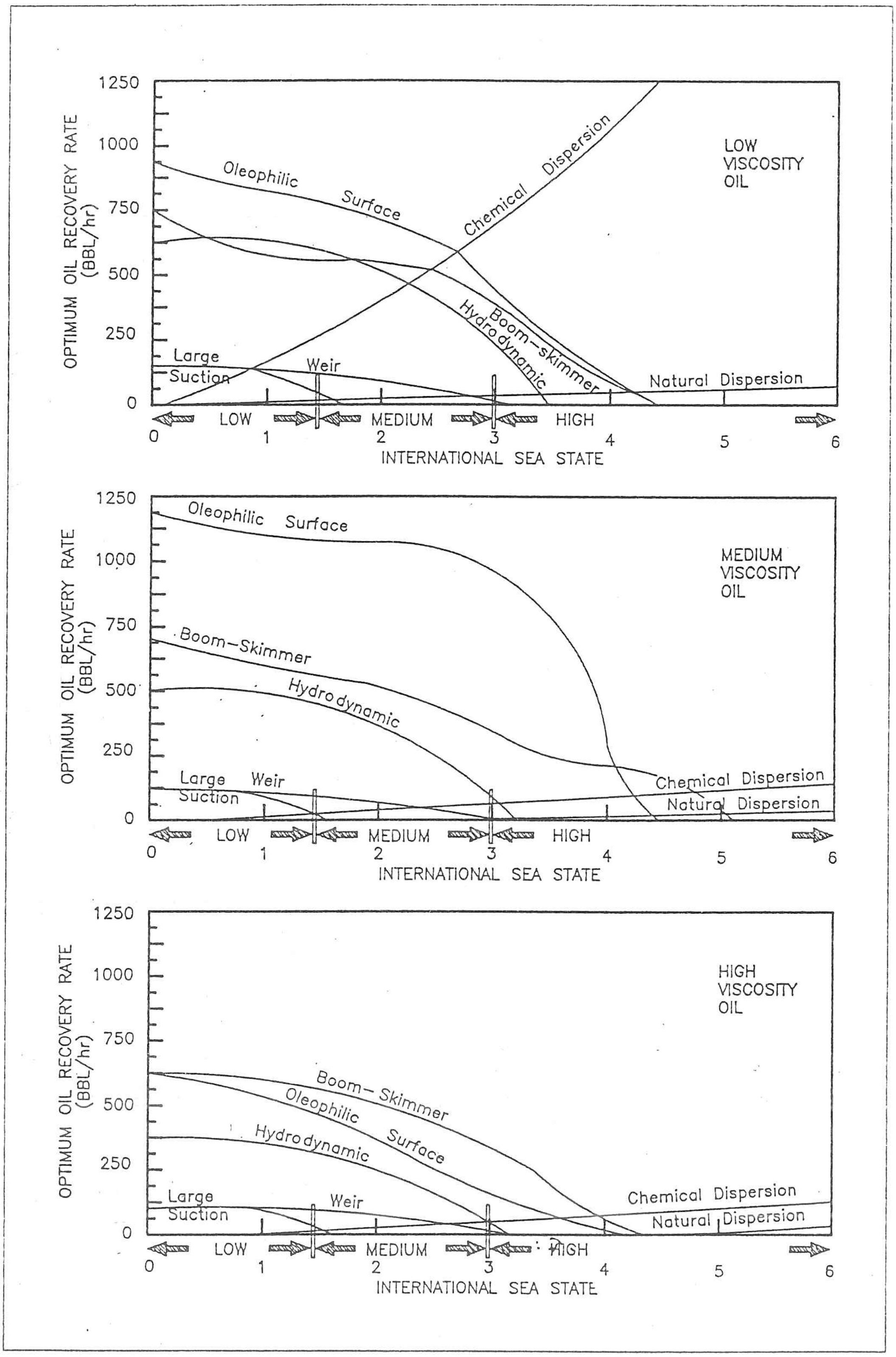


Fig. 5 Optimum oil recovery rate for generic classifications of skimmers versus natural dispersion. (U.S. Department of the Interior, 1990)

Mackay et al. (1980) investigated the effect of low temperature upon the dispersability of Alberta Mixed Blend. A reduction in efficiency with a factor of 1.75 was found after a temperature reduction from 15°C to 0°C. Similar trials with Canadian crude oil showed the same trend (Mackay et al. 1985). Byford et al. (1983) conducted similar studies with 7 dispersants on two crude oils using another test apparatus (Labofina/WSL). They showed that the effect were not so clear as the Mackay et al. this apparatus is ,however, very sensitive to the density of the oil (Daling et al., 1991) and this might have influenced the results. Brown et al. (1985) noted no significant difference in the efficiency with sinking temperatures in wave tank experiments with Corexit 9527 dispersant. Norwegian tests found only a weak reduction in efficiency when the temperature was reduced from 13°C to 6°C (Nes, 1984), and most significant reductions was found at low concentrations as shown in Fig. 6 . However all these results are strongly influenced by the fact that various dispersants act differently on assorted crude oils. The trend seems to be a strong influence of the crude oil and dispersant characteristics, loss of efficiency as the oil weathers and a small reduction with decreasing temperatures.

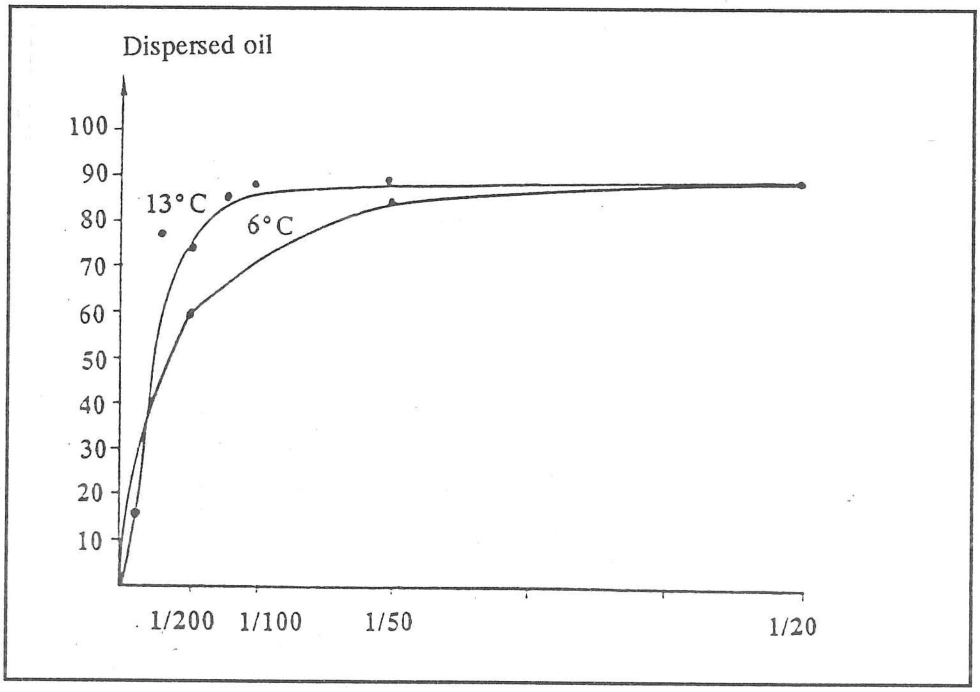


Fig. 6 Efficiency of the dispersant BP-1100 WD at increased concentrations at 6°C and 13°C. (Statoil, 1991)

Very few field experiments with the use of dispersants in ice infested waters have been conducted. Field trials by Swiss and Vanderkooy (1987) were not able to measure the efficiency of dispersants due to problems with equipment, however they demonstrated the feasibility of real life application with helicopter in ice. Several laboratory studies Brown et al. (1985), Byford et al. (1983) and Cox and Shultz (1981) have shown an increase in dispersant efficiency in the presence of ice. The increased thickness of the oil layer caused by the presence of sea ice has a positive effect upon the efficiency of the dispersant (Daling et al., 1991). However, one can conclude that field tests of dispersants have not been successful. And a number of tests clearly shows that dispersants are not highly effective, even under highly controlled experimental situations (Fingas et al., 1990). This is further complicated by the fact that the effectiveness of the dispersant in not possible, with any degree of precision, to measure using remote sensing (Goodman and Fingas, 1988).

3.3.4 Toxicity

Following the Torrey Canyon oil spill in 1967, where highly toxic dispersants were applied directly to shorelines causing greater ecological impact than the spill itself, there has been an increased concern about the toxicity of the dispersing liquid (Nelson-Smith, 1968; Linstedt-Silva, 1984). Early dispersants often had a low efficiency and a toxicity exceeding the oil itself. Chemical dispersants applied to oil spills undergo the same weathering processes as the oil (Tetra Tech. Inc, 1985; Neff, 1990). However continuous research is being conducted into more environmentally friendly dispersants.

3.3.5 Authority to make decisions

It is crucial to know in advance the conditions under which approval would be given and who the appropriate authority to give such a permission lies with. This was not the case in the Exxon Valdez incident and has become the focus of an Exxon law suit against the State of Alaska (U.S Department of Interior, 1990, pM-4)

Guidelines for the use of dispersants are important when one considers the response time required for this action. Guidelines are published regularly. Both governmental bodies like the Federal Council for Environmental Quality (QEC) (Boesh et al. 1974) and other research groups (Abbot, 1984) (Daling et al., 1992) have been involved in this work.

3.4 Other chemical additives

3.4.1 Demoussifiers/demulsifiers.

Oil in water (o/w) emulsions can have a water content up to 70-90% and can have a viscosity 1000 times the original crude oil. This will seriously inhibit the dispersion and mechanical cleanup of the oil (Daling et al., 1991). Demulsifiers or demoussifiers have surface active ingredients which prevent the formation of oil in water emulsions or break these up when applied to the slick. Low temperatures can have the effect that crude oils which would not form emulsions at higher temperatures will be able to do so in temp around 0°C. However at the same time the formation at lower temperatures will often be much slower (Johansen et al., 1990).

Ross et al. (1985), Buist and Ross (1986) and Buist and Ross (1987) have described the testing of a number of emulsion inhibitors. They conclude that the addition of demulsifiers after the formation of stable w/o emulsions is not feasible because they will not mix into the mixture due to the high viscosity of the oil. However they have a large potential to prevent the formation of emulsions in Arctic areas since it requires very small quantities to be effective (Daling et al., 1991).

3.4.2 Elastomers

Elastomers changes the viscosity of the oil and will make the oil visco elastic hence keep the integrity of the slick which in turn will increase the efficiency of mechanical devices. Tests have shown that under ideal conditions the elastomer can increase the efficiency of conventional cleanup equipment from 100% to 1000% (Brown and Goodman, 1989 and Cutter Int. Corp., 1990: In Daling et al., 1991).

The addition of elastomers will not affect the flash point of the oil and its volatility and hence not its combustive properties.

3.4.3 Solidifiers

A solidifier will increase the viscosity of the oil to the point where it loses its rheological properties as a fluid. It will form solid flakes, with properties from rubbery elastic mass to more solid tar like substances. This brings the same advantages as the elastomers to an even stronger degree. It is the only chemical which can be applied to oil under ice and hence it is interesting for use in Arctic waters

(Daling et al., 1991). The clean-up of oil treated with solidifiers can be made with non-devoted vessels equipped with fishing nets etc. The amount of solidifiers required (16-40%, of oil) makes it only feasible for smaller spills.

3.5 Biodegradation

Microbiological activity is the final factor to degrade all oil spilt on land or sea. There has been little use of stimulated biodegradation of spilled oil with the exemption of the cleanup of beaches after the Exxon Valdez spill in Alaska. This method in the application for oil in ice or water is still much in the experimental stage.

Different ways of boosting the biodegradation includes addition of bacteria, fertilizers, and biosorbants. Bacteria like Petrobac, Oil Eater, Polybac are offered on the market, however no scientific documentation is available on their performance. Of fertilizers only the EAP22 by Elf Aquitane is available on the market. The fertilizer has been tested by SINTEF under Arctic situations (under ice, water and beach) and not found viable for use in open water and ice (Sveum and Ladousse, 1989, In: Daling et al, 1990). On beaches, however, it is found to have a positive effect (SINTEF, 1990a). Biosorbents are mostly used in the cleaning of beaches however, they have never caught the popularity of the previous methods. Recent studies claim to have developed new revolutionary photocatalytic methods to increase the efficiency of the bacteria (Heller and Brock, 1992). However, no out-of-laboratory testing has yet been undertaken.

Biodegradation depends on bacterial growth, the formation of droplets (dispersion), oil composition and availability of other nutrients. The degradation velocity and cumulative volume is shown in Fig. 7.

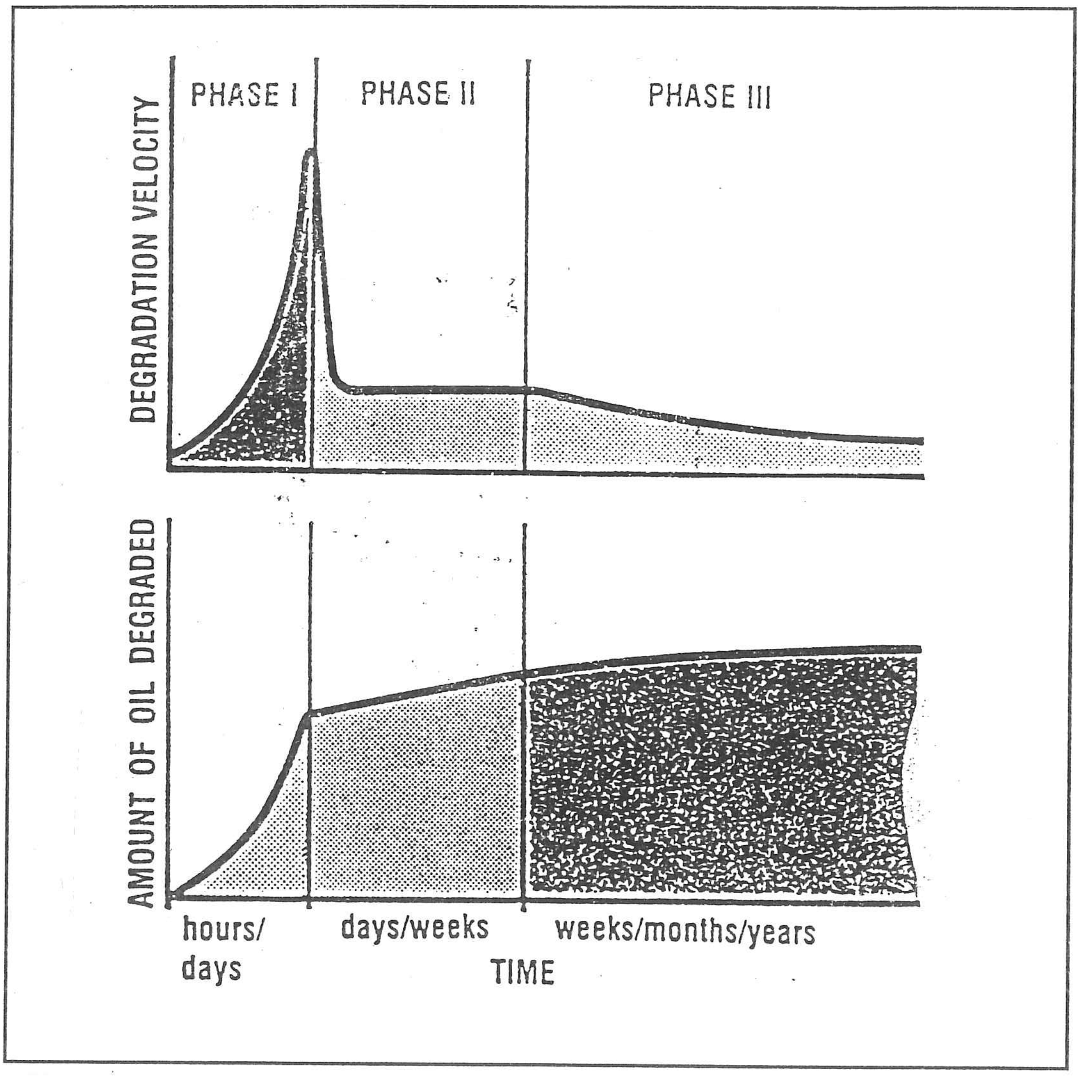


Fig. 7 Biodegradation of oil (Statoil, 1991)

3.6 In-situ burning

3.6.1 Introduction

Crude oil is a volatile hydrocarbon substance which is quite happy to burn when fresh. The requirement of burning is a production of volatile fractions of the crude oil primary caused by the heating of the burning oil itself. Burning normally ceases when the slick thins to the extent that the burning surface is cooled by the underlying layer and there is insufficient vapour generation from the oil to support continuous combustion. This failure can be prevented by maintaining the thickness of the oil slick (Mackay, 1985). As the more volatile fractions of the oil either are burned or evaporated the slick gets more difficult to ignite or keep the oil burning. However, burning of oil spills is a very novel way of treating an oil spill. It will result in a large smoke plume in the atmosphere, but it is believed that the impact of the smoke or soot, which amounts to only a few percent of the original oil mass, is minor compared to the potential impact of the unburned oil (Day et al. 1979). The experiments demonstrated that concentrations of SO_2 and CO will be acceptably low and concentrations of soot and metals will often be unsuitably high within 10 km of the fires, but will be acceptably low at greater distances. Distances for which safe human activity can be conducted within an ignited blowout is given by (S.L. Ross, 1986). Fig. 8 shows the burning efficiency versus wind speed for a number of different oils.

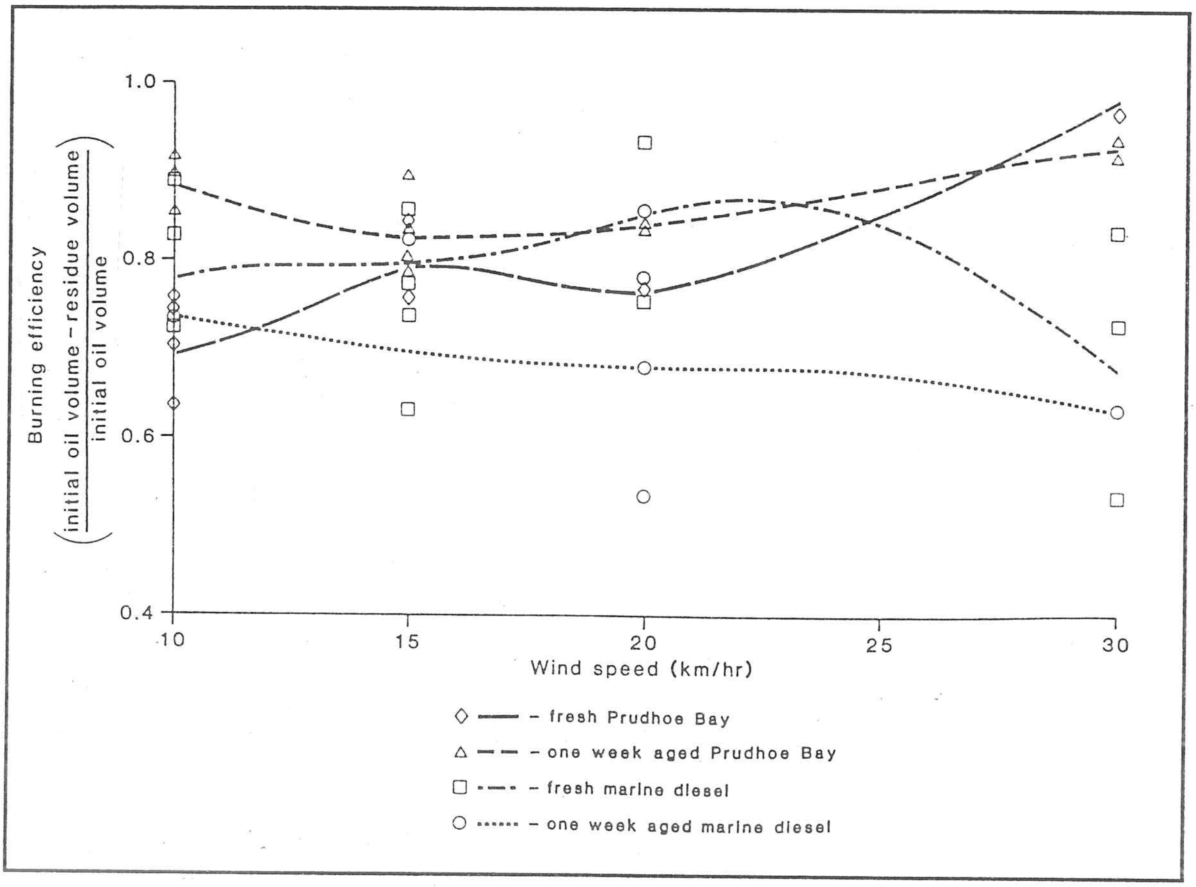


Fig. 8 Burning efficiency vs wind speed (Hume et al., 1983)

3.6.2 Burning of oil in ice.

a) on top of the ice

Early studies conducted by APOA (NORCOR, 1975) of controlled spills of crude oil under first-year Arctic sea ice demonstrated the feasibility of in-situ burning during melt-out the following spring. Research on the in-situ combustibility of spilled oil initially concentrated on crude oils (Artec, 1977, Energetex, 1977, NORCOR, 1976). Further work investigated weathered and emulsified crude oils and other diesel and bunker fuels under stimulated Arctic environments. It was found that the minimum thickness of various oils are approximately: 1 mm for fresh crude oil and diesel, 3-5 mm for weathered crude oil, up to 10 mm for bunker oil and heavily emulsified crude oils. It is possible to burn oil on ice at wind speeds up to 45 km/h, at ambient temperatures as low as -40°C and with entrained snow and slush contents as high as 60% by weight (Hume, 1983). Dome Petroleum Ltd (1981) simulated an oil blowout under first year ice in the winter of 1979-80 similar to NORCOR (1975). The oil released in this experiment appeared on the ice surface in pools the following spring. Approximately 80% of the oil discharged was burned before breakup as shown in Fig. 9. One-third was burned in-situ using igniters dropped from low-flying helicopter. Individual pool burning efficiencies averaged 80% (Buist et al, 1981). However, efficiencies of this kind would not be expected in real life due to the cost of these operations.

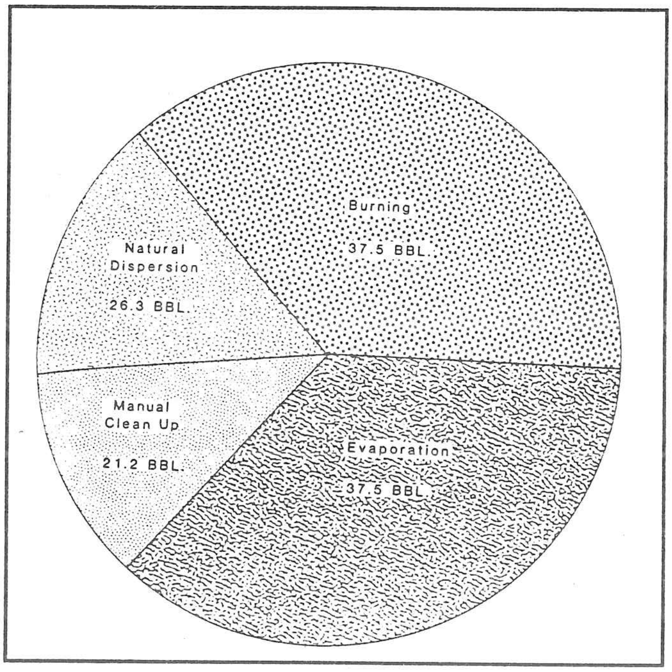


Fig. 9 Mass balance for oil (20 m^3) discharge under ice.(Hume et al., 1983)

Oil melting out of pack ice or multi year ice would be more difficult to burn than oil melting out of first year ice. Oil would melt out of pack ice much more slowly than from landfast first year ice; some oil would even take a second summer to reach the top if the ice. In addition a subsea blowout could result in a continuous spill spreading ribbons of many hundred kilometres of pack ice. The manufacture, shipment, temporary storage, and deployment of igniters, helitorches or gelled gasoline necessary to ignite thousands of oiled melt pools from a major spill, is a logistical nightmare (U.S. Department of the Interior, 1990).

b) Broken ice

Burning experiments with fresh oil in broken ice have given promising results, but results have been variable and less promising with weathered oils and emulsions. Field tests in a mud pit in Arctic conditions showed efficiencies of 55 to 85 percent of fresh Prudhoe Bay crude, but sparged (sprinkled) crude with a flash point of around 0°C could not be ignited (Shell Oil Company et al, 1983). Tests at OMSETT for fresh or sparged crude had burn efficiencies of 85 to 95 % at 22- to 34-percent ice cover and burn efficiencies of 58 to 79 percent at 78- to 85- percent ice cover (Smith Unpublished In: U.S. Department of the Interior, 1990). More recent studies concerned with in-situ burning of oil in leads investigating the effect of wind herding (Brown and Goodman, 1987). Burning efficiencies of up to 90% were possible if moderate wind herded oil into long narrow leads. For leads of other geometries with similar winds, efficiencies might be as low as 70%. Winds of up to 4 m/s across a narrow lead caused no oil herding and resulted in low efficiency burns. Brash ice impeded wind herding of the oil and resulted in lower burning efficiencies. Weathering of oil up to 20% did not significantly affect the burn efficiency in moderate winds. However, Payne et al. (1984) found that emulsification is accelerated in broken ice indicating that a slick would have to be set on fire very soon after spillage in order to obtain a high burn efficiency.

It is more difficult to burn spilled oil during freeze-up than at any other time of year. Martin (1981) has shown that wave action mixes the oil downward into the grease ice. Oil and ice would have to be recovered and the oil separated from ice before burning; there would be only a limited capability for in-situ burning. Recent realistic estimates indicates that uncontained oil from a subsea blowout cannot be ignited (Johansen, 1992). This due to the mixing between the oil and the enormous water masses which are entrained in the gas plume which in turn will attenuate the oil to such an extent that it is not ignitable.

3.6.3 Oil in open waters

The Exxon Valdez incident and the sinking of the Atlantic Express provide some evidence that it is possible to burn oil on open water with some success (Ross et al. 1979, Horn and Neal, 1981). Experiments with the burning of uncontained slick shows an efficiency around 50-60% if the spill can be immediately set on fire (Laperriere, 1984). However any delay in ignition would decrease combustion efficiency. In the Exxon Valdez spill spilled oil was still burnable on day 3 but not after the storm that occurred at the end of day 3. The successful burning of uncontained open water slicks is very much a function of spreading (temperature) and dispersion (weather). For waxy oils in-situ burning seem to offer a viable response technique. In fact, waxy oils may burn more efficiently than comparable less waxy oils. They may, however for the same reason, be somewhat harder to ignite (S.L. Ross, 1988)

In open water the use of booms is a convenient way of increasing the thickness of a spill. Prototypes of fireproof booms have been developed to thicken floating oil and contain it during combustion. Work has been conducted on several design concepts (eg. Roberts and Chi, 1978, Purves and Daoust, 1978, McAllister and Buist, 1980). They showed that stainless steel booms can contain burning crude oil for long periods, in waves equivalent to seastate 2-3 and in currants up to 0.5 m/s (McAllister and Buist, 1980, Dome Petroleum, 1981). Fig. 10 illustrates the length of fireproof booms required to burn in-situ certain volumes of oil per day. Recent tests of a new fire containment boom have been tested and been found to function well. The 3M fire boom has been designed and constructed to function as a conventional bottom tensioned curtain boom. While serving as a standard oil spill containment barrier, the boom can also be used as a fire resistant barrier for the containment of burning oil in water (Allen and Fisher, 1988).

In the case of a subsea blowout in a continuous ice cover several concepts have been considered (Chen, 1979 and Abelnour et al, 1977). However a number of problems are surfacing in the design processes of these systems; extreme costs for a system (CanOcean, 1982), long construction times, resistance towards extreme ice loads, limitations of mooring in subsea permafrost, difficulty in deployment. There are no available systems at the present and the possibility of having one lies far into the future. Other systems including the use of tankers have also been considered but no system is operational (Meikle, 1981b).

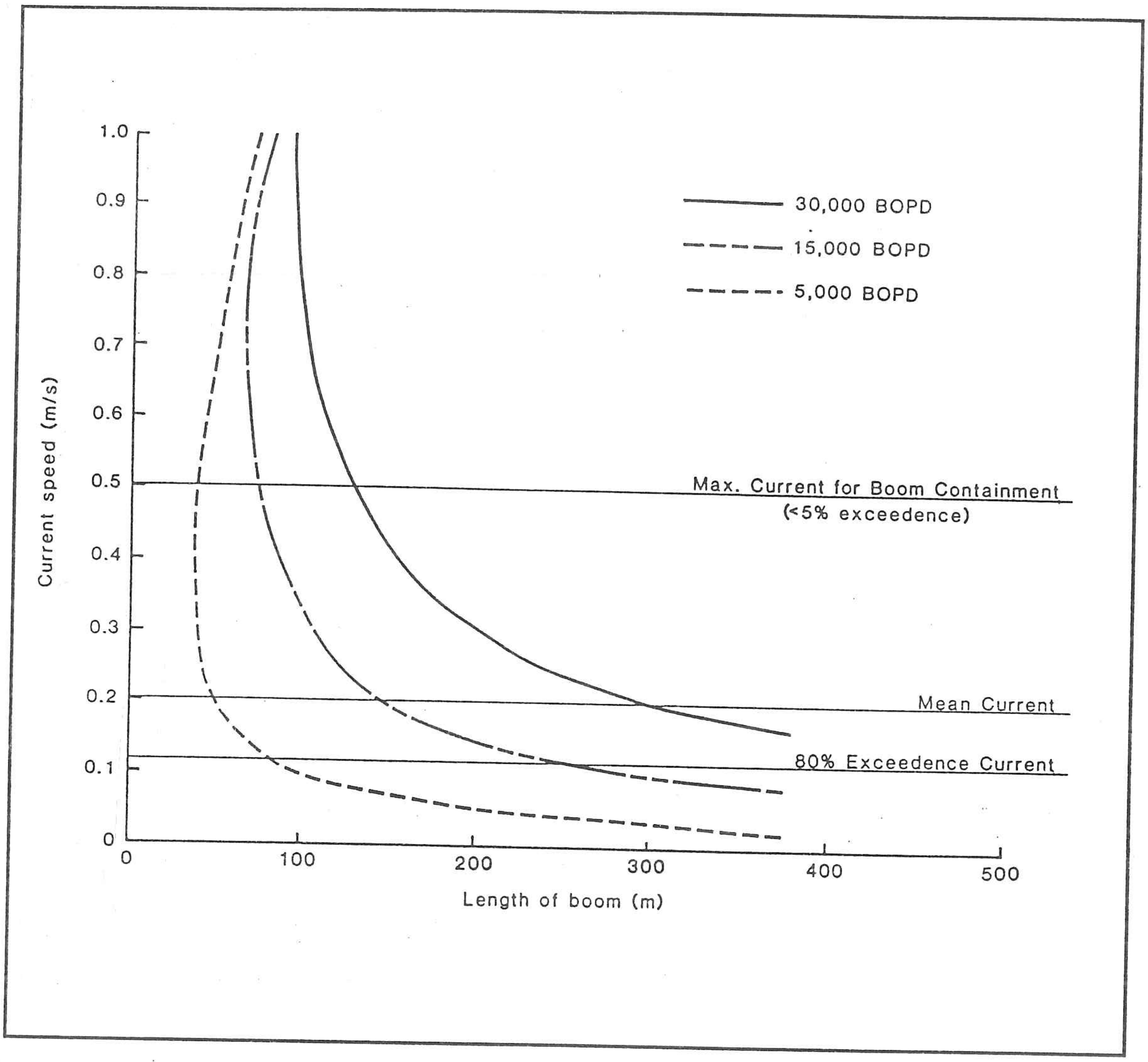


Fig. 10 The lengths of fireproof boom required to burn in-situ certain volumed per day. Also shown are the range of currants in the Kara Sea. (Hume et al. 1983)

3.7 Mechanical containment and recovery

The first line of defence for a spill is always mechanical containment. Open-water collection of spilled oil is usually not successful (U.S. Department of the Interior, 1991). Containment is useful in stopping the spreading of the oil and in providing extra time for deployment of more equipment and manpower.

3.7.1 Containment

There are numerous booms developed for the use in open water. They have however the disadvantage of being limited to fair weather conditions. The conventional boom skimmer configuration has shown its capabilities in a number of spills in good weather conditions with optimum efficiencies up to 95-100%. However with delayed response times large transit distances efficiencies can be as low as 10% or lower (Rodal, 1992). Alternative water jet booms have been tried out with little success (Punt, 1990).

The effectiveness of open water containment devices is limited when ice concentrations in dynamic ice exceed 10 to 20%. Handling, blockage and extreme ice forces are serious problems in brash ice (Logan et al, 1975). Artec Canada Ltd et al. (1977) suggested that in calm conditions a deep skirted boom might be suitable, but a floating cargo net is shown to be more suitable for up to 80% ice cover. In higher ice concentration the ice itself will contain the oil sufficiently so that it can be burned or mechanically recovered. Large floes make booms ineffective. AMOP developed an ice-oil boom which yields, reduces its angle to the ice, and then swings back under its movement (Tsang and Vanderkooy, 1979).

Little recovery can occur in fast ice. Although trenching is successful on ice covered rivers, specialized equipment is necessary to cut thick ice. Blasting of trenches can be successful in the high Arctic (Van Ieperen, 1980). Oil trenches with a 1 to 2 km circumference can be blasted around offshore rigs in strong multi year ice in two or three days.

In open water conventional offshore oil spill containment operations will be effective only during periods when wave heights are 2m or less, the wind speeds are 10 m/s or less and visibility is 1 km or greater (S.L. Ross, 1986, p5). In the Arctic winter this can be a large portion of the time indeed.

3.7.2 Mechanical recovery

Reviews of mechanical recovery devices is given by Miekle (1988) who discusses the work done by AMOP. Senstad and Gaaseines (1979), Ross (1980) and Sandkvist (1989) have summarised other available mechanical devices.

a) On water

Mechanical cleanup at sea is usually less effective on low- or medium-viscosity oils than on high viscosity oils however the boom increases its efficiency See Fig. 11. A high viscosity oil would be a weathered crude, bunker oil or thick emulsion. An oil such as Prudhoe Bay crude initially would have low viscosity but would quickly form an emulsion. In the presence of broken sea ice this transformation may take as little as 4 hours (Payne, 1984). In the absence of sea ice it may take 2 days (Payne et al., 1984). The mechanical recovery reduces almost twofold over the period this takes. However, oleophilic-rope recovery systems are a relevant exception to this twofold decrease in oil-recovery rate with increasing viscosity. The Alaskan Clean Seas has emphasized such devices in its Arctic contingency strategy, including development of oleophilic-rope skimmer, the ARCAT II Oleophilic rope system at medium sea states, between sea state 1 and sea states, can recover high-viscosity oil more readily that lesser viscosity oils. At a lower sea state (Sea State 0), highly viscous oils can be recovered at 69% of the rate of low viscosity oils (S.L. Ross Environmental research Ltd, 1983). Recovery devices for very high viscosity, waxy, crude oils have been tested by S.L. Ross Environmental Research Ltd (1986). For spills involving discrete particles of waxy oil, such as from an offshore blowout, hydrodynamic skimmers in conjunction with offshore booms were found to offer the greatest potential.

The requirement for operators in the Barents Sea is that any recovery system shall function in 1.5 knot currants and in up to 3 m significant wave heights and the cumulative equipment , which is to be in on site within 48 hrs, should have a capacity to handle 8.000 tonnes per day (NOFO, 1992).

b) In Ice

Oil Skimming Bows (OSB) working on the principle of a water jet aimed at the spill have been investigated in small scale experiments by Abelnour et al. (1986). The system could be fitted on most ice reinforced ships or ice breakers servicing the offshore industry in a particular area. The tests resulted in a maximum overall efficiency (Oil recovered/oil presented) of 21% at an ice concentration of 70%. However the average efficiency of the overall system in ice was only 10 % due to the ineffectiveness of the boom to move the oil at the outer ends of the boom. A similar device tested in full size showed similar results (Laperriere, 1989).

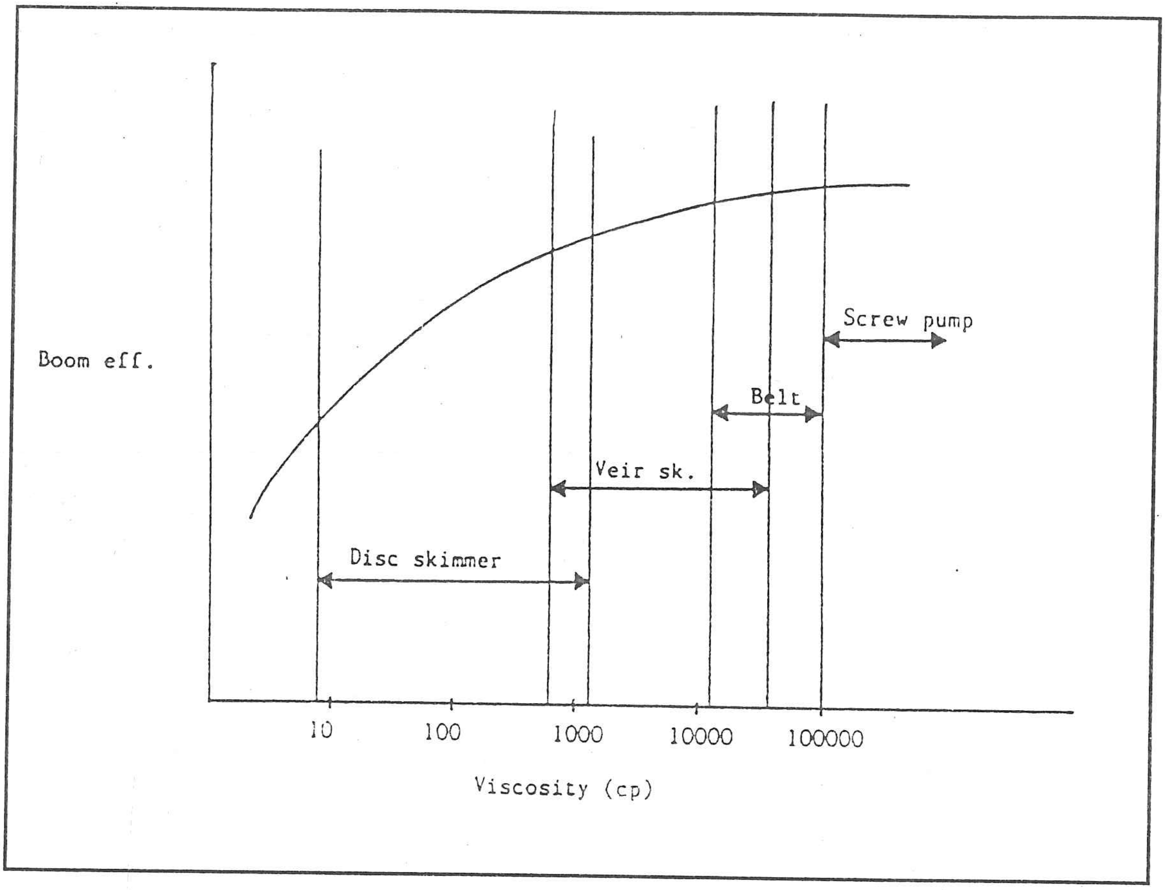


Fig. 11 Boom efficiency and skimmer type. (Statoil, 1991)

A device incorporating rotating porous drums with paddles, that was successful at processing oiled ice, has been tested by S.L. Ross (1986). It effectively submerged the brash ice and allowed the buoyant oil to flow up and into the porous drum. Recovery efficiencies up to 90%, with most values in the 40% to 60% range were achieved for crude oil. Lower efficiencies of 15-60% were achieved in tests using viscous fuel oils. In the same study an inclined plane skimmer to separate oil from brash ice presented by Smrke et al. (1984) was rejected.

3.8 Soviet technology

Although the Soviet Union has the largest coastline bordering to the Arctic Basin there has been relatively little exploration on the coast north of Siberia. Exploration has mainly been concentrated in the Barents Sea which is ice free most of the year. Due to the present political situation, very poor communication links and a very significant language barrier, information about the oil and gas industry is very sparse. In the field of oil recovery it is almost non existent. The Soviets have done a lot of theoretical work but little field work is known to the west, in particular in recovering and disposing of oil (ANR, 1991a). Just recently a biologist-engineer team associated with the USSR Academy of Sciences at Kola Scientific Centre, made claims for a new sorbent agent that would be many times more effective than anything else available (Ibid.).

There are several reports of successful cleanup operations after oil spills in the former Soviet Union. The spill after the wreck of Globe Asimi was handled with great success. Khalimovov (1986) claims that this was achieved through a routine of permanent readiness in the local subdivisions which deal with the spills. Another spill in 1972 of 100 tons of boiler fuel was recovered from a stranded vessel (Nunparov, 1991). An engineering centre at the Black Sea specialising in oil recovery vessels. More that 250 marine pollution fighters have been designed and tested by this institute. A joint Soviet-Bulgarian project has developed a new trawl for use in the Cuban oil port of Matanas. (Nurnuparov, 1990).

A large number of FRAMO skimmers have been sold to Russia and more are ordered (Soviet Shipping, 1989). In 1986 an oil-skimmer/dredger Vaidagubskiy was delivered from the Varstila yard in Turku. This ship is specially designed for the combat of oil spills. It is also believe to be ice strengthened, which makes it the biggest ice strengthened ship in the world in its class. Apart from skimming off the water surface, it can be used for fire combat, reception of bilge or other polluted water. Flexible boomguards, with a 60 metre capturing range serve the Vaidagubskiy to skim off the sea surface. The skimming range can be extended to 250m with the help of tugs. Two collectors pump oily water into the ships' tanks which has a capacity of 10 000m^3. The oil skimming capacity is up to 800m^3 and that of water and oil separation up to 300m^3. Soviet related purchases from abroad are listed in Table 3 below.

New models of oil skimmers from 1987 are now operating in 20 ports including the Arctic (Nunparov, 1991). Regular drills are held in all the basins including the Arctic regularly and the general preparedness is very high (Khalimovov, 1986). A joint Norwegian-Soviet oil spill response exercise was to take place in June 1991 offshore either Hammerfest or Tromsø to test communications and mobilization of vessels and equipment of both countries. However, no harmonization of oil spill response plans or reciprocal assistance commitment in the event of oil spills has yet been made. Such will not be done, according to the environmental ministry, until Norway and the former Soviet Union have agreed on a Barents Sea shelf border (ANR, 1991b).

Table 3 Soviet rescue, fire-fighting and spill containment vessels purchases from abroad.

Contract	Number	Description	Companies/ Country	Delivery/ Value
?	1 (Probably more)	Ice breaking tow and fire fighting vessel: Deymos. Length: 71.6m, With: 18m; Complex diving station	Wartsila, Sudoimport/ Finland	Spring 1984/ ?
?	1	Multi-purpose for spill containment, discharge processing, fire fighting and dredging. Spill containment capacity: 800 m^3/h. Capacity of each sea-bed pump: 13.000 m^3/h (10.500 dwt Gogland may be precedent).	Warstila, Mingazprom/ Finland	Under construction, January 1985/ ?
April 1984	2	Arctic class rescue tug 'SB-922'	Rauma-Reppola, Sudoimport/ Uusikaupunki, Finland	1985-86/ ?
May 1986	4	Oil-spill recovery vessel	FELS, Sudoimport/ Singapore	1987 US$ 24 million

Compiled from Bergesen et al (1987) and Soviet Shipping (1989).

4.0 ICE CONDITIONS IN THE KARA SEA.

4.1 Introduction

An understanding of the environmental conditions that a region can experience is important for providing both reasonable day to day support, as well as input to the necessary design criteria for the extreme situation. In planning logistical support, it is necessary to know in advance the type of environmental conditions that the operation may encounter. The Soviet Union has been producing observations of the state of ice for a considerably longer time than the rest of the Arctic, due to their special interest in the area. Regular studies with aircrafts and ice breakers have been undertaken since the early 1920s. The first winter reconnaissance flight was made in 1939 in the Kara Sea (Armstrong, 1950 summarised from Laktionov, 1945). In the past over 30 meterological and scientific stations have been recording ice conditions (Armstrong, 1958). Examination of historical data provides, in hindsight, expected mean conditions that could be encountered. This information would be useful in the decision-making process to determine what would be feasible and/or reasonable to expect in terms of operational activity. Meteorological and ice data also provide the input to models determining the physical and chemical fate of the oil slick.

4.2 Physical oceanography

4.2.1 Currants

The Kara Sea is overall a very shallow sea. Except for the two canyons in the south and the east Novaya Zemlya trough depths are less than 200m. The prevailing oceanographic feature of the area is the Kara Sea circulation. This is a counter clockwise current, ,i.e. cyclonic, in the southern Kara Sea. The water masses come down the east coast of Novaya Zemlya at an average speed of 3-5 cm/s, and bend off to the left as they approach the straits between Novaya Zemlya and the mainland (Kara Gates). Some of the current goes through the strait and continues up on the west side of Novaya Zemlya as the Litke Current (Trangeled, 1984 In: Johannesen, 1986). Through the same strait on the mainland side comes another current which has followed the coast from the White Sea and this joins the Kara Sea circulation on its way up the Yamal Peninsula. This is called the Yamal current (Stefanov, 1985). Approaching the tip of the Yamal peninsula a small but strong circulating current breaks off in a counterclockwise direction (Stefanov, 1985). The current then flows northward towards the Severnaya Zemlya archipelago, creating cyclonic eddies on the left, then to flow into the Arctic

Ocean. The other main feature of the circulation of the Kara Sea is controlled by the outflow of the Ob and Yenisey rivers, which mixes with seawater and moves north eastward toward Severnaya Zemlya from just east of the Yamal Peninsula (Weeks and Gow, 1978). Numerical models for the general drift pattern (Doronin, 1989) and more detailed for the small circulations (Doronin, 1983) have shown good consistency with the measured results. Currants are shown in Fig. 12.

4.2.2 Temperature

The sea temperature of the Kara Sea is heavily influenced by the seasonal ice cover. In the winter the surface temperature in the sea ranges from -1.6°C close to the coast to -1.8°C further north. However, in the surrounding waters of the estuary of the Ob and Yenisey rivers the temperature rises to -1.3°C over the vast river deltas. In the summer the southern part of the Kara Sea is ice free most years (Gorshkov, 1980). By August the temperature has risen to 4.0°C around the Karskiye Vorota strait and on the river deltas. The water gradually gets colder the further north, and in the north eastern part of the Kara Sea the water rarely gets above 0°C. In the Novaya Zemlya trough the bottom-water stays constant at less than -1.5°C through the seasons.

The average surface temperature remains fairly constant from December to March at a level of -20°C in the south Kara Sea and -28°C in the North. Deviations from this can however be very large with extremities of +4°C in the southern and -52°C in the north both reported in January (Ivanov, 1977). From March and onward the temperature rises gradually to reach the peak usually in August with average temperatures ranging from 6°C in the south and 2°C in the North. From the end of October the temperatures are below zero again and the winter is rapidly approaching. Methods for long-range forecast of the monthly air temperatures have been developed by Ivanov (1978). He found that it was strongly dependent upon the air-mass transport of the area. Long term fluctuations have been investigated by Voskresenskiy and Lyubarskiy (1981) who showed a 100 year cycle in the western Soviet Arctic and a 40 year cycle in the Eastern as opposed to earlier reports of eighty year cycles of the air temperatures in the whole hemisphere (Gedeonov, 1969). The range of the long term fluctuations in the Kara Sea were twice that in the Chukchi Sea.

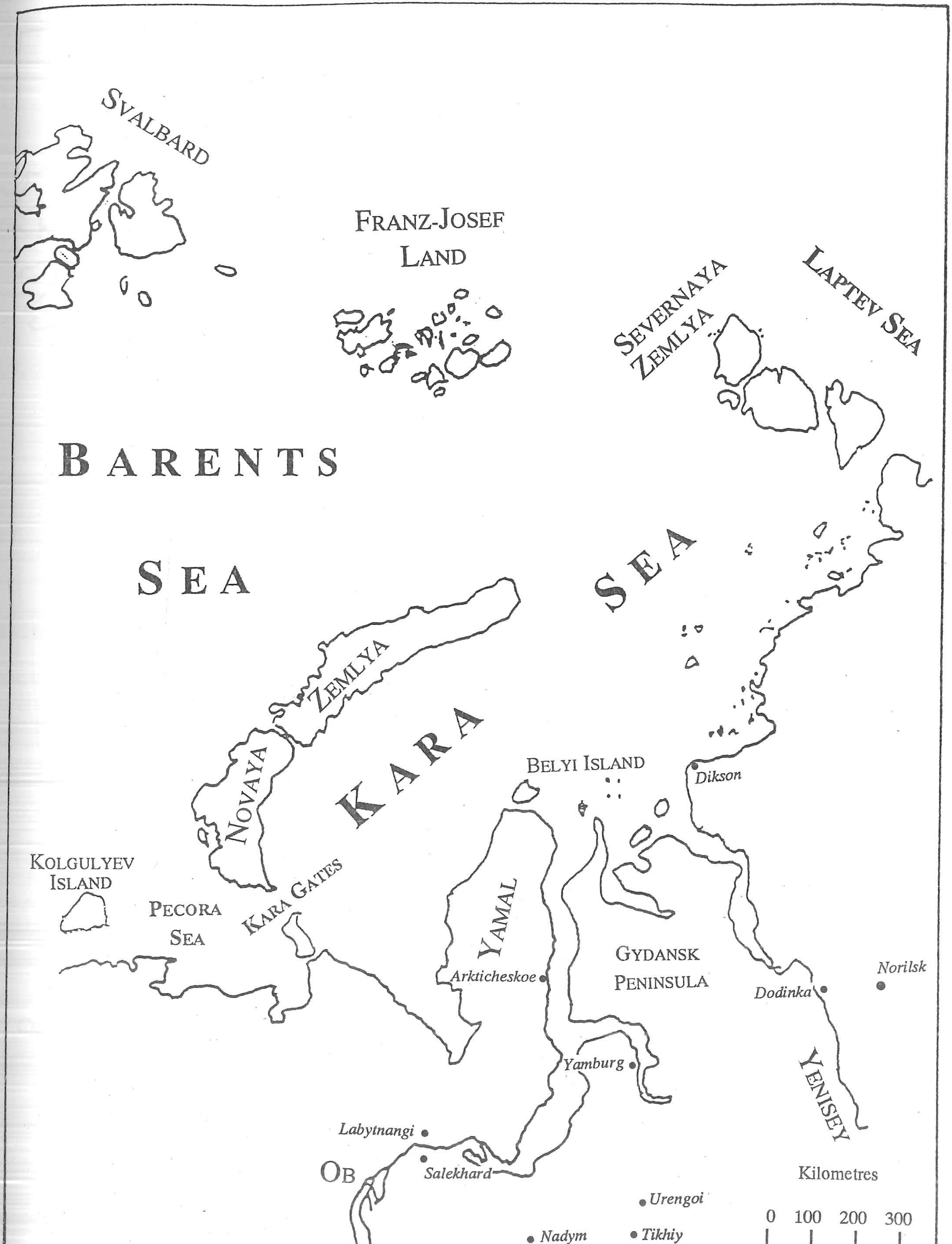


Fig. 12 General Geography of the Kara Sea region

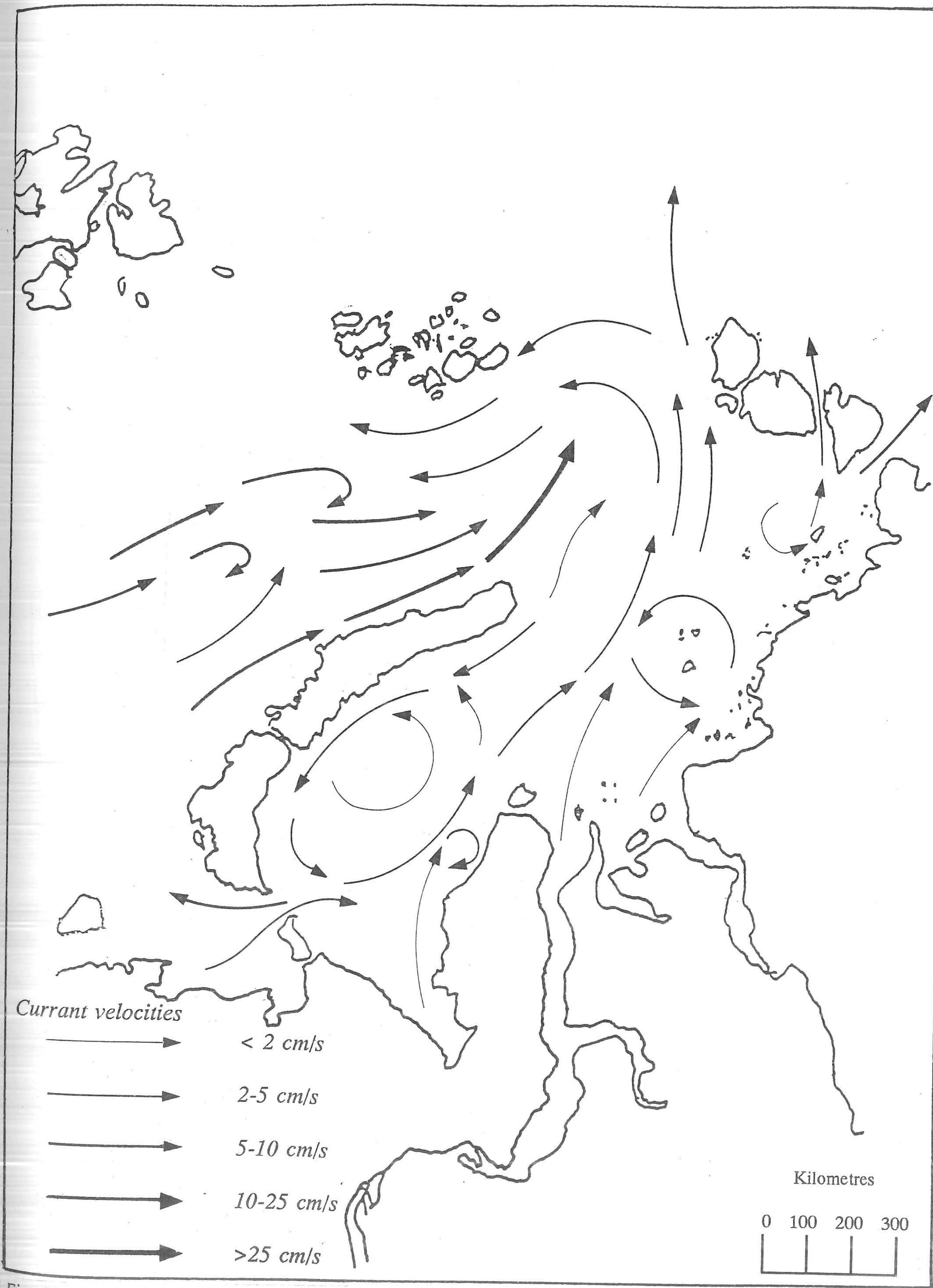


Fig. 13 Currants in the Kara Sea (Compiled from Gorskhov, 1980 and Stefanov, 1985)

4.2.3 Salinity

A main feature of the Kara Sea are the two large rivers Ob and Yenisey. Between them they are responsible for 45% of the total freshwater runoff into the Arctic ocean (Semter, 1984), of which more than half occurs in May-July (Hanzlick and Aagard, 1980) The runoff of the freshwater from the rivers dilutes the water and makes the waters of the Kara Sea less saline than the rest of the Arctic Ocean. The fresh water, being less dense than the salt water, forms a layer spreading over the sea. The salinity of the sea is at any time a function of the anomalies of the river discharge. It is possible to calculate the changes in the long term salinity by looking at the flow from the rivers (Appel' and Gudkovich, 1984). This layer is found to have an average thickness of 3.5m and containing the equivalent of 2.5 years of river discharge (Hanzlick and Aagaard, 1980). This provides a buffer against large changes in ice and hydrographic conditions that might otherwise result from an anomalous year's runoff. In the winter the salinity at the delta of Yenisey and Ob is around 2-2.5% increasing northwards until it reaches a level of 3.3-3.4% in the north and at the coast of Novaya Zemlya. Following the spring meltout and the vast discharge of freshwater, the salinity decreases. It becomes as low as 10% at the river mouths increasing to 30% further out.

4.2.4 Meterological data

a) Precipitation

An average of 300mm precipitation falls in the Kara Sea region annually (Gorskhov, 1980). 40% of this falls in August to October usually not exceeding 75mm in a month. As soon as the sea ice forms in the middle of October all precipitation will come as snow. A stable snow cover is usually established by the beginning of October (Dolgin, 1959). From November 175mm of water equivalent will fall, with a decreasing rate from 30mm in November to the driest month of May with <15mm a month.

Young ice generally carries very little snow, whereas autumn ice will have accumulated a fairly thick snow layer by spring. Jutting hummocks, which are much more numerous on drift ice than on fast ice, are enhancing snow accumulation. It would therefore seem that more snow should accumulate on drift ice than fast ice. However, drift ice shows poorer snow accumulation mainly because the incessant shifts and cracks between the floes produce clear water lanes, which act as snow traps under snowdrift conditions. Surveys carried out over the entire fast ice area of the Kara Sea show that the quantity of snow on the ice is highly variable from year to year (Nazintsev, 1976). In 1960, the prevailing snow heights reached 15-20 cm, whereas in 1967 they were 40-50 cm, i.e., almost three times as high.

For drift ice the snow accumulation is generally lower than on fast ice. Studies from 1963-69 showed that the snow thickness on drift ice was ranging from 45% to 30 % of the fast ice thickness (5-13 cm) (Nazintsev, 1976). It is significant that the minimum snow cover, 2-5 cm is the same for almost all age groups of ice.

Fog and low visibility, less than 1000m, can be expected for 100 days a year. Ostrov Belvy in the south western part of the Kara Sea has reported 158 days of fog in extreme years (Kjaerestad, 1990). More than half of this fog can be expected in the shipping season. Frost smoke, which develops when cold air is blown over relatively warm water, is not common due to the low water temperatures.

In July the mean cloud cover varies from 70% in the south and 80% in the North East Kara Sea (Vowinckel and Orvig, 1964). However, the cold period is dominated by an anticyclonic weather regime: low temperatures, weak and moderate winds and little cloudiness and precipitation (Gorshkov, 1980).

b) Wind

In the south west the wind in the winter is N-NE 65 % of the time. The north eastern Kara Sea has generally less wind and the prevailing wind direction is more N-NW. Strong winds ranging from 11-15 m/s occur 40% of the time. Approaching April the dominant wind direction turns more easterly in the South and westerly in the North. The general windspeeds decrease significantly. Towards the summer a Northerly wind builds up throughout the Kara Sea and from June to September this is the prevailing wind direction.

c) Tides

Tides in the Arctic Ocean is generally very small and the Kara Sea is no exception. Most of the sea has tides with amplitude less than 0.6m. The tides are predominantly semidiurnal with a amphidrome in the centre of the southern Kara Sea. The magnitude increases in the strait between Novaya Zemlya and the mainland and in the estuaries of the Ob and Yenisey. However the tides are seldom above 1.2m even in these regions.

4.3 Ice Cover

4.3.1 Break up

The ice in the Kara Sea is predominantly of local origin (Zubov, 1945, p445). The islands of Novaya Zemlya prevent the warm extensions of the Gulf Stream that influence Barents Sea from significantly affecting the Kara Sea. There is also little interchange between the Kara and Laptev Seas due to the blocking action of the Severnaya Zemlya archipelago. Consequently, with the continent guarding the southern boundary of the sea, only the northern opening to the Arctic Ocean allows appreciable interaction between the Kara and its neighbours (Barnett, 1991).

The ice cover in the Kara Sea breaks up after the Barents Sea. The main factors influencing the break-up are the enormous flow of warm water from the rivers Ob' and Yenisey and the branch of the Gulf stream passing north of Novaya Zemlya. Detailed mechanisms of the breakup are not known. However generally break-up usually occurs at a time of weakening of the ice cover by superficial solar melting or, more significant in the Kara Sea, by bottom melting due to the influx of freshwater from the swelling rivers (Wadhams, 1980, p46). The Kara Gates have very heavy ice conditions in the winter and as late as mid Mars the Arktika, a 75.000 hp icebreaker, has not been able to break the ice (Shabald, 1977b). By July 15th the rivers have broken up the inner estuaries and 20-40% probability that the strait is open. On the 25th the strait should be completely open and the sea-ice on the north tip of Novaya Zemlya has begun to break up (Karelin, 1937; In Armstrong, 1958 and NOCD, 1986). By 25th July the current has forced most of the ice further north towards Severnaya Zemlya and the strait should be navigable, in an average year, with a non ice strengthened ship. In the middle of August the estuaries of the rivers are completely broken up and there is a 50% probability of broken ice in the central Kara Sea. There might however be some ice clustered just north of the south tip of Novaya Zemlya.

At the minimum ice extent around 15th-25th September there are still a 0-20% probability of encountering ice in the south west Kara Sea and a 20%-40% chance of engaging in ice in the Kara gates strait. A numerical model developed by Appel' and Gudkovich (1981) has successfully modelled the summer ice conditions in the Kara Sea. The Novaya Zemlya ice cluster is also adequately modelled.

4.3.2 Ice clusters

Three summer ice clusters are distinguished: the Novaya Zemlya (Novozemelskiy), the North Kara and the Severnaya Zemlya. The location of these ice clusters is shown in Fig. 14. These local sea ice clusters (massifs) like the Novaya Zemlya are result of the local sea ice drift pattern. The Novaya Zemlya cluster generally becomes a distinct entity by separating from the ice further north sometime in July. It is composed of ice of one winter's growth, thawing entirely every summer (Armstrong, 1958). South westerly winds can cause the cluster to block the southern straits into the Kara Sea. Icebergs are found off the north-east coast of Novaya Zemlya. The North Kara cluster, which is joined to the North Barents cluster to begin with, generally remains all summer, gradually retreating northwards and decreasing in size. It can contain polar ice which has come down from the Central Polar Basin, but this is generally carried back again fairly soon by currants (Armstrong, 1958). Icebergs are found in this region.

The Severnaya Zemlya cluster has its origin in the wide belt of fast ice between Severnaya Zemlya and the western coast of Taymyr. Easterly winds tend to scatter this cluster, but westerly winds consolidate and if there is enough ice the western entrance of Proliv Vil'kitskogo is blocked. The ice is mostly one winter's growth, but since this cluster sometimes survives the summer, ice over a year old may be found. Heavy ice may drift into this region through Proliv Vil'kitskogo, e.g. tabular ice bergs, however this is not common because the current normally sets from west to east through the strait (Armstrong, 1958). Year to year variations are great, ranging from near zero percent to near 80 percent ice (NOCD, 1986).

On this account we cannot talk about an ice edge in the same sense as in Greenland or in the Barents Sea in the Kara Sea. The ice clusters will sometimes not be separated and some years will be completely broken up or completely gone (Zubov, 1945, p452).

4.3.3 Freeze up.

The north east of the Kara Sea will start to freeze up in the beginning of October after reaching the minimum sea ice extent in the end of September (Barnett, 1991). The average boundary of the ice extent runs just below Severnaya Zemlya but north of the small islands just off the Taymyr Peninsula (Gorshkov, 1980). The absolute minimum ice extent at this time would be above the Severnaya Zemlya archipelago. It has already been noted that since the indices of freezing of the coastal Siberian

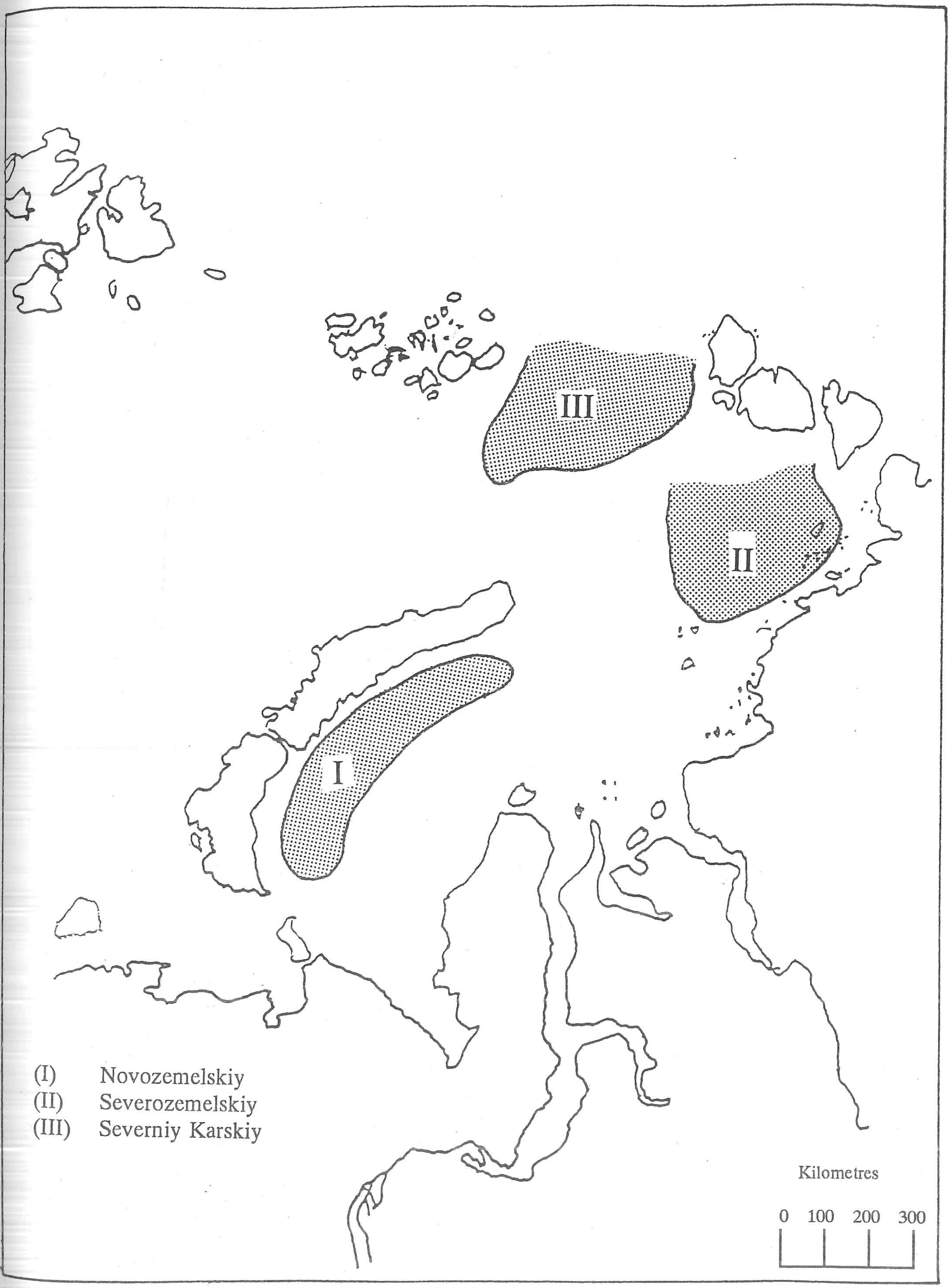


Fig. 14 Ice clusters in the Kara Sea. (Armstrong, 1958 and Arikainen, 1987)

waters are not large, directly after the commencement of cold weather the ice formation begins very quickly (Zubov, 1945). The first ice to be formed will be from the low salinity drops of meltwater especially if even small vestiges of ice have been preserved in them.

When the warming from the sun disappears gradually and the temperatures sink to below -15°C, the sea freezes rapidly up and is completely ice covered by mid-October. In September, freeze up begins with the appearance of new ice in the colder waters of the North. Freeze-up in the south starts in early October where breakup began, in the less saline waters of the estuaries. Rapid freeze-up of the remainder of the Sea east of 70°E follows. Waters of the southwest extremity are more resistant to rapid freezing. In average years, an open-water area remains from the Kara Gates to 180-275 kilometres northward as late as the first days of november. This open water disappears as early as late October in severe years but persists into the last half of December in extremely mild years (Barnett, 1991). Even in "mild" ice years the Kara Sea is completely covered in ice by the beginning of November. And from December until May the area of ice cover is fairly constant at a maximum (Parkinson and Cavalieri, 1989).

From mid-November until June, the only significant areas of weakness occur along the fast-ice boundary along the southern part of the Kara Sea. Prevailing southerly winds constantly push drifting ice northward from the immobile fast ice. This drift ice is quickly replaced by polynyas of newly formed young and new ice. This continuous process through the winter results in the thinnest ice normally being found at the fast ice boundary, with thicknesses increasing farther seaward. Early models supported by field data have estimated thickness of the first year ice to average 2m (Kochetov, 1973).

4.3.4 Ice concentration

From late November to late May the mean ice concentration in the Kara Sea is 80%-100% (NOCD, 1986). By the first of June polynias have usually developed along the east coast of Novaya Zemlya and around the Yamal Peninsula with mean ice concentration of 50%-80%. This trend continues with both these polynyas extending further northwards.

There have been attempts of correlating the sea ice distribution with the river out flow in the past (Gudkovich et al., 1981) with limited results. This might be due to the vast freshwater storage capacity of the Kara Sea discussed earlier by Hanzlick and Aalgaard (1980). Examining historical material collected by Nazarov (1947) ranging from 1580 to 1945 110 year and 160 years cycles are identified. He also predicts on the basis of these studies that the ice concentration in the latter half of this century will be decreasing. A more recent investigation of the long time trend from 1973 to 1987 of the Kara and the Barents Sea ice cover have shown a decline in the sea ice concentration (Parkinson and Cavalieri, 1989) and indeed supports Nazarovs predictions. This opposes to some extent with a 300 month sample by Walsh and Johnson (1979, p590) of the whole Arctic which shows a small but significant increase in the ice cover. Mean ice cover is shown in Fig. 15.

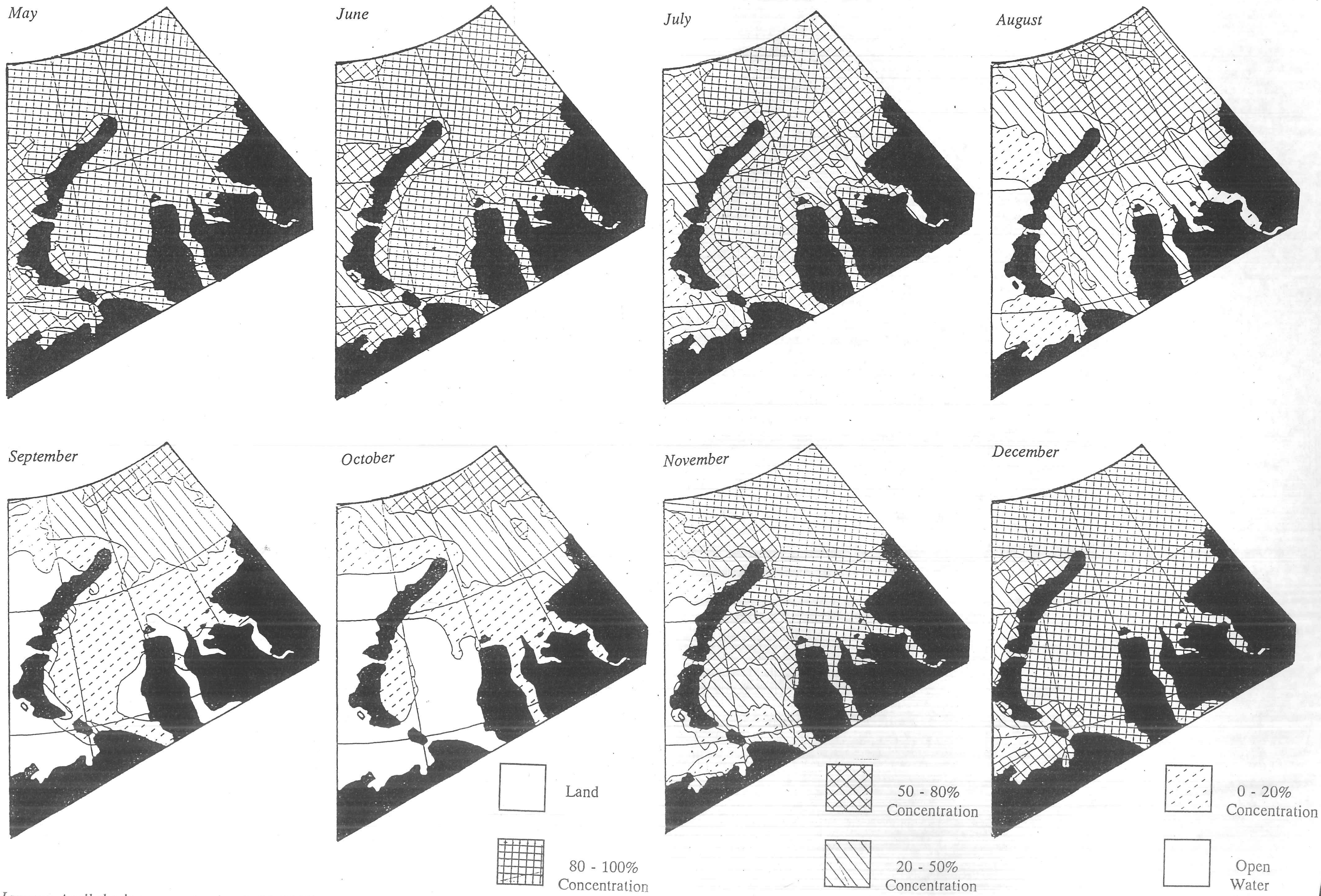
4.3.5 Fast Ice

Due to the shallow nature of the Kara Sea where the 50m isobath extends some 150 km west of the Yamal Peninsula and 250 km east of the Taymir Peninsula and the Severnaya Zemlya archipelago the fast ice area is vast. The ice is anchored both to shore, by grounding of pressure ridges and on islands. The latter especially in the north east where the ice close to the shore does not break up until spring. Due to the strong north bound winds in the winter the fast ice from the Yamal Peninsula and up to Severnaya Zemlya brakes up in the winter and moves north. New ice is formed almost immediately in the newly opened lead. In this area shallow water of low salinity makes the ice reform rapidly, the first is the most significant factor (Wadhams, 1980). Extreme pressure ridges with a depth of ca. 50m (Lyon, quoted by Weeks et al. 1971) and more recent reports which believe that the maximum draft is closer to 65m (Reimitz and Barnes, 1985) are not likely to occur in the Kara Sea. Grounded hummocks on the coast of Novaya Zemlya have been reported to reach depths of 10m (Ostenso et al., 1967) This is because multi year pressure ridges are not likely in the majority of the Kara Sea. Maximum fast ice extent is shown in Fig. 16.

4.3.6 Ice movement

Strong southerly winds force the ice northward into the polar pack leaving a polynya at the coast to Siberia. The general circulation of the Kara Sea includes a ceaseless transfer of ice and surface water out into the Arctic Ocean. New ice formation is continually occurring on the water areas which have been opened by this transfer. It is therefore natural that many consider that the main mass of Arctic Ice is formed on the broad shallows of the Asiatic coast from the costal Siberian Waters.

Fig. 15 Mean Ice concentration May to December (NOCD, 1986)



January-April the ice concentration is 80-100%

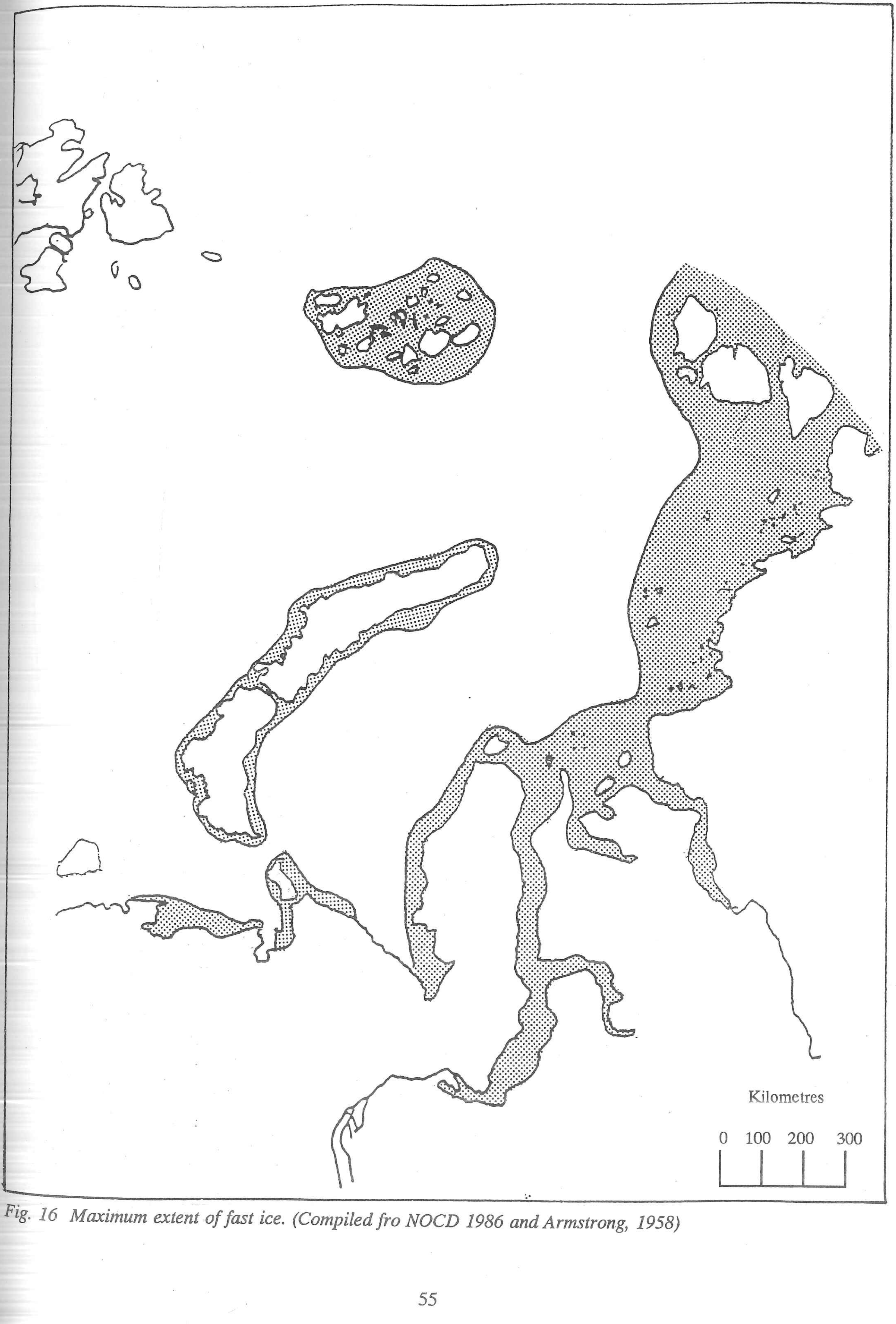
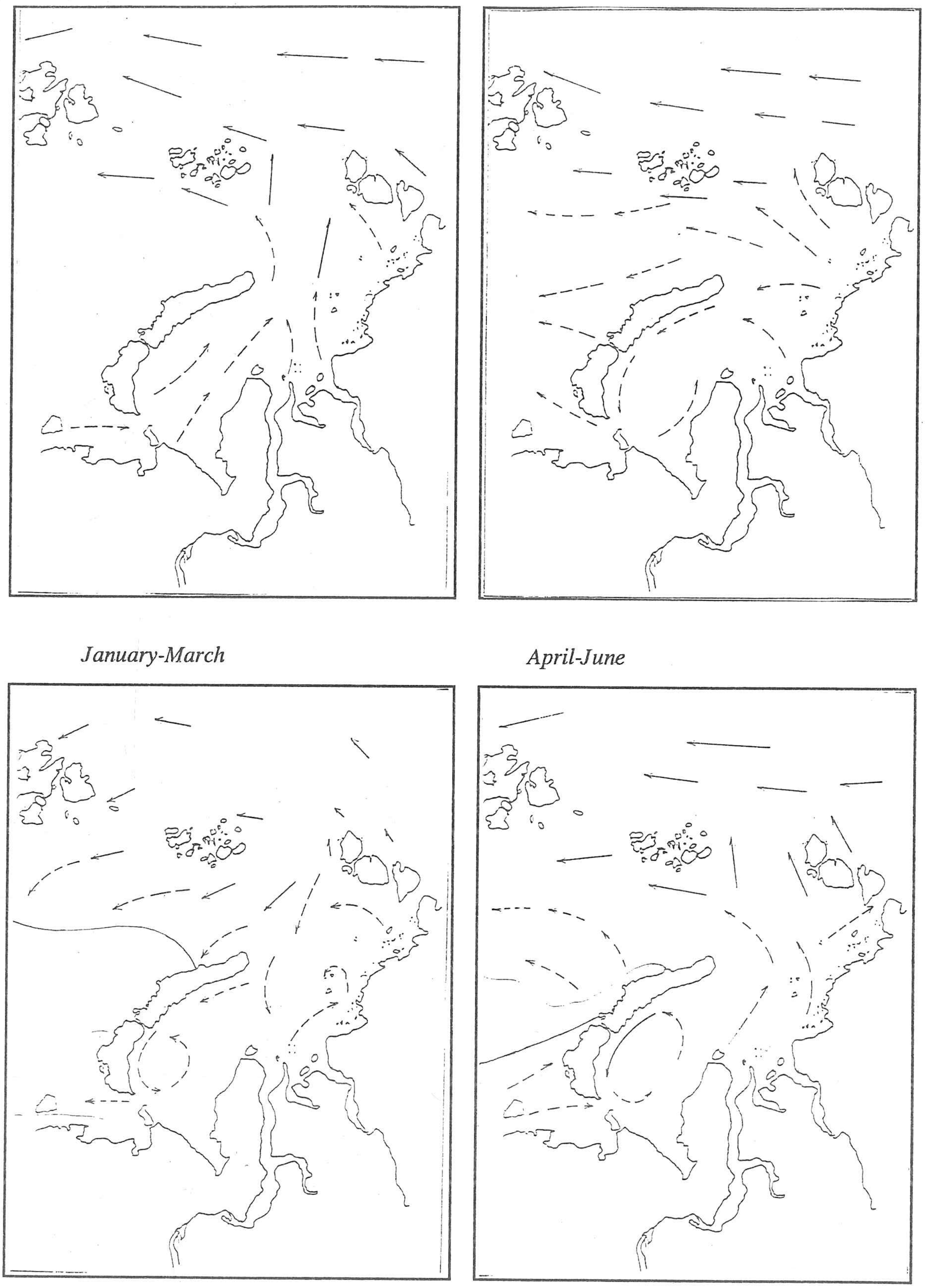


Fig. 16 Maximum extent of fast ice. (Compiled fro NOCD 1986 and Armstrong, 1958)

Little is known of the celerity of the ice movement in the Kara Sea. There are only a limited number of drifting stations and ships which have been set out in the Kara Sea. However a few crude datasets are available and certain estimates can be made. The general drift pattern has been outlined by (Gorshkov, 1980) however no data on the velocity of the drift has ever been published. On the basis of radio beacons in the North Kara in 1956 (Shesterikov, 1957), the drift of the Dimfna in 1882 (Zubov, 1945), the drift of the St. Anna (Barr, 1978) and two stations in 1907, and 1920 (Treshnikov, 1986) estimates of the drift velocities can be made.

The ice movement in the Kara Sea follows generally the current pattern, in the North a large outflow into the Arctic Ocean and in the south a circulation within the Novaya Zemlya Ice massif (cluster). Sea ice drift patterns are shown in Fig. 17. There is some exchange with the Barents Sea through the Kara Gate where ice flow both ways just like the currants. The currants vary from 2-3 km/day in the Kara Sea circulation (Gorshkov, 1980). The calculated average drift velocities of the sea-ice range from 6.0-8.3 km/day on the northward passage up along the Yamal Peninsula and 11 km/day on the downward trip along Novaya Zemlya. These figures are very approximate, however they give a rough indication of the velocity of the sea ice in the Kara sea.



January-March *April-June*

July-September *October-December*

Fig 17 Sea Ice drift patterns in the Kara Sea. Compiled from Gorskhov (1980), Zubov (1945) and Barr (1978).

5.0 HYDROCARBON EXPLORATION IN THE KARA SEA.

5.1 Current exploration and technology

5.1.1 Oil and gas policy

It has for a long time been the stated policy of the Soviet Union and now later Russia, to increase the oil and gas production from its vast reserves (Rigasi, 1988). This has in the last 5-6 years proved to be very difficult and there have been a steady decline in oil production since 1988 (Fueg, 1990). Gas production, however, has shown a steady increase over the last twenty years (Fueg, 1989). The majority of the Soviet oil and gas production comes from the enormous West Siberian reservoir covering an area of 3.35m sq km, mostly in Tuymen oblast, but extending south-eastward into Tomsk and Novosibirsk oblasts, eastward into Krasnyoarsk krai and northwards into the Kara Sea.

Up to now the development strategy has been oriented towards production needs, therefore raw material (resource extraction) approaches have been predominating (Shlikter, 1990). Problems originating from the Soviet five-year plans which put emphasis on development drilling to increase production, rather than exploration drilling to increase reserves, are dominating (Hannigan, 1988). Increasing anxiety in the public on the impact of raised activity in the region has developed (Vitebsky, 1990).

5.1.2 History of offshore exploration.

The first Arctic offshore drilling was probably made in late 70s from the Sevastopol, a ship converted in the USSR to an ice-resistant fixed platform grounded near the mouth of the Pecora River (Bergesen et al, 1986). Far offshore drilling operations in the Soviet North, beyond very shallow water drillings, were begun in May 1982 by the Finnish-built drill ship Valentin Shashin on the Murmansk High (Bergesen et al, 1986). As the Soviet crew had great difficulties in operating the drilling gear, the well penetrated only the upper part of the section. The riser broke during the operations inflicting damage on the equipment on board, and the ship subsequently had to go to Finland for repair. This was to be typical for the early Soviet efforts for exploration drilling in the Arctic. The sister ship of the Shashin, the Muravlenko, showed similar performance in the early trials. In 1985, exploration activity was stepped up considerably with the addition of, the first of two Arctic equipped, jack up rigs (OGJ, 1985). Simultaneously the Shelf-4 semisubmersible, built in the Soviet Union's Vyborg shipyard in the Gulf of Finland, started operation in the Soviet Arctic. The Soviet Offshore venture has the character of a deliberate and well-calculated effort as regards planning and input of equipment. Such underlying ambitions are, however, not matched by performance in the field, as demonstrated by the dismal drilling record (Bergesen et al., 1987).

5.1.3 Technology (Performance)

a) Drill ships

The Arctic classed drillships, ordered in 1979, are built by the Finish Rauma Reppola construction company. The ships are designed for drilling in the Arctic waters at depth of 300 metres, down to 6000 metres and equipped with dynamic positioning from the Norwegian Kongsberg Vaapenfabrikk. The drillships are considered the world's most advanced for Arctic conditions (NHS, 1985). The ships have been based in Murmansk since 1982 but their operations have been interrupted on several occasions for repair and maintenance in Finland. Serious problems with the dynamical positioning system and with broken risers have been reported (Bergesen et al, 1987)(OGJ, 1986).

b) Semisubmersibles

The Shelf exploration drilling rigs are of modified "Pacetter" type and are designed for operating in Arctic waters at depths not exceeding 200 metres and drilling to a depth of 6000 metres.

c) Jack-up rigs

Jack up rigs have been designed for operating in Arctic waters and are believed to have a maximum operating depth of 100-140 metres, total weight of 15.000 tonnes and a light draught of 5 metres (Soviet Shipping, 1986). They are reported being capable of operating down to -30°C (ANR, 1985a)

The Soviets have also acquired at least two giant catamaran crane vessels for use in installation of fixed structures. They are built according Soviet ice class L2. and can cope with uniform first year ice (ANR, 1985b). The Scottish Development Agency has in a study investigated the equipment needs of the former Soviet Union (OGJ, 1990d) which concluded that the Soviets will need equipment to improve environmental and safety performance, as well as for production in high pressure, high temperature and corrosive environments and equipment to cope with severe weather which is encountered in frontier areas. Much of the equipment designed for the North Sea is relatively low cost and will provide the Soviet Union with a fast payback. This however requires access to hard currency.

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While the U.S.S.R. is eager to buy more Finish products such as machinery, equipment etc, Moscow lack the foreign exchange required to sign additional contracts (OGJ, 1991b). Horizontal drilling, to increase the efficiency of each drill rig, has already been possible for 4-5 years (OGJ, 1987b) and the technology is still developing (OGJ, 1990d). The efficiency of the Soviet turbo drilling system has also increased greatly the last 2-3 years and is at the moment exceeding the western world (Pogarskiy and Yasashin, 1991). However it must be noted that the 80% of wells drilled in the U.S. are rotary drilled which is reckoned as superior over turbodrilling when it comes to metres per day. Another major disadvantage with the turbodrill is that the directional drilling with these is not very good, hence no high precision relief wells can be drilled with such rigs (Meyerhoff, 1985). However the offshore drilling rigs are not equipped with this type drill. Western seismic expertise is already installed in Moscow and will inevitably make its impact upon the Soviet exploration drilling programme (OGJ, 1991i).

A small oil field on Kolguyev Island has been producing oil from August 21st 1987. The produced oil is lifted from a loading buoy 4 km offshore. It has been impossible to find out from the operator, Arktikmorneftegazrazvedka Association, whether the operations including the offshore loading will go on all year or be restricted to the summer months (ANR, 1988a). Excluding this, no hydrocarbon production has yet to take place in ice infested waters in the Soviet Arctic and hence no structures have been deployed (ANR, 1986). There is still need for substantial information about the ice conditions before platforms can be deployed and production initiated. However, the technology will be expected to be similar to structures operating the western Arctic. The existing offshore production structures have been discussed by Royansky (1984) and transportation systems have bend evaluated by Lanan et al. (1984) and it is beyond the scope of this thesis to address this further.

5.2 Geological setting

In the early 1980's the Soviet government defined new search areas in the Barents and Kara Seas. The most significant change from earlier policies was the designation of an additional area of the southwestern Kara Sea as promising for hydrocarbon discovery (OGJ, 1984).

5.2.1 Geology

The main geological features of the Barents-Kara region are defined by two subordinal elements: the Pecora-Barents-Kara plate and the Paikoy-Novaya Zemlya folded area separating it from the southern

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Kara syneclise. Paleo reconstructions make it possible to re-establish the evolution of sedimentary basins since the Cambrian. They suggest that at the early stages of the plate development up to the late Devonian, the Pecora, Barents and North Kara synclies evolved with a common pattern of taphrogenic stage of platform development. At that time there were three basins of sedimentation in the region which were restricted to graben-like depressions related to the Caledonian tectogenesis (Ostistiy et al, 1990). Structural map over Kara Sea is shown in Fig. 18.

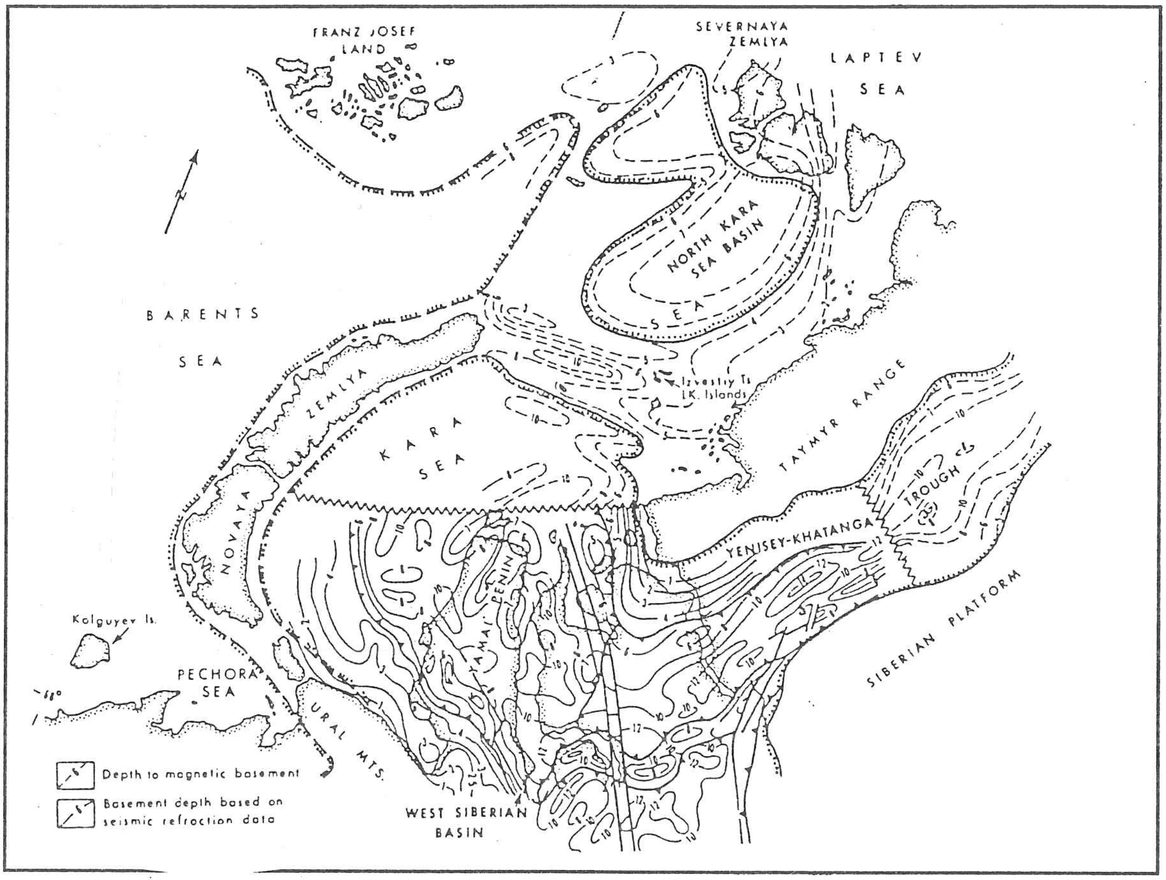


Fig. 18 Structural map over the Kara Sea extension of the West Siberian Basin, with depths to basements from seismic-refraction and subsurface data; northern half is depth to magnetic basement based on a 1972 air-magnetometer survey. Depths are in kilometres. From Meyerhoff (1983).

Favourable conditions for lateral migration of dissolved hydrocarbons are present. However high rates of sedimentation prohibited full realization of oil-generating possibilities in thermal range of 50°C to 150°C, and favoured the continuation of petroleum series hydrocarbon generation at greater depths under the temperature above 150°C (Ostistiy and Cheredeyev, 1990). This could lead to the extraction of great quantities of gas from oil and interstratified waters into a free state, to reformation of oil deposits into oil-gas-condensate and gas-and-oil ones as well as to the extraction of additional volumes of petroleum series hydrocarbons by free gas.

The prospect for oil in the northern West Siberian basin, particularly the Jurassic section, has been controversial among Soviet geologists for 20 years. Rich source rocks of middle and Late Jurassic age are known to exist and non-commercial oil was discovered below the Neocomian reservoirs at Urengoy, both of which are favourable indications of future discoveries. However, long-expected finds have not materialised (Grace and Hart, 1986). To further complicate the work, most oil pools are not controlled by structural uplifts, and seismic surveys are helpless for prospecting (Ulmishek and Harrison, 1986, p1568).

Recent tectonic analysis carried out by Soviet analysts indicate oil and gas potential in the north of the West-Siberian reservoir; mainly gas is found so far in the Barents Sea reservoirs (Khain et al, 1991).

5.2.2 Exploration

The earliest reports of drilling in the Kara Sea was a well drilled close to the western shore-line of the Yamal Peninsula in 1983. The well was drilled from a converted ship/barge to a depth of 2.150m. It was apparently dry (Ulmishek and Harrison, 1986). There are reasons to believe that this has actually taken place although there seems to be some confusion in the western press regarding this (OGJ, 1987c).

Discoveries and geophysical data recently disclosed by Moscow authorities and unofficially by the Soviet petroleum industry personnel, indicate that shallow waters of the Yamal Peninsula's Kara Sea may hold one of the world's biggest concentrations of giant and supergiant offshore gas fields (OGJ, 1990b). There is little doubt that the gas reserves found in the Rusanovoskoye field exceed the total for all developed Soviet offshore areas combined. More recently the Leningradskaya structure has been confirmed (OGJ, 1991h). A discovery well has tested numerous Cretaceous pay zones with gas flows ranging to as much as 14 MMcfd.

At least one structure on the Yamal Peninsula and another on Belvy Island just north of the peninsula, which has not yet been designated as commercial fields, extent into the Kara Sea. It is believed the Russians will continue to find gas fields on the Yamal Peninsula and in the Kara Sea. Confirmed hydrocarbon fields in the Kara sea region is shown in Fig. 19.

1988 reports of a Kara Sea oil field have yet to be confirmed from more than one source (ANR, 1988b). The oil field is located in 40-50 metres of water rather far from the coast and near the shipping lane of the Northern Sea Route traffic. More promising is western scientists' belief of finding oil along the southern flank of the Kara Sea's submerged North Siberian ridge (OGJ, 1990b, p29). The ridge apparently extends east from a point near the Northern end of Novaya Zemlya to the big Taimyr Peninsula on the central Siberian mainland, which separates the Kara and the Laptev seas. Significantly, oil shows have been found on the most northerly Kara Sea structure designated on the new Soviet Arctic exploration map (Ibid.). It is the Byeloostrovskaya structure on Belvyi Islands's north west coast and extending northwards.

Most discoveries in the Kara Sea's southwest arm are expected to be gas or gas/condensate with mainly Cretaceous pay. Their geological profiles are likely to be similar to those found in Yamal Peninsula fields along the Nurminsky megaarch. However deeper Kara Sea drilling may tap some Jurassic oil as in Murminsky megaarch fields. No commercial hydro carbons are likely to be found on the west side of the Kara Sea's southwest arm and probably not in the middle sector beyond the Yamal shelf (Ibid.).

5.2.3 Pipelines

To bring the gas produced at the Yamal gas fields on the market a pipeline is being constructed by the Ministry of Gas Industry (Mingazprom) and the Ministry of Oil and Gas Construction (Minneftegaztroy) (Vitebsky, 1990). The plan is to lay around 10 parallel pipelines running southwards along the peninsula to be built at a rate of one a year. This is a very efficient way of constructing pipelines but also one of the major reasons making them vulnerable to calamitous incidents. The pipeline was scheduled for completion in 1991, however, no gas has so far been flowing by Sept 1991 (OGJ, 1991f). The delays in the pipeline construction is one of the immense problems that the Soviet hydrocarbon industry is facing at the moment. There are reports of 3.000 wells in western Siberia being idle in November 1990 "mainly because they had not been connected to gathering lines which hadn't been laid" (OGJ, 1990a).

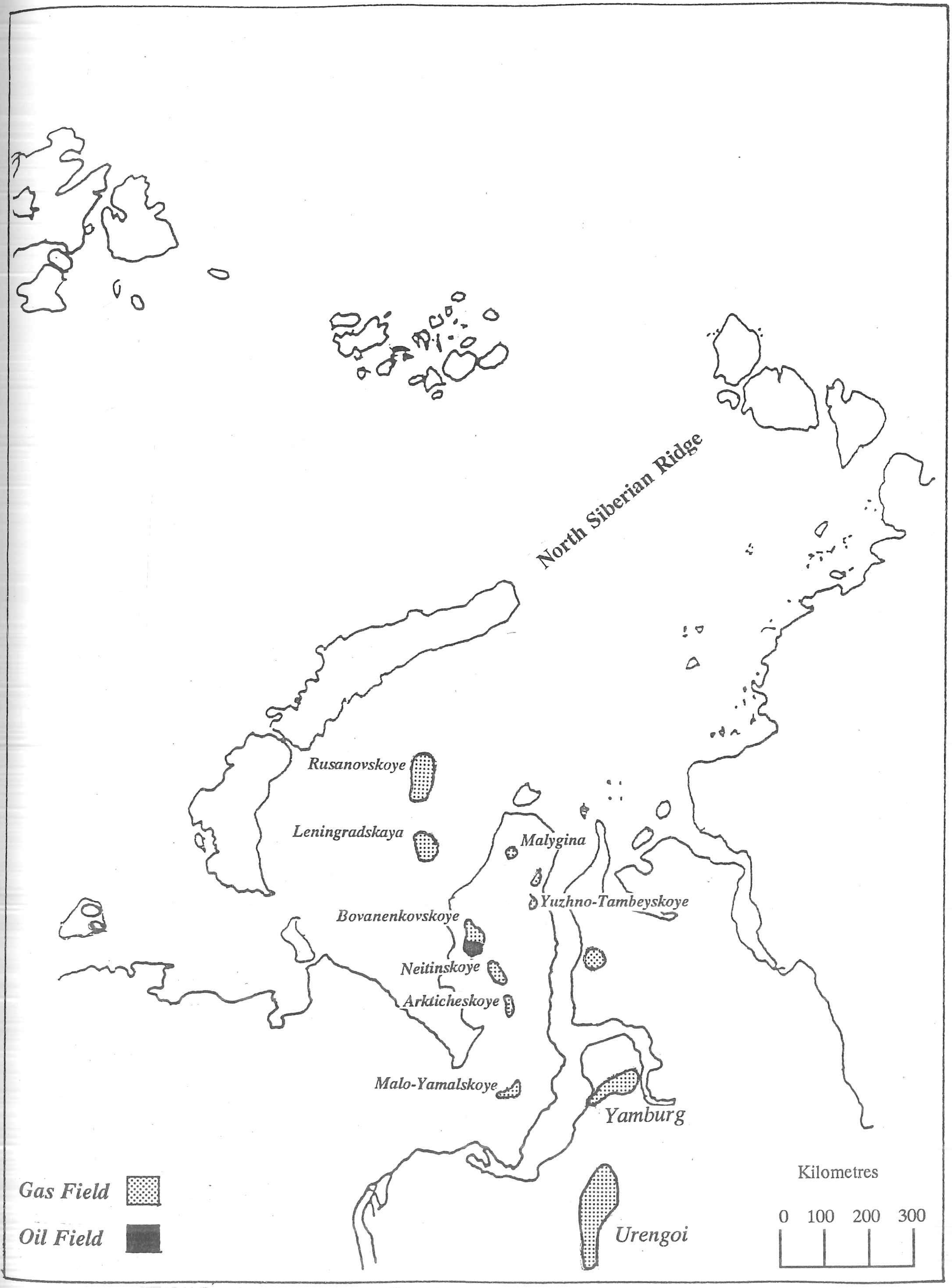


Fig. 19 Hydrocarbon fields in the Kara Sea region

6.0 OIL SPILL SCENARIOS FOR THE KARA SEA

6.1 Introduction

6.1.1 Predicting and preventing disasters

Attempting to predict and respond to potential incidents is essentially a part of futurology (Henchey, 1978). There are a wide range of techniques currently being employed by those involved in futurology. However only a few have satisfied the requirement of scientific thoroughness and credibility to be used in disaster planning. Foster (1980) has summarized the most important techniques as scenario building, simulations, role-play gaming, the Delphi technique and field exercises. In the case of an oil spill, field exercises, computer simulations and scenario building would be the most appropriate. The two first require large inputs of capital, personnel and computer power, however, the latter can be based upon other research in areas with similar environmental conditions and technology then to be superimposed upon the area of interest.

6.1.2 Theory behind scenarios

Although computer simulations can be useful for predicting the nature of potential disasters in the near-term future, they lose much of their validity if they are intended to forecast over a longer time period (Godley, 1984). The building of scenarios consists of considering the consequence of alternative assumptions about the future. Instead of trying to arrive at a single best estimate of the size of a spill or the fate of the oil afterwards, several different possible alternatives can be considered. In many cases as part of offshore oil spill contingency plans the worst-case estimate is significant ANR (1991), Milne and Smiley (1976) and others. In this way a variety of futures can be discussed, actions and strategies necessary to attain them examined, the implied trade-offs debated, and safety policies and objectives with planning designed to satisfy a wide range of other social goals and needs (Sewell and Foster, 1976).

The scenario method attempts to set up a logical sequence of events, in order to ask how, if one starts from a set position, differing futures might evolve. Their value lies in their ability to prove new insights into decisions which will stop, divert or accelerate the evolution of a potential incident. They, therefore serve as tools for assessing all kinds of disaster mitigation policies (Ericksen, 1975). Their disadvantage is that the scenario is greatly influenced by external forces, alterations in the environment, political decisions and technology improvements (Foster, 1980, p150). It neither takes the attitudes and personal reactions of the peoples involved in the incident and the cleanup afterwards into account (McLuhan, 1964). Another disadvantage is that scenarios are too often developed in isolation by a committee which then circulates a report to the individuals and agencies designated to respond. It is common practice for such documents to be read briefly and then to be filed and virtually forgotten (Foster, 1980).

6.2 Building up a scenario

6.2.1 Method

To provide a degree of rigour and repeatability in scenario building, White and Haas (1975) argue that a four-part model should be used.

1) The first components in this heuristic device are the *base conditions*. These consists of a historical review of a hazard in a specific location over a definite time period, and the types of adjustment to it that were in fact rejected or adopted. Such a review provides a base from which to generate alternative pasts. Since it terminates in the present it also provides a launching point from which to generate potential futures. The past and present of the oil and gas exploration in the Kara Sea is discussed in chapter 5.0; Hydrocarbon exploration in the Kara Sea, where the history of the exploration up to the present together with the problems of developing in the Russian North are investigated.

2) The system under review is also affected by *internal forces*. These tend to be of two types. There are those which will have an impact upon the scenario from the inside like governmental policy, contingency plans, insurance and other human factors. All these are liable to change over a short time span. These are to a certain extent discussed in chapter 3.0; Hydrocarbon combat technology and chapter 5.1.1; Oil and gas policy. In addition the system alters because of *external forces* which is beyond the control of the operator such as environmental conditions and natural disasters. These are covered in chapter 4.0; Ice conditions in the Kara Sea.

3) The evolution of the hazard system over time is simulated by *forecasting* how the crucial factors identified in the historical review will be controlled or affected by such external variables. One of the chief objectives in writing a scenario is to illustrate the probable impacts of certain adjustments

or strategies on other components of the hazard system (Foster, 1980). In the case of this scenario which covers potential oil spills in the Kara Sea the forecasting of the behaviour of ice is covered in chapter 2.0; Oil in ice.

4) The previous sections include the present situation and possible incidents. Whereas historical overviews are concerned with the long-term approaches to decision making that emphasize thresholds and alternative decisions, cross-sectional images focus attention on the *immediate* impact of a specific disaster agent. It is at such points that the efficiency of the responsible oil companies and governmental agencies' safety programme will be put to the test (White and Haas, 1975). Such an approach allows the safety plan coordinator and his committee to estimate the likelihood that safety goals will be met if current policies are pursued. It also highlights what changes are required in strategies if this appears improbable. This is the aim of the scenario study and will be discussed in the conclusion of this work.

Several investigators have published general work on the methodology and significance of scenario building. Further reference can be made to the works of Foster (1980), Cole et al. (1978) and Smil (1974).

6.2.2 Previous scenarios for oil spills in Arctic regions

There are a number of scenarios developed regarding offshore oil spills, but almost exclusively in the western hemisphere. Selected studies are listed in Table 4. It must be noted that, to the knowledge of the author after searching the majority of material published in English and Russian in the West and after communication with NOFO (Skogly, 1992) and Statoil (1992), no scenario study has been conducted for a potential oil spill in the Kara Sea. This despite the fact that exploration drilling has been going on in the Kara Sea for 10 years, as discussed in chapter 5.1.2; History of offshore exploration.

Table 4 Previous oil spill scenarios in Arctic regions

Location	*Type of scenario (Investigators Ref.)*	**Year**
Beaufort Sea Amauligak Field	Revised Beaufort spill scenario; 10.000 bbl/d (1.600 m^3/d) (ANR, 1991)	1991
Chukchi Sea	Environmental Impact Assessment; Probabilistic approach [Quantitative] (US Dep. of Interior)	1991
Beaufort Sea	Environmental Impact Assessment; Probabilistic approach [Quantitative] (US Dep. of Interior)	1990
North Slope offshore Beaufort Sea	Subsea Pipeline leak; 1000 bbl/day (160 m^3/d)[Qualitative] (Shultze, 1985)	1985
Barrow Arch Offshore East Alaska	Subsea Pipeline leak 5.000 bbl (790 m^3), Subsea pipeline leak 500 bbl/d (80m^3/d) for 100 days, Blowout 1.000 bbl/d (159m^3/d) for 75 days. (Lewbel and Gallaway, 1984)	1984
Dundas drill site Lancaster Sound	Exploration blowout [Qualitative] (Arctic Sciences Ltd and Marko, 1983)	1983
Barrow Arch Offshore Alaska	3 hypothetical oil spill scenarios Part of an EIA [Qualitative] (Lewbel and Gallaway, 1983)	1983
Lancaster Sound Northern Canada	Tanker collision, Described the oil for 21 days after spill [Probabilistic, Qualitative] (Dome Petroleum Ltd, 1981)	1981
Labrador Sea,Lancaster Snd Offshore Eastern and Northern Canada	2 hypothetical Blowout exploratory wells, Labr; 200m, 490.000m^3 and Lancr; 950m^3/d oil released. [Qualitative] (Ross, S.L., 1980)	1980
Prudhoe Bay Beaufort sea	12 scenarios range of ice zones, artificial island etc. [Quantitative] (Thomas and Wash, 1980)	1980
Labrador Sea Offshore Eastern Canada	1 very detailed scenario; 15.000 bbl/d (2.400 m^3/d), 200m Gas to oil ratio 1:150 [Qualitative] (LeDrew and Gustajyis, 1979)	1979
Beaufort Sea, Chukci Sea Navarin Basin, Norton Sound, Bristol Bay, Umiak Pass, All outside Alaska	Pipeline 15.000 bbl (2.400 m^3) under ice, 2 Oil wells 50.000 bbl/d (8000 m^3/d) and 5.000 bbl/day; 45 days, 2 tankers 50.000 bbl (8000 m^3)in ice, supply barge 10.000 bbl/d (1600 m^3) open water, [Qualitative] (Marsh and DeBord)	1979

6.3 Blowouts

6.3.1 General

During drilling formation fluids are kept under control by regulating the density of the drilling mud. The hydrostatic pressure of the mud is supposed to equate the pressure in the well and prevent any formation fluids to penetrate into the hole. Once the well penetrates a hydrocarbon reservoir, where the formation pressure is usually higher than in the formation above, a kick is achieved. This is what the exploration team are drilling, and are prepared, for. However if undetected formations are present in shallower depths or the pressure in the targeted reservoir is higher than anticipated, a critical situation may occur. If the contingency equipment is not present or is not functioning satisfactorily, a blowout is born. Offshore, gas blowouts are by far the most common (OGJ, 1989d) however, there have been at least one offshore oil blowout in the Arctic on the Steelhead platform in Cook Inlet in 1987 (OGJ, 1988). This was, however, relatively small. Of the more serious oil blowouts we can refer to the Ixtoc-1 blowout in the Gulf of Mexico and the Bravo Blowout in the Norwegian sector of the North Sea. Recent scenario studies, conducted by Statoil for development drilling in the Barents Sea, estimate the absolute maximum blowout rate to be 20.000 m^3/day, however a more likely estimate would be 5.000-12.000 m^3/ day (Statoil ,1992a).

6.3.2 Potential blowouts in the Kara Sea

In the Kara Sea it is only likely that exploration drilling, in the early phase, will take place with jack-up and drillships. Jack-up platforms are the only capable of drilling in near-pack ice conditions, however these are limited to depths below 100m. For drilling at relatively shallow depths these are most likely to be used. They are also much less technologically sophisticated and more economical than drillships. Ice strengthened drill ships escorted by ice breakers have the flexibility of operating at greater depths, higher transfer speed and ability to disconnect, and move, rapidly without lengthy anchor or jacking operations. In the Northern Kara Sea drillships are the only feasible option in the foreseeable future. Semisubmersibles are not likely to operate in the near future in the Kara Sea and the hybrid platform which made the first offshore drilling in 1983; see chapter 5.1.2, carries outdated technology.

Jack-ups are relatively less prone to blowouts due to their on-bottom stability; DP and riser failure are non existent, however, they are very sensitive to seabed stability. The mechanical properties of saline permafrost have received little attention to date, however some studies have been carried out in Alaska by Chamberlain et al. (1978) and Sellman and Chamberlain (1979). This has been identified as one of the problems of using gravity based structures in permafrost areas (Vivatrat and Watt, 1983; Watt, 1984). Although subsea permafrost is not believed to occur in the Kara Sea (Are, 1983) the seabed conditions are not very well known. Still 17% of all jack-up accidents, from 1955 to 1990, were caused by the sea bed (OGJ, 1991d). Amongst these the Arctic part is insignificant (ie <.5%). This accident frequency will be significantly higher in Arctic waters. Compared to other accidents, sea bed failure often has very serious outcomes (WOAD, 1990).

Drillships are unaffected by the properties of the sea bed, however they rely on their advanced Dynamic Positioning (DP) system. Knowing the track record of the Soviet operators in the past; as discussed in chapter 5.1.3; Soviet technology and performance, this would not be an unlikely cause of an incident. However, considering that the Russians now have the most advanced drillships for Arctic waters one must not underestimate their ability to operate them under extreme environmental conditions. An example of a serious drillship incident could be; The Viking Explorer drilled a gas kick on Sep. 7 1988, outside East Borneo, a Blowout Preventer was not installed and the well ran out of control, and the drillship sank in the gas plume due to loss of buoyancy in the gas foam (OGJ, 1991d). This might be a worst case blowout for a drill ship, however fully realistic.

Gas hydrates, which only occur in permafrost areas, can present a potential hazard to offshore exploration in the Kara Sea. However, these are mainly gas and will not be considered in this study (Watt, 1984). Despite the much stricter safety rules which apply, the offshore blowout rate is undeniably higher than onshore (Stewart, 1987). In general DEn/ Technica data gives the probability of blowout a value of $P(BO) = 9.2*10^{-3}$ vessel/year world wide (Henriksen, 1992) ie once every 108 years. However for the North Sea, which has comparable environmental conditions (excluding ice), has a probability of blowout of $P(BO) = 1.82*10^{-2}$ vessel/year or one every 55 years per vessel. If there is a blowout the general probability that it is oil is $P(BO_{oil}) = 0.113$ (Cremer & Warner, 1991).

6.4 Scenarios

6.4.1 Introduction

Due to the nature of this exercise a qualitative rather than quantitative scenario study will be undertaken. Two scenarios have been developed, one for a drill ship the other for a jack-up platform. This to highlight the limitations and the possible incidents of the two vessels. The first scenario, which is also the most likely in the near future, is an appraisal well drilled by a jack-up in 54m of water on the Rusanovskoye gas field to production test a thin oilzone underneath the giant gas field. The second scenario is an exploration well drilled by a drillship in 140m of water, in the oil promising North Siberian Ridge, in the northern part of the Kara Sea.

6.4.2 Scenario 1

The Kol'skaya Arctic jack-up drilling rig is sent to production test a 0.5-1.0m oil bearing zone on the Rusanovskoye gas field in the centre of the Kara Sea. The field was discovered in 1989 and lies 70 miles west of the tip of the Yamal Peninsula. The aim of the exercise is to investigate whether this oilzone is worth producing before the gas, since when the gas production starts, the oil is unrecoverable. The well is chosen to be drilled on a 54 m deep bank located at 64°10'E and 73°30'N. The site is picked on grounds of promising structure (OGJ, 1990b) and on the basis of Russian Admiralty chart No. 969 (RAC, 1988). This is close to the centre of the gas field. The Arctic jack up, capable of drilling in light ice conditions, is towed by a supply boat and a Yermak class ice breaker. It is to approach the given position, with the aid of the icebreaker, and start drilling as soon as the ice conditions will allow it. Location of the spill is shown in Fig. 20.

The drilling starts on the 15th of July in typical ice conditions. There is a 100% chance of ice occurring and the mean ice concentration is 50-80%, verging towards 50%. The structure which lies between 1895m-2321m (OGJ, 1991h) is reached after a typical drilling time of 45 days (Pogarskiy and Yasashin, 1991) including a 5 day stop due to unfavourable ice conditions and 15 days extra for difficulties with the cementing the well (Wilson, 1987). The formation was reached on the 29th of August and production testing was to take place. After 2 hrs of production testing, producing $1600m^3$/day, the rig capsizes due to instability, induced by vibration and shift of centre of gravity on the rig, in the weakened seabed. The crew is saved. The rig is lost, however, leaving the wellhead cascading oil at the seabed.

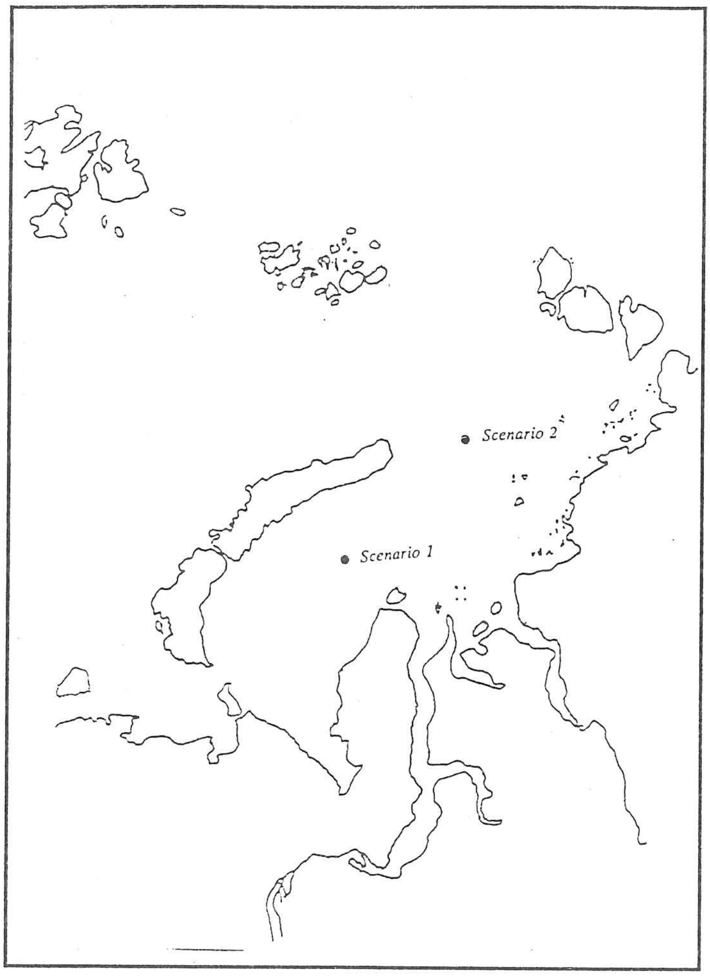


Fig. 20 Location of scenarios

It is immediately decided to divert one of the drillships operating in the Barents Sea. It is to shut down operations to drill a relief well at the scene. The drill ship spends 2 days shutting down its operations, 6 days on its 2000 km transit and 2 days to set up the relief wellhead. It then proceeds to drill a relief well through 50 days. It proceeds to pump mud into the wild well and it is under control and shut down in 5 days, on the 7th of November. The wild well has then been flowing with a flowrate of 1600 m^3/d for 67 days releasing a total of 107.000 m^3 of crude oil. On October the 15th the sea starts to freeze up, with a 20-50% ice concentration, and more icebreakers are needed to support the drill ship. Support by the nuclear ice breaker Rossyia is provided and operations can go on. The well is completed on the 7th November just before the ice conditions are too severe for the drillship to operate. The sequence of events together with the ice conditions is illustrated in Table 5.

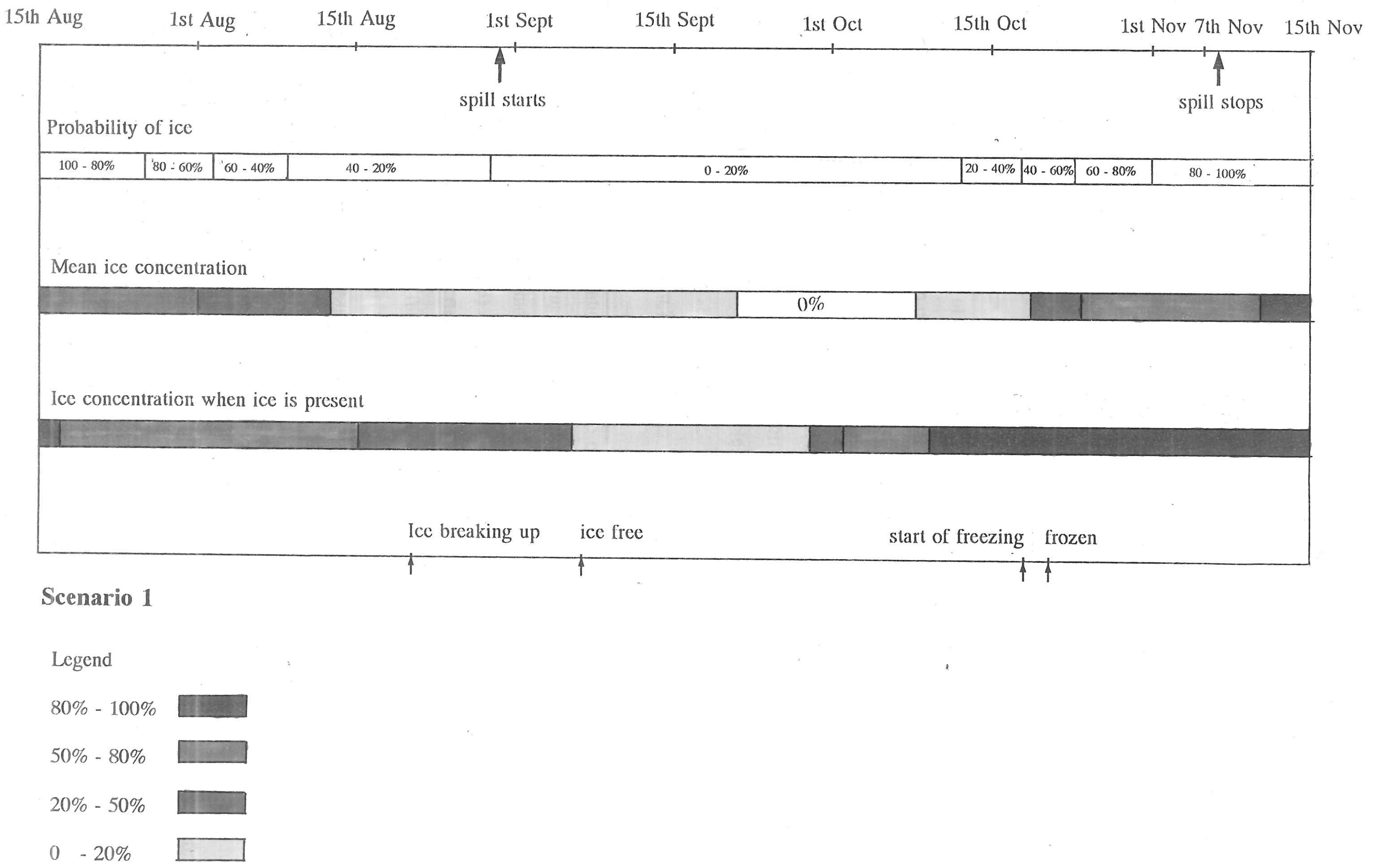


Table 5 Sequence of events and ice conditions for scenario 1

On the 15th of September the last ice is melted, however the efforts of using booms are hampered for another three days because of fog. The low visibility caused by the fog continues to inhibit the cleanup work throughout the operation at regular intervals. The wind and wave conditions, however, are moderate and winds in the region 6-10 m/s are from the West and North West are expected 45% of the time throughout the autumn.

The oil will follow the pack ice motion until the ice thaws completely out. Oil in the pack ice is burned in the leads with reasonable success. No containment booms can be used while there is still ice around. When the ice melts containment booms are used. 3-5% of the spill is mechanically recovered. After ice has broken up no oil is burnt. Some dispersants are used, which are not very effective, due to the composition of the oil which was not compatible with the available dispersant. Freeze up starts on the 23rd of October and no burning, containment, mechanical recovery or dispersing is possible from then on.

Table 6 indicated that 50-60% of the oil released throughout the spill will surface again the next summer. This oil will be in different states from thick tar balls to fresh crude. After the second summer no oil is left on the surface. The majority of the oil is evaporated, biodegraded or sunk as tar balls. However, under extremely unfavourable weather conditions, some of the oil might reach the coast of Novaya Zemlya in the second summer.

6.4.3 Scenario 2.

It is decided to drill an exploration well in the oil promising North Siberian ridge (Clarke, 1990). Seismics have shown a promising giant oil field North east of the tip of Novaya Zemlya. The well is planned to be drilled at 140 meters of water at a position 78°20"E and 77°10" North, location and depth is taken from USSR (1933) Arctic Institute map. This is the northernmost offshore drilling ever undertaken, but the prospects of finding a supergiant field justifies the risks taken. This area, although not so ice infested as the areas further south, because of the Gulf Stream rounding Novaya Zemlya, experiences strong ice conditions in the winter and summer. Some years it does not get ice free at all during the summer period. Minimum ice conditions do not usually occur before mid September. The drillship Valentin Shashin, accompanied by a supply boat and two ice breakers, is to begin exploration drilling in the structure immediately after the ice conditions at the site have cleared. On the morning of August 1 the preparations start and drilling commences from the 5th. A 50-80% ice concentration of old first-year and multi-year ice is experienced however this disappears within a few days.

Table 6 Mass balance for Scenario 1

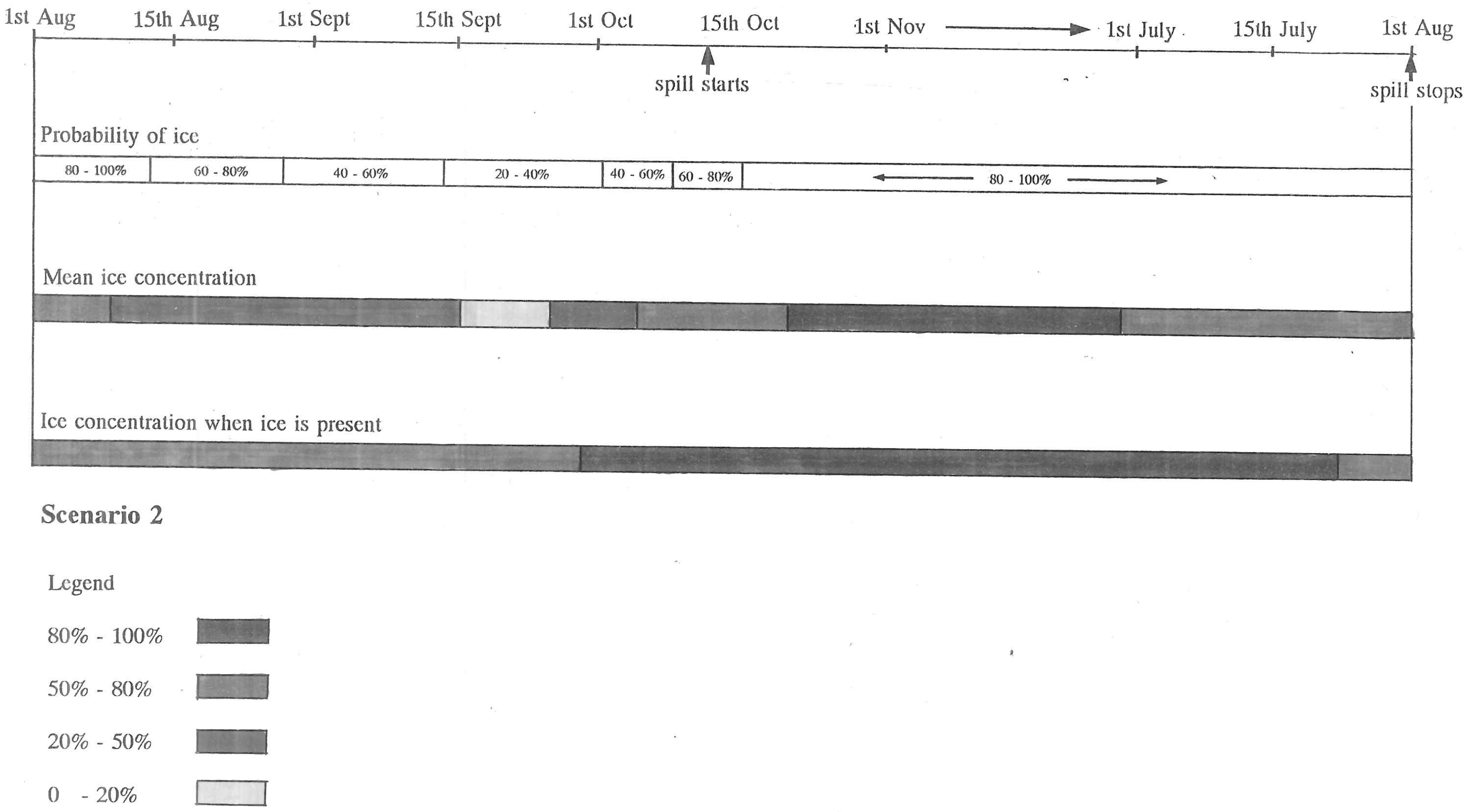
Oil Budget 1600 m^3/day. From 29th August to 7th November. All numbers related to the 7th of November when the well is closed.

Date:	29th August -5th Sept	6th Sept. -19th Sept.	20th Sept. -3rd Oct	4th Oct. -20th Oct	20th Oct. -7th Nov.	Total oil Released:	Persentage:	
oil rel. (m^3)	11.200	22.930	22.930	22.930	27.200	107.200	100%	
Ice cond.:	Ice breaking up	Open water 0-20% ice cover	Open water 0-20% ice cover	Open water 0-20% ice cover freezing up	Completely frozen up			
Evaporated:	25%	25%	23%	20%	0%			
Dispersed:	30%	26%	20%	15%	10%			
Biodeg:	12%	8%	3%	1%	0%			
Recovered and sunk:	5%	5%	5%	5%	0%			
Still floating or encapsuled.	28%	35%	49%	59%	90%			
Oil still left on surface	3.136	8.026	11.236	13.529	24.480			
Cummul. oil on surface	3.136	11.162	22.398	35.927	60.407	60.407	56%	

Evaporation, dispersion and oil left on surface calculations based on Mackay (1985).

The drilling proceeds normally for 60 days after initial problems with the dynamic positioning system, and a depth of 1.400 m is reached on the 5th of October, where a high pressure oil trap is penetrated. The well is not brought under control and drillship have to abort drilling and retreat from the site because of fire risk to the vessel. The well is discharging 8.000 m^3/d at the sea bed location. Attempts to control the well must be aborted on November 7th because the two ice breakers are not capable of establishing operating conditions for the drillship. The well is left flowing at the site throughout the winter. After 2 months the flow decreases to 3.000 m^3/d. The next summer a relief well is drilled and the well is under control on 14th of September the following year, having being active for 344 days. A total amount of 1.332.000 m^3 of crude oil is spilled. The sequence of events for scenario 2 together with the sea ice conditions are shown in Table 7.

Table 7 Sequence of events and ice conditions for scenario 2



Some of the oil will reach the surface in a partly emulsified form. The ratio of oil/emulsion/dispersed-oil is estimated as 75/5/20. The unemulsified crude will not interact with the ice but rise to the water surface rather than being trapped throughout the brash ice as solid particles. The oil spreading is very limited. On the way from the sea bed 20% of the oil is dispersed into the water column (interpolated from LeDrew and Gustajtis, 1979, p 25 and Johansen, 1992).

Once the oil reaches the under side of the ice it enters the primary phase and the equilibrium thickness of the oil in brash ice is estimated to be minimum 25.000 m^3/km^2. Once the ice cover is constant the oil will spread underneath the ice according to Fay's spreading laws. However, as soon as the dynamic pack starts to form ridges these will be the major factor governing the oil spreading. Estimated storage volume of ridged first year ice ranges from 25.000-66.000 m^3/km^2. Comparing these values to the estimated average (the absolute ice movement will be in the order of twice this) ice movement of 3-6km day pooling the oil will forms pools under the ice, governed by the shape and size of the pressure ridges. This will be the prevailing condition throughout the spill. In November the oil enters the secondary phase and will be frozen in fairly close to the surface of the growing ice sheet. The oil released further out into the winter will be frozen further down into the ice. This might lead to the result that oil frozen in early will surface somewhat earlier than oil frozen in later in the winter. This effect could however be cancelled by the fact that oil frozen in November will have travelled further north than the oil frozen up in April.

The oil will enter the tertiary phase in the spring the following year, having being transported by the ice either to the north or into the Kara Sea. The emulsified oil has not separated into its original contents which will inhibit evaporation, dispersion and recovery. The presence of gas will not influence the final appearance of the oil. A significant proportion of the oil which stays more that one summer in the ice is likely to surface in the first summer, then to be weathered on the surface, possibly melting itself down to the sea, then to be frozen in a second time. The oil which has undergone this process will have lost its higher fractions and is thicker than fresh crude.

Once the oil is in the ice it can take a number of trajectories. In early winter the most likely path for the ice is either directly north into the Arctic pack, where it is likely to be frozen-in for more than one season, later to appear either in the Greenland sea or in the strait between Franz Josef Land and Svalbard, as weathered crude. Later in the season prevailing westerly ice drift will tend to bring the oil infested ice in the North East Barents Sea, where it will be released as fresh crude. Unless oil infested ice is melted down on the east coast of Frzanz-Josef Land in the forthcoming spring, little oil will reach the shores. In early spring some oil might enter the Kara Sea again and will be contained within the ice massif and be released when this breaks up and melts. The oil might then reach the shore of Northern Novaya Zemlya. The oil which enters the Kara Sea will have a similar fate to the oil in scenario 1. The oil surfacing in the spring might be ignited within a few days after it has surfaced on the ice or been broken out of the ice sheet. Any logistical operation to carry this out is considered unfeasible due to the enormous distances from the nearest supply base or airport. Mechanical recovery is also unfeasible due to lack of equipment and severe environmental conditions. Dispersants might be used in the critical, marginal ice zone, in the spring. The feasibility of sending C-130s from Banak in Finnmark to the Barents Sea have been shown earlier. The Russian Republic has airplanes which would probably be even more efficient for this purpose like the Antonov 26, although it is not as large as the C-130 but it is just as versatile. Having an ice breaking supply ship with aerial recognisance in the area of expected release could be just as effective. Likely trajectories is shown in Fig. 21.

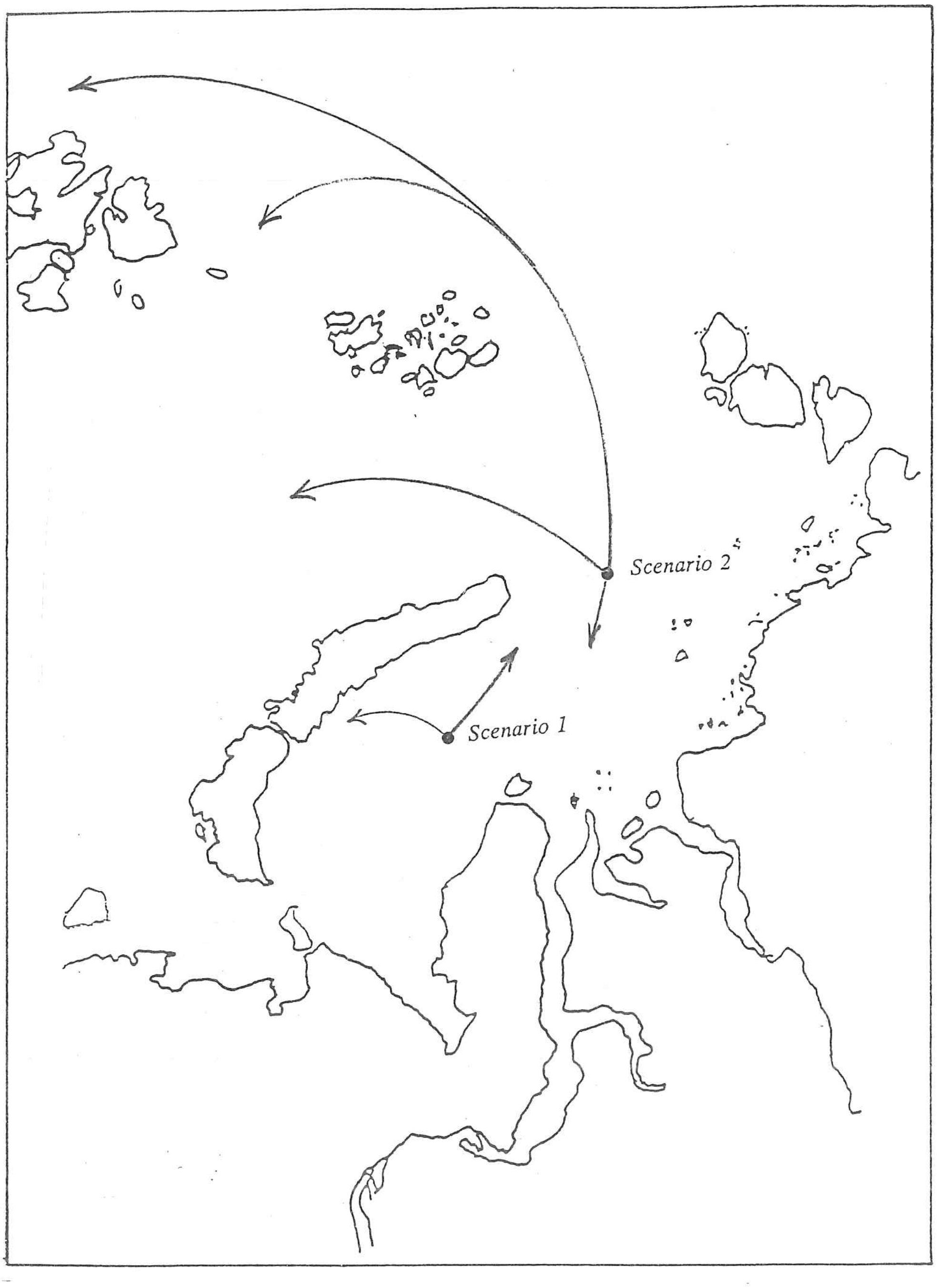


Fig. 21 Possible trajectories of the spilled oil.

7.0 CONCLUSIONS

The fate of oil spilled in ice infested waters is different from oil spilled on open water. In light ice conditions the oil will spread like on open water. When the ice closes up this will tend to inhibit spreading of the oil on the surface. Of oil spilled in a growing ice field significant proportions will be pumped up onto the ice. Under a continuous ice field oil will spread under and pool, governed by the under ice morphology. Once the oil has stopped spreading it will be frozen into the ice sheet within 24-48 hours. It will be contained without altering its properties, until the following summer. In spring the oil will rise to the surface of the ice and evaporate the lighter fractions. The oil will warm up, due to its lower albedo, and, in time, eventually melt itself down to the sea. Oil floating on the sea will disperse, emulsify and eventually biodegrade.

Tracking and modelling of a spill is possible with the aid of buoys and trajectory models. Remote sensing, apart from visual observation, is not feasible. Mechanical containment and recovery of a major oil spill in an ice field is virtually impossible. Oil from a tanker might be burned within the ice field shortly after the spill. Oil from subsea blowouts will generally not burn due to the high rate of dispersion and emulsification on its way up from the seabed. Use of dispersants can be effective in ice if they are applied shortly after the spill. Other chemical additives have also been discussed but few full-size trials have been done.

Offshore production in ice covered waters are already taking place off Alaska's North Slope. There is little doubt that the onshore production on the Yamal Peninsula will expand offshore. Exploration drilling has already taken place and giant gas fields have already been confirmed. Oil fields have yet to be confirmed although seismic investigations indicates oil in the promising North Kara basin. Offshore gas production will follow the development of infrastructure onshore and will probably not take place for another 20 years. A major oil field could speed up this development with 5-10 years. Independent of the progress, the environmental consequences of such a development should be addressed well in advance, to minimize the impact by incorporating measures to increase safety and highlight potential problems at the design stage.

The two scenarios developed in this report have highlighted potential accidents and their impact and the areas of research needed to be addressed before a development can take place. The extent and probability of ice occurring in the Kara Sea are fairly well documented. Little is known about the two most important parameters in predicting the fate of the oil; the drift and under-ice morphology of the ice. The processes which the oil from a subsea blowout experiences on its way to the surface are not known. How an oil and gas mixture is released under an ice field behaves can only be vague estimates. There is little to be done about an oil spill or blowout in the Kara Sea and the efforts will be limited to some use of dispersants. The literature search forming a basis of this work demonstrated the lack of scenario studies for the Kara Sea.

Scenario 1 indicated that approx. 50% of the oil spilled would be frozen-in the following winter for, be released in the spring. The Arctic jack-up is also dependent upon the availability of another arctic jack-up or a more ice-condition-dependent drillship to drill a relief in case of a blowout. It also addressed the fact that oil will not be weathered in the short ice free summer such that it will be melted out in the following summer. This despite that the well stopped flowing the previous summer.

Scenario 2 demonstrated the sensitivity of the drillship to the ice conditions encountered in the Northern Kara Sea. Oil spilled by a subsea blowout at this location might be encapsulated into the sea ice, allowing it to drift up into the polar pack and towards the Barents Sea or Franz-Josef Land or Svalbard. This makes any decision of exploration drilling in the northern Kara Sea clearly subject to investigation from Norwegian authorities, as they are likely to be the most affected party in such an incident. It also demonstrates that, due to the presence of ice, oil spilled in one part of the Arctic can introduce severe problems far from the origin of the spill.

This scenario study of possible oil spills in the Kara Sea has revealed a number of technological, scientific and geopolitical short-comings which will have to be addressed before any exploration drilling should take place. The fact that there has been exploration drilling in the Kara Sea for over 5 years stresses the need for more attention to the development in this area. The increased attention of the environmental impact of the Northern Sea Route the last two years should not overshadow the, much more likely and more serious, possibility of an oil blowout in the waters north of Russia.

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