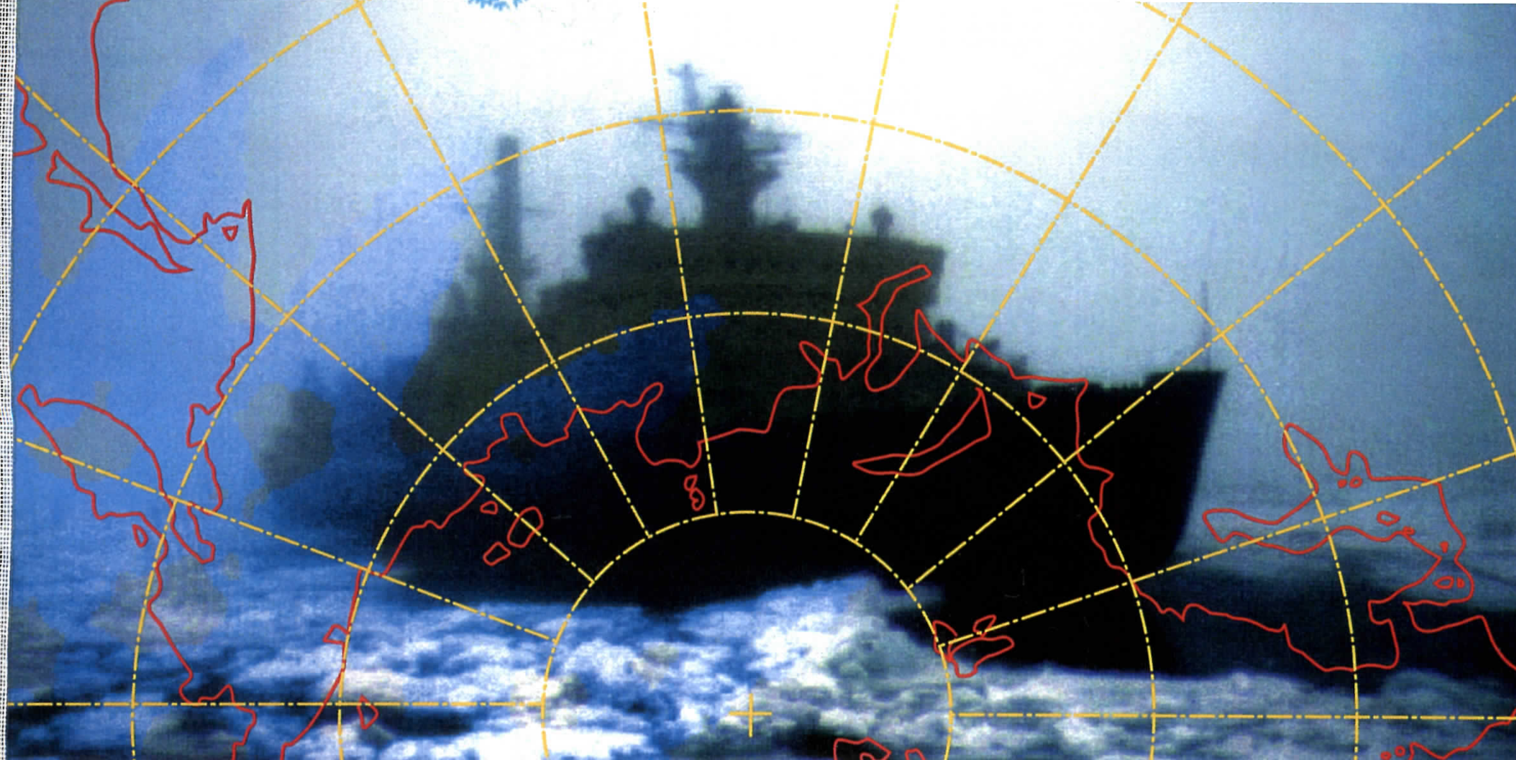
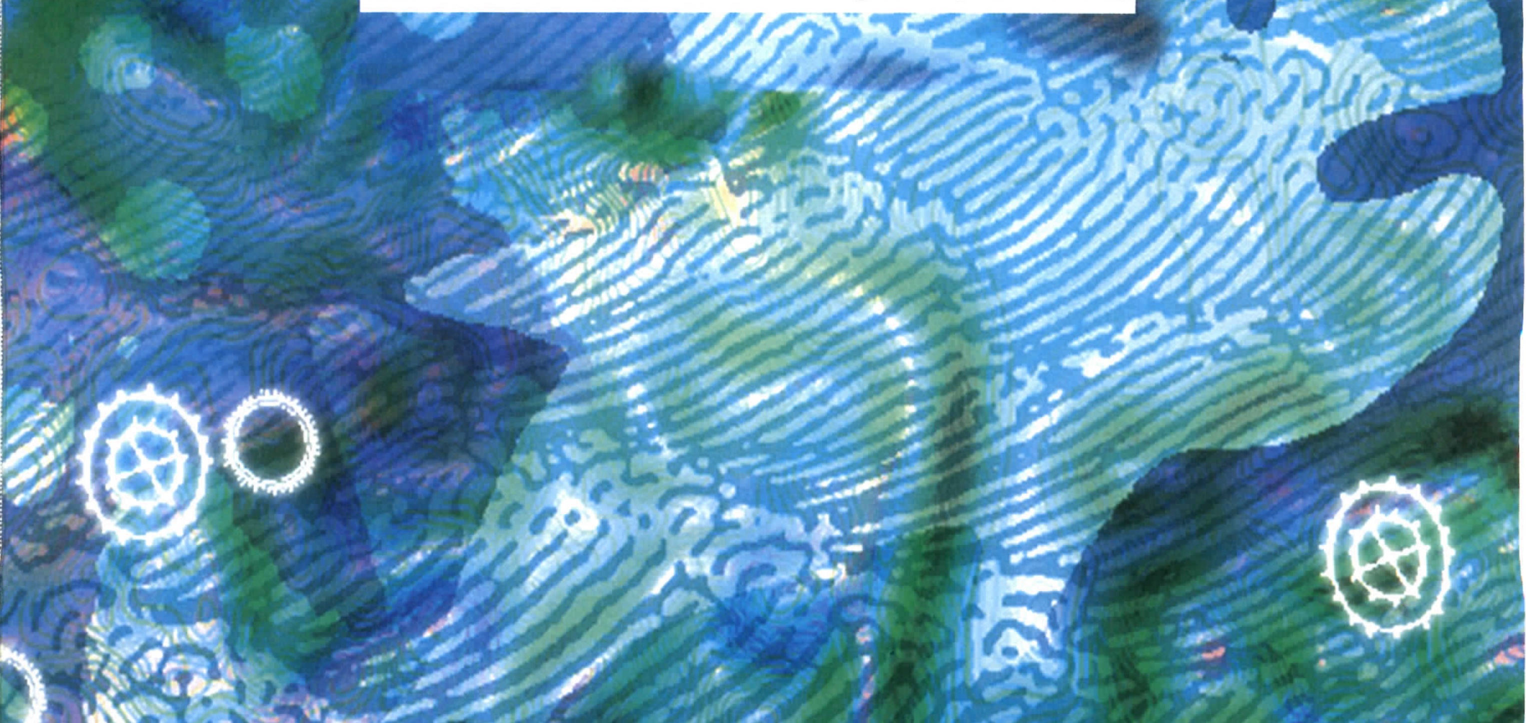


INSROP WORKING PAPER
NO. 5 - 1994, I.5.1

Content of Database, Planning and Risk Assessment

Sveinung Løset and Sylvi Vefsnmo



INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship & Ocean Foundation, Japan

INSROP - WORKING PAPER NO. 5-1994

Sub-programme I: Natural Conditions and Ice Navigation

Project I.5.1: Content of Database, Planning and Risk Assessment.

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FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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REPORT

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INSROP Natural Conditions and Ice Navigation

Project I.5.1: Content of database, planning and risk assessment

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ABSTRACT

The purpose of Project I.5.1 "Content of database, planning and risk assessment" is to specify the requirements to the database, and to identify and evaluate the data sources. A feasibility study of local oil and ice drift models should also be performed.

The GIS system shall have a structure and content that is beneficial not only for the INSROP projects but also for the planning and actual sailing of the NSR. The most important entities related to physical environment and navigability in ice are described in detail. The major ice cover parameters for ice navigation are ice coverage, ice age, ridge frequency and size, ice floe sizes and snow cover on the ice. Knowledge of the thickness and properties of the snow cover is essential for evaluating the progress of ships in ice.

An overview of the mechanisms of drift and spread of oil under different surface conditions is given and various statistical and operational concepts for oil and ice drift are discussed. In order to quantify the assessment of possible conflict between oil and vulnerable resources, oil drift data are needed to give a measure of the potential impacted area. An operational oil spill model should produce forecast of the fate and behaviour of the oil spill. Sea ice processes and parameters significantly affect the fate and behaviour of spilled oil. In order to account for these effects, a two-level concept for the ice drift model is recommended and involves a mesoscale ice drift model and a local ice drift model around the oil spill.

Oil spill combat is also briefly discussed in relation to risk assessment. The report gives an overview of the commonly available oil spill response systems with emphasis on cold waters. In principle the oil spill combat systems at sea can be divided into mechanical containment and recovery, chemical dispersants and in-situ burning.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Environment	Miljø
GROUP 2	Arctic	Arktis
SELECTED BY AUTHOR(S)	Northern Sea Route	Nordøstpassasjen
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	Oil spill in ice	Oljesøl i is

PREFACE

The main purpose of INSROP Sub-programme I "Natural Conditions and Ice Navigation" is to provide the essential supporting information on climatic variability and ice navigability which is needed for the assessment of the feasibility of opening the NSR to international shipping with an extended navigation season.

The purpose of Project I.5.1 is to specify the requirements (content, format, access etc.) to the natural conditions database, to specify and evaluate the data sources to the database, and to populate the database. In this context data sources include observations, model results and data assimilation (mixtures of observations and model results).

The 1993 activity of Project I.5.1 concentrated on specification of requirements to the database including important parameters to navigation in ice, relevant parameters for efficient icebreaker assistance, data sources and numerical models. Oil spill combat is also briefly discussed in relation to risk assessment.

Striving for an integration with the Russian projects of Sub-programme I, we arranged a workshop in Trondheim 8 - 12 November 1993. During these days we focused on which data the GIS should contain and what information products the system should deliver. Five project leaders from Sub-programme I attended the workshop with Dr. Tsoy (CNIIMF) and Dr. Brovin (AARI) representing Russia. After three days of discussion we obtained a mutual understanding of what data should have priority and what the format should be. The outcome of the workshop was also submitted to Project I.3.1.

We would like to thank all the attendees of the workshop including Mr. Anders Backlund (Kværner Masa-Yards) for their contribution during the workshop. Further, we would like to thank Dr. Sergei Ovsienko, State Oceanographic Institute (Moscow) for valuable cooperation related to specification of the operational oil drift model.

The report is divided into 3 parts:

- Part I: Physical Environmental Database - Major Entities
- Part II: Model Concepts for Drift and Spread of Oil and Ice
- Part III: Oil Spill Combat

which in total should reflect the purpose of the 1993 activity of Project I.5.1.

Trondheim, 8 September 1994

Sveinung Løset
Project Manager

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SUMMARY

The main purpose of INSROP Sub-programme I "Natural Conditions and Ice Navigation" is to provide the essential supporting information on climatic variability and ice navigability which is needed for the assessment of the feasibility of opening the NSR to international shipping with an extended navigation season.

The purpose of Project I.5.1 "Content of database, planning and risk assessment" was to specify the requirements to the database, and to identify and evaluate the data sources. A feasibility study of local oil and ice drift models was also a part of the project. This report presents the outcome of Project I.5.1 and is divided into three parts.

Part I of the report states the requirements to the physical environment database. The GIS system shall have a structure and content that is beneficial not only for the INSROP projects but also for the planning and actual sailing of the NSR. In relation to natural conditions and ice navigation, the GIS system should serve as a tool to provide information within the following categories:

- Base cartographic data
- Infrastructure information
- Planning of sailing (operational aspects)
- Risk assessment (technical, personal)
- Environmental impact assessment

In order to fulfil the requirements to the GIS system, the most important entities related to physical environment and navigability in ice are described in detail. The entities are divided into six groups that should be part of the database:

- Geodata
- Ocean and river dynamics
- Ice and snow cover
- Meteorology
- Icing on ships
- Historical voyage data

The major ice cover parameters for ice navigation are ice coverage, ice age, ridge frequency and size, ice floe sizes and snow cover on the ice. Knowledge of the thickness and properties of the snow cover is essential for evaluating the progress of ships in ice.

Part II of the report gives an overview of the mechanisms of drift and spread of oil under different surface conditions (open water, broken ice, level ice) and discusses various statis-

tical and operational concepts for oil and ice drift. Pollution is the most serious environmental threat related to traffic of the NSR. In order to quantify the assessment of possible conflict between oil and vulnerable resources, oil drift data are needed to give a measure of the potential impacted area. The report concludes that existing statistical oil drift models should be modified in order to provide oil drift data for environmental impact assessments along the Northern Sea Route.

An operational oil spill model should produce forecast of the fate and behaviour of the oil spill. If the oil spill model is to be used for decision making related to oil spill combat and protection of sensitive resources, the model must provide details on spreading, weathering and partitioning of oil in different ice types. Sea ice processes and parameters significantly affect the fate and behaviour of spilled oil. In order to account for these effects, detailed information of the ice conditions is required, including areal fraction of different ice types, floe size distribution, ice thickness and velocity. To provide the operational oil drift model with necessary details of ice information, the report recommends a two-level concept for the ice drift model. This concept involves a mesoscale ice drift model (spatial resolution about 20 km) and a local ice drift model around the oil spill. The mesoscale model will produce general forecast for the ice conditions. The local ice drift model will only operate during special conditions, for instance an oil spill situation. Since the weathering processes of the oil depend strongly on the wave conditions, efforts should be made to include wave attenuation in the ice drift model.

Part III of the report gives an overview of the commonly available oil spill response systems with emphasis on cold waters. In principle the oil spill combat systems at sea can be divided into mechanical containment and recovery, chemical dispersants and in-situ burning. This part of the report also highlights the applicability and efficiency of these combat systems under various conditions (weathering state of the oil, sea state and wind). The major conclusions are as follows:

- No one response system can handle the variety of conditions normally encountered in oil spills in open waters
- Mechanical oil spill response is still the only true cleanup technique - the other modes serve to accelerate natural processes
- Dispersant application and burning techniques provide important backup capabilities
- In-situ burning may have an increased efficiency in broken ice compared to an open water spill e.g. due to reduced spreading of the oil (thicker oil film, etc.) and calmer sea state.

Further, the efficiency of clean-up operations will depend highly on access to combat equipment.

ABBREVIATIONS

INSROP -	International Northern Sea Route Programme
JRC -	Joint Research Committee
NSR -	Northern Sea Route
NP -	Norwegian Polar Research Institute
SINTEF -	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
SINTEF NHL -	SINTEF Norwegian Hydrotechnical Laboratory
WMO	World Meteorological Organization

PART I

PHYSICAL ENVIRONMENTAL DATABASE - MAJOR ENTITIES

1 INTRODUCTION

The major purpose of INSROP Sub-programme I "Natural Conditions and Ice Navigation" is to provide the essential supporting information on climatic variability and ice navigability which is needed for the assessment of the feasibility of opening the NSR to international shipping with an extended navigation season (see Figure 1.1).

The purpose of Part I is to specify and identify information on physical environment affecting ice navigation planning and contingency preparedness. For planning purposes knowledge of the variability of the physical environment (in particular variability of the sea ice conditions) is of vital importance. The potential risks involved in sailing through the NSR will be assessed by investigating accidents and damages related to NSR transit navigation. Based on an evaluation of information content, data quality and accessibility, the data sets to be implemented in the database should be selected. The GIS system will have a major role in this project, especially when analyzing total data coverage and discrepancies between data sets, and when identifying lack of data.

Within this project, a workshop was arranged in Trondheim 8 - 12 November 1993 where we focused on data the GIS should contain and what information products the system should deliver. Five project leaders from Sub-programme I attended the workshop with Dr. Tsoy (CNIIMF) and Dr. Brovin (AARI) representing Russia. After three days of discussion we obtained a mutual understanding of what data should have priority and what the format should be.

The major topics in the discussion were:

- important parameters to navigation in ice
- relevant parameters for efficient icebreaker assistance
- parameters and data sources
- the preliminary outline of the GIS system
- priorities and grouping of data
- coverage and format of Russian data
- identification and requirements to information products from the GIS
- numerical models relevant to tasks of Sub-Programme I

Chapter 2 of the report specifies the requirements to the database while Chapter 3 gives the detailed content of the physical environment database. Each category of entity themes will include a set of queries and the queries are listed in Chapter 4 while Chapter 5 gives a preliminary overview of the data sources received from Russia.

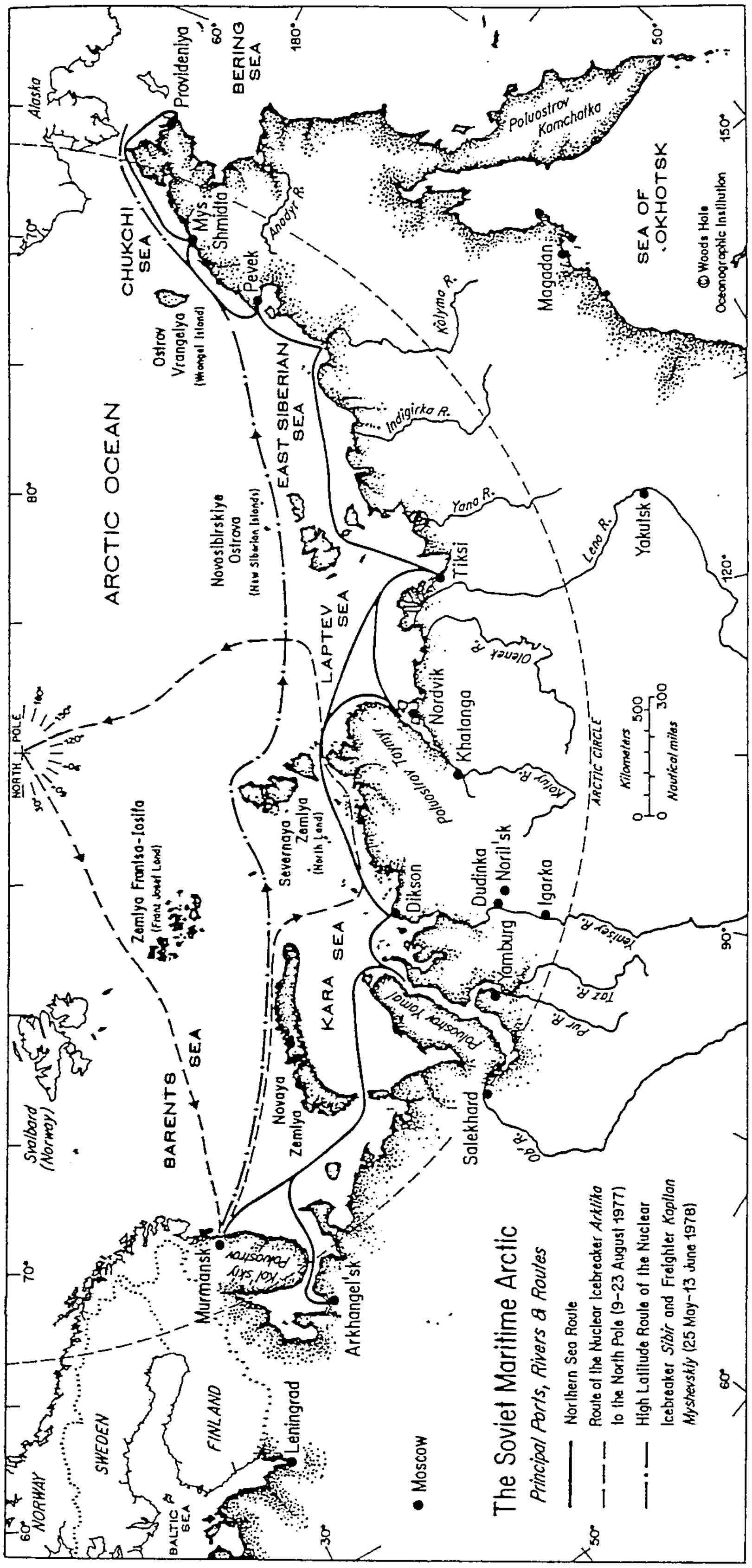

Figure 1.1 Map of the Northern Sea Route (NSR) including principal ports and rivers (Brigham, 1991).

2 REQUIREMENTS TO THE DATABASE CONTENT

The main purpose of the GIS system is to serve as a tool to store, retrieve, integrate and analyze information obtained in projects within INSROP Sub-programmes I and II. The GIS system should have a structure and content that is beneficial not only for the INSROP projects but also for the planning and actual sailing of the NSR.

The spatial resolution of the data should be adequate both for the entire NSR, the different seas of the NSR and smaller areas along the route (difficult navigation areas, etc). The spatial resolution and accuracy required for operational navigation (especially sea maps) should not be part of the GIS system. The necessary temporal resolution of the data depends on the variability of the parameters as well as of the use of the data. For producing statistical oil drift data only monthly mean of the background current is needed while daily resolution of the wind velocity is preferable.

The main purpose of Project I.5.1 is to specify and identify information on physical environment affecting ice navigation planning and contingency preparedness. The GAS system should serve as a tool to provide information within the following categories:

1) Base cartographic data
2) Infrastructure information
3) Planning of sailing (operational aspects)
4) Risk assessment (technical, personal)
5) Environmental impact assessment

Requirements to data within the different categories are briefly described below.

2.1 Base cartographic data

The sea charts are probably the most important tool for safe navigation. Navigational charts have been published for all Arctic seas at a scale of 1:500 000 and 1:200 000 for all coastal areas, with supporting charts of 1:50 000 (Ushakov et al., 1991).

In narrow straits, rivers and close to the coast more detailed charts are required. Charts of 1:25 000 and 1:10 000 are published for various gulfs, narrow passages, estuaries, port approaches and settlements, but not all of them are yet released. The GAS system should not include maps for operational navigation so the maps of the high resolution should not be included.

Nine seaports are currently in operation on the NSR. Five belongs to the Ministry of the Merchant Marine - Amderma, Dikson, Khatanga, Tiksi, Pevek- and four to other agencies - Dudinka and Igarka on the Yenisey, Zelenyy Mys on the Kolyma and Mys Schmidta. Necessary information about the seaports should therefore be part of the database.

The continental shelf along the route is very shallow, in some straits only a few metres deep. Minimum depth in most straits exceed 20 meters, but in the Sannikov Strait it is only 13 m and in the Laptev Strait only 8 m. For instance, a tanker of 70 000 tonnes with a draft of 16 m will meet serious draft limitations in the Kara-, Laptev- and East Siberian Seas. The underkeel clearance must be more than 5 m in open waters. In the rivers and the estuaries the clearance will often be marginal when the ships are loading in a river port like Dudinka and Igarka. The draft limitations will seriously influence ice routing and transit time. Detailed information about bathymetry is therefore necessary when analyzing sailing distances and speed for a specific category of vessel. Especially for the most shallow areas (straits, ports etc) detailed data are needed.

2.2 Infrastructure information

Navigational services are essential for an effective performance and safe operation of ships sailing the NSR. Publication and easy access to infrastructure information should be prepared for international use in the international shipping language English. It is important to map existing services and to contribute to the adaption of these to international accessibility. The following items should be handled within this category:

- ports
- icebreaker and pilot accessibility
- navigational aids (lighthouses, radio stations, etc.)
- communication
- special regulations (rules, required reporting, etc.)
- search and rescue (SAR)
- fuel storages
- populated areas
- airports

These items are outlined more thoroughly in a separate report of Sub-programme I (Kjerstad, 1994).

2.3 Planning of sailing

In the future when the NSR is a relevant sailing alternative, several planning tools are needed both for shippers and the ship operators and officers. For planning purposes knowledge of the variability of the physical environment (especially the ice conditions) is of vital importance. Based on historical transit sailings a preliminary model for computation of ships speed is developed by the Russians. The ice cover is classified as a navigational medium. The variability analysis will enable prediction of transit time for any particular class of ship through the NSR for any month of the year. The regularity of the transit sailings is another important aspect.

The sailing length in ice of 7-10/10 concentration serves as the criterion of the complicated ice navigation conditions. Outside the limits of the ice massifs, mainly in the summertime there are zones of open (4 - 6/10 ice concentration) and very open (1 - 3/10 ice concentration) ice. The presence of such zones significantly influence the optimum choice of the transit route.

Navigation in close ice is often accompanied by compaction, which is closely connected to the wind speed and direction and is relatively easily predictable by the weather forecasts. In fall the pressures are accompanied by the adhesion to the ship's hull and in some narrow zones with a very rapid drift. In winter the success of the voyages will depend on the polynyas and the discontinuities in the drifting ice.

When choosing the optimum ice navigation route, the following is taken into account (Baskin et al, 1994):

- the shortest way
- minimum ice concentration and total ice extent of the ice zone
- maximum amount of young ice
- minimum amount of hummocking

In the close ice zones the shipping success is governed by the following main ice cover characteristics:

- amount and location of different ice age categories
- thickness
- amount of hummocking
- degree of destruction
- presence and location of compacting zones
- geometry and distribution of open water zones

The ice conditions along the NSR are extremely dynamic, leading to large annual, seasonal and regional variations. However, experience over the years shows that formation of close pack ice occurs with a higher frequency in certain areas, followed by severe conditions for ship navigation. Such areas are called ice massifs and should be included in the database. The Taimyrsky, Ayonsky and Vranghelevsky massifs are known to exert the most unfavourable influence on navigation due to high ice concentration and presence of multi-year ice, high ice stress and lower degree of seasonal melting.

The existing theoretical and empirical -statistical methods for the assessment of the ice cover effect on the success of the ship navigation use a limited number of ice characteristics. These are ice and snow thickness, ice concentration, prevailing ice floe dimensions, amount of hummocking, degree of destruction and ice compression.

The spatial resolution of the ice information should be both on a regional and a local scale. The ice information should be presented for the different seas as well as along the sailing routes. For the ice characteristics along the sailing routes it is possible to derive the information directly from operational ice charts. For the regional ice cover characteristics the spatial resolution will be coarser. Preferably daily or weekly sea ice maps (presenting ice concentrations and ice types) for the regions should be part of the database.

2.4 Risk assessment

Sailing the NSR represents a potential hazard to the environment, personal safety and damage on vessels. A major concern is the possible impact on the environment from accidental oil spills either from cargo or bunker fuel.

Most of the hull ice damages are related to convoying. During independent sailing only 10 - 12 % of the ice damages occur. On the average the portion of damages (bulges, corrugations, dents) accompanied by leakage varies in different years within 25 - 40 % of the total number of hull ice damages. Ships of L1 and lower categories have a number of frame damages including holes along the board and bilge, dimensions of the damages of structural elements 2-3 times exceeding those for ships of the highest ice categories (Brovin and Tsoy, 1994). On ships of the highest ice categories holes occur rather seldom and are mainly associated with navigator errors in the close towing of ships by ice breakers or during especially severe ice conditions.

Experience of sailing in Arctic Sea ice shows that vessels older than 15 years are always damaged and only the features of the damage are different. The most frequent type of ice damage is hull fracture. During the years 1986-89, incomplete figures give 298 such cases or 82.5 % of the total for ice damage. The remaining 17.5 % are mostly damages to propellers, shafts and steering gear (Ushakov et al., 1991).

Statistics on ship damages due to ice and cold temperatures, convoying and shallow areas should be available information in the GIS system. The conditions of getting damages, damages' character and distribution of the damages on the hull are relevant information of the database. The consequences of the vessel damages, both for personnel, vessel and environment should be part of the database.

2.5 Environmental impact assessment

The information of the core database should include information necessary to perform consequence analysis of various aspects of marine transportation along the NSR. More specifically, the database should provide oil drift data for environmental impact assessments. The oil drift data required will be related to a regional mapping of critical parameters such as:

- probability of oil stranding
- minimum and average drift time to shore
- maximum and average drift time in the ice
- minimum and average drift time to the ice edge (spill in open water)
- average amount of oil stranding (natural dispersion and evaporation loss included)

A number of spill sites should be selected and the simulations should be made for different seasons of the year in order to reflect the effects of seasonal variations of ice and wind conditions.

A statistical oil drift model requires the following input data:

- Climatological background current, monthly averaged data gridded for the whole area is needed, the spatial resolution should be 10-20 km.
- Hindcast wind velocity, daily (or 6-12 hours) data for the whole area in a fixed grid of spatial resolution of 20 km. Minimum 20 years with data.
- Hindcast wave data, needed for the Stokes drift calculations and require daily (or 6-12 hours) data for the whole area in a fixed grid of spatial resolution of 20 km. Minimum 20 years with data.
- Ice conditions, historical data on ice coverage, landfast ice, ice type and ice velocity in a fixed grid. Minimum 20 years with data.
- Coastline (land boundaries, properties)
- Oil characteristics (properties)

3 CONTENT OF THE PHYSICAL ENVIRONMENTAL DATABASE

In order to fulfil the requirements to the GIS system, the following entities related to physical environment and navigability in ice should be included in the core database.

1) Geodata
2) Ocean and river dynamics
3) Ice and snow cover
4) Meteorology
5) Icing on ships
6) Historical voyage data

3.1 Geodata

The following base cartographic information should be implemented:

- land and ocean boundaries
- coastline characteristics (rock, gravel, sediments)
- bathymetry
- glaciers

The Russian company Transas Marine is at present the only company providing PC based sea charts for the NSR (Kjerstad, 1994). These charts are of scale 1:1250 000 and can be used for navigation planning on a regional scale within the INSROP project.

Since the continental shelf along the route is very shallow, it is important with detailed information on water depths and tides.

During the systematization of ice data the NSR has been subdivided into segments which have been determined by the main cargo flows of the operating transportation system. The data on ice navigation conditions were determined on the following segments:

- Ice edge in the Barents Sea - Dickson Island
- Dickson Island - Khatanga Bay
- Khatanga Bay - Tiksi port
- Tiksi port - Mouth of the Kolyma river
- Mouth of the Kolyma river - The Shelagsky cape
- The Shelagsky cape - the Bering strait

3.2 Ocean and river dynamics

The oceanographic conditions of the NSR zone of transit navigation will be part of the database as well as information about main rivers. One of the most important factors for transit sailing in the shallow areas, is the change in the sea level. The largest difference in sea level is found in the eastern part of the Laptev Sea, where the difference is about 5-7 m. In the Kara Sea the difference in sea level is only 2-2.5 m. For the East-Siberian Sea and the Chukchi Sea the difference in sea level may be about 3-4 m (Busuev, 1991).

With reference to the harmonic tidal constituents, the four most dominating tidal constituents are included in the list below which include the *Ocean and river dynamics* to be included in the database:

Table 3.1 Ocean and river dynamics

ENTITIES	ATTRIBUTES	UNITS
Oceanographic stations	Station-ID and type of station Water depth Start of operation End of operation	m date date date
Background current	Current speed Current direction Depth	m/s ° m
Tide tables	Refer local tide tables	
M_2-tidal data	Major and minor axis Orientation and phase angle	m/s °
S_2-tidal data	Major and minor axis Orientation and phase angle	m/s °
K_1-tidal data	Major and minor axis Orientation and phase angle	m/s °
O_1-tidal data	Major and minor axis Orientation and phase angle	m/s °
Waves	Significant wave height Wave length Wave period	m m s
Sea temperature	Temperature Depth	°C m
Sea salinity	Salinity Depth	‰ m
Oceanographic fronts	Front type Lower and upper value	
River dynamics	Current speed Flow discharge Ice thickness	m/s m^3 /s m

3.3 Ice and snow cover

The ice age is the main navigational parameter of the ice cover. According to WMO Sea-Ice Nomenclature the following ice age ranges should be used:

• Young ice	grey	-	10 - 15 cm thickness
	grey/white	-	15 - 30 cm thickness
• First-year ice	thin	-	30 - 70 cm thickness
	medium	-	70 - 120 cm thickness
	thick	-	above 120 cm thickness
• Second-year ice		-	to 250 cm thickness
• Multi-year		-	to 300 cm and above

Another main navigational parameter is the ice floe size which can be divided into five categories:

• Giant	-	over 10 km across
• Vast	-	2 - 10 km across
• Big	-	500 m - 2 km across
• Medium	-	100 - 500 m across
• Ice breccia	-	different ice types frozen together

Information about the snow cover on the ice will be included in the database since the snow cover seriously affects the navigation. Knowledge of the thickness and the properties of the snow cover is essential for evaluating the progress of ships in ice.

Information about ridges and sastrugi are also included in the database. Sastruga is a sharp, irregular ridge formed on snow surface by wind erosion and deposition. The area of sastruga on first-year ice floes in the East-Siberian, Laptev and Kara Sea ranges from 5 - 10 %. In the central Laptev Sea it is within 20 - 30 % (Romanov, 1993a).

The description of ice type and stage of development is based on the terminology in MANICE. The following information about the ice and snow cover along the NSR should be part of the core database since they influence directly the navigation planning and contingency preparedness:

- Ice concentration (governs the shipping conditions in summer time)
  - total ice concentration
  - concentration of different ice types

- Ice thickness (governs the ice resistance to the ship's motion)
  - average ice thickness for an area
  - thickness of each ice type in an area

- ice edge category (to be used when thickness data do not exist)
  - young ice
  - first-year thin ice
  - first-year medium ice
  - first-year thick ice
  - second-year ice

- Ice drift
  - speed and direction

- Ice floe size
  - floe size distribution
  - average floe size
  - sizes of ice breccia
  - sizes of vast floes
  - sizes of big floes
  - sizes of medium floes
  - sizes of small floes
  - sizes of brash ice

- Ridges
  - ridge concentration
  - ridge width and height
  - ridged zones

- Snow cover on ice
  - average thickness on first-year and multi-year ice
  - snow thickness on ridges
  - density and wetness of snow
  - sastrugi on first-year and multi-year ice

- Pack ice motion processes
  - diverging
  - compacting
  - shearing

- Ice deformation processes
  - fracturing
  - hummocking
  - ridging
  - rafting
  - weathering processes

- Openings in the ice
  - crack
  - fracture zone
  - lead
  - polynya

- Ice-surface features
  - level ice
  - rafted ice
  - new ridges
  - weathered ridges
  - consolidated ridges
  - hummocked ice
  - bare-ice
  - snow-covered ice
  - sastrugi

- Melting periods
  - average starting dates

- Icebergs (navigation danger, collision with the ship)
  - position
  - geometric dimensions

Along the transit navigation route the following information related to the ice conditions are determined:

- Occurrence frequency of the position of the optimum navigation route in a given month (10 day period).

- Length of the route in different ice age categories in a given month (10 day period).

- Length of the route in various ice formations in a given month (10 day period)
  - polynyas
  - very open first-year ice and remaining ice
  - ice massifs
  - ice massifs core
  - marginal part of the ice massifs

- Occurrence frequency of ice conditions with optimal navigation in a given month (10 day period).

- Occurrence frequency of the summer navigation types on a specific NSR segment.

- Duration of navigation for a specific vessel (with and without icebreaker assistance)
  - SA-15
  - ULA
  - UL
  - L1

- Calculated velocities of specific ships in ice zones and navigation times at the NSR segments in a given month (10-day period)
  - nuclear icebreaker of the "Arktika" type
  - Icebreaker of the "Yermak" type
  - M/V SA-15
  - M/V ULA
  - M/V UL
  - Nuclear icebreaker + ULA
  - Nuclear icebreaker + UL
  - Icebreaker + ULA
  - Icebreaker + UL

3.4 Meteorology

Wind is one of the main driving forces on the ice and will be an important parameter for the navigability in ice. The surface wind should preferably be calculated from the pressure field. The precipitation in form of snow will influence on the visibility and as well on the sailing through the NSR. Wind, air temperature and precipitation will be parameters affecting the sea spray icing and atmospheric icing on vessels. The following parameters are selected to describe the meteorological conditions along the route:

- Geostrophic wind (speed and direction)
- Air pressure (at 1000 m level)
- Air temperature
- Humidity
- Visibility
- Precipitation (rain, snow)

3.5 Icing on ships

Statistical analysis of 2000 cases of fishing vessel icing indicates that the primary cause of vessel icing is the freezing of bow spray. For NSR transit navigation in open water sea spray icing may occur and cause problems for the ship. Ice accretion interferes with the operation of equipment located on exposed weather decks. In many situations the ice must be removed from exposed decks and machinery before routine operations can take place. The ice accretion raises the centre of gravity of a ship and will cause a significant loss of stability.

Topside icing has posed a threat to vessels operating in cold weather regions for many years. Topside icing can originate from a variety of sources:

- supercooled fog
- freezing rain
- falling snow
- freezing bow spray

Information about historical icing events along the NSR should be included in the database. The icing events should also include information about wind conditions, wave heights, air- and sea temperatures. This information will be valuable when developing better relationship between meteorological/oceanographic data and icing events. Table 3.2 shows the necessary information about the icing events which should be a part of the database.

Table 3.2 Icing on ships

ATTRIBUTES	COMMENTS
Occurrence of icing	Dates and duration, position
Accreted ice loads	Estimated ice loads
Icing on rescue equipment	Life boats, davits, deck and railways
Type of icing	Atmospheric icing, sea spray icing
Location of icing on the ship	Hull, superstructure, antennas, height above sea level
Wind conditions	Wind speed and direction
Wave heights	Significant wave height, period
Air temperatures	Average and minimum air temperature
Sea surface temperatures	Average sea surface temperature
Precipitation	Rain, fog, snow

3.6 Historical voyage data

All available information about sailing periods and ship types through the NSR should be part of the core database. The ice conditions during these periods should be stored together with the sailing information. This information is essential when transforming the ice conditions to an entity giving information about the navigability for a ship. The potential risks involved in sailing through the NSR will be assessed by investigating accidents and damages related to NSR transit navigation. Table 3.3 shows the information about historical sailings which should be part of the core database.

Table 3.3 Historical voyage data

Entity	Attributes	Comments
Voyage	Ship class/name	Definition and description of ship classes, name of ship
	Ice class	Description of ice conditions
	Time	Start and end date
	Duration	Estimated and actual sailing time
	Type of navigation	Summer, prolonged, winter
	Icebreaker assistance	Waters with/without icebreaker assistance
	Ice cover	Description of ice conditions (ice type, age, ridges, destruction, concentration, thickness)
	Route location	Length of route and positions
	Accidents	Personal accidents, damages on ships

4 ANALYSIS MODULE AND PHYSICAL ENVIRONMENT QUERIES

A separate Analysis Module should be coupled to the core database. The Analysis Module will contain standard statistical and extreme value routines as well as numerical models especially tailored to the conditions in the NSR. The numerical models are described in Part II of this report. The statistical analysis should be performed both for a geographically restricted area and also along the ship route. The time period for the analysis should also be specified.

The following possibilities should be part of the Analysis Module:

- raw data
- average, minimum and maximum
- percentiles (10, 25, 50, 75 and 90 per cent))
- extreme values (10, 50 and 100 years)
- probability of exceedance/non exceedance
- duration statistics
- trend analysis
- nowcast
- forecast

The following information products should be included in the Presentation Module:

- map
  - contours
  - points
  - polygon
  - vectors
- chart
  - xy-plot
  - bar
- standard reports
- tabular listing

Each category of entity themes should include a set of queries. The information in these entity themes generally have both a spatial and a temporal distribution. The physical environment queries will only use information from the Base cartography entities in addition to the physical environment entities.

4.1 Geodata

Queries connected to *geodata* are handled in a separate report of Sub-programme I (Kjerstad, 1994). They are also listed in Løvås and Smith (1994).

4.2 Ocean and river dynamics

Within the entity *Ocean and river dynamics*, the following questions are relevant for the NSR sailing.

Tides:

- What is:
  - the tidal height at a given place at a given time?
  - the tidal range in a given area?

Current:

- What is
  - the monthly mean background current for a specified area or position
  - the tidal current for a specified position (M_2 , S_2 , K_1 , O_1)
  - maximum/ minimum and average total current
  - probability of exceedance

Waves:

- What is:
  - the probability distribution of wave heights along a given route/area in a given month?
  - the extreme wave heights that can be expected along a given route/area?

Sea surface temperature and salinity:

- What is:
  - the monthly mean sea temperature in a given area?
  - the average salinity in ports and in narrow straits along the route?
  - the mean annual variations of sea temperature in a given area?

Oceanographic fronts:

- Where are the various fronts?
- When can large area eddies be expected?

River dynamics:

- What is:

  - the mean/maximum current speed along the river in a given month?
  - the mean waterlevel in a given month?
- Where:
  - are the areas being flooded regularly?
  - are the areas being flooded occasionally?
- When:
  - are the different parts of the river open/ice covered?
  - are certain areas regularly flooded?
  - may outflow of timber occur?

4.3 Ice and snow cover

The most relevant ice cover parameters for transit sailing in ice are ice age, ridge number and size, ice floe sizes and snow cover on the ice. Within these parameters the following questions (preliminary) are of relevance and should be part of the Query Module:

Ice thickness:

- What is:
  - the mean/maximum thickness of first-year ice and multi-year ice within a specified area in a given month?
  - the probability to exceed ice thickness H > x within a specified area during a given month?
  - the duration of period with H > x?

Ice floe size:

- What is:
  - the maximum, minimum and average floe size of first-year ice, multi-year ice and ice breccia within a specified area for a given month?
  - the probability of exceedance (floe size greater than x)?
  - the frequency distribution of prevailing ice floe size?
  - the ice concentration for different ice types?

Ridges:

- What is:
  - the ridge concentration within a specified area during a given month?
  - the maximum and average ridge height and width?
  - the maximum and average size of ice pieces in ridges?

  - the probability to exceed ridge height H>x within a specified area during a given month?

- the frequency distribution of ridge height and width?
- the southernmost boundary of the zone with H>x?

Snow cover on ice:

- What is:
  - the average and maximum snow cover thickness on first-year ice, multi-year ice and ridges?
  - the probability to exceed snow cover thickness H>x?
  - the snow cover distribution within a specified area during a given month?
  - the average snow cover density on different ice types?
  - the wetness of the snow cover

Polynyas:

- Where do the polynyas larger than X km^2 occur?
- How many polynyas larger than X km^2 can be expected within a specified area during a given month?

The GIS system should also provide information within the following topics:

- Where are:
  - first-year ice (new, brash etc.)?
  - second-year ice?
  - multi-year ice?
  - level ice?
  - landfast ice?
  - pack ice?
  - hummocked areas?
  - areas with high ice pressure?
  - polynyas?

- When are these features present:
  - first-year ice (new, brash etc.)?
  - second-year ice?
  - multi-year ice?
  - level ice?
  - landfast ice?
  - pack ice?
  - hummocked areas?
  - areas with high ice pressure?
  - polynyas?

4.4 Meteorology

The following information about the meteorological conditions along the NSR should be presented by the GIS system:

Meteorological stations:

- Where are meteorological stations located (past and present)?

Wind:

- What is
  - the wind velocity in a given area at a certain time?
  - the wind in narrow straits along the route?
  - the monthly wind variability (mean, maximum)?
  - the probability of exceedance U>x?
  - the duration of wind speed and wind direction?
  - the extreme values (10-, 50- and 100-year return period) of wind speed?

Air pressure, temperature and relative humidity:

- What is
  - the air pressure/temperature/humidity in a given area at a certain time?
  - the monthly air pressure/temperature/humidity variability (mean, maximum)?
  - the probability of exceedance?
  - the duration of air pressure/temperature/humidity?
  - the extreme values (10-, 50- and 100-year return period) of temperature?

Visibility/precipitation:

- What is
  - the visibility/precipitation in a given area at a certain time?
  - the visibility in narrow straits along the route?
  - the monthly variability of the visibility/precipitation?
  - the probability of exceedance?
  - the duration of visibility/precipitation?

4.5 Icing on ships

The GIS system should provide the following information on historical icing events in the NSR area:

- What is/are:
  - the favourable periods without icing?
  - the probability of icing in different waters and different times of the year?
  - the probability of icing on rescue equipment?
  - the probability of atmospheric icing on antennas?
  - the duration of icing events?
  - the estimated ice load during the icing event?

4.6 Historical voyage data

The following information about historical sailings through the NSR should be presented by the GIS system:

- Where is/are:
  - the tracks of historical sailings?
  - the periods with no sailing through the NSR?

- What is/are:
  - the maximum, minimum and average duration of sailings?
  - the maximum, minimum and average length of sailing routes?
  - the maximum, minimum and average speed of sailings?
  - the maximum, minimum and average number of sailings within a given period?
  - the maximum, minimum and average number of sailings without icebreaker assistance within a given period?
  - the maximum, minimum and average number of sailings without icebreaker assistance within a given period?

5 DATA SOURCES, QUALITY ASSURANCE AND DATA COVERAGE

Each dataset should include information about the quality of the data. A data quality range from 0-9 is proposed (Løvås et al, 1994). Most of the available physical environmental data for the NSR are found in Russia. Non-Russian data available for the region are mainly based on satellite data.

The access to satellite images from 1966 on provides substantial improvement of both spatial and temporal coverage of ice conditions (see Vefsnmo et al.(1991) and Sandven et al. (1994)). In June 1987 the U.S. Air Defence Meteorological Satellite Program (DMSP) launched its first spaceborne passive microwave image, the Special Sensor Microwave Image (SSM/I). Total ice concentration and multi-year ice concentration are available in a 25 km x 25 km grid with a temporal resolution of about 1 day. SSM/I sea ice concentrations for the polar regions gridded in the polar stereographic projection at a resolution of 25 km x 25 km are presented on CD-ROM from the National Snow and Ice Data Center.

Time periods covered by SSM/I ice concentrations are at present:

9 July 1987 to 31 December 1991.

The SMMR sensor was operating every other day to conserve power. Therefore the data were collected on alternating days. Usually there are at least 14 days of coverage per month. The sea ice concentrations are gridded in the polar stereographic projection with grid elements of 25 km x 25 km.

Time periods covered by SMMR CD ROMs:

25 October 1978 to 20 August 1987

Both the SSM/I and SMMR data can be included in the core database representing ice data on a regional scale.

The database from the World Data Center (WDC-A) includes information of total sea ice concentration and thickness of the three thickest ice types at each grid point. Weekly data for the period January 1971 - December 1991 with a spatial resolution of not more than 15 x 15 nautical miles are included. The data originate mainly from the NOAA and the DMSP satellites.

AARI participated in the WMO Project " Global Digital Sea Ice Data Bank" and established the World Data Center "Sea Ice" (WDC-B), which forms the database of the Global Data Bank (GDB) at AARI. A comparison of data from the two databases was performed. The comparison showed good agreement in the temporal tendencies, but the data differed significantly in the values of partial concentrations and sea ice age categories. AARI has recommended that priority in the ice concentration information should be given to the WDC-A data while the priority for the age categories should be given to the AARI data.

The report (Baskin et al., 1994) from INSROP Project I.4.1 gives a relatively detailed overview of sea ice data available at AARI. The overview contains both meteorological and oceanographic data relevant for transit sailing. The sea ice data available at AARI can be divided into three groups:

- non-formalized archives
- computer readable media
- databases

The non-formalized archives include the primary data, as well as the charts of different scales. The archives of AARI are described in Baskin et al. (1994) and can be summarized as follows:

- data of visual airborne observations for 1933-1990 (about 35 000 charts)
- satellite data for the region of the North-European basin for 1985-91 (506 charts)
- satellite data for the Arctic Seas for 1981-91 (396 charts)
- data of radar surveys from aircraft for 1968-90 (98 charts)
- data of the amount of fracturing for 1959-86 (150 charts)
- data on the degree of ice destruction for 1953-1980 (280 charts)
- data on the amount of ice hummocking for 1953-1980 (220 charts)

In addition negatives of satellite images with high resolution are available as well as images of radio-echo sounding of the ice cover from aircraft.

At present the following ice data sets on computer readable media are available (Baskin et al., 1994):

- monthly data on total sea ice concentration with a temporal resolution of 60 nautical miles for the time period 1953-1990 (456 charts)

- weekly data in the SIGRID format on total and partial sea ice concentration with a resolution of 15 geographical minutes for the period 1972-1991 (1043 charts)

- 10-day interval data (SIGRID format) on total and partial sea ice concentration with a resolution of 15 minutes north/south and east/west for the period 1972-90 (the western Arctic, 571 charts)

- 10-day interval data (SIGRID format) on total and partial sea ice concentration with a resolution of 15 minutes for the period 1967-90 (the eastern Arctic, 592 charts)

- 5-days interval data (SIGRID format) with a resolution of 1°N by 2°E total sea ice concentration (the Sea of Okhotsk, January-May and December of 1971-90, 36 charts)

- 10-day interval data in the KONTUR format on total and partial sea ice concentration (western and eastern sector of the Arctic, 1933-90, 2289 charts)

- daily coordinates of the drifting transmitters and DARMS (the Arctic basin, 1953-72, 286 charts)

- daily coordinates of the drifting ships, stations, buoys and radiomarks (the Arctic basin, 1893-1985, 184 charts)

- daily coordinates of the "North Pole" drifting stations by astronomical observations and positioning by means of the space navigation systems (the Arctic basin, 1937-91, 31 stations)

- data in the KONTUR format on total and partial sea ice concentration with an averaging period of 3-7 days (the western Arctic, 1985-92, 490 charts)

- geographical coordinates and number of sighted icebergs (the northern parts of the Barents and the Kara Seas, 1936-89)

Databases including the degree of ice destruction from the Barents Sea to the Chukchi Sea are also available at AARI (Baskin et al., 1994).

The main parameter for ice navigation is the length of time sailing in ice with different characteristics (age, concentration, amount of hummocking, degree of destruction, pressure and snow depth on level ice). These data are taken from the composite ice charts, where standard and optimum navigation routes are plotted.

The report by Baskin et al. (1994) also presents overviews for other meteorological and oceanographic data which can be summarized as follows:

- daily air temperatures from the Arctic stations (from 1949, paper media)
- daily wind data from the Arctic stations (from 1949, paper media)
- mean monthly air temperatures (233 stations, from 1881, magnetic disks)
- mean monthly wind velocities (33 stations, from 1932, magnetic disks)
- mean monthly surface pressure (from 1900, magnetic disks)
- mean monthly maps of air temperatures and their anomalies (from 1881)
- pressures in the ice cover (1980-1988)
- adhesion to the ship's hull (1970-1980, paper media)
- atmospheric icing (1958-1993, paper media)
- sea spray icing (1948-1993, paper media)
- swell data from the Arctic stations (1950-1993, paper media)
- sea level (1950-1991, paper media)
- monthly mean and extreme sea level (1950-1991, paper media)
- currents in the 0-25 m layer (1930-1989, magnetic tapes)
- tidal currents database (1958-1989)

The report "Ice cover of the Arctic Basin" Romanov,1993a) and the comprehensive Atlas: "Morphometric Characteristics of Ice and Snow in the Arctic Basin" (Romanov,1993b) present statistical information of the ice cover. Treshnikov et al. (1985) also provide a comprehensive overview of the physical environment (including meteorological and oceanographic data) in the Arctic as a whole.

The data on ice cover state in the Arctic Basin have mainly been obtained from airborne surveys and observations conducted along with main oceanographic work. These ice cover observations have been carried out since 1947. Especially high quality data were obtained in the periods 1954 - 57. Therefore, the ice observations in the Arctic Basin, especially in Canadian, Alaskan and Central (Circumpolar) Regions were discontinued. In 1972 - 81, during the Polar Experiment (POLEX), ice age, ice floe sizes, ridges, snow on ice and ice drift were monitored. Some observations were followed up to 1990.

The ice cover data have mainly been obtained in the winter-spring period. However, in recent years the observations were also conducted in summer. This allows one to reveal the changes of various ice parameters all the year round. The drifting stations "North Pole" greatly contributed to the ice data collection. During 1947 - 1990 the stations operated in ice for 23 000 days and covered 140 000 km.

In Romanov (1993a), the estimation of ice cover parameters has been made both from aircraft and directly at the ice surface. The following ice cover parameters have been determined visually or instrumentally:

- Ice age and distribution
  - prevailing sizes of first-year ice floes
  - prevailing sizes of multi-year ice floes
  - prevailing sizes of ice breccia
  - prevailing sizes of consolidated multi-year floes
  - multi-year ice floe topography - aged ridge concentration

- Ridges and fractures
  - ridge concentration
  - average ridge height
  - maximum ridge height
  - ridge width
  - thickness of ice pieces in ridges
  - sizes of ice pieces in ridges
  - ridges zones
  - cracks, leads and fractures
  - ridge and fracture patterns, their direction, width, length

- Snow on ice
  - average snow thickness on first-year ice
  - average snow thickness on multi-year ice
  - snow thickness in ridges
  - sastrugi on first-year ice
  - sastrugi on multi-year ice
  - snow thickness in aged ridges
  - snow thickness on frozen puddles
  - snow thickness on plateau (between puddles)
  - snow tongues

- Sea ice drift
  - translational motion
  - rotational motion

In Romanov (1993a), the average values of all ice and snow parameters are estimated from observational series by squares 100 km x 100 km. Maximum and minimum values of any parameter were determined from the sample of observational data of High latitudinal Airborne Expedition "Sever" or ice surveys by squares.

Probability of occurrence has been estimated by means of dividing the frequency of individual events by the total number of events in the square and expressed in per cent. Since the number of observational years is limited, the average error of observational series are calculated and presented. Romanov (1993a) gives a comprehensive summary of the statistical information about the ice cover along the NSR.

Section I in the Atlas of Romanov (1993b) presents the data on snow thickness on level ice and its variability, snow thickness in ridges, height and length of snow tongues, snow thickness in sastrugi and sastrugi areas. Section II contains the data on multi-year ice thickness and its probability in the period of maximum (April) and minimum (August) development. The interannual variability of consolidated ice floes, ice breccia and their probability distribution have also been considered in Section II. Section III summarizes the information on ridge number per km, ridge concentration, ice thickness increment due to ridging, ridge height and width, thickness of ice pieces in ridges as well as multi-year ridge concentration. Section IV presents the speed of the atomic icebreakers of the "Arktika" class based on 30 years with data and a generic icebreaker with 150 000 h.p. in winter and summer conditions. Section V comprises the data on ice drift parameters, melting and distribution of level first-year ice floes.

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PART II

MODEL CONCEPTS FOR DRIFT AND SPREAD OF OIL AND ICE

1 INTRODUCTION

Commercial traffic along the NSR will increase the risk of accidental spills of pollutants such as oil and chemicals in these waters. This may either occur from

- holing of an icebreaker or a commercial cargo ship's fuel tanks leading to release of oil for a short time period,
- collision, grounding or severe ice damage causing rapid loss of cargo or crude from one or more tanks, or
- sinking of a ship with potential for slow release of cargo over a few weeks or months.

The purpose of Part II of this report is to give an overview of the mechanisms of drift and spread of oil under different sea surface conditions (open water, broken ice, level ice) and to propose strategies for model development. The physical environment will affect the drift and spreading of spilled oil, and thus the contaminated area. Cargo chemicals may also represent a risk to the environment, but such transport will probably be less frequent and is thus not highlighted here.

Further, Part II discusses various statistical and operational concepts for oil and ice drift. During the last two decades a number of such numerical models have been developed. A citation of such models are e.g. given in Spaulding (1988), Dickins (1992), and Vefsnmo and Løvås (1992). Most of these models are poor and the fact is that spreading of oil, for example in broken ice, is poorly understood. There are no theories or data that can adequately determine spreading rates, oil thicknesses and oil advection and modes of oil-ice interaction (Sayed et al., 1994).

Chapter 2 highlights the major mechanisms and indicates feasible approaches to this assessment. A more thorough and mathematical description of the different mechanisms is given by Ovsienko (1993). Chapter 3 describes different statistical oil drift model concepts and provides recommendations for model implementation. Further, Chapter 4 surveys and recommends features of regional and local operational ice drift models. Finally, Chapter 5 outlines the physical basis and numerical solution method for operational oil drift models.

2 MECHANISMS FOR DRIFT AND SPREAD OF OIL

The physical environmental conditions of the NSR introduce various possible accidental oil spill scenarios. Along the NSR the physical environment may vary from open water to level ice depending on location and time of year. Thus, the environmental impact assessment from accidental oil spills may consider the following major sea surface conditions:

- oil on open water
- oil in pack ice (brash-, broken- and level ice)
- oil on level ice (with or without snow)

To assess the distribution and fate of oil with ice and snow present is a complex task. It depends on the physical properties of the oil including surface and interfacial tension, evaporation, emulsification, dissolution, shoreline-oil and bottom-oil interaction. All these mechanisms have different physical background, different time and space scales and consequently different possibilities for modelling. Our knowledge of the different mechanisms is scanty and semi-empirical and empirical parameterizations are required.

2.1 Oil on open water

The surface distribution of oil spilled at sea is governed by both physical and chemical processes. A number of field trials have been conducted to study the different mechanisms affecting the surface distribution in open water (Audunson et al., 1979; Sørstrøm et al., 1987; Reed et al., 1990). In parallel to field studies efforts have been made to mathematically describe the different mechanisms governing the distribution of oil on open water. Several numerical models have been developed and in principle two methodologies for presenting the physical distribution of spilled oil are used.

The first and pioneer approach uses a *uniform representation* of the oil assuming a circular or an elliptical spillet with radius, thickness and other variables computed dynamically. This approach gives thickness and area of the slick applicable when fate processes are to be studied. However, field observations have shown that the oil frequently appears in irregular patches which are not readily described by this theory.

The other commonly used approach is to describe the oil as an *ensemble of particles*. On the surface these particles takes the characteristics of spillets and when entrained in the water column they are treated as droplets. The particle approach may easily give a slick aligned with the wind and with the thickest layer towards the downwind edge of the slick.

2.1.1 Spreading

Spreading of oil on open water results from turbulent diffusion, the forces of gravity, inertia, viscosity and surface tension. Thus the spreading depends on the properties of the oil and the mode of discharge (constant rate or fixed volume).

Fay's (1971) gravity-viscous equation has been used for a number of years to describe the spreading of oil. Mackay (1980) modified Fay's approach and described the oil as thin and thick slicks. The thick slick feeds the thin slick and about 90% of the total slick area is represented by the thin slick.

Most of the open water models are calibrated and refer to "warm" water conditions. On "cold" water, the equilibrium thickness of oil is observed to be much higher than suggested by Fay's theory and is reached much sooner than the time indicated by his equations (Venkatesh et al., 1990). However, we believe that much of these discrepancies are caused by poor data on oil properties including surface and interfacial tension at low temperatures.

2.1.2 Drift

The physical distribution of oil on the surface is also affected by advection of oil. The advection results from surface current and wind forcing. Field tests show that the wind-induced surface drift is dominant among these effects. However, in coastal areas and narrow straits along the NSR, currents may be just as important as the wind.

With waves present an advance of oil in the direction of the wave propagation is observed, termed Stokes drift. This drift occurs because the orbital paths followed by water parcels under a wave train are not closed, but advance in the direction of wave propagation. Observations by Reed et al. (1990) show that the Stokes drift may contribute more than 50 % of the total drift.

The wind-induced drift is typically assumed to be 2 - 4% of the wind at a constant angle of 0 - 20^0 to the right of the 10 m surface wind (Reed, 1992). The 2 - 4% rule is well-known and commonly used and gives fairly good estimates of the distribution of oil on open water. Both wind and Stokes drift are included in the 2 - 4% rule.

2.2 Oil in pack ice

The NSR represents a variety of physical environmental conditions. In this context, pack ice represents brash-, broken- and level ice. With ice present we consider the following possible discharge environment

- oil under level ice
- oil in leads and broken ice (wake of icebreaker or cargo vessel)

2.2.1 Under ice spreading

Under quiescent conditions the oil will spread upon reaching the under-ice surface. A number of force-balance models have been developed to predict spreading under a smooth ice bottom. Except for young ice the bottom surface roughness of the ice is substantial and a number of field observations have shown that the oil fills the nearest under-ice depression first before overflowing to the next depression. The key parameters in predicting the spreading of oil under an ice sheet from e.g. a stranded vessel, is the discharge volume of oil and the under-ice storage capacity.

Most laboratory data are available to predict the spreading of oil in the presence of current. In case of a sub-surface leakage from a vessel in the NSR, the discharge will at most take place at the maximum depth of the vessel. According to Dickins (1992), the current will have substantial effect on the spreading of oil first at relatively high currents (> 0.20 m/s).

Al'khimenko (1989) reported that oil spread freely without sticking to the under-ice surface. Above a certain threshold value of current oil was stripped away from the under-ice surface and transported by the current. The threshold speed was dependent on the characteristics of the oil (viscosity, pour point, interfacial tension with ice and sea water).

If such a spill occurs while the ice cover is still growing, oil under the ice may be encapsulated in the growing ice sheet. The oil is trapped by the ice and most of the oil will be released upon melting.

Kovacs et al. (1981) and Comfort (1986) estimated the under-ice storage capacity of oil to range from 0.01 to 0.13 m^3 oil per m^2 of ice surface depending on type and characteristics of the ice (the older the ice the higher the storage capacity). The storage estimates were obtained from determining the cavities in the ice above the level of mean ice thickness and assuming these to be filled with oil.

Efforts have been made to assess semi-empirical and empirical formulas, and to develop numerical models which can handle such spill situations (Hoult, 1975; Chen et al., 1974; Yapa and Chowdhury, 1990). These models are rude but the most general one by Yapa and Chowdhury (1990) can handle both a constant discharge rate and a fixed discharge volume.

Yapa and Chowdhury (1990) presented a new set of equations describing the process of oil spreading under ice in calm waters. These equations consider the gravity (buoyancy)-inertia phase, the gravity (buoyancy)-viscous, and the termination of spreading during the buoyancy - surface tension phase. The derivation considers both the constant discharge mode and the constant volume mode.

$$r = 0.751\,[(\rho_w/\rho_o - 1)g \cdot Q]^{1/4} \cdot t^{3/4} \tag{2.1}$$

where

- r = oil slick radius (m)
- ρ_w = sea water density
- ρ_o = oil density
- g = gravitational acceleration (m/s^2)
- Q = V/t = discharge rate (m^3/s)
- V = spilled oil volume (m^3)
- t = time elapsed (s)

In the buoyancy-viscous phase, the buoyancy force is balanced by viscous forces giving:

$$r = k_1\left[\frac{(\rho_w - \rho_o)g \cdot Q^3}{\mu_o}\right]^{1/8} \cdot t^{1/2} \qquad (Q = constant) \tag{2.2}$$

$$r = k_2\left[\frac{(\rho_w - \rho_o)g \cdot V^3}{\mu_o}\right]^{1/8} \cdot t^{1/2} \qquad (V = constant) \tag{2.3}$$

where

- k_1, k_2 = dimensionless constants
- μ_o = oil viscosity

The final slick radius is estimated by balancing buoyancy and net interfacial tension forces:

$$r_f = k_3\left[\frac{(\rho_w - \rho_o)g}{\sigma_n}\right]^{1/4} \cdot V^{1/2} \qquad (2.4)$$

where

r_f = final under-ice slick radius
k_3 = empirical coefficient
σ_n = net interfacial tension derived from oil/water, ice/water and ice/oil interfacial tensions and the contact angle.

Small-scale laboratory experiments (Yapa and Chowdhury, 1990) have shown good agreement with the above formulas. However, the equations are not valid for large under-ice roughness heights or for extremely high discharge rates. The equations may give a first estimate of the under-ice oil spreading in very high ice concentrations where the ice can be thought of as a continuous layer or to estimate whether oil release under an ice floe will be trapped under the floe or spread past the ice floe edge and up to the water surface. Proper use of the above formulas requires information about the ice concentration or ice floe size. The under-ice roughness is reflected in the constants k_1, k_2 and k_3, which must be derived empirically.

2.2.2 Oil in wakes, leads and broken ice

The major factors to consider for spreading and drift of oil in a wake, lead or broken ice are the ice coverage and properties of the oil. Data are scanty and one of the few controlled field studies in broken ice was made by Ross and Dickins (1987). Based on three oil releases (1 m^3 each), where two releases were on 0.35 m brash ice and one in the open water area of 40 - 60 % ice cover, they observed that spreading rates and equilibrium slick areas were much less than the corresponding values for open water. Further, they concluded that oil and ice moved together in ice concentrations above 30 %. For ice concentrations less than 30 % the oil will behave in a manner similar to a spill in open water.

Sørstrøm et al. (1994) conducted a controlled oil spill (26 m^3 of North Sea crude) in the Barents Sea marginal ice zone (broken ice of 80-90 % coverage at the spill site). The spill was extensively monitored and sampled during 6 days of operation. During the 6 day period of monitoring, the opening between the ice floes were small, and the drift buoys deployed in the spill closely followed the drifting ice. No relative drift between the oil and the ice was observed. The average drift speed of the slick during this period was 0.26 m/s with a maximum of 0.54 m/s during a passage of a pressure low. From the estimates of the mass balance of the spilled oil and the mapping of oil and ice, the average thickness of the oil/emulsion varied from about 6 -7 mm shortly after the initial spread, to about 1 mm at the end of the 6 day observation period.

Venkatesh et al. (1990) cited several data sources and also assume an oil spill in low ice concentration (< 30 %) to be treated as a spill in open water. In high ice concentrations (> 80 %) they consider oil drift and spreading to be quite different. At such a high ice concentration circular floes will be in contact and thus restricting lateral movement of the oil. In this case oil may be locked by the ice and the oil slick thickness will be much greater than the equilibrium thickness for open water. Venkatesh et al. (1990) propose a number of empirical formulas for the spreading rate and maximum slick extent for these conditions.

A few laboratory studies have been conducted to examine the spreading in brash ice (Yapa and Chowdhury, 1990; Yapa and Belaskas, 1993; Sayed and Løset, 1993; Sayed et al., 1994). Some of these studies have resulted in formulas for oil spreading rates and equilibrium extent of slicks in brash ice. However, the formulas suffer from limitations in the present knowledge of oil-ice interaction.

The spreading mechanisms of oil, for example in broken ice, is poorly understood. There are in fact no generic theories or data that can adequately determine spreading rates, oil thicknesses and oil advection and modes of oil-ice interaction (Sayed et al., 1994).

2.3 Oil on level ice

The bulk of field and laboratory studies investigating the fate and behaviour of oil and ice have focused largely on scenarios that exclude significant oil/snow interactions (Dickins, 1992). However, a few studies exist which consider surface oil spill processes on, through and under snow with ice as a substrate. These studies include field test programmes, spills of opportunity and theoretical descriptions.

Several simplified theories exist that may describe the mechanisms of oil spreading on ice with or without snow (McMinn, 1972; Chen et al., 1974; Siu et al., 1977; Kawamura et al., 1986). Several of the theories apply the principles first established by Fay (1971) for oil spreading on water. Fay assumed the spreading to be governed by gravity, surface tension, inertia and viscosity.

Ovsienko (1993) is underway with a thorough description of the various mechanisms and also numerical solution algorithms for oil on level ice with and without snow, while Dickins (1992) summarizes the different western approaches with a wide variety of formulas and parameterizations for the spreading rate and maximum areal coverage. However, it is clear that a linkage between oil weathering and oil-ice and oil-snow interactions has not been established and the validity of the different models is still quite limited.

2.4 Recommendations

2.4.1 Oil on open water

The mechanisms for drift and spread of oil are highly dependent on the spill environment. The processes on open water are relatively well understood and appropriate models exist. Efforts in modelling these processes will probably continue to apply the surface wind and underlying (non-wind-driven) current.

The approach by Kirstein et al. (1985) appears to allow a good representation of the evaporation process for open water. This methodology accounts for the changing characteristics of the oil as the more volatile components evaporate rapidly.

Further, the dispersion studies of Delvigne and Sweeney (1988) offer a good approach for characterizing entrainment (Reed, 1992). At present the emulsification algorithm of Mackay et al. (1982) is the one most widely used.

Biodegradation is rather site specific and no generic model exists. Reed (1992) suggests to describe it as a first-order decay process. Rates are suggested by e.g. the National Research Council (1985).

Modellers tend to use particle representation in their modelling efforts which also allows both 2-D and 3-D representation. In this way subsurface processes (turbulent transport, buoyancy, dissolution, suspended sediment interactions, settling) can be related to the particle size distribution.

For the NSR we cannot see that any of these processes need any further refinement.

2.4.2 Oil with ice and snow present

The presence of ice can substantially affect the fate of spilled oil. Several processes are poorly understood and a variety of limited semi-empirical and empirical parameterizations exist. There are in fact no generic theories or data that can for instance determine spreading rates, oil thickness and oil advection and modes of oil-ice interaction.

So far we have to lean on "best available data and theory" and hope for further advances in the time to come. For instance, theoretical studies by Ovsienko (1993) seems quite promising and should be promoted.

3 STATISTICAL OIL DRIFT MODELS

3.1 Introduction

Pollution is the most serious environmental threat related to traffic of the NSR. The effects of oil on Arctic primary producers (phytoplankton) and to zooplankton are poorly known. Plankton is the basis of all marine life, and significant reductions of plankton in one area will seriously affect all other life. Small oil spills and their individual effects are hard to detect. If they occur frequently, however, the additional effects may constitute a permanent stress on population and ecosystems, making them less able to withstand other natural or human induced stress factors. In order to assess the environmental effects of possible increased sailing activity along the NSR, relatively detailed information is needed on the ecosystems occurring in the area that will be affected.

In order to quantify the assessment of possible conflict between oil and vulnerable resources, oil drift data is needed to give a measure of the potential impacted area. The main objective of the statistical oil drift model is to provide oil drift data for environmental impact assessments in the region of concern. The oil drift data required in the first stage of the environmental impact assessment are mainly related to a regional mapping of critical parameters s.a.:

- minimum and average drift time to shore
- minimum and average drift time to the ice edge (oil spill outside the ice edge)
- maximum and average drift time in the ice
- probabilities for stranding within certain drift periods
- average amounts of oil stranding

Most statistical oil drift models for open waters are based on the trajectory concept which means that the models simulate the drift and weathering of the oil spill as individual points of mass released at different times within the available historical time series of wind data. Advection and loss of oil due to evaporation and natural dispersion as well as oil stranding are the main physical processes accounted for in such models.

Spreading of viscous oils in broken ice fields with very high concentrations of ice or on top of brash ice can result in oil film thicknesses several times higher than those in low ice concentration. Broken and brash ice conditions generally present hard or solid ice with water in between. Slush or grease ice on the other hand is soft and permeable and affects the spreading of oil in a different fashion. A review of available literature of oil interactions with ice has been done by Dickins (1992), see Chapter 2.

3.2 Oil drift model concepts

In order to get a realistic picture of the potential impact from possible major spills, a large number of spill scenarios must be investigated based on historical data. The need for long-term predictions of several spills implies the need for an efficient and probably simplified representation of oil-ice interactions, with the emphasis on drift and spread of the oil on a large scale.

There are no theories or data that can adequately determine, for example, spreading rates, oil advection, oil thicknesses and modes of oil-ice interactions. A review of available literature of oil interactions with ice has been done by Dickins (1992). The work of Elliot (1986) and Johansen (1985, 1987 and 1988) describe spill spreading by near-surface shear. Their approaches are based on particle representation of spilled oil. Although several studies have been carried out to understand the behaviour of oil under different ice conditions (e.g. Yapa and Chowdhury (1990), Payne et al. (1991), Ross and Dickins (1987), Sørstrøm et al. (1994)), several simplified assumptions still have to be made for oil-ice interactions. The difficulty is compounded by the need to predict how the oil will behave, as well as how the ice may change in character from day to day.

The basic choice between model concepts is mainly a choice between *Eulerian or Lagrangian* models. Most oil spill models for open waters are based on Lagrangian concepts, which means that oil is represented as oil particles advected in a prescribed current field. The original version of this type of models is represented by trajectories models, where the spill is represented as a point of mass and the outcome of the model is the trace described by this mass point in the prescribed surface current field (Krogh et al., 1978). In more recent developments of oil drift models, concepts based on particle models seem to be preferred (Reed, 1992).

During the last years the knowledge about processes influencing the spreading of oil has improved. As a consequence, a new generation of oil drift models has emerged, where the trajectory model concept has been replaced by a particle model concept. The *trajectory* model concept is however still relevant for statistical models applied for consequence studies, where the computations for a large number of oil spill scenarios calls for a simpler and less time consuming approach.

In a particle *model concept*, a continuous discharge of oil is represented by clouds of particles discharged at fixed time intervals. Each cloud represents the mass of oil discharged during the model time step. The spatial dimensions of this cloud are chosen to represent the lateral and longitudinal spreading of this mass due to e.g. gravity forces and drift in the ambient current.

In *Eulerian models* oil drift and spreading are modelled by transfer of oil from one cell to the neighbouring cells (Venkatesh et al.,1990). Oil drifting in different ice forms may in principle be treated differently, but differences in the initial spreading can not be resolved below the scale of the grid cells used in the model. The oil originating from the discharge must as a minimum fill one cell, or expand into neighbouring cells. The resulting spreading will thus to a large extent depend on the grid size. If the cell size is determined by the grid size in the underlying ice model the numerical diffusion will dominate and the spreading of the oil will be far from the reality. The problem of scale is one of the most intriguing problems in relation to oil drift models in ice-infested waters. In a region adjacent to the source, the lateral dimension of an oil spill will in general be much less than the dimension of the grid cell in an Eulerian ice drift model. The different ice forms will in general be present at scales below the grid size in such ice drift models.

Trajectory models may with some modifications be used in statistical models for consequence studies, while *particle models* may be the best choice for operational models, where details related to oil-ice interactions and portioning of the oil between different ice forms will be required. Within the Norwegian project "Oil Spill in Ice Model Development", sponsored by the operators north of 62°N (OKN), a numerical model system for oil spill in ice for the Barents Sea is specified. Both a forecast model and a statistical model as well as an ice drift model are in development. The project is carried out by The Norwegian Meteorological Institute, Oceanor A/S and SINTEF NHL and will be finished in the summer of 1995. The statistical oil drift model will be relevant for parts of the NSR to produce oil drift data for impact assessment study (Johansen, 1993).

3.3 Recommendations

Within the next phase of INSROP a statistical oil drift model should be selected and modified for computing oil drift trajectories for impact assessment studies. The mapping should be made for different seasons of the year in order to reflect the effects of seasonal variations in wind climate and ice coverage.

The statistical model should provide the following information:

- minimum and average drift time to shore
- minimum and average drift time to the ice edge (oil spill outside the ice edge)
- maximum and average drift time in the ice
- probabilities for stranding within certain drift periods
- average amounts of oil stranding

The NSR is a very large area and mapping the whole area with a spatial resolution of 20 km will result in an enormous amount of simulations. Within regions with high risk for accidents and vulnerable resources special attention should be made during the consequence study. It means that the mapping should be performed with a high spatial resolution for those areas and lower resolution for less risky areas. The statistical model should be able to handle several spill sites in one model run with the positions of the spill sites specified by the user.

The statistical oil drift model may be based on the following historical input data:

- monthly averaged background current data stored in a regular grid
- historical time series of surface wind (minimum 20 years with data)
- historical data on ice coverage (ice type and fraction of different ice types)

The historical data on ice coverage should be gridded with a temporal resolution of 1 day (or 1 week). Landfast ice will prevent oil stranding and should be one of the ice categories within the historical database. Oil spilled in slush, grease ice or brash ice will have a higher equilibrium thickness than oil spilled on open water between ice floes. Therefore, different categories of ice should be available in the geographical information system and the following are recommended:

- new ice (frazil ice, grease ice, slush and shuga)
- first-year ice
- landfast ice
- multi-year ice

In order to provide required output, the physical processes to be represented in the model should as a minimum include:

- drift of oil in open water and broken ice in response to wind and current
- reduction in the amount of oil due to weathering processes, i.e. evaporation and natural dispersion
- effects of the presence of sea ice on these processes.

Both natural dispersion and evaporation rates will be influenced by the presence of sea ice. Natural evaporation depends mainly on the wave conditions which in the open sea may be related to the wind speed. Waves propagating into the ice field (during on-ice wind) will be damped by the presence of ice floes. The evaporation rate will also be influenced by the presence of sea ice. Based on the experimental oil spill carried out in the Barents Sea (Sørstrøm et al., 1994) the evaporation was only about 20 %. During the field experiment the ice concentration was relatively high, about 75 - 90 %, and the oil drifted with the ice. Oil spilled in ice will spread more slowly than in open water and the spreading depends strongly on the ice conditions.

4 OPERATIONAL ICE DRIFT MODELS

The design of a forecast system will depend on a set of forecast criteria:

- forecast horizon
- required degree of accuracy
- acceptable costs for producing a forecast
- required degree of complexity
- available input data

The required accuracy is obviously higher for short term forecasting than for long term forecasting. For long term forecasting, whether it is seasonal forecasting for consequence studies or forecasting to estimate transit time and costs, the forecast accuracy must be satisfactory to decide on the technical and economical feasibility of sailing through the NSR. For short term forecasting the accuracy must be good enough to obtain ice breaker assistance when it is necessary or to avoid difficult ice conditions (routing of ships in ice). The short term forecast accuracy must be good enough to maintain the requested safety level for any passage. Since the wind forcing is the main driving force for rapid change in the ice conditions, the short term forecasting will be limit by the length and accuracy of the wind forecast.

The complexity of the forecast system must be sufficient to obtain the requested accuracy level. A decision on the complexity must therefore be made based on analysis of the variability and interaction of the ice condition parameters affecting transit time and safety for a particular ship through the NSR for any month of the year.

The Automatic Ice Information System of Arctic (ALISA) compiles ice information from a number of Russian remote sensing sensors, vessels in the area and various automatic and manned field stations. However, data is compiled also from the current operational western satellite sensors like AVHRR (NOAA), SSM/I (DMSP) and SAR (ERS-1, JERS-1, RADARSAT). The ALISA is a hierarchical system where the processing of ice and hydrometeorological information is carried out in centres at different levels. There are local centers in Dikson, Pevek, Murmansk, Amderma and Tiksi collecting ice data from their respective zones of responsibility. The local centres also make short term (1 - 3 days) forecast of meteorological and ice parameters. The main centre of ALISA is at AARI where information from the local centres is compiled and combined with other ice information to complex ice maps including all parts of the Arctic Ocean. The main centre produces meteorological and ice forecasts 7 - 8 days in advance.

Regional ice drift models as well as local models for difficult navigation areas are briefly discussed in the following sections.

4.1 Survey of regional ice drift models for the NSR

A literature survey has been performed in order to identify relevant models predicting the time development of the sea ice cover. The review has been concentrated to short-term ice motion models. Most of the information about the models has been derived from the Journal of Geophysical Research (several issues) and from scientists working with sea ice modelling. The reports by Nazarenko and Desrochers (1991) have also given valuable information to this study.

Previous research (Hibler, 1985; Leppäranta and Hibler, 1985) indicates that the dynamic balance of an ice cover is largely dominated by the air stress, water stress, Coriolis force and internal ice force. A viscous-plastic constitutive relation has been successfully used for calculating the internal ice force in the simulation of polar regions (Hibler, 1979; Preller, 1985). The elastic-plastic formulation originating from the AIDJEX modelling in the 1970s is still used (Pritchard et al., 1988).

The area near the ice edge where the ice field consists of a large number of discrete floes, is most probably covered by a different rheology than in the interior ice field. Work by Shen et al. (1984) explored the suitability of a floe collision ice rheology. Løset (1994) considers a viscous dissipation of energy through the brash ice in the marginal ice zone. Basically the model assumes contact forces to arise from finite duration of floe deformation (overlap), rolling and sliding. The behaviour of the assembly is determined by calculating the motion of the individual floes as they interact with each other and the boundaries. Multiple overlaps are allowed and a visco-elastic rheology is applied.

Proshutinsky et al. (1992) give a short review of the state-of-the-art of sea ice drift models in use at the Arctic and Antarctic Research Institute (AARI) in St. Petersburg. The models are of the regional type and cover the Arctic oceans and the marginal seas. Three main categories of models are presented:

1) The autumn-winter and spring-summer model of the ice and hydrological events
2) Ice drift of variable thickness
3) Wind and tidal ice drift

The spatial resolution in the models varies from 55.5 km - 200 km. None of these models focuses on local ice conditions and they are therefore not of special interest for the oil-in-ice study. Review of local ice drift models from Russia should therefore be performed.

Most sea ice models are based on an Eulerian description, but some are using a Lagrangian one. In the Lagrangian description single ice floes are identified and their motions followed, giving high resolution since the motion of each particle is followed explicitly and there is no numerical dispersion of ice across the grid lines. However, if large shearing occurs, numerical solutions become inaccurate. In the Eulerian description fixed positions in space are identified, and motion of ice floes through the grid is followed. This approach is good when severe deformations occur because the grid is not deformed, but ice within a cell at each time step is diffused throughout that cell, and there is no way to identify the position of a particle within the cell. An Eulerian description requires that a large number of cells be maintained near the ice edge and beyond, to cover the regions into which ice might drift.

4.1.1 Operational sea ice models

This section gives a summary of existing operational sea ice models which may be of relevance for the Northern Sea Route. The operational ice drift models available are mainly Eulerian models and provide forecasts of large scale sea ice drift and thickness distribution. For all operational applications models must be practical in the sense that input requirements, model initialization and model execution can be done routinely as part of normal operational activities. Table 4.1 gives an overview of relevant operational ice drift models.

Table 4.1 Summary of operational sea ice models.

Sea ice models	Space resolution	Predicted parameters	Users
AES - Regional Ice Model (RIM)	42.3 km	Ice concentration, ice strength, ice thickness, roughness, ice velocity	Federal government (AES)
Pritchard - Ice Edge Model	50 km; 5 km near the edge	Ice edge, surface current, sea surface temperature, salinity, ice velocity	University/private/industry (NPS/firms/ARCO)
NOARL - Regional Polar Ice Prediction System - Barents Sea	25 km	Ice thickness, ice velocity and ice concentration	U.S. government (NORDA)
El-Tahan - Ice Floe Drift Model		Ice velocity, ice edge	Crescent Consulting Ltd
Kozo - Sea Ice Movement Forecasting Model	5 x 5 km	Ice velocity, geostrophic wind velocity	University USNA/Alaska
Kara Sea Model (Ovsienko)	5-15 km	Ice and ocean dynamics	State Oceanographic
Amoco/Canmar Ice Forecasting	8 x 8 km	Ice concentration	Industry

Two simple operational ice forecasting systems are included in the table. Kozo et al. (1987) use surface atmospheric pressure data from a triangular station network surrounding the Bering Strait to derive hypothetical geostrophic winds. These are then used in conjunction with net daily sea ice estimates obtained from NOAA satellite imagery to project an empirical 12 hrs forecast of sea ice movement.

The Amoco/Canmar Ice Forecasting system is used for the Beaufort Sea (Steen and Trobak, 1987). The ice forecasting system consists of a deterministic and an analogue model. The complexity of the deterministic model may range from a simple wind driven model to one which uses all available measured data, ice drift, ice draft, ocean current velocity, observed wind, forecast wind etc. The analogue model consists of measured ice movement and recorded wind velocities for the corresponding period. Based on the latest weather forecast, the analogue model will then sort the data base to locate 24 hour blocks of data where the historically observed wind matches the forecast wind within specific criteria. The system monitors ice movements over the past 12 - 24 hrs and predicts ice concentrations.

A coupled ice-ocean model (Ovsienko, 1994) with prognostic temperature and salinity fields and realistic bottom topography is used to simulate the ice and ocean dynamics in the Kara Sea. A sea ice model with elastic-plastic rheology is coupled to a 3D prognostic baroclinic circulation model. Thermal forcing is determined from daily mean values of atmospheric data. Initial water temperatures and salinities are determined from satellite data. For the spatial discretization, a finite element method with triangular prismatic elements is used. The spatial extent of the elements is 5 - 15 km.

AES-Ice Branch has a mandate to provide timely and accurate ice information for Canadian waters on an operational basis. Included in this mandate is the requirement to provide prognostic ice information to support all Canadian marine activities. The Regional Ice Model (RIM) is currently used routinely at the Ice Centre in Ottawa to assist ice forecasters in the preparation of daily ice analysis charts. RIM is also used to provide information to the OILBRICE model (Venkatesh et al., 1990).

The RIM model is based on the viscous-plastic constitutive law of Hibler (1979). The model has been used for predicting ice conditions in the Beaufort Sea and in the Labrador Sea area off the Canadian east coast. In both instances a finite difference grid with a mesh size of 42.3 km was chosen and the model domain covered an area 930 km by 930 km. A time step of 3 hours was used in the model integration.

The U.S. Navy presently runs three sea-ice forecasting models on a daily basis: the Polar Ice Prediction System (PIPS), the Regional Polar Ice Prediction System - Barents (RPIPS-

B) and the Regional Polar Ice Prediction System - Greenland (RPIPS-G). These models forecast ice drift, ice thickness and ice concentration at grid resolutions ranging from 20 to 127 km. The PIPS sea ice forecasting model has successfully been coupled to the Bryan-Cox ocean model (Riedlinger and Preller, 1991).

The ice edge model in El-Tahan and Warbanski (1987) is oriented towards the strategic ice management needs of the East Coast oil and gas industry and is fully operational. The model is developed to produce short-term forecasts (one or two days) of the edge of the free drifting pack ice in support of oil drilling activities on the Grand Banks. Thermodynamic aspects (ice growth/melt) and ice-ice interaction are ignored. The model considers wind forces, wind generated currents, residual currents, Coriolis force and sea-surface slope. Ice edge data collected from aerial reconnaissance flights is used to update the model. The model can predict the position of the ice edge generally with less than 25 % error (of the drift distance over time).

A more sophisticated ice edge model is presented in Pritchard et al. (1990). They present a coupled ice/ocean dynamic model which was developed to provide Arctic offshore operators with 5- to 7-day forecasts of ice motions, ice conditions and ice edge motions. The forces acting on the ice cover include air stress, water stress, internal ice stress, sea surface tilt, and Coriolis and inertial accelerations. Thermal energy and mass budgets are included to describe the temperature and salinity changes that accompany the melt or growth of ice. An adaptive grid is introduced to follow the ice edge, and the grid may move independently of the ice motion. The grid can be Lagrangian or Eulerian at different locations away from the ice edge. The model uses a Lagrangian formulation near the ice edge, while in from the edge a computationally more efficient Eulerian approach is employed. Ice stress is described using an elastic-plastic model with strength determined by the ice conditions. The ocean dynamics model describes time-dependent, three-dimensional behaviour, including wind-driven currents and barotropic and baroclinic flows. The thermal energy budget of the ice cover is coupled to the ocean, with mass and salt interchange accompanying freezing or melting. Comparison of modelled results in the Bering Sea with observations indicate ice edge agreement to within 5 km/day.

The forecast model is driven by weather forecasts supplied by an outside source (e.g. NOAA/Navy Oceanographic Data Distribution Service or National Weather Service). The model requires that the present ice and ocean conditions are specified as initial conditions. The model can forecast motions of the ice cover, and changes in ice conditions, ice edge location, ocean currents, salinity, temperature, and density fields. The ocean and ice models are coupled explicitly, with each time step of the ocean model using a known state of the ice.

4.1.2 Research-oriented sea ice models

The purpose of this section is to document the type of research and development work that is being done on sea ice models. Undoubtedly, the review does not include every model that has been developed, but the models described are considered to represent the research presently being conducted. Table 4.2 provides a summary of most of the western research-oriented models. All the models are described in more detail in Vefsnmo and Løvås (1992).

Lu et al. (1990) presented a mesoscale dynamic thermodynamic sea ice model (SIM-2). The model differs from the large-scale Hibler sea ice model (Hibler, 1979; Parkinson and Washington, 1979) in both the dynamic and thermodynamic parts. In the dynamic calculation, a constitutive relation based on ice floe collision is used for the determination of the internal ice force in the MIZ and coupled with a viscous-plastic model used in the central part of sea ice cover. In the thermodynamic calculation a three-level approach for the ice thickness distribution is adopted instead of the common two-level approach (Hibler, 1979). It is demonstrated that this mesoscale sea ice model has the potential of a more accurate description of the dynamics and the thermodynamics than the previous models in the simulation of sea ice processes in subpolar regions.

Table 4.2 Summary of relevant research-oriented models.

Sea ice models	Type	Spatial Resolution	Predicted parameters
Lu - Mesoscale Sea-Ice Model	Meso scale	30 km/ 15 km/ 1 km	Ice concentration, thickness, ice velocity, ice edge position
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	Meso scale	15 km	Ice velocity, concentration, thickness, salinity, surface currents, SST
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	Small scale	1 km	Ice velocity, ice thickness
Oberhuber - Coupled dynamic thermodynamic ice-ocean model	Meso scale	25 km (preliminary tests with 1 km)	Ice velocity, ice thickness, ice concentration, melting/freezing rates, ice ocean stress and heat flux, ocean mixed layer thickness, ocean currents, temperature and salinity, sea surface elevation
Simple Steady-State Coupled Ice-Ocean Model	Meso scale	20 km	Ice edge, ice concentration, SST, ice thickness
Tang - Coupled ice-ocean dynamic model	Meso scale	20 km	Ice velocity, concentration, thickness and ocean current
Mellor - MIZ Coupled Ice-Ocean Model	Ice edge	7.5 km	Total and partial concentration, ice velocity
Ikeda - Labrador Shelf Dynamic/ Thermodynamic Sea-Ice Model	Regional	25 x 50 km	Ice concentration is simulated to give accumulated ice
Ikeda - Coupled Ice-Ocean Model	Regional	25 x 50 km	Ice velocity and ice concentration
Waterloo - Short-Term Sea-Ice Motion Model	Regional	40 km	Ice velocity, concentration and thickness

There are two moving boundaries in the model by Lu et al., one is an open ice/open water boundary and the other is a moving boundary between the MIZ and the central part of the sea ice cover. The former determines where the dynamic simulation should be carried out, the latter determines where the collision model should be used and where the viscous-plastic model should be used for the calculation of the internal ice force.

Danish Hydraulic Institute is working with a nested grid approach for local sea ice simulation (grid size is about 1 - 2 km). The nested grid model is based on SIM-2. The governing equations for the local model are the same as for SIM-2. The collisional rheology for the MIZ is also used in the nested grid model. The boundary conditions of the nested grid model are transferred from the mesoscale model simulation. The nested grid model has been used in the Greenland Sea with a spatial resolution of 1 km. The mesoscale model was run with a resolution of 15 km. The initial total sea ice concentration was from Landsat MSS images.

There has been evolutionary progress toward completely coupled, ice-ocean numerical models. Coupled ice-ocean models have been applied to MIZ processes in the past, notable examples being Røed and O'Brien (1983), Røed (1984), Smedstad and Røed (1985) and Hakkinen (1986a, b). The models attempted to simulate and understand ice edge processes such as upwelling/downwelling, ice banding, and eddy generation, using the simplest possible dynamics. They restricted the oceanic component to a reduced gravity model and concentrated on the ice-ocean interaction, using either simplified (Røed and O'Brien, 1983) or comprehensive (Hakkinen, 1986a, b) ice rheology. On the other hand, multi-level ocean models have been coupled to the ice and applied to the Arctic Ocean by Hibler and Bryan (1987) and Semtner (1987) and to a wind-driven coastal shelf by Ikeda (1989).

4.2 Local ice drift models

4.2.1 Introduction

A broken ice field may be described as an ensemble of ice floes. The ensemble of ice floes may then be modelled as circular discs of different diameters. The dynamic behaviour of the ensemble is determined by calculating the motion of the individual discs caused by interaction forces and body forcing (shear forces from air and water drag, surface tilt and Coriolis forcing). The interaction forces arise either directly from contacts between adjacent discs or by squeezing of brash ice which may be present between the distinct floes. Multiple contacts between discs are allowed and a visco-elastic-plastic rheology is applied at contacts.

To handle a broken ice field with the discrete element approach has been proposed by a number of scientists (Shen et al., 1986; Serrer et al.,1993; Løset, 1993 and 1994). The discs can be viewed as a granular assembly where the collisions are of finite duration (soft particle approach). The most comprehensive and generic one is probably that of Serrer et al. (1993).

Løset (1994) describes a discrete element model which applies the soft particle approach to an ensemble of circular discs of different diameters. In this section we will briefly describe the rheology of one of these models.

4.2.2 Kinematics

The broken ice field (ice fragments) is constrained in a domain with periodic boundaries. Brash ice may be present at the free water surface and it is viewed as a viscous fluid. The latter means that brash ice is treated as a material with no rigidity. The discs are allowed to translate and rotate and may interact with other discs or the domain boundaries. Using a rectangular Cartesian coordinate system, two discs in contact are labelled i and j as shown in Figure 4.1. The centre coordinates of disc i are $\boldsymbol{x}_i=(x_i,y_i)$, the angular velocity is $\dot{\omega}_i$ (taken positive in the counterclockwise direction) and the radius is R_i.

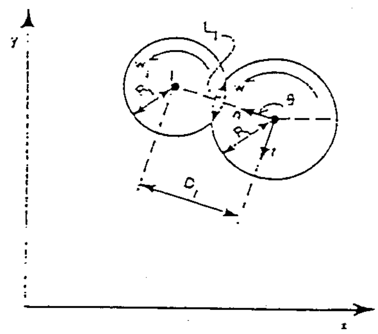

Figure 4.1. Sketch showing contact between discs i and j.

The normal and tangential unit vectors at the point of contact between discs i and j are defined by the relation

$$\begin{aligned} \boldsymbol{n} &= \frac{\boldsymbol{x}_j-\boldsymbol{x}_i}{D_{ij}} = (\cos\theta, \sin\theta) \\ \boldsymbol{t} &= (-\sin\theta, \cos\theta) \end{aligned} \tag{4.1}$$

where $D_{ij}=|\boldsymbol{x}_j-\boldsymbol{x}_i|$ is the instantaneous centre to centre distance between discs i and j. The relative velocity at the point of contact is given by

$$\dot{\boldsymbol{x}}_{ij} = \dot{\boldsymbol{x}}_i-\dot{\boldsymbol{x}}_j+(R_i\dot{\omega}_i+R_j\dot{\omega}_j)\boldsymbol{t} \tag{4.2}$$

and the relative displacement rates $\dot{n}$ and $\dot{t}$ respectively in the normal and tangential directions are the projections of $\dot{\boldsymbol{x}}_{ij}$ onto $\boldsymbol{n}$ and $\boldsymbol{t}$

$$\begin{aligned} \dot{n} &= \dot{\boldsymbol{x}}_{ij}\cdot\boldsymbol{n} \\ \dot{t} &= \dot{\boldsymbol{x}}_{ij}\cdot\boldsymbol{t} \end{aligned} \tag{4.3}$$

4.2.3 Equations of motion

A positive relative displacement rate means approaching discs. The body force (F_{bi}) comprises shear forces from air and water drag, surface tilt and Coriolis forcing. The body force is regarded as 'one way'; movements of the disc ensemble have no effect on the surface current for example. The balancing of the body force, the contact forcing (F_{ij}) and the remote forcing of disc i, may be written as

$$m_i \ddot{x}_i = \sum_b F_{bi} + \sum_{j \neq i} F_{ij} \tag{4.4}$$

$$I_i \dot{\omega}_i = \sum_b T_{bi} + \sum_{j \neq i} F_{ij} \cdot t R_i \tag{4.5}$$

where $m_i = m_{0i}(1 + C_m)$ and m_{0i} is the mass of disc i. C_m is added mass coefficient, R_i is radius of disc i and I_i is the moment of inertia about a vertical axis.

The first term on the right-hand side of Eq. (4.5) represents only the viscous resisting torque arising from the bottom water shear stress due to the spin of the disc. The second term comprises torques caused by contacts between discs or disc-boundary. Numerical integration of Eq. (4.5) is used to compute the angular position of disc i.

4.3 Recommendations

An operational model for forecasting the ice conditions must be practical in the sense that input requirements, model initialization and model execution can be done routinely as part of normal operational activities. Most of the operational ice drift models in use today are meso-scale/regional models of the Hibler type with an Eulerian grid.

The plastic rheology may be a good approximation for a closely packed collection of large ice floes, inter-locking with and grinding against one another, a situation existing in the interior Arctic pack ice. However, for the marginal ice zone, where a loose collection of relatively widely spaced small ice floes bump and grind against one another, the rheology might more appropriately be a non-Newtonian fluid rheology (Shen et al., 1987). Such collisional rheology has been used in another interesting concept for meso-scale sea ice modelling by Lu et al. (1990).

As mentioned in Chapter 2, the sea ice processes and parameters significantly affect the fate and behaviour of oil. In order to account for these effects, detailed information of the ice conditions will be required, including total ice concentration, floe size distribution, ice thickness and areal fraction covered by different ice types. Since the marginal ice zone is a highly dynamic area, the position of the ice edge is important for the oil-in-ice modelling, especially for oil spills outside the ice edge.

In order to provide the operational oil drift model with necessary details of ice information, a two-level concept for the ice drift model is recommended. This concept involves a mesoscale ice drift model (spatial resolution 25 km) for the NSR and a local model in the vicinity of the oil spill. The mesoscale ice drift model will produce general forecasts for the ice conditions in the NSR. The local ice drift model will only be run during special conditions, for instance an accidental oil spill situation.

A mesoscale sea ice model with a resolution of about 20 km coupled to an ocean model should be implemented for the NSR. The model should also consider thermodynamics. The ice drift models should be tailored to the region of concern and the NSR should therefore be covered by more than one ice drift model (perhaps one for each sea). The wind forcing should act on both ice and ocean, using drag coefficients which depend on ice roughness and ice concentration.

In most mesoscale models, some important physics s.a. tidal current effects, wave effects and floe size distribution are lacking. The weathering processes of the oil depend strongly on the wave conditions in the ice field. Present wave prediction models do not provide such data, therefore efforts should be made to include wave attenuation in the ice drift model.

The mesoscale model will not give details of the different ice types. Therefore, a local model covering an area of approximately 200 km x 200 km around the oil spill should be nested to the mesoscale model. The equations for the local model should be mainly the same as for the mesoscale model, but the local model should be run with more detailed information of ice types and concentrations. In the local model, each grid cell should include information about floe size distribution, ice type fraction and thickness. Efforts should be made to include different ice types (new ice, brash ice, first year ice, multiyear ice).

A modified version of the discrete element model (Løset, 1994) is recommended to act as the local ice drift model (a strong alternative is the model of Serrer et al., 1993). Løset treats a broken ice field as an ensemble of discs. A discrete element model is used to describe the dynamic behaviour of the ensemble. Important features of the model, are:

1) The ensemble of ice floes is treated as a granular material consisting of circular discs of different diameters.

2) The dynamic behaviour of the ensemble is determined by calculating the motion of the individual discs caused by interaction forces and shear forces from air and water drag, surface tilt and Coriolis forcing.

3) The interaction forces arise either directly from contacts between adjacent discs or by squeezing of brash ice which may be present between the distinct floes. A visco-elastic-plastic rheology is applied at contacts.

The boundary conditions for the local model will be given by the mesoscale model. The local ice drift model should also preferably be coupled to a local ocean circulation model. Interpolation techniques can be applied to derive the necessary information on the boundaries of the local model.

A fully coupled ice-ocean model better represents ice-ocean interaction. The coupling of the ice and ocean results in improved temporal variability of ocean circulation and heat and salt exchange between ice and ocean. Therefore both the mesoscale model and the local model should be coupled to the ocean.

5 OPERATIONAL OIL DRIFT MODELS

5.1 Physical basis

The behaviour of oil at sea is a complicated problem, which depends on physical properties of oil and hydrometeorological conditions and usually includes wind drift, oil spreading on the surface, dissipation under influence of shear stresses in air and water, evaporation, emulsification, dissolution, shoreline-oil and bottom-oil interaction. In ice infested waters it is necessary to add oil spreading on level ice (with or without snow), under level ice and in broken ice with different compactness.

All the mechanisms mentioned above have different physical background, different time and space scales and consequently different possibilities of being modelled. With lacking knowledge about these mechanisms, the combination of models with quite different theoretical basis and properties have to include semi-empirical and empirical parameterizations.

Let us assume an approach in two steps (Ovsienko et al., 1994). The *first part*, processes, concerns a formalization into a quasi-two-dimensional problem with free boundaries and/or contact boundaries for compressible media (oil spreading, ice dynamics), usually such processes connected with unlocal effects.

The *second part* deals with processes connected with local effects, which usually describe the property of media, such as evaporation and dissolution for oil and melting of ice. Very often for such processes it is rather difficult to find effective theoretical description and it is preferable to use semi-empirical and empirical parameterizations.

In this way the mathematical technique must be effective to solve the two-dimensional equations with free and contact boundaries and permits to include and change empirical parameterizations of local effects.

The spreading of oil on the sea surface can be described as a two-dimensional problem (for operative purposes) consisting of the following *basic equations*:

$$\rho_o H[\vec{u}_t + (\vec{u}\nabla)\vec{u}] = -g'\nabla H - \beta[\vec{u} - (\vec{u}_d + \vec{u}_T)] \tag{5.1}$$

$$H_t + \nabla\cdot(H\vec{u} + \frac{1}{2\mu}\vec{\tau}H^2) = -\frac{(k_1 + k_2 + k_3 - Q)}{\rho_o} \tag{5.2}$$

where

$\rho_o, \vec{u}$	-	oil density and velocity,
H(x,y,t)	-	oil thickness,
g'	-	$g(\rho_w-\rho_o)/\rho_w$,
ρ_w	-	water density,
β	-	empirical drag coefficient,
μ	-	oil viscosity,
k_1	-	mass flux due to evaporation,
k_2	-	mass flux due to entrainment (natural dispersion),
k_3	-	mass flux due to oil-ice interaction,
Q	-	oil discharge at the sea surface from spill source
$\vec{\tau}$	-	wind stress,
$\vec{u}_d$	-	water surface drift velocity or ice drift velocity,
$\vec{u}_T$	-	tidal or another non-local current
$\nabla\cdot$	-	horizontal divergence operator
∇	-	horizontal gradient operator

If the boundary of spilled area is R(x,y,t) = 0 it is necessary to use *boundary conditions* on the free boundary

$$R_t + (\vec{u}\nabla R) - \frac{k_1}{\rho_o}\frac{(\nabla R)^2}{(\nabla H\ \nabla R)} = 0 \tag{5.3}$$

and at fixed (shoreline) boundary

$$(\vec{u}\nabla R) = 0 \tag{5.4}$$

Wind stress is calculated as

$$\vec{\tau} = 10^{-3}(1+0.07|W_{10}|)\rho_a|W_{10}|W_{10} \tag{5.5}$$

where

W_{10}	- wind velocity at 10 m height
ρ	- air density

Surface drift velocity parameterization is

$$u_d = 0.035|W_{10}|$$

$$\alpha_d = F(H/H_o)\{ \begin{matrix} 40^o - 8\,(W)^{1/2}, & if\ W_{10} < 25\,m/s \\ 0^o & , if\ W_{10} > 25\,m/s \end{matrix} \tag{5.7}$$

where

u_d - oil drift velocity

α_d - deflection angle

$F(H/H_o)$ - "tuning" function for applications at shallow-water regions (H < 40 m).

Oil is described as a mixture of several components with known properties. Mass flux due to evaporation may be expressed by

$$k_1 = \sum_i k_m(p_i - p_{i\infty})/RT_s \tag{5.8}$$

where

k_m - empirical coefficient

p_i - partial pressure of i-th fraction in oil mixture

$p_{i\infty}$ - vapour pressure of i-th fractions in atmosphere

R - universal gas constant

T_s - water surface temperature

Under the rough sea state breaking waves cause entrainment of oil droplets from the water surface. The following parameterization of this process is used:

$$k_2 = \rho_o \frac{1.4\,V_{*a}^3 gH}{C_T^4}[1 - 0.15(\frac{1}{18}\frac{\Delta\rho}{\rho}\frac{gH^2}{0.25\,V_{*W}\nu_W})^{1/2}] \tag{5.9}$$

where

$$C_T = 0.8\,|W_{10cr}|,\ |W_{10cr}| - critical\ wind\ speed$$

The behaviour of oil in ice-infested water is very closely connected with ice cover characteristics and properties. All necessary information about ice it is possible to use from external ice dynamics model.

The main feature of the oil spreading model described by equations (5.1) - (5.9) is the possibility to use the same mathematical description for oil spreading on and under the ice. The only difference exists in empirical constants, connected with properties of ice or snow cover and the parameter g´. Hence, the fluxes of mass must be connected with oil-ice interaction.

A more complicated situation exists with modelling of oil dynamics in broken ice. For description of oil spills in broken ice, the following system of equations may be used:

$$\rho_o(1-S)H[\vec{u}_t + (\vec{u}\nabla)\vec{u}] = -g'\nabla H - B_1[\vec{u} - (\vec{u}_d + \vec{u}_T)] - B_2(\vec{u}-\vec{u}_i) \qquad (5.10)$$

$$H_t + \nabla\cdot(H\vec{u}) + \frac{(HS)}{(-S)}\nabla\cdot(H\vec{u}_i) = -\frac{(k_1+k_2)}{\rho_o}F_s(S) + \frac{Q}{\rho_o(1-S)} \qquad (5.11)$$

where

S - ice compactness (concentration)

u_i - ice drift velocity

All other variables are quite similar to equations (5.1) and (5.2). From a theoretical point of view

$$B_1 \propto \beta_1(1-S) \qquad B_2 \propto \beta_2\frac{S}{d}$$

where

d - the mean size of floes

β_1 and β_2 - empirical coefficient,

connected with configuration of the floes, physics of oil-ice interaction and so on. The function F_s describes the influence of ice compactness on mass fluxes due to "shadow effects".

5.2 Numerical solution methods

Both oil and ice models can be determined as two-dimensional problems with free boundaries. The solid boundary condition of the ice model is non-typical and has to be changed during the modelling. Special features of the oil model are the different scales for different processes (from tens metres up to tens kilometres). Because of these reasons, it is rather difficult for such a model to use the traditional Eulerian grid methods and it is preferable to work with a combination of Eulerian and Lagrangian formulation. The technology for the oil-ice model and the ice model are different in details, but the main part is quite similar. The modelling of oil distribution is performed as a group of particles.

5.3 Recommendations

An operational (forecast) oil spill model should produce short term forecast of the drift, spreading and fate of the oil spill. If the oil spill model is to be used for decision making related to oil spill combat and protection of sensitive resources, the model must provide details of spreading, weathering and portitioning of the oil in different ice types.

The importance of the local ice conditions (concentrations of different ice types) must be taken into account in the design of the ice drift model that shall support the oil drift model with ice related input data. Since the weathering processes depend strongly on the wave conditions in the ice field, input from a wave prediction model designed for ice-infested waters may also be required to obtain reasonably accurate predictions of the fate of the oil in the ice.

The concept of an operational oil drift model should follow the lines suggested in Sections 5.1 and 5.2. On a local scale we suggest using a discrete element approach for the ice drift as outlined in Section 4.2 and coupling it with movement of oil as outlined previously in Chapter 5.

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PART III
OIL SPILL COMBAT

1 INTRODUCTION

The annual discharge of petroleum hydrocarbons to the marine environment is about 3.2 million metric tonnes. About 15 per cent of this discharge is caused by accidental spills at sea. Part III of this report gives a brief overview of the commonly available oil spill response systems with emphasis on cold waters.

In principle the oil spill combat systems at sea can be divided into

- mechanical containment and recovery,
- chemical dispersants,
- in-situ burning.

Part III highlights the applicability and efficiency of these combat systems under various conditions (weathering state of the oil, sea state and wind, ice, etc.).

As long as crude oils and petroleum products are transported across the seas by ships there will be a risk of spillage with the potential to cause significant damage. The annual production of hydrocarbons in the early nineties was about 3 billion metric tonnes of which some 50 % of the production is transported at sea (including pipelines). The annual discharge to the marine environment is 3.2 million metric tonnes of which 15 % is caused by accidental spills at sea (National Research Council, 1985). In principle there are two types of oil spills

- surface spill.
- subsurface blowout (gas/oil)

In connection to the NSR we will disregard subsurface blowout because that is mainly related to oil and gas production or pipeline transport.

Over the last two decades major efforts have been made to understand the behaviour and fate of oil spilled at sea and to develop appropriate cleanup techniques. Some efforts are directed towards oil spills in ice where the response is more complicated owing to cumbersome operations and reduced access to the oil. Such a situation will be quite typical for most of the NSR.

Let us focus on the commonly available oil spill response systems of surface spills which for the last decade seem to be the most dominant form of spill. For instance, along the Norwegian coast there has been a number of accidental spills from vessels either in transit or servicing ports and oil terminals on the coast. Recently, the number has increased and it is the most dominant source of accidental spills in the Norwegian terrestrial waters (SFT, 1991). Since 1981 there have been more than ten substantial oil spills requiring action by the Norwegian State Pollution Control Authority (SFT).

Offshore response systems discussed below include application of dispersants, mechanical containment and recovery, and in-situ burning. Sorbents and nutrients (bioremediation) are considered applicable only in calm water and on shorelines. Thus they may have a potential for parts of the NSR.

Harmful effects are discussed briefly by which we mean physical contamination and toxic effects on marine life at sea. Oil spills are defined as accidental spills from any kind of vessel navigating the NSR (icebreakers, cargo vessels, etc.).

2 COMPOSITION AND WEATHERING OF OIL

An oil is characterized by a number of physical and chemical properties which affect the behaviour and fate of the oil at sea. These characteristics include specific gravity, volatility, viscosity, pour point, and flash point and wax content.

These properties are a result of the compounds of an oil which in Figure 2.1 is illustrated for a typical crude oil. In general non-persistent oils are lighter fractions such as gasolene, naphtha, kerosene and diesel while heavier fractions (crude oils, residual oils, etc.) are more persistent at sea.

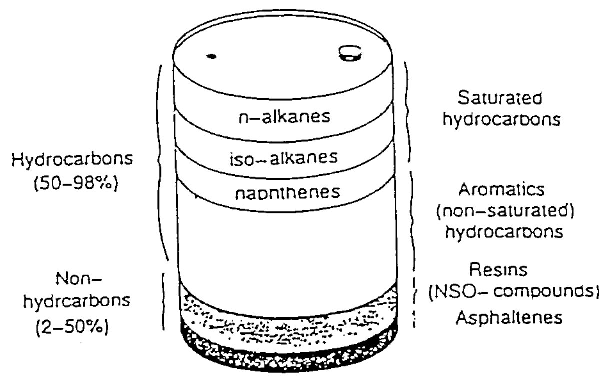

Figure 2.1 Typical composition of crude oils.

Oil spilled at sea undergoes a number of physical and chemical changes (weathering) which affect the persistence of the oil. The oil slick starts to disperse into the water column (forms an oil-in-water emulsion), while the remaining surface oil starts to take up water (water-in-oil emulsion). The major weathering processes, are

- spreading and drift
- evaporation
- dissolution
- dispersion (oil-in-water emulsification)
- water uptake (water-in-oil emulsification)
- sedimentation

and are highly dependent on the original physical and chemical properties of the oil, the weathering conditions (waves, wind, current, sunlight, air temperature, ice) and the water properties (temperature, salinity, oxygen, bacteria, nutrients, particles, etc.).

Figure 2.2 shows the different constituents of the weathering process while Figure 2.3 indicates the basic processes and their time frames. The effectiveness of equipment (countermeasures/devices) hinges strongly on the weathering state of the oil as well as on the physical environment. For instance with ice present, the access to spilled oil may be reduced as reported by Bobra and Fingas (1986) and Sørstrøm et al. (1994).

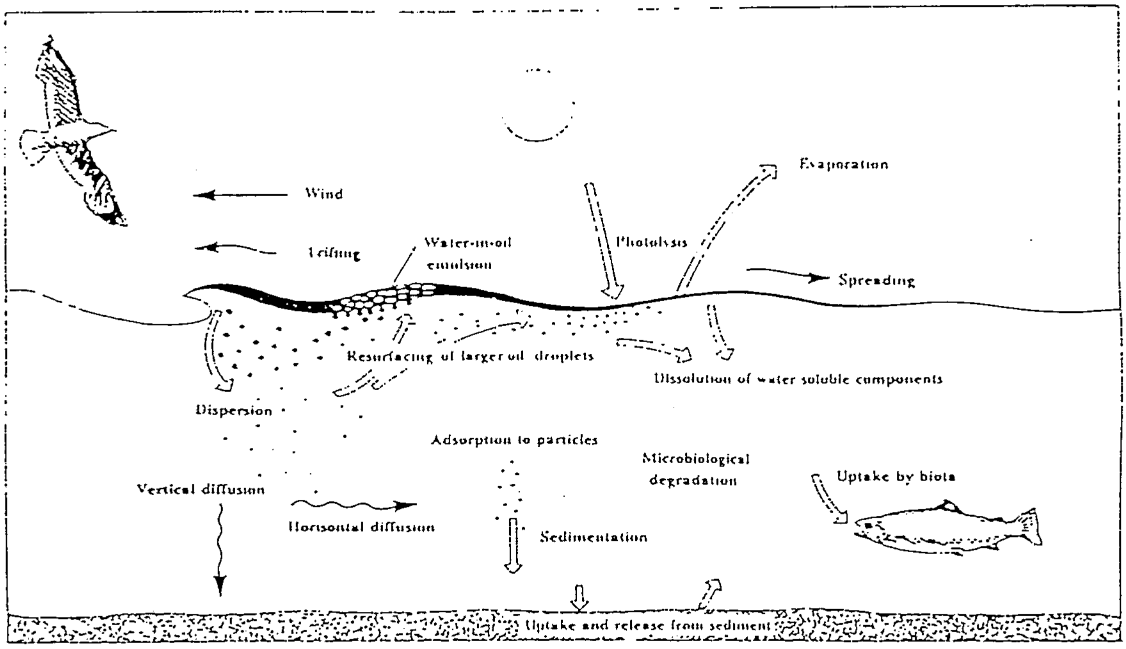

Figure 2.2 Constituents of the weathering process (Daling and Brandvik, 1991).

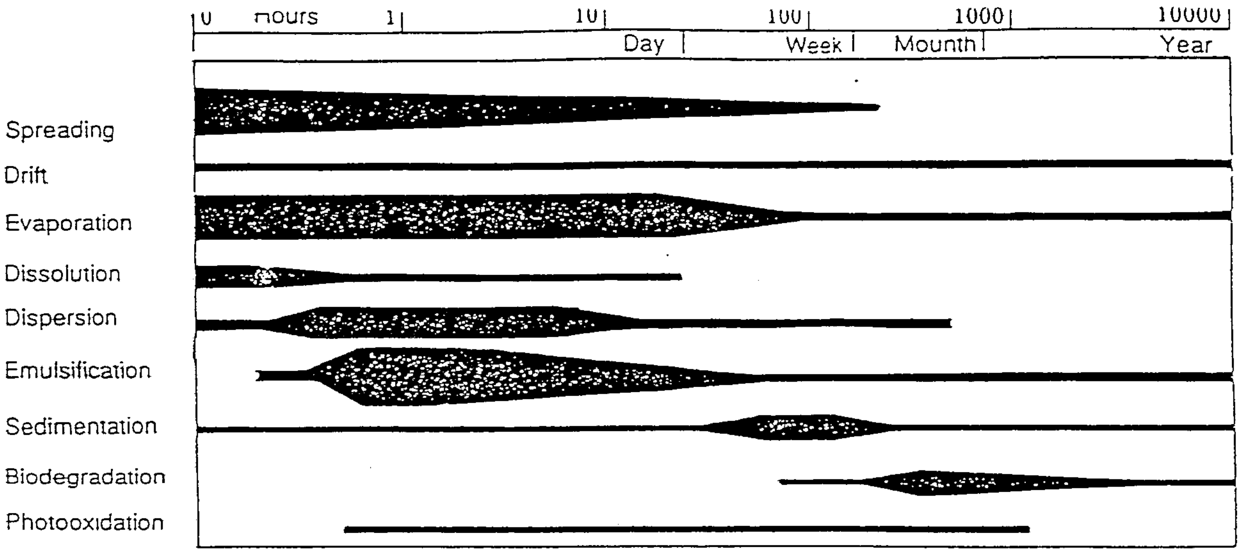

Figure 2.3 Weathering processes versus elapsed time after an oil spill.

The weathering process in the NSR (the Arctic) differs from that in waters further south. For instance, the thermal factor is the determining one in kinetics of the organic matter. The lower temperatures should make the processes of chemical, biological and biochemical oxidation slower (Serova, 1992). Also the lower quanta of light during autumn and winter reduces the chemical oxidation of hydrocarbons and the biochemical processes and vice versa during the spring and summer period. The latter period is the most potential for navigation of the NSR.

3 HARMFUL EFFECTS

Oil spills may have a serious impact on coastal activities and fisheries. Experience from the past shows that in most cases such damage is temporary and is caused primarily by the physical properties of oil creating a nuisance (refer the Braer tanker accident on the south-west tip of the Shetland Islands, January 5th 1993). However, along the NSR the environment is typically Arctic and may thus be more vulnerable than that in temperate waters.

The impact of oil on marine life can be considered as being caused by either its physical nature or by the chemical components of the oil, as well as the diversity and variability of biological systems and their sensitivity to oil pollution. The major harmful effects of oil spills, are:

- impact on marine life due to physical contamination and smothering
- impact on marine life caused by toxicity and tainting effects (chemical)
- the physical properties of the oil creating nuisance and hazardous conditions
- reduced catches of fish, shellfish and other marine organisms
- contamination of fishing equipment and loss of market confidence.

The toxicity is due to the aromatic hydrocarbons which are cyclic, unsaturated compounds such as benzene and poly-aromatic hydrocarbons (phenanthrene and benzo-a-pyrene). Adult fish and mammals may be affected by oil pollution. However, experience from major oil spills has shown that depletion of fish and shellfish stocks owing to damage to eggs and larvae are hardly reported, because the normal over-production of eggs and larvae provide a reservoir to compensate for any localised losses (Neff and Andersen, 1981).

Plankton forms the base of the marine food web. They are carried passively by water currents in the sea surface layer and may be sensitive to oil pollution. The natural patchy distribution of plankton makes significant impacts unlikely.

There are many examples of oil spills having caused large bird mortalities. This may be threatening in the case of isolated colonies with limited potential for recolonisation, but this is rarely observed at sea.

The Arctic biosystem, and so for the NSR, is relatively poor and the natural selfpurification (spreading, evaporation, dissolution, etc.) is affected adversely. For instance, under low water and air temperatures the oil viscosity increases while the spreading coefficient decreases. The presence of ice (see Part II, Chapter 2) will also reduce the spreading. The ice drift may also be considered as a mechanical factor of purification of a spill site.

Serova (1992) reports that Russian scientists have performed a number of studies of the selfpurification mechanisms in the Russian Arctic. These investigations have shown that oil slicks are heavily affected by the selfpurification mechanisms (Serova, 1992):

- Diesel fuel (light bunker) has shown to transform rapidly both on open water and with ice present and the general content of hydrocarbons changed hyperbolically with time and typically less than 10 % of the initial spill volume remained on the surface.

- In cold but open water, up to 65 % of the initial spill of crude oil is observed to have transformed after 30 - 40 days.

- Statistical processing of field observations has shown that evaporation is the dominant selfpurification mechanism. Evaporation constitutes 50 - 60 % of the evaporation of the hydrocarbons in spring and summer while the corresponding value is 80-90 % for the winter season.

Serova (1992) also concludes that the selfpurification mechanisms have shown to be typically 3 times weaker in winter than in summer.

Although the marine environment assimilates oil and little evidence exists of a build-up of oil residues at sea, major efforts are made to understand the behaviour and fate of oil spilled at sea and in ice-infested waters, and to develop efficient cleanup techniques.

4 COUNTERMEASURES IN OPEN AND ICY WATERS

Oil spill response at sea is normally divided into three primary modes of response:

- mechanical containment and recovery
- dispersants
- in-situ burning.

The relative merits of the different modes of response mainly depend on the type and magnitude of the spill, type of oil, air- and sea surface -temperature, wind, sea state and presence of ice.

4.1 Mechanical spill response equipment

The efficiency and also limitations of mechanical oil spill equipment have been demonstrated several times. The success of mechanical oil spill combat and applicability of equipment are highly dependent on the environment to operate in (open water, broken ice, level ice, etc.).

4.1.1 Open water

The principal components of oil spill containment booms, are:

- float
- skirt
- tension member/ballast
- freeboard

The performance of a containment boom at sea is mainly determined by its buoyancy and roll and heave responses. The buoyancy is important to keep the boom afloat and to maintain adequate freeboard. The roll response is the rotation of the boom due to wind, wave and current forces. Excessive roll reduces the buoyancy of the boom. The heave response is the ability of the boom to react to the vertical motion of the water surface.

For instance in Norwegian territorial waters, use of containment booms and skimmers to recover the contained oil is a primary spill response strategy. Even though containment booms in many cases can be highly successful in collecting oil, they may fail to operate in certain cases due to

• entrainment
• drainage
• splashover
• planing.

At high current speeds or towing speeds a headwave may form upstream of the boom (US Navy, 1977). A critical velocity exists at which the headwave becomes unstable and turbulence causes droplets of oil to break away from the headwave and become trapped in the flowing water (entrainment). Resurfacing of the droplets before they pass under the boom, depends on the relative current speed, specific gravity and viscosity of the oil (Figure 4.1). The critical velocity for most crude oils and refined products ranges from 0.7 to 1.2 knots (Schulze et al., 1981).

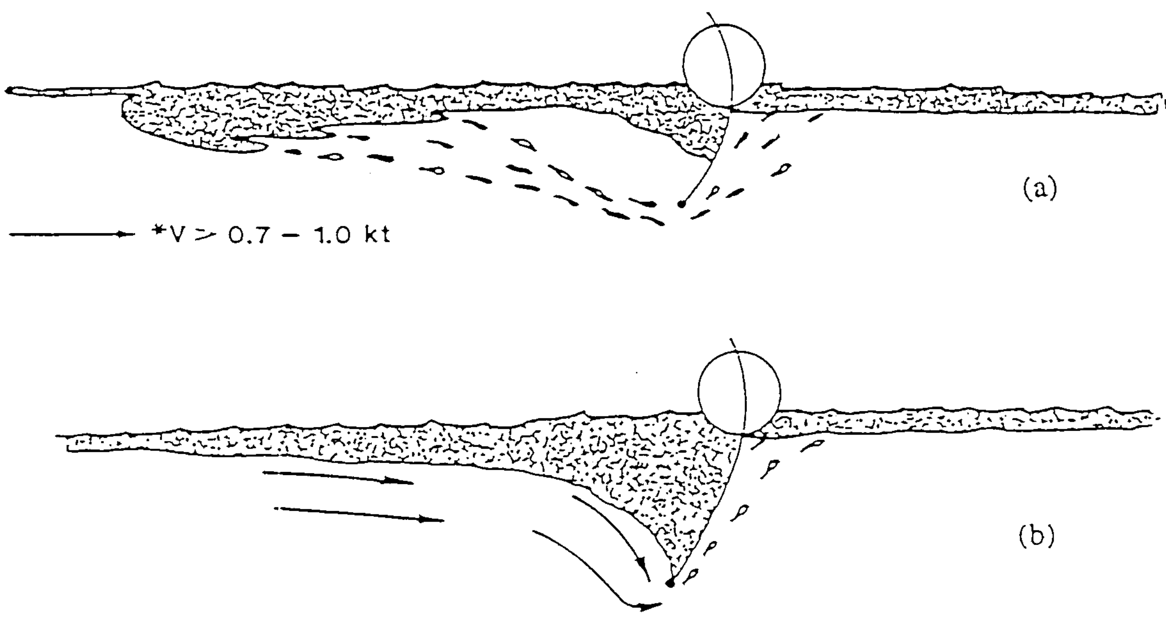

Figure 4.1. (a) Entrainment failure and (b) drainage failure (Schulze et al., 1981).

Drainage failure occurs if oil being retained by the boom exceeds the draft of the boom (Figure 4.1). The critical velocity at which drainage failure occurs depends on the draft of the boom, specific gravity and viscosity of the oil. The critical drainage failure velocity is greater than the critical velocity for entrainment failure (Schulze, 1993).

Splashover may occur in breaking waves and when the wave height exceeds the boom freeboard. Planing failure of a boom occurs when a strong current acts in the opposite direction of a wind causing a boom to heel flat on the sea surface.

As a general conclusion containment booms are effective in waves up to 3 m and currents below 0.6 m/s. The Norwegian Clean Seas Association for Operation Companies (NOFO) reports their recovery systems to function in currents of 0.7 m/s or less, and in significant wave heights of up to 2.5 m (NOFO, 1993). The operation of the boom (tension, towing velocity, handling etc.) turns out to be quite decisive for the efficiency of the equipment.

The generic types of <u>skimmers</u> include

- weir systems
- vacuum units
- oleophilic (belts, discs, ropes and brushes)
- hydrodynamic devices (hydrocyclone and water jet types)
- other methods (including paddle belt and net trawl).

Figure 4.2 shows a weir system (the Transrec skimmer) deployed in the boom's collection area. With an oil layer of 0.2-0.4 m, the Transrec skimmer has a recovery rate of 325 m^3 per hour. In calm seas four recovery systems may be sufficient for recovering 8000 tonnes per day. In general weir systems are sensitive to sea state and are most efficient in the high (> 1000 cSt) to medium (100-1000 cSt) viscosity range.

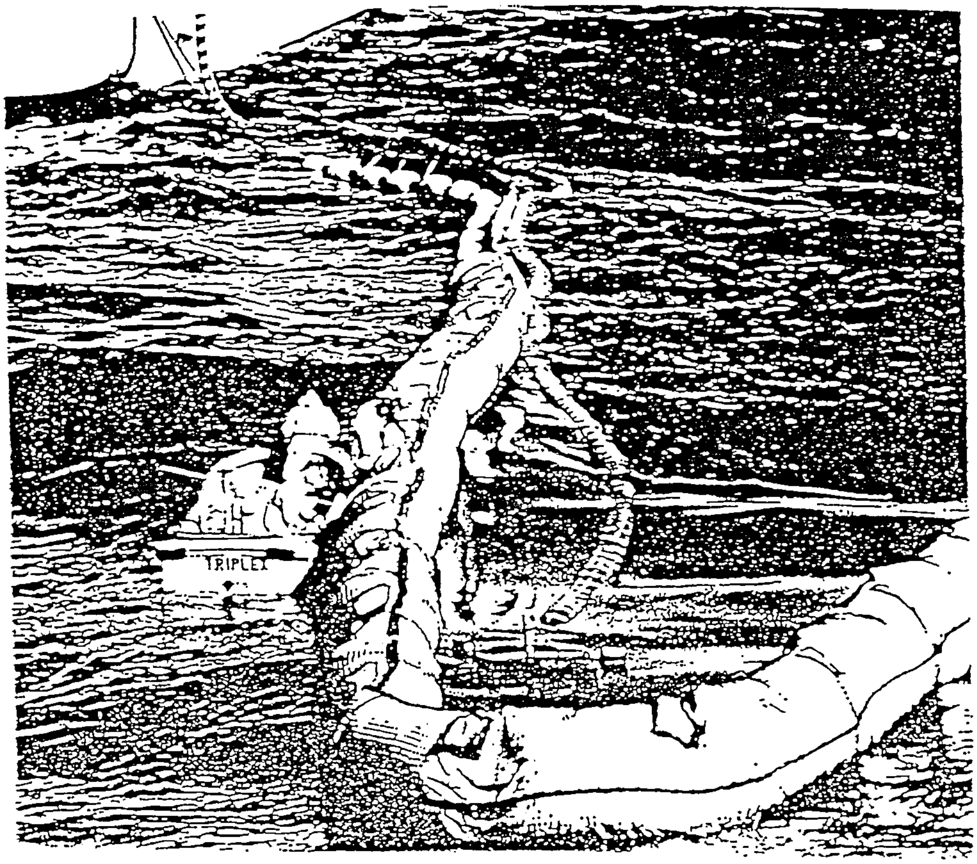

Figure 4.2. The Transrec skimmer launched at the apex of the boom.

An oleophilic system, the Foxtail vertical adhesion band skimmer, is shown in Figure 4.3. The oleophilic systems have the best recovery rate at medium viscosities and are less sensitive to sea state than the weir systems.

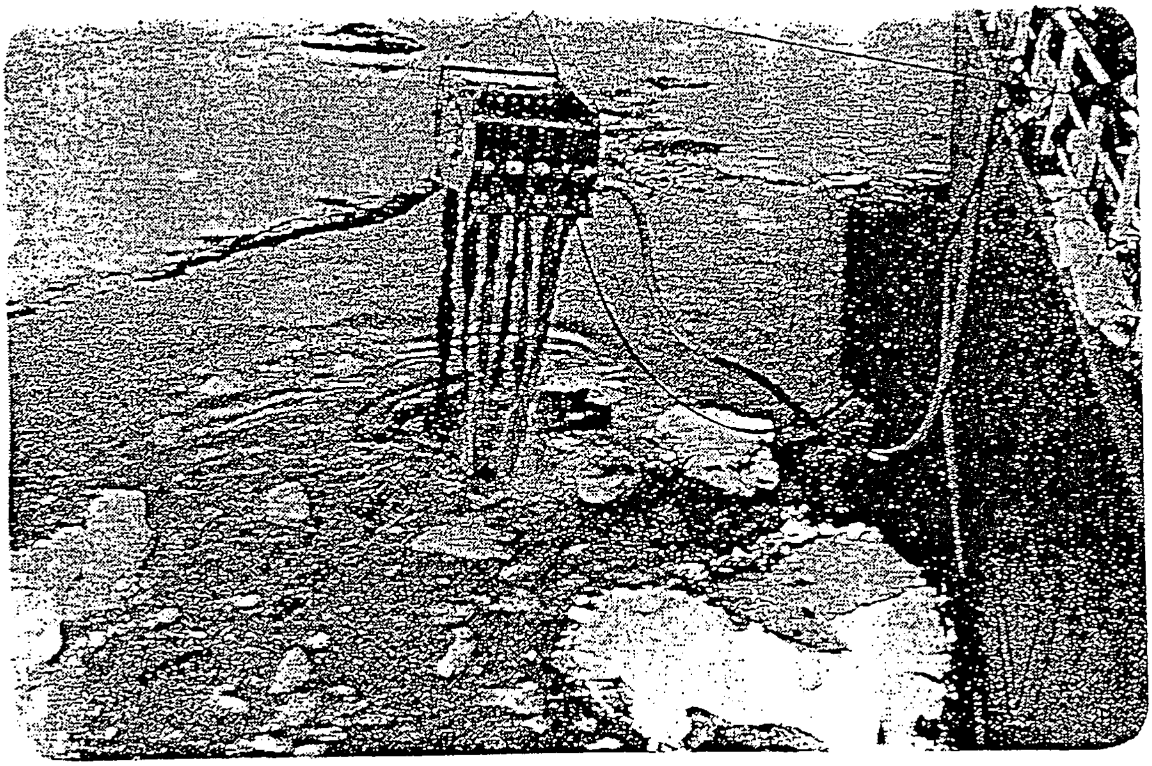

Figure 4.3. The Foxtail VAB 4-9 rope mop skimmer in operation in the Barents Sea marginal ice zone, spring 1993.

Vacuum units and hydrodynamic devices are very sensitive to sea state but less dependent on viscosity.

4.1.2 Ice and cold waters

Of the mechanical devices intended for icy waters, skimmers and sorbents are the most promising devices. For minor oil spills in ice a variety of skimmers are available. Most of them have recently been evaluated by the *Task Force on Oil Spill Preparedness* (1992) of the Canadian Petroleum Association. The report provides detailed information on 47 different skimmers and indicates advantages and disadvantages for combatting small oil spills in ice. Seven categories of skimmers for mechanical oil-in-ice recovery were evaluated:

- Disc/drum
- Rope/mop

- Sorbent belt
- Submerging plane
- Vacuum
- Weir
- Combination concepts

The report of the *Task Force Group* gave a ranking of the different concepts as they are presently and with potential for further development. The evaluation indicated a high development potential for the following four concepts (favourable ice conditions are indicated in brackets):

- WP-1 drum skimmer (small ice pieces and in brash ice)
- Foxtail vertical adhesion band skimmer (wide range of broken ice conditions)
- Vertical mop wringers (high potential among small ice pieces and in brash ice)
- Foxtail vertical adhesion band skimmer (wide range of broken ice conditions)

However, the reduced spreading caused by ice may increase the efficiency of a clean-up operation and may thus in certain cases increase the efficiency of oil spill combat.

4.2 Dispersants

A dispersant consists of different surfactants. When sprayed on an oil slick the dispersant reduces the interfacial tension between the oil and water. This enhances the natural dispersion process and increases both the dilution and degradation of the oil in the water column (Figure 4.4). The oil is broken into small droplets by wind, wave and current agitation. The oil droplets disperse into the water column and become diluted and subjected to natural processes (biodegradation, etc.).

Generally, the *efficiency of dispersants is reduced with decreasing water temperature and salinity*. Dispersants are applied either by fixed wing aircraft, helicopters or systems installed on vessels. There are several advantages by applying dispersants:

- they may reduce the concentration of oil below the acute toxicity threshold of organisms,
- they can reduce spreading of oil,
- and they allow rapid application to a large area in a timely manner.

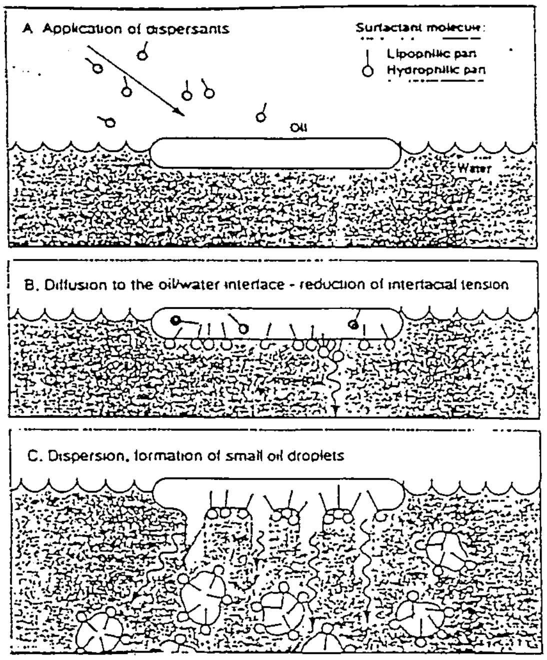

Figure 4.4. Application of dispersants reduces the interfacial tension between the oil and water and enhances the natural dispersion process.

The primary biological benefits are to reduce the hazard to sea birds. However, dispersants involve an environmental trade off and the major concerns are as follows:

- dispersants are more soluble in water than in oil and may hence leave the oil in access of water
- dispersants are only effective on unweathered oil
- the dosage ratio of dispersant to oil will range from 1:10 to 1:100.

Besides, some dispersants are toxic and may impact the environment while others are less toxic than oil. The efficiency of dispersants is hard to quantify owing to lack of hard data in actual spill conditions at sea (natural dispersion/chemical driven dispersion). The sea conditions and application techniques are decisive for the efficiency which also depends on the chemical nature of the dispersants and the oil as shown in Figure 4.5.

For instance, the efficiency of dispersants was judged to be negative in a recent controlled oil spill in the Barents Sea due to a high ice concentration (80 - 90 %, broken ice) and calm sea - the ocean gravity waves were completely damped out by the ice (Sørstrøm et al., 1994).

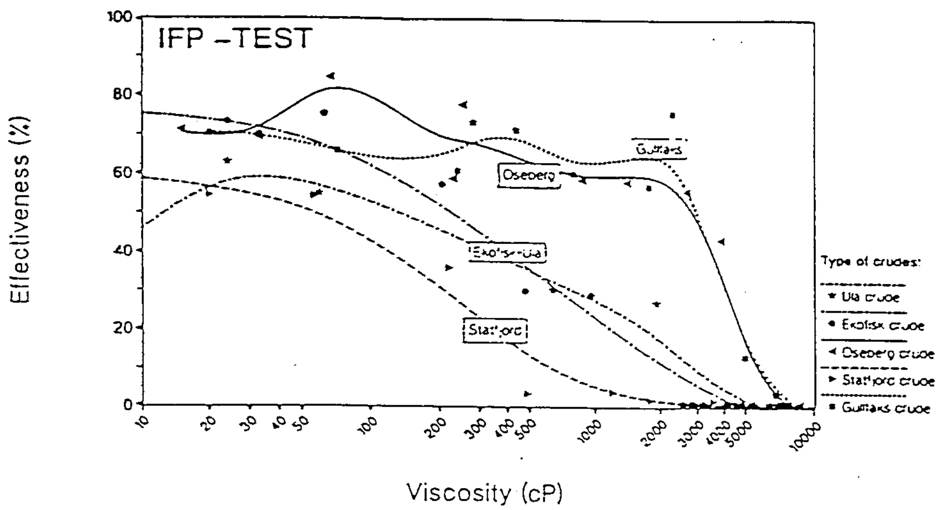

Figure 4.5. Dispersibility of weathered North Sea crudes, IFP test of dispersant OSR-5 (DOR = 1:25), temperature 13 °C (Daling et al., 1990).

4.3 In-situ burning

In-situ burning is the process of burning spilled oil in place. To ignite on water the oil must be relatively fresh, and have a minimum thickness of about 2-3 mm. Substantially thicker layers are required for sustained, efficient elimination of oil (Allen, 1988).

Some oil residue (1 mm) will remain because the flame is always quenched by the heat loss to water (Frish et al., 1988). Thus, burning at sea will not be efficient unless fireproof containment booms are used to ensure sufficient oil thickness and to isolate oil from the source (stricken vessel). The critical issues, are

- the surface of the oil must be hot enough to produce combustible vapour
- the vapour/air mixture must be raised briefly to a temperature sufficiently high to initiate combustion
- the liquid fluid must establish temperature and flow fields which transport less power into the liquid's volume than the nascent flame is capable of supplying back to the liquid surface.

It should be evident that burning is sensitive to sea state and wind. It has been observed for example, that the ignition of most oils becomes difficult at wind speeds approaching 20 knots (Allen, 1988). Other concerns are the combustion products which are released to the atmosphere, and in general the success is quite varying.

However, in-situ burning may have an increased efficiency in broken ice compared to an open water spill due to reduced spreading of the oil (thicker oil film etc.) and a calmer sea state.

5 DISCUSSION AND RECOMMENDATIONS

5.1 Discussion

History shows that every oil spill is different. Different oil characteristics, environmental/ spill conditions and access to oil spill combat equipment. Thus it is not easy to judge the success of various oil spill countermeasures. It seems that most accidental oil spills from vessels, e.g. in Norwegian waters, tend to occur in rough weather making the vessels inaccessible to salvage or offloading operations (SFT, 1991; Reed et al., 1993). This will also complicate and hamper the normal oil spill response actions (application of containment booms, skimmers etc.).

Slicks in open water will quickly spread, weather, emulsify and disperse. Wind, low temperature and sea state will influence equipment and personnel performance. Strong wind and wave conditions can render containment booms and skimmers ineffective, reduce the accuracy of applying dispersants and prevent oil from being ignited or burned efficiently. In Figure 5.1 an attempt is made to show how mechanical cleanup, dispersing and burning techniques might be related to a large range of oil film thicknesses in case of open water (Allen, 1988) . The envelopes drawn in Figure 5.1 are just indicative. NOFO (1993) reports e.g. their recovery systems to function in currents below 0.7 m/s, and in significant wave heights of up to 2.5 m.

Figure 5.1. Primary spill response options under various wind/sea conditions and oil film thicknesses (Allen, 1988).

5.2 Recommendations

The major oil spill combat systems at sea can be divided into mechanical containment and recovery, chemical dispersants and in-situ burning. The efficiency of these modes must be evaluated in light of quick access to and skilful operation of equipment, weathering state of the oil, presence of various types of ice, and wind and sea state. The major conclusions are as follows:

- No one response system can handle the variety of conditions normally encountered in oil spills in open waters

- Mechanical oil spill response is still the only true cleanup technique - the other modes serve to accelerate natural processes

- Dispersant application and burning techniques provide important backup capabilities

- In-situ burning may have an increased efficiency in broken ice compared to an open water spill e.g. due to reduced spreading of the oil (thicker oil film, etc.) and a calmer sea state.

However, the efficiency of clean-up operations will also depend on access to equipment. Most of the NSR is remote, and thus efficient transportation must be considered as part of the preparedness. Questions of concern are access to:

- oil spill combat equipment and salvage vessels?
- aircraft(s) which can move key personnel into the spill site?
- vessel(s) capable of shipping oil spill combat equipment?

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APPENDIX A

PROJECT REVIEW

National Research Council Canada
Conseil national de recherches Canada

Ottawa, Canada
K1A 0R6

Institute for Environmental Research and Technology
Institut de technologie et de recherche environnementales

Thermal Technology Program
Programme de technologie thermique

NRC·CNRC

DOCUFAX

Date : 30 May 1994

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Page: 1 of 2

Re/Objet : INSROP

Attached please find my review of Project I.5.1. I apologize for the delay.

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Comments on Project I.5.2: Content of database, planning and risk assessment.

I have not done a detailed review of the report, but have looked at the contents from a general perspective. Part I enumerates the contents of the physical environment data base. The items identified for inclusion in the database are pertinent to infrastructure, ice navigation, risk assessment and environmental impact assessment. The primary source of the required datasets will have to be Russia. As pointed out in the report on p. 21, no detailed data sets, or descriptions of data sets, have yet been received from Russia. These data sets will have to be identified before further substantial progress can be made on this task.

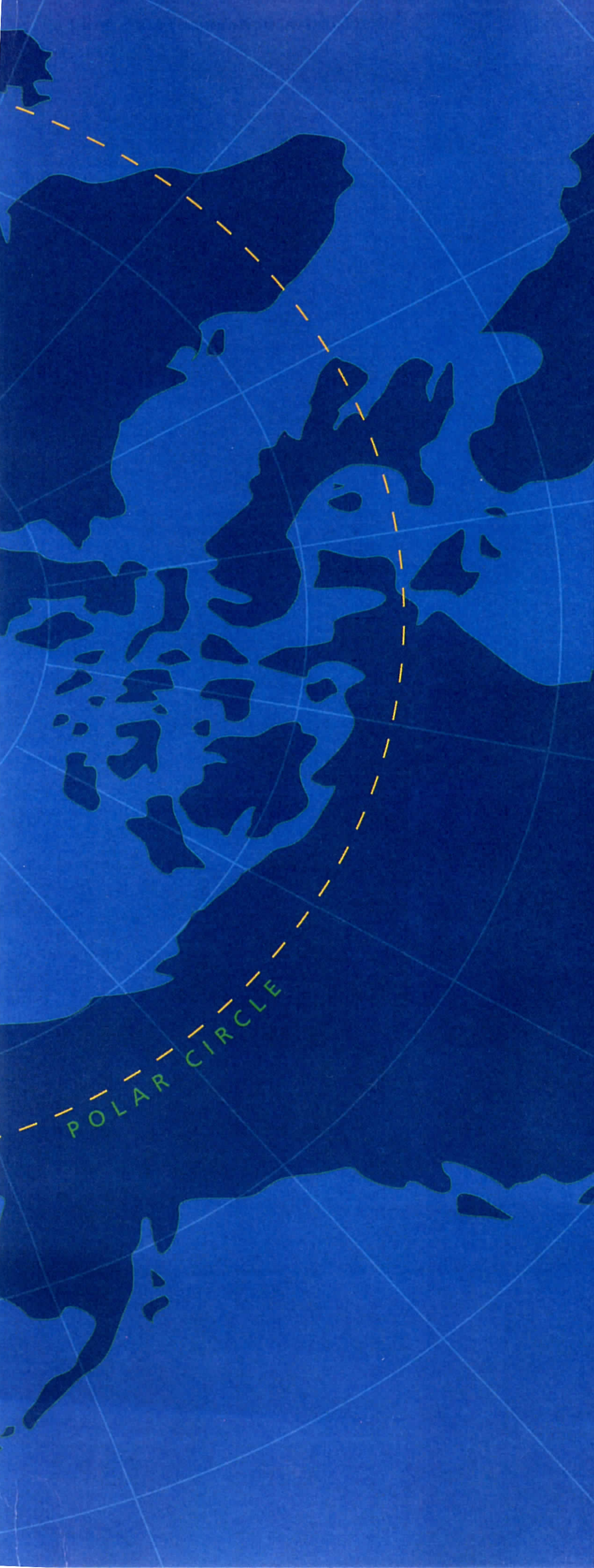
Part II deals with risk assessment related to drift and spread of oil. It is shown that this is very much a function of ice drift. A thorough and balanced review of what is known about spread and drift of oil in open water and pack ice is presented. Knowledge gaps are identified, for example influence of ice and snow on oil spills, the need for an operational forecast model for predicting ice/oil drift and the need to implement a discrete element model to predict local ice drift. I concur in the selection of these as being priority areas for further study.

Part III presents a realistic assessment of oil spill clean-up measures. The recommendation is that, within the context of INSROP, the focus should be on operational planning so as to be able to respond adequately to various types of oil spill in various locations. This is an appropriate recommendation.

Parts II and III contain a number of useful recommendations. It would be helpful to see some recommendations for Part I.

Of a more specific nature, some of the figures have not reproduced too clearly. It appears that they have been scanned and then printed. In several cases they would benefit from enlarging the lettering. In Part III the References should be section 6, not 7.

R. Frederking



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.
SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.
CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.
FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.