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IMPLICATIONS OF ICE CONDITIONS
FOR HYDROCARBON PRODUCTION ON THE GRAND BANKS

by

I. Stuart Hotzel

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment of
the requirements for the degree of Master of Arts

Department of Geography
Carleton University
Ottawa, Canada
1989

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of Master of Arts

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ABSTRACT

Offshore oil exploration operations on the Grand Banks have necessitated a clear acknowledgment and understanding of the physical environmental conditions. Data collected at drilling locations are routinely used during the post-exploration phases of offshore oil field development. These data provide the means for evaluating the climatic variability around wellsites and are essential for pre-engineering studies and design studies for production platforms.

This thesis reviews oil industry operational practices in the Canadian offshore, characterizes the general wind, wave and ice climatology of the operational areas and describes current data collection techniques and analysis methodologies. Focusing on the unique problems posed by icebergs, it gives examples of the types of data available to the environmental scientist, shows how the data affect design engineering decisions and discusses the use of operational data in the determination iceberg/structure collision risk.

An iceberg collision risk model developed for this thesis shows that the probability of a collision between a fixed structure and an iceberg is small, occurring only once every 22 to 42 years. The model also shows that floating oil production systems with the capability to leave the wellhead may need to vacate the wellhead area once per year on average and in some extreme years may need to disconnect from the wellsite up to 10 times.

Evaluations of risk are shown to be extremely dependent upon iceberg size and entry distributions used in the model. It is suggested that a centralized database of good quality east coast environmental data should be collected from both the oil industry and public sources in order to provide consistent data for use in engineering/scientific projects and for regulatory purposes.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT AND RELEVANCE

The exploitation of offshore hydrocarbon resources can be divided into three key phases: exploration, development and production. Offshore oil activity in Canada's east coast waters is influenced in all three phases by the physical environment. In the exploration stage the environment dictates the type of vessel used for drilling and has prompted the development of new technologies (such as iceberg deflection) to mitigate its influence. The development phase encompasses engineering design and the estimation of production efficiencies, both of which rely on the accurate evaluation of the impact of environmental conditions on proposed production systems. Environmental data collected during the exploration phase are collated with other historical data for the proposed production area. These data are then used to estimate, statistically, the short- and long-term influences of the environment so that decisions can be made concerning production scenarios, construction concepts and evaluation of possible impacts of the local environment on the production efficiency of the oilfield. During the production phase, oil companies are concerned with maintaining a

relatively constant supply of the hydrocarbon resource with a minimum of disruption; environmental data are used to determine optimal times to perform maintenance on the production system. Thus, although each phase has its own characteristics and goals, all require accurate environmental data for efficient and safe operation.

In spite of this, understanding the need for environmental data, or the determination of oil companies to address environmental issues and their impact on future development, has been inadequate. At the exploration stage there is a reluctance to spend much money on the systematic collection of environmental data, due to the perception that if exploration proves fruitless then the money spent on data collection was wasted. This philosophy results in higher data acquisition costs when these programs are conducted later. Also, within most oil companies, the exploration and production departments are separate, with the result that data acquisition projects funded by exploration tend to meet only their own short-term objectives (or regulatory imperatives) and are not necessarily conducted with any long-term goal in mind. Sometimes, in order to serve some regulatory requirement, money is

spent on poorly defined environmental research that proves later to be of questionable quality or value. There is also a commonly held belief within the oil industry that there will be plenty of time to collect necessary environmental data once a decision has been made to produce an oilfield; and, even if there are gaps in the data, available data can be extrapolated to give long-term extreme values. This belief is misplaced as it often takes several years of research to produce very few relevant data points.

Where few data exist for a location, the data sampling area is often increased until the site-specific characteristics are lost amidst data for areas unrelated (or little related) to the area of concern. In some cases these few data points are fitted to some standard distribution and the tail of the distribution is manipulated to estimate extreme conditions. The engineering technique of adding safety factors to design values is also fraught with problems in conditions where few data exist. Employing a safety factor that is too high may result in the choice of production concepts that are too expensive to utilize. A low safety

factor may result in a decision to use a structural concept that will inadequately withstand the environmental forces in an area.

Although long recognized as a crucial aspect in the design of offshore structures (floating or fixed platforms), the collection and manipulation of environmental data has often proceeded in a poorly structured fashion (e.g.. Bea, 1973). The judicious use of valid environmental information allows the engineer or scientist to evaluate different construction concepts, oil-field production efficiencies, risk to structures and human life, to estimate the reliability of mechanical systems and ultimately to design safe, cost-effective systems for a proposed site.

With respect to the identified importance of environmental data to the overall success of oilfield exploration and development, the objectives of this thesis are to:

1. Assess the impact of the physical environment, especially sea-ice and icebergs, on offshore technologies. (Chapters 2 and 3)
2. Examine the issues of site specific environmental data collection versus the use of historical data. (Chapter 4)

3. Show how data may be manipulated to provide design criteria and comment on the techniques used. (Chapter 4)

As part of these three main objectives this thesis will also address statistical probability and the concept of "risk", these concepts often being used interchangeably in the discussion of hazards. Events which could have a serious impact on the operation of offshore facilities (such as a catastrophic collision between an iceberg and an offshore structure) have a certain probability of occurrence. If a philosophy was adopted that prevented development if there was any probability of hazard (either to life or structure), then many engineering projects including offshore operations would not be attempted. As risk-prone projects are commonly attempted, some mechanism is needed to evaluate the potential risks of implementing a project and determine whether the benefits outweigh the risks of catastrophic loss. There may be various "acceptable" levels of risk which people are generally prepared to support. These risk levels differ, depending upon the public awareness of the hazard. People for example, are prepared to accept that there is a probability of death or injury when driving a car but

would be unwilling to make the right to drive more restrictive. Society would not be willing to accept the same probability of death or injury when using a commercial air carrier or for nuclear power plant operation. The probability of catastrophic failure must be weighed against the perceived benefits. The probability of failure which is acceptable becomes therefore the risk of failure. Although hazard to structures or operations can be minimized, it cannot be totally eliminated. It is also apparent that reducing the risk of failure to some arbitrarily low value does not ensure safety or even mean that failure will not occur within the lifetime of the structure or operation.

There is a continuing conflict between people who are concerned with the impact of systems on the environment and those who are concerned with the impacts of the environment on systems. Some researchers (e.g., Gamble & Janssen, 1981) seem to contend that because the risks to a system cannot be precisely defined, projects should either not be attempted or should have much higher design values placed on them. The cost penalties of such a philosophy are easy to imagine and the safety of a project is still not assured. Design-

ing systems to one or two high profile risks does not ensure that the system will not fail in response to some completely unforeseen event or a combination of events where the sum impact of the individual events is more catastrophic than any of the individual events.

This thesis is limited to the impact of the environment, especially icebergs and sea-ice, on systems. It does not directly address the impact of production systems on the environment, a topic that has been studied in great depth elsewhere.

1.2 STRUCTURE OF THE THESIS

This thesis is organized to provide an overview of oil industry operational practices in the Canadian off-shore, a characterization of the general wind, wave and ice climatology of the operational areas and a description of current data collection techniques and analysis methodologies.

Chapter 2 provides a brief review of exploration on the Grand Banks and the unique impact of icebergs and sea-ice on operations philosophy and technology.

Chapter 3 depicts the local wind, wave and ice climatology as it pertains to offshore operations. A discussion of the strengths and weaknesses of available environmental data is also provided.

Chapter 4 gives examples of the types of data that are available to the environmental scientist and shows, through examples, how the data affect design engineering decisions and how the data can be used to determine the risk of iceberg collision with a structure or operation.

Chapter 5 provides conclusions and some cautionary notes for the scientist or engineer when environmental data collected during oil exploration is adapted for use in the design process.

CHAPTER 2

TECHNOLOGY AND THE ENVIRONMENT

2.1 A HISTORICAL PERSPECTIVE OF OIL EXPLORATION ON CANADA'S EAST COAST

Offshore oil exploration operations on the Grand Banks have necessitated a clear acknowledgment and understanding of the physical environmental conditions. The North Atlantic Ocean east of Newfoundland was the scene of at least 45 ice-related shipping casualties between 1890 and 1977 (Littlejohn, 1979). The most famous of these was the "Titanic," which struck an iceberg and sank on April 14/15, 1912. The direct result of the sinking of the "Titanic" was the formation of the International Ice Patrol in 1914, which was given the task of collecting data relating to both icebergs and sea-ice. The objective was to use these data to warn vessels of the presence of ice hazards, thereby minimizing shipping losses. However, the loss of the Ocean Ranger semi-submersible drilling platform in 1982 clearly illustrated the continuing hazard of operating in hostile conditions and the need to better understand the climatic extremes which occur on the Grand Banks.

Oil exploration on Canada's Grand Banks started in 1971 when Total Eastcan, a company partially owned by Elf Aquitaine, started to explore for oil on behalf of the Labrador Group of Companies. Drilling occurred off the Labrador coast with drillships, vessels modified to allow drilling through their hulls. The advantages of drillships in severe environmental regimes include their manoeuvrability, small projected area and ability to leave the well rapidly. From the beginning it was realized that some compromise between the physical environment and drilling technology was needed if a safe, yet cost-efficient operation was to be maintained. The philosophy that developed from the early drilling operations was that ice avoidance was preferable to trying to design vessels to withstand all environmental eventualities. This philosophy was maintained for several years until it became apparent that although such a philosophy might work in exploration operations, if hydrocarbons were going to be produced from these wells on a year-round basis, systems would need to be designed to allow continuous exploitation of the resource. The need to determine safe designs for structures that might be placed in these hazardous off-shore environments, combined with government regula-

tions requiring environmental data to be collected prompted an extensive, but often not well coordinated, program to collect data pertaining to waves, winds, currents, sea-ice and icebergs.

Offshore drilling in severe wave and current climates was not new. Many offshore rigs were working in the North Sea which, like the Labrador Sea, is noted for its extreme conditions. What made the Canadian situation different was the presence of icebergs and sea-ice. The little that was known about these two environmental parameters was gleaned from historical documents and from sporadic airborne reconnaissance which had been carried out by the International Ice Patrol. Given this lack of knowledge, the oil companies operating in this area began to collect data concerning the ice characteristics and persistence of sea-ice and the number and sizes of icebergs that passed through the drilling areas. Initially, drilling was to be suspended if threatened by sea-ice or icebergs. As the operators became more familiar with the environment, however, techniques were developed to minimize the impact of such conditions on operations.

For example, iceberg towing allowed the drill rig operator to deflect smaller icebergs (up to about 3 million tonnes) around the drillship.

2.2 A BRIEF HISTORY OF OIL EXPLORATION ON THE GRAND BANKS

In the early 1970s, British Petroleum (B.P.) and Mobil Canada Ltd. became involved with the search for oil on the Grand Banks. As the ice conditions were not as severe on the Grand Banks as had been experienced in the Labrador Sea, there was a move away from drillships to moored semi-submersibles, which are generally more stable than drillships and provide a much larger deck area to store equipment.

After drilling two "dry holes" (i.e. no hydrocarbons were discovered), British Petroleum Ltd. did not drill again on the Grand Banks until 1986. The Hibernia Group with Mobil Canada as operator was joined in the late 1970s by the Terra Nova Group of Companies, Husky Bow Valley Ltd. and by Petro-Canada Inc., which began to explore on crown acreage (under dispute at the time by the Newfoundland Government which felt that the mineral rights belonged to Newfoundland rather than Canada). Several significant oil strikes have been

made by the Hibernia Group, the Terra Nova Group and by Husky Bow Valley Ltd. and efforts are being directed in each of these organizations toward determining the best methods for removing the oil and transporting it to shore. Until the downturn in the price of oil in late 1985 and early 1986, it was expected that oil would be shipped from Grand Banks oil fields by 1995. Given the present uncertainties in the price of oil, this date may not be realistic.

2.3 ENVIRONMENT AND OFFSHORE OIL OPERATIONS

2.3.1 Drilling Platforms

To date, wellsites on the Grand Banks have been located primarily in the northeast (Figure 2.1). Exploration activity in this area is subject to frequent storms, periodic incursion of sea-ice between December and May and icebergs, that occur primarily from February to June, but infrequently pass through the exploration zone at other times of the year (Hotzel & Miller, 1985). It is the occurrence of icebergs and sea-ice that make the Canadian East Coast drilling environment unique. Drilling takes place most commonly from large floating semi-submersible platforms, which are usually moored to the sea bed (Figure 2.2).

Figure 2.1 Map of Oil Exploration area on the Grand Banks

Figure 2.2 Types of Oil Exploration Platforms

Drilling operations on the Grand Banks are carried out throughout the year, unlike earlier operations in the Labrador Sea where the operating season was limited to the sea-ice free period. Thus the drilling vessel is faced not only with the frequent passage of severe storms through the area but also with the occurrence of sea-ice and icebergs. Owing to the high cost of operating such a system (approximately \$400,000-\$500,000 per day), it is important that a company balance the safety of the personnel on board against the necessity to remove the platform from the wellhead location. The jack-up rig, a drilling platform used in many other offshore locations such as the Gulf of Mexico, is fixed in place and rests directly on the sea bed. In contrast, semi-submersibles and drillships have the capability of moving away from the well location. As shown in Figure 2.2, two operating modes for these vessels are used :

1. Moored, where the vessel is anchored to the ocean bottom and,

2. Dynamically positioned, where the vessel is kept at the wellsite location by a series of thrusters on its pontoons. Several locating transponders are placed on the ocean bottom around the wellhead and a computer inside the vessel interrogates the transponders and adjusts the position of the semi-submersible over the wellhead.

As it is generally less expensive to keep platforms on location by mooring them in place, this method is the most widely used. The decision to use a dynamically-positioned ship is based on the perceived environmental hazards to operations. In an emergency, a dynamically-positioned platform can leave the wellsite in as little as 15-20 minutes. The moored platform may require as much as 16 hours to pull in anchors before the platform can move. The moored platform does have some extreme emergency measures available, such as shearing the anchor chains, but these mechanisms do not always operate successfully and are not the preferred response to hazardous situations.

At the exploratory stage of oil development the operating systems have wave limits which, once exceeded, produce varying levels of operational shutdown. For example, in drillship systems, compensation must be

made for the heave of the vessel so that the drill string and bit are not moved up and down the hole in response to waves at the ocean surface. It is easy to visualize the effect this ramming would have on both the drill bit and the drill rods. To reduce this effect, a damping system is used such that the vessel can move in response to the waves, while the drill string is not affected by the motion. Naturally there is a physical limit to how much motion can be damped out; on most drillships, this is 4-6 metres. Once the wave height exceeds the damping limit, drilling must be suspended and the drill string pulled away from the bottom of the hole.

2.3.2 Ice Monitoring and Management Plan

All drilling platforms operating in Canadian ice-infested waters are required by law to have an emergency response plan, one component of which is an ice management plan. In the past, each operator or rig had its own ice management plan and environmental data gathering unit. However, given the number of vessels in the Grand Banks area (at least until the recent decline in offshore activity), the operators formed a joint ice management program. This cooperative program

allowed operators to acquire better coverage of the surrounding area using: oil industry operated side looking airborne radar (SLAR); visual airborne surveillance; sea-ice and iceberg data collected by the Atmospheric Environment Service; iceberg data collected by the International Ice Patrol; and iceberg and sea-ice data collected at each wellsite. All companies involved in oil exploration now have similar ice management plans.

Decisions as to the type of action needed to cope with an environmental hazard are usually related to the speed and heading of the hazard, the amount of time the platform needs to disconnect from the well and move away and on the type of operation which is being performed, or is being anticipated, at the time of the hazard occurrence. To meet this need a number of concentric rings or alert zones are identified around the platform (Figure 2.3). The actual size of the zones depends on the platform disconnect time (the amount of time it takes a vessel to make an orderly withdrawal from the wellhead), hazard approach speed and the drilling operation presently in progress or anticipated. Some operations such as cementing the well casing (a liner down the well designed to stabilize the

Figure 2.3 Ice Alert Zones

hole and prevent material from sloughing into the hole) require a long uninterrupted time period. Thus, this operation would not be started if potentially threatening environmental hazards were present or forecasted to present a hazard within the cementing period.

The size of the inner alert zone, or disconnect zone, is generally defined as the greater of one nautical mile (1.9 km) or the drift of the iceberg (based on its speed) in one hour. The size of the middle zone, or suspend zone, is defined as the product of the present iceberg drift speed and the time required to suspend operations. The boundary of this zone fluctuates in response to the drilling operation in progress; the time needed to safely suspend the ongoing operation; and the speed of local icebergs. Icebergs in the vicinity of the rig are all assumed to have the capability of moving directly toward the rig at their present speed. Given this, a calculation of the time needed for an iceberg to reach the rig is made. When this approach time equals the time needed to suspend an operation, the boundary of the suspend zone is defined. At this point the rig commences a number of procedures to reduce its suspend time such as pulling the drill bit to the surface of the hole without actually

withdrawing it. Pulling the drill string to the surface of the hole is a time consuming process but once the drill bit is located just below the surface of the hole, the rig can abandon its location extremely rapidly (Hotzel & Miller, 1985). There are a number of reasons why there is reluctance to immediately abandon a wellsite :

1. The wellhead is often quite difficult to re-locate once the platform leaves the vicinity.
2. The hole can be damaged while withdrawing the drill string and the hole must then be cleaned out by redrilling sections of it. This is a time consuming and consequently expensive process.
3. Any time a hole is abandoned there is the potential for the accidental release of oil or gas from the well.

As icebergs rarely proceed directly toward a rig, the necessity for abandoning wellsite locations is rare. In instances where no measured iceberg speed is available, an estimate of speed based on local environmental conditions and historical data is used. Thus it is obvious that the suspend zone can change rapidly as the speeds of icebergs change, as the drilling operation changes or as new icebergs approach the rig.

The outer alert zone is located from the outer edge of the suspend zone to the marine radar limit. This outer limit is usually set approximately 30 km from the wellsite in clear, calm weather conditions but decreases in foggy, rainy or stormy conditions.

Ice in the wellsite area is monitored by radar, ship reconnaissance and air reconnaissance. The marine radar (as mentioned) has a maximum range of 30 to 40 km but can have problems in finding ice targets especially if they are small and wave heights are large. To supplement the radar reconnaissance, supply vessels in the immediate vicinity of the rig have the task of searching for ice targets that might not be identified by radar. Icebergs are often not sighted because they are masked by waves or because they are small and present only a small cross-sectional area to the radar.

Visual and SLAR aerial reconnaissance is carried out in the vicinity of platforms to gain a regional perspective on the number, location and size of icebergs presently outside the range of the marine radar but with the potential for entering the platform alert area. Aerial reconnaissance is generally limited to areas upstream from the platform (the upstream direction is determined from the prevailing current

direction). Visual reconnaissance has the advantage of providing better estimates of iceberg size and sightings tend to be more easily verified. Its major drawback is that it is weather dependent; in poor weather, where clouds or surface fog exist, and when reconnaissance support is most needed, visual techniques cannot be used. Side-looking radar has the advantage of not being affected by clouds or fog and is extremely useful for identifying the sea-ice edge and its day-to-day fluctuations. The major problem with SLAR is that in the absence of ground verification, it is very difficult to determine which targets identified are actually icebergs and which are ships, whitecaps, or photographic flaws. Edwards and Thayer (1986) showed that there is an 86% probability of identifying icebergs on SLAR imagery. They also showed that the accuracy of trained observers in identifying ambiguous targets was only 60%. This observation points out one problem with the exclusive use of SLAR, that of target verification. Given that SLAR is used primarily when the sea surface is obscured and that the data used by Edwards and Thayer (1986) appears to have a "fair weather" bias (wave heights less than 1 m.), there is still considerable concern whether SLAR can give an ac-

curate picture of iceberg distribution. One basic drawback with SLAR data is that the size of the resolution cells (approximately 40 m at near range increasing quickly with distance away from the sensor) makes it impossible to accurately define the size of icebergs and create iceberg size distributions from these data.

Owing to the fact that the identification (and re-identification) of icebergs is imprecise, there has been considerable research into developing motion forecasting models (e.g.. Napoleoni, 1979; Mountain, 1980; and Smith and Banke, 1982) so that even in the absence of precise iceberg tracking, some assessment of risks posed by individual or groups of icebergs could be made. At present, iceberg forecasting models are still problematic and not widely used for decision-making purposes on offshore platforms. Forecasts of the position of the sea-ice edge are generally based on the forecasts of wind speed and direction. This involves using a coupling factor between the wind speed and ice speed (ice speed is normally taken as 3% of the wind speed) in conjunction with an angular adjustment (the ice is assumed to move at an angle 20-25% clockwise to the wind direction) to account for the Coriolis force.

2.3.3 Ice Risk Mitigation Techniques

Three forms of ice risk mitigation are available to the platform operator :

1. Iceberg Deflection (often called towing).
2. Rig Movement.
3. Propeller washing and bow pushing.

If a drilling platform on the Grand Banks is approached by sea-ice, the only option for the operator is to move. The decision to move the platform off location under these conditions is based on the concentration, floe size and thickness of incoming ice. The ice concentration considered to be large enough to precipitate movement is 3-5 tenths of surface cover. In the last 15 years the amount of sea-ice related downtime experienced by drilling platforms throughout the Grand Banks has ranged from 0 to 70 days in a single drilling season (Hotzel & Miller, 1985).

As icebergs approach the platform iceberg deflection exists as an alternative to platform movement. The technique commonly used on the Grand Banks is shown in graphical form in Figure 2.4. Several factors con-

Figure 2.4 Iceberg Towing

significant effect on its trajectory. Second, the shape of the iceberg at the waterline must be rough enough that the tow rope does not slip over the top of it. Third, the sea conditions must be fairly calm (wave heights less than 4 metres) for successful attachment. Smaller icebergs (less than 1 million tonnes) tend to become very smooth and rounded, and are therefore extremely difficult to tow. (In 1986, Husky Bow Valley Ltd. conducted some experiments with a towing net for use with small, rounded icebergs. Although partly successful, these experiments identified problems with net deployment and net entanglement.) Finally, the wind speed must be low. In high winds, strong surface currents develop quickly; as the iceberg follows these currents it develops momentum which the tow boat is unable to counteract.

Propeller washing and bow-pushing deflection techniques are reserved for small iceberg pieces with a mass less than 100 tonnes. In propeller washing, the supply vessel is backed up to the piece of ice and the thrust from the propeller is used to push the ice in a direction away from the platform. Bow pushing occurs when the vessel pushes small ice pieces with its bow.

The success of iceberg deflection measures is difficult to assess because all icebergs that approach within a certain distance from the platform are towed and there is no way to evaluate what might have happened in the absence of intervention. In the 10 to 15 years in which iceberg towing has been used as a mitigative technique however, no serious collision has occurred between a drilling platform and an iceberg. Based on 1,000 drilling days (on the Grand Banks) the average annual downtime related to iceberg incursion was calculated to be 12% (Hotzel & Miller, 1985). Thus, in a 90-day well program a drilling vessel experiences an average of 9-10 days of iceberg related downtime.

2.3.4 Environmental Data and Post-Exploration Activities

Data collected at drilling locations have enormous potential for determining the thrust of post-exploration phases of offshore oil field development. However, there is generally very little attempt to structure the exploration data acquisition programs to address engineering needs at the production stage of oil exploitation. This lack of coordination can be traced to the oil industry attitude that until explora-

tion determines the presence of economic quantities of oil, drilling costs should be kept to a minimum. The effect of this attitude is that when oil is discovered and production schemes are anticipated, the environmental data collected during exploration does not fulfill all design engineering needs. The situation in the Grand Banks area has been ameliorated somewhat by the fact that the sea-ice and iceberg conditions require a sophisticated environmental monitoring program and that exploration has been carried out over a number of years without interruption.

For example, data on iceberg size, which are collected during the exploration stage in order to derive mass estimates for evaluating towing capability, can be used at the pre-production engineering phase to estimate the type and size of structure required to survive the iceberg environment. The same is true for other environmental data collected during exploration such as wave height and wind speed.

CHAPTER 3

REGIONAL WIND, WAVE AND ICE CLIMATOLOGY FOR THE GRAND BANKS

Environmental data pertaining to wind, wave and ice conditions are collected routinely by drilling units and have a number of uses even after the drilling program is completed. Specifically, they:

1. Serve as a historical record of conditions in an area.
2. Provide the means for evaluating the climatic variability around wellsites.
3. Are essential for pre-engineering studies and design studies for production platforms.

Decisions as to the type, size and shape of production platforms needed are based on data collected during the exploratory phases of oil exploitation and on data collected for other purposes, such as shipping safety.

This chapter presents an overview of the climate on the northeastern Grand Banks and shows the types of data available to, and required for, offshore structure design.

3.1 WIND

3.1.1 Introduction

Wind data for the Grand Banks are used during oil exploration, when local real time data and short-term forecasts are used to assist in planning drilling operations and crew change schedules. These data are subsequently used in the pre-engineering and pre-construction phases of offshore structures, when frequency and extreme value data are used to assess operating windows and design limits respectively and in ice movement and oil spill trajectory modelling where long term measured or hindcast time series are used as input to the models (DelloStritto et al., 1985). During oil exploration, these data primarily aid in forecasting severe wave conditions. The importance of wave forecasting is related to the limits that extreme waves place on operations. For example, iceberg towing is generally not attempted when the significant wave height (the wave height which is exceeded by only one third of the waves) reaches 4-5 m. Furthermore, extreme waves in conjunction with near 0° Celsius temperatures can result in ice accretion on both the exploratory platform or, more critically, on surface sup-

port vessels and helicopters. Severe winds on their own can affect aerial transportation between the off-shore platform and shore.

The effect of wind and consequently the effect of waves is less on large stable floating structures (such as semi-submersibles) than it is on drillships where the deck is closer to the sea surface. However, even on semi-submersibles, high winds in conjunction with high waves and the presence of icebergs can cause suspension of drilling operations or the evacuation of personnel to the shore. Evacuation is generally used as a last resort because the risks involved with moving personnel in high winds is often greater than the risks of leaving them on board the vessel.

Wind data provide an important input to models designed to predict iceberg and pack ice motion. In fact the accuracy of ice trajectory models can be directly related to the accuracy of wind forecasts. As the movement is most affected by wind, forecasts of pack ice motion tend to be more reliable than iceberg motion predictions. Icebergs, with most of their volume below the water surface, are not only influenced by surface, wind-driven, currents but also by subsurface currents which may not be moving in the same

direction as surface currents. The complexity of iceberg motion prediction has led many operators to rely on simple "rules of thumb" derived from the wind speed.

Time series of wind speeds are also used in the development of extreme values, which are used in conjunction with the Gumbel distribution to produce the return period of extreme events. These extreme values are subsequently utilized in the design phases of offshore structure design. The effect of extreme winds on offshore structures depends upon the type of structure being examined. The wind load on a gravity-based structure (a structure which is founded on the sea floor) is less than 10% of the total environmental load. On floating structures (compliant structures) the wind load can represent as much as 25% of the total environmental load if the frequency response of the structure is similar to the wind spectrum (DelloStritto et al., 1985). Extreme wind events also have an effect on deck equipment such as cranes and flare booms.

3.1.2 Wind Conditions for the Northeastern Grand Banks

The winds over the Grand Banks are driven by large-scale pressure fields over the North Atlantic Ocean. In winter the wind circulation over the Grand Banks is dominated by the "Icelandic Low" located between Iceland and Greenland. The effect of this intense low pressure is persistent west to west northwest winds in the oil exploration areas. In the spring and summer the "Icelandic Low" becomes weaker and moves to a position between Baffin Bay and Greenland. At the same time a high pressure zone located near the Azores (often called the "Bermuda High") intensifies causing a change in the prevailing winds to south and southwest in the Grand Banks area (Petro-Canada, 1981). Winter winds over the Grand Banks tend to be much stronger than summer winds (see Figure 3.1).

Figure 3.2 shows the seasonal pattern of principal storm tracks that cross the Grand Banks. This area lies directly along or close to the mean storm track in every season of the year. The numbers in the 10-degree grid squares in the figures represent the number of storms which occur there in each season. From these figures it is apparent that storms are more frequent in

Figure 3.1 Monthly Mean Wind Speeds for the Grand Banks Area

Source: Petro-Canada 1981

Figure 3.2 Mean Storm Tracks, Areas of Cyclogenesis and Total Number of Storms Over the Grand Banks Area, May 1965 to April 1974

Source: Petro-Canada 1981

winter than in summer. This fact, coupled with the higher wind speeds in winter, indicates the prevalence of severe winter storms on the Grand Banks.

Extreme wind speeds calculated by Danard (1977) are shown in Table 3.1. A maximum 50-year return period wind speed of 40 m/s (approximately 80 knots) is expected to occur in February. It is illustrative to note that the storm in which the Ocean Ranger was lost occurred in February.

3.1.3 Limitations of Wind Data

Thompson (1985) urges caution in the use of unmodified wellsite data for comparison with other data collected on buoys, ships and spaceborne platforms. Near-ocean surface sensors are subjected to ocean spray and more significantly, in the colder months, spray icing accretion. Other factors may also have some impact on the utility of these data. Stewart and Krakowski (1981, cited in Thompson, 1985) found a preferential bias in wind-speed data for multiples of 5 knots. The impact of biases such as this are extremely

Table 3.1 Extreme Wind Speeds (m/sec) for Various Return Periods at 47°N 47°W

Return Period (Yr)	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
5	23	25	23	19	16	15	12	16	19	18	19	22
10	27	30	27	23	20	19	14	21	23	21	21	26
20	32	35	32	27	24	22	16	25	27	25	24	30
50	36	40	36	31	27	24	18	28	31	28	26	33
Maximum Recorded (1946-1971)												
	28	33	28	27	27	21	14	28	24	25	21	29

Source: Danard, 1977

difficult to evaluate because there may be as many instances of under-estimation as over-estimation in which case, long-term statistics may not be seriously affected.

Rig-collected data are presently used to provide synoptic statistics for surrounding areas. However, it is apparent that many wind measurements made on rigs are not corrected for instrument elevation or location. Characteristically, anemometers are placed on the drilling derricks at heights varying from 60-90 m. The difference between winds measured at 80 m and those measured at the standard height of 10 m is 30% in stable atmospheric conditions and 20% in unstable conditions (Thompson, 1985).

On all ocean-going vessels anemometers are located for installation convenience and not for optimal undistorted air flow. Errors in speed readings caused by flow distortion can vary between 15-20% (Thorntwaite et al., 1965; Augstein et al., 1974).

Although 10-minute average wind speeds are considered to be a good compromise between smoothing turbulence spikes and not damping out significant events, the averaging time for most wind measurements on rigs is one minute or less. The shorter averaging period

used on oil rigs produces higher average wind speeds than measurements made with a longer averaging period. This is because the use of a short averaging period allows the inclusion of wind gusts (occurring over intervals of 1 minute or less) which inflate the average wind speed. It is often not possible to establish the averaging period for different data sets. Thus data with widely differing averaging periods are compared or used together in compiled data sets. The implications of this for calculating the extreme wind speed maxima are evident.

Thompson (1985) compares the monthly median wind speeds on the northeastern Grand Banks before the use of exploration rig data (1968-1979) with the median values calculated after the introduction of rig data (Figure 3.3). The median post-1979 wind speed (including rig data) appears to be about 10-15% higher than the pre-1980 figure. Thompson (1985) suggests that the difference is attributable to the use of unmodified wellsite data where the wind data were uncorrected for the height of the anemometer. Although this is a reasonable postulation, the amount of post-1979 data may be insufficient to produce valid statistics for comparison with the pre-1980 data.

Figure 3.3 Median Wind Speeds from Synoptic Meteorological Observations Before and After Introduction of Data from Drilling Units

Source: Thompson, 1985

3.2 CURRENTS AND WAVES ON THE GRAND BANKS

3.2.1 Introduction

The Grand Banks area is noted for its severe wave climate. As waves are a wind-generated phenomenon their severity can be directly related to the strength of the wind. As the structures used for oil exploration and production become larger and the water depths in which these structures are expected to operate become deeper, the effects of wave forces on the structure and the response of the structure to cyclic loads become much more important in the design phases of structure development (Standing, 1984).

The direct impact of ocean currents on offshore structures is less than that of waves, icebergs or sea-ice because the potential maximum force that currents can exert on offshore structures is much less. The primary impact of currents on operations is related mainly to their influence on the movement of icebergs and, to a lesser degree, sea-ice in the vicinity of the offshore platform. The majority of icebergs which cross or circuit the bank fringes follow the predominant route of the Labrador Current, along the eastern edge of the Grand Banks. Although sea-ice is primarily influenced by winds, it is also drawn much

farther south in Flemish Pass owing to the influence of the Labrador Current. Figure 3.4, which shows sea-ice conditions in February 1985, demonstrates the effect of the Labrador current on the sea-ice edge in the vicinity of the exploratory wellsites. One implication of ice being drawn further south by the Labrador Current is that under the additional influence of easterly winds, the tongue of ice can move westward over the well locations causing the termination of operations. In contrast, the sea-ice edge over much of the rest of the Grand Banks is still located north of the oil exploration areas.

3.2.2 Currents

An excellent review of the general motion of currents over the Grand Banks has been presented by Petrie and Anderson (1983). The situation in the Grand Banks is dominated by the Labrador Current. As this approaches the Grand Banks, approximately 15% of the flow is diverted into the Strait of Belle Isle while the remainder moves south over the northeastern Newfoundland Shelf. Approximately 7% of the flow moves through the Avalon Channel. This flow splits into two branches, one moving westward around the south coast of

Figure 3.4 Sea Ice Conditions on the Grand Banks,
February, 1985

Newfoundland and the other eastward across the Grand Bank, where it may join the main current flow along the eastern slope of the bank. Petrie and Anderson (1985) estimate that 80% of the flow through the Avalon Channel eventually joins the Labrador Current on the west side of the Grand Banks. The bulk of the Labrador Current that does not move through the Avalon Channel flows southward over the bank until it meets the northeastward flow of the North Atlantic Drift (Gulf Stream). A portion of this southward flow moves north of Flemish Cap and forms a clockwise flow around this bank (Petro-Canada, 1981). The general current flow in the Grand Banks area is shown in Figure 3.5.

The speed of the various current branches varies over the bank. In the Avalon Channel the average current speed is 20 cm/s. The current over most of the bank, characterized by slow variable flow primarily driven by wind and tides (Kudlo, 1975), averages 1-2 cm/s. Along the eastern slope break of the bank the current speed averages 10-20 cm/s.

Figure 3.5 Major Surface Currents in the Grand Banks Area

Source: Petro Canada 1981

3.2.3 Waves

The main source of regional wave data for the Canadian East Coast regions is synoptic wave charts produced by the Canadian Forces Meteorological and Oceanographic Service (METOC) from reports made by merchant ships, weather ships, naval vessels and oil exploration platforms. More site-specific data are obtained from buoys (often called waverider buoys after one of the principal manufacturers of these devices) which float on the ocean surface and measure wave height (Petro-Canada, 1981; Neu, 1982).

Direct measurement of waves is more precise than general ship observations which are made visually. A term frequently used in oceanography is the "significant wave height," which refers to the average height of the highest one-third of the waves. The significant wave height has been established as the height that visual observers tend to estimate as the mean height. Despite attempts by the scientific community to validate the use of significant wave heights, it is important to remember that it is a rather arbitrary value that has gained some statistical respectability over the years and that the spectral average wave

heights determined from waverider data are generally considered to be the best source of wave heights for use in offshore design.

Wave period is an important parameter for offshore structure design. When the frequency of large waves is high, a resonance can be set up in the structure. If this resonance matches the fundamental frequency of the structure, vibrations are created which cause structural fatigue and may ultimately generate structural failure. Normally, wave period decreases as wave height increases but, if the waves become steeper, the interval between waves can decrease. Wave period data can also be used to estimate the fatigue life of structures.

Figures 3.6 and 3.7 show the frequency of occurrence of wave heights and wave periods on the Grand Banks throughout the year. As in the case of winds, the most severe wave conditions occur in winter. Four-metre waves are found to occur over 50% of the time in winter as opposed to only 10-12% of the time in summer. The highest significant wave height in the AES study was 13 m.

Figure 3.6 Percentage Frequency of Occurrence of Significant Wave Height (m) in the Grand Banks Area

Grid Square 26 Covers all of the Southeast Newfoundland Coast and the Western Half of the Grand Banks; Square 27 Covers the Remainder of the Grand Banks (Petro-Canada, 1981 from AES, 1977)

Figure 3.7 Percentage Frequency of Occurrence of Wave Periods (seconds) in the Grand Banks Area

Grids are as described in Figure 3.6 (Petro-Canada, 1981 from AES, 1977)

The mean wave height calculated from post-1970 data is higher than the pre-1970 mean. This could be explained by the more variable weather in the northern hemisphere since approximately 1970 (Neu, 1982).

3.3 ICEBERGS

3.3.1 Introduction

The focus of oil exploitation in the Grand Banks area is gradually shifting from the exploration phase to the production phase. As indicated in Chapter 1, the ice management philosophy during exploration centres on avoiding environmental hazards. In the pre-production phase the operational philosophy changes to become more concerned with coping with or withstanding environmental hazards. The design of structures capable of remaining at the wellsite location for the duration of oil field production requires close examination of historical information relating to the size of icebergs and their distribution in both a temporal and spatial context. Study of their physical characteristics (length, mass and draft) and movement coupled with the environmental factors that influence their movement is necessary to estimate required platform size, strength and shape. In order to do this, it

is necessary to establish the magnitude of the relative risk factors. Risk can never be entirely removed, but risk evaluations allow the structure designer and regulatory bodies to set a level acceptable to both the operator and society.

3.3.2 The Origin and Movement of Icebergs

Icebergs are large pieces of glacial ice which have broken away from tidewater glaciers primarily located along the western coast of Greenland and to a lesser extent along the coast of Ellesmere Island. These immense pieces of ice, some as large as 100 to 150 million tonnes move from the glacier termini to fjord entrances where the larger pieces ground on a terminal moraine. In most of the Greenland fjords this terminal moraine lies at approximately 300 metres water depth. Icebergs may stay within the fjords for a number of years until they decrease in size and draft to a point where they are able to float or roll over the terminal moraine and exit the fjord.

Once icebergs escape the confines of the Greenland fjords, they move north along the western shore of Greenland carried by the West Greenland Current (an offshoot of the North Atlantic Drift). After passing

through Melville Bay, they enter the Labrador Current, which moves them south through Davis Strait and the Labrador Sea to the Grand Banks. En route, icebergs are often grounded, trapped in inlets or frozen into sea-ice cover. Thus it may take several years (an average of 3 years is generally assumed) to travel the approximately 4,000 km from the principal glacier sources in Greenland to the Grand Banks.

As icebergs travel to the Grand Banks they gradually decrease in size owing to melting and mechanical erosion. Icebergs deteriorate rapidly as they approach the main branch of the North Atlantic Drift and icebergs have usually melted completely by the time they reach 40° north. On rare occasions icebergs have been sighted as far south as Bermuda (32.18°N) and the Azores (38.30°N) (Smith, 1931; Ketchen & Hildenbrand, 1977).

3.3.3 Iceberg Flux

Iceberg flux is defined as the number of icebergs that cross a given line of latitude within specific longitudes over a fixed time period. Although iceberg flux over the Grand Banks is one of the least accurately known iceberg measures, its importance for

estimating collision risk (and consequently probable collision forces) to offshore structures must not be under-emphasized or minimized. The best estimate of flux at the offshore wellsites comes from wellsite environmental monitoring. In order to place these short-term data into a long-term perspective numerous attempts have been made to extrapolate more regional, long-term data such as those data collected by the International Ice Patrol (I.I.P.).

In accordance with their mandate, the I.I.P. (and their precursors) estimate the number of icebergs that cross 48° north. The annual estimates for the period 1880-1985 are shown in Figure 3.8. A wide variation from year to year is evident, but it is difficult to determine the amount of variation attributable to changes in collection methods, in the amount of effort expended in collecting the data or in actual iceberg flux variations. Ninety percent of the icebergs sighted on or near the Grand Banks occur in April, May and June; on average, the maximum number of icebergs are sighted in May (38%).

Figure 3.8 Estimates of Iceberg Flux at 48°N, 1880-1985

Source: I.I.P. Iceberg Season Reports, 1949-1984

3.3.4 Iceberg Morphometry in the Grand Banks Region

The importance of accurate iceberg dimension data relates primarily to estimates of collision frequency and collision forces for a structure located in the Grand Banks. At this time, most iceberg morphometry data have been collected in the Labrador Sea; some data have been collected on the Grand Banks in the last five years. Although data from the Labrador Sea can be used to estimate conditions in the Grand Banks, there is some reason to believe that the relationships between the linear dimensions of icebergs vary with latitude. For example, of icebergs measured at wellsites in the Labrador Sea (1972-1982), those with drafts less than 100 m and measured between 56-58°N had a mean estimated mass of 1,100,000 tonnes whereas icebergs with drafts less than 100 m measured between 50-52°N averaged 390,000 tonnes.

This variation is related to differences in the amount of degradation experienced by icebergs (Figure 3.9). At northerly latitudes, icebergs tend to be more "blocky" or angular, whereas at more southerly latitudes they are less blocky but can still exhibit large drafts. Icebergs sighted in more southerly areas and possessing large drafts generally have less under-

Figure 3.9 Northern and Southern Latitude Iceberg Morphometry

water volume than northern icebergs with similar drafts and thus, less mass. There is a danger therefore, in broadly applying mass distribution characteristics determined from more northerly areas to the Grand Banks. Caution should also be taken when using data from different exploration areas on the Grand Banks. It is likely that both the water depth and the position of wellsites with respect to the main flow of the Labrador Current influence size distributions.

Iceberg data from all regions and sources do not give a complete picture of size distribution. Smaller icebergs tend not to be observed or are not measured when observed. To the author's knowledge only one set of public domain data exists in which visual aerial reconnaissance was analyzed such that all verified iceberg targets (104 icebergs) were measured (to a resolution of 10 metres) and a surface area distribution was produced (Robe, 1976b) (Figure 3.10).

Above-water dimensions of icebergs are generally measured in one of two ways. The first method consists of using a sextant and range-finding device (manual or from radar) where angles from the observing platform and the sides and top of the exposed iceberg and the

Figure 3.10 Frequency Distribution the Cross Sectional area of Grand Banks Icebergs, 1976

distance to the iceberg are measured. Dimensions of the iceberg can then be obtained from simple trigonometry. The second method consists of using photographs to measure dimensions; knowing the range of the iceberg from the camera and the focal length of the camera, actual iceberg dimensions can be determined.

In order to give some indication of the size of icebergs experienced in the northeastern Grand Banks, a sample of 470 icebergs measured from aerial photography and by ship-based field surveys in the area $48^{\circ}00'N$ to $45^{\circ}20'N$ and $46^{\circ}20'W$ to $53^{\circ}6'W$, collected between 1981 and 1984 was examined. The effect of water depth on the iceberg size distribution was investigated by analyzing only those data for icebergs west of $48^{\circ}W$ and south of $48^{\circ}N$; this geographical boundary effectively limits the sample to icebergs located in 120 m of water or less.

3.3.4.1 Iceberg Length

Iceberg length is defined as the longest linear waterline dimension. Iceberg length distributions are important at the pre-engineering phase of oil production where they are used in iceberg/structure interac-

tion risk assessment (e.g. Fuglem et al., 1984). Iceberg length is also used to provide estimates of the maximum draft of icebergs.

The data identified above show a maximum length of 311 m and a median length of 88 m. For icebergs located south of 48°N and west of 48°W and a maximum length of 266 m, a mean of 79 m and a median of 63 m were calculated. This shows that if icebergs sighted in the deep water in Flemish Pass are excluded from the calculation, the mean size of icebergs in the sample decreases. Iceberg length, in this sample decreased by 30% when only icebergs located in shallower water were used.

3.3.4.2 Iceberg Width

The width of an iceberg is generally taken to be the longest linear dimension perpendicular to the length. The width of icebergs, although of limited importance in isolation from other iceberg dimensions can be used with length and draft, for example, to make some estimation of iceberg mass. A maximum width of 246 m and a median width of 56 m is calculated from the data. The mean ratio between width and length was 0.51:1, similar to the mean ratio of 0.6:1 found by

Hotzel and Miller (1983) for icebergs measured at wellsites in the Labrador Sea. These data indicate that icebergs may become more elliptical as they approach the Grand Banks. This factor becomes more important when establishing the diameter of icebergs for use in collision risk models because although the mass of the iceberg decreases rapidly, the length of the iceberg may not decrease in the same manner. For icebergs sighted south of 48°N and west of 48°W a maximum width of 246 m and a median width of 58 m was observed.

3.3.4.3 Iceberg Height

Iceberg height is presently used in some equations for mass estimation and was used in the 1970s (e.g.. Robe, 1976a) to derive height to draft ratios, which were used to estimate iceberg draft from the height. In an analysis of iceberg morphometry performed by Hotzel and Miller (1983) it was found that draft estimates from height showed a high degree of scatter. There is also some problem with the consistency of iceberg height measurements. In some cases height is taken to be the highest relief on the iceberg and in other cases is taken to be the average height of the iceberg.

Analysis of the heights of 470 icebergs measured in the northern Grand Banks (south of 48°N) showed a maximum height of 72 m and a median of 11 m. When the iceberg sample was limited to icebergs west of 48°W , height values varied only slightly, with the median value calculated as 10 m.

3 3.4.4 Iceberg Draft

Iceberg draft is an extremely difficult parameter to quantify accurately, partly due to the lack of direct measurements. Gouges caused by icebergs touching or scraping along the ocean bottom (generally called iceberg scours in Canada) are testament to occasional iceberg grounding on the sea bottom. The existence of these scours and their frequency of occurrence is of particular importance for determining the risk to subsea structures such as pipelines. Although iceberg scour tracks can be identified on the ocean bottom with downward-looking side-scan sonar, there is no foolproof way of determining their age. Some may have survived from the period of the last glaciation when the water depths were much less. Other scour tracks made more recently may have been obliterated by erosion processes on the sea-bed. With such problems, attempts are presently being made to estimate scour

frequency from iceberg incursion into these areas. For this type of study it is extremely important that the local draft distribution be well known.

Measurements of iceberg draft present many problems. Such measurements are determined with side-scan sonar, and until recently none of the sonar "fish" (the sonar unit) was equipped with inclinometers or compasses, making it difficult to determine vertical or horizontal orientation. Thus, a fish pointing slightly upward would over-estimate the draft of the iceberg whereas a fish pointing downward would underestimate the draft. For example, a draft measurement taken from a distance of 100 m with a fish tilted upward at 5° would be 10% larger than the actual draft. Numerous papers ignore these problems and cite statistics relating to the proportion of icebergs having drafts larger than their length (see Benedict, 1982). Given the uncertainty of measurement it is probably valid to assume (as did Brooks, 1982) that iceberg draft rarely, if ever, exceeds the waterline length.

In the present sample, 57 iceberg drafts showed minimum and maximum values of 20 m and 100 m respectively. The mean draft was 66 m with a median (and modal) draft of 65 m. With the icebergs in deeper

water excluded (east of 48°W), the mean, median and mode all equal 65 m. It is important to note that in ship-based field surveys, observers tend to choose larger icebergs for measurement. The smaller icebergs, apart from being more difficult to measure owing to sonar perturbations caused by the proximity of the water surface, do not show up as well on ship's radar and therefore tend to be overlooked as targets.

3.3.4.5 Iceberg Mass Estimation

Site-specific mass distribution of icebergs is useful for assessing iceberg towing feasibility during oil exploration. It is also useful during the design phases of oil production for decisions as to the appropriate size and type of structure for use on the Grand Banks. Therefore, it is critical that the distribution data be as accurate as possible. Small differences in design values can mean the difference between choosing an expensive, extremely over-designed structure or a cheaper, under-designed structure. The second option is unacceptable to both the oil operator and society. The first option can result in estimated costs being so large that the oil operator decides that oil production in an area is prohibitively expensive.

As iceberg mass cannot be measured directly, considerable effort has been expended during the last 15 years to develop a reliable estimation method. Examination of wellsite reports show that the most commonly used equation for mass estimation of icebergs at exploratory wellsites is :

$$M = 7.12 LWH C_{bf} \quad [1]$$

Where

M	=	estimated mass (tonnes)
L	=	length (m)
W	=	width (m)
H	=	height (m)
C_{bf}	=	block coefficient (an estimate of the difference between the iceberg and a rectangular slab).
7.12	=	a constant which accounts for the densities of sea water and iceberg ice. (tonnes/m ³)

An analysis by Hotzel and Miller (1983) of iceberg dimensions in the Labrador Sea compared the use of above-water iceberg dimensions and single linear dimensions to estimate iceberg mass. They concluded that, despite the non-standardized methods of collecting

iceberg data at wellsites, the relationships between the most commonly measured iceberg dimensions (length and width) and estimated volumetric dimensions appeared to have relevance to other offshore areas where icebergs are experienced. Of the linear iceberg dimensions, length is the most widely available and, given its ease of measurement, the most reliable size estimator. Hotzel and Miller (1983) developed an equation relating length to estimated mass:

$$\text{Mass} = 2.009 \times \text{length}^{2.68} \quad [2]$$

This equation was shown to provide reasonable estimates of the drafts of icebergs measured off Greenland. In view of the findings in sections 3.3.4.1 - 3.3.4.5, it appears as though a different relationship may be more appropriate for the Grand Banks.

CHAPTER 4

USE OF ENVIRONMENTAL DATA IN THE DESIGN PROCESS

4.1 DESIGN QUESTIONS

An oil company's decision to proceed with development in the Grand Banks area is dependent upon environmental, engineering, political and economic factors. A number of important questions pertaining to structure design, subsea facility configuration and transportation must be answered:

1. What type of structure is best suited for the area? How large and strong should it be? Should it be bottom founded or floating?
2. What type of subsea configuration should be used? Should the distance between satellite wells be minimized in order to decrease the probability of damage to pipelines caused by collisions with iceberg keels? Should efforts be made to orient the pipelines to decrease collision probabilities? Should pipelines be buried or have protecting berms to reduce collision probabilities? Should the wellheads be placed in holes (called glory holes) to protect them from collision?

3. Should the oil be transported to shore by pipeline or vessel? Which method presents the least risk and the best cost/benefit?

The environment has a bearing on all of these questions. The manner in which environmental data are used can drastically affect views on the approach which best meets oil industry, safety and regulatory needs.

In the discussion of oil production on the Grand Banks, the debate as to whether a floating production system or a gravity-based (sea bottom founded) structure provides the most cost-effective method for producing oil has persisted since reserves were perceived to be economically viable. The debate has also been influenced politically. Floating structures are built primarily out of steel and require facilities not readily available in Canada; therefore, such structures would be largely built outside of Canada. Gravity-based structures are typically built mainly out of concrete and the technology for concrete fabrication could be more easily developed in Newfoundland. Therefore the gravity-based structure is favoured politically. When concepts are evaluated in this more subjective fashion, biases in the way data are used appear. There

is, for example, a greater perception of the risk of iceberg collision by politicians than there is by engineers or environmental scientists.

The objective of this chapter is, therefore, to show how various environmental parameters are important for rationally evaluating the probabilities of iceberg collision with an offshore platform. As part of this process the following methodology will be followed:

1. Explain techniques that have been used to estimate factors involved in collision evaluation.
2. Outline how differing methodologies, and the design values which are extrapolated from existing data, can influence design decisions and construction costs.
3. Indicate which environmental parameters have the most influence on the evaluation.
4. Illustrate how environmental data collected to serve exploration, regulatory or political needs can be used to aid in the offshore structure design process. As an example, a conceptual framework for an iceberg/structure collision risk simulator is developed.

4.2 ICE ANALYSIS TECHNIQUES: DEFICIENCIES AND CONSEQUENCES FOR DESIGN

The intermittent incursion of sea-ice and icebergs into the Grand Banks area presents a significant problem to offshore operations of any sort. As opposed to techniques used to evaluate extremes for other environmental phenomena (such as winds and waves), techniques used to estimate the extreme values for iceberg dimensions and sea-ice occurrence are still evolving. There are numerous examples of design value estimation which exhibit serious flaws both in the data used and the techniques used to analyze these data.

4.2.1 International Ice Patrol Iceberg Flux Data

In the last 100 years, two substantial changes have occurred in the way iceberg data have been collected by the I.I.P.. Prior to 1946 data were collected almost exclusively by ships travelling along the North Atlantic sea lanes or by fishing vessels in coastal waters. There are several problems with this method of data collection :

1. The iceberg counts are spatially incomplete, with certain areas being preferentially sampled.

2. The number of icebergs counted is influenced by iceberg proximity to passing vessels.
3. Many vessels did not (and many still do not) adequately monitor the surrounding ocean for icebergs.
4. Radar, which is the principal way of identifying icebergs in modern times, did not exist prior to 1940 and earlier iceberg counts were based on visual sightings. Given that the Grand Banks is located at the confluence of the cold Labrador Current and the warm North Atlantic Drift, it is extremely foggy. Therefore, prior to the advent of radar, it is likely that many icebergs were not observed.
5. Certain events in history such as the two major 20th-century wars have resulted in dramatic changes in the patterns and volume of transatlantic transportation and consequently have influenced iceberg counts.
6. Iceberg sightings are biased towards the larger sizes because the smaller ice pieces are extremely difficult to observe in any sea state more severe than calm.

Since 1946, the I.I.P. has resorted almost exclusively to airborne monitoring with radar assistance. One might expect this new technology to have yielded an increased number of recorded icebergs. As shown in Figure 3.8, however, this has not been the case. The new data collection method did not produce a dramatic increase in the number of icebergs reported partly because the increase in transatlantic traffic needed to move troops from North America to Great Britain between 1943 and 1945 resulted in better and more extensive coverage. It is probable that had the ship and air traffic been similar to the pre-war years, fewer icebergs would have been sighted in this period and a more noticeable increase in iceberg sightings would have occurred when radar was introduced.

As with the ship-board iceberg counts, a number of problems exist with airborne reconnaissance:

1. The flights follow specific routes, thus many areas are not overflown and a problem arises in determining whether absence of data indicates no icebergs or no overflights.

2. In poor weather conditions no visual verification of radar targets is possible. This means that some targets identified as icebergs could be ships or other ocean surface perturbations.
3. With specific routes being followed some areas are crossed many times while other areas are seldom crossed. No attempt is made to normalize the data for this effect.
4. It is possible that icebergs sighted on one flight are re-sighted and recounted on subsequent flights. The observer would, in most cases not be able to re-identify icebergs on subsequent flights because icebergs are unstable and tend to re-orient themselves in the water at least once a day at the latitude of the Grand Banks. This overcounting probably inflates the I.I.P. counts. Overcounting may be balanced to some degree by the undercounts made when surface fog and low cloud conditions prevent the identification of some icebergs.
5. As with ship reconnaissance, a disproportionate number of large icebergs are counted.

Since 1983, the I.I.P. have used side looking airborne radar (SLAR) as the primary tool for iceberg reconnaissance (Edwards & Thayer, 1986). This is an all-weather instrument with the advantage of allowing iceberg monitoring even in periods of restricted visibility. As a result the number of alleged iceberg sightings has increased dramatically. For example, in 1982, the estimated flux across 48°N was 180 icebergs. In 1983, this number increased by 750% to 1,356 icebergs. This increase did not, however, appear to be reflected in the number of icebergs sighted at Mobil's exploratory wellsites (Benoit, 1985). Thus, it appears that the increase in the number of icebergs sighted may be influenced more by the new technology than by actual increases in the number of icebergs present.

While there is no doubt that SLAR is a useful tool for iceberg monitoring it does have some limitations:

1. SLAR tends to be used when poor visibility exists, thus there is usually no way to verify that targets are icebergs and not ships or other ocean surface phenomena. Studies have shown that icebergs and ships do not display different radar signatures (Rossiter et al., 1985).

2. SLAR appears to be more effective in low sea states and at low altitudes and when targets are viewed across the wind or wave direction (Rossiter et al., 1985).
3. Edwards and Thayer (1986) show that in studies designed to test the ability of trained SLAR observers to distinguish between ships and icebergs when the targets were ambiguous, the error rate was between 40-45%.

The use of SLAR as a tool for iceberg monitoring over large areas is still evolving. Suitable ground-truth information should improve the identification of small glacial ice pieces which are presently only occasionally identified. A problem exists with determining how the recent I.I.P. iceberg flux estimates, using SLAR, can be related to flux estimates made before the use of SLAR.

Another more general problem exists with I.I.P. iceberg counts. Flux estimates made by I.I.P. are not always corroborated by the map representations of iceberg sightings shown in I.I.P. annual reports. In 1960, for example, the I.I.P. stated that no icebergs

crossed 48° north, yet the I.I.P. annual report and their computerized database of icebergs show at least six sightings of icebergs south of 48° north.

Despite the problems with I.I.P. data it comprises the only long-term data set and is therefore used frequently by researchers to evaluate iceberg conditions. I.I.P. estimates of iceberg crossings into the area south of 48° north do provide a relative way of comparing the interannual variation in iceberg flux. It is also fortuitous for oil operators, from the perspective of the I.I.P. iceberg observations, that the potential oil bearing areas lie close to the principal avenue of iceberg transport in the Grand Banks area, Flemish Pass. The I.I.P. has always paid special attention to this area. It is frequently, if not always, overflowed and the statistics for the area are unlikely to suffer from discontinuous coverage.

Based on the I.I.P. summary reports, the long-term mean annual flux across 48°N (1880-1984) is 388 icebergs/year. The mean iceberg flux for the period between 1946 and 1984 is 345 icebergs/year. If the last 20 years are used to establish the mean iceberg flux, the calculated flux increases as the sampling period used decreases (Table 4.1). For example, the

Table 4.1 Iceberg Flux at 48°N Averaged Over
Different Time Periods

TIME	MEAN FLUX*
Long-term Mean Flux (1880-1984)	379
Long-term Mean Flux (Post WWII 1946-1984)	345
Last 20 Years (1965-1984)	456
Last 10 Year (1975-1984)	440
Last 5 Years (1980-1984)	768

* Calculated from I.I.P. data 1880-1984.

mean flux in the 1980-1984 period was 768 icebergs per year, almost twice the 100-year average. If one can assume that the collection of iceberg data has improved in the last 100 years this observation may indicate that the use of the long-term iceberg flux is not representative of the present flux of icebergs across the Grand Banks and that collision estimates should be based on a much larger flux of icebergs.

4.2.2 Iceberg Flux Estimation

4.2.2.1 The Raindrop Technique

A number of techniques have been used to estimate the flux of icebergs at the various exploration sites. One of the most prevalent of these is the "raindrop method". In this technique the flux of icebergs (usually the average long-term flux determined from International Ice Patrol historical records) is distributed along 48°N . The distribution of iceberg flux across 48°N is generally estimated from iceberg sightings in the one-degree grid squares south of 48°N . A Monte Carlo technique is then used to distribute the start of iceberg tracks within each one-degree of longitude along the 48°N line of latitude. The icebergs are then assumed to proceed due south (Figure 4.1

Figure 4.1 The Raindrop Method of Collision Assessment

illustrates this approach). In its simplest form, this technique assumes that all icebergs crossing 48°N (the latitude used by the I.I.P. to determine flux) also cross the wellsite areas several degrees to the south. This technique is often modified to account for the difference in water depth between the bank and the water depth at 48°N ; a draft distribution for the icebergs is assumed and it is assumed that no iceberg with a draft greater than the water depth can proceed further south. In this way large icebergs are filtered out of the flux at the wellsite. There are several problems with the raindrop technique:

1. The assumption that the icebergs move due south is unrealistic. Icebergs follow the current (and therefore the bathymetric contours along the edge of the Grand Banks) and are brought on to the bank during storm conditions or by eddies in the main current.
2. The simple assumption that all icebergs, proceed due south results in an over-estimation of iceberg flux at the wellsite.

3. No account for iceberg degradation is made, yet degradation is rapid at this latitude; and only a portion of the icebergs crossing 48°N actually survive to the wellsite latitudes.

The technique outlined above has been used by some companies to derive an annual mean flux of between 45 and 55 icebergs at Hibernia (one of the major oil exploration areas on the Grand Banks) or an iceberg crossing rate of 1 iceberg/ 1.5 km of latitude/ year.

4.2.2.2 The Latitude Ratio Method

A different evaluation is used in this thesis to estimate iceberg flux. Thirty-five years of I.I.P. summaries (1949-1984) are used to calculate the density of icebergs sighted within a one-degree grid system around the prime oil exploration area. A total of 22,386 iceberg sightings are used to calculate the individual one-degree grid densities over the entire Grand Banks. This grid density shown in Figure 4.2 clearly shows the higher iceberg densities found in the Avalon Channel and Flemish Pass, the two major iceberg

Figure 4.2 Density of Iceberg Sightings by Latitudinal Band

I.I.P. DATA (1948-1984)

2

OF/DE

2

MicroD

thoroughfares. Higher iceberg densities found along the bank edges may reflect the number of icebergs which ground in these locations and are counted on more than one overflight. These icebergs probably inflate the number of icebergs postulated for the wellsite locations.

The total number of icebergs between each degree of latitude is used to estimate a degradation rate of icebergs as they move south. The long-term annual flux of 388 icebergs/year is then distributed along 48°N latitude in proportions relative to I.I.P. sightings. Using the decrease in total numbers of icebergs between each degree of latitude, a ratio of degradation for each one-degree of latitude is established. This technique allows estimation of the number of icebergs entering the degree grid area around Hibernia, Terra Nova and Ben Nevis exploration areas (Figure 4.3).

This analysis shows a mean annual entry rate to the grid cell (47-46°N and 48-49°W) around the exploration areas of approximately 29 icebergs/year. The distance across one-degree of longitude at 46.5°N is 111 km. If all icebergs sighted within the cell moved from

Figure 4.3 Simulated Iceberg Flux by Latitudinal Band

		55 W				50 W						45 W		
	Newfoundland												LATITUDE TOTALS	
48 N		00	05	12	74	57	48	40	41	34	25	20	380	
47 N		01	06	19	47	07	35	24	17	29	36	21	17	290
46 N		01	05	06	10	17	14	17	26	21	10	06	152	
45 N		00	01	02	03	04	07	08	17	08	05	03	61	
44 N			00	00	01	03	05	10	09	03	01	01	34	
43 N			00	00	01	02	05	06	04	01	00	00	19	
42 N														
41 N		00	00	00	00	00	01	02	01	00			4	
40 N	80 m ISOBATH						00	00	01	00			1	

I.I.P. DATA 349-1984

north to south, the iceberg crossing rate across 46.5°N would be 1 iceberg/3.7 km of latitude/year, about half the number estimated using the raindrop method.

If this type of analysis is taken one step further, it can be estimated that the average return period between icebergs striking a fixed structure with a diameter of 120 metres at the wellsite latitude would be 31 years.

Comparison of the iceberg flux estimated using the latitude ratio method with fluxes seen at wellsites in the Terra Nova oilfield is outlined in the following discussion. Data from end-of-season environmental reports for Terra Nova K-08 (drilled in 1984) show that there were 55 sightings of icebergs around the wellsite. Of this total, 15 icebergs crossed the wellsite latitude from the north while 2 icebergs crossed from the south. The net southward flux, therefore, was 13 icebergs within a 30-km radius of the wellsite. The percentage of icebergs sighted at the wellsite which then contributed to the flux along a 60-km line at the latitude of the wellsite was calculated to be 24%. Although one can not say for certain where the other 76% of the icebergs go, it can be safely assumed that most of them are carried off the

bank into the main flow of the Labrador Current or completely degrade and do not pose any threat to structures on the bank. This appears to support the argument that the raindrop method is a poor estimator of fluxes at the various wellsite locations. The raindrop method also suggests that all wellsites bounded by the same lines of longitude would have the same flux regardless of their proximity to the shelf break or their distance south from the northern flux boundary. Flux estimates determined from the raindrop method or its various modified forms should be viewed skeptically with these identified problems in mind.

4.2.3 Effects of Flux Estimation on Design Decisions

Iceberg flux is used to estimate the number of collisions that a structure could encounter during its operating lifetime. The number of estimated collisions is then used to help determine which type of wellsite structure provides the best combination of safety and efficiency. If the estimated iceberg flux is low then the structure could be either a floating structure or a bottom-founded structure. The floating structure, which is relatively cheap to construct, can move away from the wellsite should icebergs approach thereby

reducing the risk of collision; it can also incur some lost oil production and still be cost efficient. The bottom-founded structure which is expensive to build (approximately 10 times the cost of a floating structure), would potentially experience even fewer periods of lost oil production than the floating production platform but would require a longer field life in order to recoup the initial capital expenditure.

If the actual iceberg flux is high, the floating production option may not prove to be cost effective. The amount of time which the vessel is off location to avoid icebergs might result in unacceptably long periods of lost production. In this case the bottom founded structure may prove to be more cost efficient, despite its initial high cost.

In the worst case situation presented in section 4.2.2.2, all icebergs contributing to the flux at the wellsite are considered to be dangerous to the structure. The problem of iceberg flux is, however, not only concerned with the numbers of icebergs but also with their size. One of the principal reasons for using a large bottom-founded structure is that it can be designed to resist impacts with large icebergs. The

situation for floating structures is different because the icebergs posing the largest threat are smaller icebergs that are not easily detected with radar and can be moved against the structure in high waves where they can develop much more speed and therefore more kinetic energy than is possible when they are driven by only wind and current.

4.2.4 Iceberg Size Measurement and Estimation

Iceberg size is one of the most important parameters used in the evaluation of different structural concepts. Iceberg sizes have been measured and estimated in the vicinity of wellsites for approximately 15 years as part of drilling programs. Despite the length of observation time there are still very few data which can be used to define size distributions for the Grand Banks area. A study by Hotzel and Miller (1983) of icebergs measured in the Labrador Sea showed that only a third of the icebergs for which length measurements were taken also had draft measurements. This lack of data coupled with identified measurement problems has led to a number of theories

about the relationship between iceberg draft and other more easily obtainable iceberg dimensions such as length.

Hotzel and Miller (1983) found a maximum length to draft ratio of 1.69. This indicates that the draft of this particular iceberg was 69% longer than the waterline length. It is possible, but unlikely, that an iceberg could have floated in this position very long and almost certainly represents an error in draft measurement. However, such measurements are often accepted by researchers as accurate and then used to produce worst case evaluations of iceberg dimensions. Wellsite measurements of iceberg size are biased toward large icebergs because larger icebergs present a greater threat to the drilling vessel. The smaller iceberg masses (growlers and bergy bits) thus are poorly represented in any sample of icebergs measured at wellsites.

One of the better techniques used to measure iceberg dimensions is vertical aerial photography. The images produced in this way are analyzed with sophisticated stereoscopes to calculate both linear and volumetric dimensions of icebergs. This technique however, has one major drawback in that icebergs

sampled in this way tend not to be representative of the entire distribution and are biased toward the larger icebergs because they are easier to locate from the aircraft. Therefore, once again the population of growlers and bergy bits is poorly represented.

A number of techniques have been employed to define the size distributions of the iceberg dimensions that are more difficult to measure directly. The most widely used techniques attempt to relate simple above-water linear measurements (length, width and height) to other important parameters such as mass and draft. There are dangers in placing too much faith in correlations between these dimensions. The quoted height of an iceberg sometimes refers to maximum height of the iceberg and in other instances refers to the average height of the iceberg. Length is generally accepted to be the longest linear waterline dimension, but from surface observation platforms it is difficult to be sure that the linear dimension reported is actually the longest dimension. Mass is calculated by a number of techniques almost all of which incorporate a subjective evaluation of "block fullness" (a factor used to account for the amount of iceberg degradation and the ef-

fect of this degradation on the calculated volume). An iceberg shaped like a cube would have block fullness factor of 1.0.

In order to calculate the unmeasured dimensions of icebergs, statistically tenuous techniques have been used. For example, in an effort to produce a simple method of estimating draft from other above-water dimensions El-Tahan and Davis (1982) regress draft against a ratio between draft and height. This type of analysis violates one of the fundamental assumptions of regression, that of independence of the regressed variables, and casts considerable doubt upon the validity of the relationship. Kinsman (1957) warns of the dangers in manipulating data to produce a "high" correlation and that cause and effect can not be inferred from correlation alone.

Despite all the problems inherent in iceberg dimensional data, it is still necessary to provide guidelines to designers and regulators concerning the statistical variance and the possible extreme values. In 1976 the I.I.P. assembled aerial photographs of the Grand Banks and counted all icebergs using 10 m² as the smallest piece of ice which could be resolved (Robe, 1976). The result of this study was a frequency dis-

tribution of 104 iceberg waterline areas. The advantage of this data set over other site-specific time-limited data sets is that no preference was given to counting the larger iceberg pieces and a more representative number of small ice pieces is included. The problem with these data is that only the waterline area was measured (or at least reported) and therefore other linear dimensions such as length and width were not presented.

Using a number of assumptions based on the relationship between different waterline dimensions, a methodology is presented to convert this distribution to distributions of length, mass and draft. Hotzel and Miller (1983) report an average length to width ratio of 1.67, suggesting that icebergs have an elliptical or rectangular plan area in the Labrador Sea. This ratio was also found to be similar to that of icebergs off southern Greenland (Danish Hydraulic Institute, 1979), in Davis Strait, the Grand Banks and Antarctica (Orheim, 1980). Hotzel and Miller (1983) assumed that icebergs on the Grand Banks are more degraded than those off the Labrador coast and that they tend toward a spherical shape. They calculated a draft distribution based on the assumption that Grand Banks icebergs in

plan view would look circular. It is notable that the draft distribution calculated in this way indicated 90 m as the maximum draft value. This is similar to the average water depth on the Grand Banks in the area presently being explored by the oil industry. After this paper was published it was found that icebergs in the Grand Banks had an ovoid shape, resulting in a length-to-width ratio similar to that of icebergs measured in other offshore areas.

If the iceberg areas in the I.I.P. study are used to calculate lengths and widths using the length-to-width ratio of 1.7 developed in Hotzel and Miller, it is possible to develop frequency distributions of both length and mass. These distributions are presented in Figures 4.4 and 4.5. This distribution indicates that the median iceberg in the Grand Banks region is quite small, approximately 10,000-15,000 tonnes with a length of 25-30 m and a draft of 15-20 m. The median iceberg calculated from wellsite and aerial surveys as shown in Chapter 3 is 63 m long with a draft of 65 m and a mass of 130,000 tonnes. Oil industry data show the median mass for icebergs an order of magnitude higher than

Figure 4.4 **Cumulative Distribution of Iceberg**
Length

Figure 4.5 Cumulative Distribution of Iceberg Mass

that calculated from the more spatially complete distribution of the I.I.P. survey. There are three possible reasons for this difference:

1. A bias in industry data toward larger icebergs which are viewed as being the greatest threat to an offshore platform.
2. Many of the iceberg sightings in the oil industry data set are made in deeper water off the edge of the Grand Banks and statistics generally do not account for the water depth at wellsites and the effect that this would have on the iceberg size distribution in the restricted water depth.
3. The I.I.P. data were collected during a period when icebergs were much smaller than average.

With these problems in mind it is apparent that no data set can be used without a good understanding of collection methodologies and error sources in the data. There are many examples of erroneous data which are still often quoted as truths. An alleged 50 million tonne iceberg off Labrador is still quoted as the largest iceberg sighted in this area despite the fact

that an addendum to the original report adjusted the linear dimensions significantly, such that the iceberg mass could not have exceeded 30 million tonnes.

4.2.5 The Effects of Iceberg Size Estimation on Design Decisions

Iceberg size data, coupled with motion characteristics, allow the designer to evaluate an iceberg's kinetic energy. Together with a knowledge of the frequency of iceberg occurrence, it is then possible to evaluate the frequency and type of interruptions which might occur in a production environment. The floating production concept provides the ability to disconnect from the wellhead and move away from incoming hazards such as icebergs or encroaching sea-ice. Smaller icebergs pose the greatest threat to floating platforms. These small icebergs move in response to large waves and can be thrust against a structure at speeds greater than their horizontal motion owing to the influence of gravity. Small icebergs are generally not detected very well with conventional marine radars and could approach the structure undetected. Icebergs as small as 50-100 tonnes could seriously damage structural members on a floating structure. The impact of

smaller icebergs on the overall size distribution is critical for collision or damage risk assessment and must therefore be better defined.

Once an understanding of the potential for "downtime" is developed, certain critical decisions can be made concerning the type and size of structure that can safely and productively be placed in the production area. Despite the "profit at any cost" image of the oil industry sometimes painted by special interest groups, system breakdown is not in the oil industry's best interest and is not a policy routinely followed. From the preceding discussion it is seen that depending upon the construction philosophy followed, the type of data needed changes. Corporate philosophy often dictates the way in which data are used. Some companies assemble the environmental design data and use it to assess various structural concepts. Other companies decide upon the type of structure they believe to be viable (in an engineering sense as well as within the political realities) and then use the environmental design data to justify their choice.

4.3 THE CONCEPTUAL FRAMEWORK FOR AN ICEBERG/STRUCTURE COLLISION RISK MODEL

The probability of iceberg collision with an offshore platform has resulted in the expenditure of millions of research dollars on the formulation of offshore platform designs which would withstand or mitigate large iceberg forces. Understanding the limitations of iceberg data has resulted in efforts to estimate the risk of collision between icebergs and offshore platforms. Simulation techniques allow one to utilize available environmental data to estimate risk and determine error bounds for the results.

The principal data sources needed to produce a collision risk simulator are:

1. Iceberg flux estimates at the wellsite.
2. Time series of iceberg speed and direction.
3. A distribution of iceberg entry positions on the periphery of a 30 km circle circumscribed around the wellsite location.
4. Distributions of iceberg mass and length.

The following discussion outlines the complete process one might take to produce a collision risk simulation model for the Terra Nova region ($46^{\circ}30'$ N - $48^{\circ}30'$ W) of the Grand Banks. The model boundary is fixed at a 30-km radius from the wellsite.

4.3.1 Iceberg Flux Model

In section 4.2.2.2 techniques were presented which show how one might use the I.I.P. data to estimate the flux through a one-by-one degree area around an exploration area. These techniques are beneficial for estimating the flux in areas where few ground-supported data are available. In the case of Terra Nova, data measured in the vicinity of the wellsite are available and can be used to determine the flux more precisely. Two methods were used to determine the flux at Terra Nova.

The first method consisted of examining wellsite data and counting the number of icebergs which cross the wellsite latitude within a certain distance from the platform. The second method involved relating the I.I.P. estimation of iceberg flux at 48°N to the number of iceberg sightings recorded by I.I.P. in the one-degree area around Terra Nova (as outlined in section 4.2.2.2). The reason for using both techniques is to ensure that the flux value used in risk calculations is not under-estimated.

For the first evaluation, data from two wellsites located in the Terra Nova exploration area (Ben Nevis B-75 (1985) and North Trinity H-71 (1985)) were used to

determine the iceberg flux. These wellsites are 4-5 km apart and the fluxes should, therefore, be quite similar. At Ben Nevis B-75 a total of 48 icebergs were sighted at the wellsite; of these, 12 crossed the wellsite latitude within 30 km to the east or west of the wellsite. At North Trinity H-71, 62 icebergs were sighted, 11 of which crossed the wellsite latitude within 30 km of the wellsite.

In this flux evaluation method it is important to eliminate icebergs with a mass (and consequently draft) too large to enter the water depth at the wellsite. One of the icebergs which was sighted from the drilling platform at North Trinity had a measured draft of 100 m which is 8-10 m greater than the water depth at this location and was, therefore, not used in the flux calculation, reducing the number to 10 icebergs. Thus the flux at the location of these two wellsites in 1985 was between 10 and 12 icebergs (1 iceberg / 6 km at North Trinity H-71 and 1 iceberg / 5 km at Ben Nevis B-75).

In the second method the flux reported by I.I.P. at 48°N was related to iceberg entries into a one-degree area (47°- 46°N and 47°-48°W) around Terra Nova. Table 4.2 shows the results calculated for an arbitrary

Table 4.2 Flux at 48°N Versus Icebergs Entering 46-47°N / 48-49°W Grid Square

YEAR	FLUX at 48°N	NUMBER IN WELLSITE AREA	PROPORTION OF FLUX
1970	85	0	0.00
1971	73	3	0.04
1972	1587	102	0.06
1973	850	92	0.11
1974	1386	24	0.02
1975	101	8	0.08
1976	151	18	0.12
1977	22	0	0.00
1978	75	11	0.14
1979	152	6	0.04
	4482	264	0.06
Mean	= 0.059		
Median	= 0.05		

10-year period 1970-1979. The average proportion of the flux at 48°N that enters the area around Terra Nova area is 0.06. If the average annual flux of icebergs at 48°N for the same 10 years is calculated (448), an average of 27 icebergs would be expected to enter the area annually. This number of entrances must be adjusted to account for the difference between the distance (75.8 km) between two line of longitude at 47°N and the 60 km line used to evaluate flux at the wellsite. This reduces the number of incoming icebergs by 20%, making the average annual incoming number of icebergs approximately 22. Further examination of the iceberg data collected at the wellsites shows that only 20-25% of the icebergs that come within a 30 km radius of the wellsites contribute to the flux at the wellsite latitude. The other 75-80% of the icebergs re-enter Flemish Pass and pass well to the east of the wellsite. Using these numbers it is calculated that the average annual iceberg flux at the wellsite is 5 to 6, and can range from 0 to 13. The measured flux of icebergs measured at Ben Nevis and North Trinity in 1985 falls within this range, lending some credence to the technique.

The iceberg flux quoted by I.I.P. for 1985 was 1,465. With the increase in iceberg sightings that has resulted since I.I.P.'s adoption of SLAR, the I.I.P. recommends reducing flux numbers for the post-SLAR period by 50% to make them comparable with pre-SLAR estimates. Using the method outlined above, the number of icebergs entering the one-degree area around the wellsites would be estimated at 44 (if the average ratio is used) while the wellsite flux would be 9 icebergs, ranging between 0 and 21 icebergs. The mean value is comparable to the actual flux measured at the wellsites.

4.3.2 Iceberg Motion Model

Considerable research has been carried out in the development and testing of motion models. For purposes of risk simulation, the motion of icebergs can be described in probabilistic terms with a Markov model. The principal reason for not modelling iceberg motion in deterministic terms is related to the complex interactions between the driving forces, which are presently only partially understood. Iceberg motion represents the net effect of all the local driving forces, thus iceberg trajectory data are used to develop stochastic

models. The two principal assumptions made in this type of model are that: (1) driving forces in the exploration areas are similar throughout the area modelled and (2) icebergs react in a consistent manner to driving forces.

As no statistical relationship between speed and direction has been established (a least-squares regression of iceberg speed versus direction at North Trinity H-71 yielded a correlation coefficient of .06) it is computationally more efficient to treat speed and direction separately. In order to generate iceberg motions, therefore, it is necessary to develop transition matrices for both iceberg speed and direction. These transition matrices can then be used jointly to produce iceberg trajectories which approximate the motion of icebergs.

As opposed to modelling iceberg motion with dynamic models, the objective of this type of simulation is not to reproduce the actual tracks of icebergs, but to develop a distribution of iceberg tracks. Transition matrices can be derived from existing iceberg trajectory data. Iceberg positions are recorded infrequently when the icebergs are located more than 50 km from the wellsite, however, as they move to within 30

km of the platform the positioning is generally recorded hourly. Once the iceberg approaches within 5 km of the platform, the position is generally recorded every half hour. To be used in the development of transition matrices, the iceberg positions (consisting of a range and bearing from the platform) must then be transformed into velocity vectors. An hourly time step has been found to provide adequate resolution for the simulated iceberg trajectories (see Fuglem et al., 1984).

Data used for the development of transition matrices must be closely examined for anomalous data points. Radar positioning error; and operator errors are common and can have a serious impact on speed and direction values. It is unlikely that speeds greater than 2 m/s are valid. It is often possible to fit a spline curve to the unequally spaced velocity vectors but this technique is prone to "ringing" (the over and underestimating of values caused by a data smoothing technique). Where data interpolation seems appropriate, simple triangular smoothing has been found by the author to yield adequate results.

4.3.3 Iceberg Entry Distribution

The iceberg entry distribution is an important aspect of the motion model. If icebergs are entered into the model uniformly and from any angle, an unrealistic number of icebergs enter from the south. This causes imbalances in the density of icebergs within the model domain and produces unrealistic results. The best way to determine the entry distribution is from actual iceberg trajectory data collected at wellsites in the model area. The entry distribution must be developed using icebergs close to the 30 km model boundary. In the area around the Terra Nova wellsites, icebergs predominantly approach from the northwest and northeast and proceed in a southeasterly direction. As icebergs get closer to the platform the approach direction becomes more uniform and modelled collision directions are almost uniformly distributed around the platform. Problems arise with the entry probabilities owing to inconsistencies in the way icebergs are monitored at the wellsite and to degradation in radar effectiveness caused by foggy and rainy weather.

Monitoring inconsistencies occur because the ice observer must evaluate the risk posed by different icebergs and decide which targets to watch most closely. Small icebergs often are not recorded in the iceberg log until they are within 10-15 km of the wellsite, whereas large icebergs are monitored 60-70 km away from the rig. Icebergs to the north of the rig are more closely monitored than icebergs to the south of the rig (in fact in many cases the observation area is located on the north side of the platform).

4.3.4 Iceberg Mass and Length Distributions

For the purposes of collision risk, the length distribution of icebergs in the wellsite area is extremely important. Length is relatively easy to measure and is, therefore, the most available linear dimension. There are a number of sources of iceberg length data.

1. Aerial photography by both the oil industry and I.I.P.
2. Wellsite observations made by the oil industry as part of their ice management programs.

3. Government vessels and vessels of opportunity.

Some of these data are archived by Ice Central, a branch of the Atmospheric Environment Service. Access to oil industry data can often be acquired by contacting oil companies operating on the Grand Banks.

Care must be taken to ensure that the icebergs included in the distribution were actually measured over the subsea bank and that extreme lengths used are credible. In the discussion of iceberg morphometry it was shown that the draft of icebergs in comparison to their length varies from 50% to 100% of the length (with a median value of about 65%). Thus it would be extremely unlikely to find icebergs over the Grand Banks longer than 160 m. Although there is one report of a large low freeboard iceberg or ice island approaching the Grand Banks (I.I.P., 1976) the evidence suggests that icebergs of this type are extremely uncommon. Iceberg length can be linked to mass distribution using relationships developed between length and mass (Chapter 3).

When icebergs are entered at the model boundary they are provided with a length and mass chosen randomly from the length/mass distribution. Coupled with the speed of the iceberg generated by the iceberg motion model, it is possible to gain some insights into the probable collision kinetic energies. The estimate of probable kinetic energies and the return period of extreme kinetic energies allow the designer to make decisions about the type of structures most suitable for the production area.

One of the last issues that can be addressed with a simulation model as outlined, is the risk to subsea well facilities (primarily pipelines, wellheads and templates) of collision with iceberg keels. The methodology presented in this thesis for determining the risk of iceberg collision with water surface piercing platforms can be adapted to give preliminary evaluation of this problem. The distribution of iceberg keel widths would need to be substituted for the distribution of waterline diameters. The iceberg keel collision problem is more complicated than the surface piercing platform case because the iceberg could collide with facilities located on the ocean bot-

tom as well as those buried under the surface thus, a distribution of scour depths for the area would need to be established and related to iceberg draft.

4.3.5 Simulation Model

To test the concepts presented, a simulation program was developed. Data used in the model were released to the author by Petro-Canada and oil industry partners operating in the Terra Nova exploration area. A general schematic diagram of the simulation process is shown in Figure 4.6.

4.3.5.1 Input Data

Transition matrices for iceberg speed and direction were generated from iceberg trajectories from North Trinity H-71, West Ben Nevis B-75 and Terra Nova K-08. Data used in the transition matrices were limited to hourly positions where possible. Icebergs tracked for less than six hours were not used and interpolation between sightings was only performed if the time interval was three hours or less. The transition matrices are shown in Table 4.3.

Figure 4.6 Flow Diagram of Simulation Model

Table 4.3 Transition Matrices

		Iceberg Direction															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1		.468	.723	.766	.787	.787	.787	.830	.830	.851	.851	.851	.851	.851	.872	.872	1.00
2		.130	.543	.655	.847	.869	.891	.891	.891	.891	.891	.913	.913	.913	.913	.956	1.00
3		.109	.174	.457	.674	.761	.826	.891	.956	.956	.978	.978	.978	.978	.978	.978	1.00
4		.000	.027	.164	.520	.739	.863	.903	.944	.971	.985	.985	.985	1.00	1.00	1.00	1.00
5		.020	.040	.050	.150	.680	.810	.880	.920	.930	.950	.960	.960	.960	.980	.990	1.00
6		.019	.038	.067	.125	.250	.625	.817	.894	.942	.971	.971	.981	1.00	1.00	1.00	1.00
7		.017	.026	.035	.052	.104	.259	.673	.854	.923	.957	.966	.992	.992	1.00	1.00	1.00
8		.011	.022	.067	.112	.146	.202	.359	.617	.797	.876	.910	.944	.978	.989	1.00	1.00
9		.000	.000	.020	.050	.080	.169	.278	.387	.654	.882	.961	.971	.981	.991	1.00	1.00
10		.007	.007	.021	.035	.035	.056	.113	.148	.276	.765	.928	.971	.978	.992	.992	1.00
11		.000	.000	.008	.008	.008	.024	.024	.047	.149	.282	.735	.946	.954	.970	.996	1.00
12		.000	.000	.000	.000	.000	.007	.007	.037	.074	.134	.313	.843	.970	.985	.992	1.00
13		.000	.000	.000	.000	.000	.019	.019	.077	.115	.132	.288	.538	.807	.961	.980	1.00
14		.000	.019	.019	.019	.019	.019	.019	.019	.056	.075	.094	.150	.280	.854	1.00	1.00
15		.000	.045	.045	.068	.068	.068	.068	.091	.114	.137	.160	.274	.365	.437	.865	1.00
16		.176	.176	.176	.205	.205	.234	.234	.263	.263	.263	.322	.351	.380	.380	.586	1.00

		Iceberg Speed															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1		.525	.787	.935	.968	.968	.968	.968	.984	.984	.984	.984	1.00	1.00	1.00	1.00	1.00
2		.099	.628	.859	.909	.959	.967	.984	.992	.992	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3		.028	.186	.678	.864	.926	.932	.960	.966	.966	.977	.977	.977	.994	.994	.994	1.00
4		.014	.053	.212	.768	.894	.942	.947	.966	.985	.990	.990	.990	.990	.990	.995	1.00
5		.012	.024	.106	.312	.794	.906	.947	.971	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
6		.019	.029	.048	.116	.349	.699	.835	.893	.942	.961	.971	.971	.981	.991	.991	1.00
7		.012	.024	.047	.059	.210	.408	.699	.885	.932	.979	.991	.991	.991	.991	1.00	1.00
8		.011	.011	.032	.085	.096	.149	.370	.728	.865	.939	.981	.981	1.00	1.00	1.00	1.00
9		.020	.030	.030	.050	.060	.120	.210	.390	.820	.920	.960	.980	.980	.980	.990	1.00
10		.000	.000	.000	.000	.037	.093	.093	.204	.426	.722	.870	.944	.944	.963	.982	1.00
11		.000	.000	.000	.026	.079	.105	.131	.157	.368	.474	.789	.894	.920	.920	1.00	1.00
12		.038	.038	.038	.038	.038	.153	.153	.230	.422	.537	.729	.921	.920	1.00	1.00	1.00
13		.000	.000	.000	.000	.083	.166	.166	.249	.332	.415	.415	.748	.915	1.00	1.00	1.00
14		.000	.000	.000	.000	.000	.000	.000	.033	.066	.066	.133	.166	.233	.900	.967	1.00
15		.000	.000	.000	.000	.000	.000	.071	.071	.071	.142	.142	.428	.428	.642	.928	1.00
16		.000	.000	.000	.000	.067	.067	.067	.067	.067	.067	.134	.201	.268	.335	.402	1.00

The iceberg entry distribution (Figure 4.7) was determined from the approach direction of observed icebergs at a radius of 30 km from Terra Nova wellsite locations. Sixteen principal compass directions were used to determine the entry sector, with icebergs within each sector distributed uniformly between the sector boundaries. A high order polynomial was fit to the entry frequency distribution and start positions on the model boundary were picked from the distribution using random numbers between 0 and 1.

In section 4.3.1, the average annual iceberg flux at the wellsite latitude was found to range from 5-9 using two different methods. A number of simulation runs were carried out to determine the number of icebergs which would need to be entered into the model to produce this flux. These runs showed that 50 icebergs were needed to produce a flux of 7 icebergs at the wellsite latitude. This number was used to calculate the number of simulated years.

The length distribution used in the model was drawn from the iceberg length data presented in section 3.3.4.1. As with the iceberg entry distribution, a high order polynomial was fitted to the iceberg length

Figure 4.7 Iceberg Entry Distribution for Model

distribution (Figure 4.8). Icebergs entered at the boundary were assigned a length drawn randomly from this distribution.

4.3.5.2 Model Runs

Once the input variables were prepared and verified the model was run. A structure or zone of fixed dimension was placed at the centre of the model area. At the point of entry the iceberg was assigned a length (used as the iceberg diameter), an initial speed and direction (velocity vector). The Markov model was used to move the icebergs through the model area. The effective width of the iceberg was taken to be the diameter of the iceberg plus half the width of the structure. When a collision or zone entry occurred, the speed, direction and length of the iceberg was recorded for subsequent analysis.

In simulation it is important to evaluate the number of simulation runs necessary to produce accurate and stable statistics. To have confidence in the results it is often necessary to simulate several thousand years. Operation of a collision risk model showed that even when 8,000 simulated years were used to analyze collision probabilities, statistical

Figure 4.8

Iceberg Length Distribution Used in the Model

stability was not completely achieved for small collision targets (200 metres and less)(Fuglem et al., 1984). For the purposes of the model presented in this thesis, a simulation of approximately 2,300 years for a 200 m collision zone and 1,300 years for a 2,000 m zone were chosen to represent a good compromise between computing costs and statistical accuracy . Given the expected 30- 50-year lifetime of an oilfield located on the Grand Banks these simulation periods are expected to provide adequate statistics.

4.3.5.3 Simulation Results

Two entry zones, located within 2 kilometers and 200 metres of the wellsite, were modelled. The larger zone provides data pertaining to the potential amount of downtime which might be experienced by a floating platform not designed to withstand iceberg impact. The smaller zone provides an estimate of the number of the collisions which could be expected with a fixed platform at the wellsite.

For the 2 km zone, 62,753 icebergs were generated. Of these icebergs, 789 entered the zone (or one every 1.7 simulated years). The median return period was 1.62 years, indicating that an iceberg can be expected

to approach to within 2 km of a wellsite at Terra Nova every second year. Ninety-two percent of the icebergs which entered this zone stayed in the zone for four hours or less (Figure 4.9) and 1% of the icebergs stayed in the zone for 10 hours or more. This indicates that many icebergs skirt the edge of the zone without penetrating any closer to the wellsite. The smallest return period was 0.1 years (or 10 icebergs in one year entering this zone) and the largest return period was calculated as 3.9 years.

A total of 115,311 icebergs were generated for the 200 m zone simulation. Fifty-five of the generated icebergs entered the zone, representing an average of one entry every 42 years. Three of the icebergs entered the zone twice suggesting that there is a 6% chance of the same iceberg hitting a platform of this size twice. The smallest entry return period was 0.7 years, while the largest entry return period was 228.6 years. The median return period was 22 years and probably represents a more conservative estimate for use in platform design calculations. The estimated mass of the median iceberg penetrating to 200 m was calculated to be 750,000 tonnes (using the relationship developed by Hotzel and Miller, 1983).

Figure 4.9 **Iceberg Persistence Within Simulation Zones**

A comparison of the speed and length distributions of icebergs which entered the two zones (Figures 4.10 & 4.11) showed that the icebergs which enter the 200 m zone tend to be larger and move faster than the general iceberg population. This is because, although large icebergs represent only a small proportion of the population, the area they cover when they move through the model area is large owing to their diameters. The probability that they will pass over a point in the model area is consequently higher.

4.3.6 Verification of the Model

How does the present model compare with observed iceberg zone entry? In the past 7 years of exploration in the Terra Nova area, 2 icebergs have approached to within 2 km of a wellsite. The closest approach was 1.3 km (0.7 nautical miles). This equates to approximately one iceberg entry every 3 years. The simulation gives a slightly more conservative entry rate of one iceberg every 2 years. There have been no confirmed observations of any icebergs within 200 m of a platform in the Terra Nova area. One instance of an

Figure 4.10 Speed Distributions of Icebergs Entering
Two Zones Around the Wellsite

Figure 4.11 Length Distributions of Icebergs Entering Two Zones Around the Wellsite

iceberg which might have been within 200 m of the platform occurred in 1986 at wellsite operated by Husky Bow Valley. It is difficult to verify this event because the platform had vacated the wellhead and positioning of the iceberg is therefore less accurate. Estimates of iceberg entry rates into a 200 m area around a platform cannot be compared to real world observation.

In 1984, Fuglem et al. published a paper which outlined the use of a model similar to the one developed in this thesis. There are a number of differences between the two models. The Fuglem model was designed not only to address the risk of collision but also to evaluate evacuation times for platforms when icebergs approach the wellsite. It is a large computer mainframe discrete event model linked to a proprietary simulation language "SLAM" (copyright Pritsker and Associates, Illinois). The model used in this thesis was designed specifically to monitor iceberg entry into zones and is therefore, less ambitious but more efficient and can be run on one of the higher power MS-DOS (copyright Microsoft Corp., Washington) based microcomputers. The data used in the Fuglem model was comprised of iceberg observations from a number of dif-

ferent areas including Labrador. The present model uses data limited to the Terra Nova area of the Grand Banks.

Fuglem et al. (1984) simulated 8,400 years of iceberg incursion into the northeastern Grand Banks in the model. It is illustrative to compare the results of this model to the model results presented in this thesis.

Analysis of the simulation runs in Fuglem et al. (1984) showed an average collision return period of 17 years for a collision between any size of iceberg with a structure of 120 m diameter; this is about twice the collision rate shown by the present model. In both models it was found that the distributions of speed and length for colliding icebergs are not identical to the general iceberg population and that these icebergs are usually larger and move faster than would be expected from general population statistics. The difference in the average collision rate is attributable to model technique. In Fuglem et al. (1984), it was assumed that icebergs would be distributed more uniformly throughout the simulation area, with a fixed relationship between iceberg density to the east and west of the platform. No such assumption was made for this

model. It was felt that icebergs in nature would primarily follow the Labrador Current through Flemish Pass and move onto the subsea bank during storm periods or when eddies in the current moved onto the bank. It would be expected therefore, that many icebergs would enter and leave the model area quickly, having no impact on operations at the wellsite.

Both models show that although colliding icebergs are bigger than the general iceberg population, the probability of a collision between a large iceberg and a platform is low. In the case of Fuglem et al. (1984) the average return period is 233 years. For the present case this return period was found to be 80 years. The differences in this return period are due to differences in the iceberg length distribution used. In the model presented by Fuglem et al. (1984), large icebergs represented only 5% of the population whereas, in the present model, large icebergs represented 20% of the population.

There is always a danger that statistical results for a complete iceberg population will be applied to a portion of the population. An interesting aspect of the study by Fuglem et al. (1984) was that the model results were broken down to show the return period of

collisions for different sized icebergs and stratified with respect to the distance between the centre of the iceberg and the offshore platform at the time of collision (Table 4.4).

The collision offset distance stratification helps in determining the proportion of kinetic energy which would be imparted directly to the platform and the proportions which would be imparted to rotation of the iceberg around the platform. Subdivided in this way, the most probable collision was between a platform and a small iceberg (5,000 - 200,000 tonnes) occurring once in every 35 years. More significantly, the probability that this collision could be considered to be direct impact (where the centre of the iceberg is offset no more than 10 metres from the centre of the platform) increases the return period to once in 323 years. In the present study no attempt was made to stratify colliding icebergs by offset from the structure, however, the most probable iceberg collision involved a medium sized iceberg (200,000 - 2,000,000 tonnes) occurring once every 70 years. Once again the differences in the results are believed to be caused by differences in the input iceberg length distribution and the iceberg movement model.

Table 4.4
Yearly Return Periods For Iceberg/Platform Collisions
Stratified by Mass and Collision Offset Class

Iceberg Size	Offset Distance from Structure Centre (Metres)						
	0-10	10-20	20-30	30-40	40-50	>60	Any
Bergy Bit							
Average Flux	933	2800	933	525	840	840	127
100 Yr. Flux	227	681	227	128	204	204	31
Small Iceberg							
Average Flux	323	195	336	247	263	155	35
100 Yr. Flux	79	48	82	60	64	38	9
Med. Iceberg							
Average Flux	525	646	764	525	494	107	52
100 Yr. Flux	128	157	186	128	120	204	13
Large Iceberg							
Average Flux	4200	2800	8400	1680	1400	494	233
100 Yr. Flux	1022	681	2043	409	341	120	57

Average Flux = 27 Icebergs / Year

100 Yr. Flux = 111 Icebergs / Year

Iceberg Mass Classes

Bergy bit	= 100 - 5,000	tonnes
Small Iceberg	= 5,000-200,000	tonnes
Medium Iceberg	= 200,000-2,000,000	tonnes
Large Iceberg	= 2,000,000 - 10,000,000	tonnes

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Production of oil and gas from Canada's east coast waters will almost certainly commence before the turn of the century. Decisions as to the type of platforms which are best suited to the severe environment of this area have been guided by both politics and engineering.

The environment has influenced operational philosophies from the inception of offshore exploration to the present stage of platform design. Sea-ice and icebergs provide a unique challenge to oil companies and government regulators. Even at the present time, understanding of certain aspects of icebergs and sea-ice such as inter-annual occurrence, distribution, size and persistence is poor. The lack of knowledge can be related both to the design of data collection programs and climatic variability.

This thesis has demonstrated one way in which environmental data can be used to provide guidance to platform designers and regulators with respect to the probable risks posed by icebergs. The simulation outlined in Chapter 4 shows that the probability of colli-

sion between icebergs and structures of the size anticipated for the Grand Banks (120-200 m diameter) is small. The average return for a collision between any size iceberg and a platform of 200 m diameter was calculated to be 42 years. The median return period was calculated to be 22 years, or half the average return period, suggesting that use of the average return period is not conservative and that the median return period should be used for evaluating iceberg collision risk. Iceberg entrance into a 2 km zone around Terra Nova was calculated to average once every 2 years. This is relevant to operators contemplating the use of floating platforms because it indicates that disconnection from the wellhead will probably be necessary at some point. The median probability of zone entry is once per year thus, a floating platform may need to disconnect every year. This will incur rig downtime which will need to be factored into the economics of producing oil in this area.

Comparison of the simulation model presented and another collision model shows that the length distribution used as input to the model is critical to the overall evaluation of risk and that these distributions are probably site specific. Composite distributions

comprised of data collected at a number of different locations and in various water depths probably do not adequately represent the conditions at any single production site.

The author has shown that in order to extend limited data sets, numerous techniques have been used which employ spurious logic and infringe basic statistical principles. Part of the problem can be attributed to a lack of standardization in data collection techniques and an unwillingness in certain cases to distribute data. There is an urgent necessity to assemble all the public domain and proprietary industry data into a single database where data are subject to quality control. The author is aware of at least four different databases used by different organizations and comprised of widely differing data. One result of the use of these data sets is conflicting answers to the question of iceberg risk and a suspicion in the general population that no risk evaluation will produce statistically valid results.

The model presented in this thesis is still evolving. Areas which still need to be addressed relate to:

1. Better definition of the input distributions and evaluation of the effects of different distributions on the collision risk. There is still considerable uncertainty in the iceberg entry position and the length distributions.
2. Updating transition matrices as more data is collected.
3. Ensuring that the icebergs motion algorithm realistically distributes the icebergs within the simulation area.
4. Evaluation of the appropriateness of a 30 km radius as the model boundary.

Much of the focus of this thesis has been related to the use of available data to assign risk probabilities to potentially catastrophic events. It is evident from the literature that care must be taken when using data for design engineering purposes. Examples, of misuse of data were presented to alert researchers to the strengths and weaknesses of both fundamental data and analysis techniques used to reduce this data to design values. It is apparent that in an attempt to maximize the amount of data used in these analyses that data sets of varying quality, collected in various

areas not necessarily similar to the area which the data are used to characterize, have been amalgamated in an attempt to achieve statistical significance. On the Grand Banks the wellsite locations, water depth at the wellsites and the local ocean bottom topography appear to be extremely important. These factors are, however, only infrequently used in analysis yet must be utilized if an accurate assessment of collision risk is to be achieved.

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