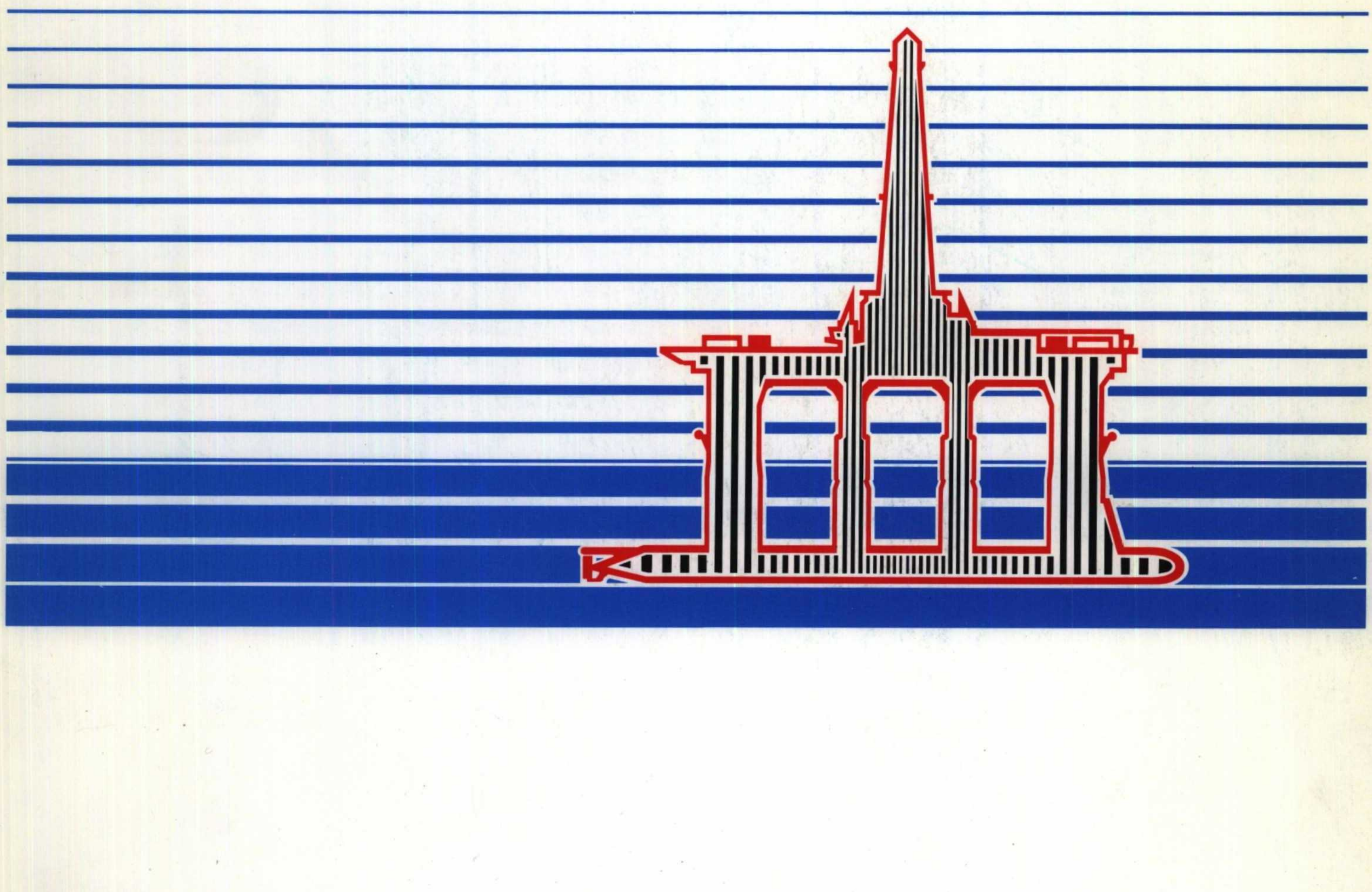
Royal Commission on the *Ocean Ranger* Marine Disaster

Canada

Commission Royale sur le Désastre Marin de l'*Ocean Ranger*

Newfoundland & Labrador



Report Two: Safety Offshore Eastern Canada
Summary of Studies & Seminars

The Royal Commission on the *Ocean Ranger* Marine Disaster was jointly established and funded by the Governments of Canada and Newfoundland

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The two reports of the Royal Commission on the *Ocean Ranger* Marine Disaster consist of the following four volumes:

Volume 1	**Report One: The Loss of the Semisubmersible Drill Rig *Ocean Ranger* and its Crew**
Volume 2	**Report Two: Safety Offshore Eastern Canada**
Volume 3	**Report Two: Safety Offshore Eastern Canada** ***Summary of Studies & Seminars***
Volume 4	**Report Two: Safety Offshore Eastern Canada** ***Conference Proceedings, 1984***

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PREFACE

During its inquiry into the safety of drilling operations off eastern Canada, the Royal Commission followed a consultative process. Factual information, views, and suggestions directed towards identifying practical means of improving safety were solicited. A study program was carried out for the Commission by consultants and study teams to provide a concise but comprehensive review of the state-of-the-art in the main areas of concern. Twenty-four studies were undertaken over a two-year period in four principal areas: environment, design, safety and training, and regulations. The draft study reports were reviewed by knowledgeable individuals from government, industry, and universities as well as by Commission staff, but the views expressed and the conclusions reached in these reports are those of the study authors. They represent input to rather than the output of the Royal Commission.

A number of seminars were also held to focus expert knowledge and opinion in several key fields and to update studies and fill gaps in the data base. The technical data gathered in the Part One inquiry, the reports prepared on the Part Two studies, briefs and submissions received, and the proceedings of seminars and the Conference on Safety Offshore Eastern Canada (see Volume IV) all form an important part of the data base for the final report.

Summaries of the seminar proceedings and of selected study reports are included in this volume. They have been prepared by Commission staff and contain the essential data from those documents. A complete set of seminar proceedings and reports has been deposited by the Royal Commission in the archives of the governments of Canada and Newfoundland, with the Canada Institute of Scientific and Technical Information (CISTI) at the National Research Council of Canada, and with the Centre for Newfoundland Studies at Memorial University of Newfoundland.

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INTRODUCTION

INTRODUCTION

THE RISKS OF OFFSHORE DRILLING

The Risks of Offshore Oil and Gas Exploratory Drilling in Eastern Canadian Waters
Ian Burton, Director
Institute for Environmental Studies
University of Toronto
Toronto, Ontario
May 1984

A questioning attitude toward acceptable levels of risk is a characteristic of the last decades of the twentieth century. The explanation for that attitude is difficult to establish, in that, for Canadians at least, life today is safer than it has ever been. Our infant mortality rate is the among the lowest in the world and Canadian citizens live longer lives than people in most other countries. As the nation has prospered and developed, the wealth we have created has enabled us to reduce risks. Given this situation, how can the paradoxical and sometimes even obsessive preoccupation with risk be explained?

One major factor is that the type of risks we face has changed. The development of science and the application of technology have indeed created new risks that did not exist before. In general the new risks have so far proved to be less serious than the old risks that we have managed to control and reduce. On balance, development reduces risks.

While it is true that Canadians are more fearful about risks than ever before, it is not always the case that those most at risk are the most concerned. The concern for the dangers of offshore oil and gas exploration is a case in point. The concern for the safety of the workers and perhaps especially for the possibility of environmental damage sometimes seems to be greater the farther one gets away from the sea. In some ways this is an encouraging sign of national maturity; no civilization in the latter part of this century would wish to be seen as subjecting some of its citizens to an undue risk so that others may benefit. There is an overriding need for the question of risk in offshore oil and gas exploration to be approached in an open-minded, reasonable, and objective fashion.

A number of new methods of analysis have been developed precisely for the purpose of handling these difficult and often emotional considerations. Collectively called "risk assessment", these methods establish a framework to provide perspective and to facilitate choices; ultimately the choices to be made require judgement based on sound knowledge, sympathetic understanding, wisdom, and common sense. It should be noted that risk assessment is not a panacea. It provides a formula for decisions on the basis of quantitative analysis but does not thereby solve the problem of risk.

To develop an understanding of risk, it is necessary to realize that there is no such thing as "absolute safety". Risk is a part of life and the only successful method of dealing with it is to identify, assess, and choose your risks wisely. Excessive concern over the wrong risks does not lead to greater safety; it actually increases overall risk by leading to the neglect and exacerbation of other risks. A recent example illustrates this point. When artificial sweeteners used in soft drinks, cyclamates, were withdrawn from the market because they were suspected of being carcinogenic, risk assessors pointed out that, were consumers of soft drinks to substitute an equivalent amount of sugar in their diet, there would be a resultant increase in obesity and heart disease. Calculations were made to show that the net effect on human health would be worse from consuming sugar than cyclamates. Thus the initial attempt to reduce risk could turn out to have quite the reverse effect.

In theory a balanced risk or minimum aggregate risk approach is desirable, but reliable comparisons of this kind are rarely possible. The lesson to be noted is that the apparent elimination of risk is not necessarily the safest course. Not to take the risks, of offshore oil and gas development, could well prove to be the more risky course. But to take these risks in a careless fashion, putting those involved at too high a risk would also be, if done knowingly, an irresponsible act.

■ *DEFINITION* Risk in everyday language means "exposure to possible loss or injury". Scientists have, however, developed a more technical definition of risk; namely, the probability of an event multiplied by its consequence or, where many events are being considered, the sum of the probabilities of those events times their consequences. Using this definition, risk has four components: the probability of an event occurring; the time span or conditions under which it can occur; its consequences; and the decision by some person or group to take the risk.

In theory, avoiding hazards is a way of eliminating the risk completely. Where chance, necessity, or the search for economic gain brings human activity into contact with hazards some risk exists. Safety is but the corollary of risk. In practical terms, the focus on safety is somewhat different from the focus on risk. It is almost axiomatic among safety experts that things are not safe enough and that safety should be improved. The risk analyst on the other hand must first determine the actual level of risk and then determine the level of risk that is acceptable.

Risk assessment may be thought of as the process of identifying, estimating, and evaluating risk in an economical, social, and political context. Risk identification and estimation can be approached in a scientific manner and to some extent may be expressed quantitatively. Risk evaluation is the social process undertaken to determine the terms and conditions under which a risk-generating activity should proceed.

■ *ANALYSIS* There are three approaches to the analysis of risk: historical analysis, the transfer of experience from similar circumstances, and risk modelling. The use of historical data has two major deficiencies: in many cases the necessary data to make reliable risk estimates is lacking, and the past record may not be a reliable guide to the future. Generally, experience and advances in technology steadily improve the safety record. At the same time, the larger scale of operations made possible by new technology increases the possibility of larger scale catastrophies.

In applying risk analysis to eastern Canada offshore oil exploration, there is a fundamental limitation to the historical approach; the record is too short to provide a reliable sample from which to estimate risk, especially for those events that occur with low frequency. In these circumstances one can transfer the experience gained elsewhere and apply it to the new location. A major question arises as to whether it is reasonable to suppose that the risks of offshore oil and gas exploration off Canada's East Coast are equivalent to those associated with similar activities in the North Sea or elsewhere in the world. There is no question that Canada, coming late to offshore exploration, benefits from the experience of others but Canadian offshore waters are different from those found in other parts of the world, with environmental conditions which may exceed those of other areas. These considerations imply that the data and the estimates used to transfer experience from elsewhere must be treated with caution and some allowances must be made to account for the dissimilarities.

The recognized deficiencies of both the historical approach and the transfer of experience have led to the development of relatively new methods, all of which are variations of theoretical model building. This approach to risk analysis was first fully developed under the U.S. National Aeronautics and Space Administration (NASA). Space flight presented a situation where historical comparisons were non-existent and the transfer of experience from similar programs, such as that of the USSR, was impossible. These deficiencies resulted in the adaptation of a modelling approach.

Two modes of analysis are applied; fault-tree and event-tree analysis. In fault-tree analysis a specific fault is postulated. Then the possible causes of such a fault are determined and in this way a branching fault-tree is constructed working upstream away from the fault. Fault-trees may be used to estimate probabilities of failure by attaching probabilities to each step in the causal chain. In event-tree analysis an initiating event is postulated and the model is developed in a downstream direction by asking what the possible consequences of an initiating event could be. Again a branching network is developed, working away from the initial event.

The human imagination is an important limiting factor in both types of analysis. An accident sequence has to be thought of before it can be modelled and estimated. In a complex and large scale engineering system things can go wrong in so many different ways that it is not always possible to imagine them all in advance.

■ *ASSESSMENT AND EVALUATION* In the application of risk assessment to offshore exploratory drilling, historical analysis, transfer of experience, and risk modelling are not mutually exclusive. Risk modelling is substantially more expensive and time consuming than the other two. Because of the cost, the limitations of this method, and the relatively small scale of the Canadian offshore industry to date, it seems more sensible to use the simpler and less costly methods first and then decide what further analysis is needed and justified.

Once actual levels of risk have been measured, there remains the crucial task of evaluation which involves many decision makers at different levels. Federal and provincial governments, petroleum operators, MODU owners, contractors, workers, and their immediate families, all play some part in this evaluation. Members of each group have their own perception of risk which varies with the position they occupy and the responsibilities they are expected to bear. There is a tendency among scientific risk analysts to assume that measured risk is "real" whereas the perception of risk adopted by others, such as those at risk or the lay public at large, is somehow unreal or distorted. In fact, both points of view are risk perceptions. Even objective scientific methods apply value judgements, often in a concealed way. Both perspectives are valid perceptions of risk and both have to be taken under consideration by decision makers.

Similar comments may be made regarding the amount or level of risk that is "acceptable". A critical question then becomes "acceptable to whom?" Social conflicts arise in which a few are asked to bear a higher level of risk for the benefit of a large number. Resolution of these conflicts can be achieved if it is understood that adequate compensation has been paid to those who face higher risks for the general good and if it is understood that such risks are not accepted for all time but are only "tolerated". The fact that workers accept employment on offshore drilling units at a given compensation level does not mean that further efforts to reduce risk are not in order.

A common approach to risk evaluation is to compare one set of risks with another. Four comparisons are often made; with natural or background risk, with the risk of alternatives, with other unrelated risks, and with benefits. In offshore drilling, a comparison with natural or background risk levels is not possible as there is no useful preexisting level of risk with which a comparison of incremental risk might be established. The second method, that of comparison with the risks of alternative methods, would involve the comparison of the risks of offshore drilling with onshore oil and gas exploration or with other energy-producing activities such as coal mining. The third type of risk comparison examines risks in one activity in relation to other activities that are not alternatives but are totally unrelated. A favourite comparison is with cigarette smoking; if smoking can be shown to be more hazardous than the risk-taking activity under consideration, the implication is that if people are prepared to accept the risks of smoking, then logically they have no reason to object to activities which produce much lower risks. Neither comparisons with alternatives nor those with non-related risks provide an adequate basis for accepting risk. They are, in fact, forms of risk rationalization. The fourth method, that of comparing risks with benefits, is a more valid criterion for risk evaluation.

There are three elements in the comparison: costs, benefits, and risks. For a given project or activity the preferred alternative may be specified as that which maximizes net benefits, at least risk and cost. After evaluating the risk in a particular activity, the degree to which safety can be increased by a further expenditure of funds must be assessed. If the cost of making a system "safe enough" is so high that it absorbs all or most of the profitability or benefit from the system, then it is probably too risky. Tolerable levels of risk and acceptable levels of profit or benefit are not fixed quantities and both may change according to circumstance. While in theory an objective of maximizing benefits over risks may be ideal, in practice some rule-of-thumb judgements have to be made. To make these difficult value judgements, it becomes essential to know existing accident and fatality rates and to be in a position to assess their causes. Calculations of accident rates based on a short period of record are statistically dubious; a first priority for the making of rational decisions concerning further expenditures on risk reduction is an adequate data base from which to specify the actual level of risk involved.

Broadly speaking, there are two directions in which risks may be reduced, both of which fall under the decision-making process that may be called risk management. In the first case, better systems design and operation can reduce the probability of accidents. In the second case, since accidents cannot be altogether eliminated, efforts can be made to mitigate the consequences. The mitigation of consequences is a generally neglected area of risk management.

■ *OFFSHORE DRILLING OPERATIONS* An assessment of risk in offshore drilling is hampered by a number of limitations. The brief history of offshore drilling makes analysis on an historical basis difficult and often impossible. The total service of MODUs worldwide is approximately 5,000 rig-years and in the eastern Canadian offshore less than 50 rig-years up to the end of 1983. This is far too short a period of record for the reliable estimation of the frequency of accidents, especially of the more rare events, because the data that do exist for this short period are neither complete nor reliable.

The available Canadian data collected by provincial governments are incomplete, lacking satisfactory reporting of person-hours worked. Therefore, calculations of accident rates and measures of safety performances are not possible. Federal government data are also incomplete because they are stored in a "raw" form and have not been abstracted or tabulated. In the United States, United Kingdom, and Norway similar data problems and analysis limitations exist. In making comparisons between operations in various nations, the difficulties of data deficiencies are compounded by a lack of standard reporting categories. Under present circumstances, data are incomplete and unreliable for each country and are not strictly comparable internationally. Judgements, therefore, have to be made about which estimates or data sources are more reliable. In general, the higher figure has been used on the grounds that accidents and fatalities might go unreported but accidents and fatalities that have not occurred are unlikely to be invented. It is also thought more prudent to overestimate risk than to underestimate it. The purpose is not to exaggerate the risk but to be especially careful to avoid underestimating it.

The knowledge of causes is an important step in risk analysis. If certain causes occur more frequently than others, they represent the priority point of attack for risk management. In offshore oil exploration the cause of an accident can include weather and other environmental conditions, design and operation of the MODU itself, and capability of those on board to deal effectively with a dangerous situation. An examination of reports of accidents at sea reveals that in almost every case all three sets of factors are involved.

It is always a simplification to speak of a single cause or of a cause as a single event. In theory, the logical approach to the analysis of hazard events is to identify "event sequences". Risks can then be calculated in terms of the probability of whole event sequences rather than separate events. In the absence of that analysis, the analyst is forced to rely upon more primitive concepts of cause in order to relate them to the historical accident record. There are severe weaknesses in these classifications of cause from a statistical point of view. The categories are not mutually exclusive. Accidents may occur not only on the rig itself but also in associated activities such as diving.

Det norske Veritas has recently established a worldwide offshore accident data bank which indicates that the number of fatalities per 1,000 persons working offshore has declined over the period 1970 to 1978. This decline is interrupted by the sequence of three major accidents in the 1979 to 1982 period resulting in the loss of 277 lives. In fact, of the 486 lives lost worldwide in the period 1970 to 1982, a total of 349 or 72 percent were lost in four major disasters. It would seem reasonable for the purposes of risk analysis to divide offshore drilling fatalities and injuries into two distinct populations. These might be described as marine disasters and industrial accidents. In the case of marine disasters the focus has to be on making MODUs less vulnerable to accidents that may result in their total loss, and on developing emergency plans and precautions to maximize the possibility of rescue when a disaster does occur. In the case of industrial accidents it may be that the safety precautions applied on land with some necessary changes are sufficient.

The most comprehensive study of the safety of offshore oil exploration and production activities so far conducted in North America is a U.S. National Research Council study entitled *Safety and Offshore Oil – Report of the Committee of Assessment of Safety of Offshore Continental Shelf Activities* (1981). That study noted the deficiencies in existing data and lamented the fact that no comprehensive source of data on accidents on the U.S. outer continental shelf existed. This resulted in workplace safety data that were neither consistent nor comparable in a national or international sense. The study concluded that a standard accident reporting form, collected by a single agency, could provide the kind of information needed to gain a better understanding of the causal factors and characteristics of workers that could lead to improved safety.

The report stated that at the end of 1979 about 61,500 U.S. workers were regularly employed in offshore continental shelf oil and gas exploration, development, and production. The estimate was qualified as very tentative since no census had ever been undertaken. During the period 1970 to 1978 the U.S. Geological Survey reported that 187 workers were killed in 116 accidents. Between 1962 and 1977 there was a fourfold increase in the number of person-hours worked, but a 35 percent decrease in accident frequency. In comparing the risks of work offshore to that of other industries, the report found that the frequency of injuries in oil and gas operations was comparable to that in industries such as mining, marine transportation, and heavy construction and that the injury and illness rates per 100 full-time workers was about the same as that found in general manufacturing. Comparisons of this sort must be qualified by the knowledge that definitions of "injury" and reporting practices vary widely from industry to industry and company to company. In a comparison of fatality rates between the Gulf of Mexico and the North Sea it was concluded that incidents of fatalities were lower in the Gulf of Mexico and holding relatively constant. The study also indicated that incidents of fatalities were declining in the North Sea.

The study went on to ascribe a substantial part of the responsibility for workplace accidents to worker characteristics, limitations, and attitudes. Experience was noted as a key factor, in that 76.5 percent of injuries occurred to employees with less than one year on the job and 54.8 percent of all injuries occurred within the first six months of employment. The study concluded that a principal item demanding attention in improving workplace safety was not technology but improvement in personnel performance.

A major review of the safety in the United Kingdom sector of the North Sea was conducted in 1980 and presented in the report *Offshore Safety* commonly referred to as the "Burgoyne Report". As in all other credible reports on this subject the Burgoyne Report contains the inevitable lament about the availability and the quality of data. Doubts were cast on the validity of figures for minor accidents because of underreporting. Similarly, the figures for dangerous occurrences were thought to be unreliable because of the doubt about the definition of a reportable occurrence and the difficulty of educating all concerned to make such reports.

According to the U.K. Department of Energy estimates, the work force in the United Kingdom sector of the North Sea grew from a total of 4,030 in 1974 to approximately 12,500 by 1978. The fatality rate per 1,000 employed ranged from 0.8 to 2.0. This compares with 0.6 to 1.12 per 1,000 "workers per year" in the United States and 1.7 to 2.8 fatalities per "1000 man-years" in the Norwegian sector of the North Sea. It is not certain that the estimates are comparable since the "per 1000 employed" used in the U.K. study and "per 1000 workers per year" in the U.S. study are not necessarily the same as "per 1000 man-years" for Norway.

The Burgoyne Report concluded that an offshore worker is about twice as likely to have an accident as a worker in general manufacturing and about half as likely as a miner. It was concluded, however, that an accident offshore is much more likely to be fatal.

More detailed and comprehensive studies of risk have been carried out for the Norwegian offshore petroleum industry than for any other in the world. Norwegian studies have taken as their point of departure the need to estimate risk levels before judgements are made about safety levels and procedures. Nevertheless, the problems with data encountered elsewhere are also found in the 1979 report of the Royal Norwegian Council for Scientific and Industrial Research, *Risk Assessment, A Study of Risk Levels Within Norwegian Offshore Petroleum Activities*. Variations in definition, coverage, and method of collection resulted in wide divergencies among data sources.

The upper estimates of the size of the Norwegian Continental Shelf work force grew from 100 person-years in 1966 to 16,705 person-years in 1978. The high estimate of person-years worked tripled between 1975 and 1978. There were 82 fatalities (Norwegians and foreigners) reported in different offshore activities from 1966 up to and including 1978. The largest single area of fatalities was in the category of field development involving helicopters. The data analysis revealed that 42 percent of the 82 fatalities were caused by helicopter crashes and ditching; 21 percent were caused by what could be called industrial accidents; 11 percent occurred during emergency evacuation (including the grounding of the *Deep Sea Driller*); 10 percent were diving accidents; 4 percent occurred during drilling operations; and 12 percent were allocated to the miscellaneous category. The Norwegian offshore industry had a fatality rate for that period in the range of 1.7 to 2.8 fatalities per 1,000 person-years. If helicopter accidents and the *Deep Sea Driller* grounding are excluded the rate drops to the range of 0.85 to 1.4 fatalities per 1,000 person-years.

The report noted that the injury frequency on fixed and mobile platforms offshore was comparable to that in land-based activities such as mining and wood conversion. Injury seemed to be more frequent on MODUs than on fixed installations (production platforms) and this was attributed to the drilling activity. To reduce the accident frequency the report suggested that the drilling activity be studied more closely.

■ *THE EASTERN CANADA OFFSHORE AREA* In the presence of a short operating history offshore eastern Canada and the absence of reliable and complete data, numerous assumptions have had to be made in order to establish an estimate of the total number of rig-years of operation and the size of the work force. These estimates provide a reasonable basis for some comparisons. In comparing the frequency of disabling injuries in oil exploration off Nova Scotia with the rate for Norway, both rates fall within the same order of magnitude, within the limits estimated for person-hours worked. It is not known, however, if the reporting requirements for "injuries" in Norwegian data correspond to those for disabling injuries in Nova Scotia. The most that can be said is that the rates appear similar; no radically different rates have been detected. The average frequency rates for lost-time accidents or disabling injuries off Newfoundland are of the same order of magnitude as seen in Nova Scotia and Norway.

Nevertheless, serious doubt is cast on the value of average frequency data when the range is large. For example, one semisubmersible operating offshore Newfoundland in 1980 reported an average of 56.48 accidents per month, but the monthly values ranged from zero accidents in each of seven months to 217.7 accidents in a single month. It is conceivable that such extreme variations might be caused by radical changes in conditions, such as severe deck icing, but incomplete reporting is the more likely explanation. For instance, the Newfoundland and Labrador Petroleum Directorate information for 1980 shows data from only three rigs, whereas other data sources report that there were eight rigs operating off Newfoundland in 1980. The frequency of lost time accidents in Newfoundland and Labrador areas for the period 1978 to 1983 is generally lower than that reported for Norway in the same period, but again, the lack of accuracy in the data and doubts regarding their strict comparability permit no more than the conclusion that they are not radically different.

■ *CONCLUSIONS* If accident and fatality rates are considered to be important in Canada as a means of assessing risks, monitoring safety performance, and providing comparable data, then a single accident reporting form collected by a single agency with the authority to ensure that its reports are complete and accurate is necessary. In addition, standardization of reporting categories and definitions is desirable in both the national and international forum.

The risk of fatality for an offshore oil rig worker in eastern Canada on an annual basis lies somewhere between 0.006 and 0.0004. While this is not a very precise estimate, it is the most that can be said on the basis of present data. The available data on injury rates in the four countries studied do not even allow for such an imprecise estimate, although this analysis has not been able to establish any major differences in injury rates among the four countries.

On the basis of the limited comparison of Canadian offshore exploration with land-based industries, it might be judged that offshore drilling and related activities are safer in terms of industrial accident rates, and more dangerous only in terms of the low probability of a "marine disaster". It is quite clear that the limited periods of record make risk analysis, based on the type of offshore activity, impractical. It is an axiom of risk analysis that accidental events can be reduced in frequency but not completely eliminated; risk management must include the making of preparations to help reduce the effects of accidents when they do occur.

Summary of Risk Analysis Seminar

On May 2, 1984, the Royal Commission sponsored a one-day seminar to investigate the application of analytical techniques for the identification and assessment of risk in offshore drilling. The participants were invited from offshore industry and regulatory groups and also from the nuclear industry, where risk analysis techniques have been employed for many years as part of the management decision-making process.

Risk analysis involves methods of estimating the probability and consequence of adverse events; such a process is not designed to "predict" future events, but to provide a rational basis for decisions aimed at minimizing the occurrence or consequences of such events. Risk analysis also provides a framework for processing large amounts of data to facilitate review and assessment.

It was noted by the participants that risk analysis has a number of limitations. There is considerable difficulty in estimating the possibility and consequences of low probability events, and such estimates are often the subject of disagreement. In addition, risk analysis techniques involve subjective input, especially where objective data are questionable or non-existent, and the opinions and judgement of the analyst are reflected in the results. Risk analysts must also be aware that changes in technology and significant corrective action instigated to compensate for past accidents may limit the effectiveness of comparison with historical data.

The Canadian and American nuclear industries have benefited from the application of risk analysis techniques for almost 20 years. During the last 10 years, these techniques have evolved as a major element of the industrial and regulatory decision-making process in a number of industries, including the oil and gas production industry. The process has been improved by developments in data processing techniques and computer simulation, especially where large volumes of data are involved. The general perception of the participants was that the benefits of risk analysis outweigh the limitations imposed by the necessity of qualitative input.

To date, in the offshore oil industry, only the Norwegian Petroleum Directorate (NPD) has introduced a regulatory requirement for the application of such techniques. To acknowledge the alternative ways of performing these evaluations and to encourage operators to develop suitable techniques for offshore application, the requirement has been introduced in the form of a guideline, as opposed to a regulation. One representative of NPD pointed out that, although the industry was initially somewhat reticent about having a regulatory requirement for risk analysis, every operator now performs a broader analysis than required by the NPD guideline. It was generally agreed that the regulatory framework for risk analysis should avoid the stipulation of arbitrary numbers for "acceptable" levels of risk, as this obscures the goal of the assessment and tends to turn it into an exercise of proving that the situation is "safe enough". The operator must be convinced that he is carrying out the assessment for his own benefit, to identify problems and implement effective improvements.

The use of risk analysis techniques for evaluating existing offshore installations and operations was considered a reasonable and beneficial proposition; the application of the same techniques used during the design of offshore systems may have an even greater effect on the level of safety achieved. The earlier that risk analysis is employed in the design process, the greater the potential for identifying and decreasing risk factors.

A considerable amount of discussion took place regarding the public perception of risk, and the regulators' responsibilities to the public, the offshore workers, and the petroleum industry. It was noted that the mandate of the regulator should be to establish levels of risk that are "acceptable", possibly in comparison to the risks encountered by workers in other industries. Risk levels should also be established through the comparison of overall risk with potential benefits, and the regulator should opt to protect the interests of those who are not in a position to influence the decision-making process. Risk analysis was seen as an adjunct to more subjective influences, such as the public perception of and the potential benefits from offshore activities.

In general, it was agreed that the information obtained through the judicious and systematic application of risk analysis techniques considerably exceeds that which can be obtained from a less structured, intuitive inspection. Risk analysis is a powerful and desirable tool for identifying and evaluating risk levels and provides a basis for establishing methods of eliminating or mitigating the consequences of such risks.

2

ENVIRONMENT

ENVIRONMENT

ICE AND ICE MANAGEMENT

A Review of Ice Information for Offshore Eastern Canada
NORDCO Limited
St. John's, Newfoundland
August 1984

An Evaluation of Ice Management Systems in Support of Eastern Canada Offshore Exploratory Drilling Operations
Manadrill Drilling Management Inc.
Calgary, Alberta
August 1984

Three categories of ice are encountered in the study area: glacial ice in the form of icebergs, sea ice, and freezing precipitation or spray. The last of these creates super-structure icing, which while long recognized as a problem for fishing vessels, has only recently been addressed as a concern for offshore drilling operations. The other two forms of ice, however, have been major factors for a number of years in determining drilling schedules and the type of unit employed. Year-round drilling has only been possible off Nova Scotia and, with due attention to icebergs and occasional sea ice, on the Grand Banks. In both these locations anchored semi-submersibles are routinely used, although in the shallow waters close to Sable Island and in the Gulf of St. Lawrence, jack-up units are often preferred. Farther north off the Labrador Coast and in the Davis Strait, drilling is limited to the summer months and to dynamically-positioned drillships or semisubmersibles that are mobile enough to move away from ice on short notice. In the extreme north, off Lancaster Sound, drilling permits have been sought but actual drilling has not yet begun.

None of the drilling units used so far on the East Coast have been "ice class", although some of the semisubmersibles have extra strengthening in their vertical columns. Supply boats, particularly those used off Labrador, are often ice class, for example, Lloyd's Arctic Class 2 or 3, since these vessels are frequently required to tow icebergs or deflect small pieces of ice away from rigs.

The basic methods used in the industry for dealing with icebergs were developed in the early 1970s for operations on the Labrador Shelf. The ice management strategy is based on avoidance. The security of the drilling operation depends on the detection of all potentially hazardous ice or icebergs in sufficient time to either deflect the ice, or move the drilling vessel out of its path. The possibility of a collision between a drilling unit and an iceberg is thus limited to those situations when the ice is not detected in time to move the unit, or when deflection is not possible and the unit is for some reason unable to move off the site.

■ *ICEBERGS* Icebergs are defined in terms of their approximate mass. The smallest pieces, referred to as growlers, have dimensions of up to 1 metre of freeboard, 6 metres in length, and 200 tonnes in mass. A "bergy bit" has a sail height (height above sea level) of 1 to 5 metres, a length of 6 to 20 metres and a mass of 200 to 7,000 tonnes. Icebergs that exceed these approximate dimensions are simply referred to as small, medium, large, and very large icebergs with relative sizes established for each category.

The size and shape of an iceberg will directly affect its detectability, its response to both environmental forces and deflection strategies, and the impact that it would have in collision with an offshore platform.

The method normally used to calculate the above-water dimensions of an iceberg is to measure angles with a sextant and ranges with radar or a visual range finder. Since there is a fixed relationship between the above- and below-water mass of icebergs, the mass can be estimated from this information by using standard formulae. In some cases aerial stereo photography has been used to estimate iceberg mass. Length and draft are also important iceberg dimensions. Draft is normally measured using a side scan sonar or estimated from the density of the ice and the iceberg's above-water geometry.

The principal source of data on iceberg dimensions off the East Coast are the observations made by oil companies in support of their offshore drilling programs. Data from drill sites indicate that growlers are frequently not observed even when they are closer than ten kilometres, and they are not always included in the statistics when they are observed.

The maximum credible size of an iceberg may not be an important factor in terms of drilling unit design or safety. The maximum credible iceberg has a very low probability of occurrence, an even lower probability of hitting a structure since it would be easy to detect and track, and practically no probability of colliding at any considerable speed. If the probability of impact is held constant, the maximum energy level involved in a collision is associated not with the maximum credible iceberg but with a much smaller iceberg travelling at higher speeds.

Each year tens of thousands of icebergs calve from the glaciers of West Greenland and, to a lesser extent, Baffin Island but only a fraction of them find their way out of the fjords and into Baffin Bay, and an even smaller number will survive the 3,000 kilometre two-year journey along the Baffin and Labrador Coasts. South of 49 degrees north latitude the icebergs follow two branches; the inshore branch flows southward through the Avalon Channel while the offshore branch follows the eastern edge of the Grand Banks. Once an iceberg is free of pack ice and drifting in open and warmer water it decays rapidly. A small berg in +2°C water will have disappeared in about nine days and in 10°C water in three days.

The number of icebergs moving through a cross section in a given time interval is known as the iceberg flux and in eastern Canadian waters variability is its principal characteristic. The maximum flux usually occurs in April and May on the Grand Banks, in May off Labrador, and in July in Baffin Bay; the minimum flux is in October, November, and December in all areas. The annual flux across 48 degrees north latitude, which has been documented by the International Ice Patrol since 1913, ranges from zero to as high as 1,500 icebergs per year, thus demonstrating how extreme the interannual variability can be.

There is also operational interest in information about the size distribution of bergs. This is well known for Labrador because of the large data set accumulated during the several years of drilling along that coast in the 1970s. The data base for the Grand Banks is not nearly as well developed. Analyses suggest that in the waters off Labrador about one-third of all icebergs have displacements of a million tonnes or more while on the Grand Banks only about ten percent are that large. The populations upon which these percentages are based do not include bergy bits and growlers of under 1,000 tonnes because of the lack of any reliable data on their numbers. They tend to be short-lived, difficult to detect under adverse conditions, and when detected are not always reported.

The movement of an iceberg is governed largely by wind and current. Since both wind and current vary considerably over time and distance, large variations in iceberg speed and direction occur even over distances as short as a few kilometres. Some conclusions can be drawn regarding iceberg drift speeds in offshore areas of eastern Canada. For sites not in the main current, iceberg drift speeds averaged over several days range from 0.10 to 0.25 metres per second (m/s) while in high current environments these can approach 0.50 m/s. A few observations of short duration drift speeds of 2.0 m/s and daily averages of 1.5 m/s have been made in high current environments under severe storm conditions. There is very little quantitative data and no field data on expected instantaneous speeds of small icebergs such as growlers in waves.

At present the only area for which design criteria for maximum iceberg drift speeds have been proposed is Hibernia. Both the Newfoundland and Labrador Petroleum Directorate and Mobil Oil Canada Ltd. proposed a maximum of 1.0 m/s. Although no design criteria have been proposed for Labrador, a value of 0.80 m/s is quoted in the Offshore Labrador Initial Environment Assessment as the maximum iceberg drift speed. Other research suggests that the Hibernia figure represents a long-term maximum, and that both values need to be reassessed.

A second aspect of iceberg drift which is important in designing impact probability models (and which several of the existing models do not take into account) is the direction of drift. Analyses of data collected at drill sites in the Labrador Sea have demonstrated that, although there is normally a predominant drift pattern, icebergs move in all directions.

The mechanical properties of ice define its strength, an important aspect in determining the effect this material will have on impact with a structure. Different types of loading (compression, bending, indentation, shearing, pulling) are used to identify different failure modes (cracking, crushing). Mechanical properties are difficult to quantify because of their variability with temperature, age of ice, brine content, and the manner of formation of the ice. This natural variability cannot be replicated in the laboratory and field measurements are difficult to obtain. Further, if ice is taken from its natural setting, many of the variables affecting its mechanical properties (temperature, brine drainage) change dramatically. For these reasons, there are few measurements of the mechanical properties of ice.

Iceberg ice is characterized by small bubbles entrapped during the formation of the glacier when pressure converts snow into ice. These small bubbles of compressed air are in the order of a few tenths of a millimetre in diameter and occur in the order of a few hundred per cubic centimetre. The limited test results which are available indicate that iceberg ice has exhibited a higher strength than, for example, lake ice; this characteristic is attributed to these bubbles which appear to inhibit crack propagation.

■ *SEA ICE* Sea ice is formed by the freezing of the sea surface; pack ice is free-floating sea ice. Once an ice sheet has formed, its visual appearance reflects its stage of development and hence a classification terminology has evolved for identification of young ice (newly formed, dark, thin) through to first-year ice (older, white, thick). Ice which survives the summer melt is subjected to brine drainage. As a result, this older ice (second or multiyear ice) is considerably stronger than first-year ice.

Pack ice occasionally extends to the Hibernia area during the winter months, and the ice edge is normally just north of the drill sites off Labrador at the start of the season. Throughout the northern part of the study area (Baffin Bay, Lancaster Sound) sea ice is present for most of the year and would pose problems to any drilling activities. Although pack ice from the Gulf of St. Lawrence does occasionally cover the northern Scotian Shelf, it has not been reported at Sable Island.

Data on sea ice types and concentrations in the study area are normally obtained from ship, shore, aerial, and satellite observations and are processed by the Ice Central Branch of the Atmospheric Environment Service (AES). This branch uses aircraft to provide sea ice information on the Grand Banks, Labrador Coast, and the Gulf of St. Lawrence. The service has been much improved recently with the introduction of Side-Looking Airborne Radar (SLAR) on the aircraft. Because of the large geographical area involved and the mandate of AES to service shipping interests as well as the oil industry, coverage of the Hibernia area during the winter and of the Labrador Coast during the spring is limited to once every two to three days, but this may vary considerably. In both these areas the oil industry has developed its own ice reconnaissance programs which supplement the AES flights.

New sea ice begins to form in late September in northern Baffin Bay and slowly advances southward. By late December the Labrador Coast is completely enclosed by ice, and ice is starting to form in the Gulf of St. Lawrence. By mid-March the sea ice has reached its maximum extent covering most of the Gulf of St. Lawrence and much of the northern Grand Banks. This ice begins to melt in April and by May these two areas are usually clear. The Labrador Coast clears of ice during June and July, and by mid-August the southern extent of pack ice is restricted to Baffin Bay. Mid-September generally represents the minimum distribution of sea ice. Seasonal variations in the timing and extent of ice coverage can range up to about a month.

The rate of movement of the ice edge is the most important consideration for drilling near the pack ice edge since this factor determines the lead time available to move the drilling unit off the site. Analyses of pack ice drift speeds off Labrador suggest a maximum observed drift speed of 0.8 m/s with mean speeds ranging from 0.17 to 0.32 m/s. Most of the measurements available are from pack ice situations; isolated floes could be expected to travel considerably faster. There are few measurements of sea ice drift speeds on the Grand Banks; however, a maximum rate of advance of the ice edge towards the Hibernia site of 277 kilometres per week (average speed 0.43 m/s) has been noted. Rapid advances of the pack ice on the Grand Banks normally occur in the area of the Labrador current during periods of strong north or northwest winds behind a low pressure system. During one such instance the AES ice charts for March 1973 reported movement of sea ice south through the Avalon Channel at a rate in excess of 50 kilometres per day (0.6 m/s).

Although first-year sea ice rarely grows to more than two metres in thickness through the process of freezing, other conditions related to the pack ice environment can result in considerably thicker floes. Rafting, where one ice sheet overrides another, is a factor in the building up of thinner ice, while ridging, where a line of broken ice is forced up or down by contact between individual pieces under pressure, can occur in thick ice and result in the formation of even thicker floes as the ice blocks comprising the ridge become frozen together. This latter phenomenon is most likely to occur in areas with high concentrations of ice of varying degrees of thickness where there is considerable interaction between floes. Commonly, ridge formation occurs when currents squeeze the pack ice against land or landlocked ice. In addition, ridges are more likely to retain their identity if they are formed in a cold environment with little wave action. For these reasons ridge formation occurs more frequently in the northern parts of the study area than on the Grand Banks.

Ice thickness measurements in the Labrador Sea indicate that the mean first-year ice thickness during the winter months ranges from 0.5 to 3 metres, with the maximum thickness near 5 metres. There are few measurements of multiyear floes but the available data indicate that thicknesses in excess of 14 metres are possible. There are not enough representative observations from the Grand Banks to determine the mean or extreme sea ice thicknesses in this area.

The floe size distribution within the study area varies regionally, seasonally, and with the distance from the ice edge. The largest ice floes, found in Baffin Bay and off the Labrador Coast during the winter months, can reach tens of kilometres in diameter and are composed of smaller floes that have frozen together. Since these floes would be quickly broken up by wave action, they are normally found well inside the ice edge. Near the edge of the Labrador pack in winter there is normally a zone 5 to 10 kilometres wide of small, broken floes with diameters of 10 to 20 metres. Measurements of floe size on the Grand Banks indicate that within 100 kilometres of the ice edge the majority of ice floes will be less than 30 metres in diameter. Again data limitations preclude estimates of maximum floe size for this area.

Sea ice is also measured in relation to ridges since this surface feature may affect ice/vessel interactions. Laser profilometer data collected off Labrador indicate that the largest ridge observed had a sail height of three metres. Using sail to keel ratios of 3:1 to 5:1, these measurements would give maximum ridge thicknesses of 12 to 18 metres. Based on the same statistics, a typical ridge in this area has a height of approximately 1.5 metres and a total thickness of from 6 to 9 metres. There are few measurements of ridge height on the Grand Banks.

There are limited measurements of the mechanical properties of sea ice; most are from the Labrador offshore, none have been reported from the Grand Banks. The strength of sea ice varies principally with temperature and brine volume. Old, multiyear ice can be expected to have higher failure strength than first-year ice.

■ *ICING* Icing can originate either from freezing sea spray or flooding by waves, or from atmospheric sources such as freezing precipitation, rime icing in clouds, fog, and wet snow which freezes on contact with a surface. These icing events, particularly when they occur either simultaneously or sequentially, have a number of direct and indirect effects on drilling operations. The stability of drilling platforms and support vessels is reduced by ice loading; the operation of helicopters and fixed-wing aircraft is restricted by rime icing; the danger of on-deck accidents is increased by ice encrustment; and the operation of safety equipment such as lifeboats and rafts is interfered with by several of these conditions. Research attempting to establish maximum icing conditions and loads for supply boats and platforms is seriously hampered by the lack of reliable data on ice accretion on offshore structures.

Freezing spray, the most common source of icing, occurs when spray droplets are cooled below their freezing point without freezing. When these supercooled droplets come into contact with a cold surface, icing occurs. The ratio of ice accumulation from freezing spray is a function of the relative wind speed, sea state, the air and water temperature, and the physical features of the structure. A small vessel such as an offshore supply boat, steaming into the wind in the open sea will start to generate spray at wind speeds of 17 to 21 knots and will be showered in spray in winds of 22 to 27 knots. Spray blown from the tops of waves, the primary type of icing to affect a MODU, is not a major factor until winds reach 41 to 47 knots. At air temperatures of −3°C ice accumulation from spray starts to be a problem and the rate of accumulation increases with lowering air temperatures. As sea surface temperatures rise from the freezing point, the formation of freezing spray tends to lessen but icing has been reported with water temperatures as high as 6°C.

Minimal observations of sea spray icing are included as part of the standard marine meteorological reports sent in by ships and drilling units off the East Coast of Canada. This data is greatly limited by lack of detail, by procedural variations, and by the frequent failure of ships to report on this factor. The National Research Council of Canada (NRC) attempted to collect a better data set from 1968 to 1979, but the study was limited in its spatial coverage and dependent on reports from fishing vessels. To supplement this limited data base, a number of empirical and theoretical prediction models have been developed to calculate the rate of sea spray icing using various combinations of air temperature, wind speed, and sea surface temperature.

Sea spray icing is a problem in all regions of the study area. The most severe icing occurs in February except in areas with seasonal ice coverage where it occurs prior to freeze up. A study for Mobil Oil of sea spray icing on the Hibernia and Sable Island sites predicts the average frequency of severe icing during February as 8 percent at Sable Island and 9.5 to 12.5 percent at Hibernia. This study also determines some parameters for the most severe sea spray icing conditions at Hibernia, with the overall worst conditions being cold northwest winds behind a low-pressure system, particularly one stalled in the Labrador Sea for several days. This study arrived at a figure for maximum potential ice load from sea spray icing of 549 tonnes using a number of assumptions regarding the type of rig and the distribution of ice on it.

Atmospheric sources of ice accretion on offshore structures and service vehicles include freezing precipitation, supercooled fog (cloud icing), and wet snow which turns to ice. Snow which accumulates on deck surfaces but does not freeze is also within this category.

The sources of data on atmospheric icing in the study area are meteorological reports from transient ships, drilling platforms, and land stations. None of these sources is entirely reliable. While observations from transient ships provide the largest amount of information, they seldom provide a continuous record of an icing event. Drilling platforms provide continuous coverage but with little detail and few long-term records. Land station reports supply detail on icing conditions but rarely specific measurements. In all these cases, reports would be more helpful if they provided measurements of the amount of precipitation and the thickness of ice on standard surfaces. To overcome the problem of an inadequate data base, various methods have been developed to compute ice thickness using wind speed, air temperature, and precipitation observations.

Freezing precipitation is estimated to occur less than one percent of the time for all months at the Hibernia site but little data is available for other areas. Rime icing is caused by supercooled fog which freezes on contact with a surface. Due to its low water content this type of icing is generally not a problem for platforms or vessels, but can be a serious one for fast-moving objects like helicopters or aircraft. Forecasts of cloud or rime icing frequently prevent flights, or force pilots to change altitude or alter flight plans. This problem could become serious in an emergency situation where helicopters are unable to fly because of rime icing, or where an airborne craft is unable to change altitude because of mechanical problems.

When calculating ice loadings on vessels and drilling platforms the possibility of combinations of icing events occurring either simultaneously or sequentially must be considered. A Mobil Oil study of the Hibernia site concluded that a combination of sea spray with freezing precipitation and snow could result in the greatest accumulations of ice, that these events would be unlikely to occur together but they would frequently occur sequentially, and that they were relatively independent (that is a maximum sea spray event would be unlikely to be followed by a maximum precipitation event). A maximum ice load from all sources (marine and atmospheric) used the maximum sea spray event plus 50 percent of the maximum freezing precipitation event to produce a combined ice load of 831 tonnes. (Snow accumulation accounted for 17 percent of this amount.) Attempts to estimate icing loads, and particularly extreme or 100-year events are seriously limited by the lack of reliable data bases covering 20 years or more and by the fact that the bulk of data collection is done by ships which tend to avoid areas where severe icing is reported. For this reason the Mobil Oil study identified the most severe event rather than attempting to calculate the 100-year event.

The lack of reliable observations of icing on supply boats and particularly on semisubmersible drilling platforms presents difficulties for designers, operators, and regulatory agencies in estimating and controlling ice accumulation on offshore structures. Of particular importance are lack of understanding regarding icing on the underside of platforms, vertical profiles of icing rates, and effects of icing on the operation of safety equipment.

■ *ICE MANAGEMENT* Current East Coast drilling practice assumes all ice will be detected in sufficient time to take any action necessary to ensure the safety of the operation under any weather condition or drilling situation. To this end an ice management system has been put in place which, to date, has been successful. There have been no reports of serious damage by ice to either rigs or supply vessels. It is, however, well recognized that there is much room for improvement to ensure that this safety record is maintained.

Only from the Grand Banks northward does floating ice pose a significant concern to drilling operations. During the winters of 1982-83 and 1983-84, the Grand Banks experienced severe ice conditions for the first time since winter drilling commenced. Programs to manage the situation were quickly developed, building on the earlier drilling experience with pack ice and icebergs in Labrador. The underlying policy is to avoid contact with the ice. The programs consist primarily of a detailed ice surveillance system, a site-specific ice detection system, and a series of procedures for either deflecting the ice from the site by towing or propeller washing or moving the drilling unit off the well location.

The effectiveness of any ice management strategy depends on the technical ability to detect, monitor, and measure ice and ice movement in a systematic manner. There is an ice observer on duty at all times on each drilling unit. Overall detection performance has been conclusively linked to the technical training, practical experience, and constant vigilance of these observers. The primary ice detection tool on board is marine radar, supplemented with radar and visual observations from other resources, usually supply boats and aircraft. Once detected, the ice is monitored, at regular intervals, to evaluate the level of threat involved and to decide whether collision avoidance procedures are necessary. This decision depends on the distance of the ice from the unit; the size and draft of the iceberg (with respect to wellhead damage potential); the drift speed, direction, and trajectory of the ice; the safe stand-down time involved in moving the unit; and environmental constraints such as weather and sea state. The procedure for assigning level of threat is based on a configuration of concentric alert zones centred on the drilling vessel.

Ice management programs rely on information on both regional and local scales. Local data originate from the ice observers on an individual drilling unit; regional data are provided by a mixture of government and dedicated operator-sponsored agencies and sources of opportunity. In the case of a dynamically-positioned drilling unit, local control will normally be sufficient since the unit can withdraw fairly quickly. Moored drilling units take considerably longer to move off location, and the decision to suspend operations or to prepare for moving off may have to be made very shortly after a potentially troublesome iceberg or pack ice drifts within local surveillance range. Because the last line of defence for a MODU is its quick release mooring system, it is important that this system be reliable, simple to operate, and thoroughly understood. Regional ice data are required where drilling units are clustered together and ice avoidance action such as iceberg towing at one site may endanger another site.

Even though drilling operations in the study area have not been subjected to any serious ice-related accidents to date, there are a number of problems associated with the availability and reliability of data needed for ice-event predictions, and with the adequacy of ice detection devices in current use.

Icebergs are poor radar targets; the maximum range of detection is limited because of low signal return and short-range detection is limited because of competing sea clutter return. Research using many different categories of radar equipment has produced a very wide range of estimates of the iceberg detection capability of those instruments. It has been found by a number of researchers that, visibility permitting, most icebergs will be seen before marine radar detects them, and that icebergs of all sizes, but particularly growlers, quite often go undetected.

Imaging radar (Side-Looking Airborne Radar and Synthetic Aperture Radar) because of their all-weather, day and night capability, have proven to be very valuable reconnaissance tools, even though there is considerable confusion regarding their true detection capability against what are essentially point targets. One limitation of Side-Looking Airborne Radar which may prove problematic in a high-traffic area such as the Grand Banks, is the difficulty it has in differentiating ship versus iceberg targets. A positive feature is that it is an ideal instrument for the reconnaissance of sea ice, since it can classify ice type and provide accurate positional information on, for example, multiyear floes in the middle of a pack of relatively harmless first-year ice. Testing and evaluation of these and other sensing devices is ongoing.

A major problem on the Grand Banks is the poor visibility which limits the effectiveness of both airborne visual reconnaissance and long-range visual observation from surface vessels. Rough sea conditions also frequently restrict the movements of support vessels thus reducing their capability to perform reconnaissance work when it is most needed. Information provided by support vessel crews is not always reliable since there are no trained ice observers on these vessels.

Individually, then, each method of ice detection (airborne and shipborne, visual and radar) has its shortcomings. In general terms, for long range strategic reconnaissance upstream from a drill site, combinations of both airborne and ship-based visual reconnaissance along with Side-Looking Airborne Radar have been used; for short range tactical monitoring a combination of marine radars and visual observations from drilling platforms and service vessels are used. Even with the integration of all these methods, small targets may still slip through undetected, particularly during storm situations when detailed and accurate information is most crucial.

■ *OPERATING REGULATIONS* Design and construction standards for vessels, including MODUs, which operate in ice-infested waters have been developed by classification societies, largely for insurance purposes. The *Arctic Waters Pollution Prevention Act*, and the accompanying *Arctic Shipping Pollution Prevention Regulations* specify the design and construction standards required for vessels operating north of 60 degrees north latitude. These regulations divide the Canadian Arctic into ten geographical regions and stipulate at what time of year a certain class of vessel can enter a region.

The proposed *Interim Standards for the Design, Construction and Operation of MODUs*, recently issued by the Canadian Coast Guard, requires the calculation of ice and snow forces and the effect of ice and snow accumulation on the unit's structure, but they do not specify the method or degree of accuracy required in making these calculations. The "Interim Standards" also require that total ice loads be calculated for 100-year return events, but this report has shown that there are not enough data on most ice parameters to calculate realistic 100-year events.

This lack of reliable, long-term data is compounded by the lack of experience of regulatory agencies in dealing with the requirements for exploratory drilling operations in ice-prone environments. Several European countries have specified MODU designs for severe weather operations. These designs include such features as flush surfaces to minimize structural icing, covered work areas, and emergency assembly areas, and in some cases, "ice strengthening", although it is not clear how effective such reinforcing would be in the event of a collision with glacial ice. Some attempts have also been made by the Newfoundland and Labrador Petroleum Directorate and the American Bureau of Shipping to relate design criteria to ice conditions. Theoretical studies have shown that the damage which a small, undetected piece of ice is likely to inflict on a MODU could be more severe than that described in the Interim Standards. Again, however, no large scale experiments have been carried out to confirm initial findings.

Very little consideration has been given by regulatory agencies to the operation of exposed emergency equipment such as lifeboats and launching mechanisms, under freezing spray or precipitation conditions, nor is it clear from regulations whether lifeboats or life rafts could operate in loose pack ice without a significant risk of hull puncture.

■ *CONCLUSIONS* In general it can be concluded that ice alone will rarely constitute a hazard to offshore exploratory drilling and support operations, providing good ice management procedures are in place and followed. Nevertheless, ice combined with other factors, such as bad weather or mechanical failure, may constitute a risk to offshore operations.

The study has identified a number of gaps in our knowledge of icebergs. The most significant is associated with assessing the probability and consequences of a growler, bergy bit or small iceberg colliding with a structure during severe weather situations. All aspects of this problem are poorly understood including: the frequency of occurrence of these icebergs; methods of detecting and managing them, particularly in severe weather; the motion of these bodies in high sea states; and the results of an impact with a structure or vessel.

Because current operating procedures in the study area call for the drilling unit to move off the site if sea ice is encroaching, and because sea ice is fairly easy to detect, this factor does not pose a threat to human safety.

Although superstructure icing on drilling platforms and supply boats has not been a major problem in the study area to date, there is a need to define the maximum ice loading on platforms and ships and the effect that these ice loadings have on stability and on the operation of safety equipment.

The organizational structure and operating ice management procedures in current use provide adequate insurance against ice-related hazards in the study area. Significant improvements have been made over the past three years for operations on the Grand Banks. Research and development are proceeding on a number of fronts, and operations personnel are gaining expertise in the deflection of icebergs and in streamlining alert and abandonment procedures. A government-initiated collaboration was established to coordinate overall ice reconnaissance and management performance. There is wide recognition of a continuing need for ice detection and surveillance system research; for the establishment of a consistent physical environmental data base; for more carefully researched regulations and guidelines; and for the review and standardization by a joint government and industry management group of ice detection and control procedures used within the study area.

MARINE CLIMATOLOGY

A Review of the State-of-the-Art in Marine Climatology on the East Coast of Canada
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The majority of work in marine climatology in Canada is done by the Atmospheric Environment Service (AES) of the federal Department of Environment. The AES participates in data collection, quality control and archiving, and instrument development as well as the provision of climate information and expertise, and applied climate research. Oil industry activities related to climate largely parallel those of government in data acquisition, archiving and system development; however, many industry studies are site-specific and proprietary. Actual data used in marine climatological studies are derived from many sources including transient ships, weatherships, drill rigs, buoys, land stations, and hindcasts. Data obtained from these sources vary widely in quality, quantity, and applicability. Quality is affected by the instrumentation used and by the training and motivation of the observer. Spatial coverage of marine areas is poor. Land stations, buoys, and weatherships are few in number; drill rigs are limited to specific areas; and transient ships tend to follow well-defined shipping lanes. Temporal coverage is very good for land stations and weatherships but again, variable from other sources. As yet, satellite data bases are inappropriate for any climatological analysis, due to their short term and the sporadic nature of their coverage.

To overcome these deficiencies, hindcast data have been produced, particularly for wind. Hindcast data are synthesized from historical records such as surface pressure and upper air weather maps, using theoretical models of the atmosphere and ocean, and then verified against quality surface measurements. Hindcasts are the most frequent source of data for such applications as design studies and wave models since all other data sets lack the temporal and/or spatial coverage to be widely applicable. These hindcast data are produced on a grid for periods of 20 years or more. This is ideal for many climatological applications, including persistence and extreme value analyses, and examination of spatial and temporal variability. Limitations in grid size, however, may allow important small-scale features to pass undetected.

■ *WIND* Knowledge of wind speed, direction, profile with height, and character (for example gustiness) is very important to an assessment of hazards to safety. The wind exerts considerable force on drill rigs, supply vessels, and aircraft. Since this force is proportional to the square of the wind speed, extreme winds are especially critical. The wind speed alone will probably not be sufficient to affect the survivability of either rigs or supply vessels, but may be critical to helicopter operations or rescue procedures. High winds can also create dangerous working conditions for personnel on exposed decks. In addition to its independent effects, the wind is also the major forcing factor in generating waves, which usually produce the predominant loads on offshore structures, and is a major factor in wind chill, spray icing, and mechanical turbulence.

Although wind is the most widely studied of the climatological parameters under consideration, much of this work has been oriented toward the wave generation problem and not toward the stresses of the wind itself on structures. Very little research has been done on describing the vertical profile of wind in the marine atmosphere, particularly at anemometer height, which in the case of rigs, can be up to 100 metres above the sea surface. Other areas that have received little study are the determination of gust factors over the ocean; the potential effects of the wave field on the winds; the relationship between rig-measured winds and the true overwater wind field; the optimum averaging time for wind measurements at sea; and refinements in the calculation of extreme or design winds. In general, the present data base of wind information is insufficient to define adequately the temporal and spatial variability of the wind field, the effects of structures on the wind field, or the extreme values to be expected.

In an attempt to delineate an accurate marine wind field, there are areas of disagreement relating to the analysis of wind data which should be resolved. It is not certain, for example, what averaging period is desirable for marine applications. One-minute means have been the standard for years. The World Meteorological Organization has recommended the adoption of ten-minute means while designers may prefer a number which is the highest one-minute average in an hour. The commonly accepted reference height for winds over the ocean is 19.5 metres, yet relatively few wind observations are actually made at this height. The empirical adjustment of other measurements to this standard height may lead to inconsistencies in results.

A program should be initiated on and around several drill rigs to measure the variability of the wind in space and time and the effect of the rig on airflow. Experimental turbulence measurements should also be a part of this study. The utility of high frequency radar and bottom-mounted acoustic sounders for wind measurement should be considered or continued for Canadian waters. In addition, studies should be initiated to produce relationships between wind speeds taken for several averaging periods from one second to six hours. Wind measurements from various reference heights should be compared for a variety of stability conditions and wind speeds to develop wind profiles for several areas so that standard reference heights and averaging periods can be established. Work is necessary to review extreme value analysis techniques and data bases for wind on the East Coast, in order to produce acceptable design wind speeds and to determine the effects of the wave field on the wind field.

■ *ICING* Ice accretion poses a hazard to drill rigs, supply vessels, and especially helicopters. Few measurements exist of icing over the ocean, particularly with respect to its vertical distribution, thus it is difficult to verify existing methods for producing icing statistics or to develop new techniques. For atmospheric icing, most of the present techniques were developed over land, so their applicability to the marine environment is unknown.

Freezing spray is the most dangerous source of icing, accounting for 89 percent of ship icing cases. Combinations of spray and precipitation accounted for a further 8 percent. Because of the lack of observed data on freezing spray, most climatologies and design studies are based on hindcasts of "freezing spray potential", using one of several empirical techniques. These models relate atmospheric and oceanographic parameters to icing rates. Some models use only wind speed and air temperature. Other models also include sea surface temperature, wave height, and salinity. Icing rates are usually given in classes of light, moderate, and heavy or severe, since the actual rate of icing depends on the course, speed, and structural characteristics of the ship.

Because icing poses serious safety problems offshore, it should be a priority area for the development of new programs. Each of the three icing types (sea spray, precipitation, and rime or cloud) should be studied to determine the vertical distribution; the occurrences and rates should be compared against meteorological and oceanographic conditions at the time of occurrence. Existing techniques for icing forecasting and hindcasting can thereby be evaluated and new techniques developed if necessary. Estimates should also be produced of the total amount of accreted ice due to the occurrence of each type of icing which may accumulate on structures, either independently or in combination, so that the effects of realistic maximum loads can be studied.

■ *SEA SURFACE TEMPERATURE* Sea surface temperature is subject to considerable spatial variation, particularly in the vicinity of the Gulf Stream/Labrador current interaction zone. The present density of observations from conventional sources is inadequate to describe the complex nature of these patterns. The accuracy of sea temperature measurements from ships or drilling rigs is greatly limited by variations in methods, water depth, and adjacent heat sources.

Present satellite systems are able to produce reliable estimates of sea surface temperature within $\pm 0.5°C$. The sensors employed, however, are passive infra-red radiometers, which do not have the ability to penetrate cloud. The next generation of sensor is the microwave radiometer, which will not be affected by cloud, but which involves a considerable reduction in spatial resolution. A combination of data from the two satellite sensors may prove to be the optimum solution for analysis. Climate analysis of sea temperature is not possible at present since there is only a limited archive of radiometer data and no archive of microwave data.

■ *AIR TEMPERATURE* Methods of measuring air temperature on board ships or drilling rigs are limited by siting problems involving instrument height and heat sources. Air temperature is not usually subject to large variations in a given area of the marine atmosphere. Therefore, a few observations, if well distributed, can describe a large area of ocean. Exceptions occur in the vicinity of coastlines, fronts, and the Gulf Stream.

■ *ATMOSPHERIC PRESSURE* Atmospheric pressure is not itself a hazard to safety, but it is a very important parameter. In real time, it is essential for the preparation of the weather charts from which weather forecasts are produced. It is also necessary for the altimeter settings for aircraft. The same analysed surface pressure chart which is used for forecasting is used later in wind/wave hindcast studies. The ability of the hindcast to represent adequately the overwater wind depends on the accuracy, and temporal and spatial coverage of the barometric pressure.

Most ships and all rigs, land stations, and automatic stations report pressure as a basic element. At land stations, the pressure is usually measured with a mercury barometer. Other reporting systems tend to use aneroid barometers.

Pressure is a parameter measured relatively easily and inexpensively by drifting buoys transmitting to satellite. Measurements are, in general, accurate; however, more observations are necessary in data-sparse areas. Drifting buoys would provide additional information which would enhance rig safety, both in the climatological sense, through design, and as a forecast aid through increased resolution of storms and advanced warning in an area where significant storms can form and move rapidly.

To improve this situation, drifting buoys, measuring a few parameters such as atmospheric pressure, air and sea temperature, should regularly be deployed along the East Coast. Moored buoys, similar to those now operated by the United States, or a suitable Canadian alternative, should be deployed on the Scotian Shelf and Grand Banks.

■ *TURBULENCE* Turbulence is not usually measured but is computed through empirical techniques as a gross estimate from wind speed and air/sea temperature difference measurements. Instruments are available which will measure the actual wind motions in three dimensions for short time resolution. It is unrealistic to consider this type of instrumentation for a ship, and unnecessary since most ships do not support aircraft operations. Such instrumentation would, however, provide useful information for both design and real-time applications, if mounted near the helipad of a drill rig. Turbulence measurements cannot be extrapolated to other rigs, since the disturbance of the wind field will vary substantially depending on rig structure.

■ *STORMS* Storms are obviously a major factor in consideration of offshore safety. Many investigations have dealt with frequency and tracks of travelling low pressure systems, including tropical storms and hurricanes. Most of these studies are derived from sets of historical weather maps, in either original or digital form. These maps frequently suffer from a lack of data, particularly in areas with significant ice cover. This may result in poor estimation of the location, intensity, and motion of storms, and may cause storms to be missed altogether. This is particularly true of severe small-scale storms known to occur off the East Coast of Canada.

In recent years, satellite information has aided greatly in the detection and location of storms. Future satellite systems, with capability for wind field determination, will further aid in this regard. Buoys have also aided in storm detection. Deployment of multiple-sensor moored buoys and pressure-sensing drifting buoys in data-sparse areas would also be of considerable utility, as would automatic stations in remote land areas such as the northern Labrador Coast. Such additional information would not only improve the climatology of storms but would be of value in real time for storm warnings and as input to operational weather forecasting.

■ *CLOUDS* Two aspects of clouds are particularly significant in marine climatology, the total cloud amount and the ceiling height (the altitude at which the total cloud cover is at least five-eighths). Automatic stations and satellites have the capability of determining cloud amount and height, although the satellite systems to determine cloud bases are still developmental. Some automatic stations have ceilometers, (light systems which measure the altitude of the cloud base). In order to improve data collection on cloud ceilings, preferred locations for fog, and general visibility conditions, shipboard automatic stations should be placed on ships and rigs whenever possible.

■ *RAINFALL* Rainfall observations at sea are mostly visual estimates, categorized as light, moderate, or heavy. The present data base of information on rainfall rate is adequate in southern areas, since there are numerous land stations with recording rain gauge installations. The gauge at Sable Island, in particular, gives a good estimate of design rainfall for the Scotian Shelf. Similarly, there are several sites on the periphery of the Gulf of St. Lawrence which can be used for design values. For Newfoundland waters and areas farther north, however, gauges are few, and the results cannot be reliably extrapolated to offshore areas, since much of the precipitation is induced or modified by the surface geography of the land.

A few drill rigs have recently begun to measure six-hour rainfall amounts, but these observations are not included in the digital archive. The data produced, although the best presently available, are also of questionable quality due to the difficulty of finding an unobstructed location for the gauge. There is very little information on the short duration, high rainfall rates which are likely to affect deck drainage and the quality of radio transmission.

■ *CONCLUSIONS* The primary factor inhibiting our understanding of the marine environment is a general lack of baseline data for all parameters. As a result, many important analyses cannot be performed, and some that are done are of questionable quality. Correcting this situation would involve improved data acquisition through the development of new or expanded programs.

Satellite systems capable of measuring atmospheric and oceanographic parameters should be supported. Of particular importance are wind measuring scatterometer systems and microwave sensors for sea surface temperature. Satellite-derived data should be archived in digital form. Existing hindcast data sets should be evaluated against quality measured surface data. If no suitable hindcast sets can be identified, a new Canadian hindcast should be produced. Networks of drifting buoys would provide pressure data essential to the analysis of surface weather maps on which hindcasts are based, in order to describe accurately the location and intensity of cyclonic storms. These improved maps would also benefit weather and wave forecasting. Shipboard automatic stations should be implemented wherever possible on ships and rigs; and automatic stations reporting through satellites, should be set up in remote coastal locations.

Very little work has been done on effects produced by combinations of factors. It may not necessarily be the maximum values of these conditions which cause the maximum loadings. Resonance conditions or differing stabilities may result in some other combination of factors being more critical. Occurrence of low visibility in conjunction with high winds or waves, for example, may pose problems that the independent occurrence of either would not. Various combinations should be considered for critical operating ranges, and joint frequencies computed.

The ramifications of weather conditions at supporting land stations have had minimum study. These conditions may affect operations or, more critically, emergency response capability. The occurrence of severe conditions which might require evacuation at a rig should be correlated with conditions such as flying weather (ceiling, visibility, icing) at the nearest search and rescue locations. Consideration of flying weather at supporting land stations is important at all times since potential evacuation is not restricted to severe weather occurrences at the rig. Studies of the persistence factors should be incorporated into plans for all proposed support locations.

Published climatologies, contingency plans, and impact statements are usually limited to frequency information on a few basic parameters. In order to properly assess and describe potential hazards to human safety, additional analyses should be performed including:

- Persistence, extreme values, and gust factors of winds;
- Persistence analysis of low ceilings and visibilities;
- Frequency and persistence of icing conditions for each of the three icing types;
- Frequency of thunderstorms and heavy rains;
- Minimum and maximum air temperatures, persistence of high and low values, wind chill frequency and extremes;
- Statistical summaries of cyclonic storm distribution, frequency, persistence and intensity;
- Joint frequency distributions of hazardous combinations of conditions, such as high winds and low visibility;
- Frequency and persistence of adverse weather conditions, particularly flying weather, for all supporting land stations, both independent of, and combined with, adverse weather conditions at drill sites.

WEATHER FORECASTING SERVICES

Weather Forecasting Services for the Canadian Offshore
Part 1: Organization of Responsible Agencies and Current Practice
Part 2: Assessment of Adequacy
Seaconsult Limited
St. John's, Newfoundland
August 1984

■ *ORGANIZATION* Traditionally the Atmospheric Environment Service (AES) has been responsible for weather forecasting throughout Canada. Their jurisdiction includes marine and aviation forecasts in addition to forecasts for general public use. Under offshore drilling regulations, operators are required to contract location- and route-specific weather forecast services. In the eastern Canadian offshore these services are provided by private corporations catering specifically to this need. These firms are required by regulation, to have personnel trained to AES standards. All of the agencies involved are therefore tightly linked and the forecasts they deliver are highly similar. Prognoses are based on the same cascade of information from within the AES organization, and they approach weather forecasting using the same meteorological principles and equipment.

Despite the fundamental similarities among forecasts, the presentations offered by private versus AES sources do differ. The private forecast firms have tended to adopt rather scientific formats for presenting wind and sea state parameters as a function of lead time in six-hour increments. It is tempting to ascribe an "observational" accuracy to these predictions, and to treat them as being more accurate than they really are. As shown by verification results on quantitative element forecasts for storms (wind, sea state, visibility) there is a gradual reduction in forecast ability up to 24 hours lead time that then steepens to become a major decline after 48 hours. As a result there is considerable uncertainty associated with the long-range parameters, especially at lead times greater than two days, which must be taken into account in the use of these forecasts to make decisions controlling offshore operations.

The meteorological and sea state parameters or elements that presently form the basis of forecast data are: wind speed and direction, sea wave heights and periods, temperature, pressure, visibility, and freezing spray. These parameters are presented in descriptive and/or numeric terms to cover an area or a point in the ocean, at regular increments of time or valid periods which are usually 6 or 12 hours apart.

■ *CONTENT* The information level of current forecasts is very low when one considers how much prognostic data have been distilled to produce them. One example of how the information content could be increased relates to wave spectra. Sea state parameters are usually specified as a wind-sea and two swell components. These are added up to give a "combined" sea wave height, period, and direction. There are no parametric hindcast procedures which truly model the physics of old swell seas, and to date, large-scale discrete spectral wave models, which would approximate the propagation of swell components, are not used in Canada for wave forecasting. Therefore, the two forecasted swell components are largely meaningless and about the best one can do is interpret the combined sea height as roughly equivalent to a significant wave height averaged over the valid time of the forecast. Thus the sea state forecasts issued by private firms actually contain the equivalent of one wave height and period, and a rough indicator of direction to represent a given location at sea. The maximum wave height is just a statistical extrapolation of the first value and does not increase the information contained in the forecast. This prognosis is updated every six hours. During a storm these are the minimum data requirements for assessing the expected motion of a floating drilling vessel. A more reliable motion analysis would be obtained from predicted wave spectra computed with two-dimensional models on a one-hour time step. Such spectra would resolve crossing seas and rapid changes in wave growth as the storms peak over specific locations. Thus the presentation of spectra, properly computed as opposed to wave height and period would provide a significant increase in the information contained in sea state forecasts.

Other limitations in content of current forecasts are a result of gaps in available forecast technology. For reasons based on the sparseness of observing points over the ocean and incomplete understanding of atmospheric physics, forecasts deal with changes in weather on synoptic scales, over distances exceeding 200 to 300 kilometres and durations of 2 to 3 days. Smaller mesoscale events, occasionally producing the most severe, albeit short-lived conditions, are not encompassed in the preparation parameters. Increasing the information content and thus effectiveness of forecasts by, for example, including wave spectra or mesoscale atmospheric processes, would involve fundamental changes to present data acquisition and presentation techniques.

■ *PRESENTATION* Forecasts are presented in a very rudimentary manner with all parameters given equally for the same lead times, and transmitted over telecopier circuits or broadcast. For users receiving analysis charts and satellite imagery over photo-facsimile machines, prognoses can be supplemented with current information on the spatial structure of weather systems. There is little use of colour graphics displays showing two-dimensional prognoses blended with observational data such as satellites and weather radar images. A computerized system of forecast dissemination, given present-day transmission capabilities, would make it possible, for example, to show the dynamic behaviour of storm systems in the past and projected into the future, to isolate and predict some small scale events within them, and to present both area and site-specific forecasts rapidly and interchangeably. This procedure would allow short lead-time prognoses with detailed information to be sequenced with longer lead-time, less detailed presentations.

■ *VERIFICATION* Verification of marine forecasts given by private firms is a well established procedure which provides a great deal of information about forecast quality. Current programs, however, tend to be statistical and remove the connection between storm history and the nature of forecast errors for severe events. Routine verification of forecast performance using time series analysis techniques to show the relationship between magnitude and timing errors would also be of value. Useful, too, would be an analysis of the consequences of various kinds of missed events on offshore operations, for example the storm peak predicted too early or too late by several hours. Because forecasting is based upon manipulation of observed or forecast synoptic weather systems, post-mortem analyses of particularly difficult events, together with a formal mechanism to transfer the experience so gained to all forecast personnel, would be valuable and must receive more attention. The intent should be to improve procedures and "build in" this information.

■ *ASSESSMENT* Operator experience in eastern Canadian waters has long since revealed those adverse weather conditions that pose a threat to human safety. Two are particularly important: severe winter storms that would endanger the rig and its entire crew, and fog that makes helicopter operation hazardous. These two situations demand very different types of forecast information.

Operators require long-range forecasts of severe winter storms to carry out specified procedures for securing the well, and for securing or evacuating the drilling unit. Long-range forecasts are provided that describe weather elements including winds and sea states with sufficient lead time and resolution. The communication of information is effective and timely because of the personal briefing methods used, especially during alerts. Element forecasts beyond 12 to 18 hours, however, tend to be uncertain. This means that the prediction of whether a storm will produce site-specific winds exceeding certain thresholds is also uncertain. The practice adopted to deal with this uncertainty is to monitor the storm development, from perhaps 48 to 72 hours down to 18 to 24 hours lead time and in this way obtain the best possible estimate of the need to evacuate the rig.

The consequence of this monitoring may well be the loss of safe evacuation time for all personnel. The fall-back of leaving personnel on board the drilling unit must then be adopted. There is some variation among operators in their stated approach to this problem of how long to monitor since evacuation is both expensive and with some danger of its own, and storms producing winds exceeding 85 knots are extremely rare. Although variations from storm to storm must be expected, the situation described above is likely to represent the worst case, that of the winter storm so severe that it, by itself, poses the hazard. Even in these circumstances, however, the tactic of securing the well and the rig, and leaving personnel on board to wait out the storm is considered by the operators to be an acceptable approach to ensuring human safety. Moreover, it meets regulatory expectations for safety at a perceived acceptable level of risk. Since the weather forecasting services provide the information needed to carry out the response plans, and those, in turn, are accepted as the means of ensuring safety in storms, then the forecasting services are adequate as presently available.

■ *HELICOPTER OPERATIONS* Helicopter flight planning requires accurate wind speed and direction, and terminal visibility prognoses so that fuel and payload can be optimized while providing an acceptable safety factor on a round-trip without refueling. These forecasts are provided to the pilots by AES, using personal briefings in the presentation offices. Communication between the pilots and the AES presentation personnel is excellent. The people involved on both sides are experienced in weather needs and the peculiarities of forecast marine data, and allow a margin of error in their decisions.

The timing of the weather forecast information available to the pilots presents a problem. The shift to daylight saving time in Newfoundland and the scheduling of flight departures from St. John's before 07:00 Newfoundland Daylight Time (NDT) may lead to the use of marine forecast data issued at 00:30 Greenwich Mean Time (GMT) or 22:00 NDT, instead of the more current 06:30 GMT forecast. The synoptic description, and the wind and visibility prognoses may therefore be inaccurate. This situation could be remedied most easily by delaying departures from St. John's until about 09:00 NDT, or by improvements in data transfer to pilots at this time of day. On balance, present forecasting services are considered adequate for helicopter operations during the fog season.

■ *FORECAST ADEQUACY* The examination of weather forecasting services to the operators conducting exploratory drilling programs has shown that the needs of the industry to ensure human safety are being satisfied. Emergency response in the face of major storms, whether complicated by well, rig or ice problems, is technically and logistically complex. The facilities put in place by the industry ensure that the kind of weather forecast data needed for decisions on securing or evacuating the rig are available. Moreover, clearly defined response procedures recognize the limitations in forecast data and attempt to deal with these in the most rational manner.

The major limitation with forecast weather data is the reliability of specific elements such as wind speed or wave height. Improvements in prediction accuracy are constantly being made in national weather services in both Canada and the United States, and these will benefit industry as they come into operational use. Weather forecasting is a very complex science, involving a great deal of human experience and judgement. Agencies now providing these services are working at the state-of-the-art; there are no serious gaps between national services in Canada or the United States and the private forecasting firms contracted for site-specific data by the operators. It appears that operating oil companies are obtaining the best information available.

■ *AREAS OF IMPROVEMENT* There are a number of areas where improvements could be introduced into the system and these could be expected to yield benefits in terms of more accurate forecasts, or more confidence in dealing with hazardous weather.

Success in storm forecasting over marine areas depends on timely, accurate data. Improvements in element forecasts would be expected from the deployment of tethered buoys that telemeter pressure, temperature, and possibly wind data via satellite. More reliable short-term (up to 24 hour) forecasts over the drilling areas would result from buoy deployments in Canadian waters; this has been demonstrated by an experimental program organized by AES in the winter of 1983-84 off the East Coast. Increased accuracy in long-range storm predictions (24 to 48 hours) would also be expected by deploying buoys along the eastern U.S. seaboard; these would give earlier and better definition of weather system behaviour before it reaches Canadian waters. Parallel improvements in monitoring upper air winds would also increase the accuracy of predicted storm trajectories and hence site-specific winds. These "upstream" data would be of great value to the numerical weather prediction models that are so important for long-range prognoses.

Monitoring programs of this nature are costly and logistically complex, both for instrument servicing and ensuring that data is properly entered in the distribution network. They are probably best approached by a joint government/industry program recognizing the benefits to accrue to all marine forecast users.

Forecast presentation methods need improvement. Weather-related emergency response plans call for the active participation of the person in charge of the drilling unit and the drilling superintendent. Offshore personnel must rely on a combination of their own judgement and the weather interpretation given from shore by voice contact. Forecast data may be received on the rig in a variety of hardcopy formats. The offshore personnel must either sort through these transmissions and interpret them for a broader understanding of events to come, or rely strictly on the element forecast provided by the contracted firm, which gives a much more restricted picture. The crew often copes with this situation by expecting the contract weather observer to function as a forecaster, a role for which he generally has no qualifications.

These problems could be eliminated by upgrading presentation technology and bringing the drilling unit personnel in voice and image contact with the forecast office on shore. At a first level, existing television technology could be used simply to relay data and communications. At a more advanced stage, digital image processing and manipulation software could portray storm formation and predicted developments, and element forecasts, all interfaced with two-way communications. The purpose would be to condense information going to the rig into its most meaningful forms, and ensure consistent information flow between the forecaster, the emergency coordination office on shore and the drilling unit. It would also remove the need for inappropriate demands on the observing personnel.

During interviews with marine crews and environmental coordinators, a desire for more training was noted. This could take the form of dedicated short courses covering weather elements, sea state, ice and currents that are pertinent to eastern Canadian waters, methods of forecast preparation and dissemination, monitoring equipment and response procedures. Marine crews commented that they have some training in meteorology and waves, but that it is too general, giving a global picture rather than characteristics of a particular area. Responsible personnel within oil companies felt benefits would follow from specialist briefing in all environmental factors affecting operations.

Presently, verification at the Canadian Meteorological Centre is done on all forecasts using SI scores which provide only an averaged indication of performance. Overwater element forecasts should be verified in a time-series manner, adopting a common procedure with the private firms to establish how accurate the 24- to 72-hour forecasts are, and to identify those weather systems that are difficult to forecast with certainty. A better understanding of long-range prognoses, between AES and its users, would be one result of this process.

Consistent forecast verification procedures are lacking between private firms, and the various levels of AES. Private forecast companies could extend their present procedures to look at more storms on a case-by-case basis in time-series format. This would reveal whether errors in predicted parameters were due to poor estimates of weather system intensity, position, speed of advance, or some combination of all three. The current statistical approaches do not easily allow this type of diagnostic examination.

Currently many countries provide sea state predictions using advanced spectral models coupled to their numerical weather prediction systems. Canada does not do so, relying instead on parametric significant wave height models. Forecasting services in this country now give wave heights associated with swell and wind sea, their directions, and a combined maximum wave height. It has not been clearly demonstrated that for this level of information, the more elaborate spectral models give more accurate results. Operators, and particularly marine crews on the drilling units and supply boats have expressed a concern about receiving complex wave information that they would have difficulty understanding. In fact, the opinion was that the parameters presently available were quite adequate for their needs, being both familiar and "reasonably accurate".

Spectral sea state modelling, routinely linked to numerically predicted wind fields, is beneficial to offshore exploration, if not in extending forecast parameters now, then in terms of its other advantages. These include: a physically more correct and accurate treatment of swell; a physically more correct procedure for propagating storm waves in concert with the generating weather system (crossing sea prediction); and a climatological data base that accumulates from the analysis fields, which would extend knowledge on wave conditions into presently deficient areas. For these reasons, and for the benefits to users other than operating oil and gas companies, advanced wave generation models should be seriously considered for eastern Canadian waters.

WAVE CLIMATOLOGY

An Assessment of the State of Knowledge of East Coast Offshore Wave Climatology
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W.F. Baird, W.F. Baird and Associates
Ottawa, Ontario
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A wind-generated wave field propagating over the oceans is an extremely complex phenomenon which is not well understood and can only be described by numerical methods that involve many simplistic assumptions.

Waves are formed by a complex interaction between turbulent wind and the water surface. Their growth is governed by speed of the wind, length of time that it blows, and distance (fetch) over which it blows. There is almost no mass movement of water associated with the propagation of waves except when a wave breaks. A small object floating on the surface describes a circular path as the wave moves past; the diameter of the circle is equal to the wave height and the time required to complete the circle is the wave period. An individual wave is not permanent; it slowly increases in height and then decreases as the wave moves forward.

Locally generated wind waves do not all move in the same direction, but the directions will lie within 45 degrees either side of the mean. As waves move out of the influence of the wind that generated them, they tend to increase their period and become long crested. These waves are known as swell. The slope, or steepness, of the leading side of the wave may be steeper than that of the rear side. If the front slope becomes steep enough, a breaker forms (a mass of foaming water moving down the front face at a speed greater than that of the wave itself). In very severe sea states, waves may reach heights of at least 40 metres, periods of 18 seconds, and lengths of 500 metres. Swell waves can have even longer periods and wave lengths, but the heights will be lower.

There are many organizations associated with offshore exploration for oil and gas who have an interest in wave climate: the operator, drilling contractor, rig designer, builder, classification society, regulatory agency, consultant, and research laboratory. To get an appreciation of their particular concerns in respect to wave data, a review was conducted of published material, especially design manuals and classification society rules and standards. This was followed up with interviews and/or correspondence with organizational representatives. All discussed the need for improved or additional data in Canada. The urgency with which the data should be obtained depends on the location under consideration, the type of structure and the responsibilities of the organization. None of the design, classification or regulatory agencies identified any limitations of existing methods for obtaining wave data, of analysing wave data, or of applying wave data to design procedures that lead to unsafe structures, structures that are significantly overdesigned, or problems with operation of these structures. Research and development in the area of wave measurement and prediction, and wave-structure interaction is continuing but without a sense of urgency.

The best achievable values for the maximum wave height and its associated period to be expected in a given return period, typically 100 years, are needed to determine the motion response of structures, the stresses produced in their components, and the maximum crest elevation to provide for underdeck clearance. In the analysis of fatigue in rig components, it is necessary to have bi-variate frequency of occurrence, that is, scatter diagrams of typically significant wave heights and peak periods by direction. Twenty years of records may be necessary. Similar data but based on shorter periods (three to five years) provide for exceedance and persistance statistics and other criteria which are essential to operational planning. All of these statistical descriptions of typical or extreme sea states are essential inputs to modelling studies whether by computer or wave tank.

■ *INSTRUMENTALLY MEASURED DATA* Extensive measurement of waves has been undertaken in eastern Canada since 1970 primarily by the Marine Environmental Data Service (MEDS) of Fisheries and Oceans Canada. Much offshore data has been acquired through cost-shared programs between MEDS and the oil companies operating the drilling units. The instrument used is the Datawell Waverider Buoy, which consists of an accelerometer housed in a floating sphere that is tethered with a single point mooring. The standard products for each location are the significant wave heights, H_s (the mean of the highest one-third of the waves in a record), and the peak period obtained at 3-hour intervals when H_s is less than 4 metres and every 20 minutes when it is greater than 4 metres.

Waverider data have a number of limitations. For offshore eastern Canada, the area covered is limited to drilling sites already occupied and the length of record at each site is too short for reliable statistical estimates of extreme events such as the 100-year significant wave height for which a minimum of 20 years of data is desirable. There are few winter records as yet. Waverider data is of limited value for certain engineering applications where the shape of wave is important because the restraining effect of the mooring results in a distorted record of the surface profile.

Notwithstanding these limitations, the data from this instrument is invaluable for many applications. It has been virtually the only source of objectively measured, site-specific information on waves continuously recorded over months of time and, most importantly, providing coverage of storm events.

There are firm requirements for instrumentally recorded data on wave direction and wave amplitude. Only since 1983 has a buoy that records both parameters been in use, on a trial basis. It will be a long time, at least 20 years, before data from this directional buoy can be used to estimate extreme probabilities. In the short term, these records can provide a check on the accuracy of a hindcast model depiction of a storm event including, in particular, the wave directions at a site.

Remote sensing techniques have been used to measure waves from satellites and aircraft. These techniques are even more recent than the waverider measurement program, and the time series are, therefore, shorter. The techniques involve the use of laser altimeters, scatterometers, and sophisticated radars. To date only the satellite-borne laser altimeter, which produces a wave height value, has been proven capable of providing accurate results on the continuing basis required to develop climatological data sets. The first and as yet only satellite to carry a wave-sensing radar was Seasat launched by the U.S. National Oceanic and Atmospheric Administration (NOAA) which operated for just three months. It produced worldwide coverage of significant wave height. Selected wave data from Seasat have been acquired by MEDS and evaluated against measured waverider data for the times and locations where coincidences of measurement occurred. The results indicated the Seasat data were accurate to within ten percent, suggesting that similar data from future satellites would be valuable from a wave climate perspective given sufficient spatial and temporal coverage. Several satellites including the Canadian Radarsat, carrying among them a variety of sensors for measuring waves, are planned for launch toward the end of the decade.

■ *VISUALLY OBSERVED DATA* Observations of wave conditions as well as meteorological phenomena are routinely reported from many ships at sea. The wave observations are a visual estimate of the average height and period of the larger well formed waves, roughly equivalent to the significant wave height and period. This data is reported by radio to the appropriate meteorological service, in the case of Canada to the Atmospheric Environment Service (AES). The program has resulted in a data bank extending back many years and covering much of the eastern Canadian offshore. It is the basis of an 11-year wave data set called METOC.

■ *METOC DATA* METOC is derived from significant wave charts prepared twice daily by the Canadian Forces Meteorological and Oceanographic Centre in Halifax. The charts are prepared from ship observations supplemented with real-time waverider buoy data from exploratory oil rigs and coastal locations and data derived from simple hindcast procedures for areas where no real-time data are available.

The METOC wave data cover the North Atlantic Ocean between 25 degrees north latitude and 70 degrees north latitude, excluding the Gulf of Mexico, Gulf of St. Lawrence, and Hudson Bay. The quality of this data set can be considered to be higher than that of the ship observation data from which it has been prepared because of the subjective quality assessment carried out. The analysts compare observations from nearby ships to identify errors and use the previous chart and hindcasting monograms to assess individual observations and fill data gaps.

There are two applications for METOC data. The first is the determination of the wave climate for operational concerns, two examples are that waves would be larger than a given height for 30 percent of the time in February, and that once the waves exceeded 6 metres at a given time of year, they persisted above that height for 36 hours on the average. In areas where there have been sufficient ship reports over the years and throughout the seasons of the year, the METOC data is good for this sort of application. The second use of METOC data is in estimating return periods for extreme events. This process depends on the accurate determination of peak wave heights for all the most severe storms. The METOC data is not as reliable for this application as a carefully prepared hindcast which is a more sophisticated procedure relying on more detailed and accurate historical data sets.

■ *NMIMET DATA* NMIMET is a suite of computer programs developed at the National Maritime Institute (NMI) in collaboration with the U.K. Meteorological Office, for the purpose of synthesizing statistics of wave climates from visual observations of wave height and wind speed, or wind speed alone. In NMIMET a parametic model of the joint probability of wave height and wind speed is used as a best fit function for smoothing and enhancing the quality of the ship observations of waves. Implausible observations are thus suppressed without subjective intervention. The NMIMET procedure has been extensively assessed against measured data in the vicinity of the United Kingdom. The results there were good for the exceedence of wave heights. NMIMET data for three locations in the study area – the mid-Labrador Coast, near Hibernia, and in deep water off Sable Island – gave the following values for the 100-year significant wave height: 14.2, 14.5, and 17.0 metres respectively.

■ *HINDCAST DATA* The wave climate of any body of water, can be described to a reasonable degree of accuracy if the wind field over the water and its time history are known. This is known as hindcasting. Ideally, the calculation requires a numerical model that simulates the physical processes of wave generation by wind, wave growth and propagation, and the interaction of waves with other waves, currents, and the seabed.

There are two categories of models. The simplest models represent an empirical approach that provides an estimate of the significant wave height and period, or similar parameters, and does not deal in depth with the physics of the problem. The other category includes the spectral models that describe the sea state by a directional variance spectrum. These models may include equations that deal with the spectral energy balance and the transfer of energy between wave periods (wave-wave interaction) and generally involve far more complex computing than empirical models do.

In the simplest models, the wind velocity is assumed to be constant over the generating area, while in the complex models, the wind velocity is input at grid points. The accuracy of the latter is partially dependent on the size of the grid and the time interval between the wind velocity data. The wind data for the grid are determined from pressure gradients, although in some instances, these may be blended with wind measurements obtained by other means.

The U.S. Navy Fleet Numerical Oceanographic Center has produced a 20-year hindcast of the North Atlantic, using their spectral ocean wave model (SOWM). Although this model produces good descriptions of wave climate in the open sea it has two serious faults when applied in the study area. It models the shoreline far to the west of its actual position resulting in unrealistically long fetches for westerly winds. Also, it does not take pack ice into account, so again fetches are too long for winds blowing off the ice. Both faults lead to significant overestimation of wave heights. The SOWM model cannot be considered applicable to the study area.

A wave information study (WIS) for eastern North American coastal waters has been done by the U.S. Army Engineers Waterways Experiment Station covering the same period of time (1956 to 1975) as the SOWM study. It appears that the WIS hindcast benefited from some of the limitations of the SOWM study and the use of a new wave prediction model. The WIS model, however, also doesn't define the shoreline in the study area well enough and doesn't allow for ice. It, therefore, overestimates wave heights, although not as much as the SOWM.

The Oceanweather Inc. hindcast for Mobil Oil Canada Ltd., prepared in 1982, determined the extreme wave conditions required for design of structures for the Hibernia area. This study used a smaller grid than the WIS model thus providing a better definition of the shoreline; took into account the effect of pack ice, when present; selected storms over a longer period (30 years instead of 20); and generally improved input wind data. The result of this process was the development of the best hindcast to date in the study area. Nevertheless, there is a question about the selection of storms used in the hindcast. Since some of the storms used appear to be less severe than the "one-year" storm and since 20 storms were selected from a 30-year period, there is doubt about whether the most severe storms were used.

The Oceanweather Inc. study was verified by comparing the results of the hindcast with waverider data for two storms during which the instrument was in operation. The model predicted a maximum significant wave height of 11.3 metres for one storm and 8.9 metres for the other whereas the corresponding values from the waverider records were 10.1 and 8.7 metres. The hindcast gives a measure of the large spatial gradient in wave climate eastward from Newfoundland; the 100-year significant wave height is shown as increasing from 13 metres near the coast to 16 metres some 200 nautical miles to the east. For the vicinity of Hibernia, the most appropriate value for the 100-year return period maximum wave height was found to be 30 metres, with an associated period of about 16 seconds.

A hindcast done in 1978 for Total Eastcan Exploration Ltd. produced data for four points spaced evenly along the Labrador Shelf. The 100-year significant wave heights ranged from 13.5 metres in the north to 16.3 metres in the south. The major limitation of this study is the small sample of seven years from which extreme events were estimated.

■ *EXTREME VALUE ANALYSIS* Extrapolating time series of a given parameter, to estimate the largest value that parameter is likely to take in a given period of time, is a major theoretical and practical problem. There are two types of procedures in general use today. One fits a statistical distribution function to all observed values in a time series. The log-normal and Weibull distributions are the most frequently used for estimating wave heights. The other type is concerned with the statistics of extreme events in the time series. Observed large values are selected and, typically, fitted to a Fischer-Tippett type I, II or III distribution. In the case of waves, it would be observed storm waves that are selected for the analysis. The underlying objective of the use of extreme value distribution is to develop a description of the total population of all storms (waves) and then reliably estimate the magnitude of the maximum storm wave which should occur in a specified interval of time, for example, once every 100 years.

For the Scotian Shelf, reliable data describing severe storms do not exist but a study supported by the Environmental Studies Revolving Funds (ESRF) is in the process of defining the 30 to 50 most severe storms that have occurred over the area. Studies have also been undertaken to identify procedures for treating wave propagation in shallow water areas such as exist on the Scotian Shelf. Special problems of the Scotian Shelf include shallow water effects, sheltering due to Sable Island, and possibly wave-current interactions.

There has been more work done on the prediction of extreme events on the Grand Banks and particularly in the Hibernia area than anywhere else in the study area. The Mobil hindcast provides the only data that should be considered for extreme value analyses at this time. The questions on the selection of storms in the study should be addressed, and it would be desirable to undertake additional verification of the procedure before the design values are accepted. The ESRF storm identification project will assist in answering at least part of this question. Special problems in this area include the presence of the ice edge and possibly the effects of bathymetry on extreme wave conditions. An in-depth analysis of the effects of bathymetry and currents on extreme wave conditions is required.

There is considerably less information for describing the wave climate of the Labrador Sea than for the southern parts of the study area. The SOWM model must be discounted as a source of wave climate information for the area. The WIS data were not archived for the Labrador Sea north of 53 degrees. The METOC data are probably adequate for operational concerns during the summer-fall seasons when reasonable numbers of ships' reports are available. The most carefully executed analysis for extreme events appears to be the Total Eastcan hindcast; it must be used with caution, however, because only seven years of storms were treated. It would now be possible to undertake a significantly improved hindcast because there are considerable more data than were available in 1976. The ESRF storm identification project should be a start in this direction.

The Gulf of St. Lawrence has been the subject of only one hindcast study and that was for the limited purposes of the Gulf Corrider Project. The data should be of some value in planning and conducting operations but of very limited use for the estimation of extremes. Nevertheless, the wave climate of the Gulf is clearly less severe than that of the open ocean parts of the study area.

There are no measured data and no satisfactory hindcast data for Davis Strait, Baffin Bay, or Lancaster Sound. The wave climate is less severe in these northern areas than in the Labrador Sea because of the presence of ice and the limited fetch available in most directions for wave growth.

■ *SPECIAL STUDY AREAS* The techniques of wave climate estimation discussed so far assume deep water and thus do not take into account the effect of shoaling on wave characteristics. At a depth of about 100 metres the largest waves begin to undergo transformation involving their height, length, period, speed, and direction. These effects are felt by progressively smaller waves or the water shoals, and they become particularly significant where water depths are less than 50 metres. The Grand Banks and Scotian Shelf have a number of areas shallower than this. An outstanding example is the Venture site where the water depth is only about 20 metres.

The modelling of the transformation of waves moving into shoal water is at an early stage of development and it suffers from the poor state of knowledge about the physics involved. Existing models describing the process are either unverified or verified with limited data applicable in special circumstances. There are no available reports of an analysis of the wave transformation process for any location in the study area.

A number of possible wave characteristics are recognized as having the potential to produce motion or stress responses in a structure that are significantly different from those estimated to occur using analysis procedures with standard wave characteristics. These non-conventional wave events, include non-symmetric wave geometry, breaking waves in deep water, wave grouping, and "freak" waves.

There is evidence of wave assymetry from wave recordings; the average slope on the leading side of a wave is steeper than that on the following side. The steepness on the leading side may be greater than assumed in design procedures and has the potential of producing larger loadings when the wave interacts with a structure.

Breaking of waves in deep water is a manifestation of strong non-linearities of the free surface boundary conditions and is one of the least understood aspects of water waves. Wave steepening and breaking is known to result where waves move into an opposing current and also when non-linear interaction of several waves in a train occurs.

Wave grouping can be observed in many wave records. The larger waves are grouped together rather than being randomly dispersed within the wave record. It has been demonstrated that some structures respond differently to the two wave trains (one with the larger waves grouped together) even though the average or significant wave height for the two records may be the same. The effect is due to two phenomena – a group set-down under a wave group and an associated set-up between groups which leads to the formation of long waves which can excite structural response. This is important in shallower water. The successive occurrences of several large waves leads to excitation frequencies which are related to the group repetition frequency rather than the wave frequencies. This is important for large structures.

The words "freak", "rogue", "episodic", "abnormal" are used to describe very large waves that are occasionally encountered at sea. There are many reports of ships being damaged by them, but there is no theoretical basis to describe their frequency of occurrence. In the presence of a horizontal current gradient, refraction of waves can result in a concentration of wave energy. This can combine with wave steepening that occurs when the current and wave direction are in opposition to produce extremely rough conditions. Many of the ship reports of "freak" waves have occurred in areas where strong ocean currents exist. A notorious area is located near the edge of the continental shelf off southeast Africa where the Agulhas current moving strongly southward and large waves from the southern ocean travelling northward interact to produce very damaging seas. An analysis of wave interaction with currents that may occur in the study area and the possible consequence of increased wave heights has not been published.

The most serious limitation to research into non-conventional wave events is the lack of prototype measurement of them, that is, a measurement which records their characteristic features with precision and in three dimensions. Rectifying this calls for a program of measurement which should emphasize the following: point measurement of surface profile from a fixed location, as complete a description as possible of directional wave characteristics, continuous recordings during storm events, and mapping of the sea surface at an instant of time (as might be obtained from stereo photography).

■ *CONCLUSIONS* In summary, the minimum requirements of the design, certification, and regulatory agencies are well defined in the available literature. Industry is, in general, satisfied that if these requirements are met, safe, efficient, and effective structures can be designed and operated. The authors have found no evidence to suggest the opposite.

For operational purposes, three to five years of simultaneous measurements of wave, current, and wind conditions are needed. For design purposes, a hindcast of wave conditions during all storms for which reliable meteorological data exist is necessary to define the wind field adequately. These data should cover a minimum period of 20 years.

These required data are not available throughout the study area. Adequate estimates of the wave climate for operational concerns exist only in some of the southern areas. There are no values of extreme wave conditions for any part of the study area which can be accepted without further analyses. The values produced for the Hibernia area in the Mobil Oil hindcast appear to be the best available at the moment, but it only estimates extremes and not wave climate and it is limited to a small geographical area. Much of the complex data required by research organizations has not been acquired because of the extreme difficulty in measuring the necessary parameters or because suitable instrumentation is not available.

Wave data must be developed in the near future that will be suitable for the accurate estimation of extreme conditions in selected parts of the study area. The urgency of this requirement in the case of exploratory drilling may be somewhat less if units having unlimited class are used or if conservative assumptions are made. In the case of production facilities designed for the wave climate at the location where they are to be used, this requirement is of the highest priority. It could best be accomplished through a joint program by all organizations requiring the data.

Wave models are needed which are capable of describing the behaviour of waves in shallow water and the interactions of waves with currents. These should be subject to verification of field observations from sites in the eastern Canadian offshore. Further development and field testing remains to be done on instrumentation to measure the directional properties and profiles of waves.

Satellite-borne systems of remote sensing will be an important source of wave data in the future. It is important that progress in that field be monitored and that suitable actions be taken to incorporate the data into wave programs as soon as it becomes advantageous to do so.

Simultaneous measurements of waves, currents, and winds are required in areas where drilling programs are concentrated. Wave data collected with corresponding if conservative assumptions are then made. In the case of production facilities designed for the wave climate at the location where they are to be used, this requirement is of the highest priority. It could best be accomplished through a joint program by all organizations requiring the data.

OCEANOGRAPHIC INFORMATION

Oceanographic Information for the Eastern Canadian Offshore: Adequacy for Exploratory Drilling
Seaconsult Limited
St. John's, Newfoundland
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Currents in the sea may affect drilling operations by increasing loading on the rig, interfering with downhole or diving operations, transferring sediments, and increasing or decreasing wave steepness. The dominant characteristics of currents are variability and the multiplicity of space and time scales over which they occur. At the largest scales and longest periods (several tens of kilometres and days to months) the important influences on sea motion are seasonal changes in weather and runoff, and variations in topography. At slightly smaller scales, storm winds, meanders and eddies all contribute to displacing and changing the large-scale currents that affect a given site. At scales of a few tens of kilometres and periods of a few hours to about one day, tides and storm-generated surges are present. Both bathymetry and local stratification play major roles in modifying these flows. At the smallest scales, of a few hundred metres and a few minutes in time, internal waves account for most of the fluctuating motion. In places these waves may have very large amplitudes and generate strong currents.

Instruments, analytical techniques and some predictive models are geared at resolving and explaining some but not all of these scales. This situation affects two aspects of the problem. First, in order to estimate extreme currents, one must be able to predict how variations, ideally over all scales, combine to give the worst flow condition at a known probability of occurrence and with some acceptable confidence. Second, environmental conditions which may threaten human safety during such normal operations as diving or handling underwater drilling components, are often associated with rapid and localized phenomena. It is precisely those phenomena that are poorly measured and among the least predictable at present.

■ *PARAMETERIZATION AND MEASUREMENT* In describing ocean currents and water masses, basic physical parameters (speed and direction at a point, temperature, salinity, and density) have always been used in modern oceanography. These are entirely appropriate because they are fundamental to a dynamical understanding of currents, and are with the exception of density, directly measured in the ocean. Sensors have been developed to measure these parameters accurately, and the instruments and mooring techniques now used in offshore waters are adequate for most purposes.

Regulatory guidelines have dictated the use at drilling sites of 3 current meters distributed over the water column at 20 metre depth, mid-depth and near-bottom, usually 20 metres above the seabed. Much available data has come from moorings placed by offshore operators. In shallow areas (less than about 100 metres depth) 3 meters may give adequate vertical resolution of currents. In other areas, for example, along the Labrador Shelf, this scheme may not be satisfactory as the spacing between the meters may bracket core currents. Frequently, the description provided by these data of wind-driven currents and internal wave motions will be unsatisfactory for verifying predictive or interpretive models. Instrument deployments that are rationalized for dynamical oceanographic needs and take existing knowledge into account would lead to more useful data.

Instruments for detailed sampling of temperature and conductivity over depth are fully developed. They provide data on vertical density stratification essential to the prediction of wind-driven current extremes. Regulatory guidelines do not require collection of these data in conjunction with current meter deployments by industry. This is a serious shortcoming in these measurement programs since the absence of this data greatly limits interpretation and modelling.

■ *ANALYTICAL TECHNIQUES* The purpose of data analysis methods is to produce valid observations from instrumental records, and to separate motions into components that can be explained by various forcing mechanisms. Included in this latter category would be techniques to reveal those characteristics of the flow resulting from the interaction of waves (for example, tides) with the bathymetry. This is an area, tied to predictive models, of extremely active research in the oceanographic community. New procedures may be expected to come along regularly. There is no evidence to suggest, however, that present analytical methods are inadequate for data being collected in Canadian waters. Problems that exist have more to do with what data are collected, and where, than with the processing methods used on them.

■ *PREDICTIVE TECHNIQUES* Statistical methods for deriving extreme currents rely on having a long time-series of data. Ideally these are directly measured current data at a sufficient number of depths over the water column to define a velocity profile. Alternatively the current data could be hindcasted using empirical or deterministic models but there are limitations imposed by the quality of the wind data and by the models themselves. Rules for how long the time-series should be are lacking. This problem was examined in Davis Strait and it was found that errors in mean flow estimates would be about ±50 percent (±10 cm/s in 20 cm/s) for the 60-day records there. To improve this estimate significantly, about 3 years of continuous sampling would be required, but to achieve a ±10 percent error in the variance of the mean flow (important for estimating extremes) about 28 years of data would be needed.

These conditions are not fulfilled anywhere in eastern Canadian offshore waters. For only one area near Hibernia are there approximately three years of data. Even there, the data were collected at slightly different locations and while one expects the current differences to be small, differences must necessarily exist and have some influence on the accuracy of the predicted extremes. Moreover, the quality of instrumental measurements improved with time so that the data base has uneven accuracy.

■ *TIDAL CURRENTS* In general where there are 30 or more days of measured currents (hourly or more frequent sampling) tidal currents can be predicted by the harmonic method. Since most instrument deployments are longer than 30 days, estimates of maximum tidal currents that are likely to be adequate for rig evaluation and drilling operations can be made at the measurement locations. The accuracy of these predictions has yet to be established, however, and this limits confidence in the extremes.

A more serious problem arises when attempting to interpolate tidal currents between measurement sites. The bathymetry of the continental shelves and the coastal landforms produces strong spatial variations in tidal flows (for example, the area surrounding the mouth of Hudson Strait where tidal flows exceed five knots). These effects can, in principle, be calculated using numerical hydrodynamic models given tidal water level variations along the model boundaries. Water level data at strategic deep-sea points are lacking over most of the study area. Exceptions include the extreme southern Scotian Shelf and the Grand Banks which are the focus of a recent data collection program.

It appears, then, that predictions of the magnitude and timing of maximum tidal currents at specific data locations can be made with reasonable accuracy. Because data points are clustered and spatial variations in tidal flows can be strong, interpolating site-specific data will be difficult. Deterministic models offer the potential to do this with reasonable accuracy; to date, however, this type of modelling has not been carried out and is constrained by lack of deep-sea water level data.

■ *WIND-DRIVEN CURRENTS* Wind-generated current extremes can be estimated using statistical models, or deterministic models forced by 50- or 100-year return wind histories. The first method requires that wind-driven currents be isolated from measurements, which is possible with present analytical techniques, and that the records span many years. This latter condition is not met by records in the study area.

Deterministic modelling driven by a time-series of local wind stress at the sea surface has the potential to provide good current predictions if the density stratification giving rise to the maximum response can be specified. In principle this is possible from the water property data archived by the Marine Environmental Data Service (MEDS) in Ottawa, although there may be some uncertainty introduced by the interpolation over depth. The second requirement is for field data to calibrate the models. These data are available over the Hibernia area, and the Scotian Shelf around Sable Island, where they have been measured with proper vector-averaging current meters. Elsewhere calibration data are few.

Empirical models based on the multiple coherence between wind and measured currents have the potential to greatly extend the measured data base by hindcasting currents from long-term wind records. These methods have not been applied to any location within the study area, but could be with a reasonable chance of success for Hibernia and some sites near Sable Island.

■ *RESIDUAL CURRENTS* Low-frequency background currents produced by density variations and seasonal changes in the surface wind stress distribution can only be predicted with confidence using statistical models based on time-series measurements; again, the requirement is for multiyear data sets, which are not available. Spatial variations are also large, depending on bathymetry and topography; thus interpolating between measurement sites is extremely difficult. Regional maps of geostrophic currents do exist for many areas of exploratory interest but these provide only the roughest guide as to where major currents may be located and their average flow speeds. These maps are of extremely limited accuracy in the engineering sense because they account for only a fraction of the net flow, and reveal nothing about the variability of the flow, over time scales of a few days to weeks.

Residual currents cannot be neglected in the derivation of extremes. Much of Canada's eastern offshore acreage is located in or near the major ocean currents along the coastline. These include the Baffin current in Lancaster Sound, Baffin Bay, and Davis Strait with maximum speeds ranging from 50 to 80 cm/s and the Labrador current along the Labrador Coast and the eastern edge of the Grand Banks with maximums ranging from 35 to 70 cm/s. In these areas the residual currents may exceed the tidal currents away from the coastal zone. Measurements will be required to estimate extremes of speed in these areas. Three-dimensional deterministic modelling incorporating density variations and changes in atmospheric forcing could, in principle, be applied, if sufficient data to initialize and run these models were available. This, however, is not the case. Another problem is the cost of computing for models of this kind, together with uncertainties in the results due to assumptions made in their formulation. For these reasons, instrumental measurements, even for a short period, are to be considered more reliable than model predictions at this time.

■ *HIGH-FREQUENCY CURRENTS* Rapidly fluctuating currents, with periods of a few minutes to a few hours, are often disregarded when estimating extreme design currents. They are caused by such factors as internal waves near the surface or gravity currents along the sea bed, and can be sufficiently strong to disrupt drilling operations. Diving is particularly sensitive to rapid changes in current. Because large high-frequency currents are either rare or sporadic, their prediction is nearly impossible. This situation results from a poor understanding of their causes, for example, what triggers the formation of solitons in Davis Strait, and how do they propagate through the ocean. There are weaknesses with theoretical models in this area and a severe lack of oceanic observations.

Historical data have been collected (with the exception of the Davis Strait soliton work) with a view to ignoring high-frequency signals. Instruments were used with sampling intervals that were too long to resolve internal waves or they were placed too high above the sea bottom to record large currents there. It appears, however, that potentially dangerous current events are rather rare in the eastern Canadian offshore. Prediction will rely on measuring the phenomena that affect a given site, determining their frequency and periodicity if any, and using this information to anticipate the event and to schedule accordingly.

New data will be required to discover these phenomena (satellite imagery as well as conventional *in situ* measurements) and real-time data may well be needed to carry out exploratory operations. These techniques were successfully applied in Davis Strait for detecting solitons. Large amplitude internal waves have also been observed on the edge of the Scotian Shelf and tidal conditions along the Grand Banks may generate waves there. To date, though, no observations have been made of large internal waves over the Grand Banks.

■ *AVAILABILITY OF DATA* Current data have originated from three basic sources: government scientific research, industry baseline studies of a regional nature, and industry deployments in conjunction with well drilling. The last contribution is the largest. In view of the spatial distribution of data and the record durations at each location, it is apparent that no mulityear master plan has evolved that is oceanographically sensible. What is available now is a haphazard set of short-term records largely clustered around areas of active drilling or discovery. Systematic long-term measurements at locations that would delineate major currents and that would provide input data for predictive modelling, have not been undertaken. Thus it is possible to use some data for the derivation of extremes, but due to changes in instrument types and mooring locations, this exercise involves a great deal of judgement and patching together of records. Assumptions must be made about spatial variability with little hard evidence for guidance.

Regulatory guidelines for the industry have led to a policy of deploying current meters near well sites regardless of the time taken to complete a drilling program. There has been no impetus or necessity for measurements at fixed locations that would be of an essentially continuous nature. The guidelines produced data that were useful, perhaps, for answering questions about changes in proposed drilling programs on a well-by-well basis, but of much lower applicability for deriving long-term extremes. That approach was understandable in the early years of exploratory drilling but is less obviously correct in the light of recent discoveries and greatly expanded drilling in certain areas, for example, the northeast Grand Banks.

Any meaningful interpretation or modelling of ocean currents requires concurrent data on density variations over depth, and local and far-field winds. Local anemometer winds are generally available with industry data, but are seldom measured in government programs, even in terms of installing automatic shore-based weather stations. In none of the data base archives are meteorological data incorporated into the current meter records, although the data do exist and can be obtained by going to separate agencies such as the Atmospheric Environment Service.

Another serious shortcoming is the fact that conductivity and temperature depth profile data are not routinely collected with industry current-monitoring. As a result, detailed stratification data at the time and location of current measurements are generally lacking. This factor greatly constrains the interpretation of current observations, especially with respect to estimating wind-driven extremes. As with wind, stratification data that do exist are not identified and archived with current meter records. This means that dynamical studies of maximum currents must assemble data from several different sources, a time-consuming and often unsatisfactory task because of differences in identification, storage, and quality. As noted above, it seems as if no master plan or strategy oriented toward understanding currents, and the prediction of extremes of speed in response to natural forcing mechanisms, has been adopted for data collection and archiving. This argument can be extended also to wave data. The attention of offshore designers and operators is turning more and more to the joint occurrences of extremes of wind, waves, and currents. The separation in Canadian practice of how these data are measured, processed, and archived for climatological analysis makes this type of study difficult at present.

■ *CONCLUSIONS* From an oceanographic perspective there are many shortcomings in how data are collected and stored for later use, and these have a direct impact on how well design currents can be evaluated. Available data are not adequate to derive current extremes with the confidence that one normally associates with wind or wave criteria. Nevertheless, the existing data, their scientific interpretation, and industry studies have not revealed conditions that are beyond the drilling technology in use today, nor that appear to be limiting for rig design over most of the East Coast. A decade of offshore experience has also failed to turn up serious problems that could be attributed to ocean currents or extremes of temperature. The effects of waves and ice are much more serious.

One area of obvious concern is the mouth of Hudson Strait because currents there are very strong. Operational problems would be expected with spudding, BOP handling, riser design, and drill rig station-keeping. There are some data for the region collected in 1979, and industry personnel are aware of the conditions to be faced. Safe drilling in this area would demand more data than are presently available.

Also as exploratory drilling moves into deeper water along the edges of the continental shelf the role of currents may be expected to increase. One area of interest is the Flemish Pass where, because of the bathymetry, the outer branch of the Labrador current is focussed into a strong, persistent flow. Clearly the potential exists for large currents with a complex vertical structure, resulting from storm currents combining with the more permanent Labrador current. Here also more data, over many depths, are required.

The evaluation of rig performance and seakeeping ability demands that the vessel be analyzed for worst-case combined loads due to winds, waves, and currents. Traditional practice has involved adding up the individual extremes as derived largely from distinct and separate analyses of the various data types. Canadian practice has, seemingly, oriented data collection and archiving to respond to this approach. A major hurdle to examining combined events in nature is the separation of historical data in different archives, some missing data, and uneveness in quality. More detailed, data-based studies into the response of the atmosphere and ocean together under extreme forcing is desirable. This approach would lead to more rational and realistic conditions for rig evaluation in any of the operating modes (transit, survival or drilling).

If we look ahead and anticipate more offshore drilling, followed by production, it would seem logical to reorient oceanographic data collection along more rational lines than are presently followed. Essential aspects include:

- Establishing predictive techniques for current extremes, and determining data requirements for them;
- Organizing long-term strategic monitoring stations that would provide meteorological, wave, current, and water property profile measurements;
- Standardizing instrumental and analytical techniques;
- Putting all data into one archive suitable for a dynamic analysis of winds and currents, in combination with wind waves.

SEABED INFORMATION

The Adequacy of Available Seabed Information as Input to Design Criteria and Operating Constraints for Eastern Canada Offshore Exploratory Drilling
Jacques, Whitford & Associates Limited
Halifax, Nova Scotia
January 1984

Although all drilling units involved in exploratory drilling off eastern Canada interact with the seabed through their anchoring systems and well connector devices, the interaction is most significant in the case of jack-up rigs which depend completely upon the seabed and underlying materials for support. Jack-up foundation systems fall into two categories: mat (three or more legs supported by a common foundation base) and footing (three or more footings or "spud cans") each supporting an individual leg. Mat-supported rigs have been developed to operate in areas with very soft seabed sediments while individual footing-supported rigs can more readily accommodate site variability. About 75 percent of jack-up units in use today, and all those employed to date in the study area, have footing-type foundations.

■ *FOUNDATION FAILURES* Foundation preloading has been widely used as a method of proof testing jack-up rigs. Ballast is added to force additional penetration of the footings to a level where the total bearing capacity exceeds, by an acceptable margin of safety, the maximum load anticipated by the designers. For most three-leg jack-ups, preloading is accomplished by pumping sea water selectively into a series of holding tanks, maintaining approximately equal loading on all legs during the process. The preload is generally held for a minimum time of two to four hours after all footing penetrations have ceased.

The most serious hazard associated with preload is "punch-through". In certain locations the subbottom soil profile includes a strong layer of soil overlying a weaker layer. If the bearing capacity of the hard layer is sufficient to allow the unit to elevate, but not sufficient to carry the preload, punch-through will occur as a spud can (usually only one) penetrates the hard layer and plunges rapidly until adequate resistance is encountered at some lower level. The magnitude of vertical movement and resulting tilt of the rig will depend on the depth of the weak layer of soil and the height of the rig's hull above water since the footing load will diminish once the hull submerges. There is little possibility for control once punch-through begins, since the applied load cannot immediately be removed or reduced although in some cases quick action (for example, jacking down the plunging leg and raising the others) can minimize damage.

There are several geologic factors that can produce the conditions for punch-through. Available seabed data are not sufficient to predict the occurrence of these conditions, but there are recognized methods of identifying their presence at a given location.

There are other circumstances related to seabed conditions that may lead to jack-up foundation failure. There have been many instances of stability problems produced by scour on the sea floor. Scour undermines footings and reduces the depth of embedment, thus resulting in reduced bearing capacity. Depressions in the sea floor, whether naturally occurring such as pock marks, or caused by a previously installed rig, can create problems for spud cans positioned adjacent to the depression.

After a jack-up rig has reached location and raised its hull out of the water, its foundations are subjected to two types of loads, gravity and environmental. Gravity loads consist of the operational lightship weight and a variable load, and can usually be calculated within two percent accuracy by maintaining a careful inventory of equipment, materials, and supplies. Environmental loads include some combination of wind, wave, current, and structural icing and are considerably harder to calculate with any degree of accuracy. Estimates for environmental loading are based upon statistical data for each parameter specific to the site of operation.

During a storm, overturning moments caused by wave and wind forces may increase the vertical load on a footing by as much as 35 to 50 percent of the gravity load. The horizontal footing load during a storm may range from about one-tenth to one-third the magnitude of the total vertical footing load. There have been cases of excessive, uncontrolled penetration of one or more footings when storm loadings exceeded the maximum estimates established by the rig designers for preload testing.

Wave action, the most significant form of environmental loading, can produce about 55 to 65 percent of the total lateral loading with wind representing about 25 to 35 percent. Forces generated by the typical 1-knot design current amount to about 10 percent of lateral loading but in some places, like the Bay of Fundy where currents of as much as 4 knots occur, the resulting forces become much larger and hence more significant.

Jack-up foundation problems which may affect safety arise in two main circumstances: if the rig is unsuitable for the site, or if a procedural error takes place in moving the rig on or off location or during jacking operations. Accident reports suggest that the first of these is the most common cause of foundation failures. A rig that is "unsuitable" in this context could be one with insufficient leg length, or a footing area that is too small to avoid punching through a hard layer. In order to choose a suitable unit for a site, the operator must have advance knowledge of seabed conditions at the site and of how these conditions relate to the proposed unit's performance. Regional surficial seabed maps do not provide information in sufficient detail for this purpose and it is necessary to undertake site-specific and geotechnical surveys.

Some classical analytical procedures have been adapted to predict the bearing capacity of jack-up unit footings in different soil systems. Potential scour problems can be identified from boring data or geological evidence and solved by placing scour-resistent material around the edge of the foundation (traditionally sand bags, oyster shells or gravel), or by using an airlift waterjet system to achieve penetration of at least five metres below the sea floor prior to preloading.

Procedural errors such as insufficient preload, incorrect estimation of gravity or storm loads, excessive elevation of the hull prior to preloading, and improperly balanced leg loads when setting up or preparing for a storm are believed to have contributed to a number of foundation accidents. It therefore appears that better instrumentation and predictive techniques for estimating loads, and more specific attention to foundation problems in operating manuals are important in maintaining safety standards.

■ *ANCHORING SYSTEMS* The catenary anchoring systems in general use today by moored drilling units consist of chain or wire rope with sufficient length and weight to remain tangent with the sea floor even under maximum line tension. The holding capacity is predicted from the empirical relationships between weight and seabed soil type, previous experience, and extrapolations from small-scale tests. The standard verification procedure for holding capacity, proof testing by short-term static pull or drag at relatively high velocity, ignores the effect of the cyclic load component present during storm conditions, and so may not provide a realistic measure. Proof testing of heavy anchors is also impractical and costly, and this method of verification could be supplemented by holding capacity predictions based on soil mechanics principles. Development work in this direction is underway at a number of institutions.

■ *WELL CONDUCTORS* Conductor pipes and casings are used primarily for well control during drilling and are more related to down-hole considerations than to seabed conditions. They do, however, interact with the seabed materials since it is from these materials that the conductor pipe and the upper portions of the conductor casing derive their support.

The loads which conductors are required to resist include gravity loads from self-weight and well-head equipment such as blowout preventors, and imposed loads from marine risers, waves, and currents. The loads are generally more severe in the case of floating drilling units where well-head equipment is located on the sea floor than for jack-ups where the equipment is located on the structure.

Lateral and flexural loads on the conductors are resisted by horizontal soil reaction stresses. Soil mechanics procedures developed for the analysis of laterally loaded piles can be used for analysis and design. The lateral resistance of the soil near the sea floor is significant to the analysis and the effects of scour and soil disturbance on this resistance during conductor installation have to be considered.

■ *CONCLUSIONS* Available information on the eastern Canada seabed offshore is considered to be useful as a guide to probable conditions but is not sufficient to permit evaluation of their potential effects on the safety of drilling operations. Such an evaluation would require detailed knowledge and an engineering assessment of both the geological features which may occur at the site and such geotechnical parameters as soil strength and density.

Geological studies on continental shelves are directed mainly towards identifying the depositional history and distribution of materials forming the shelf deposits. These studies, despite their usefulness in other areas, do not provide the data necessary for quantifying the risk associated with drilling operations. Geophysical surveys carried out with side scan sonar and acoustic profiling systems are an essential part of the investigation of potential drilling sites and are required by the Canada Oil and Gas Lands Administration (COGLA) regulations. These remote-sensing methods provide data from which information on seabed materials and formation must be inferred. Geotechnical investigations, which are not required by regulation, involve the actual sampling and testing of the seabed materials at a proposed site; physical properties can then be measured directly rather than inferred. Methods using gravity corers, geotechnical borings, and laboratory and *in situ* testing can determine with a high degree of accuracy the stratigraphy and engineering properties of the seabed material. The most useful data source on a specific site would be an integrated study of geophysical data and geotechnical borings. This combination allows geotechnical conditions to be correlated with acoustic profiles through the boring site, and thus provides information on the probable extent and thickness of soil layers as well as on their physical properties over a considerable distance. These combined studies are even more effective if they are tied into the regional geological framework.

Existing statutory regulations applicable to the overall eastern Canada offshore do not specifically require geotechnical investigations at proposed drill sites. They thus do not ensure that the information required to quantify the risk related to seabed/structure interaction is obtained. Requiring site-specific geotechnical investigations would provide the data necessary to minimize the risks involved with offshore exploration activities.

Summary of Environment Seminar

Upon completion of draft reports on the physical environment (Ice, Wave Climatology, Forecasting, Climatology, Seabed, Oceanography) a seminar was held by the Royal Commission. Attending were authors of the studies plus a number of representatives of the Canadian Petroleum Association, Offshore Operators Division (CPA) member companies selected through consultation with the Environment Committee of CPA.

While the scope of studies addressed requirements for design as well as operations, the seminar was called to focus on the latter, reflecting the experience and role of CPA. Resource persons from Memorial University of Newfoundland, Bedford Institute of Oceanography, and the federal government (COGLA), along with members of the Royal Commission resulted in a total of 46 attendees. The seminar was organized into a number of topics corresponding to studies with each author making an initial summary presentation of their work followed by discussion. The final session ended with a round table where each participant presented concluding views.

Perhaps the most consistent theme that emerged during the discussions was the view of industry representatives that the reports presented for consideration did not contain enough input from the operational community and did not adequately distinguish, in the words of one participant, "what was scientifically desirable from what was operationally, technically, and physically feasible."

Although there was general agreement that more baseline data are needed in a number of environmental areas, concern was expressed that any new data collection programs be developed with industrial as well as scientific goals in mind. If the overall purpose of improving the existing systems is to improve safety conditions for offshore workers, then some attempt should be made to break the general recommendations of the reports down into specific instances where obtaining more or better data would lead directly to safer working conditions. General agreement was reached on the need for more real-time data dissemination, particularly in the area of ice, and on the desirability of improving the accuracy of weather forecasts. At the same time, though, it was recognized that inadequate data are often less problematic than poor understanding of user needs by the data originator, ineffective communication between the two, or an inability in terms of time or expertise for the user to interpret properly the data received. Improved training for those on board rigs who are responsible for manipulating environmental data, and automatic collection and transmission methods that minimize the time required of key personnel should result in better use of present data bases.

In the area of research and development, the priorities in terms of human safety were identified as the operation of safety and emergency equipment during harsh weather conditions, particularly icing, and improvements in ice detection techniques. Some concern was expressed about the need to distinguish between environmental data considerations related to exploratory drilling as distinct from those related to production.

Industry representatives encouraged the Royal Commission to incorporate the feedback obtained through the seminar into the study reports, and to seek more input from operational and regulatory groups wherever possible. They also suggested that the reports be amended to permit some focus on the present safety record of industry in order to provide a more balanced view of the risks involved in offshore work, and on the efforts that have already been made to assemble an industry-generated data base for the Hibernia site. Other participants cautioned against complacency and pointed out that despite the excellent safety record, the situation on the Grand Banks was still largely untested and many of the ice-related parameters were as yet poorly understood.

It was felt by a number of industry representatives that Newfoundland Oceans Research and Development Corp. (NORDCO) had overdramatized the situation in its report on the adequacy of available ice information. The present operational safety record is based on a philosophy of ice avoidance and carried out through a controlled program of detection, tracking, and deflection where possible. This ice management strategy allows for the uncertainities of present environmental data bases. Despite their general conclusion that existing ice information was, in fact, adequate to protect human safety, industry-based participants did make several suggestions for improvement. They felt that there should be a regulatory requirement that everybody involved in the offshore submit their ice information in real time to one source, and that that information be collected, analyzed and sent back to the users. It was also suggested that detection capability be improved and that a government-sponsored ice detection program be initiated. Some discussion followed on who should be responsible for regional and site-specific ice detection; emphasis was placed on current cooperative industry programs in ice detection and management and on the research efforts being funded by industry through the Environmental Studies Revolving Funds (ESRF).

Representatives of several research agencies updated the seminar on ice-related developments, and pointed out specific areas of concern. It was maintained, for instance, that small pieces of ice moving at high velocities are difficult to detect, and do pose a threat to human safety. Industry spokesmen questioned this claim and again emphasized the present safety record, current industry-sponsored programs to develop more effective radar, and ongoing ESRF programs aimed at improving ice towing and handling techniques.

The Climatology report produced by the Atmospheric Environment Service was reviewed and those in attendance were brought up to date on recent developments in climatological research. Industry representatives suggested that the scientific data needs of marine climatology are much more demanding than the operational data needs for offshore safety, and that many of the areas cited for concern in the report, do not, in fact, pose operational problems. The point was also made that the report failed to acknowledge the extensive body of climatological data being collected by industry on an individual company or cooperative basis. Delegates from AES agreed with the need to place more emphasis on the user and pointed out that the main user requirement tended to be for 100-year or extreme events. For this particular application, the present data base offshore eastern Canada is, in their opinion, inadequate.

The Seabed report by Jacques, Whitford and Associates highlights those seabed conditions which may lead to jack-up accidents, particularly punch-through. It was established during discussion that conditions which could result in punch-through do exist on the Grand Banks, although no accidents of this type have occurred to date. Considerable debate followed on whether regulations should require site-specific geotechnical investigations, including borehole programs. The author maintained that seismic studies can only lead to inferences about geotechnical properties; it is, therefore, good engineering practice to use a borehole program to determine from actual evidence whether punch-through conditions exist before locating a jack-up rig on a specific site. Scour and anchor problems were then discussed and an industry spokesman concluded that the report did not qualify many of its more pessimistic statements, and that in view of the present safety record of jack-ups, the available seabed information and the techniques in current use were, in fact, adequate.

The general conclusion of the Wave Climate study by Marine Environmental Data Service and W.F. Baird Associates is that the present data base is weak, particularly in the northern regions of the study area and that improvements in collection and forecasting techniques are desirable. Most of the discussion was devoted to clarifying technical points from the report. Industry again expressed some dissatisfaction with the lack of direct correlation between the report's recommendations and operational safety considerations and emphasized that accuracy was in many ways less important than clarifying user needs. The point was also made that while much of the data may be important to designers, the rigs operating off the East Coast of Canada are already in existence and more attention should have been paid to the capabilities of these units. The report's authors commented that there wasn't enough publicly available data to make a link between wave criteria and operational requirements.

The Oceanography report by Seaconsult was received favourably by industry, and general support was expressed for its conclusions that available oceanographic data were adequate as input into design criteria and operational safety offshore. Some discussion ensued on the archiving of data and the time lag involved in making it accessible, and support was expressed for standardized procedures. Industry representatives pointed out that many oceanographic data collection programs had been carried out by oil companies either individually or conjointly, and that these studies were not recognized in the report's review of available data sources.

The Weather Forecasting report was prepared by Seaconsult Ltd. Delegates from AES provided an update of verification procedures used by that organization and a COGLA spokesman added that they were presently undergoing a review of verification requirements for private forecasting firms. AES reported on preliminary results verifying forecast accuracy for the Grand Banks in winter, noting that AES forecasters predicted the correct Beaufort scale wind speed range only about 37 percent of the time for lead times of up to six hours. Industry representatives stressed the need for uncomplicated, standardized verification procedures, and questioned the necessity for "higher content" forecasts as recommended in the report. Seaconsult personnel explained that the concern expressed in the report regarding mesoscale phenomena related to overall improvements that were needed in forecast technology and not specifically to the offshore, where these phenomena do not last long enough to pose problems. It was agreed that an application of the report's findings to offshore operations would be useful, and the Royal Commission reported that Seaconsult would prepare a supplementary report, in consultation with rig and regulatory personnel, which would relate the findings of the first one directly to user needs.