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EFFECTS MONITORING STRATEGIES AND PROGRAMS FOR CANADA'S EAST COAST

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PREFACE

Environmental effects monitoring strategies and programs for offshore oil and gas developments are evolving continuously and are subject to review by government agencies, industry and other active interests. Researchers in this field can be expected to have a range of opinions on both the best strategy for offshore effects monitoring and specific elements of monitoring program design. The team of specialists assembled for the present study was no exception, and differing opinions were expressed during the workshop. The report does, however, convey the majority judgement on an appropriate strategy for effects monitoring and on requirements for specific monitoring projects for Hibernia and Venture.

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SUMMARY

Environmental effects monitoring strategies and programs have been conducted in conjunction with a number of offshore hydrocarbon developments in the Gulf of Mexico and the North Sea during the last decade. The recent success of exploratory drilling programs off the east coast of Canada has provided impetus for the development of environmental effects monitoring strategies and programs that consider both the environmental conditions that exist in this region and the experience gained from past monitoring efforts in other parts of the world.

For the purposes of this study, environmental effects monitoring is defined as the repetitive measurement of variables to detect changes directly or indirectly attributable to a specific development activity or to test predicted environmental changes.

The objectives of this study were: (1) to review the environmental effects monitoring programs which have been conducted in conjunction with offshore petroleum hydrocarbon developments in the Gulf of Mexico, North Sea and Cook Inlet (Alaska); (2) to evaluate the merits and shortcomings of monitoring programs conducted or ongoing in these areas; (3) to develop a complete monitoring strategy for east coast Canadian offshore areas south of the 60th parallel; and (4) to provide recommendations on specific monitoring programs to accompany development of oil reserves on the Grand Banks and gas reserves on the Scotian Shelf. The latter objective was restricted to monitoring programs that would be most suited to potential developments at the Hibernia Oil Field (Grand Banks) and at the Venture Gas Field (Scotian Shelf). As concluded in this study, adequate planning has been the greatest shortcoming of most monitoring studies conducted in the past, and far too little emphasis has been directed at this critical aspect of scientific methodology. It is clear, therefore, that the in-depth planning process required to identify the numerous specific details of sampling, storage, analysis and data interpretation of the various chemical, biological and biogeochemical measurements required for an effects monitoring study is largely beyond the scoping and strategy development objectives of this project. These details should be the responsibility of disciplinary experts and practitioners during the design of specific monitoring plans.

PREVIOUS AND ONGOING MONITORING PROGRAMS

There have been substantial differences in the objectives and scope of environmental monitoring programs conducted in the Gulf of Mexico, North Sea and Cook Inlet. In the Gulf of Mexico,

environmental effects monitoring studies have largely been fate-and-effects studies, initiated years after the development of offshore hydrocarbon resources. In the North Sea, monitoring programs have been implemented largely because of the nature of the discharges and characteristics of the receiving environment. The primary focus of these programs has been on chemical monitoring of hydrocarbons in sediments and concurrent evaluation of the effects of oil on benthic community structure. Finally, environmental effects monitoring (as defined in this study) has not been conducted in Cook Inlet because most oil and gas development occurred in Cook Inlet at a time when environmental concerns related to offshore hydrocarbon development were minimal and when the regulatory framework for review of such projects was not in place, and because the anticipated high flushing rate and dispersal capacity of this area were expected to result in minimal environmental concerns related to waste discharge.

STRATEGY FOR EAST COAST ENVIRONMENTAL EFFECTS MONITORING PROGRAMS

The primary reasons for environmental effects monitoring are to address uncertainties associated with environmental impact predictions (i.e., to test impact hypotheses) and to assess the effectiveness of mitigative measures. The environmental effects monitoring program is an integral part of the environmental management of offshore production facilities. It should recognize the certainty of a local high-impact zone surrounding an offshore production facility and concentrate monitoring efforts beyond the outer boundary of this zone. The purpose of measurements within the high impact zone is to establish the worst-case effects against which changes occurring beyond this zone can be compared. The emphasis of the program should be to detect the presence of environmentally important contaminants (hydrocarbons, persistent chemicals and heavy metals) in the sediment phase rather than the water column. If biological indicators are used, it is recommended that emphasis should be placed on sessile sediment-dwelling organisms and oriented toward individuals or individual species rather than communities. Regardless of the monitoring focus, no monitoring programs should be initiated until sampling and analytical methods, appropriate to the monitoring objectives and having a proven history of satisfactory performance, have been chosen. The use of experimental techniques should be discouraged in routine monitoring programs, although they may be a valid component of a supplemental research program conducted within or outside the monitoring program. Although environmental monitoring is intended to occur throughout the duration of a project and should influence the operation of an industrial facility, it is anticipated that the level of monitoring will decrease as the project proceeds as cause-effect hypotheses are tested and the logical conclusion of monitoring is achieved.

All monitoring programs designed for the east coast of Canada should consider a number of essential program management components including: (1) an annual planning phase; (2) integration of disciplinary activities; (3) quality control; (4) appropriate statistical approaches and use of pilot projects to refine monitoring program design; (5) proper data management; and (6) periodic external review and liaison with other researchers involved in effects monitoring programs for offshore oil and gas developments.

HIBERNIA MONITORING PROGRAM

Only limited monitoring is recommended for the Hibernia area if water-based muds are used because it has been shown repeatedly that the environmental effects of water-based drilling discharges on the marine environment are almost always short-range and short-term. Four impact hypotheses related to the release of oil-based drill cuttings and production wastes, however, were developed for Hibernia.

The initial design of the sampling strategy should be guided by mass balance calculations which will provide an estimate of the scale of disturbance. Use of a two-grid sampling system is also recommended. The sampling effort should be directed toward the detection of gradients in effects and the measurement of hydrocarbons and heavy metals (primarily barium and chromium) in surficial sediments at progressive distances from the drilling site. An absolutely essential element of the analysis program for hydrocarbons and metals includes blind replication of samples, intercalibration of methods and results, and archiving of replicate samples. Sample collection and work-up methods should be standardized to allow intercomparison of data sets. Biological sampling efforts should focus on monitoring the abundance and species composition of benthic communities around the Hibernia development. The measurement of mixed function oxygenase (MFO) activity in fish should be included in a monitoring program at Hibernia as an indicator of pelagic contamination by petroleum hydrocarbons.

VENTURE MONITORING PROGRAM

No monitoring of the marine environment was recommended unless it is expected that oil-based drilling muds will be used. In that case, a feasible monitoring strategy would involve predetermined locations for sampling on a two-grid general arrangement of sampling stations (with one grid aligned to the direction of net residual current flow) to limit the risk of not sampling contaminated areas which could occur upstream of the predominant zone of impact. The main focus and analytical methods of the monitoring strategy would be similar to those outlined for Hibernia.

RESUME

Des programmes stratégiques pour le contrôle de répercussions sur l'environnement ont été menés à bien en coordination avec un certain nombre d'exploitations offshore d'hydrocarbures dans le Golfe du Mexique et en Mer du Nord au cours de la dernière décennie. Le succès récent des opérations de sondages au large de la côte est du Canada a donné une impulsion au développement des programmes et des stratégies pour le contrôle de répercussions sur l'environnement qui prennent en compte les conditions de l'environnement existant dans cette région et l'expérience résultant d'opérations passées de contrôle dans d'autres régions du monde.

Dans le cadre de cette étude, le contrôle des répercussions sur l'environnement est défini comme étant une série de mesures de variables permettant de déceler les changements directement ou indirectement imputables à une activité d'exploitation spécifique ou de tester les changements prévisibles sur l'environnement.

Les objectifs de cette étude étaient : (1) de passer en revue les programmes de contrôle de répercussions sur l'environnement qui ont été menés à bien en coordination avec des exploitations offshore d'hydrocarbures pétroliers dans le Golfe du Mexique, en Mer du Nord et dans le Détroit de Cook (Alaska); (2) d'évaluer les mérites et les défauts des programmes de contrôle menés à bien ou en cours dans ces régions; (3) de mettre sur pied une stratégie de contrôle exhaustif pour les régions au large de la côte est du Canada au sud du 60 ème parallèle; et (4) de donner des recommandations pour des programmes spécifiques de contrôle qui accompagneraient l'exploitation des réserves pétrolières des Grands Bancs et des réserves de gaz de la Plate-forme Scotian. Le dernier objectif était limité aux programmes de contrôle qui seraient appropriés aux exploitations potentielles du champ pétrolifère Hibernia (Les Grands Bancs) et du champ de gaz Venture (Plate-forme Scotian). Conformément à la conclusion de cette étude, le plus grand défaut de la plupart des études de contrôle réalisées par le passé a été un manque de planification adéquate et trop peu d'importance a été attachée à cet aspect essentiel de la méthodologie scientifique. Par conséquent, il est clair qu'un processus de planification en profondeur, nécessaire à l'identification des nombreux aspects spécifiques d'échantillonnage, de stockage, d'analyse et

d'interprétation des différentes mesures chimiques, biologiques et biogéochimiques nécessaires pour une étude sur le contrôle des répercussions, dépasse largement le champ d'action et les objectifs de développement stratégique de cette étude . Ces aspects devraient être traités par des experts et des praticiens en la matière au cours de la mise sur pied de programmes spécifiques de contrôle.

PROGRAMMES DE CONTROLE ANTERIEURS ET EN COURS

Il y a eu de grandes différences en termes d'objectif et de champ d'action au sein des programmes de contrôle de l'environnement menés à bien dans le Golfe du Mexique, en Mer du Nord et dans le Détroit de Cook. Dans le Golfe du Mexique, les études sur le contrôle des répercussions sur l'environnement ont été surtout des études de cause à effet, mises en route plusieurs années après l'exploitation des ressources offshore d'hydrocarbures. En Mer du Nord, des programmes de contrôle ont été mis sur pied principalement à cause de la nature des déchets et des caractéristiques de l'environnement alentour. Le centre d'intérêt principal de ces programmes a été le contrôle chimique des hydrocarbures dans les sédiments et l'évaluation concomitante des effets du pétrole sur les structures communautaires vivant au fond de l'océan. Enfin, un contrôle des répercussions sur l'environnement (tel que défini dans cette étude) a été mené à bien dans le Détroit de Cook parce que la plupart des exploitations de pétrole et de gaz dans cette région ont été dirigées à une époque où les inquiétudes quant à l'environnement, relatives à l'exploitation offshore d'hydrocarbures, étaient minimes et où les limites légales pour un examen de tels projets n'existaient pas; et parce que le haut niveau prévu d'injection d'eau et de capacité de dispersion dans cette région semblait soulever de faibles inquiétudes concernant l'environnement quant aux déchets.

STRATEGIE POUR LES PROGRAMMES DE CONTROLE DES REPERCUSSIONS SUR L'ENVIRONNEMENT DE LA COTE EST

Les principales raisons pour un contrôle des répercussions sur l'environnement sont de soulever les incertitudes relatives aux prédictions de l'impact sur l'environnement (par exemple, de tester les hypothèses d'impact) et de déterminer l'efficacité de mesures allégées . Le programme de contrôle de répercussions sur l'environnement fait intégralement partie de la gestion de l'environnement pour les installations de production offshore. Il devrait identifier à coup sûr une zone locale de grand impact autour de l'installation de production offshore et concentrer les efforts de contrôle au-delà des limites extérieures de la zone. Le but des mesures au sein de la zone de grand impact est de déterminer les effets dans le cas le plus néfaste par rapport auxquels les changements intervenant au-delà de cette zone peuvent être comparés. Le point principal du programme devrait être de détecter la présence de sources de contamination (hydrocarbures, produits chimiques persistants et métaux lourds) importantes en ce qui concerne l'environnement dans la couche de sédiments plutôt que dans la colonne d'eau. Si on a recours à des indicateurs biologiques , il est recommandé de mettre l'accent sur les organismes sessiles vivant dans les sédiments et de l'orienter vers les membres ou les espèces individuelles plutôt que vers les communautés. Sans tenir compte du centre d'intérêt du contrôle, aucun programme de contrôle ne devrait être mis en oeuvre jusqu'à ce que l'échantillonnage et les méthodes analytiques (correspondant aux objectifs de contrôle et ayant une expérience réussie en termes de résultat satisfaisant) aient été choisis. Le recours à des techniques expérimentales devrait être découragé pour les programmes de contrôle de routine , bien qu'elles puissent être des éléments valables pour un programme de recherche supplémentaire mis en oeuvre dans le cadre ou en dehors du programme de contrôle. Bien que le contrôle de l'environnement doive avoir lieu tout au long de la durée d'un projet et doive influencer l'exploitation de l'installation industrielle, il est prévu que le niveau de contrôle diminuera au fur et à mesure de l'avancement du projet, les hypothèses de relations de cause à effet étant testées et la conclusion logique du contrôle atteinte.

Tous les programmes de contrôle conçus pour la côte est du Canada devraient prendre en compte un certain nombre d'éléments essentiels pour la gestion du programme, tels que: (1) une période de planification annuelle; (2) l'incorporation des activités disciplinaires; (3) un contrôle de qualité; (4) des approches statistiques appropriées et l'utilisation de projets-pilotes pour affiner la conception du programme de contrôle; (5) une gestion des données adéquate; (6) une révision périodique menée de l'extérieur et une liaison avec d'autres chercheurs impliqués dans des programmes de contrôle de répercussions pour les exploitations offshore de pétrole et de gaz.

LE PROGRAMME DE CONTROLE HIBERNIA

Seul un contrôle limité est recommandé pour la région Hibernia si l'on a recours à des boues hydriques car il a été démontré à plusieurs reprises que les répercussions de déchets de forage hydriques sur l'environnement marin étaient presque toujours sur une petite échelle et d'une courte durée. Quatre hypothèses d'impact relatives au rejet de déchets du forage pétrolier et de déchets de l'exploitation ont cependant été étudiées pour Hibernia.

La conception initiale de la politique d'échantillonnage devrait être guidée par des calculs d'équilibre de masse qui fourniraient une estimation de l'importance de la perturbation. L'utilisation d'un système d'échantillonnage à double composante est également recommandée. L'essentiel de l'échantillonnage devrait être dirigé vers la détection de dénivellations en réaction et vers les mesures d'hydrocarbures et de métaux lourds (pricipalement le baryum et le chrome) dans les sédiments de surface à des distances allant croissant à partir du site de forage. Des éléments absolument essentiels du programme d'analyse des hydrocarbures et des métaux comprennent une réplique à l'aveugle des échantillons, l'inter-étalonnage des méthodes et des résultats et l'archivage des duplicatas d'échantillons. Le rassemblement des échantillons et les méthodes de développement devraient être standardisés afin de permettre la comparaison de données. Les échantillonnages biologiques devraient se concentrer sur le contrôle de l'abondance et de la composition des espèces communautaires vivant au fond de l'océan autour de l'exploitation Hibernia. Les mesures de l'activité de l'oxygenase multifonctionnelle (OMF) sur les poissons devraient être incluses dans le programme de contrôle Hibernia en tant qu'indicateur de la contamination pélagique par les hydrocarbures de pétrole.

LE PROGRAMME DE CONTROLE VENTURE

Aucun contrôle de l'environnement marin n'était recommandé à moins que l'on ne prévoie le recours à des boues de forage pétrolier. Dans ce cas, une stratégie de contrôle possible serait de déterminer des emplacements prédéterminés pour l'échantillonnage sur une base générale à double composante des stations d'échantillonnages (une des composantes étant dans la direction du flux de courant résiduel net) afin de limiter le risque d'un non-échantillonnage des zones contaminées qui pourrait se produire en amont de la zone d'impact prédominante. Les points essentiels et les méthodes analytiques de la politique de contrôle seraient similaires à ceux décrits pour Hibernia.

INTRODUCTION

During the last few years, considerable emphasis has been placed on exploration for petroleum and hydrocarbons in the Scotian Shelf and Grand Banks regions of Canada's east coast. The success of recent drilling programs in locating and delineating potential commercial reserves of oil (Grand Banks) and gas (Scotian Shelf), has prompted the Canadian Government and petroleum industry to consider the future need for environmental effects monitoring strategies and programs to accompany offshore hydrocarbon production. Both government and industry recognize that environmental effects monitoring strategies which have been applied in existing oil and gas production regions may be at least partially relevant to offshore Canadian waters, and have therefore initiated a study through the Environmental Studies Revolving Funds (ESRF) to review these strategies and provide recommendations on monitoring options for Canada's east coast.

This report contains a review and evaluation of past and current environmental effects monitoring strategies and programs in a number of offshore oil and gas producing areas, a recommended general strategy for environmental effects monitoring on the east coast of Canada, and proposed monitoring programs for the Grand Banks (Hibernia oil field) and Scotian Shelf (Venture gas field).

The specific objectives of the study were to provide:

1) A review of past and state-of-the-art environmental effects monitoring strategies in the North Sea, Gulf of Mexico and Cook Inlet petroleum-hydrocarbon production regions;

2) A critical evaluation of these monitoring efforts;

3) A recommended strategy for environmental effects monitoring on the east coast of Canada, south of the 60th parallel; and

4) Two monitoring programs: one for the shallow waters of the Scotian Shelf overlying the Venture gas field, and the other for deeper waters of the Grand Banks overlying the Hibernia oil field.

The monitoring programs and east coast strategy were developed during a three-day workshop attended by the authors and reviewers of the study, as well as two members of the ESRF Effects

Monitoring Program Study Committee (see Appendix 1). The experience and disciplines of the participants included marine ecology, chemical oceanography, physical oceanography, and chemical and waste treatment engineering. The workshop approach was used to encourage the participants to work together in an interdisciplinary manner to produce an integrated monitoring strategy and monitoring programs.

Participants in this workshop are identified in Appendix 1.

RELEVANT MONITORING EXPERIENCE FROM EXISTING PRODUCTION AREAS

Within the context of offshore hydrocarbon production, monitoring is the study of long-term, chronic environmental effects associated with the discharge of wastes such as drilling muds, produced waters and other substances associated with routine activities of support vessels and aircraft and with other disturbances, rather than the study of effects resulting from short-term or episodic events. The purpose of monitoring is to measure effects on the environment and to analyse cause-effect relationships. Accordingly, this review does not include a discussion of research programs that have focused on the effects of catastrophic occurrences such as wellhead fires and large oil spills. Similarly, baseline or benchmark studies conducted without subsequent application to offshore petroleum field operations have not been included in this review. It should also be emphasized that, because most monitoring programs are ongoing (particularly in the North Sea), the long-term results and success of some studies cannot be fully assessed.

NORTH SEA

Environmental effects monitoring of offshore oil and gas production operations in the North Sea started during the early 1970's and increased in intensity after 1975. The Institute of Offshore Engineering (1982) completed a comprehensive review of environmental monitoring experience in this region for Mobil Oil Canada Ltd. The environmental effects of the use of oil-based drilling muds in the North Sea were also recently reviewed by a joint industry and government working group, United Kingdom Offshore Operators' Association (UKOOA 1983). However, many of the original monitoring reports related to offshore production in the North Sea are proprietary and have not been available for general review.

Overview of Petroleum Hydrocarbon Development

The North Sea is approximately 1100 km long and 180-650 km wide. The northern part of this waterbody is exposed to the North Atlantic Ocean and offers the longest fetch, although most open waters in the North Sea are high-energy environments. Fifty-year maximum wave heights range from 13 m in the south to 30 m in the north (Draper 1973, cited in Stride 1982). The seafloor is a characteristic continental shelf environment and water depths are generally less than 200 m. Most of the oil and gas fields have been developed in areas where water depths exceed 75 m. Maximum near-bottom tidal current velocities are likely about 20-25 cm/s over the finer grained sediment bottoms at 100 m depths (Stride 1982).

The offshore sedimentary environment is summarized in Stride (1982) and consists of predominantly mud facies in most offshore areas where oil and gas activities occur (particularly in the north). Sand facies are found in southern portions of the North Sea, as well as in a rough arc of 100-km radius off Aberdeen, and in a 25- to 50-km band encircling the Orkney and Shetland islands off northern Scotland. These islands are separated and surrounded by gravel facies. Gravel facies also occur in the southern North Sea off East Anglia and the southeastern English coast. Except for areas near major discontinuities, the texture of the seabed over many tens of kilometres in the North Sea appears to be more uniform (Institute of Offshore Engineering 1982) than that documented on the northeast Grand Banks of Newfoundland (Hutcheson et al. 1981; Fader and King 1981).

Oil is the predominant hydrocarbon extracted in the northern part of the North Sea. On the other hand, the southern North Sea only contains gas fields from which no condensate is extracted. Offshore facilities in the south are, therefore, small and require few staff. Most of the oil fields in the north consist of fixed offshore platforms with subsea pipelines running to onshore loading and storage terminals. The largest fields are Brent, Forties and Statfjord. In some cases, these fields have been developed with either water-based or oil-based drilling muds, whereas both mud types have been used for other fields. Diesel oil has been used traditionally in oil-based mud formulations, but mineral oils have recently replaced diesel in many cases. Since 1978, the types of muds used have influenced the choice of fields where government monitoring programs have been initiated, with recent monitoring efforts focused on fields where oil-based muds have been used.

The North Sea oil fields are relatively young in comparison to those in the Gulf of Mexico. Since most major offshore development has taken place in the past 10 to 15 years, development drilling often continues simultaneously with production activities in the same or adjacent fields. Satellite well drilling also occurs in some major fields away from the main well heads. These parallel activities result in the simultaneous introduction of all types of wastes associated with development and production to the same area from several point sources. The confounding effects from multiple wastes (e.g., oiled cuttings, produced water, ballast water and storage displacement water) have often made it difficult to attribute any measured environmental change beyond background to one specific type of contaminant.

Unlike the situation in the Gulf of Mexico, crude oil is stored offshore at some platforms in the North Sea. As a result, discharged displacement water from these storage tanks (150,000-200,000 m^3) and ballast water from shuttle tankers are additional sources of petroleum hydrocarbon input to the marine environment. However, most tanker ballast discharge now occurs in coastal waters at the onshore terminals rather than at offshore production facilities

Offshore Production Regulations

There has been no legal requirement for environmental monitoring for offshore (>48 km from shore) oil and gas operations in the United Kingdom sector of the North Sea. Oily discharges into marine waters are controlled by permits which specify maximum allowable oil discharge concentrations, based on best practicable control technology. However, regulatory control over the discharge of cuttings in offshore areas may be in place in the near future (Department of Energy 1983). Monitoring of hydrocarbons on the sea bed would then be required around offshore development and production drilling operations where either low toxicity mineral oil-based muds or diesel-based muds are being used. Government laboratories have, however, conducted numerous monitoring studies around selected offshore and inshore fields, and many operators also have undertaken monitoring studies on their own initiative. No environmental monitoring has been conducted near the southern North Sea gas fields, except at West Sole where oily cuttings have been discharged.

Norway also controls offshore effluent disposal by issuing permits based on the best practicable technology. The view prevails that detailed monitoring is needed because of the uncertainties regarding the long-term effects of continuous discharges of oily-water effluents. Operators are, therefore, required to commission independent monitoring studies around their platforms; these programs consist of baseline studies and sampling at a minimum of twice per year for determination of petroleum hydrocarbon distributions and concentrations in surficial sediments and selected biota.

General Environmental Concerns

The concerns behind the implementation of monitoring programs in the North Sea have originated from the nature of discharges and the characteristics of the receiving environment. The primary concerns have been: (1) to ensure the maintenance of the large commercial fishery; (2) to protect the general health of marine life; and (3) to determine whether or not effects that occur in individual oil fields are serious enough to warrant costly remedial action (Dicks 1982). Monitoring at the Ekofisk oil field evolved out of an awareness of the possible effects of oily ballast-water discharges from a central storage tank (Addy et al. 1978). Monitoring at the Forties field was initiated because of concerns regarding the volume of treated produced water discharged with a residual oil content averaging 40 ppm total hydrocarbons (Hartley 1979; Hartley and Cartlidge 1982; Ferbrache 1982). The widespread use of diesel-based muds and subsequent discharges of oiled cuttings have also caused concern about the fate of discharged oil and resultant effects on biota. [Oily cuttings recently have been shown to be the largest source of hydrocarbon discharges associated with North Sea oil field development (Thomas et al. 1983). This contrasts with the Gulf of Mexico where produced water has been determined to be the largest source of contaminants from offshore production (Middleditch 1982).]

General Monitoring Approaches and Objectives

The objectives of most monitoring programs in the North Sea have included:

1) Biological Objectives: To describe quantitatively the macrobenthic species, their abundances, spatial distributions and long-term dynamics; to provide comparative data for successive surveys; and to detect effects of installations on the benthic fauna.

2) Chemical Objectives: To establish the natural levels and chemical nature of hydrocarbons (and selected metals to a much lesser extent) around oil and gas production platforms; and determine the degree of and probable sources of hydrocarbon contamination around platforms.

After the identification of program objectives, a survey of waste sources has often been recommended and sometimes used prior to the design of monitoring programs (Johnston and Appelbee 1981; Dicks 1982; Johnston 1982). Such a tabulation of types and quantities of wastes then permits a refinement of program objectives and design. This approach has been used in the Forties field monitoring (Ferbrache 1982) and is identified in Shell's environmental monitoring programs (Wilkinson 1982).

Rather than monitor every field in the North Sea, the British government has taken the approach of conducting detailed studies around representative oil and gas fields (Dicks 1982). Fields have been selected generally on the basis of: (1) their represent- ativeness of an area; (2) characteristic features of their discharges (e.g., large volumes of production wastes); and (3) the types of muds used in development. Usually, sampling has been conducted over a distance of thousands of metres from platforms to account for the relatively large contaminant discharges (hydrocarbons in particular) from oily cuttings and, in some cases, ballast and storage displacement water. Major monitoring efforts have been directed at the Brent, Beryl, Forties and Beatrice Fields. As a result of the regulatory environment and monitoring objectives and approaches described above, a diverse group of monitoring programs has been implemented.

Water Column Monitoring

Sampling the water column as part of effects monitoring programs has occurred to a modest extent in the North Sea. The general conclusion has been that sampling program designs cannot address the sources of natural variability in water column parameters adequately, and hence cannot distinguish effects related to oil field operations from natural variations (Dicks 1982).

Water column studies conducted to date have encountered plankton patchiness on scales as great or greater than the positioning of pollution monitoring stations. This patchiness masks any effects that may be associated with waste discharges. Consequently, IOE (1982) and Dicks (1982) have noted the need for a thorough knowledge of local hydrography prior to the design of water column studies. This type of information has generally been lacking in North Sea monitoring programs and little emphasis has been placed on acquiring new hydrographic data during studies.

Sessile, filter-feeding animals such as mussels are used as a global sentinel of marine pollution; for example, the Mussel Watch Program (Goldberg et al. 1978). Mussels are also being used as monitoring sentinels at a few offshore oil fields in the North Sea. For example, petroleum hydrocarbon concentrations have been measured in tissues of mussels in the rig biofouling communities at the

Forties and Beatrice fields, while caged mussels have been used at the Brent Field. Mussel transplants to locations in the Moray and Cromarty firths are also being used for monitoring general environmental conditions in the region of the Beatrice Field and its storage and tanker loading terminal (Britoil, no date). However, because no original reports or data are available for review, the usefullness of this approach to monitoring could not be evaluated.

Benthic Chemical Monitoring

Chemical monitoring has been used to a large extent in the North Sea to provide an early warning of potential environmental harm. It has been the basis for most monitoring programs. This emphasis has increased with recognition of the possible risks associated with the discharge of oiled cuttings. Most studies have concentrated on measuring hydrocarbons in surficial sediments and biota, with a secondary emphasis on measuring metals. Because sediment chemistry is closely linked to the physical nature of the surficial sediments, it is desirable to know the sediment characteristics in an area to be studied before designing benthic sampling programs. However, there appears to be little evidence that this approach has been followed in the majority of North Sea monitoring programs. Only one of numerous replicate grab samples taken at most monitoring stations in North Sea studies is routinely subjected to chemical analysis. Other reviewers report that replicate variability is usually determined, and is low in uncontaminated sediments and often high in areas of contamination (IOE 1982).

The analytical approaches generally used include quantitative determination of total hydrocarbons in all sediment samples (as a screening step) with infrared (IR) spectophotometry or ultraviolet (UV) fluorescence spectrophotometry. A gravimetric determination also is used routinely for screening. Various gas chromatography (GC) techniques are used to determine specific compounds when screened samples show elevated hydrocarbon concentrations.

Most routine surveys have included analyses for normal and branched alkanes, and aromatic hydrocarbons including polynuclear aromatics. The Norwegians and now the British at Brent and Cormorant, have adopted an NPD (naphthalenes + phenanthrenes + dibenzothiophenes) or similar value as a measure of the extent of aromatic hydrocarbon contamination from diesel-oiled cuttings, rather than completely characterizing all polynuclear aromatic hydrocarbons.

In addition to the variety of instrumentation used, many different sample extraction and processing techniques have been followed in North Sea effects monitoring programs. The results of these programs have been relatively consistent, despite the lack of standardized methods. There are instances where methodologies have been changed in mid-study, without comparisons between earlier and later techniques (Massie et al. 1981; McIntosh and Ward 1982). Results between years have, therefore, not been comparable.

As noted earlier, metal concentrations in sediments or biological tissues have been measured much less frequently than hydrocarbons in North Sea monitoring programs. Barium has been measured most often, presumably because it is a major constituent of drilling muds and can serve as a conservative tracer for discharged muds or cuttings. Zinc, iron, copper, chromium, cadmium and strontium have been measured in a few instances, although interest in monitoring heavy metals has decreased in more recent monitoring programs. IOE (1982) indicates that moderate interstation variability has been observed in sediment metal concentrations during North Sea monitoring programs, probably resulting from differing silt and clay contents in sediments. Several attempts have been made to assess the role of varying silt and clay contents in determining metal concentrations in sediments, although this approach has not been followed in all programs. Elevated concentrations of chromium, copper, zinc and iron have been detected in sediments in the immediate vicinity of some platforms, but there have been only limited attempts to relate these data to metal levels observed in biota.

Less emphasis has been placed on monitoring biological accumulation of contaminants from offshore oil and gas operations than on sediment chemistry or benthic faunal analyses, which in part reflects the scarcity of larger macrofauna in the offshore sediments of the North Sea. Tissue-related work in this region has included limited tissue analyses for metals or hydrocarbons, tainting tests with taste panels, and limited determinations of the activation of tissue enzyme systems for degrading petroleum hydrocarbons. For example, taste panel evaluations of caged scallops were used to examine the oily water discharges from the Sullum Voe shoreline terminal (McIntosh and Ward 1982), although it is emphasized that monitoring at this inshore site is a statutory requirement of the British government. Considerable work on contaminant accumulation and tainting has been conducted at Sullum Voe. Limited determinations of aryl hydrocarbon hydroxylase activity in fish livers have been completed as part of the monitoring programs by the Department of Agriculture and Fisheries of Scotland around North Sea oil platforms (Massie et al. 1981).

There is an apparent lack of rigour in some North Sea monitoring programs directed at measurement of contaminants in biota. Problems noted during the present review include: (1) small sample sizes in some studies; (2) lack of consideration of seasonal and spatial variability, and organism size and condition in some assessments; and (3) the limited range of species which have been examined (e.g., no infaunal deposit-feeding animals).

Apparent shortcomings of several sediment chemistry studies conducted in this region include: (1) the lack of a statistical approach that would allow testing of the significance of spatial and temporal changes in sediment chemistry; (2) the extremely limited use of sediment cores for geochemical assessments of the chronology of deposition and diagenesis of metals and hydrocarbons; (3) the minor emphasis placed on determination of the rates of hydrocarbon mineralization by microbiota at different depths in the sediments; and (4) the fact that a limited number of monitoring reports have either evaluated the input of petroleum hydrocarbons and metals to sediments in terms of loading (input/time) or flux (input/surface area/time), or have presented comparative data on natural flux rates versus those from anthropogenic inputs.

Benthic Biological Monitoring

Extensive benthic faunal studies have been an integral part of most monitoring programs in the North Sea. A recognition by scientists of the usefulness of accumulating (sediments, sedentary biota) rather than dispersing media (water column) has been in large part responsible for the emphasis on benthic studies (IOE 1982). Studies of benthic fauna generally have been completed in conjunction with monitoring programs for sediment chemistry. A notable feature of all benthic faunal studies conducted to date in this region has been the high degree of variability in their results and interpretation.

The approach of British government laboratories to the design of benthic monitoring programs has been to arrange a number of sampling stations at various distances from the field installations so that those stations at the periphery of the field (which may be beyond the influence of the discharges) can serve as reference stations (Hartley 1982). In practice, stations have been placed along radiating transects (e.g., Ekofisk, Maureen), on grids with regularly spaced stations (Murchison, Beatrice, Buckan, Magnus) or at strategic locations usually closer to the platforms. The majority of the stations have been located within 4 to 6 km of the platforms, and between nine and 70 stations have been sampled. Most

British government programs use the radiating transect approach with the stations placed at distances of 0.8, 1.6, 3.2, 4.8, 6.4, 8.0, 16.0, and 32.0 km from the centre.

While IOE (1982) notes that the relatively homogeneous nature of the sea bottom around the oil fields in the North Sea has simplified the design of sampling programs, there are some exceptions such as the Murchison Field, where the water depth increases and sediment textures change across the field. However, knowledge regarding the heterogeneity of the bottom environment does not appear to have been considered routinely in the design of benthic monitoring programs in the region. The spatial distribution of stations has been regular rather than random or stratified; therefore, any inherent variability in monitoring parameters due to sedimentary (and depth) variability has not been taken into account in experimental design. In many cases, knowledge of local hydrography also has not been used for the location of stations.

The accuracy of position fixing can be important in contributing to benthic sampling variability, and it is uncertain how often this has been recognized in many North Sea studies. The need to obtain numerous replicate samples at designated stations and to return subsequently to these sites has been integral to North Sea monitoring programs. Positioning in many of the studies has been with radar, which has an accuracy of ±50 to 100 m during daylight hours. Navigational accuracy has been much better close to production platforms, where range and bearing can be used for position fixing. Because the scale of sedimentary variability on offshore sea beds (which is reflected in biological community structure) can be in the order of tens of metres (Stride 1982), sampling variance resulting from environmental heterogeneity can be large when the replicate sampling positioning accuracy exceeds this dimension. On the other hand, ranges and bearings to fixed reference points (i.e., platforms) or the use of satellite and laser positioning fixing systems has resulted in accuracies of ±5 m in some sampling programs.

North Sea benthic monitoring programs have almost always involved the collection of 0.1 m^2 samples. The frequency of sampling has been from once to twice per year, with many studies (including baseline surveys) lasting from five to seven years. Sampling frequency, degree of replication and the mesh sizes used for sorting macrofauna have been largely dictated by sampling objectives and financial constraints. Most benthic studies have emphasized community composition, spatial distribution, and the numbers of species and distributions of individuals among species (Hartley 1982; IOE 1982). Little attention has been directed at the dynamics of individual species.

Most benthic surveys in the North Sea have been standardized with respect to the time of year that samples are collected, with programs generally occurring between April and September. In some cases, sampling has been scheduled to avoid the heavy recruitment of juveniles that occurs in the spring and early summer. The degree of benthic sample replication in North Sea studies has been relatively high, despite high sample analysis costs and the absence of statutory requirements for monitoring. Five to ten replicates have been collected in most benthic monitoring programs initiated to date in the region.

Several types of bottom grab samplers have been used in the North Sea. In some programs, more than one type of grab has been used for collection of macrobenthos, and this has undoubtedly led to variability in the data (IOE 1978; Pearson and Eleftheriou 1981). A detailed study of the sampling performance of various grab samplers under a variety of sampling conditions has been completed recently by the Institute of Offshore Engineering.

Epifauna have been sampled infrequently with bottom trawls (usually an Agassiz trawl) in North Sea benthic monitoring programs. The information collected during these studies has been qualitative in nature, and only used to provide a more detailed description of the species associated with the sea floor.

Macrofauna in grab samples have been separated from sediments with both 0.5- and 1.0-mm mesh sieves, although the latter screen size has been used more frequently. Smaller (0.5 - 1.0 mm) individuals, usually ephemeral juveniles, are not retained on the larger mesh (1.0 mm); therefore, processing time is considerably reduced. However, small polychaetes (which can account for a large percentage of numbers of individuals in benthic communities) can be present in the 0.5- to 1.0-mm size class. In one instance, the number of additional individuals retained by the use of a 0.5-mm sieve after a 1.0-mm sieve increased by an average of 72 percent (Hartley and Cartlidge 1982). Hartley (1982) views his laboratory's use of the 1.0-mm sieve standard for monitoring programs as an effective compromise between ease of sorting and accuracy of results. A differing view, recommending serious consideration of the adoption of the 0.5-mm sieve, has been advanced by Ferbrache (1982) in a retrospective examination of three years of monitoring in the Forties Field. The use of both sieve sizes in North Sea monitoring programs has therefore prevented, or rendered questionable, intercomparisons between the data from different fields, and in a few cases, between various samples from the same field (Pearson and Eleftheriou 1981), although intercomparisons between the results obtained using 0.5- and 1.0-mm sieve mesh sizes have been completed for several studies by IOE. In addition, criteria for accepting or rejecting a particular grab sample based on the volume of sediment obtained have been used by most research groups.

The approach to interpretation of benthic faunal data in North Sea studies has been to concentrate initially on the compilation of extensive species lists, because of the concept that changes in species richness due to environmental stress are usually characterized by the disappearance of the uncommon species (IOE 1982). Once this detailed faunal characterization is complete, data are analysed usually by conventional methods for evaluating numbers of species and individuals, including diversity indices, rarefaction curves, density means and variance expressions (Gray 1981). One of the more promising and widely applied measures for assessing pollution-induced disturbance in marine benthic communities in the North Sea (IOE 1978; Hartley 1979; Hartley and Cartlidge 1982) has been examination of the degree of fit of individuals per species to a log-normal distribution (Gray and Mirza 1979). This relationship is reported to hold well for data from large, heterogeneous samples from unpolluted areas, and exhibits deviations from the log-normal distribution when there is pollution-induced disturbance (Gray 1980). However, caution in its use is necessary, because changes from the log-normal distribution were observed prior to pollutant input at the Ekofisk and Forties fields. These natural changes can result from seasonal recruitment of large numbers of juveniles to the bottom, gregariousness of certain species, and sampling bias introduced by sampling gear or treatment (IOE 1982). Nevertheless, this technique, when cautiously applied, is viewed by some workers as a useful tool for monitoring the stability of offshore benthic communities.

Approaches that have not been used extensively in this region are population structure analyses through the examination of size frequency relationships for certain species, and biomass/production determinations, although both are being used in the monitoring programs for the Murchison and Hutton fields. The first approach can be very useful for detecting changes in the populations of those species where year classes or generations are distinguishable (e.g., bivalves). Overlap of year classes or generations complicates the interpretation of data. In practice, population structure analyses are often completed on the more numerically abundant species. The second technique is hampered by high spatial variability; therefore, it has not been a favoured approach for analysis of benthic data.

Benthic faunal monitoring programs in the North Sea have been successful in detecting and describing a number of the biological effects that can be attributed to offshore oil and gas exploration and development in northern temperate open seas. A notable feature of these programs has been the large variability in results obtained between different fields. Much of this variation has been caused by natural heterogeneity of the physical environment (which could be decreased with improved program design), while part of the between-field variability can be attributed to non-standardization of sampling techniques (sampler type and sieve size).

Microbial Monitoring

The capability of sediment-associated bacteria to degrade hydrocarbons has been documented in numerous laboratory studies. Many of the monitoring programs in the North Sea have therefore included: (1) an assessment of the distribution of oleoclasts in sediments in relation to oily-waste discharge sites; and (2) experimental determinations of mineralization rates of labelled hydrocarbon compounds. British government monitoring studies in 1975 included colony counts of marine heterotrophs and oleoclasts, and showed the highest numbers of oleoclasts in the areas of greatest industrial activity. Since this approach alone provided no indication of the capacity of sediments to degrade petroleum hydrocarbons, mineralization rates of specific substrates (usually 1-^{14}C naphthalene; 7, 10-^{14}C benzo(a)pyrene; and 1-^{14}C hexadecane) were determined in subsequent surveys to indicate the potential biodegradation rates of environmentally-important hydrocarbons.

Laboratory-derived data on mineralization rates have been used to estimate the longer-term fate of petroleum hydrocarbons discharged from North Sea oil and gas production facilities (IOE 1982; McIntosh et al. 1983). Some workers express reservations about the extrapolation of the results of laboratory simulations of mineralization rates (the type of studies primarily undertaken) to field conditions (Law et al. 1982; Poley and Wilkinson 1983; UKOOA 1983). Such extrapolations may result in overestimates of field mineralization rates. Misleading results may occur when sediment subsamples containing hydrocarbon compounds labelled with radioisotopes are incubated in sealed containers, if oxygen concentrations and nutrient concentrations are not monitored.

GULF OF MEXICO

There have been three large-scale programs in the Gulf of Mexico designed specifically to assess the environmental effects of offshore petroleum production:

1) The Offshore Ecology Investigation, conducted by the Gulf Universities Research Consortium and sponsored by a group of industries involved in offshore petroleum exploration and development;

2) The Buccaneer Gas and Oil Field study, conducted by the National Marine Fisheries Service and sponsored by the Environmental Protection Agency; and

3) The Central Gulf Platform study, conducted by Southwest Research Institute (San Antonio, Texas) and sponsored by the Bureau of Land Management.

None of these programs can be described accurately as state-of-the-art, since they were completed between five and ten years ago, and there have been significant advances in offshore hydrocarbon production technology, and considerable improvement in data analysis and synthesis techniques, since that time. Nevertheless, some of the methods employed in the Buccaneer Gas and Oil Field study and the Central Gulf Platform study are still current.

The Offshore Ecology Investigation

The Offshore Ecology Investigation (OEI) was a multidisciplinary program conducted during 1972-1974. Eight roughly synoptic field sampling programs (about 10 days each) were conducted in south Louisiana, an area exposed to petroleum exploration and production for over 25 years. The goal of the OEI was "to assess the cumulative ecological effects of normal oil and gas drilling and production operations on estuarine and offshore ecosystems" (Menzies et al. 1979).

The OEI offshore study area included two adjacent platforms (about 25 km offshore in about 20 m of water), and five "control" transects: one between the platforms and shore on the main channel connecting Timbalier Bay and the sea; and four perpendicular to shore, upcurrent from the OEI platforms and 20 to 60 km away. The general types of research and studies that were completed during the OEI were investigations of:

1) Regional currents and routine hydrographic parameters;

2) Effects of production platforms on water turbidity and temperature, and on surficial sediment texture and elemental composition;

3) Concentrations of dissolved and particulate nutrients and organic carbon in water and sediments surrounding platforms;

4) Concentrations of hydrocarbons and free fatty acids at the air/water interface and in offshore sediments;

5) Distribution of hydrocarbon-degrading bacteria in relation to petroleum concentrations in sediments and water;

6) Effects of platforms on phytoplankton, zooplankton, pelagic invertebrates, fish, and benthic invertebrates; and

7) Description of the biofouling community recruited to platforms.

An executive committee (the OEI Council) was selected to interpret and condense the results of the 23 principal investigators (Menzies et al. 1974). However, the final reports of the investigators were not readily accessible until they were brought together in a single volume published by Rice University (Ward et al. 1979). There was also a detailed independent appraisal of the OEI and its earlier conclusions, as well as a re-examination of the program and resultant data using more current data-analysis methods (Bender et al. 1979). The results of the OEI are also discussed in a recent review of the ecological effects of produced water effluents from offshore oil and gas production platforms (Middleditch 1984).

Because historical data from the OEI study area were in many cases insufficient for pre- and post-development comparisons, the OEI investigators were forced to use several alternative strategies to describe pre-development conditions. It was necessary to select *a posteriori* control sites as comparable ecosystems, and investigators relied on cumulative scientific experience in other areas to draw conclusions regarding the study results.

The independent examination of OEI data also stressed that many contaminants of potential interest were not examined. The number of sediment samples collected was found to be inadequate to assess possible hydrocarbon build up or effects on benthic organisms. The absence of data necessary to reject hypotheses of synergistic effects of various combinations of trace metals or hydrocarbon compounds was also viewed as a significant shortcoming of the study.

Perhaps the major weakness of the OEI program was that most investigators did not take into account the need for statistical analysis of their data, while some investigators did not define impact hypotheses. In many cases, large-scale discharges and easily-detectable effects were anticipated by investigators; consequently, individual programs were designed such that the results were suitable only for qualitative characterizations. Replication was frequently inadequate and many investigators used non-standardized methods, thereby making statistical interpretation very difficult.

The other principal weakness of the study was a misunderstanding of the scale or rate of change of measured phenomena. Throughout the program, investigators selected experimental and control areas for subsequent comparison. A few experimental stations were designated and contrasted with others many hundreds of metres (or tens of kilometres) away. Ignorance of scale in the OEI program often led to inappropriate station location. For example, experimental stations were located much too far from the platforms to delineate changes spatially, since detrimental effects frequently cannot be documented except immediately adjacent to, or within a few hundred metres of, platforms.

Since most or all of the detectable effects of petroleum platforms are closely associated with the platforms themselves (on a scale of tens to thousands of metres), it is also of limited value to select control sites which are located tens of kilometres away. It seems probable that as the distance between two areas increases, they are more likely to differ in various features due to natural variability within the region.

Although the stated goal of the OEI was to evaluate cumulative ecological effects of petroleum development, improper or inadequate experimental design, combined with natural variability, made it difficult (or impossible) to assign many observed environmental differences to their proper causes with any degree of assurance. This was particularly the case for low-level effects such as chronic exposure of organisms to potentially toxic compounds. The sampling period (two years) also was probably too short to establish convincing baseline values for many highly variable parameters.

The re-examination of the OEI concluded with a number of recommendations for future study. While some were region- specific, others were more general and are applicable to monitoring programs for petroleum development in offshore east coast Canadian waters. They include:

1) Generating and maintaining a single, expanding environmental monitoring data base for each area to incorporate data from government, industry, and academic programs;

2) Focusing chemical contamination studies upon sediment and/or sessile biota, especially those of commercially valuable species, rather than on water column measurements or studies of planktonic organisms;

3) Conducting adequate preliminary surveys of physical and chemical parameters before selecting biological sampling stations;

4) Directing studies of chronic effects toward benthic communities;

5) Designing all studies in a statistically sound fashion, taking into account natural variability, the degree of replication required, and the use of proper controls or other unaffected areas for comparison;

6) Restriction of taxonomic identification to groups of organisms which can be identified reliably to the species level; and

7) Planning comprehensive synoptic, interdisciplinary studies to minimize the risk of misinterpreting ecological phenomena.

The Buccaneer Gas and Oil Field Study

The Buccaneer Gas and Oil Field (BGOF) study was a five-year (1975-1980), multidisciplinary examination of an active, producing gas and oil field about 50 km south of Galveston, Texas. The field had been in production for about 15 years at the time the study was initiated. The BGOF study had two general objectives: (1) to assess biological, physical and chemical changes in the environment that could be attributed to petroleum development and production; and (2) to assign any detected changes to their proper causes (e.g., specific contaminants). The study is therefore best described as a fate-and-effects program.

The Buccaneer field was particularly well suited to this type of study because of its circumscribed nature and isolation from other gas and oil fields. The field contained two large, adjacent production platforms and 13 smaller satellite structures (not all of which were active during the study) connected to the shore by a single pipeline. There was only one other offshore platform within 30 km, and few within several hundred kilometres. It was, therefore, not difficult to define control areas near the Buccaneer Gas and Oil Field.

The entire BGOF study was described in a single volume summarizing the proceedings of a public symposium (see Appendix for authors of component studies) held to disseminate the study's findings (Middleditch 1981a). The following general topics were investigated during the BGOF program:

1) Regional currents and routine hydrographic parameters;

2) Hydrodynamics, transport, and dispersion of discharges and contaminants;

3) Distribution of hydrocarbon-degrading, sulphur-oxidizing, and other heterotrophic bacteria in water and sediments surrounding platforms;

4) Toxicity of produced water to aquatic organisms;

5) Description of the biofouling community recruited to platforms;

6) Effects of platforms on surrounding aquatic biological systems and birds;

7) Effects of platforms on surficial and suspended sediments; and

8) Concentrations of organic carbon and carbon isotopes in sediments.

The review volume includes a description of a platform ecosystem model designed to simulate BGOF operations and their environmental effects, emphasizing community structure and function (Fucik and Show 1981).

The BGOF study was designed to be a long-term project oriented toward offshore production operations (Middleditch and Gallaway 1981). However, the study had a definite end-point, and was not an ongoing monitoring program. Consequently, the program followed a rapid evolutionary sequence using the findings from each year to design the subsequent year's plan. The first year of the BGOF program included a brief pilot study. The second year was a major descriptive effort, and involved comparison of control and platform areas. Intensified sampling within the BGOF occurred during the third year, to allow comparison of conditions around production platforms (sources of contaminant discharges) to those around well jackets (structures without contaminant discharges). The fourth year focused on production platforms and involved an emphasis on process studies of quantities, fates, and effects of discharged materials. There was a reduction in field efforts during the fifth year; emphasis during this year was placed on filling gaps from previous studies, and on data analysis and synthesis.

In a subsequent review of research issues relating to ecological effects of offshore oil and gas production, Middleditch (1982) commented on the strengths and weaknesses of the BGOF program. On the positive side, data sharing and compatibility were substantially improved over the OEI program, and the length of the study was adequate to characterize the central tendency and variability in most measured parameters. The use of SCUBA divers to collect samples made it possible to delineate density gradients for biological and chemical samples very close to platforms, thereby avoiding some of the scale difficulties associated with the OEI. The process studies (Gallaway et al. 1981) provided important information on the development of sessile platform biota, thereby making it feasible to include biofouling concerns in future platform design. Furthermore, several modelling efforts (e.g., Fucik and Show 1981; Gallaway and Margraf 1979) resulted in ecosystem overviews which were most useful for heuristic purposes. In addition, the importance of platforms as artificial reefs was convincingly demonstrated (Gallaway et al. 1981).

The major weakness of the BGOF study seems to have been that many of its investigators measured a very large number of parameters expecting that some meaningful trends would be evident at the end of the program. As Middleditch (1982) stated, "Invariably, this...led to unconvincing conclusions that there are no 'measurable' or 'apparent' ecological effects."

The variability in water column measurements and the high rates of contaminant dilution encountered in the OEI study were also evident in the BGOF study. Water column measurements of contaminants were only marginally useful for determining petroleum production effects more than a few metres from the discharge point. As in the OEI program, the BGOF study confirmed that measurable ecological effects of petroleum production are typically very local, and that sampling over a distance of hundreds of metres from platforms is adequate to delineate the spatial distribution of the majority of measured phenomena. (In contrast to the North Sea, where sampling to detect ecological impacts has often been conducted over a distance of thousands of metres, no oily cuttings discharges associated with the use of oil-base muds occurred at the Buccaneer field.)

Middleditch (1982) made a number of recommendations following his review of the BGOF studies. Most of the recommendations applied to future research on produced water, which was recognized to be the primary source of contaminants from Gulf of Mexico production platforms. The most general recommendation was that future studies be directed toward determination of the spatial distribution of toxic components of effluents, especially those associated with produced-water discharges. Consideration should be given also to the possibilities that some locations away from platforms may act as sinks for contaminants, or may be particularly sensitive ecologically to the effects of contaminants. Other more specific recommendations of Middleditch (1982) follow:

1) Discharge studies should determine concentrations of carcinogenic and otherwise toxic compounds (e.g., radionuclides) in produced water and in sediments, particularly polycyclic aromatic hydrocarbons, and should determine the toxicity of these compounds to aquatic organisms (preferably through in situ bioassays);

2) Water column studies should only be conducted under calm conditions when factors contributing to dispersion of contaminants are minimized. It would be desirable also to collect a large number of samples in the immediate vicinity of platforms rather than at more distant stations where concentrations are unlikely to exceed background;

3) Chemical identification of compounds should be taken to the most detailed analytical level possible;

4) Sediment chemistry should be accompanied by sediment texture analysis of the same samples, since sediment texture is an important determinant of contaminant retention; and

5) A project to delineate concentration gradients and dilution factors from various modes of produced water discharge (e.g., subsurface vs. overboard aerial pipe) should be undertaken.

The Central Gulf Platform Study

The Central Gulf Platform (CGP) program was designed to be "the first comprehensive 'fate and effects' study", whose goal was to "show where previous development has brought about problems and to point out those habitats and production techniques which need close monitoring or further study in a particular lease area" (Bedinger 1981a). The CGP study was not intended to be either a baseline investigation or a monitoring program. The CGP investigators, therefore, purposely selected a highly disturbed environment that had been exposed to long-term and possibly cumulative discharges from petroleum platforms. The CGP study area encompassed the previous OEI study area near the Mississippi River delta, within the most heavily developed offshore area in the world.

The results of the CGS study were published as a technical report (Bedinger 1981b) that included final reports of the various principal investigators and an executive summary (Bedinger 1981a). The stated objectives of the CGP study included:

1) Determination of the distribution and concentration of petroleum hydrocarbons, selected trace metals, and substances related to well drilling both in sediments (including vertical profiles to assess stratification and persistence) and in tissues of commercially or ecologically important benthic and demersal species;

2) Examination of microbial hydrocarbon degradation and nutrient cycling chemistry and processes in surficial sediments;

3) Comparison of benthic communities in the immediate vicinity of platforms with those at control sites, with emphasis on selected "indicators"; and

4) Investigation of biofouling communities and the "artificial reef" effect of platforms in various locations and of various ages.

The CGP study involved investigation of twenty platforms and four control sites in waters extending from 5 to 120 km offshore, and ranging in depth from 6 to 75 m. Three cruises were completed to cover the three seasons which characterize the weather regimes in that portion of the Gulf of Mexico. Four of the platforms and the control sites were studied intensively during each cruise, while 16 other platforms considered of secondary importance were visited only once during the course of the investigation. At each platform, one or more transects extending outward were sampled by a variety of commonly used techniques involving both vessels and divers. Synoptic sampling was emphasized to maximize data transfer between investigators. The following general topics were investigated (Bedinger et al. 1981):

1) Spatial distribution, depth, and persistence of drill spoils, especially with respect to sediment characteristics and platform presence;

2) Concentrations of hydrocarbons and trace metals in sediments and biota, and the relationship of contaminant concentrations to platform proximity, age, and activities;

3) The possible effects of human consumption of contaminated seafood;

4) Activity and abundance of predominant and hydrocarbon-oxidizing bacteria in sediments;

5) Condition of biological communities on and near platforms compared to communities in control sites, emphasizing selected indicator species or taxa; and

6) Possible correlations between biological parameters and physical, chemical, and geological factors potentially influenced by platform presence.

The CGP study was generally well designed. Excellent intersample comparison and correlation were possible due to a high degree of program organization from the outset of the investigation.

Perhaps the major uncontrolled variables in the study area, which affected the results of the CGP study, were two natural events, a tropical storm and massive flooding by the Mississippi River. The storm (which was described as neither very large nor strong by Bedinger [1981a]) completely mixed surficial sediments to a depth of at least 5 cm at all sites with water depth up to 50 m. The storm was followed by rapid immigration of a variety of benthic fauna, and drastically altered infaunal community composition. River flooding also caused area-wide hypoxic benthic conditions and resulted in widespread mortality of marine organisms.

Such large-scale physical disruptions made comparisons of pre- and post-storm benthic data almost impossible to relate to petroleum activities. It is almost certain that analogous phenomena in other areas would have effects on biological communities that far outweigh any chronic effects of petroleum development. In high-energy areas, not only are toxicants such as hydrocarbons more rapidly diluted, but the periodic homogenization of benthic communities by water movement typically obscures any subtle trends (Menzie 1983).

COOK INLET

Long-term or regional monitoring programs to assess the biological effects of offshore oil production were not conducted in association with the development of Upper Cook Inlet (Alaska) petroleum reserves. The primary reasons for the lack of effects monitoring programs in this region relate to the time when development occurred, and available information regarding oceanographic conditions in Upper Cook Inlet, and operational aspects of the planned oil and gas production facilities.

At the time when the commercial reserves of hydrocarbons in Upper Cook Inlet were brought into production (1964-1967), there was very limited public and government concern regarding environmental protection. In addition, legislation for dealing with industrial pollution (e.g., U.S. Water Pollution Control Act 1972) and requirements for mitigative measures were not in place until after production in Cook Inlet had peaked, while the Alaska Department of Environmental Conservation, which is responsible for monitoring and surveillance of water and air quality, was not created until 1971.

The lack of concern over possible detrimental effects of oil and gas production in Cook Inlet also appears to have resulted from the expectation that the vigorous tidal flushing of the inlet would prevent any environmental damage. In addition, biological productivity of the area is low due to the large input of glacial silts which severely limit light penetration in the water column. As a result, the emphasis of past research and monitoring has been on modelling the circulation of Cook Inlet and calculation of rates of water mass transport.

Several operational factors for the production facilities also minimized the degree of environmental concern. These included: (1) the onshore treatment of produced waters and reduction of total oil concentration to 10 mg L^{-1} or less before coastal discharge; (2) the limited use of drilling muds containing oil for spotting purposes; (3) the location of lease areas away from designated "critical habitats"; (4) the disposal of solid wastes and oily sludges at special landfill sites; (5) the secondary treatment of sanitary wastes; and (6) the use of drilling mud formulations which have been accepted for general use in offshore drilling following detailed evaluations of their acute toxic effects.

OVERALL STRATEGY FOR DESIGN OF EAST COAST MONITORING PROGRAMS

DEFINITION OF ENVIRONMENTAL EFFECTS MONITORING

For the purposes of this report, environmental effects monitoring is defined as the repetitive measurement of variables to detect changes directly or indirectly attributable to a specific development activity, or to test predicted environmental impacts. It is important to recognize that a definitive demonstration of "no impact" is an impossible goal.

REASONS FOR MONITORING

The primary reason for monitoring is to address the uncertainty associated with environmental impact predictions. Two somewhat different types of monitoring arise from this reason:

1) Monitoring to determine whether a predicted detrimental effect occurs, and that the direction and magnitude of the effect is about the same as predicted; and

2) Monitoring to provide assurance that harmful effects that were predicted to be insignificant are, in fact, insignificant.

The latter kind of monitoring has been termed "comfort" monitoring. A secondary reason for monitoring that may arise during the life of a development is to assess the effectiveness of mitigative measures.

Two essential types of information are required for the satisfactory resolution of cause-effect relationships. First, the cause-effect relationship being monitored must be understood to the point that appropriate parameters can be chosen to produce meaningful test criteria. Second, each factor and its relative contribution to the natural variability of the index parameters must be known to the degree required by the pre-set level of confidence expected in the monitoring result. When the above information is unavailable, monitoring cannot proceed. In its place, basic research programs must be developed to provide the essential information.

Environmental monitoring is intended to be operative throughout the life of a project, and should influence the operation of an industrial facility. The process whereby operational protocols are influenced by the results of environmental monitoring programs should form part of a total environmental management approach. It is anticipated, however, that the level of monitoring effort will decrease with time into a development project, as cause-effect hypotheses are tested and the logical conclusion of monitoring is achieved. The results of scientifically valid, project-specific monitoring studies will probably be very useful in either justifying or rejecting the need for monitoring other similar projects.

ENVIRONMENTAL MANAGEMENT OBJECTIVES

In general, the primary environmental management objective will be to ensure that the effects of the development do not exceed previously specified acceptable levels. These levels must be specified prior to production, and if they are exceeded, they should dictate a response through a change in operating practice or equipment design. Government and industry should reach an a priori agreement on these acceptable levels of environmental disturbance (effect), and should jointly ensure that the monitoring program is adequate to evaluate whether the levels of disturbance (effect) are being exceeded.

Pre-set environmental performance criteria for an offshore production facility are fundamental to the design of a monitoring program. Without such criteria, a monitoring program will be aimed at detecting change, independent of the significance of the change. The criteria must be quantitative and must include spatial and temporal dimensions.

There has been some concern related to a corollary of the pre-set performance criteria approach, that effects which do not exceed the criteria are acceptable. This concern centres around the question of who should determine what is acceptable. However, this is not an issue related to offshore effects monitoring because:

1) Each offshore production facility will have substantial physical and biological effects immediately below and around the structure;

2) The decision to allow the development to proceed is the decision that determines if these immediate-area effects are acceptable; and

3) Once the decision is made to allow oil and gas development and production to proceed, the purpose of monitoring is not to document the effects in this immediate area (where detrimental effects are certain), but to determine if effects are occurring beyond the immediate area.

Pre-set performance criteria are, therefore, a key factor in concentrating efforts in the areas where there is uncertainty regarding harmful effects, rather than in the area close to the well.

The emphasis placed on monitoring outside the "high-impact", near-platform zone must be put into perspective. As already stated, the benthic environment near an offshore production structure will be highly disrupted. Most of the effects will be physical rather than chemical in nature. There has been a tendency, in previous surveys, to study the near-structure area intensively because harmful effects can be detected easily and monitoring design is relatively simple. We believe, however, that such intensive study (usually performed because it is easiest to do) diverts attention and resources from the more difficult but more important objective of attempting to determine if longer-term and more wide-reaching effects are occurring.

Although we advocate placing the greatest emphasis on monitoring outside the "high-impact" zone, we recognize the need to study the near-structure area, primarily to identify some of the important effects requiring study. This is expected to be very useful for guiding the monitoring program in its early stages. A legitimate concern about accepting a certain level of environmental risk within the "high-impact" zone is that improvements to pollution control technology will be stifled. This is not likely to occur, however, in situations where such improvements are clearly needed, namely when existing controls prove inadequate in achieving the pre-set performance criteria.

OPERATIONAL AND ENVIRONMENTAL CONSIDERATIONS FOR PROGRAM DESIGN

The review of monitoring experience from existing production areas indicated that differences in operating procedures for offshore production, oceanographic conditions and biological receptors must all be considered during the design of a monitoring program. These are discussed in the following sections.

Contaminants and Disturbance Sources

The type of wastes associated with offshore oil and gas production were recently reviewed by Thomas et al. (1983). These are:

- produced water;
- drilling fluids and cuttings;
- ballast water;
- storage displacement water;
- produced sand;
- deck drainage;
- well completion and workover fluids;
- miscellaneous well fluids (cement, BOP fluid);
- sanitary and domestic wastes;
- gas and oil processing wastes; and
- miscellaneous discharges (slop oil, cooling water, desalination brine, and fire control system test water).

The first four of the above wastes are considered significant from an environmental perspective, while the remaining wastes are not considered significant because they are discharged only intermittently or in very small quantities.

Three groups of important contaminants are present in one or more of these waste discharges:

1) Hydrocarbons (both refined and crude oils): aromatic hydrocarbons are of greatest environmental concern because these compounds have a high potential to cause detrimental biological effects. The main sources of hydrocarbon input to the marine environment are oiled drill cuttings from the use of oil-based mud systems, produced water, ballast and storage displacement water, and to a lesser extent, deck drainage.

2) Persistent chemicals and chemicals which do not occur naturally: synthetic organics and biocides are included in this group, and many of these chemicals have very long biological half-lives. The main sources of such chemicals are drilling muds, produced water and associated well and formation fluids such as completion and work-over fluids.

3) Metals: some heavy metals such as mercury may accumulate in biota and others (chromium, lead, cadmium) are highly toxic. The primary source of metals is drill muds and cuttings, and to a far lesser extent, produced water.

An effects monitoring strategy should be based on examination of the presence of these contaminants (hydrocarbons, persistent chemicals and metals) in the environment, rather than the wastes which are the source of the contaminants.

Sources of disturbance other than production wastes may be important also in some east coast Canadian waters. These include effects resulting from the physical presence of structures, airborne noise, underwater noise and artificial illumination. In general, these disturbances are most likely to affect birds and marine mammals.

Zones of Influence

The "zone of influence" is the area around a production facility within which some effect directly attributable to the production activities can be distinguished with confidence from the background condition. The size and shape of the zone of influence will vary with the effect used to define it. A zone defined by the physical presence of drill cuttings, for example, will be different from the zone defined by the presence of a certain chemical contaminant. Both will be different from the zone defined by the incidence of a particular behavioural or physiological response of a particular benthic invertebrate. The zone is three dimensional, extending through the water column, sediments and atmosphere.

An appropriate monitoring strategy for offshore production should focus on the zone of influence in the sediments, because it is easiest to define and measure effects in this part of the receiving environment (see following subsection). The discharge of drill cuttings and other wastes will produce a very definite high-impact zone where effects will be unavoidable. The effects may include smothering of benthos and major alterations to benthic habitat. The dimensions of this zone will vary; previous experience gained through numerous field studies indicates that the zone will extend from tens to hundreds of metres from a discharge (platform) source (Thomas et al. 1983; UKOOA 1983). Experience in the Gulf of Mexico with production platforms where oil-based drilling muds have not been used, and the major waste discharge has been produced water, has shown a zone of influence of a few metres to a few tens of metres. The recent summary report by UKOOA (1983) indicates that when drill cuttings from use of oil-based muds have been discharged in the North Sea, the outer limits of the high-impact zone (characterized by anoxic sediments and complete smothering of benthos) have extended approximately 200 to 500 m from the platforms. It is recommended that the monitoring strategy for the east coast of Canada recognize the certainty of a high-impact zone. A reasonable outer boundary for the zone will have to be defined, although up to about 500 m seems appropriate and consistent with previous experience (if oil-based muds are used). Monitoring efforts should be concentrated outside this boundary (as measured along a contaminant gradient), and limited attention should be placed on monitoring within it. However, as indicated above, measurements within the "high-impact" zone will be useful to guide the monitoring program in its early stages, by identifying some of the effects requiring study and to establish a worst case against which other measurements can be compared.

The location of field sampling sites for contaminant monitoring should be based on:

- "mass balance" calculations;
- receiving environment concentrations; and
- oceanographic conditions including dispersal mechanisms.

The first step is the mass balance calculation. It is important to realize that the mass balance calculation is not an absolute determination of any environmental consequence of a hydrocarbon development. It is simply a relatively quick and inexpensive tool for guiding investigators toward an approximate scale of environmental disruption and the approximate amounts of wastes and waste accumulation patterns around the production platform, to provide a focus for what and where something should be monitored. This involves predicting accumulation rates of contaminants in the sediments, by taking into account the rate of waste discharge, physical characteristics of the waste and the concentration of significant contaminants in the discharge. Much of this will be provided by data from compliance monitoring. The importance of this step should not be underestimated. By providing a first approximation of the scale of the disturbance, the detection limits required to resolve the contaminant inputs against natural (background) levels can be calculated. Another benefit of having an approximate indication of the scale of disturbance is that this information can influence the frequency of sampling and the distance between grid points.

The natural (background) concentrations of those elements or compounds which are also tracers of the waste discharges will influence the monitoring strategy by setting detection limits. As the natural concentration of a constituent decreases in the receiving environment, it becomes progressively easier to resolve the constituent associated with the discharge source from the background, assuming that detection limits are sufficiently low.

Finally, oceanographic conditions (water depth, water column density structure, currents, tides, water column particulate load, frequency and duration of high energy events, and bedform movements) indicate the probable direction of waste migration, and the rate of dispersion in both the water column and sediments. Such information will help to define the requirements for sampling equipment, sample replication, sampling frequency, and station locations.

Where and When to Sample Contaminants in the Environment

Emphasis should be placed on sampling the sediments for the following five reasons:

1) The sediments are an accumulating medium through two mechanisms: sedimentation of solid particulates; and demobilization of dissolved compounds which adsorb on biogenic and non-biogenic fractions. Consequently, the sediments can integrate contaminant effects.

2) Concentrations of contaminants tend to be higher in sediment than in the water column; this allows the use of higher detection limits (less costly, more accurate) and leads to a greater confidence in results, and easier interpretation of data than is usually the case for water column effects.

3) Variability in concentrations of contaminants in sediments on short time and distance scales tends to be small (compared to concentrations in water); it is, therefore, much easier to obtain "synoptic" data and demonstrate a gradient during sampling.

4) Samples are easily replicated.

5) Through the use of sediment cores, historical data on the input of contaminants can be obtained for use as a reference without the need for pre-development baseline studies.

Three reasons for not sampling contaminants in the water column follow:

1) The water column is a dispersing medium; contaminants tend to become more dispersed with time and the spatial distribution of contaminants tends to be very patchy;

temporal variability is large; and large numbers of observations are required to allow adequate interpretation of trends.

2) Monitoring of the effects of offshore oil production on the water column has been attempted in the Gulf of Mexico and the North Sea. In both regions, these studies were considered unsuccessful because the results were inconclusive and largely uninterpretable. The difficulties with interpretation of results was related primarily to insufficient information on the factors and relative importance of factors contributing to natural variability in the water column.

3) Except within several metres of point source waste discharges, the concentrations of contaminants found in the water column are usually several orders of magnitude below 96-h LC50 values for most marine organisms. Any effects of discharged wastes on organisms in the water column, therefore, will be subtle and sub-lethal in nature. These effects are most difficult to detect and interpret (Thomas et al. 1983).

The emphasis placed on the sedimentary environment as a monitoring focus in this report is more a reflection on the difficulties associated with sampling and interpreting results for contaminants in the pelagic environment, rather than a judgement that the pelagic environment is not an important concern. Indeed, the most important resource to the Grand Banks and Scotian Shelf - fish - reside in the pelagic environment. An appropriate monitoring focus related to fish is discussed in the section on what to measure.

An annual sampling program is recommended as the most practical strategy for east coast effects monitoring programs. More frequent sampling periods are not justified because measurable and significant cumulative effects on the sediment environment are not likely to occur over shorter time scales. Furthermore, large numbers of samples collected frequently to establish natural variability are not required because the recommended monitoring strategy is based on detection of changes along a pollution gradient, not on absolute concentrations. It is also recommended that the sampling times be chosen to avoid periods of heavy recruitment into the benthic invertebrate populations and to coincide, if possible, with seasons of favourable sampling conditions. Once the concentration of, or population characteristics of the gradient have been determined, alteration of the sampling frequency may become justifiable. Thus, a possible time series of measurements might be year 1, year 2, year 3, year 5, year 7, etc.

The Sampling Grid

It is recommended that two overlapping series of stations form the basis of the sampling network. The first series of stations should be aligned with the net residual current (if this is known). Stations should be concentrated along the residual axis downcurrent from the point sources. An arrangement of stations similar to that shown in Figure 1 would be appropriate; spacing of stations, length of the residual axis and the farthest situated reference station should depend on local conditions (magnitude and consistency of direction of the residual current). Typically, the stations would be 200 to 500 m apart. Reference stations should be situated such that they are far enough from the point sources to lie outside the main zone of influence but close enough that they, and intermediate stations, all occur within the same approximate oceanographic regime (i.e., changes along the gradient should result from the influence of the point sources, not from different oceanographic factors affecting different portions of the sampling area).

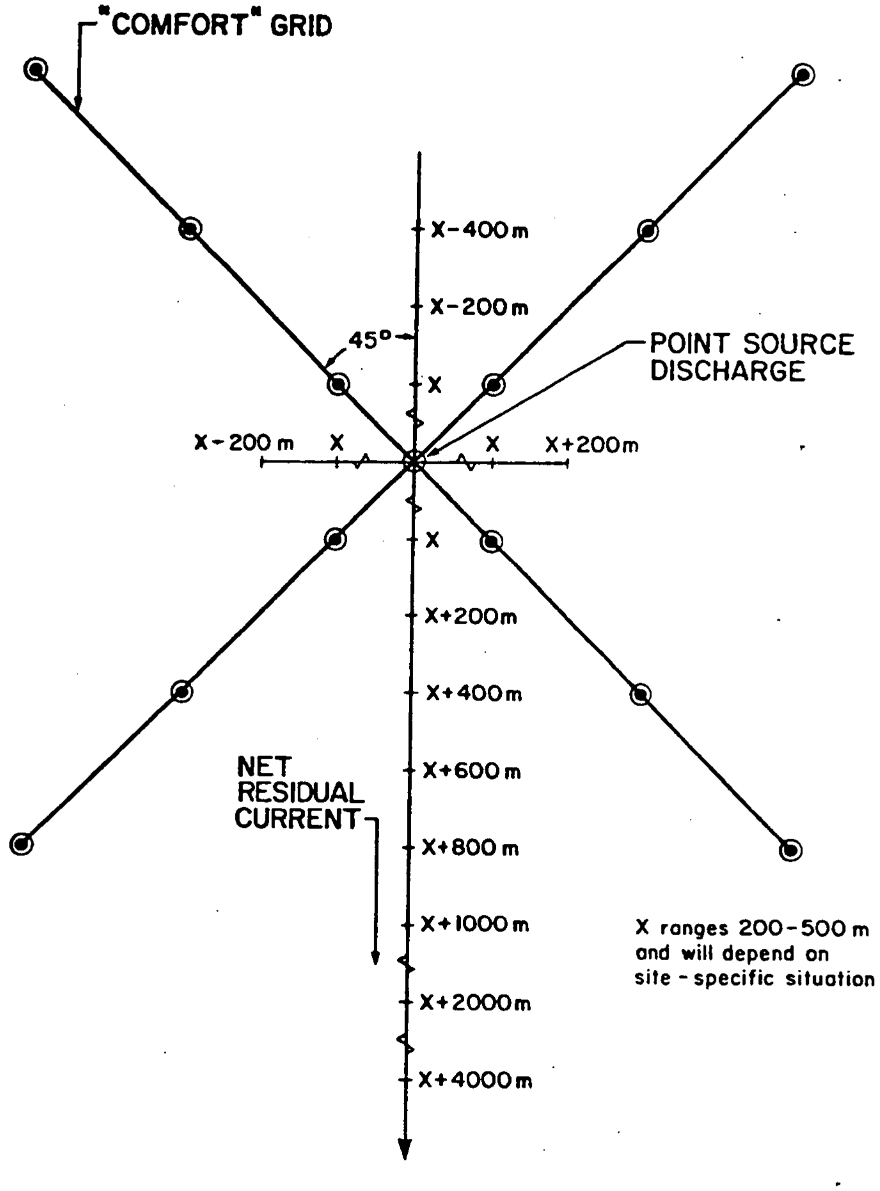
A second sampling grid (which could be considered a "comfort" grid), aligned 45° to the residual current grid (Fig. 1) should overlie the first grid. Sample station locations on this grid would be regularly spaced, making no presumption about the location of possible contaminant accumulations. Previous monitoring programs in the North Sea have shown repeatedly that the maximum contamination in sediments may occur upstream from, or in some other location away from, the direction of the net residual current. Consequently, this type of occurrence may not be detected if sampling is completed on the basis of a grid aligned with the residual current alone. The use of the two grid system will limit the risk of significant effects going undetected, particularly in cases where confidence in the position of the residual current is low. Regardless of grid orientation, accurate station positioning is an essential requirement for this type of monitoring program. The sampling vessel must remain on station for sufficient periods of time to allow collection of an adequate number of replicate samples.

The emphasis of the two-grid system is the detection of change along a gradient. This approach has the advantage of not requiring detailed pre-development baseline data. If information regarding pre-development conditions is required, it can be obtained after the fact by using sediment cores.

Important Biological Receptors

A key to ensuring that the monitoring program will meet the environmental management objectives is to specify which biological resources are important. On Canada's east coast, the local economy

Figure 1 General Design of Overlapping Two Grid Sampling System



depends partially on the harvests of marine resources, primarily fish and shellfish. Monitoring must determine whether or not these commercially important species are likely to be affected by offshore petroleum industry activities.

The commercially important species will seldom be the direct target of monitoring, because they are usually larger animals that are capable of migratory movements that only occasionally bring individuals into the zone of influence of the production activities. However, these important species must be kept in mind when choosing the biological receptors for monitoring. For example, it may be appropriate to monitor the food organisms on which these important species depend.

WHAT TO MEASURE

There is usually no perfect index for use in evaluating a particular cause-effect hypothesis. It is clear, however, that monitoring strategies should rest firmly on indices and techniques that have a proven history of satisfactory performance. Because new techniques for monitoring are evolving and being evaluated continually, monitoring strategies must include a mechanism for evaluating new techniques from time to time, in terms of their potential usefulness to a specific project. Allowance should be made for promising techniques to be evaluated and phased into existing monitoring programs if they are considered beneficial to a project.

The reasons for monitoring contaminant concentrations in the sediments, rather than in the water column have already been discussed. Much of the same rationale applies to the question of what animals to monitor. Sessile, sediment-dwelling organisms are preferred over water-column organisms as targets for monitoring because:

1) Their condition (e.g., body burden), community and population parameters may sometimes be correlated with well-defined sediment characteristics (contaminant levels, particle size distribution, etc.);

2) Some benthic fauna (e.g., bivalves) filter very large quantities of sea water and remain in one location, thereby making them excellent indicators of the cumulative pollution stress in a certain location; and

3) Replicate samples are relatively easy to obtain.

A key decision will be the choice of sieve size for screening biota from sediments for subsequent individual or community analyses. The problems resulting from lack of standardization of sieve sizes in North Sea monitoring programs were mentioned in a previous section. Coleman (1980) discusses the considerations related to the choice of sieve size, and notes that the most appropriate size depends upon the purpose of the survey and, therefore, which animals should be retained.

The nominal 0.5-mm sieve size has been used more frequently than larger sieve sizes for quantitative benthic community studies on the continental shelves of eastern North America (Baffin Island/Ungava Bay - Stewart et al. in press; Davis Strait - Stewart 1983; Grand Banks - Hutcheson et al. 1981; Georges Bank - Mauer and Leathem 1981). The relative advantages and disadvantages of the 0.5-mm and 1.0-mm sieve size follow:

1) 0.5 mm sieve

- the general standard used to date for the east coast of Canada and, therefore, will yield data that are more consistent with existing data;
- retains most smaller fauna (polychaetes) and juvenile stages;
- facilitates provision of data for use in size frequency analyses which can then be used to assess population structures; and
- more time consuming and expensive to employ.

2) 1.0 mm sieve

- less costly and time consuming to employ;
- has been used in North Sea monitoring programs with some success;
- appropriate if studies focus on larger organisms or when whole community information is not required;
- may be more cost effective in depauperate areas with few smaller individuals; and
- misses smaller individuals which provide size frequency information.

The designation of the "best" sieve size in benthic invertebrate sampling programs remains an issue of professional disagreement. Supporters of the 0.5-mm mesh sieve point out that this size has been used extensively in the past and is an unofficial international standard, while supporters of the 1.0-mm mesh sieve argue that the amount of additional information obtained when using the 0.5-mm as compared with the 1.0-mm sieve does not justify the much greater cost and effort required by its use.

Rather than reject the more costly method, two approaches are suggested for choosing sieve size. For both Hibernia and Venture, initial samples should be double sieved through a 1.0-mm and a 0.5-mm mesh. The additional information on species abundances, variety, biomass and sizes provided by the smaller mesh should be compared against that provided by the larger mesh. An informed management decision on the most appropriate sieve size can then be made based on both scientific and financial considerations. Alternatively, all samples may be double sieved. Material retained on the 0.5-mm mesh could then be preserved and archived unsorted for the use of other investigators.

Pelagic fish rarely will be good target species for monitoring programs. Demersal fish are preferable because of their association with the bottom sediments, and their lower tendency for migratory movements.

In recognition of the importance of fish to the Grand Banks/Scotian Shelf ecosystem and regional economy, some monitoring effort should be directed toward fish. Enzyme induction, such as that which occurs in fish exposed to petroleum hydrocarbons, may be used as an indicator of hydrocarbon contamination in the water column. Numerous laboratory and field investigations have established mixed function oxygenase (MFO) induction in fish as an indicator of oil pollution (Payne 1976; Burns 1976; Stegeman 1978; Davies et al. 1981). Measurements of MFO enzymes in fish do not provide evidence of quantifiable, biologically-significant effects on populations and communities, but can be used effectively to establish whether an area has been contaminated by hydrocarbons (provided that the fish sampled are habitat-faithful to the area sampled). Monitoring using MFO absence/presence provides either assurance of no detectable effect or a rationale for a more comprehensive monitoring program.

The usefulness of the biofouling community for monitoring measurements is a subject of some debate. On the negative side, there are likely to be engineering reasons for control of the biofouling community, either by mechanical removal or through application of biocides. In addition, the biofouling community is within the area around the platform where major effects can be expected, and therefore studies of these organisms will add little information to the definition of boundaries of the zone of influence around a platform. On the positive side, however, if no harmful effects are observed in the biofouling community, this finding might justify substantial reductions in effort farther from the platform. Similarly, if effects are detected in the biofouling community and not elsewhere, this might provide the necessary evidence that the zone of influence is very limited in size.

Monitoring should be oriented toward individuals, rather than communities, for the most part because effects at the community level are often uninterpretable without an extensive understanding of the natural variability that characterizes various biological communities in both time and space. In addition, detrimental effects at the community level are simply the integration of effects on individuals. This is not to suggest that community measurements are inappropriate, but rather that emphasis is best placed on individual measurements.

PROGRAM MANAGEMENT

During this project, both in the review of monitoring experiences elsewhere, and in the workshop held to develop east coast monitoring strategies, a number of program management considerations became apparent that should influence the design and execution of monitoring programs. These are summarized in the following sections.

Planning

The importance of the planning phase of a monitoring program should not be underestimated. Approximately 15 - 20 percent of the annual budget should be allocated to various planning tasks. This proportion should be maintained from year to year, since the planning phase for each year after the first must include a thorough evaluation of results from the previous year.

Interdisciplinary Integration

Monitoring programs for offshore hydrocarbon production involve a broad range of physical, chemical and biological disciplines. Ensuring adequate scientific, technical and logistic integration of the disciplinary components is a formidable but necessary task that must be part of planning, field sampling, analysis and reporting. Administrative or contractual arrangements that conflict with the integration process should be discouraged.

Quality Control

The program budget should include adequate funding for blind replicate analyses[1], including the cost of independent verification at alternate laboratories. This process should be co-ordinated by program management. The importance of quality control is now realized among physical scientists in recent years. Details of various quality control programs are reported in Keith et al. (1983), Kirchmer (1983) and Taylor (1981).

Statistical Design

Appropriate statistical approaches need to be applied to preliminary data during the planning process to ensure that program goals for both accuracy and precision are met. The authors recommend two components to this planning process:

1) A pilot project should be undertaken in the area around the production facilities to be monitored for evaluation of a number of key determinants of sampling design, including the distribution and abundance of species which may be the focus of monitoring; physical and chemical dynamics (currents, sedimentation rates, etc.); and the natural variance in parameters which may be measured.

2) A statistical model should be developed using Monte Carlo approaches for distribution generation, to test the ability of the planned monitoring program to detect the anticipated effects. This model will require input from the pilot project results. A simulation (synthetic sampling) should

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1 Blind replicate analysis refers to a procedure designed to determine the "true" precision and accuracy of a particular analytical measurement. Samples having identities unknown to the analyst are analysed together with their counterparts of known identity. Deviations between "known" and "unknown" replicates are almost always greater than those obtained for samples of known identity.

be used next to choose the most appropriate sampling strategy (random vs. systematic) and the number of stations and sampling replication required to determine an expected effect at a pre-set level of confidence.

Data Management

Data management is necessary, but should follow a pragmatic approach that limits the amount of funds spent on this task. The data management system should: (1) be consistent over time; (2) use simple and cost-effective storage and retrieval methods; (3) include information that will permit future quality evaluation of each data type; and (4) serve the monitoring process, rather than *vice versa*.

Review and Liaison

Effects monitoring of offshore oil and gas activities is a scientific process that is evolving rapidly and is currently practised at several widely separated locations in the world. Review of other program results and liaison with foreign workers is necessary and desirable; effort and funds must be allocated to establish and maintain this communication.

It is recommended that a regular external review process be instituted to ensure continuing high quality of monitoring program design and results, and to assure funding agencies that resources are being allocated wisely.

OVERVIEW OF PROPOSED EAST COAST OIL AND GAS DEVELOPMENTS

HIBERNIA

Environmental Setting

The following sections describe environmental conditions relevant to the monitoring programs presented in the next section and are not intended to provide a comprehensive overview. The Grand Banks extend to a distance of 320 km from shore off the southeast coast of Newfoundland. Most of this region has water depths between 50 and 100 m and has a pronounced platform shape. The Hibernia P-15 area is 76 to 86 m deep and has a bottom composed of silt, gravel, shale and occasional boulders.

Physical Oceanography. The dominant feature of the Grand Banks area is the cold Labrador Current that is driven by varying combinations of Hudson Strait outflow, the Baffin Current and the west Greenland Current. It influences most of the Grand Banks, and has a marked effect on the oceanography and biota of the region. This current flows over the northern and eastern slopes of the Banks to depths greater than 100 m. The Labrador Current appears to separate into inshore and offshore components in the vicinity of the northern banks. Gulf Stream-derived waters, which normally lie well outside the continental shelf of Newfoundland, also may influence at least the southeastern portion of the Grand Banks periodically. The slope water of the Banks is derived from contributions of both the Gulf Stream and the Labrador Current. Currents over the Banks are generally weak and fluctuating (Petrie and Anderson 1983). The southeast Grand Banks may have a clockwise gyre, while the Flemish Cap area may be characterized by a weak clockwise circulation of approximately 0.02 ms^{-1} (Ross 1980a, b cited in Petrie 1980).

Pack ice may invade the Grand Banks region from January to June, with maximum concentrations usually occurring in April and May (Allen 1980). Icebergs are commonly observed from April to July, and may range in size from several thousand to 25 million tons (Brusset 1981). The larger icebergs can scour the sea bottom to considerable depths.

Benthos. Only two major studies of benthos of the Grand Banks have been conducted: Nesis (1965) on the biocenoses and biomass in the Newfoundland and Labrador region; and the Mobil-sponsored study for the Hibernia EIS (Hutcheson et al. 1981). The following summary is taken verbatim from the latter report.

The benthic communities of the Grand Banks are composed of primarily arctic-boreal and boreal species. Arctic species are found in communities in the north and northeast portions of the Grand Banks, while some warm water species are found on the southern part of the Grand Bank. The prevalent sediment types were sand and gravel in varying combinations. Polychaete worms are numerically the dominant type of organism present, while molluscs and echinoderms account for the greatest percentage by weight. Large-scale differences in species distributions are correlated with water mass type, while small-scale variability is correlated with sediment types.

A major feature of the benthic communities of the Grand Banks is the dense assemblage of the clam (Mesodesma deauratum) on the southeastern portion of the Banks. These populations may possibly cover up to 20 percent of the bottom of this area. Mean standing crops of up to 22 kg/m^2 make this the most dense single species community reported on the continental shelves of North America. A small fish, the sand lance, is a consistent feature of benthic communities in most areas. Greatest densities of sand lance observed in this study occurred in the Hibernia area.

There was little indication of seasonal changes in species composition, densities or biomass distribution of benthic communities. However, reproductive patterns for many species displayed definite seasonality. A major spawning peak was noted in the March-May period for many species, with phytoplankton and zooplankton production. The predominant feeding types present were suspension feeders and surface deposit feeder-detritivores. These feeding types indicated a relatively direct link between water column production of organic matter and production by benthic species. Estimated annual production by benthic invertebrates on the Grand Banks is somewhat greater than that calculated for North American east coast continental shelves further to the south, although it is similar to those in other portions of the world. Greatest production occurs on the Southeast Shoal, primarily due to the high standing crop of Mesodesma deauratum.

The communities that exist in the Hibernia area are a mixture of arctic-boreal and boreal with a few more cosmopolitan forms. The area is a relatively cold one with an annual mean bottom water temperature of -0.1° C. The diversity of species is lower than at other stations on the Grand Banks. Alternating sand and gravel patches support three major types of communities: a coarse sand with gravel community; a finer-grained sand with some gravel community; and a community living in poorly-sorted sands with some silt, clay and gravel. Localized coarse gravel cobble communities also exist. Spring (March-May) is the major period of larval hatching in this area, with some species hatching in the summer and fall. Dominant crustaceans have two to three-year life cycles. Limited data for one of the dominant molluscs (Liocyma fluctuosa) suggest steady recruitment to the population over the last few years. Sand lance are common in the Hibernia area. Benthic production processes are judged similar to those at other stations on the Grand Banks (except on the Southeast Shoal) and the magnitude of annual benthic productivity around Hibernia is similar to that for the Grand Banks average.

Fish and Fisheries. The Grand Banks of Newfoundland are recognized to be one of the world's most productive commercial fishing areas. The high productivity of this fishing ground is generally believed to be a result of the mixing of cold Labrador Current water with the warmer Atlantic water, which creates a large area with enhanced primary production. The major gear used in the region is the otter trawl hauled along the bottom by stern, side, or pair trawlers. However, a variety of gear is used depending on the species sought and the country of origin of fishing vessels. Other common fishing gear includes seines, handlines, longlines, pots and traps.

Reported spawning times (Sandeman 1980) for major Grand Banks commercial species include:

- Cod - spring and summer at edge of shelf;
- Yellowtail - peak spawning in late June throughout the area;
- American plaice - spring spawning;
- Greenland halibut - in very deep water along shelf edge;
- Witch - spring spawning in deep water;
- Redfish - extrusion of larvae during the spring in warm deep water;
- Haddock - June-July spawning in southern Grand Banks; and
- Capelin - offshore spawning occurs in shallow parts of the Bank during mid-June to mid-July.

In addition to being important commercially, a number of species including capelin, herring and sand lance, and the larvae and juveniles of many species are key food sources for important commercial fish such as cod, as well as for certain species of marine birds and mammals.

Development and Waste Discharge Scenario

Hibernia will be developed using either concrete gravity-based structures capable of withstanding collisions with icebergs and sea-ice floes, or floating platforms that can be moved away from dangerous ice. Subsea structures may have to be protected from iceberg scour by fenders or by burial.

Platforms will be serviced by supply boats based on the Avalon Peninsula. Transportation of crude oil from the production site is expected to be by subsea pipeline to shore or by shuttle tankers (segregated ballast type) loaded from an offshore single-point mooring system.

The production scenario (adapted from Thomas et al. 1983) used in developing a monitoring strategy assumed the following conditions:

1) Recoverable oil reserves from the Hibernia Field are 240 million m^3, produced at a rate of 32,000 m^3d^{-1}. The typical well depth is 3000 m, and the reservoir covers an area of 100 km^2.

2) The production system will consist of four clusters of ten wells each (30 producing, 10 injection) tied into a single platform through sea-floor pipelines. Wells are drilled over a period of three years. The platform contains the wellheads for all four clusters, processing facilities and accommodation for all offshore personnel (250 individuals).

3) All drilling wastes, produced water, storage displacement water, processing wastes and minor wastes such as deck drainage, sewage, cooling water and desalination wastes are discharged from the single platform. Offshore crude oil storage capacity is 160,000 m^3. (There is a possibility that drilling wastes may be discharged at the site of each of the four well clusters rather than from one point at the platform.)

During the development and production phases of Hibernia, discharged wastes will include drilling fluids and cuttings during the initial stages (untreated if water-based muds are used, and treated if oil-based muds are used), produced water, ballast and storage displacement water (if offshore loading of crude oil to tankers occurs), sanitary and domestic wastes, deck drainage, desalination brine and cooling water later on. The composition, quantity and probable fates and effects of these discharges were reviewed in detail by Thomas et al. (1983).

According to Thomas et al. (1983), the primary environmental concern associated with production at Hibernia is the input of aromatic hydrocarbons to the sediments, and the concommitant exposure of bottom-associated biota to oil-contaminated cuttings (likely "low" toxicity paraffin oil rather than diesel oil) discharged during drilling, if oil-based muds are used. During the development of the Hibernia Field, about 40 wells will be drilled and 32,000 m^3 of cuttings will be discharged. If only water-based muds are used, 88,000 m^3 of drilling muds would also be discharged. If oil-based muds are used, no drilling fluids will be discharged to the sea. The waste dispersion model used by Thomas et al. (1983) did not predict heavy metal accumulation in the sediments associated with the use of water-based muds, nor did it predict the input of aromatics to the sediment from produced water (at a discharge rate of 16,000 m^3d^{-1}). However, the authors identified produced water as a concern due to the potentially large quantity which may be discharged over the life of each well (the amount of produced water increases with the age of a well). In addition, a potential for the introduction of some exotic chemicals during offshore hydrocarbon development (e.g., biocides) was identified.

Important Resources at Risk

The Grand Banks support, either year-round or seasonally, a number of biological resources of importance to man. At least five species of baleen whales, eight species of toothed whales and four species of seals occur in the Grand Banks region. However, their absolute numbers and detailed distribution and migration patterns are not well documented. None of these marine mammals are known to calve in the Hibernia area.

The waters of the Grand Banks are used all year by seabirds as a feeding area, and there are several large seabird colonies on the east coast of Newfoundland. The total number of seabirds inhabiting the Grand Banks over the period of a year is unknown, but has been estimated to be in the tens of millions (Williams et al. 1981). At least 50 species of seabirds have been recorded in the coastal and offshore waters of the banks.

The Grand Banks of Newfoundland are best known as a fishing ground. There are 31 commercially-harvested species, including various invertebrates (e.g., squid, crab, lobster and shrimp). In the Northwest Atlantic Fisheries Organization Statistical subarea 3L (which includes the northern half of the Grand Banks and the Hibernia site), the five major species harvested and the catch (tonnes) for each in 1981 (NAFO 1983) were:

- Atlantic cod 79,651;
- American plaice 37,269;
- Capelin 24,440;
- Queen crab 12,863; and
- Squid 10,798.

Of these major species, cod and plaice are groundfish that are common (at least at certain times of the year) in the Hibernia area. Capelin are pelagic and highly mobile, and are most concentrated within inshore waters during the summer spawning season. Crab and squid are harvested usually inshore of the Hibernia area. Of the three most important biological resources on the Grand Banks (i.e., fish, seabirds and marine mammals), groundfish, such as cod and plaice, are more likely to be exposed to potentially detrimental production-related discharges than pelagic forms.

Another fish species that is not presently harvested commercially, but may be most common in the area, is sand lance (Ammodytes spp.). They spend part of the time buried in sand, and migrate vertically to feed. They are found usually in very large schools and are an important food species for cod, haddock, and certain marine mammals and seabirds.

Disturbances other than those caused by production wastes are not considered in the present monitoring strategy for Hibernia. These may include the effects of noise on marine mammals or the presence of structures and flares on migrating marine birds. Any potential effects on birds and mammals would be extremely localized (in the case of a single production platform), and expensive to document and monitor in a credible scientific manner.

VENTURE

Environmental Setting

The following information is derived entirely from the Mobil Oil Venture Development Project environmental impact statement (EIS). The contents have been condensed as much as possible to provide the reader with a brief overview of those components of the environmental conditions on the Scotian Shelf, which are relevant to the monitoring program presented in the last section.

Sea Bed Physiography. The Scotian Shelf consists of three distinct physiographic zones: the Inner Shelf, bordering mainland Nova Scotia; the Central Zone, which is about 80 to 100 km wide and lies between the Outer Shelf and the Inner Shelf; and the Outer Shelf. The Venture Field is located on the Sable Island Bank portion of this Outer Shelf. The Outer Shelf is oriented with the shelf edge and is 50 to 75 km wide. Water depths are generally less than 100 m on this shelf, and at the Venture Field depths range from 14 m in the northwest corner to 28 m in the north. The Continental Slope lies offshore of the Shelf. A submarine canyon (The Gully) penetrates the shelf to the east of the Venture Field.

Sedimentary Environment. The surficial deposits of the Scotian Shelf are primarily sands and gravels, with finer-textured silts and clays in the deeper waters. These deposits overlie the sedimentary rocks of the East Coast Geosyncline, a basin-like geological structure in which sediments accumulate.

Subsea sediments are transported by the forces of moving water and gravity. Water movement due to waves, tides and currents, results in bedforms such as sand waves and sand ripples in offshore areas, and beach cusps and bars along the coast. Gravity-driven processes result in the mass movement of sediment downslope in the form of slides.

Large sand waves, the result of water-driven dynamic processes, have been found south and west of Sable Island on the Sable Island Bank. They lie in water depths of 10 to 75 m, have heights up to 6 m, and are usually 300 to 900 m from crest to crest. Sand waves which are smaller in height but with longer wavelengths have been noted along the eastern and western margins of the Venture site. Limited evidence to date suggests that these sand waves may be stable, and only the uppermost sediments in the features are transported.

Physical Oceanography. The waters over the Scotian Shelf are derived from several sources. The Cape Breton Current originates from the Gulf of St. Lawrence, the Labrador Current flows from the Grand Banks, and the Slope Water is a mixture of Labrador Current, coastal and Gulf Stream waters. The southwesterly flow of water over the inner portion of the Scotian Shelf, parallel to the coast of Nova Scotia, is called the Nova Scotia Current.

Tidal currents range from 1 cm s^{-1} in the slope region to 14 cm s^{-1} on the outer shelf, and may reach about 40 cm s^{-1} at the Venture Site. At the mainland coastal boundary, the mean coastal current flow is approximately 8 cm s^{-1} (Sutcliffe et al. 1976).

Sea ice can be present in the region from mid-February to mid-May, although the ice decays rapidly and is not considered a hazard to shipping. The entire Venture development area lies outside the extreme limit of iceberg drift.

Wind action causes periodic episodes of upwelling of bottom water over the Scotian Shelf. The Gully, northeast of the Venture site, is a probable site of regular upwellings, which bring nutrient-rich deep water onto the Shelf and enhance biological production. Upwelling also occurs regularly off the south coast of Cape Breton and west of Emerald Bank. Oceanic fronts which occur at the boundaries between water masses may also promote nutrient enrichment of surface waters. The boundary between the shelf and slope water is the only persistent frontal system in this region.

Nearshore areas of the Scotian Shelf have higher nutrient concentrations than offshore areas, probably due to nutrient enrichment by the Cape Breton-Nova Scotia Current system and nearshore oceanographic processes. Trace metals and hydrocarbons are also present in higher concentrations in nearshore areas. Trace metals in this region occur primarily as a result of natural crustal weathering, while hydrocarbons enter the marine system through wastes and emissions from industrial and urban centres.

Benthos. There are several basic types of benthic habitats in the Scotian Shelf region and each supports different dominant fauna. These include: sand substrates which are characterized by sand dollars; finer-textured substrates where ocean quahogs dominate; mud and silt habitats of the deeper basins where brittlestars, shrimp, sea pens and heart urchins are all present to a certain extent; and coarse substrates which are characterized by horse mussels and other filter feeders. Benthic organisms reproduce throughout the year, although reproductive activity is lowest in the winter.

The area to the east of Sable Island, where a portion of the Venture development would occur, has primarily sand substrate with moderate-to-high rates of sediment movement. Stanley and James (1971) reported up to 18.5 sand dollars per square metre in an area north of the east spit of Sable Island. The sand dollars preferred moderately sorted fine-to-medium sand. However, strong currents and very mobile sand prevent high densities of sand dollars in some habitats. The highest densities of sand dollars occur in an arc north of Sable Island, whereas the area southeast of the island, the crest of the bar extending from the east spit, and the area immediately adjacent to Sable Island are virtually devoid of sand dollars (Stanley and James 1971). These authors also concluded that sand dollars are responsible for considerable reworking of surficial sediments on Sable Island Bank.

This region is essentially devoid of macrophytes because the unstable shifting sands within the euphotic zone do not provide a suitable habitat for colonization.

Fish. Groundfish, particularly Atlantic cod, form the mainstay of the commercial fishery on the Scotian Shelf, although haddock and pollock are also important offshore species. The domestic seasonal fishery is directed towards herring, swordfish and tuna, whereas the foreign seasonal fishery is focused on silver hake and squid, which are species that are currently of low domestic value. Sand lance is an important prey species that spawns on sand bottoms throughout the Scotian Shelf. Adult cod overwinter along the middle and nearshore portions of the shelf. Haddock, silver hake and American plaice move into shallower bank waters during the spring.

In summer, the shelf is used extensively by a number of fish species. Silver hake spawn on the shallow bank regions of the shelf which are occupied also by adult and juvenile cod and haddock. Sable Island Bank is used by juvenile haddock and winter and yellowtail flounder, and is an important nursery and rearing area for several species. Cod, herring and winter flounder are concentrated in shallow water close to shore, whereas redfish and pollock are found in deep holes near shore.

In autumn, migratory species present on the Scotian Shelf move off the banks into deeper water or other wintering areas. Juvenile haddock, silver hake, tuna and swordfish migrate over the Central Zone of the shelf, while cod migrate from the shallow banks to deeper parts of the shelf to spawn. Mackerel and herring also migrate throughout the Central Zone, while other species such as pollock, redfish and argentine are present in deep holes near shore.

Development and Waste Discharge Scenario

The Venture Gas Field is located approximately 16 km east of the northeast tip of Sable Island and covers about 38 km^2. The production scenario is envisaged in the Mobil Oil Venture Development plan and submission:

1) Recoverable reserves from the Venture gas field are 85 x 10^9 m^3 produced at a rate of 11 x 10^6 m^3d^{-1}. The typical well depth is 6000 m and the reservoir covers an area of 38 km^2.

2) The offshore production complex envisaged will consist of two separate well-head platforms, a processing and utilities platform, a separate flare structure and an

accommodation platform. Platforms will be connected by bridges. Up to 40 wells may be required for the development of this gas field, and it is expected that directional drilling will be necessary. Gas and condensate will be transported to a landfall by a two-phase-flow subsea pipeline.

3) Drilling wastes will be discharged from each of the two well-head platforms. Processing and utilities wastes (including produced water) will be discharged from the processing platform, while sewage will be discharged from the accommodations platform.

Produced water discharges will be small from Venture gas production and are unlikely to exceed 65 m^3d^{-1} (Thomas et al. 1983). During development drilling, a total of 60,000 m^3 of drill cuttings will be discharged from the two wellhead platforms (based on a total of 40 wells). If only water-based drilling muds are used, 124,000 m^3 of drilling fluids would be discharged. If oil-based muds are used, no drilling fluids would be discharged to the sea.

The current schedule has initial field construction and development drilling starting in late 1984 and continuing into 1987. Up to four separate drilling units may be used during the development drilling. Use of paraffin oil-based drilling muds may be considered during the directional development drilling. Well-head platforms will be situated over well templates, and pipeline installation would take place during the summer of 1985.

Important Resources At Risk

The potential environmental consequences of the Venture Development were discussed in detail in the various EIS documents submitted by Mobil Oil. Many of the anticipated effects were expected to be limited to the construction phase (particularly installation of the subsea pipeline), and could include interference with fishing vessel operations, effects on benthos and fish due to seabed alterations and increased suspended sediment levels. Noise associated with aircraft overflights during the construction of offshore facilities and the subsequent operation of these facilities was identified as a potential source of moderate harm on the Sable Island tern population. The discharge of oiled cuttings (if oil-based mud systems are used) during development drilling was expected to have only a minor effect on benthic communities surrounding offshore production facilities, but warrants monitoring because of the input of considerable amounts of hydrocarbons to the sea bed.

Because produced-water discharges will be small for the Venture Gas Field Development (unlike oil development at Hibernia), significant effects on local benthic invertebrate and fish populations are not expected to result from routine operations at the offshore production facility.

EFFECTS MONITORING PROGRAM FOR HIBERNIA OIL PRODUCTION

PROGRAM RATIONALE

Four hypotheses were developed with respect to the release of oil-based drill cuttings and production wastes at Hibernia. These are shown in Figure 2 and discussed in detail in the following subsections. A more limited monitoring program is recommended for the Hibernia area if water-based muds are used because previous monitoring studies conducted to evaluate the effects of water-based mud discharges on the marine environment have shown repeatedly that effects are almost always short-range and short-term (Neff 1981; Petrazzuolo 1981; Ayers et al. 1980; Ecomar 1978). The results of many of these studies are summarized in Thomas et al. (1983) and provide the following indications:

1) Water-based drilling discharges are not very toxic. The majority of the materials used in water-based muds are either inert or non-toxic derivatives of natural products. 96-h LC50s for whole muds are typically in the range from 10,000 to 100,000 ppm;

2) Water-based drilling discharges have never been shown to cause any significant adverse effects on the open-ocean water column. This is due mostly to rapid settling and dilution. Water column concentrations of drilling fluid and its toxic components usually decline to values that are orders of magnitude lower than 96-h LC50s for marine fauna within metres of the discharge point. Background concentrations are usually reached within 1000 m downstream of the drill site; and

3) Water-based mud discharges may adversely affect the benthic community near the well site. The effect is often temporary and physical rather than toxic in nature. The only significant adverse effect which has been noted is burial of sessile organisms within 100 to 200 m of the well site.

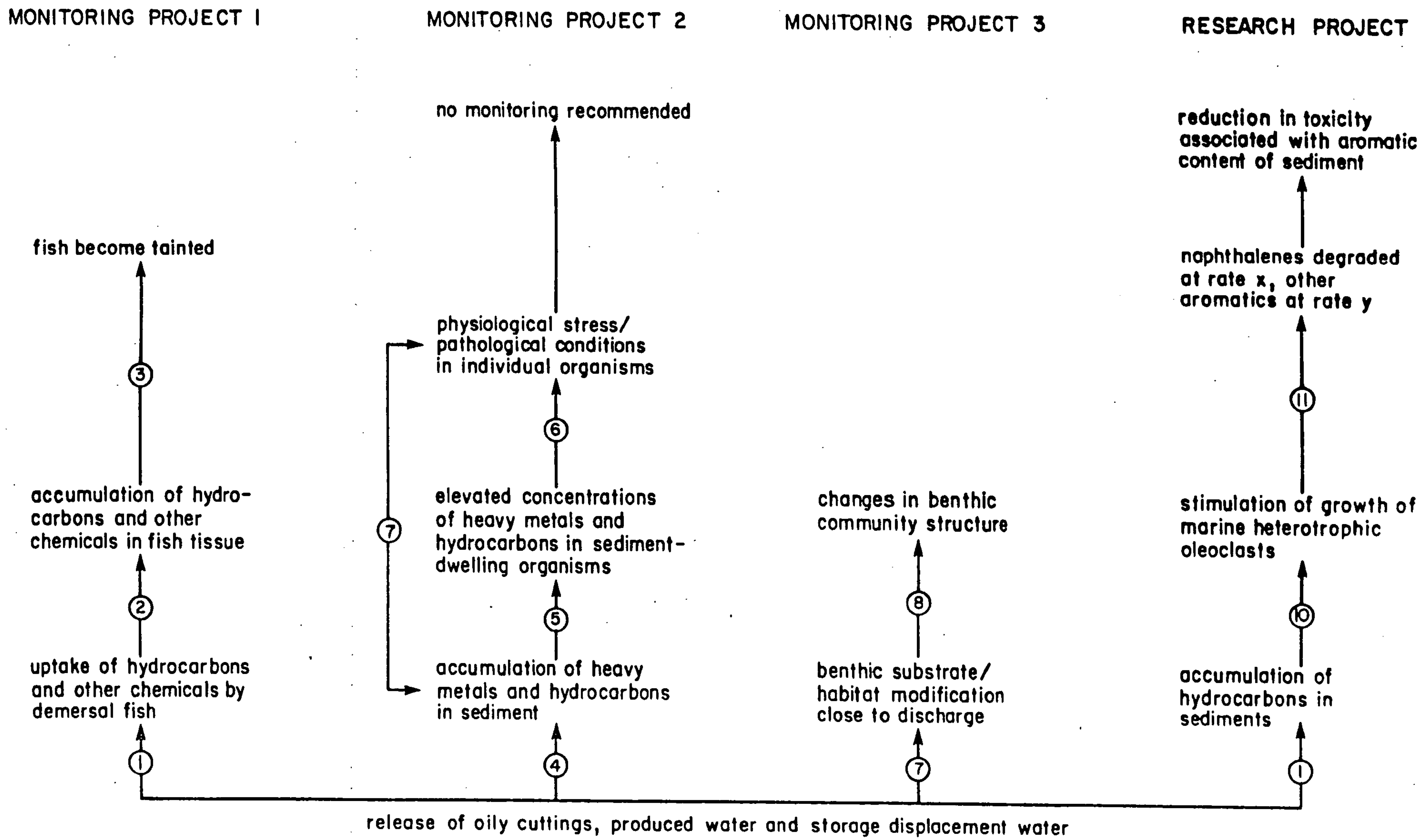
It must also be emphasized that the data base related to water-based drilling fluid discharge into the marine environment is extensive. In the United States alone, over 30,000 offshore wells have been drilled since 1927. No noticeable detrimental effects on fisheries have been observed during that time. In addition, the results of a large number of field and laboratory studies indicate that heavy metals associated with used drilling fluids have only a limited availability to marine fauna. Following a review of literature on this subject, Neff (1981) concluded that "the available evidence indicates that there is little likelihood that heavy metals would be accumulated from environmentally realistic levels of used (water-based) drilling muds in edible portions of shell or finfish to concentrations that would pose a health hazard to human consumers of such fishery products."

Consequently, water-based drilling mud discharges are not expected to be of concern at Hibernia (if they are to be used) provided that the formulations used are not significantly different from those upon which the previous experience has been based.

A limited monitoring program is recommended at Hibernia, however, even when water-based muds are used because produced water discharges remain a potential concern due to the large volumes (16,000 m^3d^{-1}; Thomas et al. 1983) which may be discharged from platforms, and because diesel oil is sometimes used to "spot" water-based muds. The monitoring strategy would be similar to that developed for oil-based muds (see section on Monitoring Project 2). The sediment should be the target environmental medium for monitoring because of the inherent difficulty in sampling the water column effectively and because the contaminants associated with produced water will tend to be removed from the water column when the suspended particulate matter sinks and becomes incorporated into the bottom sediments. The accumulation of metals, hydrocarbons and other waste components from produced water in the bottom sediments probably will be much slower and spread over a wider area than that expected when oil-based muds are used. Consequently, the number of sampling stations (and their spacing) and the frequency of sampling would be different from that required for the monitoring program associated with oil-based mud cuttings discharge.

In general, environmental information for the Hibernia area is considered adequate for the design of monitoring programs. Data on sediment patchiness are known to exist but are not yet interpreted. Other information obtained during various well-site surveys conducted by, or on behalf of, oil companies include data on tides, currents, water column structure and general oceanographic features. The general geochemistry of the Grand Banks is also documented to the extent required for the purposes of planning a monitoring program. Specific details regarding heavy metal and hydrocarbon geochemistry are lacking at well-site areas, although this is not considered a serious shortcoming because the recommended approach to monitoring will be to sample gradients in effects at progressive distances from the platform. Consequently, initial (pre-development) data are not required.

Figure 2 Hypothesis Link for Hibernia Monitoring Program



Experience from North Sea effects monitoring programs is relevant to Hibernia for several reasons:

1) The oil field technology proposed for use at Hibernia is similar to that used in the North Sea;

2) Both the North Sea and Grand Banks are cold-water environments;

3) The Grand Banks have an open-shelf water circulation similar to that found in the northern portion of the North Sea (note: the southern portion of the North Sea clearly has a different, more restricted oceanographic regime than that of the Grand Banks); and

4) The wave climates at Hibernia and in the North Sea are similar.

Experience from the North Sea indicates that some effects associated with offshore production are unavoidable within a certain distance of the platforms. Benthic organisms are smothered by discharged cuttings; benthic community structures are altered; hydrocarbons and heavy metals may accumulate in sediments, and anoxic conditions may result from the high organic loadings (E and P Forum 1983; Poley and Wilkinson 1983; UKOOA 1983).

MONITORING PROJECT 1

Hypothesis: **Offshore production facilities will discharge sufficient quantities of hydrocarbons and other chemicals to cause tainting of fish.**

Hypothesis Links:

1) Hydrocarbons and other chemicals present in water and sediments as a result of discharges from offshore production platforms will enter harvested fish species and the prey organisms of these fish.

2) Hydrocarbons and other chemicals can accumulate in fish tissues as a result of exposure.

3) Fish may become tainted following exposure to hydrocarbons and various other compounds.

Project Rationale. Petroleum hydrocarbons (particularly aromatic compounds) and persistent or non-naturally occurring chemicals will be present in oily cuttings discharges during development drilling and in other waste streams (including produced water and storage-displacement water) during actual production. Demersal and pelagic fish may be attracted to platforms because of the presence of food and warmer water, thereby increasing their exposure to sediments and water containing higher-than-background concentrations of hydrocarbons and other chemicals. If fish become tainted, or if human consumers merely suspect that fish have become tainted, serious consequences may result for the Grand Banks commercial fishery. Therefore, the type of monitoring recommended in connection with this hypothesis falls into the category of "comfort" monitoring.

Project Design. It is recommended that a taste panel be established to monitor for the presence of tainted fish. Cod and American plaice, two very important commercial fish species, would be preferred for these tests. Samples of fish should be collected on an opportunistic basis by supply boats operating near the offshore platform, while background or non-tainted fish should be obtained from the commercial fishery in areas far from the offshore platform.

The taste test would then involve a carefully controlled comparison of the taste of fish obtained from near the platform with that of fish obtained in areas distant from the platform. No chemical analysis of fish tissues would be necessary unless the presence of taint was established by the taste panel. If tainting were perceived, chemical techniques could be used to try to establish the source of contamination; appropriate mitigative actions could then be initiated through changes in waste treatment design or development and production operating procedures.

For the reasons given in the subsection on what to measure, it is recommended that the monitoring program include measurement of MFO activity in habitat faithful fish. This indicator provides evidence for exposure or non-exposure of fish to hydrocarbons and will be useful in either demonstrating that no detectable effects have occurred or demonstrating that detrimental effects have occurred, in which case additional sampling could be undertaken to delineate the approximate zone of impact.

MONITORING PROJECT 2

Hypothesis A: Offshore production facilities will discharge sufficient quantities of heavy metals and hydrocarbons to contaminate sediments and benthic biota within 500 m of the discharge point.

Hypothesis B: The heavy metals and hydrocarbons accumulated by benthic organisms will cause physiological stress responses and pathological conditions in these organisms.

Hypothesis Links:

4) Hydrocarbons and heavy metals will accumulate in the sediments surrounding offshore waste discharge sites.

5) Hydrocarbons and heavy metals can accumulate in the tissues of organisms living in or on the sediments affected by production waste discharges.

6) and 7) Physiological stress and pathological conditions can occur in organisms (a) in response to increased concentrations of hydrocarbons and heavy metals in tissues or (b) directly in response to contaminants in sediments, without any accumulation in the biota.

Project Rationale. Petroleum hydrocarbons will enter the water column and sea bed as a result of the discharge of oily cuttings (if oil-based muds are used) and to a lesser extent in other wastes such as produced water and storage-displacement water. Heavy metals will enter the sea-floor sediments primarily through drilling-waste discharges (drilling fluid if water-based muds are used, and formation cuttings). It is expected that society will consider a large and widespread increase in concentrations of heavy metals and hydrocarbons in sediments to be an unacceptable deterioration of environmental quality.

Project Design. The monitoring program should focus on the measurement of heavy metals and hydrocarbons in surficial sediments, for the purpose of detecting the magnitude of increases above background and the spatial extent of the contamination. It is important to realize that any effects of the production facilities will probably be localized, especially in the early stages of the development. Consequently, an appropriate sampling grid must be selected to allow for the detection of any effects. For example, at Hibernia the cuttings discharge from one well is expected to be about 800 m^3 (Thomas et al. 1983). This could result in the formation of a cuttings pile 20 x 20 x 2 m deep. Formation of a pile of this relatively small size is possible because cuttings coated with oil-based mud are very cohesive. In North Sea locations, having bottom current velocities similar to those found in the Hibernia area, virtually all cuttings were deposited within 30 m of the platform (Poley and Wilkinson 1983). At Hibernia, after one year (13 wells) there would be about 5200 m^2 or 0.7 percent of the area within a 500 m radius of the platform covered with drill cuttings to a depth of about 2 m. After complete development (40 wells in three years), this would increase to 2.0 percent of the area within a 500 m radius of the platform. A small proportion of the total cuttings load would be distributed over a much wider area.

Design of the sampling strategy is essential to the resolution of effects. The first step would be to complete a mass balance calculation to estimate the scale of the expected disturbance. Input data for waste volumes and characteristics would come primarily from compliance monitoring records. This approach would produce an estimate of the accumulation rate of a contaminant in the receiving sediment by taking into account the composition of the various drilling and production wastes, waste discharge rates, dispersion processes, and natural sedimentation processes.

Information on the development scenarios for Hibernia will be essential for the proper design of this monitoring program. For example, it is important to know if the wastes will be discharged through one or several point sources. Multiple point sources of waste discharge will exist if subsea completions are used. If the subsea completions must be maintained or interfaced on a regular basis, then cuttings on the seafloor will have to be removed or jetted away. This would result in very effective dispersion, although the zone of influence would possibly be greater because cuttings would be dispersed in a thinner layer over a wider area. In addition, if diesel-based muds are used, cuttings would probably be washed prior to discharge, and therefore the free oil content of the cuttings on the sea floor would likely be very low. On the other hand, if paraffin ("low-tox") muds are used, cuttings washing probably will not be required, and as a result, much greater amounts of free oil would enter the marine sediments. In the latter case, "weeping" of the oil from the cuttings would occur and the oil would be much more mobile in the sediments.

Use of the mass balance approach also will offer the advantage of being able to estimate whether a certain contaminant can be detected in the receiving environment. For example, it is assumed that an accumulation of 1 mm of drill cuttings could be expected in the surficial sediment after a certain period of time. (This thickness of drill cuttings deposition was observed by Poley and Wilkinson [1983] at a distance of 200 m from the platform in the Brent/Cormorant area of the North Sea during 1981.) Assuming that: (1) the cuttings had an oil content of 5 percent; (2) background sediment hydrocarbon concentration was 100 μgg^{-1}; and (3) the top 1 cm of sediment was sampled, then the oil originating from cuttings would be about 40 times background and, therefore, easily detected. Thinner accumulations of cuttings or the presence of other contaminants at lower concentrations would become progressively more difficult to resolve from background. The monitoring program design should take into account the probability of detection of each contaminant in waste discharges, and either eliminate from measurement at an early stage, those compounds or contaminants which are unlikely to be distinguishable from background, or consider special sampling and analytical techniques to improve the chances of detecting changes in contaminants that are environmentally important.

Coring is the preferred method for obtaining sediment samples for chemical analysis of the surface layer because an undisturbed sediment/seawater interface is required for accurate results. Sediment cores also provide an historical record of pre-development concentrations without the need for detailed pre-development baseline studies. The Craib corer (Craib 1965), a soft-landing, hydraulically damped gravity corer, is recommended as the best method for taking undisturbed cores from material ranging from soft fine mud to hard coarse sand. Baxter et al. (1981) suggest that the commonly encountered problems in core collection (loss of highly porous upper layers of sediment, significant shortening during penetration, mixing of layers, over-penetration, and tilting) can be eliminated to a great extent by using the Craib corer.

At Hibernia, the prevalent sediment types are sand and gravel in varying combinations. Consequently, grab sampling will have to be used at those locations where coring is difficult or not possible. The most effective grab samplers for sediments containing gravel are the Shipek grab and Smith-McIntyre grab. A properly and carefully deployed Smith-McIntyre grab is probably the most effective grab sampler for obtaining relatively undisturbed surface sediments. Care must be taken when using grab samplers because the bow wave from these devices can flush away the surface accumulation of contaminants, while wash-out during the retrieval process can cause loss of the fine surface material and alteration of sediment particle-size distribution. In addition, the surface layer can become diluted with sediment from deeper parts of the grab sample during the process of sampler penetration and retrieval and shipboard subsampling, thereby reducing the chance of detecting the presence of a contaminant in the surface layer. Because grab samplers may be the only alternative when coring devices fail, the problems associated with this technique must be considered and minimized throughout the monitoring progam.

It is expected that the collection of benthic biota at Hibernia for analysis of metal and hydrocarbon uptake could be successfully achieved by employing any one of several qualitative sampling devices including dredges, trawls and grab samplers (Smith-McIntyre, van Veen).

Sampling of benthic invertebrates for quantitative community analyses can create substantial problems because each sampling technique has inherent limitations and a variable efficiency with respect to collection of different members of the benthic community and different substrates. Epifauna can avoid some samplers, while infauna can retreat too deeply into burrows to be captured with most grabs. It is usually necessary to determine the number of samples required to provide valid estimates of the number of species present, population density and biomass of the benthos. This is determined empirically by constructing a species/area cumulative curve (Holme and McIntyre 1971), where the minimal sampling area is indicated by the position of the asymptote of the recruitment curve.

The sampling grid must also reflect the sampling strategy. It was recommended earlier that sampling should be focused on the area outside of the high-impact zone. A great deal of effort could be required to locate the position of a small pile of cuttings at a location near the platform. This could be both difficult and dangerous in close proximity to a production platform. Consequently, the sampling effort should be directed toward the detection of gradients in effects at progressive distances from the platform.

It is recommended that the system of two overlapping series of stations described earlier in the subsection on the sampling grid form the basis of the sampling network.

The following analyses should be completed on sediment samples collected at each station:

- hydrocarbons
- barium and chromium
- organic matter
- redox
- aluminum or silicon
- particle size distribution.

A practical strategy for hydrocarbon analyses of sediments would be to analyse samples by UV fluorescence, IR spectrophotometry or gravimetry as an inexpensive screening technique. Samples showing elevated hydrocarbon levels could then be examined in greater detail by GC or GCMS. It is considered appropriate to limit the heavy metal analyses to barium and chromium, since these two metals should be the best tracers of the drill cuttings discharge. Barium, in particular, should be a useful tracer of drilling fluid/cuttings discharge because it is conservative in marine sediments (i.e., its concentration in sediment will be affected only by dispersal). Metals should be analysed by atomic absorption or plasma emission spectrophotometry.

Metals are not homogeneously distributed over the various grain-size fractions of natural sediment. The finer-grained clay mineral fraction usually contains relatively high metal contents compared with the coarser fraction dominated by quartz components. Comparison of metal concentrations in various samples and the evaluation of metal contamination in sediments requires a correction for grain size. Several methods have been used; these include mechanical separation of grain-size fractions, extrapolation from regression curves (metal content vs. percent less than fraction), correction for inert mineral constituents (e.g., silicon-free sediment), treatment with dilute acids or complexing agents and comparison with "conservative" elements (e.g., metal/aluminum ratio) (Forstner 1980; Salomons and Forstner 1984). The need to account for grain size effects when interpreting analytical results for metals in sediments is, therefore, the rationale for including aluminum, silicon and particle-size distribution on the above list of parameters measured at each station during the monitoring program. Particle-size distribution and organic-matter content of sediments also will aid in the interpretation of results for humic substances and other organics that tend to be surface active and collect more on fine-to-medium-sized sediment grains than on coarser material (Salomons and Forstner 1984).

Quality assurance of chemical analyses is the fundamental basis upon which the level of confidence in chemical results is placed. Because the interpretation of analytical results is related directly to evaluation of cause-effect relationships, quality assurance is an essential part of an environmental effects monitoring strategy. The importance of quality assurance in measurement systems is discussed in detail in Taylor (1981), Keith et al. (1983) and Kirchmer (1983). It is recommended that a quality assurance program be an integral part of any environmental effects monitoring strategy and include:

1) blind replication of samples (approximately 10 percent);
2) standardization samples (approximately 10 percent);
3) intercalibration of methods and results with other laboratories (approximately 5 percent); and
4) archiving of replicate samples for potential future use with new parameters, checking results, or tracing changes in contaminant concentrations with time.

It is recommended that the following components not be included in a monitoring program at Hibernia at the present time:

1) Measurement of body burdens of hydrocarbons and heavy metals in benthic fauna should not be included in the monitoring program. In general, these analyses are difficult and costly to complete, and the results are almost never clearly interpretable. The major problem encountered during the interpretation of data on the accumulation in biota is determining the relevance of a specific tissue or body burden to the fitness of organisms or health of the community. Interpretation of such data also is hampered by the fact that organisms have the ability to detoxify, and acquire tolerance to, a wide range of environmental contaminants. For example, Jenkins and Brown (1984) suggest that rather than determine total body burden, a superior approach would be to measure the partitioning of contaminants between sites of detoxification and sites of toxic action, because it is only those contaminants which reside at sites of toxic action that pose a direct problem to an organism. The details of this approach are not yet resolved fully; remaining questions include variability of detoxification limits seasonally, within populations, between populations and between species, and the influence of other stresses such as temperature/ salinity changes, moulting and reproduction on toxification/detoxification mechanisms.

2) Examination of physiological stress responses and pathological conditions in individual benthic organisms should not be included in the monitoring program. Techniques such as measurements of metalloenzyme induction,

various histopathological changes and lysosomal latency are still evolving. Their potential usefulness as monitoring tools has, therefore, yet to be established.

MONITORING PROJECT 3

Hypothesis: **Offshore production facilities will discharge sufficient quantities of wastes to alter benthic sediment chemistry and substrate and habitat characteristics near the discharge site, and these factors will cause an alteration in benthic community structure.**

Hypothesis Links:

7) Drill cuttings will accumulate in the sediments near the platform. Oxidation of associated hydrocarbons will cause anoxic conditions. Cuttings piles will alter substrate composition and modify benthic habitat.

8) Changes in benthic community structure will occur.

Project Rationale. Changes in benthic community structure often occur near a source of chemical pollution or physical disturbance. For example, the presence of one- and two-ring aromatic compounds may result in the loss of certain species from the community (due to toxic effects), and at the same time encourage the proliferation of opportunistic species. Studies of changes in benthic community structure have been a successful component of effects monitoring programs in the North Sea (Dicks 1982; Hartley 1982).

Project Design. It is recommended that studies be initiated to monitor the numerical abundance and species composition of benthic communities around the Hibernia development. Samples should be collected at the dual grid stations described in Monitoring Project 2. The program should focus on delineation of gradients in effects. Essential supporting measurements should include sediment hydrocarbon (total) and heavy metal concentrations and sediment particle-size distribution. Sample replication should be adequate to allow resolution and statistical description of spatial gradients, and provide the necessary number of samples for supporting analyses and archiving.

The interpretation of benthic community data can be hampered seriously by the lack of standardized methods. There have been many cases in the North Sea and Gulf of Mexico where intercomparison of data sets has not been possible because of differences in sample collection and work-up methods. Consequently, every attempt should be made to standardize methods for the Hibernia effects monitoring program in three ways:

1) Sampling Device: Sample efficiency, depth of bite, area sampled, and volume sampled should be evaluated and selected by organizations or persons undertaking the monitoring program. The ability of the various sampling devices to obtain representative samples should be determined in the early stages of the program, through field trials at Hibernia, if necessary.

2) Sieve Size: Two sizes of sieves (0.5 mm and 1.0 mm) have been used to remove benthic fauna from sediments in most investigations. A consistent approach should be adopted for Hibernia. Evaluation of the most suitable sieve size should consider the species composition of benthic communities in the study area, and the relative efficiency of each sieve size in obtaining a representative sample.

3) Taxonomy: An attempt should be made to "calibrate" taxonomists. Large biases can occur in taxonomic results because of the different sorting/identification efficiencies of various taxonomists. An emphasis should be placed on independent identifications by recognized experts.

SUPPORTING RESEARCH

Hypothesis: **Petroleum hydrocarbons will enter sediments around the Hibernia oil production facilities from waste discharges directly to the sea floor and to the water column above. These hydrocarbons will be selectively degraded by oleoclastic bacteria. Naphthalenes will be degraded 'x' times more quickly than higher molecular weight aromatics.**

Hypothesis Links:

9) Petroleum hydrocarbons will accumulate in sediments surrounding the Hibernia oil production site.

10) Growth of marine heterotrophic bacteria will be stimulated in these areas.

11) Naphthalenes will be degraded at a rate 'x', in comparison to a rate 'y' for other aromatics; bacterial degradation will lead to a reduction in the total toxicity associated with the aromatic content of the sediments.

Project Rationale. Determination of the residence time of aromatics, and of the metabolites of aromatic compounds (which may be more toxic than the parent compounds), is necessary to assess the environmental significance of these contaminants. In general, naphthalenes cause significant environmental damage because they are among the most toxic of the aromatic compounds to marine organisms.

The workshop participants did not endorse this project as a necessary part of the monitoring strategy for Hibernia. Rather, it was believed that the project had merit as a potential research program.

PILOT PROJECT

A large part of the reasoning that was used to establish hypotheses and evaluate concerns related to offshore hydrocarbon production facilities at Hibernia was based on experiences from the North Sea and Gulf of Mexico. Events at Hibernia should lie within the range of this previous experience. Consequently, the above monitoring strategy should delineate the nature and spatial extent of projected consequences adequately. However, the most appropriate sampling techniques and other special considerations in the Hibernia region can be determined only through direct experience. A small-scale pilot project is, therefore, a logical initial step toward implementation of a larger monitoring program.

There is an opportunity for this approach to be followed at Hibernia. The drilling of one or more delineation wells probably will occur at Hibernia in the near future using low-toxicity paraffin oil-based muds.

It is recommended that this situation be used to advantage in developing a final monitoring strategy and in identifying the most appropriate sampling methods for the Hibernia region. A sampling survey should be conducted as near to the time of completion of drilling activities as possible, but while supply boats are still operating in the area. The objectives of the survey should be to:

1) Collect sediment core samples and evaluate various samplers and methods of sampling;

2) Obtain additional samples of substrates and of the benthic invertebrate community;

3) Locate the cuttings pile with side-scan sonar techniques, sample in a grid centered from the pile, and assess the detection limit for specific chemical tracers in the surficial sediments surrounding the cuttings pile; and

4) Obtain estimates of the variance of parameters measured for development of a statistical model which is needed to determine the sampling design (replication, frequency of sampling, spatial grid dimensions) necessary to detect the expected effects.

DATA SYNTHESIS AND INTERPRETATION

Few field studies, no matter how well planned, are ever completed without some departure from the original plan. It follows, therefore, that a good understanding of the preliminary results of an ongoing study should form the basis of any alteration to a study plan. The authors recommend that field data should be worked up as quickly as possible following the completion of each field segment of a monitoring program, so that the following four questions can be answered:

1) Are sampling techniques, calibration procedures, number of replicates, supporting measurements and frequency of sampling adequate?

2) Do results form a coherent data set? If not, attempts should be made to determine why not, so that the problems can be corrected.

3) Are analytical procedures "in control"? If not, changes are warranted before any additional sampling is conducted.

4) Do the data provide the information required to fulfil the objectives of the monitoring plan?

The primary purpose for the internal interdisciplinary audit and interpretation of results described above is to keep the project dynamic and flexible, to avoid the all-too-frequent situation of detecting serious problems and shortcomings of expensive environmental studies only after the project has been completed.

EFFECTS MONITORING PROGRAM FOR VENTURE GAS PRODUCTION

PROGRAM RATIONALE

Waste discharges from development and production of gas and condensate at the Venture field will be limited, except for discharges of drill cuttings, and of drilling fluids if water-based muds are used. Although little produced water would be released during operation of the facilities, it may have a higher aromatic hydrocarbon content than similar waste streams at the Hibernia oil field. However, no storage displacement water will be associated with the Venture development, and smaller quantities of chemicals will be used to treat the low-volume wastes during production. As indicated in an earlier section, most detrimental effects of the Venture development are likely to be associated with the construction of the pipeline and onshore facilities; therefore, they are not relevant to this report.

The receiving environment in this region is shallow and dynamic, and is characterized by considerable coupling of surface and bottom processes. As a result of these energetic processes, the sea bed is covered with relatively homogeneous sand, with major sand wave activity. The immediate area of the Venture development is expected to have high dispersal capacity for wastes. It is a productive commercial shelf area with several important fish species.

There are believed to be two possible sinks for pollutants entering this area; these are located behind Sable Island and in the deeper canyons on the shelf. However, inputs of pollutants to these sinks, as a result of waste discharges associated with the Venture development, are expected to be minor.

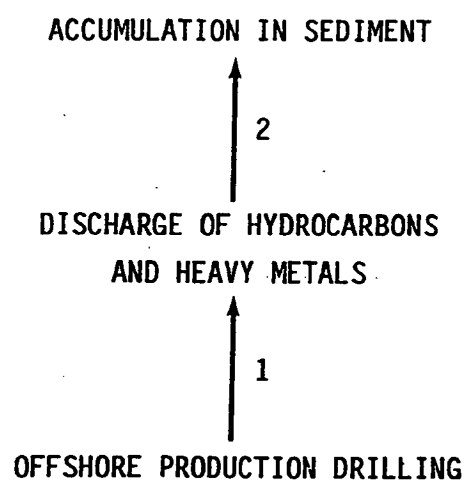
Rationale 1: Use of Water-Based Muds (Only). As indicated earlier, there is a vast literature on the use and effects of water-based drilling muds, and it is generally agreed that environmental disturbances from mud disposal in offshore areas are both local and short term. This limited degree of environmental concern, in conjunction with the low level of production wastes expected from routine operations at Venture, and the highly dispersive nature of the receiving environment, led workshop participants to conclude that no monitoring of the marine environment would be necessary if water-based muds were used throughout exploration and production drilling. It was suggested, however, that some limited attention should be directed at monitoring bird movements in the vicinity of operations due to possible harm to important species in this region, such as roseate tern.

Rationale 2: Use of Oil-Based Muds. Available information suggests that oil-based drilling muds will not be required at Venture. However, with their increased use in development drilling of deviated holes through deep strata in other parts of the world, it is important to consider a monitoring strategy in the event that oil-based muds are eventually used for this development.

The North Sea experience with oil-based drilling muds provides some useful guidelines for the design of a monitoring program for Venture. However, the shallower water and highly dynamic sediments are unique factors which must be considered in this region. The present experimental use of paraffin-based muds by Shell Canada Resources at the Alma F-67 well on the Scotian Shelf could provide fundamental information on the behaviour of oily cuttings in such a dynamic environment. Pre- and post-drilling environmental studies that are being conducted at this site could provide a basis for the design of a pilot project to assess the possible requirements of a detailed monitoring plan for Venture.

MONITORING PROJECT 1

Hypothesis: **Offshore production drilling discharge of 'x' tonnes of cuttings containing 'y' percent oil will result in an increase in hydrocarbon and heavy metal accumulation in sediments within 500 m of each well-head platform.**



Hypothesis Links:

1) Petroleum hydrocarbons will be discharged with drill cuttings if oil-based muds are used; heavy metals will be discharged with drilling fluids if water-based muds are used.

2) Hydrocarbons and heavy metals will accumulate in the sediments surrounding drilling-waste discharges.

Project Rationale. A large decrease in environmental quality, in the form of increases in hydrocarbons or heavy metals within marine sediments, is considered unacceptable by society. Such contamination of marine sediments also could increase the risk of contamination and subsequent effects on benthic infauna and other organisms closely associated with the sea floor, including commercially harvested species (see next subsection).

Project Design. The present development scenario for Venture indicates that drilling will be completed from two platforms (20 wells each) located 2 km apart. As a result, there will be two point sources of cuttings discharge and a potential for overlap of the zones of influence of each platform.

Unlike the situation at Hibernia, the more homogeneous nature of the sediments would make a general grid-sampling strategy with predetermined station locations feasible at Venture. Nevertheless, a dual overlapping grid system, with one grid aligned to the direction of net residual current flow, is recommended to minimize the risk of not sampling contaminated areas which are upstream of the predominant zone of impact. The possible mixing of surface sediments and burial of oily cuttings in this area would necessitate the use of corers to obtain a true record of the fate of cuttings. In addition, it is recommended that flexibility in the design of the monitoring program be retained, to allow changes to be incorporated into the plan should development audits suggest new sources of environmental risk.

Contaminants and Chemical Analysis. Hydrocarbons resulting from the discharge of oil-contaminated drilling cuttings should be identified in marine sediments as follows:

1) "Total hydrocarbons" (e.g., by IR spectrophotometry or gravimetry);
2) Aromatic hydrocarbons initially screened by a method such as UV-fluorescence; and
3) If screening suggests elevated hydrocarbon levels, examination of samples in greater detail by GCMS.

Analyses of heavy metals expected to be derived from drilling muds should be limited to barium and chromium. Concentrations of these metals in sediment samples should be determined using atomic absorption or plasma emission spectrophotometry.

Analytical methods which are selected finally should be those frequently employed in successful effects monitoring programs, and should include full standardization procedures including intercalibration with independent laboratories.

Contaminant monitoring should be related to general sediment characteristics by measurement of:

- particle size analysis
- organic matter (or organic carbon)
- redox.

Sampling. Initially sampling should be conducted over a grid covering the expected zone of influence of the two platforms. Twenty to thirty stations extending 2 km from platform centres will be necessary. As in the case of the Hibernia monitoring program, most stations should be located outside the "high impact zone" (200-500 m) surrounding each platform. Later in the monitoring program, it may be possible to reduce the number of stations and establish an orientation based on local hydrography and the documented pattern of cuttings dispersal. It may be desirable to collect a limited number of samples at stations within suspected sinks, such as deep canyons.

Although some samples should be taken by a conventional grab, such as the 0.1-m^2 Van Veen, to allow integration with any benthic community studies, it is recommended that chemical samples be collected by a corer that takes undisturbed samples (e.g., box corer). Use of a diver to collect benthic samples for chemical analyses may be possible and practical on the Scotian Shelf, at least in areas where diver operations do not represent a hazard to production facilities. Visual inspection of the seabed being sampled (e.g., by video) is strongly recommended. The degree of core division for analysis should depend on stratification of sediment within the core and any evidence of the actual location of cuttings.

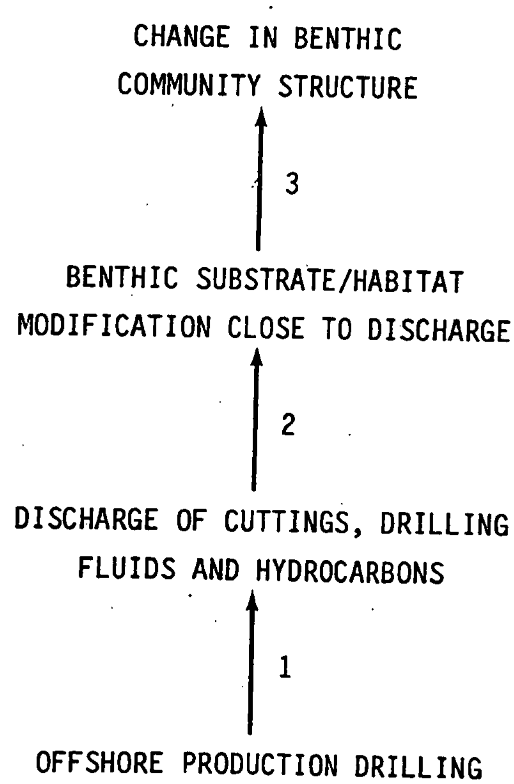
At least three replicate samples should be taken at each station, although a pilot study and initial screening is the recommended approach to determine the final work-up strategy. Such preliminary surveys should be undertaken prior to development drilling and again after completion of the main development drilling phase.

As with the Hibernia monitoring program, this project should include:

1) blind replication of samples;
2) standardization samples;
3) intercalibration of methods with other laboratories; and
4) archiving of replicate samples for potential future use in examining new parameters, checking results, or tracing changes in contaminant concentrations with time.

MONITORING PROJECT 2

Hypothesis: **Offshore production facilities will discharge sufficient quantities of wastes to alter benthic sediment chemistry and substrate and habitat characteristics near the discharge site, and these factors will cause an alteration in benthic community structure.**



Hypothesis Links:

1) Cuttings, drilling fluids and hydrocarbons will be discharged periodically to the marine environment during offshore production drilling.

2) Drill cuttings will accumulate on the sea bed near the well-head platforms. Oxidation of associated hydrocarbons (if oil-based muds are used) will cause anoxic conditions. Cuttings piles will alter substrate composition.

3) Toxic effects (hydrocarbon toxicity, anoxia) and substrate alteration will cause an alteration in benthic community structure.

Project Rationale. North Sea monitoring programs conducted at sites where oily cuttings have been discharged provide clear evidence of a significant gradient in the effects of these wastes on benthic community structure. If oil-based muds are used at Venture and oil-contaminated cuttings are discharged to the marine environment, a monitoring program should be initiated to determine effects of these discharges on benthic community structure (particularly infauna).

Project Design. Physical disturbance, organic enrichment and specific toxic effects of hydrocarbons (particularly one- to two-ring aromatics), or combinations of these factors, can cause changes to benthic community structure in habitats affected by oily cuttings discharge. These changes may be manifested in loss of certain species, altered dominance of remaining species, and the appearance of opportunistic species.

Sampling. Stations for benthic community monitoring should be identical to those selected for chemical contaminant monitoring, and replicate grab samples (e.g., 0.1-m^2 Van Veen) should be collected at each station. The number of replicates should be determined following evaluation of the results of pilot studies. Initially, sample work-up may be restricted to selected stations until chemical contamination gradients are established.

The sand bottom community around Sable Island is dominated by sand dollars. Little is known about the associated infaunal community except that shifting sand substrates do not generally support large populations of infauna. The large mobile epifauna such as sand dollars and scallops, which also occur in the area, are not efficiently sampled by grab samplers because of the scale at which they are distributed in relation to the size of quantitative samplers. For this reason, quantitative community sampling to obtain estimates of species densities in the Sable Island area may not be accomplished easily . There are presently no good quantitative methods for censusing benthic communities on scales of both tens of metres and centimetres. Sleds, trawls and dredges are all qualitative (or semi-qualitative at best) and not suitable for providing density estimates in community studies. If data on specific target species such as scallops and sand dollars are required, then towed samplers with smaller-mesh bags may be used to obtain sufficient numbers of individuals for use in contaminant assays, or determination of size-frequency relationships. Photographic or video surveys may be used to quantitatively census the larger epibenthos, although this approach is ineffective for smaller fauna.

It is apparent that no one method will be appropriate for sampling in the Sable Island area. A combination of approaches should be taken for specific components of the benthos. If grab samples are obtained, the limitations of this technique on shifting sand substrates should be recognized. In addition, use of a smaller sized mesh (0.5 mm) for sieving samples is recommended because infauna will be probably very small. It should be recognized that some of these infauna may fall in the meiofauna size classification and would therefore still not be retained on the 0.5 mm mesh. The degree of sample replication required should be determined in a preliminary survey.

There are opposing arguments regarding the value of regular pre-operational surveys, although it is recommended that at least one such survey be undertaken. This survey should be conducted at a time that avoids the period of annual juvenile recruitment. A major survey should be undertaken immediately after the completion of production drilling, followed by additional programs at one- to two-year intervals. Although initial sampling should extend over a complete station grid, sample work-up in post-drilling surveys could be restricted to stations along defined chemical contamination gradients.

As indicated above, benthic samples should be sieved through a 0.5-mm mesh screen with emphasis placed on resolution of spatial gradients in community structure. As identified earlier for the Hibernia monitoring program, it is considered essential that the effects monitoring strategy include "confirmatory" identifications by recognized experts and the archiving of a proportion of the samples for potential future time-series analyses. Data analysis should include determination of a range of indices of community structure.

REFERENCES

Addy, J.M., D. Levell, and J.P. Hartley. 1978. Biological monitoring of sediments in the Ekofisk Oilfield. In: Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills, American Institute of Biological Sciences, June 1978, Keystone, Colorado, p. 514-539.

Allen, J. 1980. Untitled paper on physical environment. In: Proceedings of Offshore Environment in the 80's. Workshop held in St. John's, Newfoundland, December 2-4, 1980. Sponsored by East Coast Petroleum Operators Association, Environment Canada, Dalhousie University, Memorial University, Newfoundland Department of the Environment, Nova Scotia Department of the Environment.

Ayers, R.C. Jr., T.C. Sauer Jr., R.P. Meek, and E. Bowers. 1980. An environmental study to assess the impact of drilling discharges in the mid-Atlantic. In: Proceedings of a Symposium on Research on Environmental Fate and Effects of Drilling Fluids and Cuttings, Washington, D.C. Courtesy Associates: 382-418.

Baxter, M.S., J.G. Farmer, I.G. McKinley, D.S. Swan, and W. Jack. 1981. Evidence of the unsuitability of gravity coring for collecting sediment in pollution and sedimentation rate studies. Environmental Science and Technology 15(7):843-846.

Bedinger, C.A. Jr. 1981a. Executive summary. In: Bedinger, C.A. Jr. (ed). Ecological Investigations of Petroleum Production Platforms in the central Gulf of Mexico, Volume III: 29 p. Report from Southwest Research Institute, San Antonio, Texas, to the U.S. Bureau of Land Management, New Orleans, Louisiana.

Bedinger, C.A. Jr. (ed.). 1981b. Ecological investigations of petroleum production platforms in the central Gulf of Mexico. Report from Southwest Research Institute, San Antonio, Texas, to the U.S. Bureau of Land Management, New Orleans, Louisiana. Volume I, Pollutant fate and effect studies, approx. 1768 p.; Volume II, The artifical reef studies, 199 p.; Volume III, Executive summary, 29 p.

Bedinger, C.A. Jr., R.E. Childers, J.W. Cooper, K.T. Kimball, and A. Kwok. 1981. Background, program organization and study plan. In: Bedinger, C.A. Jr. (ed.). Ecological Investigations of Petroleum Production Platforms in the central Gulf of Mexico, Volume I:1-53. Report from Southwest Research Institute, San Antonio, Texas, to the U.S. Bureau of Land Management, New Orleans, Louisiana.

Bender, M.E., D.J. Reish, and C.H. Ward. 1979. Re-examination of the offshore ecology investigation. Chapter III, Independent appraisal, p. 35-116. In: Ward, C.H., M.E. Bender, and D.J. Reish (eds.). 1979. The Offshore Ecology Investigation: Effects of Oil Drilling and Production in a Coastal Environment. Rice University Studies, Volume 65 (Nos. 4 and 5):35-116. William Marsh Rice University, Houston, Texas. 589 p.

Britoil. no date. The Beatrice Project Environmental Monitoring Programme. The British National Oil Company, Aberdeen U.K.

Brusset, H.L. 1981. Drilling considerations for exploration offshore Newfoundland. Drilling Canada, May/June: 43-48.

Burns, K.A. 1976. Microsomal mixed function oxidases in an estuarine fish, Fundulus heteroclitus, and their induction as a result of environmental contamination. Comparative Biochemical Physiology 53:443-446.

Coleman, N. 1980. More on sorting benthic samples. Marine Pollution Bulletin 11:150-152.

Craib, J.S. 1965. A sampler for taking short undisturbed marine cores. Journal du Conseil International pour l'Exploration de la Mer 30(1):34-39.

Davies, J.M., R. Hardy, and A.D. McIntyre. 1981. Environmental effects of North Sea oil operations. Marine Pollution Bulletin 12:412-416.

Department of Energy. U.K. 1983. Regulation of oil containing discharges resulting from offshore drilling operations. Proposed schedules attached to Section 23 of the Prevention of Oil Pollution Act 1971: PED4b, 10 November.

Dicks, B. 1982. Monitoring the biological effects of North Sea platforms. Marine Pollution Bulletin 13(7):221-227.

Ecomar, Inc. 1978. Tanner Bank mud and cuttings study. Conducted for Shell Oil Company. Ecomar Inc., Goleta California. 495 p.

Fader, G.B. and L.H. King. 1981. A reconnaissance study of the surficial geology of the Grand Banks of Newfoundland. Current Research, Part A, Geological Survey of Canada Paper 81-1A:45-56.

Ferbrache, J. 1982. Forties Field benthic surveys. A review with recommendations for future requirements. BP Petroleum Development (U.K.) Ltd., Exploration and Production. 14 p.

Forstner, U. 1980. Trace metal analysis on polluted sediments. Environmental Technology Letters 1:494-527.

E and P Forum. 1983. Oil-based drilling muds. Review of environmental effects of discharged cuttings. Exploration and Production Forum. London. 23 p.

Fucik, K.W. and I.T. Show. 1981. Environmental synthesis using an ecosystem model. In: Middleditch, B.S. (ed.). Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study:329-353. Plenum Press, New York.

Gallaway, B.J. and F.J. Margraf. 1979. Simulation modelling of biological communities associated with a production platform in the Buccaneer oil and gas field. NOAA Technical Memorandum. NMFS-SEFC-37. 49 p.

Gallaway, B.J., L.R. Martin, R.L. Howard, G.S. Boland, and G.S. Dennis. 1981. Effects on artificial reef and demersal fish and macrocrustacean communities. In: Middleditch, B.S. (ed.). Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study:237-299. Plenum Press, New York.

Goldberg, E.D., V.T. Bowen, J.W. Garrington, G. Harvey, J.H. Martin, P.L. Parker, R.W. Risebrough, W. Robertson, E. Schneider, and E. Gamble. 1978. The mussel watch. Environmental Conservation 5(2):101-125.

Gray, J.S. 1980. Why do ecological monitoring? Marine Pollution Bulletin 11:62-65.

Gray, J.S. 1981. The ecology of marine sediments. Cambridge University Press. Cambridge, 185 p.

Gray, J.S. and F.B. Mirza. 1979. A possible method for the detection of pollution-induced disturbance on marine benthic communities. Marine Pollution Bulletin 10:142-146.

Hartley, J.P. 1979. Second biological survey of the benthic sediments in the Forties oil field. June 1978. Report for BP Petroleum Development Ltd. Oil Pollution Research Unit, Orielton Field Centre, Pembroke, Dyfed, Wales. 50 p.

Hartley, J.P. 1982. Methods for monitoring offshore macrobenthos. Marine Pollution Bulletin 13:150-154.

Hartley, J.P. and D.M. Cartlidge. 1982. Third biological survey of the benthic sediments in the Forties oil field, June 1981. Report for BP Petroleum Development Ltd. Oil Pollution Research Unit, Orielton Field Centre, Pembroke, Dyfed, Wales. 64 p.

Holme, N.A. and A.D. McIntyre (eds.). 1971. Methods for the study of marine benthos. International Biological Program Handbook No. 16. Blackwell, Oxford and Edinburgh. 334 p.

Hutcheson, M.S., P.L. Stewart, and J.M. Spry. 1981. The biology of benthic communities of the Grand Banks of Newfoundland (including the Hibernia area). Unpublished MacLaren Plansearch Report for Mobil Oil Canada, Ltd. 99 p.

IOE (Institute of Offshore Engineering). 1978. Murchison Field. Environmental Baseline Study. August 1978 Survey. Report for Conoco North Sea Inc. Heriot-Watt University, Edinburgh. 140 p.

IOE (Institute of Offshore Engineering). 1982. Offshore environmental monitoring - North Sea experience. Report for Mobil Oil Canada Ltd. Heriot-Watt University, Edinburgh. 213 p.

Jenkins, K.D. and D.A. Brown. 1984. Determining the biological significance of contaminant bioaccumulation. In: H. White (ed.). Concepts in Marine Pollution Monitoring, Proceedings of the Workshop on Meaningful Measures of Marine Pollution Effects. University of Maryland Sea Grant Program. College Park, Maryland, U.S.A. 258 p.

Johnston, C.S. 1982. The role of environmental audit and survey in offshore production management. Paper Presented at European Petroleum Conference, London. SPE 291:167-172.

Johnston, C.S. and J.F. Appelbee. 1981. Strategy for environmental studies in North Sea oil development. Procedings of Offshore Europe '81 Conference, OE81 SPE10407.1. Aberdeen.

Keith, L.H., W. Crummett, T. Dugan, R.F. Libby, J.K. Taylor, and G. Wantler. 1983. Principles of environmental analysis. Analytical Chemistry 55:2210-2218.

Kirchmer, C.J. 1983. Quality control in water analyses. Environmental and Scientific Technology 17:174A-181A.

Law, R.J. and R.A.A. Blackman. 1981. Hydrocarbons in water and sediments from oil-producing areas of the North Sea. ICES CM 1981/E:16. Copenhagen.

Law, R.J., R.A.A. Blackman, and T.W. Fileman. 1982. Surveys of hydrocarbons around five North Sea oil production platforms in 1981. ICES CM 1982/E:14. Copenhagen.

Massie, L.C., A.P. Ward, J.S. Bell, H.A. Saltzmann, and P.R. Mackie. 1981. The levels of hydrocarbons in water and sediments in selected areas of the North Sea, and the assessment of biological effect. ICES CM 1981/E:44. Copenhagen.

Mauer, D. and W. Leathem. 1981. Ecological distribution of polychaetous annelids from the New England Outer Continental Shelf, Georges Bank. International Revue Geshalt Hydrobiology 66:505-528.

McIntosh, A.D., L.C. Massie, and P.R. Mackie. 1983. A survey of hydrocarbon levels and some biodegradation rates in water and sediments around North Sea oil platforms, 1981, 1982. ICES CM 1983/E:42. Marine Environmental Quality Commission. Copenhagen.

McIntosh, A.D. and A.P. Ward. 1982. The levels of hydrocarbons in the water and sediments in areas around Sullom Voe and the Beatrice oil field. ICES CM 1982/E:42. Copenhagen.

Menzie, C.A. 1983. Environmental concerns about offshore drilling --muddy issues. Oceanus 26(3):32-38.

Menzies, R.J., J.P. Morgan, S.Z. El-Sayed, and C.H. Oppenheimer. 1974. The offshore ecology investigation, final project planning council consensus report. Gulf Universities Research Consortium, Houston, Texas. Report Number 138. 39 p.

Menzies, R.J., J.P. Morgan, S.Z. El-Sayed, C.H. Oppenheimer, and J.M. Sharp. 1979. Design of the offshore ecology investigation. Chapter II, Methods and summary results. In: Ward, C.H., M.E. Bender, and D.J. Reish (eds.). 1979. The Offshore Ecology Investigation: Effects of Oil Drilling and Production in a Coastal Environment. Rice University Studies, Volume 65 (Nos. 4 and 5):19-32. William Marsh Rice University, Houston, Texas.

Middleditch, B.S. 1981a. Environmental effects of offshore oil production - the Buccaneer gas and oil field study. Plenum Press. New York and London. 446 p.

Middleditch, B.S. 1981b. Biocides. In: Middleditch, B.S.(ed). 1981 Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study: 55-57. Plenum Press, New York.

Middleditch, B.S. 1982. Research issues relating to ecological effects of offshore oil and gas production. Technical Report to Outer Continental Shelf Environmental Task Force, Gulf Universities Research Consortium, Bellaire, Texas. 11 p. (unpublished).

Middleditch, B.S. 1984. Ecological effects of produced water effluents from offshore oil and gas production platforms. Ocean Management (in press).

Middleditch, B.S. and B.J. Gallaway. 1981. Prologue. In: Middleditch, B.S. (ed.). 1981 Environmental Effects of Offshore Oil Production: The Buccaneer Gas and Oil Field Study:1-14. Plenum Press, New York.

Northwest Atlantic Fisheries Organization 1983. Statistical Bulletin Volume 31. Fishery Statistics for 1981. Northwest Atlantic Fisheries Organization, Dartmouth, Canada. 276 p.

Neff, J.M. 1981. Fate and biological effects of oil well drilling fluids in the marine environment: a literature review. A report prepared by Battelle New England Research Laboratory for Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Gulf Breeze, Florida. 151 p.

Nesis, K.I. 1965. Biocoenoses and biomass of benthos of Newfoundland-Labrador region (in Russian). Fisheries Research Board of Canada Translation Series No. 1375. 74 p.

Payne, J.F. 1976. Field evaluation of benzopyrene hydroxylase induction as a monitor for marine petroleum pollution. Science 191:945-946.

Pearson, T.H. and A. Eleftheriou. 1981. The benthic ecology of Sullom Voe. Proceedings of the Royal Society of Edinburgh. 81B:241-269.

Petrazzuolo, G. 1981. Preliminary report: an environmental assessment of drilling fluids and cuttings released onto the Outer Continental Shelf. Volume 1: Technical Assessment. Volume 2: Tables, Figures and Appendix A. Draft report prepared for Industrial Permits Branch Office of Water Enforcement and Ocean Programs Branch, Office of Water and Waste Management, U.S. Environmental Protection Agency, Washington, D.C., U.S.A.

Petrie, B. 1980. Physical characteristics of the marine ecosystem: an Atlantic east coast example. In: Proceedings, Offshore Environment in the 80's. Workshop held in St. John's, Newfoundland, December 2-4, 1980. Sponsored by East Coast Petroleum Operators Association, Environment Canada, Dalhousie University, Memorial University, Newfoundland Department of Environment, and Nova Scotia Department of Environment.

Petrie, B. and C. Anderson. 1983. Circulation on the Newfoundland Continental Shelf. Atmosphere - Ocean 21:207-226.

Poley, J.P. and T.G. Wilkinson. 1983. Environmental impact of oil base mud cuttings discharges - a North Sea perspective. Paper presented at IAOC/SPE 1983 Drilling Conference, New Orleans. IADC/SPE 11400:335-339.

Salomons, W. and U. Forstner. 1984. Metals in the Hydrocycle. Springer-Verlag, Berlin. 349 p.

Sandeman, E.J. 1980. The fish and shellfish resources of the offshore area. In: Proceedings, Offshore Environment in the 80's. Workshop held in St. John's, Newfoundland, December 2-4, 1980. Sponsored by East Coast Petroleum Operators Association, Environment Canada, Dalhousie University, Memorial University, Newfoundland Department of Environment, and Nova Scotia Department of Environment.

Stanley, D.J. and N.P. James. 1971. Distribution of Echinarachnius parma Lamarch and associated fauna on Sable Island Bank, southeast Canada. Smithsonian Contributions to Earth Science No. 6.

Stegeman, J.J. 1978. Influence of environmental contamination of cytochrome P-450 mixed function oxygenases in fish: Implications for recovery in the Wild Harbour Marsh. Journal of Fisheries Research Board of Canada 35:658-674.

Stewart, P.L. 1983. Measurements of benthic macroinvertebrate standing crop from the Canadian Continental Shelf and slope of southern Davis Strait and Ungava Bay. Canadian Journal of Fisheries and Aquatic Science 40:652-657.

Stewart, P.L., P. Pocklington, and R.J. Kunjak. 1984. Distribution, abundance, and diversity of benthic invertebrates on the Continental Shelf and slope of southeast Baffin Island and Ungava Bay. Arctic, in press.

Stride, A.H. (ed.). 1982. Offshore tidal sands. Chapman and Hall, London. 222 p.

Sutcliffe, W.H., R.H. Loucks, and K.F. Drinkwater. 1976. Coastal circulation and physical oceanography of the Scotian Shelf and the Gulf of Maine. Journal of Fisheries Research Board of Canada 33:98-115.

Taylor, J.K. 1981. Quality assurance of chemical measurements. Analytical Chemistry 53:1588A-1595A.

Thomas, D.J., G.D. Greene, W.S. Duval, K.C. Milne, and M.S. Hutcheson. 1983. Offshore oil and gas production waste characteristics, treatment methods, biological effects and their applications to Canadian Regions. A report prepared by Arctic Laboratories Limited, ESL Environmental Sciences Limited, SKM Consulting Ltd., and Atlantic Oceanics Company Ltd. for Environment Canada, Ottawa. 447 p.

UKOOA. 1983. Environmental effects of oil-based mud cuttings. United Kingdom Offshore Operators' Association. London. 24 p.

Ward, C.H., M.E. Bender, and D.J. Reish (eds.). 1979. The offshore ecology investigation: effects of oil drilling and production in a coastal environment. Rice University Studies, Volume 65 (Nos. 4 and 5). William Marsh Rice University, Houston, Texas. 589 p.

Wilkinson, T. 1982. An environmental programme for offshore oil operations. Chemistry and Industry, Feb. 21:115-123.

Williams, N.A., C.M. Paton, M.A. Purdy, and D.K. Cairns. 1981. Distribution and abundance of marine birds of the Grand Banks, 1980-1981. Unpublished MacLaren Plansearch Report for Mobil Oil Canada, Ltd. 135 p.

APPENDIX 1

Table A-1. Participants in the Workshop to Develop Effects Monitoring Strategies for Canada's East Coast

Participant	Affiliation
Alan Birdsall	LGL Limited
Robert Buchanan	LGL Limited
Wayne Duval	ESL Environmental Sciences Limited
George Greene	Private Consultant
Michael Hutcheson	Atlantic Oceanics Company Limited
Clifford Johnston	Institute of Offshore Engineering, Heriot-Watt University
George Lewbel	LGL Ecological Research Assoc. Inc.
John McDonald	ESL Environmental Sciences Limited
David Stone[a]	Indian and Northern Affairs Canada
David Thomas	Arctic Laboratories Limited
Phil Tsui[a]	Mobil Oil Canada Limited

a ESRF Effects Monitoring Program Study Committee representative.