

Design and Conclusions of the Baffin Island Oil Spill Project

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ABSTRACT. The Baffin Island Oil Spill (BIOS) Project sponsored multidisciplinary field studies between May 1980 and August 1983 in Canada's eastern Arctic at Cape Hatt, on the northern end of Baffin Island. Forty-five cubic metres (45 000 l) of a sweet medium gravity crude oil were released in a typical coastal arctic environment for purposes of scientific investigation. The experimental spills were monitored to quantitatively assess and compare the short- and long-term fate and effects of chemically dispersed oil and a beached oil slick, as well as the effectiveness of shoreline cleanup techniques. Hydrocarbon analyses were carried out on water samples, intertidal sediments, subtidal sediments and macrofaunal tissue. Biological measurements were made on populations of macrophytic algae, benthic infauna and epifauna and microorganisms. Oceanographic, geomorphologic and meteorologic support studies were also performed.

The main conclusions of the BIOS Project relate to oil spill countermeasures for arctic nearshore and shoreline areas typified by the experimental site. First, the results offer no compelling ecological reasons to prohibit the use of chemical dispersants on oil slicks in such nearshore areas. Second, the results provide no strong ecological reasons for the cleanup of oil stranded on such shorelines. Thus consideration would be given to the use of chemical dispersants in the nearshore where prevention of shoreline contamination is warranted to protect wildlife or their critical habitat or traditional human land-use sites.

Key words: Arctic, marine, oil pollution, oil spill countermeasures, chemically dispersed oil

RÉSUMÉ. Le projet de déversement de pétrole à l'île Baffin (BIOS) a commandité des études multidisciplinaires sur le terrain, entre mai 1980 et août 1983, dans l'est de l'Arctique canadien au cap Hatt, à l'extrémité nord de l'île Baffin. Quarante-cinq m³ (45 000 l) de pétrole brut non sulfuré, de densité moyenne, ont été déversés dans un environnement arctique côtier typique, à des fins de recherche scientifique. Les déversements expérimentaux ont été suivis, pour évaluer quantitativement et comparativement l'évolution et les effets à court et à long terme d'un pétrole dispersé chimiquement et d'une nappe de pétrole échouée, ainsi que l'efficacité des techniques de nettoyage du littoral. Des analyses ont été faites pour détecter les hydrocarbures dans des échantillons d'eau, des sédiments de la laisse, des sédiments situés sous le niveau des marées et des tissus de la macrofaune. Des mesures biologiques ont été effectuées sur des populations faisant partie des algues macrophytiques, de l'endofaune et de l'épifaune benthique ainsi que des micro-organismes. Des études d'océanographie, de géomorphologie et de météorologie ont complété le projet.

Les principales conclusions du projet BIOS se rapportent aux mesures d'intervention contre les déversements de pétrole en milieu arctique, dans les secteurs littoraux représentés par le site expérimental. Tout d'abord, les résultats n'indiquent aucune contre-indication majeure d'ordre écologique à l'utilisation d'agents de dispersion chimique sur des nappes de pétrole proches de tels rivages. Ensuite, ils ne fournissent aucune justification écologique pour nettoyer le pétrole échoué sur ces littoraux. Il faudrait donc considérer l'utilisation d'agents de dispersion chimique près du rivage, dans le cas où la prévention de la pollution du littoral est nécessaire pour protéger la faune ou son habitat critique, ou encore un site d'utilisation traditionnelle des terres.

Mots clés: Arctique, milieu marin, pollution par le pétrole, mesures d'intervention contre les déversements de pétrole, pétrole dispersé chimiquement

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INTRODUCTION

This paper provides the historical background and an explanation of the overall design to orient the reader to the Baffin Island Oil Spill (BIOS) Project and to this issue of the journal *Arctic*. The various component studies are placed in context and the findings are discussed from the perspective of the project objectives and their potential application to practical oil spill countermeasures in northern waters.

A detailed reporting of results from the various component studies is presented in the individual papers that constitute this issue of *Arctic* and in technical reports available from the project office (authors' address). Documents for a less technical audience (Sergy, 1986) and on selected followup studies are also available from the same source.

PROJECT HISTORY AND ORGANIZATION

By 1978 the scientific and technical development of measures to respond to arctic marine oil spills had advanced to a stage where further progress required the experimental releases of oil in the field. Only through this field approach was there a high probability of obtaining a timely answer to important and specific questions with some certainty that the results were

applicable to the real environment. It was felt that the impact associated with the experimental spills could be minimized by careful planning and that a small sacrifice was warranted in order to allow the development of a response capability for a major spill. Representatives from the Canadian oil industry, public environmental groups, universities and government reinforced this concept at the Seventh Arctic Environmental Workshop (Thornton, 1978). Soon thereafter, an experimental oil spill planning committee was formed under the auspices of the Arctic and Marine Oilspill Program (AMOP) of Environment Canada. The committee identified research and technology needs requiring field discharges of oil and developed these into a general plan that recommended and outlined five independent studies. The plan was distributed widely in an attempt to solicit feedback from public environmental groups, the inhabitants of arctic communities and Canadian and overseas agencies interested in collaboration. Subsequently, it was decided to combine two of the five studies that had complementary objectives and study site requirements. It was recognized that there were advantages to the use of one logistics base and to a reduction in the number of areas disturbed by the experimentation. These two experiments, the "shoreline study" and the "nearshore study," became known as the BIOS Project.

The physical and ecological requirements of the two studies

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established the technical criteria upon which to base the selection of a test site. Sections of coastline were examined for acceptability. In descending order of preference, but all potentially appropriate, were the Labrador coast, Lancaster Sound and the Beaufort Sea region. Air and ground-level reconnaissance and community consultations were first initiated in Labrador, but sites could not be found that were mutually acceptable to the project and the local inhabitants. As a result, the search moved to the northern Baffin Island-Lancaster Sound region. In the fall of 1979 several potential locations were investigated at the suggestion of the Pond Inlet and Arctic Bay hamlet councils. Based on underwater and aerial reconnaissance and further discussions with the local people and regulatory authorities, the site of Cape Hatt, Baffin Island, was chosen for the experiments. Subsequently the required regulatory permits and approvals were obtained for the experiment.

In early 1980 a management committee was formed from representatives of agencies making significant contributions (Appendix 1 of this issue). This committee had authority for final approval of project activities. A BIOS Project office was established in Edmonton to provide full-time functional coordination and management. Due to the magnitude and complexity of the scientific studies, they were broken down into five related working areas: physical, chemical, biological, oil discharge and shoreline countermeasures. Corresponding technical committees, composed of experts in the appropriate fields, advised the project office during various phases of the scientific work (Appendix 1). Owing to the large and remote nature of the operation, the logistical expertise and support of Petro-Canada were utilized.

The BIOS Project was ultimately funded by agencies of both the government and the oil industry from four different nations. About 75% of the support came from within Canada. Funding and supporting agencies are listed in Appendix 2 of this issue of *Arctic*.

OBJECTIVES AND RATIONALE

The primary objectives of the BIOS Project were to determine if the use of chemical dispersants in the arctic nearshore would reduce or increase the environmental effects of spilled oil and to determine the relative effectiveness of other shoreline protection and cleanup techniques. The secondary objective was to determine the chemical and physical fate of oil in the arctic nearshore and shoreline areas.

The resulting information was intended for those involved in the planning, approval and operational phases of hydrocarbon development, who are faced with the possibility or reality of a major oil spill. Such an event demands many difficult decisions, one of which is determining the appropriate action to take with respect to slicks threatening nearshore areas or those that have already been stranded on the beach face. Essential to such decisions is a knowledge of the available countermeasure options and the consequences of their implementation.

One alternative is to apply a chemical dispersant to the floating oil slick with the intent of dispersing it down into the water column. If successful, this action reduces the likelihood of contact with sea birds and sea mammals at the surface and reduces shoreline contamination. By creating a cloud of dispersed oil in the water column, the impact of the oil is quickly reduced by dilution. Additionally, the application of dispersants is less sensitive to certain factors that seriously hamper all arctic

oil spill countermeasures — the harsh environment, poor access and a lack of nearby support facilities. However, a major objection to the use of dispersants is that in shallow water areas the dispersed oil cloud may contact bottom sediments and adversely affect organisms that live in or utilize this habitat. The potential severity of these effects in arctic waters was unknown at the time the BIOS Project was initiated.

A second response option is to decide to take no immediate action, leaving oiled shorelines to natural cleaning processes. Information about the fate and effects of beached oil is required to determine the acceptability of this option, both in absolute terms and as a benchmark against which to compare other countermeasure responses. Such knowledge about the Arctic was sparse before the BIOS Project.

A third response option is the "mechanical" cleanup of oiled shorelines, an action that may be warranted by environmental or social considerations. In the Arctic, shoreline restoration is both a costly activity and one for which our capabilities are severely limited, due, in part, to a lack of efficient cleanup technology, the need to rely on labour-intensive manual operations and environmental and logistic constraints. There are few techniques developed specifically for the Arctic. The applicability of some existing southern countermeasures was unknown for northern beaches when BIOS was planned. Clearly, more information was required on the limitations of existing techniques in order to make realistic evaluations about shoreline cleanup.

The BIOS Project addressed the foregoing issues by means of two separate but complementary studies, each involving the controlled release of crude oil. The majority of resources and effort were directed to the "nearshore study," which compared the consequences of dispersing an oil slick close to shore with the option of allowing the oil to beach and leaving it to natural self-cleaning processes. The study compared the fate and effects of a short-term high concentration of dispersed oil with the fate and effects of a long-term low-level release of oil stranded on the shoreline. In the "shoreline study," factors and methods pertaining to the technological cleanup of beached oil were evaluated. Findings on oil fate and persistence were used to compare the relative effectiveness of promising arctic shoreline cleanup techniques against the benchmark of natural self-cleaning processes.

EXPERIMENTAL FIELD SITE

The experimental field site is located near Cape Hatt, on a small peninsula of northern Baffin Island, Northwest Territories, Canada (Fig. 1). It is bordered on the west by Ragged Channel, which has characteristics suitable for the nearshore study. On the east side is a well-protected embayment (Z-Lagoon), which was utilized for the shoreline study (Fig. 2). Pond Inlet, the nearest community, is some 65 km northeast.

In May 1980, a field camp was constructed at a location approximately midway between the two study areas (Fig. 2) and adjacent to both a freshwater lake and an area suitable as an aircraft landing strip. The main camp consisted of both hardshell and Parcoll structures capable of accommodating up to 60 people during peak work periods. Laboratory facilities, a maintenance shop and communication installations were also provided. Local transportation was provided by all-terrain vehicles, Zodiacs and helicopters. A secondary camp, located at Bay 12, was utilized for diving operations, sorting of biological samples

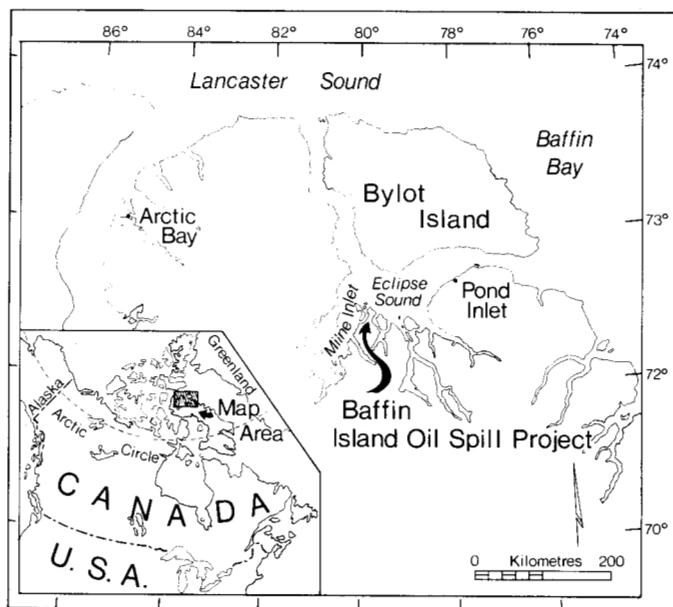


FIG. 1. Location of BIOS Project site.

and laboratory studies requiring flowing sea water. The main camp was operated during the ice cover period in May and the open water period of four successive years.

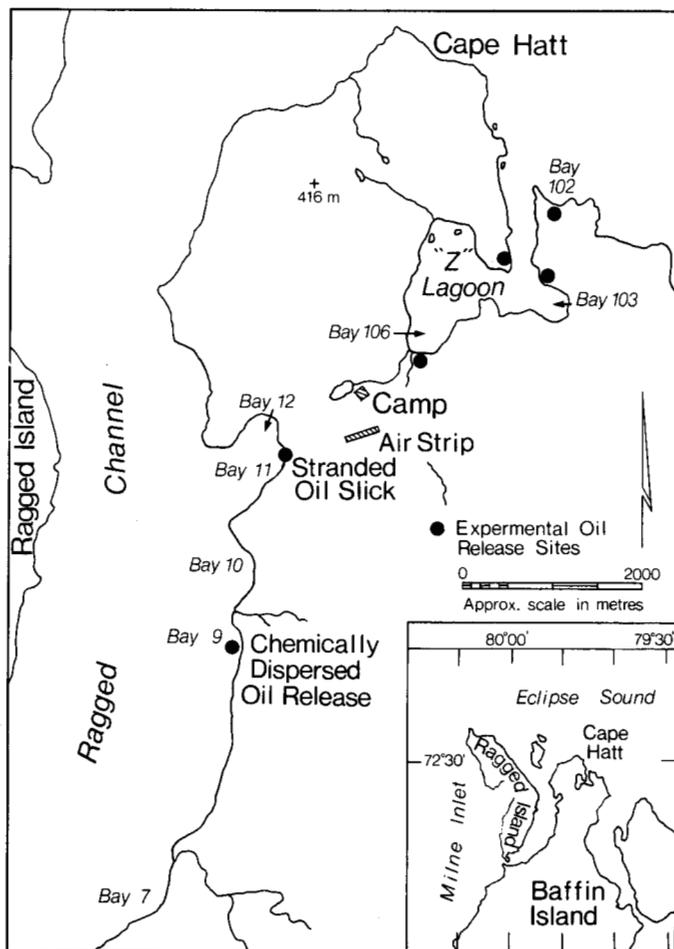


FIG. 2. BIOS Project experimental area.

The area near Cape Hatt consists of moderately high (500 m) mountainous terrain dissected by fiords and separated by broad valleys. Some wet lowlands support tundra meadow vegetation, while polar semi-desert and desert communities dominate the hills and higher elevations. Steep, rocky promontories separate the coarse sand, gravel and cobble beaches. Open water conditions occur for about 65 days each year (late July to early October). Tides are semi-diurnal and range from 1 to 2 m, and the mid-summer mean maximum air temperature is about 7°C. Studies on climate (Meeres, 1987), ice conditions (Dickins, 1987), geomorphology (Sempels, 1987) and oceanography (Buckley *et al.*, 1987) document physical features of the area and discuss them in relation to regional conditions.

Pre-spill analysis of water and sediment samples and the tissue of benthic fauna indicated little in the way of background petrogenic hydrocarbons and confirmed the pristine nature of the study area (Cretney *et al.*, 1987a,b,c). As is common in the Arctic, intertidal areas are biologically barren but subtidal areas are productive. Subtidal benthos of the study area consisted of a wide variety of plant and animal species. Biologically, the subtidal habitat of Ragged Channel is considered representative of the Canadian eastern and High Arctic (Snow *et al.*, 1987). As was desired, Cape Hatt does not specifically support any large concentrations of marine mammals, birds or fish. In perspective, it must be appreciated that only a very small proportion of the vast arctic coastline is actually critical habitat for resource species or utilization by man.

EXPERIMENTAL DESIGN OF THE NEARSHORE STUDY

The nearshore study was planned with an integral four-year design. It required the use of several similar bays or test areas, one of which was to be impacted by a surface slick of untreated crude oil and another by chemically dispersed crude oil. Physical, chemical and biological baseline data were collected and analyzed in the first year (1980). The two experimental oil spills were planned for the second year and were timed to allow for a second round of pre-spill sampling and a period of post-spill sampling before freeze-up. In the third and fourth years, the design called for repeated post-spill samplings to document the longer term fate and effects of the spills.

Pre-spill Studies

Pre-spill studies established the suitability of the Cape Hatt area for the experiment, provided an environmental baseline from which to make post-spill comparisons and supplied crucial information necessary to finalize the scientific design. As in most field experiments, limitations to design were also imposed at this early stage by logistic factors. The short open water season determined the length of the study period and scheduling of activities. Time and mode of travel for divers and other field crew affected acceptable distances between study sites.

Pre-spill physical and biological data were used to screen potential test bays for similarity. Control over the oil and its movement and the general scientific study requirements were the two major criteria used in matching the bays with oil treatments. For practical reasons the separation between treatment areas was less than ideal but judged to be within acceptable limits. It was concluded that Bay 11 (Fig. 2) would receive the surface slick of oil, while the release of chemically dispersed oil would occur in Bay 9. Bay 10 was initially designated as a reference site but later, because of the potential for cross-

contamination, was designated as either a reference site or a second dispersed oil treatment area. The more remote Bay 7 was selected as an alternate reference bay in the event of contamination of Bay 10.

Data on geomorphology (Sempels, 1987), meteorology (Meeres, 1987), ice movement (Dickins, 1987) and bathymetry and oceanography (Buckley *et al.*, 1987) were used to make predictions about the physical fate and behaviour of the released oil. This information was essential in the final design and placement of the discharge equipment and in deciding on the environmental conditions required for the oil releases. The oil discharge systems were field tested with dyed water, first in southern waters and then on-site under the final conditions chosen for the oil releases (Dickins *et al.*, 1987).

Fate and Effects Studies

Oil fate was monitored in the intertidal and shallow subtidal zone. The measurement of biological effects focused on the small and less mobile subtidal benthic flora and fauna, which are well-suited for cause-effect studies. Particular emphasis was placed on the infauna, which are a major component of the benthic biomass (Cross and Thomson, 1987). Their long life spans and relative immobility also facilitate data interpretation. As in most of the Arctic, ice scouring, freezing and summertime reduction in surface salinity render intertidal zones barren of life forms. The transient nature of planktonic organisms limited the practicality of their inclusion in the study. Although the impact of oil on fish, sea birds and marine mammals is also of great concern, our experimental approach was not suitable for the direct measurement of effects on these higher organisms.

Systematic chemical and biological monitoring was used to measure the fate and effects of the chemically dispersed oil and the beached oil slick. Sampling and analytical procedures used during the project and design limitations are presented by Cretney *et al.* (1987a,b,c) and Snow *et al.* (1987). In the initial planning stages it was obvious that financial, political and logistic realities constrained an ideal design, particularly with respect to interspersing and duplicating treatments. It could not be argued scientifically that these factors were essential to satisfy project objectives. It was therefore accepted that the nearshore study design included what is termed pseudo-replication (Hurlbert, 1984). Within the practical limitations imposed, a rigorous statistical design was utilized to address concerns over natural variability in biological populations. A temporal control was provided by collecting pre-spill baseline data and a spatial control by using Bay 7 and, in some instances, the more remote west side of Ragged Island (Fig. 2). Although both the water column and intertidal zone were monitored, the intensity and diversity of study was greatest in the shallow water subtidal habitat between 3 and 10 m of water depth.

The fate of oil in terms of concentrations and composition changes was monitored in four major environmental components: the water column (Humphrey *et al.*, 1987b), the intertidal beach sediments (Owens *et al.*, 1987a), the subtidal sediments (Boehm *et al.*, 1987) and the tissue of selected benthic invertebrates (Humphrey *et al.*, 1987a). Biodegradation of oil was monitored in the intertidal and subtidal sediments (Eimhjellen and Josefson, 1984; Bunch and Cartier, 1984). The effects of oil on bacterial numbers and microheterotrophic activity were monitored in the water column and subtidal sediments (Bunch, 1987). Macrobiological studies monitored oil effects on the macrophytic algae (Cross *et al.*, 1987b), the benthic infauna

(Cross and Thomson, 1987) and the epibenthos (Cross *et al.*, 1987a). A histopathological examination was also made of two infaunal species (Neff *et al.*, 1987). On-site toxicological testing was conducted to further investigate behavioural and metabolic responses, uptake and clearance patterns of selected invertebrates exposed to dispersed oil (Mageau *et al.*, 1987). Additional complementary studies examined the effects of oil and dispersed oil on nearshore under-ice meiofauna, amphipods and primary productivity (Cross and Martin, 1983).

Oil Spill Scenario and Oil Discharge

Perhaps the most controversial issue of the experimental design dealt with the actual details of the spills. Considerable interest focused on this matter throughout the project and is therefore elaborated on here and in Dickins *et al.* (1987).

The nearshore study scenario was that of a relatively fresh offshore oil slick approaching and predicted to impact the arctic coastline during the ice-free season. If chemically dispersed at that time, the resulting cloud of dispersed oil particles would contaminate the water column and subsequently impinge on shallow sea floor and intertidal areas. If the slick were not dispersed or if other measures were not taken, winds would drive the oil to strand on the beach, where it would remain subject to natural cleaning processes.

The scenario assumed that sufficient oil would be available to coat the shoreline to a thickness of 1 cm (considered a lower limit of heavy oiling). Further, it was assumed that oil concentrations in the water column following the application of the chemical dispersants would be in the order of 10 ppm within the 10 m surface layer. The length of time nearshore areas would be subject to a continued influx of new oil (i.e., the experimental period of discharge) was selected to be 6 h (half of a tidal cycle). It was calculated that 15 m³ (75 drums) were required for each of the two experimental spills. A sweet medium gravity crude oil (Venezuelan Lagomedio) and a common concentrate type dispersant (Corexit 9527) were selected as the spill products because a reasonable data base existed for both. Prior to the releases, the oil was lightly weathered, i.e., artificially aged by evaporation (8% by volume), to simulate the natural aging on the water surface before either stranding or chemical dispersion.

As planned, the surface slick release began at high tide and under the influence of an onshore wind. The oil was carried up and deposited on the beach by wind and wave action as the tide receded. Control of the slick and the prevention of cross-contamination were accomplished by booming off the test area. To model the normal removal by tide, wind and currents, the oil remaining on the water surface after completion of the full tidal cycle was collected with skimmers. The booms were left in place for several weeks to contain subsequent oil sheen, which was being naturally redistributed within the test beach area.

The dispersed oil cloud was created by discharging an oil/dispersant/sea water mixture through a subsea diffuser pipe. The normal method of dispersant application on an oil slick was not deemed suitable. Effectiveness of dispersion was not an issue of the experiment, and it was considered highly undesirable to have a partially dispersed slick with respect to both oil control and the comparison of the fate and effects with the surface release. To enhance the dispersion, the oil was premixed with dispersant (10:1 ratio) and pumped with sea water into a discharge system. This mixture was released to the environment through a diffuser pipe placed on the bottom just outside the study area. The predicted currents provided the mixing and

movement patterns required to distribute the oil throughout the study areas. As in a real spill, there was no control over the behaviour of the dispersed oil cloud. Booms were positioned to control any slicks resulting from re-coalescence.

THE EXPERIMENTAL DESIGN OF THE SHORELINE STUDY

The shoreline study of the BIOS Project required the use of several sections of coastline with different beach material and exposure to wave and tide action. Shoreline geomorphologic surveys and other pre-spill studies were used in the selection of suitable test beaches and in the comparison of their characteristics in a regional context. The beaches bordered a very confined embayment (Z-Lagoon) and its more exposed entrance (Fig. 2).

Procedures followed during the experimental oil releases are presented by Owens and Robson (1987). Small plots (20-40 m²) were used in the intertidal and backshore zones of the test beaches. Consistency was maintained in the type, quantity and method of application of oil. Unlike the nearshore study, the actual mode of deposition was mechanical rather than natural. This method was more practical in light of the large number of small plots required, the need to oil backshore areas and the need for a uniform application of oil across all plots. The oil was Lagomedio crude of the same stock used in the nearshore study. Both emulsified and non-emulsified oil were used in paired plots. After application of oil to the beach, the plots were left for 24 h prior to the initiation of cleanup tests. This procedure was adopted to simulate minimal response time.

A staged four-year design was utilized. During the first year, intertidal and backshore control plots on both a very sheltered beach and an exposed gravel beach were oiled in order to monitor the natural fate and persistence of stranded oil. During the second year, in the intertidal zone of a partially exposed coarse gravel beach, both control plots and test plots were oiled in order to test the effectiveness of cleanup techniques. In the third year, cleanup techniques were tested on the intertidal and backshore zones of a very sheltered fine-grained beach.

All plots were sampled and surveyed before oiling and at scheduled intervals during the four years after oiling. The sample area was restricted to the intertidal and backshore sediments.

The applicability and effectiveness of selected cleanup techniques were compared with the natural cleaning process on adjacent control plots. The cleanup methods so tested were dispersant washing, mechanical mixing, chemical solidification, flushing and burning (Owens *et al.*, 1987b). The natural fate and persistence of oil was further examined to determine the rate and physical factors influencing the self-cleaning process (Owens and Robson, 1987). The natural biological degradation of oil was compared with microbial action enhanced by the artificial application of nutrients (Eimhjellen and Josefson, 1984).

A DISCUSSION OF THE FINDINGS

Results of the BIOS Project are presented in publications as referenced herein. Many are included in individual papers in this issue of *Arctic*. Some are discussed below in order to provide a holistic account of the collective events and findings and to highlight items of interest to those responsible for oil spill countermeasures.

Nearshore Study

The experimental oil spills of the nearshore study were both successful in achieving conditions to determine oil fate and effects that would be relevant to future arctic oil spills. The countermeasure options, chemical dispersion and natural shoreline restoration, were thus assessed and compared in an intertidal and subtidal habitat common in the eastern and High Arctic.

Nature of the Experimental Spills: The untreated surface slick was stranded in the intertidal zone in a manner representative of an accidental spill of moderate severity. The light oil loading was less than originally designed but it was the maximum that the beach would retain under the spill conditions. Therefore, in terms of oil loading, the experimental spill was not a worst-case example but is considered typical. Such a spill would usually be of concern because it occurred on a low-energy shoreline where oil would be expected to persist.

The chemically dispersed oil spill produced a variety of conditions, ranging from those normally expected after the application of dispersants to an oil slick to those that can be considered as abnormally severe. Conditions in the immediate vicinity of the release (Bay 9) represent a worst-case scenario in terms of total oil concentrations in the water column. As a result of the subsurface discharge technique, benthic organisms at both this and the adjacent study site (Bay 10) were exposed to unusually high concentrations of toxic aromatic compounds, which would otherwise have been rapidly lost to surface evaporation. Additionally, oil was introduced at greater water depths than would likely be the case with an oil slick dispersed at the surface in the Arctic. In many arctic coastal areas, the often present and well-pronounced pycnocline would suppress the downward mixing of oil to productive benthic depth-zones.

Fate of the Stranded Oil Slick: In terms of initial oil retention, it appeared that relatively stable conditions were reached after about 48 h (four complete tidal cycles), when oil on the beach was no longer being refloated in large quantities. During this 48 h period, 5.5 m³ of oil were recovered from the water surface by skimming and 5.3 m³ (about one-third of the original total) were left stranded on the beach. Evaporation and dissolution in sea water accounted for the balance.

Quantities of oil in the intertidal sediments and its persistence are discussed by Owens *et al.* (1987a). Over the next two years (*i.e.*, 18 weeks of open water conditions) the original amount of stranded oil was reduced by 70%. This rate of natural shoreline cleaning is surprisingly high in light of the short period during which it could occur and the protected nature of the shoreline. Biological degradation is considered to have removed only minor quantities of stranded oil. The majority of oil removal is attributed to physical processes.

Oil residues were highly visible on the beach after two years. However, the distribution of oil was very patchy within the original oiled area. Owens (1984) suggested that this condition could easily give rise to large errors in visual estimates of oil cover and oil quantities typically made following accidental spills.

The majority of the oil remaining on the beach after two years was incorporated into an asphalt pavement. Such a formation would be expected to increase the persistence of the stranded oil but decrease the rate of leaching to offshore waters and, therefore, reduce the likelihood of shoreline users contacting "liquid" oil.

Some of the oil from the beach was transported by run-off and wave action to the adjacent subtidal sediments. Boehm *et al.* (1987) reports the quantities of this oil residue increased slowly over time. Actual concentrations, however, were still relatively low after two years. These results indicate the high persistence of oil in this environment. Bunch and Cartier (1984) were unable to confirm the occurrence of biodegradation *in situ*. It is, therefore, considered a negligible factor in the removal of sedimented subtidal oil at the low concentrations encountered.

Concentrations of oil in the water column were low beneath the initial slick and only trace amounts were monitored over the subsequent two years, during which time oil leached from the shoreline (Humphrey *et al.*, 1987b). The water-column pathway of exposure to organisms is, therefore, not considered significant in the case of the stranded oil slick.

The persistent oil residues in the intertidal and subtidal sediments are of concern due to the long-term chronic exposure potential to biota.

Fate of Chemically Dispersed Oil: Currents swept the cloud of dispersed oil particles through the designated study areas in Bays 9 and 10. Oil contacted bottom sediments and organisms from the shoreline to a depth of 15 m. Within a few days the oil was distributed throughout the surface waters of Ragged Channel, including the reference site (Bay 7). This is not considered overly detrimental to the interpretation of results, as actual exposures of benthos to oil at the reference site were very low, several orders of magnitude less than treatment sites with which comparisons were made.

Movement and concentrations of oil in the water column are presented in Humphrey *et al.* (1987b). The subtidal benthos within the study areas received an average exposure of 300 mg·kg⁻¹ h in Bay 9, 30 mg·kg⁻¹ h in Bay 10 and 3 mg·kg⁻¹ h in Bay 7, with sustained concentrations of 50, 6 and 0.12 mg·kg⁻¹ respectively. Concentrations of oil in the water column were diluted to near background levels within a period of days. The length of time that flora and fauna were exposed to water-borne oil was therefore short. Other than in very unusual circumstances, such as low water circulation, longer exposure periods would not be encountered during a real spill, except possibly in the area immediately adjacent to the release point where multiple oilings could occur.

There was minimal re-coalescence of oil on the water surface and negligible oiling of intertidal sediments.

Chemically dispersed oil rapidly contaminated subtidal sediments. However, the quantities of oil in the sediments were minor, even in areas of extreme exposure. In the vicinity of the release, oil residues remained at low levels through 1983 (Boehm *et al.*, 1987). Concerns over the retention and persistence of chemically dispersed oil in subtidal sediments are similar to those for the stranded oil slick.

In the experimental spill, as would normally be expected when dispersants are applied to a floating oil slick, it is the short-term exposure of animals to oil in the water column that is considered most significant in terms of potential biological effects.

Biological Effects: It is of considerable interest and importance that the biological impacts from both spills were relatively minor. All short-term effects were temporary and apparently without serious consequence. After the two-year post-spill monitoring period, there is no evidence of large-scale mortality of subtidal benthic biota attributable to either the chemically dispersed oil or the oil-contaminated beach. Few changes were

detected in the populations or community structure of infauna, epifauna or macroalgae. These are reported in Cross and Thomson (1987), Cross *et al.* (1987a) and Cross *et al.* (1987b) respectively.

There were no measured biological effects in the intertidal zone due to the absence of arctic intertidal life. In more temperate regions, such as southern Labrador, much greater effects would be expected because the intertidal zone is both biologically productive and vulnerable to oil spills.

Both of the experimental releases temporarily reduced the density of the amphipod *Gammarus setosus* at the shoreline/water interface. It is thought that in a real spill the recovery of amphipod populations affected by dispersed oil would be more rapid than those affected by beached oil, because of the persistence of the latter.

In the nearshore subtidal environment there were two primary exposure pathways that caused biological effects. Both the short-term exposure to the chemically dispersed oil in the water column and the long-term exposure to oil in subtidal sediments produced responses in the population and accumulation of oil in benthic fauna.

Relatively severe exposures to water-borne chemically dispersed oil in Bays 9 and 10 produced acute behavioural and physiological effects in a wide variety of animals and, in a few species, a short-term reduction in number. Most dramatic was the emergence from the sediment and/or immobilization of infaunal and epibenthic invertebrates. Recovery and reburial occurred in the two weeks following the spills, although during this period some mortality of organisms and predation on stressed organisms was also observed. No behavioural changes were observed at other Ragged Channel sites, which had been exposed to very low levels of dispersed oil.

Behavioural changes similar to those in the field, as well as other metabolic effects, were recorded by Mageau *et al.* (1987) in laboratory post-spill-simulation tests. The responses were related to oil exposure levels and not to body burden.

Heterotrophic bacteria in the water column were not affected by the surface oil slick and only temporarily affected by the chemically dispersed oil. Effects of oil on bacteria living in subtidal sediments were also minor (Bunch, 1987).

As expected, the creation of a chemically dispersed oil cloud can increase the short-term vulnerability and sensitivity of subtidal benthos to an oil slick. However, the arctic subtidal benthic community appears able to withstand relatively severe exposures for a short period. The acute effects observed in the experimental spill would be expected in similar organisms at other eastern arctic locations. Further, Wells and Percy (1985) concluded there is no evidence that the effects of oil will be more severe for arctic benthos than for comparable temperate forms.

There are indications that exposure to the persistent oil residues in subtidal sediments (from both experimental spills) was responsible for medium-term (1-2 year) sublethal effects, but only in a few species. There is generally little knowledge of toxicity to benthos living in oiled substrates or the mechanisms by which effects are produced. It is most probable that the lack of population effects seen in the BIOS experiment stem from the relatively low concentrations and the composition of the oil residues. Continuing exposure may be sufficient to produce sublethal changes in the condition of benthic animals. It is possible that greater effects would have occurred given a heavier oiling or repeated oilings.

Monitoring for bioaccumulation of oil is reported in Hum-

phrey *et al.* (1987a). Exposure to even very low concentrations of chemically dispersed oil resulted in a rapid and significant uptake by subtidal benthic fauna, particularly the filter-feeding bivalves. Organisms were affected over a relatively large area due to extensive vertical and horizontal movement of the oil cloud. However, the water column was only a short-term source of oil exposure. On a wide-scale basis, body burdens of filter-feeding bivalves were reduced notably within two weeks and those of all organisms monitored were reduced considerably within the first year. The events that occurred were not unexpected, since other experimental studies have demonstrated that similar organisms readily take up petroleum components and that the process of elimination is initiated very shortly thereafter. Many invertebrates can also metabolize some hydrocarbons.

On a longer term but very localized basis, deposit-feeding benthos living in contaminated sediments had elevated body burdens two years post-spill, thus reflecting the continued influence of oil from this source. In some cases an uptake-depuration balance appeared to exist. Body burdens of animals living offshore from the stranded oil (Bay 11) are not expected to decrease rapidly due to the long-term availability of oil from the beach and the chronic exposure to oil residues in the subtidal sediments.

Although beyond the scope of the BIOS Project, indirect effects of the bioaccumulation can be anticipated. Tainting may occur in shellfish harvested for human consumption, although this is not a common practice in northern waters. Bioaccumulation might also be of ecological significance in concentrated feeding areas for birds and mammals that utilize benthic biota as a food source. It should, however, be noted that direct oiling of birds and mammals is viewed with much greater concern than the transfer of hydrocarbons up the food chain. It is generally acknowledged that critical habitats for resource species should be protected from oil of any type, and particularly from floating and beached oil slicks.

Shoreline Study

Whereas the nearshore study assessed the use of chemical dispersants and natural shoreline cleanup in terms of comparative fate and effects, the shoreline study evaluated options for enhancing the cleanup of oiled shorelines by comparing the methods to natural self-cleaning. The information gained in these experiments may be applied to similar coastlines in most arctic and temperate regions, bearing in mind the controlling influence of arctic climate. There is little doubt that the edge effects resulting from the use of small-scale experimental plots overestimated the rates of oil removal in the intertidal zone. The natural redistribution of oil by tide and waves removed oil from the small study plots rather than moving it around or redepositing it within the oiled zone. The latter would be the case in reality where larger areas would be oiled, such as occurred on Bay 11. Therefore, only short-term results (up to 8 days) are used in comparisons of the small beach plots. The edge effects of small plots in the backshore are considered to be negligible.

Retention and Persistence of Oil: Owens and Robson (1987) present findings on oil deposition and on retention and persistence under natural conditions. The intertidal plots were oiled to their maximum holding capacity, as evidenced by the migration of surplus oil down the beach face. Where beach conditions

were similar to those in Bay 11, the resulting loading rates were also comparable. Initial retention of oil was a function of sediment characteristics, the level of the water table and oil type.

Wave energy was the dominant factor in the removal of oil from exposed beaches (e.g., about 99% within 48 h on Bay 102). On the partially exposed beach, the majority of oil was removed within the first open water season (about 40 days) and by the end of the second season less than 0.05% remained. It was surprising to find energy levels high enough to rapidly remove oil naturally from beaches in an area generally considered a low-energy archipelago. It was estimated that 30-40% of arctic coastlines may have equal or greater exposure to that of the experimental site (Sempels, 1982).

On the sheltered beaches (Bays 103 and 106), rising tides removed large quantities of oil during the first two days, after which relatively stable conditions prevailed. As expected, oil was less persistent on the fine-grained sediments than on the pebble-cobble beach. In the latter case oil residues were still visible four years after the spill.

The experimental backshore plots were not affected by marine processes. Climate and soil conditions played major roles in the fate of the oil. Significant amounts of oil remained in surface and subsurface sediments after three years. However, there was considerable change in the composition of the oil due to weathering and biodegradation.

Beach-Cleaning Methods: Results of the techniques evaluated are contained in Owens *et al.* (1987b). Chemical solidification was effective in stabilizing the oil but very labour intensive. Low-pressure flushing by sea water of oiled fine-grained beach sediments did not reduce oil concentrations. Burning also proved ineffective as even high-temperature igniters failed to sustain combustion on oiled cobble beaches. Application of commercial fertilizers to the plots increased bacterial numbers and degradation of oil on fine-grained backshore sediments, but not on those of coarser material (Eimhjellen and Josefson, 1984). Nevertheless, biodegradation, enhanced or natural, is unlikely to be a factor of quantifiable significance except over a long period of time.

On very sheltered beaches, wave energy was insufficient to mix dispersant and oil. Therefore, the treatment in these cases was ineffective. On cobble beaches partially exposed to waves, the use of dispersants quickly reduced the amount of oil present on the sediment surface. It was generally concluded that dispersants would be most effective on small sections of coast where stranded oil might otherwise have a severe short-term impact or where long-term persistence was not desirable. Prior to implementation, consideration would have to be given to the effect of flushing the oil from the beach into adjacent nearshore waters. In all likelihood, the exposure of the biological community resulting from shoreline flushing would be much less than that measured in the nearshore study. This would be due to factors such as the presence of a pycnocline, lack of energy to mix oil to any significant depth and the impoverished shallow-water populations.

Generally, mechanical mixing of oiled intertidal and backshore areas reduced the total hydrocarbon concentrations in surface sediments, but in many cases at the expense of increasing subsurface concentrations. Mechanical mixing was considered to be relatively low cost and operationally simple on accessible beaches. Large areas can be treated rapidly and the technique could be applied where the objective is to reduce contamination

of surface traffic, to prevent or reverse asphalt pavement formation or, in the backshore, to increase rates of weathering and to enhance biodegradation.

APPLICATION TO OIL SPILL COUNTERMEASURES

The BIOS Project has acquired reliable data concerning the fate and effects of chemically dispersed oil in the arctic nearshore and of oil stranded on the arctic shoreline, as well as data concerning the effectiveness of shoreline cleanup techniques. These data can be applied when making decisions regarding the use of chemical dispersants on an oil slick approaching an arctic coastline and the cleanup of oil-contaminated arctic beaches.

The Use of Chemical Dispersants on Oil Slicks

The BIOS Project results provide no major ecological reasons to prohibit the use of chemical dispersants on oil slicks in nearshore areas similar to the experimental site.

Despite unusually severe conditions of exposure to chemically dispersed oil, the impact on a typical shallow-water benthic habitat was not of major ecological consequence. Concerns over the accumulation of oil by benthic fauna are valid in areas where a heavy utilization of this resource has implications for consumers (e.g., man, bearded seal). The results indicate that this accumulation of oil could occur over a large area but would persist for only a short time.

In a real spill, the actual approval and use of chemical dispersants would depend on a great number of factors. Economic, technological and logistic criteria would play roles in the determination of a final outcome, as would the environmental implications. The BIOS Project studied only the latter, but results indicate that the use of chemical dispersants in coastal areas can be an environmentally acceptable countermeasure and can reduce the negative effects of spilled oil. Chemical dispersion may be the only alternative in situations where the immediate protection of shoreline and nearshore habitats is of primary importance or where a shoreline cleanup operation is environmentally less desirable.

Where practical and effective application methods and dispersant formulations are available, it would seem appropriate to give pre-spill approval for dispersant use along sections of arctic coastline with ecosystems typified by the Cape Hatt site. This would be the case where shoreline protection is a high priority and where other means of protection are not possible. Such pre-spill approval would improve the oil spill response capability.

Conversely, it would appear that in many situations there would not be many advantages to nearshore dispersion and, therefore, it would be unlikely that dispersant use would be proposed.

Priorities for Shoreline Protection and Cleanup

The BIOS Project results provide no strong ecological reasons for the cleanup of oil stranded on arctic shorelines, except where wildlife is present or their critical habitat is threatened, or in areas of human use.

There was a relatively minor impact on the oil-contaminated beach left to natural processes. Exposure to low-level oil residues in the sediments did not cause significant changes in the subtidal benthic populations over a two-year period following the spill.

The results indicate that oil residues persist for long periods of time on low-energy beaches and backshore areas and in nearby

seabed sediments. Those involved in making cleanup decisions should, therefore, consider the implications of oil contamination to shoreline users and the potential for chronic bioaccumulation or sublethal effects in subtidal benthos. The results also confirm that arctic beaches can be cleaned of oil by natural processes, despite the short open water season, and that this can occur very quickly on beaches exposed to moderate wave action.

The findings suggest that natural cleaning of oil-contaminated beaches can be an environmentally acceptable option for low-priority shorelines similar to those at Cape Hatt. Response efforts can be more effectively directed toward areas of greater importance and sensitivity, such as shores adjacent to communities, wildlife breeding and staging areas and traditional hunting and fishing camp locations.

Shoreline Cleanup Methods

Climatic, logistic and technical constraints still severely reduce the practicality of shoreline cleanup (and protection) in many arctic spill situations. Effective countermeasures are limited in type and application, and many of them serve only to marginally increase the rate of recovery. It is, therefore, essential in any spill to carefully select the most suitable strategy and technique where enhanced shoreline cleanup is required.

Of the cleanup methods studied in the BIOS Project, two — namely, dispersant flushing and mechanical mixing — produced an immediate reduction in the quantity of oil on the beach surface. These might be desirable where the objective is to reduce contact between oil and wildlife that frequent the shoreline.

Dispersant washing could also be considered as a means to prevent oil-sediment consolidation (asphalt pavement) in the intertidal zone and to reduce the persistence of oil residues stabilized in this manner.

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