ARCTIC
VOL. 40, SUPP. 1 (1987) P. 230-243

Experimental Design and the Retention of Oil on Arctic Test Beaches

EDWARD H. OWENS[1] and WISHART ROBSON[2]

(Received 12 June 1986; accepted in revised form 7 January 1987)

ABSTRACT. Oil was laid down in a series of experiments at Cape Hatt, Baffin Island, N.W.T., on pairs of control plots in the upper intertidal zone at four beach sites, each with a different wave exposure, and on backshore pairs of control plots at two sites. The control plots were established as a basis for comparison with a series of intertidal shoreline cleanup experiments. Sites with different wave-energy exposures were selected in order to provide a range of energy level environments and also a variety of intertidal sediment characteristics. The experimental design of this phase of the project attempted to reproduce conditions similar to those that would result from a large spill. At each location one plot was oiled with an aged Lagomedio crude oil and the other with an emulsion of water in aged crude oil. Replication of total hydrocarbon (t-h) analytical results within and between plots initially proved difficult due to the variability of grain size and to the presence of pooled oil on the beach surface. Although the subsequent collection of large (2.4 *l*) composited samples reduced this element of variability in the t-h data sets, changes through time or differences between plots were considered significant only if these were in the range of one order of magnitude or greater. At the gravel beach sites the initial retention of oil on the intertidal emulsion plots was considerably less than on the aged oil plots, probably as a result of the different adhesion properties, viscosity and density of the emulsified oil. Observations and measurements indicate that there was a maximum loading of oil that is believed to be a function of: (1) the size of sediments and of the surface interstitial spaces; (2) the surface properties of the sediment particles (including wetness and dryness of the surface); (3) the level of the water table; and (4) the type and volume of the oil. On the most exposed of the four intertidal locations over 99% of the spilled oil was removed from the surface of the plots within 48 h. This removal was due to the mechanical energy of wave action and to sediment redistribution (erosion). At the more sheltered sites, oil was removed by rising tides after application of the oil. Rates of oil removal from the two sheltered beaches varied independently of wave exposure. Observations and analytical results indicate that after seven or eight days dispersion and edge effects became significant on the intertidal plots. Data from the intertidal plots, therefore, were considered to replicate patchy oil contamination and were not representative of large natural spill situations beyond one week after the oil was laid down.

Key words: Arctic, shoreline experiments, oil spills, oil retention, maximum oil loading

RÉSUMÉ. Dans une série d'expériences faites au cap Hatt, dans l'île Baffin (T. N.-O.), on a répandu du pétrole sur des paires de lots témoins dans la partie supérieure de la laisse à quatre endroits sur des plages, présentant tous une exposition différente aux vagues, et sur des paires de lots témoins situés sur l'arrière-plage à deux endroits. On a établi les lots témoins pour qu'ils servent de référence pour une série d'expériences de nettoyage de la laisse. On a choisi des endroits présentant différentes expositions aux vagues afin d'avoir des environnements couvrant une gamme d'énergie des vagues et aussi une variété de caractéristiques des sédiments de la laisse. Les conditions expérimentales de cette phase du projet essayaient de reproduire les conditions résultant d'une importante marée noire. A chaque endroit, un lot était couvert de pétrole brut vieilli Lagomedio et l'autre d'une émulsion d'eau dans du pétrole brut vieilli. Au début, on a trouvé difficile de reproduire les résultats d'analyse de la teneur totale d'hydrocarbures (t.t.h.) à l'intérieur d'un même lot ou d'un lot à l'autre, en raison de la variabilité de la taille des grains et de la présence de pétrole concentré en flaques à la surface de la plage. Bien qu'on ait pu par la suite réduire cet élément de variabilité dans les données de t.t.h. en prélevant de grands échantillons composés (2,4 *l*), on a considéré que les changements avec le temps ou les différences entre les lots n'étaient significatifs que s'ils étaient d'un ordre de grandeur ou plus. Sur les plages de gravier, la rétention initiale du pétrole sur les lots converts d'émulsion, était nettement moindre que sur les lots couverts de pétrole vieilli, probablement à cause de différences dans les propriétés d'adhésion, dans la viscosité et dans la densité du pétrole émulsifié. Ces observations et les mesures indiquent qu'il y avait une charge maximum de pétrole que l'on croit fonction (1) de la taille des sédiments et des espaces intersticiels en surface, (2) des propriétés superficielles des particules sédimentaires (y compris la sécheresse et l'humidité de la surface), (3) du niveau de la nappe d'eau, et (4) du genre et du volume du pétrole. Sur le plus exposé des quatre endroits de la laisse, plus de 99% du pétrole répandu était éliminé de la surface dans les 48 heures. Cette élimination était due à l'énergie mécanique des vagues et à la redistribution des sédiments (érosion). Aux endroits plus abrités, le pétrole était éliminé par les marées montantes après son déversement. Le taux d'élimination du pétrole sur les deux plages abritées variait indépendamment de l'exposition aux vagues. Les observations et les résultats analytiques indiquent qu'après sept ou huit jours, la dispersion et les effets de bord deviennent significatifs sur les lots de la laisse. On considère donc que les données sur les lots de la laisse reproduisent une pollution fragmentaire et ne sont plus représentatives des grands déversements naturels au-delà d'une semaine après que le pétrole a été déversé.

Mots clés: Arctique, expériences sur le littoral, marée noire, rétention de pétrole, charge maximum de pétrole

Traduit pour le journal par Nésida Loyer.

INTRODUCTION

The Baffin Island Oil Spill (BIOS) Project was established to study the fate and effects of oil spilled in nearshore arctic waters. A general overview of the entire project is provided by Sergy and Blackall (1987). Other papers in this issue of *Arctic* provide detailed descriptions of the Cape Hatt coastal environment: Sempels (1987) describes the geomorphology and sedimentology; Buckley *et al.* (1987) the physical oceanography; Meeres (1987) the climate and meteorology; Dickins (1987) the ice conditions; and Snow *et al.* (1987) the marine biology. The shoreline component of the BIOS Project involved: (1) a study of the fate of a stranded crude oil; and (2) an assessment of selected shoreline cleanup countermeasures on oiled intertidal and backshore plots.

The countermeasure experiments were the primary effort of the shoreline component of the BIOS study and were conducted in Z-Lagoon, Cape Hatt, N.W.T. (Figs. 1, 2) at Crude Oil Point in 1981 and at Bay 106 in 1982. Control plots were established in 1980 to provide baseline data in the intertidal zone in Bays 102 and 103 and in the backshore (supratidal) zone at Crude Oil Point (Fig. 2). Countermeasure and control sites were selected that differed in their geomorphology, sedimentology and exposure to wave action. A complete list of the shoreline study locations and of the activities carried out at each site is given and the results from the countermeasure experiments and from the

---

[1] Woodward-Clyde Consultants, 7330 Westview Drive, Houston, Texas 77055, U.S.A.
[2] Halliburton Manufacturing and Services Ltd., Ctra. Madrid-Barcelona, K.M. 15,300, Coslada (Madrid), Spain

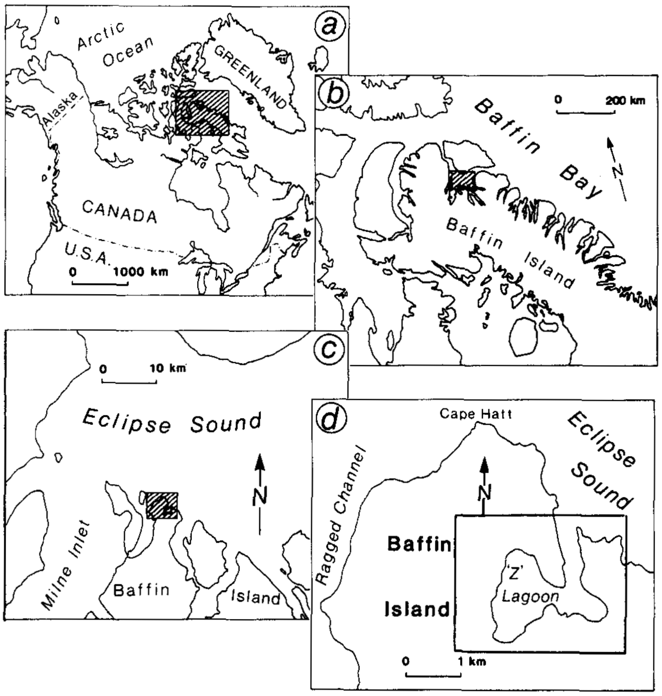

FIG. 1. Regional location maps. The area within the rectangle in (d) is shown in more detail in Figure 2.

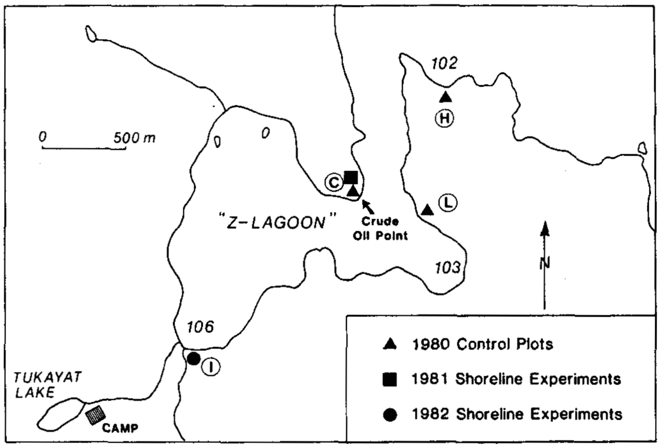

FIG. 2. Experimental and control locations in the Z-Lagoon area. The letters H,C,I and L are codes assigned to the individual sites (see Table 1).

Z-Lagoon control plots are reported in detail elsewhere in this issue by Owens *et al.* (1987a). As part of a nearshore component of the BIOS Project, 15 m^3 of crude oil were released in 1981 on the surface of the waters of Bay 11 in Ragged Channel. This slick was allowed to strand and the distribution and weathering of the standard oil was studied as part of the shoreline program. The results from the Bay 11 onshore study are reported in this issue in detail by Owens *et al.* (1987b).

The purpose of this paper is: (1) to present the experimental design for the investigation of fate and persistence of oil on beaches, and (2) to discuss the results that relate to the initial deposition and retention of oil on the various beaches studied. In achieving (2), the results from the plots in Z-Lagoon used for the shoreline countermeasure experiments, where oil was directly applied to the beach, are compared with those from the Bay 11 beach, where a crude oil release was allowed to strand.

SITE DESCRIPTION AND ACTIVITIES

Study Area

A large embayment on the east coast of Cape Hatt, Baffin Island, N.W.T., Z-Lagoon (Fig. 1), was selected as the site for the shoreline countermeasures experiments. The location was sufficiently distant from the other BIOS experimental oil releases to preclude the possibility of cross contamination. The embayment was selected because it contains a series of discrete beaches suitable for testing intertidal countermeasures (Fig. 2). There were sufficient beaches to provide a good range of wave-energy levels and to allow for comparison of treated and untreated beaches of similar types. The nearshore release of crude oil, which was allowed to strand and formed part of both the nearshore and the shoreline components of the BIOS Project, was carried out at Bay 11 in Ragged Channel on the opposite (west) coast of Cape Hatt.

The area around Cape Hatt is typical of the coasts of the southern Queen Elizabeth Islands and of the arctic archipelago between Victoria Island and Baffin Island. Shoreline sediments in the region as a whole are generally coarse (pebbles and cobbles), with a secondary fine fraction (muds and sands). Fetch distances are generally <100 km in this ice-dominated arctic region, which has an open-water season on the order of 2-3 months each summer. The study sites provide a representative range of high, intermediate and low-energy wave environments, and energy levels at the shoreline are directly related to local fetch characteristics. The results of the experiments and studies should not be restricted in their application to only this arctic region. Many lower latitude environments are directly comparable in terms of shoreline processes, wave-energy levels, tidal range, beach sediments and beach morphology.

Bay 102. This pocket beach is the most exposed of all the sites in the Z-Lagoon study area. The maximum fetches are in the order of 90-100 km toward the east-northeast (Fig. 1c). Wave heights > 1 m were observed at this site on various occasions during the study. In terms of arctic environments, this beach has relatively high wave energy levels at the shoreline. The intertidal beach slope is approximately 10° and the sediments are composed of sandy gravels (Table 1). The steep, sandy beachface in the intertidal zone gives way to a coarse, gravel and pebble berm above the high-water mark. Seaward of the berm crest the slope is relatively gentle, composed of a sandy gravel, and is an area occasionally inundated by storm surges. At the upper limit of marine activity a boulder-cobble fringe marks the boundary between marine and terrestrial sediments.

Two control plots (H_1 — crude oil; H_2 — emulsion), each 40 m^2 in area, were laid down in 1980 in the upper intertidal zone (Fig. 3) (Woodward-Clyde Consultants, 1981). These plots were intended to represent a relatively high wave energy location for this area.

Bay 103. This site is a sheltered location within Z-Lagoon (Fig. 2). The beach sediments are poorly sorted and range from clays to boulder-size material, with a predominance of sandy-gravel sediments (Table 1). The beach has a high groundwater table, is approximately 15 m wide with a low-angle slope (<10°)

TABLE 1. Site characteristics of the study beaches*

Site	Location	Year oil spilled	Approximate intertidal width (m)	Sediment characteristics	Fetch (km)	Exposure
H plots	Bay 102	1980	20	well-sorted sands, pebbles and cobbles	~90	open to NNW through E (100° arc)
C plots	Crude Oil Point	1981	10	moderately sorted sands, pebbles and cobbles	~90	very narrow fetch window (20°) to the N
L plots	Bay 103	1980	15	poorly sorted sands, pebbles and cobbles; secondary population of clays and boulders	1.7	sheltered: open to waves in lagoon from SSE through WNW (160° arc) and to refracted waves through narrow (20°) lagoon entrance
I plots	Bay 106	1982	50	fine-grained sands	1.4	very sheltered: subject only to waves from N through NE (45° arc) generated within the lagoon

*Located on Figure 2.

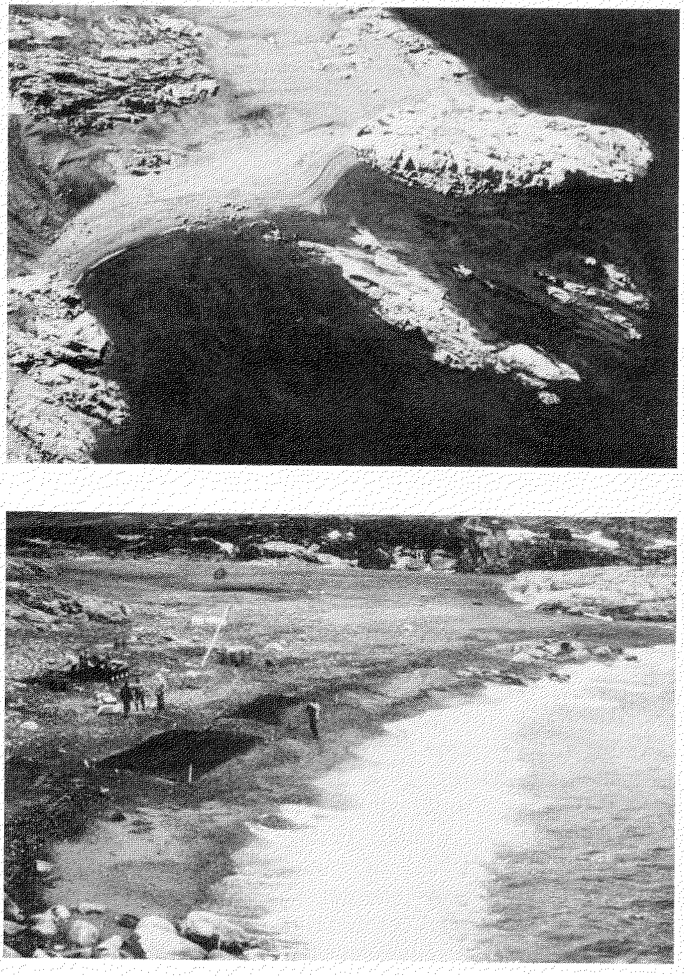

FIG. 3. Bay 102 "high-energy" control beach: (top) aerial view of beach, 14 August 1982; (bottom) ground view of plots H_1 and H_2 on 23 August 1980, immediately after oil application.

and gives way landward to a tundra backshore with no ridge or berm crest present at the high-water line.

The beach was selected as a control site that would be representative of a relatively low wave energy location for the study area. Two control plots (L_1 — crude oil; L_2 — emulsion), each 40 m^2 in area, were laid down in 1980 in the upper intertidal zone (Fig. 4) (Woodward-Clyde Consultants, 1981).

Crude Oil Point. This study beach is a spit that has formed at the entrance to Z-Lagoon and is partly exposed to waves generated in Eclipse Sound (Figs. 1, 2). The site was initially chosen for two backshore (supratidal) control plots (T_1 — crude oil; T_2 — emulsion), each 40 m^2 in area, which were laid down in 1980 (Woodward-Clyde Consultants, 1981). These backshore control plots were established above the limit of wave and tidal action to provide a comparison of oil weathering not directly affected by active marine processes. The plots were laid down on a raised beach (Fig. 5) that consists of a sandy gravel substrate covered by a thin shingle lag deposit. The surface slopes at a low angle toward the shore (<5°) and the seaward edge of the plots is located approximately 0.5 m above mean high-water level. The depth of the ice-bonded surface at the time of oiling was 0.8 m, with a perched groundwater table at approximately 0.7 m.

The east-facing beach of Crude Oil Point was selected for a series of intertidal countermeasure experiments that were conducted on pairs of crude oil and emulsion plots. The intertidal plots, listed below in Table 5, were laid down in 1981 in the upper half of the intertidal zone on a relatively steep beachface (10-15°). The experimental design included the establishment

FIG. 4. Oblique aerial view of the "low-energy" control plots (L_1 and L_2) at Bay 103 (29 July 1981).

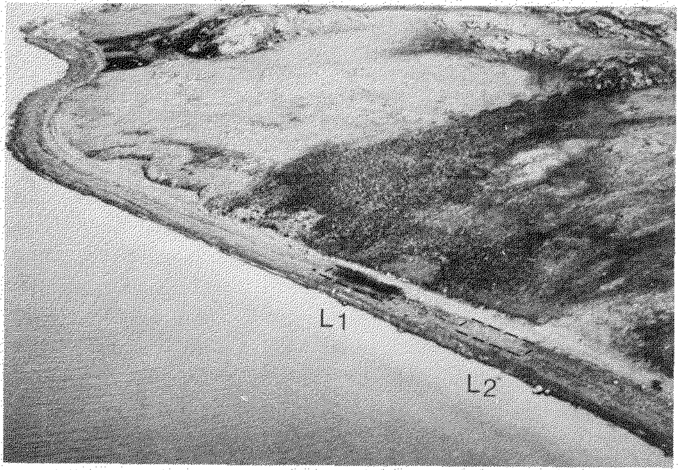

FIG. 5. Site of the backshore control plots (T_1 and T_2) on the southern section of Crude Oil Point (14 August 1982).

of crude oil and emulsion intertidal control plots (coded CC and CE respectively). The location of the individual plots is shown on Figure 4 in Owens *et al.*, 1987a. The intertidal sediments are predominantly sand with a secondary pebble component, giving way at the berm crest, the high-water mark, to a more coarse matrix of pebbles and gravel. The sediment transport direction on the east-facing study beach is from north to south under the influence of refracted waves generated in Eclipse Sound.

Bay 106. Following an evaluation of the 1980 and 1981 control and countermeasure results it was decided to conduct further countermeasure studies in 1982 at a more sheltered shoreline location than the Crude Oil Point experiments. A site was selected within Z-Lagoon, at Bay 106, which has a maximum fetch in the order of 1500 m (Figs. 2, 6). Pairs of countermeasure and control plots were laid down in the upper intertidal zone on a section of shoreline where the width of the intertidal beach is in the order of 35-40 m (see Owens *et al.*, 1987a: Fig. 5). The sediments are fine grained (silt to fine and medium sands) and the beach angle is predominantly <5°.

A section of backshore at the east end of the study beach (Fig. 6) was also oiled in 1982 to provide a pair of countermeasure plots for an additional mixing experiment and to provide a pair of associated control plots. The exact site was at the berm crest, which is composed of pebble/cobble material. These supratidal plots were intended to represent oil that would become stranded by spring tides or during a storm surge.

Bay 11. The beach is located on the west side of Cape Hatt and faces into Ragged Channel (Fig. 1d). The maximum fetch of approximately 10 km is typical of the region, and Sempels (1987) indicates that 72% of the coastline in the Baffin Island area has a similar limited exposure. The beach is 400 m in length and is bounded by rock outcrops. Tidal conditions have been measured in the 1.9 m range and wave conditions are generally very low (<10 cm wave heights). Intertidal sediments vary from cobbles in the lower sections through silt, sand and pebbles to sand and pebbles on the beach-face slope. The southern half of

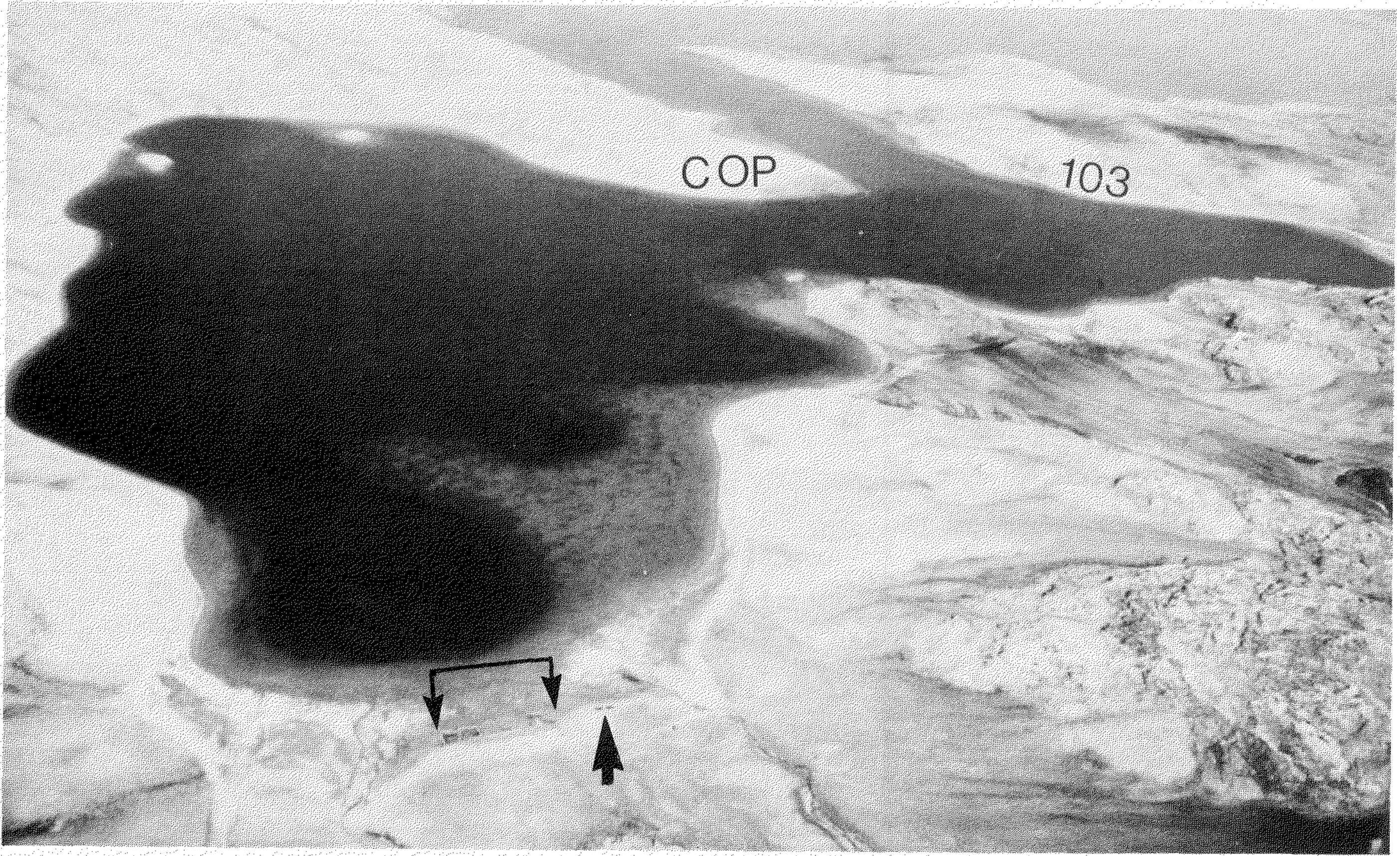

FIG. 6. Bay 106 Site (14 August 1982) in Z-Lagoon indicating location of intertidal (double arrow) and backshore (single arrow) plots. Crude Oil Point and Bay 103 are located by COP and 103 respectively.

the beach has relatively flat intertidal slope of 10-15°, whereas the northern half of the beach has an incipient boulder barricade in the lower intertidal zone, which is separated from the beachface slope by a well-defined trough or runnel. A series of small pebble berms mark the mean and spring high-water levels. At this location a release of 15 m^3 of aged crude oil on the nearshore water surface was allowed to drift ashore (Dickins *et al.*, 1987; Owens *et al.*, 1987b).

EXPERIMENTAL DESIGN AND METHODS

The experimental design was predicated upon two considerations: that the establishment of intertidal and backshore control plots would replicate as closely as possible real world spill conditions, by which oil becomes stranded from the adjacent water surface; and that these control plots would provide a baseline against which the results of the countermeasure experiments could be assessed. The control plots also would provide information on the weathering and fate of crude and emulsified oil left to degrade naturally.

A series of control plots was laid down in the intertidal zone at Bays 102 and 103 and in the backshore (supratidal) zone at Crude Oil Point (in 1980) to provide a set of baseline data. Subsequently, plots were laid down in the intertidal zone at Crude Oil Point (in 1981) and in both the intertidal and backshore zones at Bay 106 (1982) to assess the relative effectiveness of promising countermeasure techniques, and at the same time to allow a comparison of active vs. passive cleanup options on identical intertidal and backshore sediments.

Each control and countermeasure activity involved a pair of plots; one was oiled with an aged Lagomedio crude oil and the other with a 50% water in aged Lagomedio crude oil emulsion. The surface and subsurface sediments of the paired plots were consistently sampled at regular intervals for subsequent chemical analysis.

The Bay 11 surface oil release (Dickins *et al.*, 1987), and the subsequent stranding on the adjacent intertidal sediments, was intended to be a more realistic scenario than that which could be achieved in the Z-Lagoon experiments. It was anticipated that the results from Bay 11 would provide a natural cleanup background data set against which the countermeasure experiments could be compared; it was not until late in the study that the adequacy of the Z-Lagoon control plots (Crude Oil Point, Bay 106 and, in particular, Bay 103) could be assessed relative to their use as long-term controls.

Oil

Two forms of the same oil were used throughout the program: a Lagomedio crude oil that was artificially aged (8% by weight) (Dickins *et al.*, 1987) and a 50% water in aged crude oil emulsion. The emulsion was prepared on-site by recirculating a mixture of two barrels of seawater with two barrels of the aged crude oil through a pump and tank until the desired emulsion was created. Each four-drum batch of emulsion was labelled and, in an attempt to reduce the number of variables, only oil from the same batch was used on any single plot. A sample was collected for GC analysis from each batch of crude oil and emulsion prior to application.

The emulsion was stable over a number of days. On one occasion, in 1983, an attempt was made to re-emulsify two drums of emulsion that had been made up the previous year. The emulsion had broken and intensive mixing did not cause the materials to re-emulsify.

The Application of Oil to Plots

Oil was applied to each plot as described below in a relatively even coating, to a thickness of 1 cm for the aged crude oil and to a thickness of 2 cm for the water in oil emulsion, in order to approximate a large oil spill stranded on the shoreline. The intertidal plots were oiled at approximately mid-tide on a flooding tide. A lined trough was prepared at the base of each plot, prior to application of the oil, to collect any oil that would run downslope off the plot. In addition, plastic drip mats were located at the end of each plot to prevent contamination outside the designated plot area.

The application system consisted of an oil drum, mounted on the back of an All-Terrain Vehicle (ATV), which was connected by hoses and a pump to an oil distribution pipe mounted on the rear of the ATV (Fig. 7). The ATV traversed the test plot and oil was distributed behind the vehicle over a 2 m wide swath. The speed of the vehicle was determined by the calibrated flow rate (3.1 $l \cdot sec^{-1}$; 14 Imperial $gal \cdot min^{-1}$) necessary to cover the plot with a 1 cm thickness of crude oil and 2 cm of the emulsified oil (Table 2) (Woodward-Clyde Consultants, 1981; Owens *et al.*, 1982).

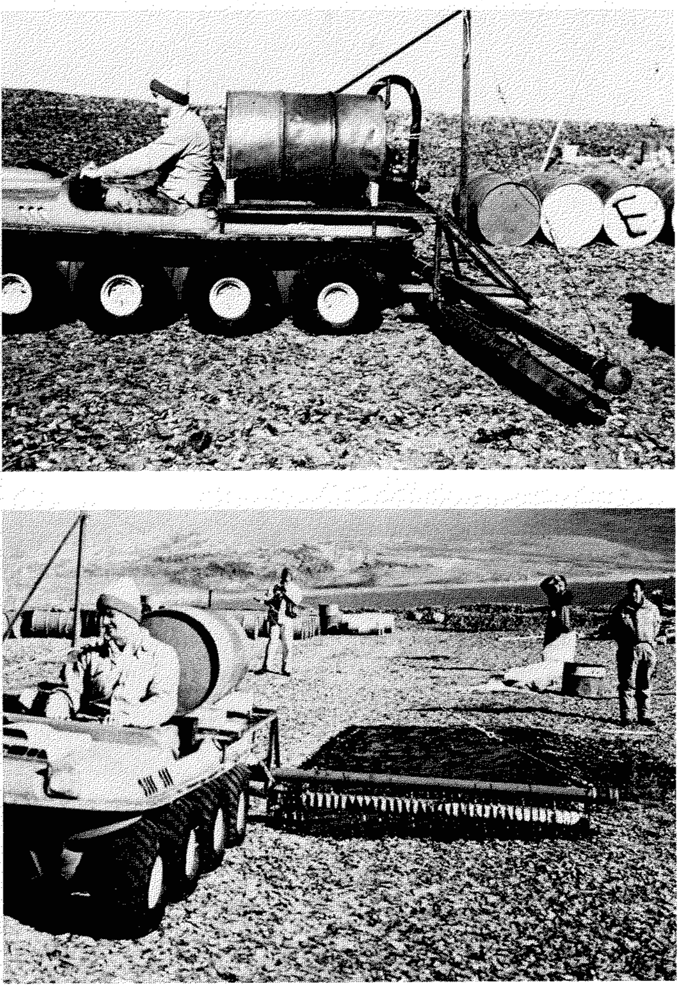

FIG. 7. Application of oil: (top) distribution system on ATV; (bottom) application of emulsion onto the backshore plot (T_2) at Crude Oil Point (2 August 1980).

TABLE 2. Oil application parameters for test plots in Z-Lagoon

Application system	modified, 8-wheel ATV with self-contained storage drum, pump and distribution pipe
Capacity	0.208 m^3 or 208 l (45 Imp. gal)
Pumping rate*	2.3-3.1 $l\cdot s^{-1}$ (30-40 Imp. gal·min^{-1})
Distribution swath	2 m
Application rates*	8-10 m·min^{-1} or 2.3-3.1 $l\cdot s^{-1}$ (30-40 Imp. gal·min^{-1})

*Partially dependent on oil viscosity at the time of the spill.

Bay 11 Release

The release of 15 m^3 of aged crude oil was carried out from a floating discharge hose at the water surface between 15:40 and 21:40 on 19 August 1981. At the time the tide was falling and the light winds were onshore. The bay was boomed to collect oil that did not strand and to prevent cross-contamination to adjacent experimental bays. Oil contained within the boomed area on the water surface was removed until 16:00 on 21 August, and a total of 5.5 m^3 were recovered. Losses attributed to natural processes included 0.26 m^3 to dissolution, 1.95 m^3 to evaporation during the release and 0.45 m^3 to evaporation over the following 18 h (Dickins *et al.*, 1987). By deduction an estimated 6.8 m^3 was therefore unaccounted for and was presumed to have initially stranded and have been retained on the shoreline over an area of approximately 9000 m^2 (Owens *et al.*, 1987b).

Sediment Sampling and Chemical Analyses

Samples were collected by the BIOS chemistry field team for the analysis of the total hydrocarbon (t-h) concentrations (Green, 1981; Green *et al.*, 1982; Humphrey, 1983, 1984) and for compositional information as determined by gas chromatography (GC) analyses (Boehm, 1981, 1983; Boehm *et al.*, 1982, 1984). Surface samples were taken from the top 2 cm and subsurface samples were collected from 5-10 cm. Subsamples were composited to give samples with a total volume up to a maximum of 2.4 l. The sample collection patterns varied from site to site and from year to year, depending upon the specific objectives of sample collection from individual plots. Complete details on the sample design for each site are provided in Woodward-Clyde Consultants, 1981; Owens *et al.*, 1982, 1983; and Owens, 1984.

The total hydrocarbon analysis consisted of a solvent extraction followed by measurement of CH_2 absorbtion at 2850 cm^{-1}. During 1980, baseline concentrations were determined by extraction with CCl_4 and concentration by evaporation of solvent. The detection limit was 0.25 mg·kg^{-1}. In subsequent years, the large number of samples and the high level of contamination precluded the concentration step. For these analyses, the detection limit was 30 mg·kg^{-1}, with a precision at low concentrations of 10 mg·kg^{-1} and of 1% at high concentrations. In 1982 the solvent was changed to Freon 113 for safety reasons.

Extraction, fractionation and analysis of the samples was based on the method of Brown *et al.*, 1979. GC/FID was used to quantify the n-alkanes and isoprenoids, whereas selected parent and alkylated benzenes and polynuclear aromatics were quantified by GC/MS. Diagnostic ratios describing the state of the oil were calculated from these values (Boehm *et al.*, 1987; Owens *et al.*, 1987b).

Physical Measurements

Physical and sedimentological studies of the experimental site were conducted prior to the field experiments (Barrie *et al.*, 1981; Sempels, 1987). Additional data were collected during the study period; in particular, beach profiles were surveyed across the intertidal zone at each test site during each of the years of observation. Wave and tide data were collected at several sites during the 1980 and 1981 field seasons (Buckley *et al.*, 1987). A detailed photographic record was made during all phases of the program.

A series of ground temperature measurements was made in 1980 on the Crude Oil Point backshore crude oil plot (T_1) and on an adjacent unoiled section of backbeach. The ground temperatures in the active layer were monitored using two rods with thermistors placed at 10, 20, 30, 40, 50, 60 and 70 cm depths. The ground temperatures were measured daily over a 12 d period using a Wheatstone Bridge. Incoming short-wave radiation was measured at the BIOS camp (Meeres, 1987), and net radiometers were set up adjacent to each thermistor rod. The objective of these measurements was to record any effects that the presence of surface oil might have on subsurface ground temperatures.

Evaluation of Experimental Time Element

The oil in sediment concentrations that were achieved on the Z-Lagoon plots where the oil was laid down artificially in the intertidal zone were considered to be compatible with those measured at Bay 11, where oil drifted onshore from a nearshore source. The results from the plots were therefore considered to be sufficiently accurate in replicating real world spill conditions and the initial stranding of oil. However, the use of relatively small plots, from which oil could be dispersed along shore and across shore away from the experimental plot by wave action became of greater concern in terms of the experimental design.

The most crucial data set in the evaluation of this aspect of the experimental design was obtained from the two intertidal controls at Crude Oil Point. After a careful assessment of the 1980 and 1981 results it was decided, for evaluation of the Crude Oil Point countermeasure techniques, to utilize only those data collected on or prior to 8 d after the application of the oil. Observations at this site, at Bay 11 and a review of the analytical results (Table 3) indicate that after 8 d the role of sediment transport and dispersion away from the plots by waves became a significant factor. These edge effects would not occur in the real world situation of a large spill with extensive contamination, and the data from the intertidal test plots were considered not to replicate natural large spill situations after this period. A similar decision was made for the results obtained from Bay 106, where

TABLE 3. Total hydrocarbon content (mg·kg^{-1}) of surface sediments from intertidal control plots

Crude Oil Point			Bay 106		
	Crude oil plot (CC)	Emulsion plot (CE)		Crude oil plot (ICC)	Emulsion plot (ICE)
Day 0*	21 000	12 000	Day 0*	15 300	8800
+8 d	17 000	21 700	+7 d	5240	4630
+40/41 d	3100	930	+33 d	2130	830

*Post-oiling/pre-testing.

considerable redistribution of oil occurred across the intertidal zone. At this site the cutoff designated for the interpretation of the analytical results was taken as 7 d following the tests (Table 3).

The use of small plots, approximately 20-40 m^2 in area, is representative of patchy intertidal contamination, rather than of a continuous cover of oil in the intertidal zone. However, the data prior to the cutoff dates described above are considered to be applicable within the experimental objective to replicate a situation similar to that following the stranding of oil in Bay 11.

The results from the intertidal plots represent patchy contamination of fresh oil and emulsion. In this context these data are considered valid for the entire study period. However, it is our experience that patchy contamination usually occurs with oils or emulsions that have been on the water surface for some time before stranding. Patchy contamination from fresh oil or emulsion would normally be associated only with spills of small quantities of oil.

Limitations of the Experimental Design and Methods

There are a number of difficulties with an experimental design that attempts to obtain field data from intertidal gravel beach areas. Considerable variance exists over very short distances, often on the same pocket beach, in sediment type, across-beach sediment sorting, beach slope, intertidal beach width, water table levels, wave exposure and in aspect. This variability must be taken into account in the experimental and sampling design and in the interpretation of the results. It is unrealistic to hold all of these parameters constant in time or space for field experiments, except where they would be conducted on a wide, long, uniform straight sand beach.

The use of only one crude and emulsion limits the general applicability of the results, but the addition of other types of oil would not have been practical for this project in terms of both the available beach space for the experiments and the analytical costs.

After the first set of beach studies in 1980, it was decided, because of the considerable difference between the two intertidal control areas, in Bay 102 (H plots) and Bay 103 (L plots), that these would have to be supplemented in 1981 by control plots in the intertidal zone at the countermeasure experimental site on Crude Oil Point itself. A similar decision was subsequently made for the 1982 countermeasure experiments at the Bay 106 site. The on-site controls, established at the same time and in the same location as the countermeasure experiments, are the most useful controls for the countermeasure experiments. The Bay 102, Bay 103 and backshore control plots set up in 1980 are appropriate for (1) background data on the fate and persistence of the oil in different local wave energy environments (relatively high and relatively low), and (2) comparison with the results from the Bay 11 experimental spill.

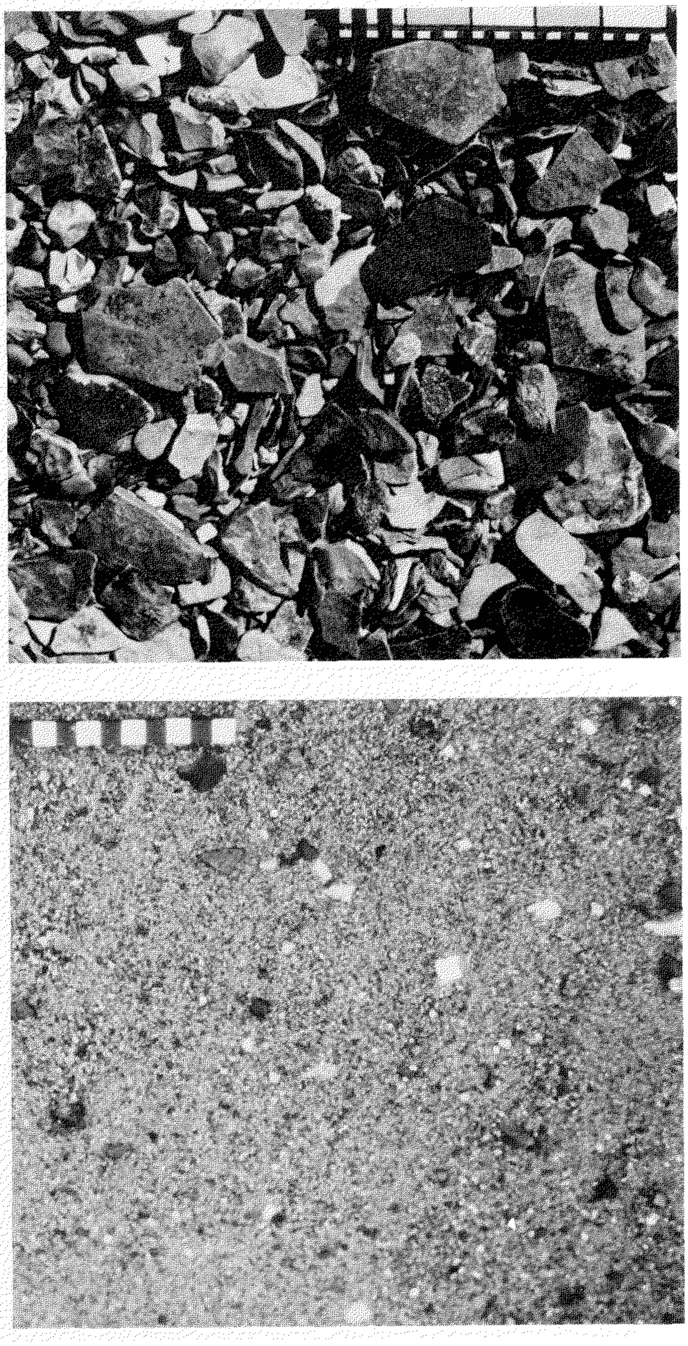

FIG. 8. Sediments on the surface of: (top) Crude Oil Point at the mean high-water level (scale is 25 cm long); (bottom) Bay 106 (scale is graduated in cm).

The nature of the sediments (predominantly poorly sorted mixed sands, pebbles and cobbles) initially caused problems in the sampling program. A sample collected from a site characterized by a well-sorted sediment of uniform size (Fig. 8a) could be replicated with a high degree of confidence. This would be the case for most sand-sized sediment populations. With the exception of the Bay 106 intertidal zone, the beaches of the study sites are characterized by very poorly sorted sediments that may range in size on a single plot from silts or very fine sands <0.0625 mm diameter to cobbles >64 mm diameter (Fig. 8b). The effect of the presence of a cobble or pebble in a volumetric oil in sediment analysis would be to decrease the proportion of oil by reducing the available pore space that could be occupied by the oil. The effect on an analysis of oil in sediment by weight also is to decrease the oil fraction as (1) the volume of oil is decreased due to the reduction in the pore space volume, and (2) the density of the sediment is in the order of 2.5 times greater than that of oil.

The beach and backshore areas that have pebble and/or cobble surface material have an uneven micro-topography as a consequence of the sediment characteristics. The oil tended to collect and pool in small depressions on the beach surface, resulting in an uneven surface distribution (Fig. 9). A surface

FIG. 9. Close-up of water in oil emulsion on the surface of intertidal plot D(E)E at Crude Oil Point immediately after application, showing the uneven surface of the beach and the pooling of the emulsion in micro-depressions (5 August 1981).

sample collected from a micro-topographic "high" would be expected to yield a much lower oil in sediment concentration than one taken from a "low" that contained pooled oil.

The use of an objective sample acquisition approach, based on predetermined sample coordinates, results in the random presence or absence of (1) pebbles or cobbles or (2) oil pools. In a 100 cc (approx. 250 g) sample the effect of a 50 mm diameter pebble, which occupies a volume of approximately 50 cc, would be to halve the oil content of the sample. The initial design involved the collection of a series of small (50-100 g) surface and subsurface sediment samples from each plot. The results of the t-h analyses from the 1980 study were extremely variable within and between plots, due to the effects of non-uniform sediment grain size and of oil pooling. To reduce this problem it was decided thereafter to collect large integrated or composite samples (1250-2000 cc) from each plot, rather than to collect a series of smaller samples.

In 1980 three samples, each composed of three subsamples, were collected both from the surface and subsurface of each plot at four different time intervals over an 8 d period (Woodward-Clyde Consultants, 1981). In 1981 one t-h sample was composited from four subsamples from both the surface and subsurface of each plot at five different times over a 41 d period (Owens *et al.*, 1982).

The validity and the level of confidence in the analytical results from this project depend on the statistical validity of the sampling, not on the precision of the method of analysis (Humphrey, 1983). The sampling pattern and the exact location of individual samples within a plot were predetermined to avoid subjectivity. It was evident that this was the best method but that the actual sample distribution might not adequately describe the oil conditions on the plot. In such cases, particularly in Bay 11, additional samples were collected. Humphrey (1984) commented that the sample strategies from 1981 to 1983 were consistent and also estimated the statistical usefulness of the results by examining the t-h results from Bay 11. On the basis of these tests he recommended that: (1) the results from the plots be assumed to represent concentrations at a single point, rather than over the entire plot; and (2) care should be taken when comparing results that are within one order of magnitude of each other.

RESULTS

Initial Loading and Retention of Oil

The initial loading of oil and the amount of oil retained on each plot was estimated on the basis of the volume of oil removed from the trenches at the base of each plot. The volumes of oil applied and the amounts retained are given in Table 4 for each of the six 1980 control plots and in Table 5 for the ten 1981 countermeasure and control plots.

The most obvious feature of the data set is that the initial oil retention values on the Crude Oil Point plots show considerable uniformity, with crude oil loadings concentrated between 0.8 and 0.9 $cm^3 \cdot cm^{-2}$, whereas the emulsion loadings are lower, in the range of 0.5-0.7 $cm^3 \cdot cm^{-2}$. No significant loading differences were evident between the two oil types of the intertidal

TABLE 4. Oil application and retention amounts — 1980 control plots*

Plot		*Amount applied (m^3)	Amount retained (m^3)	Approx. loading ($cm^3 \cdot cm^{-2}$)
H_1	crude	0.41	0.36	0.9
H_2	emulsion	0.41	0.36	0.9
L_1	crude	0.41	0.25	0.6
L_2	emulsion	0.20	0.08	0.2
T_1	crude	0.41	0.33	0.8
T_2	emulsion	0.41	0.34	0.8

*All plots are 40 m^2 in area: numbers refer to the amount of oil, so that numbers for the emulsified plots should be doubled to obtain the total amount of water and oil emulsion applied (e.g., 0.08 m^3 of oil equals 0.19 m^3 of oil in water emulsion).

Bay 102 control plots (H_1 and H_2) or of the backshore control plots (T_1 and T_2). By contrast, the retention on the Bay 103 crude oil control plot (L_1) was considerably lower than on all of the other intertidal crude oil plots and on the Bay 103 emulsified control plot (L_2) was more than half of the value of the next lowest emulsion plot retention (Table 4). This is attributed to the combination of a high water table and fine-grained sediments, both of which limited the penetration of oil into the beach at this site.

The amounts of retained oil on the Bay 106 (1982) intertidal plots are not directly comparable with the results from the other sites due to the difference in sediment type on this beach (Table 1). The first rising tide lifted oil from the original 20 m^2 plots and contaminated up to an additional 80 m^2 above each plot. Total hydrocarbon results indicate that the application of the crude oil resulted in higher oil in sediment concentrations as compared to the emulsion plots (mean values of 8400 and 7310 $mg \cdot kg^{-2}$; Table 6). Little or no oil penetrated the subsurface sediments on these plots.

The oil in sediment concentrations achieved in Z-Lagoon, as shown by the first set of surface samples, taken within 24 h, range from 4000 to 77 000 $mg \cdot kg^{-1}$ for the crude oil plots and 1300-24 000 $mg \cdot kg^{-1}$ for the emulsion plots (Table 6). As a general conclusion, on the three gravel beaches in Z-Lagoon (Bay 102, Bay 103 and Crude Oil Point) more oil was retained on the aged crude oil plots than on the water in oil emulsion plots.

On the Bay 106 intertidal plots, the mean oil in sediment concentration (based on three composite samples) on the crude oil plots decreased from 9400 $mg \cdot kg^{-1}$ immediately after application of the oil to 2220 $mg \cdot kg^{-1}$ after 24 h, following the redistribution of the oil above the plots by the tides. The mean value on the emulsion plots decreased from 7310 to 5115 $mg \cdot kg^{-1}$. Composite samples collected in the area of the high-water mark above the plots 24 h after application of the oil produced mean values of 14 000 for the crude plots and 3000 $mg \cdot kg^{-1}$ for the emulsion plots (Owens *et al.*, 1983). These results indicate that on this beach apparently more oil was redistributed from the crude oil plots, as compared to the emulsion plots, resulting in higher oil concentrations on the upper sections of the extended crude oil plots.

TABLE 6. Post-oiling total hydrocarbon content of surface sediments

	Mean ($mg \cdot kg^{-1}$)	Number of samples	Range ($mg \cdot kg^{-1}$)
(1) Crude oil plots			
Bay 102	36 500	3	11 600 - 77 400
Crude Oil Point	17 825	4	4310 - 25 000
Bay 103	17 133	3	6700 - 36 000
Bay 106	8400	3	4090 - 15 300
Bay 11	7100	9	470 - 18 000
ALL SAMPLES	17 600	22	470 - 77 400
(2) Emulsion plots			
Bay 102	13 667	3	1900 - 23 200
Crude Oil Point	13 843	4	7370 - 24 000
Bay 103	3167	3	1300 - 4500
Bay 106	7310	3	4850 - 8800
ALL SAMPLES	9500	13	1300 - 24 000

The mean and range of values for individual samples collected from Bay 11 in three across-beach zones at three profile sites during the first low tide following the oiling of the beach show higher oil concentrations on the beach-face slope (upper intertidal zone) and on the low-tide terrace than on the mid-tide level trough (Table 7). The two former zones are characterized by sandy-gravel and cobble sediments, whereas the latter is a silt-sand environment.

TABLE 7. Initial surface total hydrocarbon concentrations ($mg \cdot kg^{-1}$) at Bay 11 one day after the spill (20 August 1981)

	Profile			
Location	2	4	6	$\bar{X}$
Upper intertidal	7050	3440	16 000	8800
Middle intertidal	480	4800	6 090	3800
Lower intertidal	18 000	470	7340	8600

TABLE 5. Volumes of oil* applied to intertidal countermeasure plots at Crude Oil Point (1981)

Plot		Code	Volume of oil applied (m^3)	Volume of oil retained (m^3)	Approx. loading ($cm^3 \cdot cm^{-2}$)
Control:	crude	CC	0.19	0.18	0.91
Control:	emulsion	CE	0.18	0.10	0.52
Exxon disp:	crude	D(E)C	0.19	0.18	0.91
Exxon disp:	emulsion	D(E)E	0.18	0.14	0.68
BP disp:	crude	D(B)C	0.18	0.16	0.79
BP disp:	emulsion	D(B)E	0.18	0.14	0.70
Mixing:	crude	MC**	0.39	0.37	0.91
Mixing:	emulsion	ME**	0.36	0.21	0.53
Solidifier:	crude	SC	0.18	0.16	0.79
Solidifier:	emulsion	SE	0.19	0.15	0.73

* Volumes and loading rates refer to amount of aged oil; volumes of water in aged oil emulsion would be double those indicated.
**All plots are 20 m^2 in area, except MC and ME, which are 40 m^2.

The mean values and the range of values of the total hydrocarbon samples collected from the crude oil intertidal test plots in Z-Lagoon are in the same general range, although slightly higher, than the total hydrocarbon samples collected from the Bay 11 beach. This indicates that the experimental plots were reasonable replicates of the "real" oil contaminated beach areas of Bay 11, at least over the short term. Table 8 compares the total hydrocarbon analyses through time of the composite sample from the crude control plot at Crude Oil Point (CC) with the mean of nine surface samples from Bay 11. The data from Bay 11 are relatively constant through time, whereas the values from Crude Oil Point show a significant reduction after Day 8, due primarily to redistribution of oil from the plot, by wave action, to uncontaminated adjacent sections of the beach.

TABLE 8. Comparison of crude oil control plot (CC) at Crude Oil Point and Bay 11 surface total hydrocarbon analyses (mg·kg^{-1})

(a) 1st O/W season	+1 d	+8 d	+26 d	+40 d
Crude Oil Point	21 000	17 000	n/s	3100
Bay 11	7100	6600	5900	n/s
(b) 2nd O/W season	10 Aug 1982	2 Sept 1982		
Crude Oil Point	300	80		
Bay 11	4400	n/s		
(c) 3rd O/W season	16 Aug 1983			
Crude Oil Point	22			
Bay 11	9400			

n/s = no sample.
O/W = open water.

Maximum Oil Loading Concept

All plots were oiled to excess; runoff oil was collected from each plot as the oil or emulsion was applied. Visual observations following the oiling of the Bay 11 beach indicate that for several days oil did not readily adhere to the sediment and that oil on the beach was redistributed several times by the rising and falling tides. The lower energy control plots in Z-Lagoon (Bays 103 and 106) had significant percentages of oil and emulsion removed within 24 h, whereas 8 d after oiling of the two control plots at Crude Oil Point the hydrocarbon values remained within the range of values of those samples collected immediately following application of the oil. These observations suggest that there was a maximum loading volume for these beaches, which may be a function of:

- the size of the sediments,
- the size of the interstitial spaces of the surface sediments,
- the surface properties of the sediments (including texture and wetness/dryness),
- the level of the water table with respect to beach morphology, and
- the type and volume of oil.

Once a section of beach has reached the maximum loading for a particular type of oil then further oil will not be retained. Removal of this additional oil occurs either by gravity flow downslope or by lifting as the tide floods. If the oil is not removed it will remain as surface pools in depressions. The different retention values for the crude and emulsions can be explained in terms of the different maximum loading volumes for these different types of oil on similar, adjacent plots. Differences in viscosity would permit the emulsion to flow downslope and to float on the surface of the flooding waters more readily than the aged crude oil.

Subsequent to this study, further experimental work has been conducted (Harper *et al.*, 1985) that supports the concept that there is a loading thickness beyond which there is little increase in oil retention. The experimental results indicate that the viscosity of the oil prevents further penetration once the oil has saturated the surface sediment layer. The maximum loading limit is therefore considered to be a function of sediment size, as this affects permeability, or porosity, and oil viscosity.

Persistence of Oil

On the exposed beach at Bay 102 mechanical wave action was effective in rapidly dispersing the intertidal oil. Within 48 h the surface mean oil concentration (three samples) was reduced from 36 500 to 1200 mg·kg^{-1} on the crude plot (H_1) and from 13 700 to 20 mg·kg^{-1} on the emulsion plot (H_2) (see Owens *et al.*, 1987a: Table 6). Oil remained in high concentrations in the subsurface sediments of the crude oil plot after 8 d (mean value 10 000 mg·kg^{-1}), whereas values from all three subsurface samples on the emulsion plot were < 10 mg·kg^{-1}. The following season, on 28 July 1981, oil was present only in the surface and subsurface samples taken from the upper section of the two plots, but by 29 August the plots were oil free (Owens *et al.*, 1982).

Changes in the oil content of the sediments can be expressed, for the purposes of comparison, by taking the total hydrocarbon concentration as a percent of the original post-oiling value (Table 9). Eight days after oiling at Bay 102 the change is 3.3% on the crude oil plot (H_1) and 0.15% for the emulsion plot (H_2), indicating that virtually all of the oil had been removed from these two plots. Using this approach, at the more sheltered control location in Bay 103, 70% of the oil on the crude plot (L_1) and over 90% of the oil on the emulsion plot (L_2) was removed within 48 h (see also Owens *et al.*, 1987a:Table 7).

By the eighth day the amount of oil remaining in the surface sediment was 38% on L_1 and 4% on L_2 (Table 9). Subsurface oil values on L_1 initially decreased to 34% of the initial concentration after 2 d, then increased to 90% after 8 d. Values in the subsurface of the emulsion plot (L_2) were low, with $< 5\%$ remaining after 48 h. Wave action is not a significant factor in Bay 103, so that the primary processes by which oil was removed were related to water level changes (i.e., tides). Removal of oil was found to be most significant at sites characterized by a high groundwater table. The lower retention of oil and subsequent persistence of remaining oil on the emulsified plot, as compared to the crude plot, was due primarily to a finer sediment size and to a higher groundwater table on the L_2 plot.

After the initial period of removal during 1980 the oil concentrations on the Bay 103 L_1 control plot remained fairly consistent through the 1981 and 1982 field seasons, both in the surface (mean of 12 samples — 3400 mg·kg^{-1}, range 440-11 500 mg·kg^{-1}) and subsurface (mean 7000, range 1820-15 700 mg·kg^{-1}) sediments. By 1983 the mean of the three surface samples was reduced to 600 mg·kg^{-1}, which represents only 4% of the original oil concentration value, whereas the mean for the subsurface samples of 8500 mg·kg^{-1} remained high and is 55% of the initial value (Owens, 1984). The emulsion plot (L_2) produced mean values for the 12 surface and subsurface samples

TABLE 9. Changes in oil in sediment concentrations on intertidal plots over the first season

Plot	t-h concentration immediately after oil application (mg·kg^{-1})	t-h concentration at end of first open-water season (mg·kg^{-1})	Number of days after oil application	% change
(a) Surface				
H_1	36 500	1200	8	3
H_2	13 500	30	8	0.2
L_1	17 000	6500	8	38
L_2	3000	130	8	4
CC	21 000	3110	40	15
CE	12 000	930	40	8
ICC	15 300	2130	33	14
ICE	8800	830	33	9
(b) Subsurface				
H_1	12 000	10 000	8	83
H_2	10 500	5	8	<0.1
L_1	15 500	14 000	8	90
L_2	1300	75	8	6
CC	3020	150	40	5
CE	1060	110	40	10
ICC	trace	0	33	—
ICE	trace	0	33	—

collected in 1982 of 140 and 90 mg·kg^{-1} respectively and was essentially oil free before sampling commenced in 1982.

Redistribution of oil from the control plots in Bay 106 occurred during the first flooding tide following application of the oil. Approximately 25% of the original oil remained on the crude oil plots, whereas on the emulsion plots approximately 70% was retained after 24 h. Subsequent changes on the control plots were relatively small during the sample collection period up to 7 d following the initial oiling. A further reduction occurred in the period up to 33 d after oiling (15 September 1982), and these concentrations were similar to those found on the control plots during the following open water season (20 August 1983).

The total hydrocarbon concentrations on the Crude Oil Point control plots showed lower rates of change as compared to the 1980 intertidal control plots. On the crude plot (CC) the oil concentration decreased only from 21 000 to 17 000 mg·kg^{-1} over the first 8 d interval, but then dropped to 3110 mg·kg^{-1} after 40 d, primarily as a result of wave processes and wave-induced edge effects on the plot (Table 9). The emulsion control plot (CE) values showed an initial increase from 12 000 to 21 700 mg·kg^{-1}, followed by a drop to 930 mg·kg^{-1} after 40 d (see also Owens *et al.*, 1987a:Table 9).

The results show that major changes in the oil concentrations on three of the four pairs of control plots occurred within 48 h of the initial oiling and that subsequent changes were relatively small. The exception is the Crude Oil Point plots, which, despite some variability, did not change significantly until after the 8 d sample set.

In the context of using the data to examine the persistence of fresh oil stranded as patchy, rather than as continuous, contamination, the results show that by the end of the first season of sampling the reduction of oil in sediment concentrations was 85% or greater on the surface of seven out of the eight plots (Table 9). The exception to this trend was the L_1 plot, which retained high t-h values throughout the study period. The reduction of t-h concentrations in the subsurface sediment samples was > 90% on six out of eight plots, and L_1 again retaining high values and with the H_1 value remaining high at 8 d after the oil application, but falling to 500 mg·kg^{-1} at the first sample period in the next season (28 July 1981) and then to 0 mg·kg^{-1} by 29 August 1981. The conclusion can be drawn that, with the exception of the L_1 plot, the patchy contamination was cleaned rapidly, within 1-6 weeks, even within the sheltered beaches of Z-Lagoon.

Notwithstanding the important element of edge effects on the plots, over the longer time frame of months the natural cleaning rate on the Bay 103 crude oil plot (L_1) was slower than that on the Bay 106 crude oil plot (ICC) over the same time period, even though the latter is more sheltered. This difference is probably due to the sediment characteristics of the sites. In Bay 103 the pebble/cobble sediments have a much higher degree of micro-relief as compared to the very flat surface on the fine-grained Bay 106 sediments (Fig. 8b). The fate and persistence of stranded oil is a function not only of wave energy levels at the shoreline, but also of the oil loading, the sediment character and beach topography.

Effects of Oil on Subsurface Ground Temperatures (adapted from Woodward-Clyde Consultants, 1981: Section 8.0)

Ground temperatures in the active layer were monitored during 1980 at Crude Oil Point by thermistor rods in the crude oil plot (T_1) and in an adjacent non-oiled section of ground. These two sites are located in the backshore and, although not under the active influence of marine processes, they are on a relict beach comprising material similar to the present beaches. The rods, installed in mid-August, were not able to penetrate the frost table, which was encountered at about 80 cm depth. Ground temperatures were measured daily from the day of oiling (20 August 1980) until 31 August 1980.

Comparison of the temperatures measured in the oiled and non-oiled plots shows that the ground beneath the oiled plot was significantly warmer than that beneath the non-oiled plot (Fig. 10). The temperature in the upper 10 cm was initially colder under the oiled sediments and subsequently warmer by approxi-

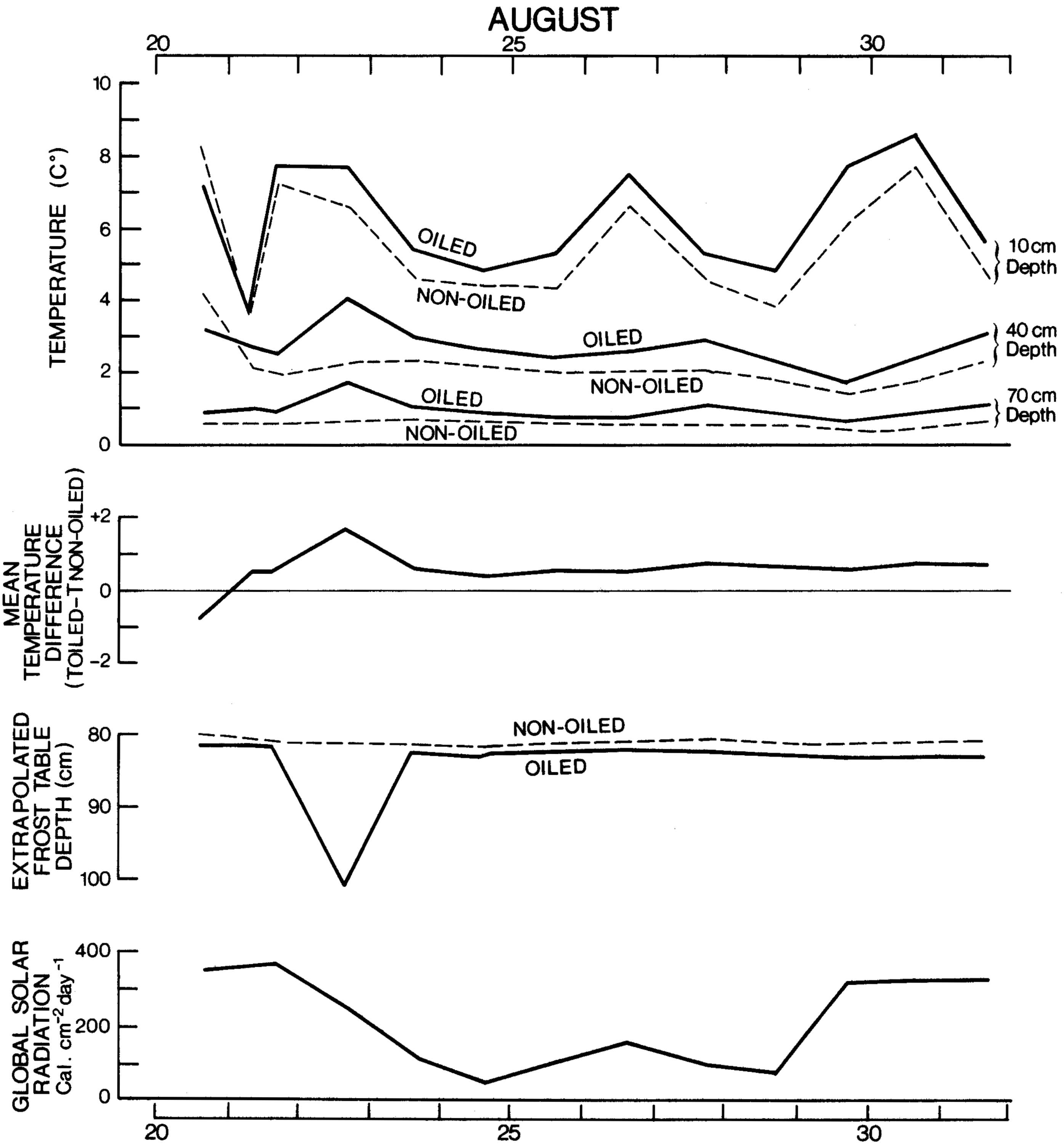

FIG. 10. Ground temperature data: (a) time series of the subsurface temperatures at various depths below the aged oil control plot (T_1) and an adjacent non-oiled plot; (b) mean temperature differences between the oiled and non-oiled plots; (c) estimated frost table depths, based on extrapolated temperature profiles, beneath the oiled and non-oiled plots; (d) global solar radiation measured at the nearby Base Camp.

mately 1°C; temperature trends at the 40 cm depth were similar in that ground temperatures were warmer beneath the oiled plot by a little more than 1°C; sediments at the 70 cm depth were warmer under the oiled plot by about 0.25°.

The mean daily temperature difference from all levels also indicates that the ground temperatures were higher under the oiled plot and that the mean difference increased from 0.5°C to 0.75°C during the study (ignoring the point on 22 August) (Fig. 10b).

The depth of the frost table (0°C isotherm) was estimated by extrapolating the temperature profiles. The large increase shown for the oiled plot on 22 August is an artifact of an anomalous temperature profile that occurred on that day and does not reflect the true frost table depth. Frost table depths were similar at both sites (Fig. 10c) but were slightly lower at all times under the oiled plot (80-85 cm). During the study, the estimated frost table depth increased at both plots, but at a slightly greater rate under the oiled plot.

These results from the thermistor rod measurements indicate a definite influence of spilled oil on subsurface ground temperatures. After the first 2 d of the experiment, ground temperatures under the oiled plot were in all cases greater than under the non-oiled section. The temperature difference tended to increase during the study, and there is a suggestion that the oiling may have caused an increase in the frost table depth.

The correlation between surface ground temperature and global radiation measurements indicates a causal relationship, and some qualitative estimates are possible regarding the effect of oil on some ground temperature measurements. The oiled surface was much darker and, as such, has the capacity to absorb increased amounts of net solar radiation. Any increase in the amount of net solar radiation (Q_N) must be balanced by changes in the latent heat flux from the surface (Q_E), the sensible heat flux from the surface (Q_H) or the flux of heat into the ground (Q_G). The balance is expressed by the equation:

$$Q_N = Q_E + Q_H + Q_G$$

Without significant changes in the surface roughness of the plots, Q_E and Q_H would not be expected to change; hence, increases in net radiation values would be largely balanced by increases in the ground heat flux. The correlation noted between the temperature at 10 cm depth and global radiation (Figs. 10a, 10d) indicates that net solar radiation was the significant parameter controlling ground temperature variations, and it is suggested that the increase in ground temperatures noted under the oiled plot during the study resulted from increased net radiation on the plot surface. The implications of this observation are important in that increased ground temperatures may result in increased microbial activity in the surface sediments and that the active layer thickness may be increased, which would allow a greater amount of sediment to be reworked by marine processes.

CONCLUSIONS

(1) Analytical results show that an application of oil was achieved on the Z-Lagoon plots that closely replicated the stranding of oil in the intertidal zone at Bay 11.

(2) The major changes in the volume of oil on the intertidal plots occurred within 48 h of the initial oiling, and subsequent changes were relatively small. The exception to this trend occurred on the paired control plots at Crude Oil Point, which were stable over the first 8 d period but showed a significant reduction in oil concentrations over the following 30 d period.

(3) Interpretation of the results on the intertidal retention of oil suggests that there exists a maximum loading for beaches that may be a function of the: (a) size of sediments; (b) size of interstitial spaces between sediments; (c) surface properties of the sediments; (d) level of the water table of the beach; and (e) type and volume of the oil.

(4) At the sandy-gravel beach sites, oil retention on the intertidal emulsion plots was less than on the aged oil plots. At Bay 106 the intertidal zone is characterized by silty-sand sized sediments, and virtually all of the crude oil was rapidly removed by the first flooding tide and carried to higher sections of the intertidal zone.

(5) Observations and results throughout the project show that data from the intertidal plots are representative of natural conditions following large-scale contamination with a continuous oil cover only within the first week (7 or 8 d) following application of the oil. Thereafter, dispersion, sediment redistribution and edge effects become important. Small-scale (e.g., 20-40 m^2) experimental oil plots should therefore only be utilized for very short-term studies on oil fate that attempt to replicate a large spill with a complete intertidal oil cover.

(6) The intertidal plots replicated patchy contamination by fresh oil or emulsion. The t-h analyses from the control plot samples show that in this context the majority of the oil was removed rapidly from the beaches, within between one and six weeks even in this relatively low wave energy environment.

(7) The sampling of intertidal sediments on a beach of mixed sand and pebble posed a number of problems. However, the data show temporal changes in the total hydrocarbon values that are greater than one order of magnitude.

(8) Oil on the surface of a backbeach plot resulted in an increase in the surface sediment temperatures of up to 1°C at a depth of 40 cm. The effect of surface oil is to lower the depth of the frost table within the beach, and the elevated subsurface temperatures could result in increased microbial activity.

ACKNOWLEDGEMENTS

Carl R. Foget and John R. Harper were closely involved with the field program and data interpretation. In particular, Foget contributed significantly to the development of the experimental procedures and personally designed and built the oil application system for the ATV. Harper conducted the ground temperature investigation. The geochemistry team, most especially Blair Humphrey, Dave Hope and Dave Green, were closely involved in the design of the sampling program; Humphrey and Hope collected all of the samples. All of the BIOS field staff contributed to make the study possible. Comments by E. Gundlach, J. Bishop and an unknown reviewer are appreciated.

REFERENCES

BARRIE, W.B., SEMPELS, J.-M., and McLAREN, P. 1981. Baffin Island Oil Spill Project — geomorphology data report. Unpubl. report to Petro-Canada Exploration Inc., P.O. Box 2844, Calgary, Alberta, T2P 2M7. 200 p.

BOEHM, P.D. 1981. Chemistry 2: Hydrocarbon chemistry — 1980 study results. (BIOS) Baffin Island Oil Spill, Working Report 80-2. Ottawa: Environmental Protection Service, Environment Canada. 184 p.

———. 1983. Chemistry 2: Analytical biogeochemistry — 1982 study results. (BIOS) Baffin Island Oil Spill, Working Report 82-2. Ottawa: Environmental Protection Service, Environment Canada. 210 p.

———, FIEST, D.L., and HIRTZER, P. 1982. Chemistry 2: Analytical biogeochemistry — 1981 study results. (BIOS) Baffin Island Oil Spill, Working Report 81-2. Ottawa: Environmental Protection Service, Environment Canada. 354 p.

BOEHM, P.D., STEINHAUER, W., COBB., D., DUFFY, S., and BROWN, J. 1984. Chemistry 2: Analytical biogeochemistry — 1983 study results. (BIOS) Baffin Island Oil Spill, Working Report 83-2. Ottawa: Environmental Protection Service, Environment Canada. 139 p.

BOEHM, P.D., STEINHAUER, M.S., GREEN, D.R., FOWLER, B., HUMPHREY, B., FEIST, D.L., and CRETNEY, W.J. 1987. Comparative fate of chemically dispersed and beached crude oil in subtidal sediments of the arctic nearshore. Arctic 40 (Supp. 1):133-148.

BROWN, D.W., RAMOS, L.R., FRIEDMAN, A.J., and MacLEOD, W.D., 1979. Analysis of trace levels of petroleum hydrocarbons in marine sediments using a solvent/slurry extraction procedure. In: Trace Organic Analysis:

A New Frontier in Analytical Chemistry. National Bureau Of Standards, Special Publication 519.

BUCKLEY, J.R., DE LANGE BOOM, B.R., and REIMER, E.M. 1987. The physical oceanography of the Cape Hatt region, Eclipse Sound, N.W.T. Arctic 40 (Supp. 1):20-33.

DICKINS, D.F. 1987. Ice conditions at Cape Hatt, Baffin Island. Arctic 40 (Supp. 1):34-41.

———, THORNTON, D.E., and CRETNEY, W.J. 1987. Design and operation of oil discharge systems and characteristics of oil used in the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):100-108.

GREEN, D.R. 1981. Chemistry 1: Field sampling and environmental chemistry — 1980 study results. (BIOS) Baffin Island Oil Spill, Working Report 80-1. Ottawa: Environmental Protection Service, Environment Canada. 93 p.

———, HUMPHREY, B., and FOWLER, B. 1982. Chemistry 1: Field sampling and total hydrocarbon analysis — 1981 study results. (BIOS) Baffin Island Oil Spill Working Report 81-1. Ottawa: Environmental Protection Service, Environment Canda. 111 p.

HARPER, J.R., MISKULIN, G.A., GREEN, D.R., HOPE, D., and VANDERMEULEN, J.H. 1985. Experiments on the fate of oil in low-energy marine environments. Proc. AMOP (Arctic Marine Oil Spill Program). Edmonton. 64 p.

HUMPHREY, B. 1983. Chemistry 1: Field sampling and measurements — 1982 study results. (BIOS) Baffin Island Oil Spill Working Report 82-1. Ottawa: Environmental Protection Service, Environment Canada. 64 p.

———. 1984. Chemistry 1: Field sampling and measurements — 1983 study results. (BIOS) Baffin Island Oil Spill, Working Report 83-4. Ottawa: Environmental Protection Service, Environment Canada. 64 p.

MEERES, L.S. 1987. Meteorological operations at Cape Hatt in support of the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):42-50.

OWENS, E.H. 1984. Shoreline countermeasures — 1983 study results. (BIOS) Baffin Island Oil Spill, Working Report 83-4. Ottawa: Environmental Protection Service, Environment Canada. 102 p.

———, HARPER, J.R., and FOGET, C.R. 1982. Shoreline countermeasures — 1981 study results. (BIOS) Baffin Island Oil Spill, Working Report 81-4. Ottawa: Environmental Protection Service, Environment Canada. 123 p.

———. 1983. Shoreline countermeasures — 1982 study results. (BIOS) Baffin Island Oil Spill, Working Report 82-4. Ottawa: Environmental Protection Service, Environment Canada. 129 p.

OWENS, E.H., ROBSON, W., and FOGET, C.R. 1987a. A field evaluation of selected beach cleaning techniques. Arctic 40 (Supp. 1):244-257.

OWENS, E.H., HARPER, J.R., ROBSON, W., and BOEHM, P.D. 1987b. Fate and persistence of crude oil stranded on a sheltered beach. Arctic 40 (Supp. 1):109-123.

SEMPELS, J.-M. 1987. The coastal morphology and sedimentology of the Cape Hatt peninsula. Arctic 40 (Supp. 1):10-19.

SERGY, G.A., and BLACKALL, P.J. 1987. Design and conclusions of the Baffin Island Oil Spill Project. Arctic 40 (Supp. 1):1-9.

SNOW, N.B., CROSS, W.E., GREEN, R.H., and BUNCH, J.N. 1987. The biological setting of the BIOS site at Cape Hatt, N.W.T., including the sampling design, methodology and baseline results for macrobenthos. Arctic 40 (Supp. 1):80-99.

WOODWARD-CLYDE CONSULTANTS. 1981. Shoreline countermeasures — 1980 study results. (BIOS) Baffin Island Oil Spill, Working Report 80-4. Ottawa: Environmental Protection Service, Environment Canada. 83 p.