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A Field Evaluation of Selected Beach-Cleaning Techniques

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ABSTRACT. A series of experiments was conducted to evaluate selected countermeasures for the cleanup of oil on remote beaches. These experiments formed part of the Baffin Island Oil Spill (BIOS) Project, which was conducted at Cape Hatt, N.W.T., between 1980 and 1983. An isolated lagoon was selected with a series of segregated bays that could be used for discrete experiments with control and countermeasure plots. Intertidal control plots were established in 1980 at an exposed site and at a relatively sheltered location. The oil on the exposed intertidal control plot was removed rapidly by natural processes so that subsequent attention was focused on low wave energy sites. Countermeasure experiments were conducted in 1981 in the intertidal zone at a relatively sheltered site and in 1982 in the intertidal and backshore zones at a very sheltered beach. At each of these two locations, control and countermeasure plots were duplicated using an aged Lagomedio crude oil and a water in aged Lagomedio emulsion. Countermeasures were selected for testing on the basis of existing experimental or practical knowledge and the applicability to remote or arctic beach environments. The selected techniques were incendiary combustion, mechanical mixing, chemical dispersion, solidifying and low-pressure flushing.

Samples of surface and subsurface sediments were collected throughout the experiments for total hydrocarbon and GC/MS analysis. Two chemical dispersants (BP 1100X and Corexit 7664) were effective on the relatively sheltered beach but neither was effective on the very sheltered beach due to the lack of wave energy to agitate or to redistribute the oil/dispersant mixture. The mechanical mixing of backshore sediments accelerated the removal of surface oil but increased subsurface hydrocarbon concentrations. Low-pressure flushing on the very sheltered fine-grained beach did not reduce surface hydrocarbon concentrations and resulted in higher oil in sediment concentrations when compared to an adjacent control plot. The solidifying agent was an effective method for encapsulating oiled beach sediments. Over a five- to six-week period the control plot data indicates that rates of natural cleaning resulted in similar total hydrocarbon values when compared to the countermeasure plots. However, these results must be considered in the context of edge effects and dispersion that are a function of using small (10 m × 2 m) intertidal plots. Such plots represent only patchy contamination. As the experimental concept was aimed primarily at the cleanup of heavily contaminated beaches, the primary evaluation of the countermeasures relates to data obtained only from the first week of each experiment. Neither the incendiary device nor the low-pressure flushing techniques proved to be effective, whereas over this short period mixing and chemical dispersion demonstrated a potential to mitigate the effects of beach contamination or to accelerate the removal of stranded oil.

Key words: countermeasures, dispersants, flushing, incendiary devices, mixing, natural cleaning, oil spill, shoreline, solidifying agent

RÉSUMÉ. On a mené une série d'expériences visant à évaluer une sélection de mesures pour combattre la pollution par le pétrole sur des plages éloignées. Ces expériences faisaient partie du projet BIOS (projet de déversement de pétrole à l'île Baffin) qui a eu lieu au cap Hatt (T. N.-O.), entre 1980 et 1983. On a choisi une lagune avec une série de baies séparées, où l'on a pu faire des expériences de nature différente sur un terrain témoin et sur un terrain servant aux mesures d'intervention. En 1980, on a établi des terrains témoins dans la laisse, à un endroit exposé et à un autre relativement abrité. Sur le terrain témoin de la laisse dans la zone exposée, le pétrole a été rapidement enlevé par des processus naturels. On s'est donc ensuite concentré sur les sites ayant une faible énergie de vagues. On a mené des expériences de mesures d'intervention dans la laisse d'un site relativement abrité en 1981, et dans la laisse et sur l'arrière-plage d'un site très abrité en 1982. A chacun de ces deux endroits, on a établi des paires de terrains comprenant chacune un terrain témoin et un terrain servant aux mesures d'intervention, en utilisant un pétrole brut vieilli Lagomedio et une émulsion d'eau dans du pétrole Lagomedio. On a choisi des mesures d'intervention pour les essais à partir des connaissances expérimentales ou pratiques actuelles et de leur possibilité d'application sur les plages de l'Arctique ou de régions éloignées. Les techniques choisies comprenaient le brûlage, le brassage mécanique, la dispersion chimique, la solidification et le nettoyage à grande eau à basse pression.

Tout au long des expériences, on a prélevé des échantillons de sédiments à la surface et sous la surface pour en mesurer la teneur totale en hydrocarbures et pour l'analyse par CG/SM. Deux agents de dispersion chimiques (BP 1100X et Corexit 7664) ont été efficaces sur la plage relativement abritée, mais aucun des deux ne l'a été sur la plage très abritée, en raison du manque d'énergie des vagues pour agiter ou redistribuer le mélange pétrole/agent de dispersion. Le brassage mécanique des sédiments de l'arrière-plage a permis d'enlever plus rapidement le pétrole en surface, mais a augmenté les concentrations en hydrocarbures sous la surface. Sur la plage de sable fin très abritée, le nettoyage à grande eau à basse pression n'a pas diminué les concentrations en hydrocarbures à la surface et a augmenté les concentrations en pétrole dans les sédiments, par rapport à un terrain témoin adjacent. La solidification a été une méthode efficace pour enrober les sédiments de la plage polluée par le pétrole. Les données obtenues sur le terrain témoin pendant cinq à six semaines indiquent que les taux de nettoyage naturel ont produit des teneurs totales en hydrocarbures semblables à celles des terrains de mesures d'intervention. Ces résultats doivent cependant être considérés dans le contexte des effets de bord et de dispersion qui découlent de l'utilisation de petits terrains (10 m × 2 m) situés dans la laisse. De tels terrains ne représentent qu'une pollution fragmentaire. Comme ce concept expérimental visait surtout le nettoyage des plages très polluées, l'évaluation la plus importante des mesures d'intervention se rapporte seulement aux données obtenues durant la première semaine de chaque expérience. Ni le mécanisme incendiaire, ni le nettoyage à grande eau à basse pression ne se sont montrés efficaces, alors que durant cette courte période, le brassage et la dispersion chimique ont prouvé qu'ils pouvaient mitiger les effets de la pollution de la plage ou accélérer l'enlèvement du pétrole échoué.

Mots clés: mesures d'intervention, agents de dispersion, lavage à grande eau, mécanismes incendiaires, brassage, nettoyage naturel, déversement de pétrole, littoral, agent solidifiant

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INTRODUCTION

In 1979, the Arctic Marine Oilspill Program (AMOP) identified certain areas of shoreline countermeasure technology that required further investigation. During the design stages of the Baffin Island Oil Spill (BIOS) Project, it became clear that it would be possible to combine a shoreline countermeasure experiment that could address some of these knowledge gaps with the BIOS nearshore oil release project. The shoreline countermeasure studies were then developed as one component of the BIOS Project to evaluate selected techniques for the cleanup of oiled beaches. Sergy and Blackall (1987) provide a history and description of the BIOS Project.

Since the *Torrey Canyon* spill in 1967 and the Santa Barbara spill in 1969, there has been a considerable effort expended upon the evaluation and development of countermeasure tech-

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niques for different shoreline types (Lindstedt-Siva, in press). Despite numerous research and testing programs that had been conducted before the design of this project, there remained a number of significant gaps in the knowledge base. One element of the program design was therefore to address information or knowledge deficiencies related to techniques for beach cleaning. Some of the selected techniques had been tested or evaluated in lower latitudes, but it was considered important that tests be conducted in an arctic environment to determine their applicability to these remote shorelines.

The experimental design for the shoreline countermeasures program was not finalized until after small-scale field evaluations of the selected countermeasures were conducted to determine their suitability for full-scale testing. Considerable attention was focused upon the amount of oil applied to the plots and the amount of oil retained (Owens and Robson, 1987). These data were then compared to (1) the intertidal control plots established in 1980, and (2) results from studies conducted on a contaminated beach where oil was allowed to strand from a large nearshore surface oil release that was conducted in a nearby bay as part of a separate but related study (Owens *et al.*, 1987).

This paper focuses initially upon the experimental design for the program and upon the results from the various experiments conducted in 1981 and 1982. Considerably more detail is provided on all phases of this experiment in the annual project reports (Woodward-Clyde Consultants, 1981; Owens *et al.*, 1982; Owens *et al.*, 1983; Owens, 1984), and these should be consulted for descriptions of the countermeasure tests and for complete sets of the analytical data.

The results of the field experiments are considered in the context of the existing knowledge base and of arctic coastal environments, and conclusions are presented that may be applied to countermeasure planning for remote or arctic coastal environments. Although the focus of the experiments relates to arctic coasts, there are many similar shoreline environments in lower latitudes to which these results could be applied. The results of this series of experiments and the evaluations can be used therefore in a much wider context than was initially defined in the program design.

BEACH-CLEANING METHODS AND SELECTION OF EXPERIMENTAL TECHNIQUES

In the decade prior to 1980 a series of operational studies and onshore oil spill cleanup assessments resulted in the development of a range of shoreline countermeasures that were described and defined by the literature (e.g., Sartor and Foget, 1971; Foget *et al.*, 1979; Tramier *et al.*, 1981; Deslauriers *et al.*, 1982; and Castle *et al.*, 1982). The available shoreline cleanup options can be subdivided into four basic methods (Table 1). The removal and disposal of contaminated sediments or of oil in the shore zone can be undertaken by a variety of either manual or motorized techniques. These range from such simple procedures as using cans or sorbents to remove oil from intertidal rock pools to the use of earth-moving scrapers or graders for the removal of contaminated sediments from the surface of a sand beach. Physical removal is probably the most extensively used shoreline countermeasure following spill incidents. The range of dispersion techniques includes flushing, steam cleaning or sand blasting on hard substrates and the application of chemicals either by hand or by spray booms mounted on surface vehicles or aircraft. This method of cleanup by dispersion has been used only rarely in beach environments. Sediment cleaning, either on the beach itself or at an adjacent site, includes a wide range of techniques such as chemical or hot-fluid washing of contaminated material, the sieving of tarballs from beach sediments and the incineration of contaminated material. In all cases the objective of the method is to clean contaminated materials at or near the area of contamination and to replace the cleaned material in the shore zone. Although a variety of sediment-cleaning techniques have been developed and evaluated experimentally, few have been used at spill incidents. Mixing techniques are designed to accelerate natural weathering and degradation of stranded oil by the addition of mechanical energy. Again, this method has not been used to any large extent at spill incidents.

TABLE 1. Shoreline cleanup methods

Method	Examples of techniques	Implementation
Removal/disposal	earth-moving machinery	motorized
	vacuum pumps	manual or motorized
	shovels, rakes, etc.	manual
Dispersion	chemical	manual or motorized
	flushing (low or high pressure)	manual
	steam cleaning	manual
	sand blasting	manual
Sediment cleaning	chemical washing	motorized
	sieving	motorized
	burning/incinerators	motorized
Mixing	mix into sediments	motorized
	push into surf	motorized
	break-up pavement	motorized

Despite the wide range of shoreline cleanup techniques identified, only a few have been studied or evaluated in detail. In reviewing the literature and in consultation with numerous individuals, a set of techniques was selected for the countermeasures program. The criteria involved in the selection of the techniques to be evaluated included: (1) utility under arctic or remote conditions, (2) existing knowledge base, and (3) applicability of existing information to arctic or remote coastal environments.

The major consideration in the selection of the techniques to be evaluated was the operational realities of the eastern Canadian Arctic. A small labour force and the impracticability of disposing of large volumes of contaminated materials (Table 2) are primary limiting factors in this area. Therefore, emphasis was placed on the selection of techniques that would have either a low labour and/or a simple waste disposal requirement. The techniques selected initially for the field tests in 1981 were: (1)

TABLE 2. Operational factors relating to beach-cleaning methods

Method	Labour requirements	Disposal volumes	Efficiency
Removal/disposal: manual	high	moderate	slow
Removal/disposal: motorized	low	high	rapid
Dispersion: manual	high	low	slow
Dispersion: motorized	low	nil	rapid
Sediment cleaning: motorized	low	low	slow
Mixing: motorized	low	nil	rapid

in-situ combustion using an incendiary device, (2) mechanical mixing of contaminated sediments, (3) application of chemical surfactants to disperse stranded oil, and (4) application of a solidifying agent to the stranded oil. In the 1982 experiment, a limited evaluation was conducted using: (5) low-pressure flushing.

EXPERIMENTAL DESIGN

The basic concept behind the experimental design of this component of the BIOS program involved the establishment of crude oil and emulsified oil control and countermeasure plots in intertidal and backshore (supratidal) environments to replicate heavy shoreline contamination. The plots were established on a series of beaches on the east coast of Cape Hatt, in the vicinity of Z-Lagoon (Fig. 1d). The site is on the opposite side of Cape Hatt to the nearshore release experiments in Ragged Channel at Bay 11 (Fig. 1d) (Sergy and Blackall, 1987) and was, therefore, unaffected by oil from these studies. Z-Lagoon contains a series of separate sandy-gravel beaches and was suitable for discrete intertidal experiments with minimal danger of cross-contamination. The coasts in this area are characterized by a range of wave energy environments with fetch areas that vary from a minimum of 1 km to a maximum of approximately 100 km (Owens and Robson, 1987).

In 1980, the year prior to the first countermeasure experiments, six control plots (two backshore and four intertidal) were created (Woodward-Clyde Consultants, 1981). The primary backshore control plots (the "T" plots) were established at Crude Oil Point (Fig. 2) and consisted of an aged crude oil plot (T_1) and a water in aged crude oil emulsion plot (T_2) (Fig. 3). The plots were located well above the mean high-tide level to document the effects of non-marine weathering phenomena,

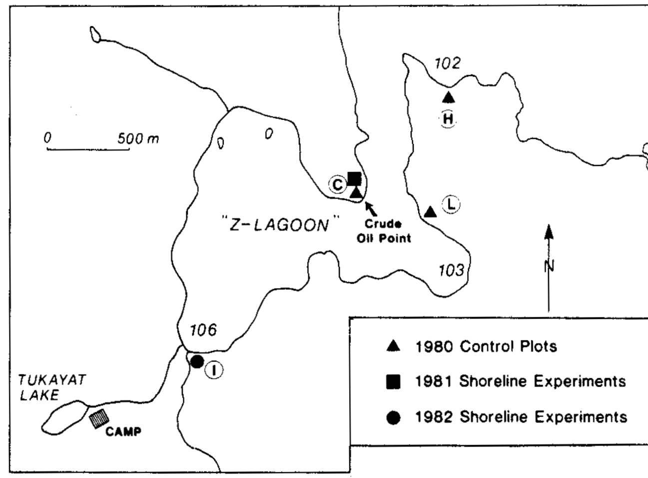

FIG. 2. Experimental and control plot locations in the Z-Lagoon area. The letters H, C, I and L refer to the sites described in Table 3.

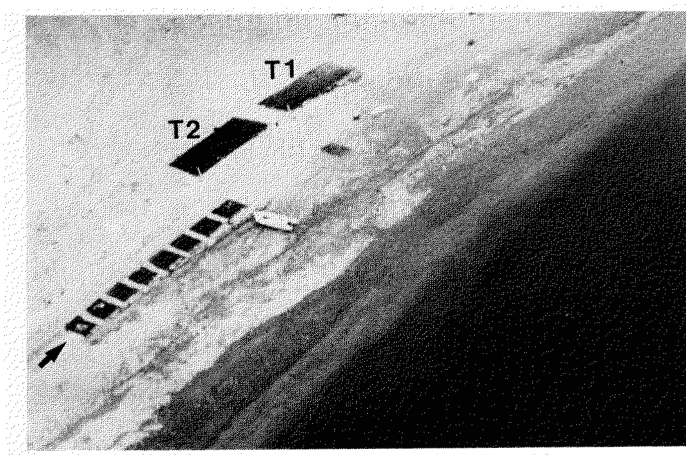

FIG. 3. Crude Oil Point (14 August 1982). Site of backshore control plots (T_1 and T_2) and test plots (arrow).

such as microbial degradation and atmospheric weathering. The four 1980 intertidal control plots were established in the upper half of the intertidal zone, two in the high-energy environment of Bay 102 (the "H" plots) and two in the low-energy environment of Bay 103 (the "L" plots). The plot identification codes are given in Table 3 and the beach sites are located on Figure 2. At each bay, one plot was an aged crude oil (Bay 102: plot H_1, and Bay 103: plot L_1) and the other plot was a water in aged crude oil emulsion (Bay 102: plot H_2 and Bay 103: L_2). An oil-loading rate of 1 $cm^3 \cdot cm^{-2}$ of plot surface was attempted and was achieved for all plots except L_1 and L_2, where the high water table contributed to lower loadings. Data and information on (1) the emulsification and application of the oil, (2) the oil loadings and the retained oil, and (3) the control plots are presented in Owens and Robson, 1987.

In 1981, prior to the actual experiments, eight test plots were laid down to evaluate the potential countermeasure techniques (Owens *et al.*, 1982). These test plots were established in the upper intertidal zone on the southwest side of Crude Oil Point (Fig. 3), approximately 100 m from the later countermeasure experimental plots. Samples collected immediately prior to the countermeasure experiments showed that these pre-experiment tests did not contaminate the nearby countermeasure plots.

The 1981 experimental plots were established at Crude Oil

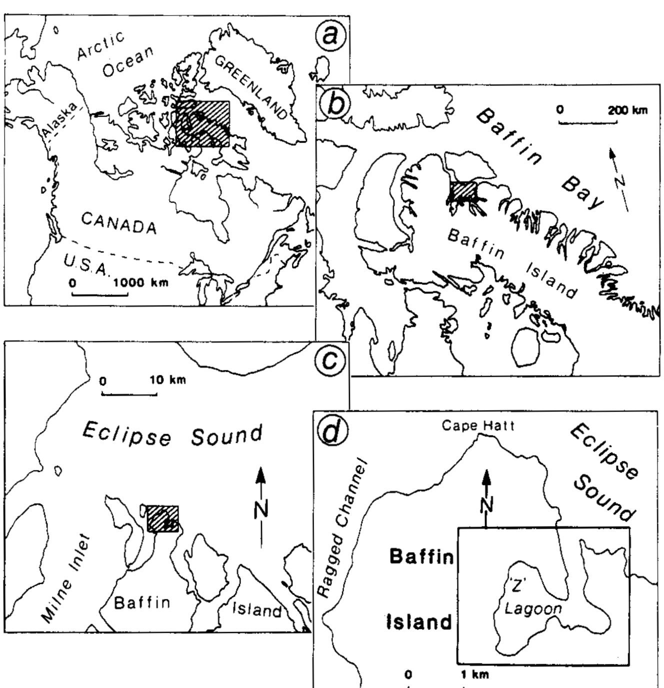

FIG. 1. Regional location maps. The area of Z-Lagoon, within the rectangle in d, is shown in more detail in Figure 2.

TABLE 3. Experimental plot locations and codes; sites are located on Figure 2

Site	Location	Year oil spilled	Plot designation	Type of oil	Beach zone	Activity
H	Bay 102	1980	H1	crude	intertidal	control
			H2	emulsion	intertidal	control
L	Bay 103	1980	L1	crude	intertidal	control
			L2	emulsion	intertidal	control
C	Crude Oil Point	1980	T1	crude	backshore	control
			T2	emulsion	backshore	control
H	Bay 102	1980	TE1	crude	backshore	control
			TE2	emulsion	backshore	control
C	Crude Oil Point	1981	CC	crude	intertidal	control
			CE	emulsion	intertidal	control
			D(B)C	crude	intertidal	dispersant (BP1100X)
			D(B)E	emulsion	intertidal	dispersant (BP1100X)
			D(E)C	crude	intertidal	dispersant (Corexit 7664)
			D(E)E	emulsion	intertidal	dispersant (Corexit 7664)
			MC	crude	intertidal	mixing
			ME	emulsion	intertidal	mixing
			SC	crude	intertidal	solidifier
			SE	emulsion	intertidal	solidifier
I	Bay 106	1982	ICC	crude	intertidal	control
			ICE - W	emulsion	intertidal	control
			ICE - E	emulsion	intertidal	low pressure flushing
			ID(B)C	crude	intertidal	dispersant (BP1100X)
			ID(B)E	emulsion	intertidal	dispersant (BP1100X)
			ID(E)C	crude	intertidal	dispersant (Corexit 7664)
			ID(E)E	emulsion	intertidal	dispersant (Corexit 7664)
			IMC	crude	backshore	mixing
			IME	emulsion	backshore	mixing

Prefix codes:
H high-energy control
L low-energy control
T backshore control
C intertidal control
D dispersant plot
M mixing plot
S solidifier plot
I Bay 106 plot

Suffix codes:
1 crude oil
C crude oil
2 emulsion
E emulsion
(B) BP 1100X dispersant
(E) Corexit 7664 dispersant

Point on the west shore of the entrance of Z-Lagoon (Fig. 2). This site represents an energy level environment intermediate between those of Bays 102 and 103. The layout of the plots with respect to the mean high-tide level is shown in Figure 4. The plot identification codes are in Table 3. The countermeasures were applied to oil retained on the plots approximately 24 h after they were oiled (two complete tidal cycles). The delay between oiling and application of countermeasures was built into the experimental design to replicate a likely optimal response time to a real spill at a remote location. This set of experiments took 3 d to conduct, as separate plots were oiled and countermeasures conducted over several days in order to control and minimize the threat of contamination of adjoining plots. A single cross-plot was created from the lowest low-water level, across the intertidal zone, to above the normal highest high-water level. The purpose of this cross-plot was to provide a reference point from which it would be possible to determine the upper limit of reworking by wave action of oil-contaminated sediments on this beach. As in 1980, a design loading of 1 $cm^3 \cdot cm^{-2}$ of oil was established for the Crude Oil Point intertidal plots. The approximate loadings achieved on all plots, except the cross-plot, which was not included in the sampling program, are given in Owens and Robson, 1987:Table 5.

In 1982, countermeasure and control plots were established in the intertidal and supratidal zones of Bay 106 to conduct a second series of experiments (Owens *et al.*, 1983). Six intertidal plots, approximately 10 m × 2 m, and four backshore plots were laid out, as shown in Figure 5. These plots are prefixed "I" and the plot identification codes are in Table 3. The intertidal countermeasure experiments were conducted on 13 August, approximately 24 h or 2 tidal cycles after the oil was laid down. During this period (12-13 August), the oil on the intertidal plots had been redistributed over the upper beach up to the high-water swash line indicated in Figure 5b. There was no cross contamination between plots due to control measures taken to prevent this occurrence. As a result of the redistribution of oil beyond the original plot limits, the sampling program was revised to cover the newly contaminated areas (Fig. 6).

A set of two supratidal control (IMCe and IMEe) and two countermeasure (IMCc and IMEc) plots was established on the backbeach adjacent to the intertidal site in Bay 106 (Fig. 5b). These plots were laid down on the upper beach to replicate oil stranded above the high-tide level due to wave and tidal action.

Countermeasures

Four countermeasure techniques met the experimental design criteria and were selected for field testing in 1981 (burning, chemical dispersion, mixing, solidification). The incendiary device, two dispersants and the solidifier were applied to small-scale crude oil and water in oil emulsion test plots on the west side of Crude Oil Point in order to gain operational experience, improve performance during the actual experiments and minimize the number of oiled plots to be established. The field techniques used for each of the countermeasures and the test evaluations are described by Owens *et al.*, 1982.

Four identical Defence Research Establishment Valcartier (DREV) incendiary devices (Meikle, 1981) were tested, one of which failed to ignite. Combustion was not maintained beyond burn-out of the device on the three tests despite the use of different configurations. On the basis of these tests it was decided to delete this countermeasure from the full-scale experiments (Owens *et al.*, 1982).

A wide range of chemical dispersants is available commercially, and it was decided to use two very different products in the experiment in order to provide a more comprehensive information set than if a single dispersant were used. BP 1100X, a hydrocarbon-based dispersant, was applied using a hand-sprayer and a backpack system. The other dispersant, Corexit 7664, was applied with a 51 mm internal diameter firehose and an eductor for the addition of the chemical (Owens, *et al.*, 1984). This latter dispersant is designed for use with a relatively high velocity system to provide mixing energy. Both dispersants demonstrated their effectiveness on the test plots and were included in the full-scale countermeasure experiments.

Mixing was to be carried out with a portable gasoline-powered roto-tiller used to simulate the action of heavier earth-moving equipment, such as a bulldozer, front-end loader or tractor. The machine had been tested on a sandy-gravel beach in

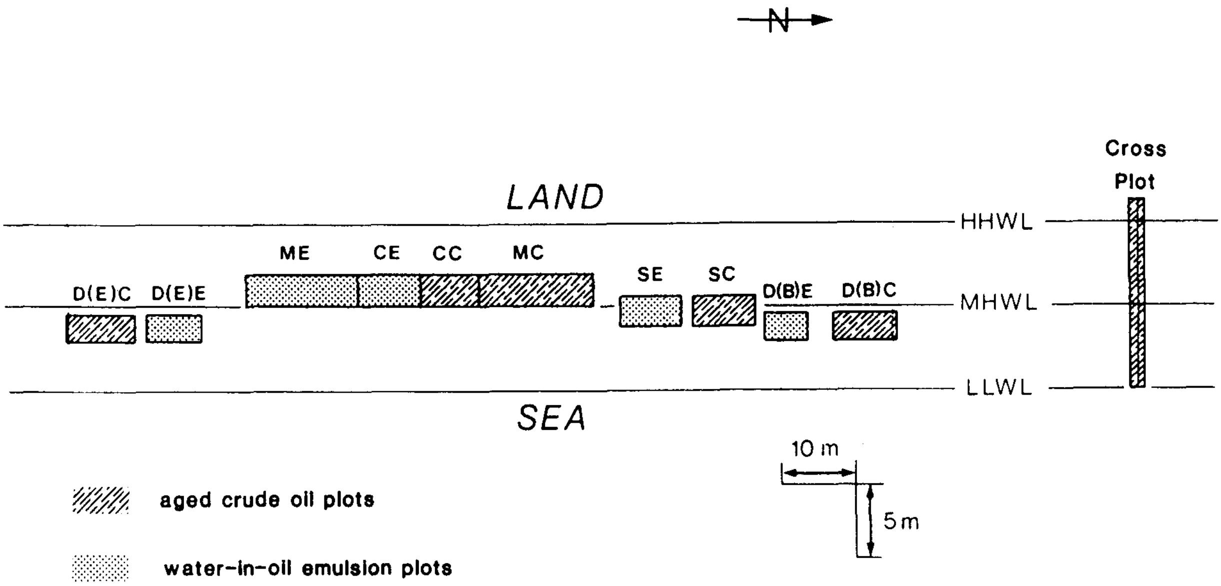

FIG. 4. Layout of 1981 countermeasure experiment and control plots at Crude Oil Point; plot codes are given in Table 3.

British Columbia and was able to thoroughly mix sediments to a depth of 30 cm. The method was not tested again in the on-site pre-experiment evaluation.

The solidifier was a new product being tested by the manufacturer (BP Chemicals, 1985a, b). Although logistically difficult to apply, it showed considerable potential in the test evaluations and so was selected for the 1981 experiments. The active ingredients of the compound account for approximately only 5% of the volume. The remainder consisted of odourless kerosene.

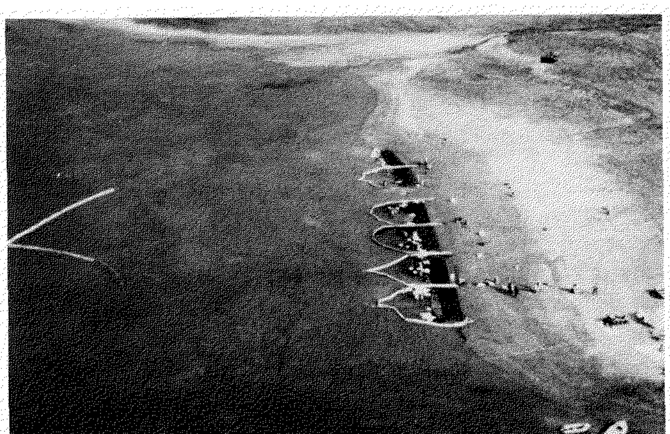

FIG. 5a. Bay 106: Intertidal plots immediately following application of the oil.

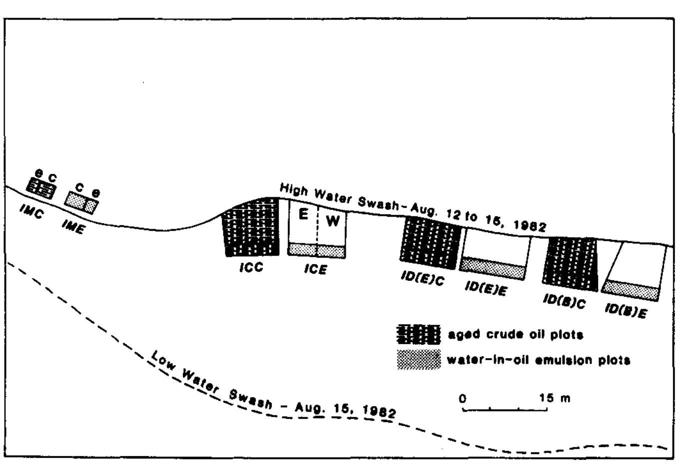

FIG. 5b. Bay 106: Plot dimensions on 13 August 1982, 24 h after oiling.

Following interpretation and evaluation of the 1981 results and review of the observations and analytical results from the intertidal control plots at Bay 103 in Z-Lagoon, it was decided to partially replicate the 1981 experiments in a lower wave energy environment at Bay 106 during the 1982 field season. This series of experiments is described by Owens *et al.*, 1983.

In 1982, the same two dispersants were applied to intertidal crude oil and water in oil emulsion plots for comparison with adjacent control plots. One-half of the emulsion control plot was treated by low-pressure flushing with water, as this technique was considered potentially viable on the beach sediments of Bay 106 (Figure 5b). Two backbeach plots were also created to evaluate the effectiveness of mixing backshore sediments should oil become stranded above the mean high-water mark. Controls were established with the backshore countermeasure plots, and it was evident that the results could be used to make comparisons between these plots and the long-term control plots at Crude Oil Point (T_1 and T_2).

Sampling and Analytical Program

An individual sampling program was designed for each experiment prior to any oil being laid down on the control or countermeasure plots. The designs dictated that samples be collected on a fixed grid and permitted sampling to be conducted over several years. The individual sampling programs are detailed in the annual project reports (Owens, 1984; Owens, *et al.*, 1982, 1983; Woodward-Clyde Consultants, 1981).

Samples were collected on the plots from the top 2 cm (surface samples) and from the 5-10 cm depth interval (subsurface samples). Samples for hydrocarbon analysis were collected according to the sampling program and composited into a sample of approximately 2.4 *l*. The total extractable hydrocarbons were determined by infrared spectrophotometry. There were minor changes in the methods of extraction and of analysis during the course of the project; however, these changes did not

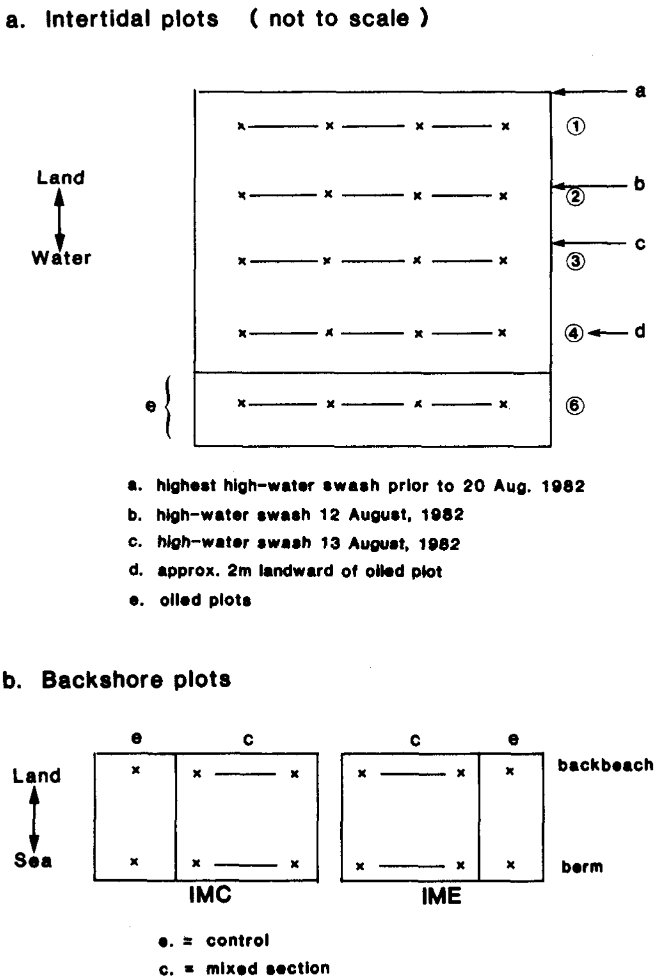

FIG. 6. Sketches of Bay 6 sampling patterns.

affect the ability to compare data either between plots or over time. The changes were made in response to: (1) the low detection limit technique required for baseline vs. oiled samples, (2) the decision to move the oil extraction procedure from a southern laboratory to an on-site field laboratory, and (3) the requirement for dealing with large numbers of samples, particularly in 1981 and 1982.

The analytical methods have been previously described in detail in the BIOS chemistry working reports for 1980 (Green, 1981; Boehm, 1981), 1981 (Green *et al.*, 1982; Boehm *et al.*, 1982), 1982 (Humphrey, 1983; Boehm, 1983) and 1983 (Humphrey, 1984; Boehm *et al.*, 1984). These reports also contain explanations concerning the changes to the extraction and analytical methodology.

Samples for gas chromotographic (GC) analysis were collected from the same grid points and at the same time as the samples for total hydrocarbon analysis. GC sample preparation and analytical techniques have been previously described by Boehm *et al.*, 1982. The results of GC analysis provide the biodegradation (Alkane/Isoprenoid: ALK/ISO) and weathering (Saturated Hydrocarbon Weathering: SHWR) ratios, as described in Owens *et al.*, 1987.

The sampling programs proved adequate for all control and experimental plots with the exception of the Bay 106 intertidal experiments. The surface area of oil contamination at this location increased by a factor of five as rising tides redistributed the oil. The Bay 106 sampling program had to be modified to accommodate this factor, and additional compositing of samples was required (Fig. 6). In 1982, a set of samples was collected throughout Z-Lagoon to determine if the experiments had caused any cross contamination of intertidal sediments. The results were negative (Owens *et al.*, 1983).

DATA — RESULTS AND DISCUSSION

Extensive, pre-oiling, post-oiling and post-countermeasure sampling programs were conducted. The data for all these analyses have been reported and discussed at length in the BIOS working reports. Subsequent review and discussion have considered the validity of these data in respect to the real world type of spill more closely represented by the Bay 11 surface oil release in Ragged Channel on the west coast of Cape Hatt (Fig. 1d). A comparison of the results from the Z-Lagoon plots with the Bay 11 beach experiment is presented in Owens and Robson, 1987. The results of analyses conducted on samples collected on all control and countermeasure plots are discussed up to and including those from the samples collected at day 8 after the countermeasure experiment. After this initial period, dispersion and edge effects would affect the results. Individual small plots are representative only of patchy oil contamination, whereas the study was aimed at the evaluation of countermeasures for heavily contaminated shorelines.

The backshore plots at Crude Oil Point (T_1, T_2) (Fig. 3) and Bay 106 (IMC, IME) (Fig. 5b) were not subjected to the forces that created the cross contamination and redistribution observed on the intertidal plots. Based on visual observations and sample analysis results, the intertidal plots generally exhibited a rapid removal of surface oil and corresponding reduction in subsurface oil concentrations. Exceptions to this trend were the low-energy intertidal control plots at Bay 103 (L_1 and L_2), the subsurface oil values for the mixing plot (MC) at Crude Oil Point and, to a lesser extent, the subsurface values from the dispersant plot D(E)E also at Crude Oil Point. These four plots continued to give longer term data and there were measurable and visible amounts of oil remaining on or in these plots during the 1983 field season.

The reference to visible and measurable oil is intended to distinguish between plots that can be sampled using total hydrocarbon (t-h) analytical techniques as opposed to those where hydrocarbons are detectable only by GC methods. The GC methods have much lower detection limits and the results are used to generate diagnostic weathering ratios that detect the activity of various weathering processes. These processes, which may take place over several years, can be detected even in very low oil concentrations.

1980 Backshore Control Plots

The two long-term backshore control plots established at Crude Oil Point, T_1 and T_2 (Fig. 3), were set up to document the effects of atmospheric and microbial weathering (i.e., non-marine weathering) for comparison with the intertidal control plots. Although the amounts of oil retained on the two plots were virtually identical (Owens and Robson, 1987:Table 4), the initial oil concentrations were considerably higher on the T_1 (the aged crude oil) plot as compared to the T_2 (the water in aged crude oil emulsion) plot. Surface mean total hydrocarbon values on the aged crude oil plot over the 4 d following the oiling

TABLE 4. Annual mean total hydrocarbon concentrations of samples from Crude Oil Point backshore control plots (mg·kg^{-1})

		1980	1981	1982	1983
T1	surface	47 000	31 000	28 500	9000
(Crude oil)	subsurface	28 000	23 000	15 000	9500
T2	surface	16 000	15 000	17 000	22 500
(Emulsion)	subsurface	20 000	19 000	15 000	6000

ranged between 22 000 and 85 000 mg·kg^{-1}, whereas the values from the emulsified plot initially ranged between 9500 and 28 000 mg·kg^{-1}. The combined means for sample sets show that oil concentrations were greater by a factor of three on the aged crude plot surface (Table 4). Subsurface concentrations were higher in the crude plot than in the emulsion plot, but in the latter case the mean subsurface concentrations were higher than those from the surface sediments. This would indicate that the lower surface oil concentrations on the emulsion plot were due to a greater degree of penetration associated with a different oil viscosity.

Total hydrocarbon results from the 1981 survey indicate that surface oil concentrations were reduced considerably and subsurface concentrations reduced slightly on the aged crude plot but remained unchanged on the emulsified oil plot. The weathering ratios (Table 5) indicate that considerable weathering had occurred on the crude plot (T_1) between the last 1980 survey and the 1981 survey. On the emulsion plot (T_2) some evaporative weathering, but little or no biodegradation, had taken place, whereas the processes had been significant on the crude oil plot. On the basis of the 1981 survey, it was apparent that a significant amount of oil remained on both plots.

The results of the total hydrocarbon analyses on samples collected in 1982 show that the oil concentrations were in the same range as the 1981 values (Table 4). The 1982 diagnostic weathering ratios show that both evaporative weathering and biodegradation were not significant processes between the 1981 and 1982 sample intervals on either plot. This period was therefore one of negligible change (Table 5).

In 1983, there was a very significant decline in both surface and subsurface total hydrocarbon concentration values on plot T_1 as compared to results obtained in previous years. Although one part of the eastern section of T_1 was used by another study group (Eimhjellen *et al.*, 1983) as part of a separate experiment, these activities were not considered to present a risk to the long-term value of the control plots. Visually, there was no indication of this substantial decrease and there exists no obvious explanation for this dramatic change in total hydrocarbon content of the sediments. The total hydrocarbon content of the surface samples from the emulsion plot T_2 show that little or no change had occurred between 1982 and 1983. The subsurface samples from this plot do, however, show a significant reduction in hydrocarbon values from 1982.

The diagnostic ratios (Table 5) indicate that in 1983 both SHWR and ALK/ISO ratios were lower on the crude oil plot (T_1) when compared to previous results. By contrast, there were no changes on plot T_2. These results suggest that on the crude oil plot there has been significant physical evaporative weathering and significant biodegradation of the surface oil between 1982 and 1983. These processes were not significant on the emulsion plot and were not considered to be important factors in the dramatic decrease in oil content of surface samples from T_1.

TABLE 5. Geochemical results from Crude Oil Point backshore control plot surface samples

(a) Saturated Hydrocarbon Weathering Ratio (SHWR)

		1980 (initial)	1980 (8 d)	1981	1982	1983
T1	(crude)	2.4	2.2	1.6	1.6	1.1
T2	(emulsion)	1.9	1.8	1.6	1.3	1.4

(b) Alkane/Isoprenoid Ratio (ALK/ISO)

		1980 (initial)	1980 (8 d)	1981	1982	1983
T1	(crude)	2.4	3.0	2.1	2.4	1.9
T2	(emulsion)	2.6	2.3	2.4	2.4	2.2

1980 Intertidal Control Plots

Plots H_1 and H_2 were established in the high energy environment of Bay 102. Plots L_1 and L_2 were established in the lower energy environment of Bay 103 (Fig. 2). The oil retention on most plots was within 80% of the design amount of 1 cm^3·cm^{-2} of surface area, but on both the low energy plots oil retention was poor due to a high groundwater table (Owens and Robson, 1987).

On the exposed, or high energy, beach in Bay 102, mechanical wave action was effective in rapidly reducing the oil content of the sediments. Within 48 h 99% of the oil had been removed from the surface sediments (Table 6). The plots ceased to have any real value as a long-term reference data set after 31 August 1980 due to the rapid removal or redistribution of oil at this site.

In contrast, at Bay 103 the crude oil plot (L_1) continued to provide data on the long-term persistence of oil in a low-energy environment (Table 7). The emulsified plot (L_2), which initially retained far less oil than the crude oil plot due to a finer sediment size and to a higher groundwater table, rapidly lost oil by removal due to physical marine processes. Virtually no oil was detected at L_2 in 1982.

The initial observation of higher surface and subsurface oil content values on the crude oil plot as compared to the emulsion plot can be seen as a trend when the four years of data are compared. By 1983, although oil was still visible in the upper part of plot L_1, the amount of oil remaining on the surface was considerably less than in previous years. The detailed data (Owens *et al.*, 1983) show that natural cleaning had occurred in the lower and middle sections of the L_1 plot. Redistribution of contaminated sediments to areas above the plot had occurred even in this low energy environment, as demonstrated when

TABLE 6. Mean total sediment hydrocarbon content (mg·kg^{-1}), high-energy control plots (H_1 and H_2) in Bay 102

	1980				1981		
	23 Aug	25 Aug	27 Aug	31 Aug	28 July	29 Aug	1982
(a) H_1 — crude							
surface	36 500	70	90	1200	50	0	0
subsurface	12 000	3000	6700	10 000	500	0	0
(b) H_2 — emulsion							
surface	13 500	15	30	30	1200	0	0
subsurface	10 500	15	30	5	250	0	0

TABLE 7. Mean total sediment hydrocarbon content ($mg \cdot kg^{-1}$), low-energy intertidal control plots (L_1 and L_2) in Bay 103

	1980				1981			
	21 Aug	23 Aug	25 Aug	29 Aug	28 July	29 Aug	1982	1983
(a) L_1 — crude								
surface	17 000	5000	4000	6500	4700	1500	4000	600
subsurface	15 500	5000	7300	14 000	5000	5000	9000	8500
(b) L_2 — emulsion								
surface	3000	200	150	130	140	150	50	5
subsurface	1300	70	10	75	65	150	0	0

samples collected from the sediments above the L_1 plot all had oil contents similar to those from the upper portion of the oiled plot.

Gas chromatographic analysis was conducted on samples from the surface and subsurface of all four H and L plots (Table 8). There appears to have been considerable physical evaporative weathering (SHWR ratios) on the low energy plots between the 1981 and 1982 samples. In 1983 the L_1 samples collected from the oiled (upper) and clean (lower) sections of the plot showed little difference in the weathering ratio. The data from the H plots show no significant trends, which is most certainly related to the rapid removal or burial of the oil at this location.

The Alkane/Isoprenoid ratio indicates microbial activity. The high energy plots exhibited such activity in 1981 (H_1) and 1982 (H_2). The L_1 and particularly the L_2 plots showed significant microbial activity between 1980 and 1981 but no further activity in 1982. In 1983, when samples were collected from the oiled (upper) and clean (lower) sections of L_1, there was evidence that microbial forces were at work in the section of the plot that was more heavily oiled. The clean section of L_1 had the same Alkane/Isoprenoid ratio as that of L_2 in 1983, which indicated a slow degradation rate.

1981 Intertidal Countermeasure Plots

The 1981 countermeasure plots, located at Crude Oil Point (Fig. 4), received an initial oil loading that resulted in total hydrocarbon concentrations of up to 25 000 $mg \cdot kg^{-1}$ oil in sediment by weight on the beach surface. However, data from the control plots (CC and CE) indicate that after 40 d 80% of the oil had been dispersed naturally. Although the levels of contamination after 40 d on the control plots were similar to the levels on the countermeasures plot, these data are not considered to be relevant for the primary objectives of this study due to edge effects, dispersion and cross contamination.

TABLE 8. Geochemical results from 1980 intertidal control plots at Bay 102(H) and Bay 103(L)

(a) Saturated Hydrocarbon Weathering Ratio (SHWR)

		1980				
		(initial)	(8 d)	1981	1982	1983
H-1	(C)	1.3	1.8	2.0	1.8	—
H-2	(E)	1.0	1.2	2.1	1.7	—
L-1	(C)	2.5	2.5	1.1	1.3	1.1/1.0
L-2	(E)	2.1	2.0	1.0	1.1	1.3

(b) Alkane/Isoprenoid Ratio (ALK/ISO)

		1980				
		(initial)	(8 d)	1981	1982	1983
H-1	(C)	2.6	2.8	1.6	1.4	—
H-2	(E)	3.0	2.4	2.4	1.4	—
L-1	(C)	2.4	2.5	1.9	1.7	0.9/1.7
L-2	(E)	2.7	2.8	1.1	1.1	1.7

C: crude oil.
E: emulsion.

The application of different commercially available brands of dispersant resulted in an immediate and significant reduction of surface and an increase in subsurface oil in sediment concentrations (plots D(E) and D(B) in Tables 9 and 10). This increase in the subsurface concentrations reflects penetration of oil into the sediments caused by viscosity changes as a result of application of the chemical dispersant. The surface data indicate that after 8 d the dispersants had reduced the oil in sediment concentrations by at least an order of magnitude, although subsurface concentrations were as high as 3000 $mg \cdot kg^{-1}$. At the 40 d sample interval, only traces of oil were identified on the BP dispersant plots and values from the Exxon plots were < 400 $mg \cdot kg^{-1}$.

The application of the solidifying agent (with both fast and slow cross-linking agents) to the plots was successful in terms of the experiment objective, as the oil was effectively encapsulated within the polymer matrix. The solidified oil was still present in 1982, with a surface cover on approximately 25% of the plot. During the 1983 survey remnants of the solidified oil from plots SC and SE were present at the high-water mark above the plots. It is of interest to note that several of these large pieces of solidified beach had undergone little or no visible change.

Mechanical mixing (plots MC and ME) with the roto-tiller caused an initial increase in the surface oil in sediment concentrations and an increase in the subsurface oil concentrations on the crude oil plot (Table 9). Over the 40 d post-test period some reduction in oil concentrations was evident on the emulsion plot (ME), whereas the surface sediments on the crude oil plot (MC) retained high values. Resurveys and resampling of these countermeasure plots took place twice in 1982 and in 1983. Subsurface oil concentrations remained relatively high on all plots in 1982, but by September 1983 only the mixed oil subsurface samples (MC) had a total hydrocarbon value > 100 $mg \cdot kg^{-1}$.

Oil was observed at the highest high-water mark above the plot locations in 1982 and 1983. The location of the oil line varied each year, which indicates that the oil was still being redistributed. In aerial photographs the oil appears as a dark stain; on the ground the oil is visible as a band of stained sediments in the vicinity of the highest high-water mark. Analysis of four surface sediment samples collected from this band in 1983 produced values of 80, 440, 680 and 1200 $mg \cdot kg^{-1}$. These values are considerably higher than the results from the surface of the intertidal plots themselves. The oiled sediments in the vicinity of the high-water mark were redistributed by wave processes that cleaned the countermeasure and control plots

TABLE 9. Results of total extractable hydrocarbon analyses — Crude Oil Point 1981 countermeasures control and experimental plots (mg·kg^{-1})

Code		1981				1982		1983
		Pre-test	Post-test	+8 d Aug 15	+40/41 d Sept 16	Aug 10	Sept 02	Aug 20
CC	surface	21 000	*	17 000	3110	300	80	22
	subsurface	3020	*	1500	150	3380	220	430
CE	surface	12 000	*	21 700	930	90	500	21
	subsurface	1060	*	380	110	390	300	190
MC	surface	21 000	28 000	4980	19 000	160	140	32
	subsurface	3020	10 000	16 000	1800	1240	2280	3200
ME	surface	12 000	21 000	19 000	1890	230	100	20
	subsurface	1060	290	310	190	1070	450	84
D(E)C	surface	25 000	6070	440	360	80	90	20
	subsurface	300	5940	2390	170	900	50	20
D(E)E	surface	24 000	20 000	2370	330	130	370	0
	subsurface	150	513	290	tr	170	260	120
D(B)C	surface	4310	10 000	tr	tr	0	0	0
	subsurface	*	3130	3190	tr	30	0	0
D(B)E	surface	7370	2740	70	tr	0	0	0
	subsurface	70	4400	80	tr	0	0	0

*No sample.

Prefix codes:
C control
M mixing
D dispersant
(B) = BP 1100X
(D) = Corexit 7664

Suffix codes:
C crude oil
E emulsion

TABLE 10. Percentage of oil remaining through time from initial oiling, Crude Oil Point, 1981 countermeasure plots

Code[1]	Surface 1981			Subsurface 1981		
	Pre-test	+8 d	+40/41 d	Pre-test	+8 d	+40/41 d
CC	100%	81	15	100%	50	5
CE	100%	+181	8	100%	36	10
MC	100%	24	81	100%	+530	60
ME	100%	+158	16	100%	29	18
D(E)C	100%	1.8	1.4	100%	+797	57
D(E)E	100%	10	1.4	100%	+193	1
D(B)C	100%	0	0	*100%	+1063	1
D(B)E	100%	0.9	0	100%	+114	1

[1]Codes are explained in Tables 3 and 9.
+ = increase in volume.
*No sample: value assumed to be 300 mg·kg^{-1} (the subsurface D(E)C value).

after the 1981 experiments. The process of redistributing the contaminated sediments farther up the beach resulted in the deposition of this material in an area of minimal wave activity. Wave action is only possible at this elevation during periods of spring tides or at times of storm-generated high-water levels during the restricted open water season. The rate of natural cleaning of this contaminated line of sediments is therefore slower than the sediments lower down the beach in the intertidal zone.

1982 Intertidal Countermeasure Plots

The total hydrocarbon data from samples collected in 1982 and 1983 from this fine-grained beach (Owens and Robson, 1987) are shown in Table 11 for the surface sediments and in Table 12 for the subsurface sediments. The data sets are presented in a geographical format related to across-shore sample rows (Fig. 6) and along-shore plots (columns) (Fig. 5b).

The first post-oiling flood tide that inundated the plots resulted in a significant redistribution of the oil up the beach (Owens *et al.*, 1983). The original plots were approximately 20 m^2 in area, and this was increased by an additional 50-80 m^2 of contaminated beach above the plots (Fig. 5b). Considerably more oil appeared to have been lifted from the crude plots when compared to the emulsion plots (*c.f.* ICC/ICE and ID(B)C/ID(B)E on Day 0 in Table 11). In particular, total hydrocarbon values on ICC and ID(B)C were reduced by an order of magnitude. Within 24 h (+1 d) the mean total hydrocarbon value from the crude plots was reduced by 76%, whereas the reduction of the mean from the emulsion plots was 30%. Little oil, either crude or emulsion, initially penetrated the subsurface sediments (Table 12) due to a combination of the viscosity of the oil, the permeability of the fine-grained sediments and the high water content within the subsurface sediments.

The countermeasure experiments produced significant changes on the low-pressure flushing (ICE-E) and Exxon crude (ID(E)C) plots. In the former case (ICE-E) the mean surface across-plot total hydrocarbon concentration increased fourfold (2777 to 11 272 mg·kg^{-1}), whereas in the latter the value was halved (8543 to 3832 mg·kg^{-1}). The Exxon dispersant produced virtually no change in values on the emulsion plot (ID(E)E). As expected, the BP dispersant proved to be ineffective on either

TABLE 11. Bay 106 total hydrocarbon results — intertidal surface samples (mg·kg^{-1})*

	ICC	ICE-E	ICE-W	ID(E)C	ID(E)E	ID(B)C	ID(B)E
Post-oiling, 12 August							
6	15 300	8800	8800	4090	4850	8810	8280
Pre-test, 13 August (day 0)							
1	—	—	—	—	—	—	—
2	11 000	1730	1730	21 200	2080	9690	5220
3	—	—	—	—	—	—	—
4	160	270	270	70	690	2860	540
6	1460	6330	6330	4360	1680	840	7340
Post-test (+1 day)							
1	—	—	—	—	—	—	—
2	—	11 000	1600	12 800	2160	20 400	40 900
3	—	9660	2390	1980	1320	18 500	34 000
4	—	430	310	130	230	30	8960
6	—	24 000	5910	420	1520	8300	20 200
Post-test, 22 August (+7 days)							
1	—	70	50	80	910	1140	390
2	6860	1170	230	8770	15 200	27 900	29 100
3	620	33 600	1040	930	2180	10 500	6340
4	100	460	260	260	530	5060	4810
6	5240	15 900	4630	120	1510	2760	11 800
Post-test, 15 September (+33 days)							
1	400	40	230	330	450	320	530
2	200	1370	8210	5530	1520	12 300	6870
3	650	15 100	530	270	380	1730	1810
4	620	1180	200	1290	1200	3240	1590
6	2130	11 900	830	30	130	170	690

*Values are arranged to conform with sample locations on the ground for each set of samples. The plots (columns) are located on Figure 5b and the row numbers at left refer to locations shown on Figure 6a. Identification codes for the plots are explained in Table 3.

TABLE 12. Bay 106 total hydrocarbon results — intertidal subsurface samples (mg·kg^{-1})*

	ICC	ICE-E	ICE-W	ID(E)C	ID(E)E	ID(B)C	ID(B)E
Post-oiling, 12 August							
6	—	—	—	—	—	—	—
Pre-test, 13 August (day 0)							
1	—	—	—	—	—	—	—
2	50	0	0	30	0	370	0
3	—	—	—	—	—	—	—
4	0	0	0	0	0	0	0
6	40	90	90	5440	0	50	410
Post-test (+1 day)							
1	—	—	—	—	—	—	—
2	—	0	30	40	100	200	1320
3	—	90	50	0	30	40	30
4	—	0	0	0	0	7130	60
6	—	40	80	460	0	0	50
Post-test, 22 August (+7 days)							
1	0	0	0	0	0	0	0
2	0	0	0	0	100	70	30
3	0	30	0	50	0	50	0
4	0	0	0	0	0	0	0
6	0	30	0	0	0	0	0
Post-test, 15 September (+33 days)							
1	50	—	30	0	0	30	150
2	50	180	5720	1270	0	2300	7910
3	420	180	0	2530	200	2230	360
4	0	90	0	0	30	3240	4340
6	0	270	0	0	0	210	260

*Data are arranged in the same format as in Table 11.

plot due to the lack of wave energy to mix the dispersant with the oil. The surface total hydrocarbon values on these plots were significantly elevated, as the dispersant itself contains hydrocarbons.

Observations in August 1983 indicated the presence of very little visible surface oil. From the air no oil could be discerned in the intertidal zone. On the ground a line of weathered oil was identified in the vicinity of the high-water swash line. Despite the lack of visible oil, in many areas the water that gathered in footprints on the intertidal plots contained an oil sheen.

Table 13 presents the mean values of all surface samples by plot for selected dates. This comparison of all samples collected at one time from each of the plots illustrates the progressive trend of a reduction in the surface total hydrocarbon values after Day 7 (22 August 1982). The ICC data set is an exception to this trend, as this plot registered an unusually high total hydrocarbon concentration (9100 mg·kg^{-1}) at the high-water level in August 1983, in contrast to the other samples from this plot on that date, which ranged in value between 70 and 380 mg·kg^{-1} (Owens *et al.*, 1984).

TABLE 13. Bay 106 total hydrocarbon results — mean values of all surface samples by plot for selected dates (mg·kg^{-1})

	ICC	ICE	ID(E)C	ID(E)E	ID(B)C	ID(B)E
22 Aug 1982	3205	4356	2032	4066	9472	10 488
15 Sept 1982	719	3959	1490	3680	3552	2298
20 Aug 1983	1978	1944	717	1453	2618	1533

1982 Backshore Countermeasure Plots

The backshore plots in Bay 106 were laid down across the beach berm onto the backshore (Fig. 6), thus straddling the active and rarely active beach zones. The data are therefore considered as two sets to reflect this physical distinction.

The backshore mixing experiments conducted on these two plots provide a strong contrast to the intertidal mixing study carried out in 1981 at Crude Oil Point. The oil content values on these backshore plots remained high (>7000 mg·kg^{-1}) in all the surface samples into the 1983 sample period (Table 14). There is an order of magnitude difference between the lowest and highest values on both the surface and subsurface plots (Tables 14 and 15), although the highest concentration in the subsurface samples is the same as the lowest value in the surface samples.

A comparison of remaining oil in August 1982 and August 1983 (Table 16) shows there was a greater reduction in the total hydrocarbon values on the surface of the mixed plots than on the control plots. The reduction, although more marked in the backbeach portion of the plot, was also evident in the berm portion. The subsurface analysis of total hydrocarbons reveals a major increase in the backbeach portion of the plot. The berm portion does not show this trend.

1982 Backshore Plots — Geochemical Results

Evaporative weathering (SHW ratio) occurred to surface oil between 1982 and 1983 (Table 17a). This change was the same for mixed and control plots and is almost identical to that recorded for the backshore control T plots (Table 5a). It appears therefore that the mixing action did little to enhance this weathering process. The subsurface samples collected in 1983

TABLE 14. Bay 106 total hydrocarbon results — backshore surface samples ($mg \cdot kg^{-1}$)*

	IMC		IME	
	Control	Mixed	Mixed	Control
Pre-test, 14 August 1982				
Backbeach	23 800	24 200	42 200	18 400
Berm	106 000	56 500	17 100	12 400
Post-test, 15 August (day 0)				
Backbeach	20 600	12 700	12 300	34 500
Berm	66 900	23 200	9270	7730
Post-test, 22 August (+7 days)				
Backbeach	38 200	14 500	24 800	40 000
Berm	88 600	18 700	13 800	8640
Post-test, 15 September 1982 (+31 days)				
Backbeach	32 600	18 200	16 700	65 200
Berm	57 100	31 100	8510	5350
20 August 1983				
Backbeach	22 000	11 000	11 000	14 000
Berm	62 000	31 000	7400	11 000

*The plots are located on Figure 5b in which the two controls are marked "e" and the mixed plots labelled "c". Values are posted for each sample interval to represent the location of each sample on the ground as shown in Figure 6b.

TABLE 15. Bay 106 total hydrocarbon results — backshore subsurface samples ($mg \cdot kg^{-1}$)*

	IMC		IME	
	Control	Mixed	Mixed	Control
Pre-test, 14 August				
Backbeach	100	270	360	140
Berm	2200	7010	17 900	14 500
Post-test, 15 August (day 0)				
Backbeach	570	8400	11 900	120
Berm	1420	—	12 600	11 200
Post-test, 22 August (+7 days)				
Backbeach	170	9400	15 100	220
Berm	1860	26 900	7670	11 500
Post-test, 15 September (+31 days)				
Backbeach	590	7510	15 100	3050
Berm	7380	22 500	11 500	12 800
20 August 1983				
Backbeach	480	4500	5500	280
Berm	930	2300	7800	7100

*The results are set out in the same format as in Table 14.

generally show less evaporative weathering than the surface sediments, but again no trends between mixed and control plots can be modified.

The only discernible trend in the degree of biodegradation (ALK/ISO ratio) in the surface sediments between 1982 and 1983 is a possible high rate of weathering on the control as compared with the mixed plots (Table 17b). Once again, the changes in the ratios are similar to those recorded on the T plots (Table 5b). The ratios for the 1983 subsurface samples are relatively uniform and similar in range to the surface ratios. The mixing process apparently resulted in no major change to the rates of weathering.

EVALUATION OF COUNTERMEASURES

The field tests and experiments have provided a large volume

TABLE 16. Bay 106 backshore plots — percentage of oil remaining after one year (comparison between 14 August 1982 and 20 August 1983)

	IMC		IME	
	Control	Mixed	Mixed	Control
(a) Surface				
Backbeach	92%	45	26	76
Berm	58	55	43	89
(b) Subsurface				
Backbeach	480%	1667	1528	200
Berm	42	33	44	49

TABLE 17. Geochemical results for Bay 106 1982 backshore plots (1983 samples were collected on 17 August; berm samples were collected only in 1983; all 1982 values are a mean of three ratios)

		1982 surface	1983 surface		1983 subsurface	
		Backshore	Berm	Backshore	Berm	Backshore
(a) Saturated Hydrocarbon Weathering Ratio (SHWR)						
Crude control	(IMC)	2.0	1.5	1.4	2.4	1.9
Crude mixed	(IMC)	2.2	1.6	1.7	2.1	1.9
Emulsion mixed	(IME)	2.0	1.7	1.6	2.0	2.1
Emulsion control	(IME)	2.0	1.7	1.5	2.0	1.6
(b) Alkane/Isoprenoid Ratio (ALK/ISO)						
Crude control	(IMC)	2.6	2.2	1.9	2.3	2.1
Crude mixed	(IMC)	2.6	2.3	2.1	2.3	2.1
Emulsion mixed	(IME)	2.6	2.3	2.4	2.2	2.3
Emulsion control	(IME)	2.0	2.1	1.4	2.3	2.0

of physio-chemical data, which is presented in the BIOS Working Report series and is summarized above on a site-by-site basis. The primary objective of this study was to evaluate individual techniques rather than to compare the relative efficiencies of the selected countermeasures. It is therefore appropriate to discuss each of the methods individually.

Burning

A series of small burning tests was conducted prior to the 1981 experiments using four identical DREV incendiary devices (Meikle, 1981). The device is a sandwich configuration with a delay column and an incendiary composition that produces flame temperatures in excess of 1500°C (Twardawa and Couture, 1980). One test was conducted on an aged crude plot and two on emulsion plots. Although the igniters burned in each case for approximately five minutes, none of the oils was ignited, except with a very short distance of the incendiary device (approximately 20 cm). On one of the emulsion tests it was observed that two small pools of oil immediately adjacent to the incendiary device were not ignited, even though the surface of the oil was heated and bubbled. Hot splashes of incendiary composition landed in the small oil pools, but these produced no flames.

On the basis of these tests and observations, it was decided not to conduct a countermeasure experiment on burning as part of the field experiment (Owens *et al.*, 1982). The conclusion was reached that the incendiary device would not be a practical countermeasure technique for stranded oil deposited on the shore zone. The ignition test took place on plots that had been oiled only a matter of hours previously, before the test plots were covered by a high tide.

Solidifier

A solidifying agent, developed by British Petroleum, was applied to crude and oil emulsion plots with the objective of encapsulating the stranded oil. The agent consists of a polymer and a cross-linking agent that solidifies to form three-dimensional lattices that absorb and contain the oil (BP Chemicals, 1985a, b). Two cross-linking agents were used, a fast and a slow cross-link, and these were linked with the polymer in the oil-contaminated sediment. The exact procedures and plot layouts are described by Owens *et al.*, 1982.

Although the application of the solidifying agent and the composition varied among plots, in all six tests the compound solidified quickly and encapsulated the surface oil. Field observations indicated that the solidifying agent retarded sediment reworking in the intertidal zone. Lumps of the solidified oil/sediment mixture were still present on the shoreline in 1983, the third open-water season (Fig. 7). The method proved to be effective in encapsulating stranded oil. However, the technique is presently labour-intensive and expensive.

Low-Pressure Flushing

A single low-pressure flushing experiment was conducted on plot IC(E)E in 1982 in Bay 106. This experiment resulted in an increase in the total hydrocarbon values of the surface sediment samples in the order of four times greater than the oil in sediment concentrations on the adjacent emulsion control plots. Although this evaluation does not consider data collected after seven days following the experiment, these high oil in sediment concentrations were still evident on the low-pressure flushing plot in September 1982 and August 1983. Oil was not driven into the subsurface sediments.

This one limited experiment showed that total hydrocarbon concentrations were not reduced in this environment by the use of low-pressure flushing. The technique is labour intensive and it is unlikely it would have a significant application to arctic or remote environments.

Intertidal Mixing

Mechanical mixing of the contaminated intertidal plots at Crude Oil Point (Fig. 8) did not initially result in the reduction of total hydrocarbon concentrations in the surface sediments (Table 9). Oil was pushed deeper into the beach, and this action delayed rather than accelerated the natural cleaning of those plots. The value of this technique would lie primarily in the prevention or reversal of the formation of an asphalt pavement in the intertidal zone. Apart from this application, the technique does not appear to offer any major advantage over natural cleaning of the shoreline. The procedure is a comparatively low-cost and low-labour-intensive method that requires a relatively simple logistic operation. The technique is one therefore that can be used on accessible beaches, and large areas can be mixed rapidly using mechanical equipment.

Backshore Mixing

The mixing experiments on the backshore plots in Bay 106 were conducted to replicate the method on sections of beach where oil was deposited above the normal limit of wave action. In this experiment the mixing procedures reduced total hydrocarbon values of the surface sediment and oil was driven into the subsurface. Again, this action could prevent or reverse the formation of an asphalt pavement on the upper beach. Such a result may also transform an unacceptable oiling situation with respect to the movement of wildlife over the backbeach area. Where access is possible, the method can be applied to extensive areas in a relatively short time by the use of mechanical methods.

Hydrocarbon-Based Dispersant BP 1100X

The hydrocarbon-based dispersant BP 1100X was applied with a hand sprayer and backpack to intertidal plots at Crude Oil Point and Bay 106. At Crude Oil Point the dispersant application immediately resulted in a significant reduction of surface and an increase of subsurface oil in sediment concentrations. The total hydrocarbon analyses conducted at this site indicate

FIG. 7. Blocks of solidified sediments collected near the high-water mark above plots SC and SE at Crude Oil Point on 11 August 1983.

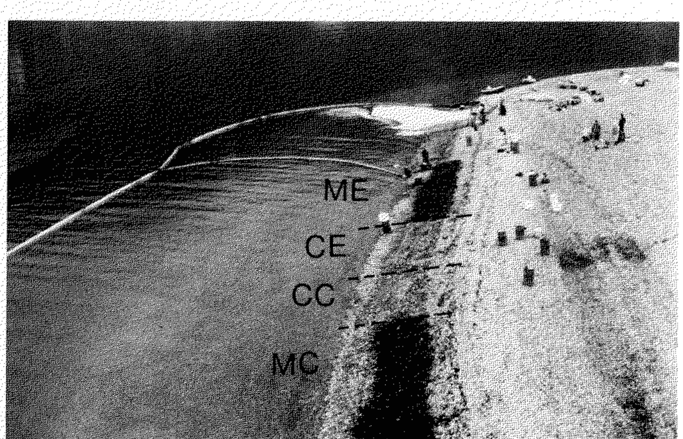

FIG. 8. Aerial view of the mixing and control plots at Crude Oil Point on 6 August 1981. The codes are described in Table 3.

that the dispersant virtually cleaned the surface sediments, with only trace concentrations being detected after 8 d. In Bay 106 this dispersant was not effective, as a hydrocarbon-based dispersant is designed to penetrate oil and requires either naturally available energy or added energy to produce the desired effect. The experimental conditions at Bay 106 were selected to provide a direct comparison with Crude Oil Point. In this sheltered location there was insufficient wave energy available to agitate the oil/dispersant mixture. As expected, little oil was removed from this pair of experimental plots within the 7 d period following the test.

Dispersant Corexit 7664

At the Crude Oil Point site the application of this dispersant resulted in a reduction of the total hydrocarbon content of the surface sediments by an order of magnitude, with an increase in subsurface concentrations. By Day 40 all samples produced oil concentrations $< 400\,mg \cdot kg^{-1}$. At the more sheltered Bay 106 site the application of the dispersant resulted in a significant decrease in surface total hydrocarbon values 1 d after the test on the crude oil plot but resulted in little change on the upper sections contaminated by the redistributed crude oil and on the emulsified oil plot and adjacent areas. This trend was again evident 7 d following this experiment. As the effectiveness of this dispersant, which was applied with relatively high energy to mix the dispersant and the oil, resulted in relatively little change, the use of dispersants on the type of shoreline exemplified by Bay 106 cannot be considered to be effective.

Natural Cleaning

Comparison of total hydrocarbon data from the Crude Oil Point and the Bay 106 control and countermeasure plots (Tables 9, 10, 11, 12 and 13) shows that after the initial sampling period (up to 7 or 8 d) there was some discernible difference between sections cleaned by countermeasures and those cleaned naturally. It is recognized that the data from the plots are affected by dispersion and edge effects after the initial period of 7 or 8 d. However, in the 1981 experiments after 40-41 d the dispersant plots were cleaner than the control plots, but in turn the controls were an order of magnitude cleaner than the mixed plots. In the 1982 experiments at Bay 106 after 33 d the results are inconclusive, due to the extensive redistribution of oil within the first 24 h. General consideration of the results as a whole over a five- to six-week period suggests that the countermeasures did not significantly reduce the total hydrocarbon values when compared to the plots that were cleaned naturally, with the exception of the dispersants used at Crude Oil Point. In terms of spill countermeasures for arctic or remote beaches, the experiments would indicate that in most cases natural cleaning is as effective as the tested countermeasures.

CONCLUSIONS

(1) Monitoring of the large-scale contamination of shorelines in Bay 11 demonstrated that oil does remain in significant quantities over long periods of time. However, the small intertidal control plots in Z-Lagoon did not retain oil in significant quantities after the initial period of one or two weeks. After this period, dispersion and edge effects reduced the value of the results in terms of replicating heavy oil contamination on the intertidal zone. The small plot results are therefore most applicable to the short-term assessment of countermeasures or to spill incidents that result in patchy contamination. The short-term results from the plots can be applied, however, in the wider context of their potential to reduce long-term contamination.

(2) The incendiary device tested did not ignite freshly deposited oil on the beach despite flame temperatures > 1500°C.

(3) A solidifying agent that encapsulates stranded oil was found to be an effective method by which oil could be "frozen" in place. The method is, however, very labour intensive and expensive.

(4) Low-pressure flushing on a fine-grained beach in a very sheltered area was found to be ineffective. Analytical results show that surface oil concentrations were significantly increased. This method is also labour intensive.

(5) The mixing of oily sediments resulted in lower surface oil concentrations on the backshore plots only and elevated subsurface concentrations. The method is not labour intensive and large sections of contaminated shoreline could be made more acceptable in terms of shoreline sensitivity/trafficability for wildlife.

(6) Both the hydrocarbon-based BP1100X dispersant and the Exxon Corexit 7664 dispersant worked well on the semi-exposed Crude Oil Point plots by reducing surface oil in sediment concentrations. As expected, there was an increase in subsurface total hydrocarbon concentrations on the experimental plots. Neither dispersant was effective on the very sheltered Bay 106 beach. Dispersant use should be limited to locations where there is sufficient wave energy to agitate and redistribute the oil/dispersant mixture.

(7) There exists a range of countermeasure options for remote or arctic shorelines that can reduce oil contamination effectively and efficiently. Only a few of these options were tested in this experiment. Some proved to be of limited or no positive value on beaches (incendiary devices and low-pressure flushing), whereas others (mixing and chemical dispersion) could mitigate the effects of contamination or accelerate the removal of stranded oil on beaches.

(8) It is likely that the use of chemical dispersants or mixing countermeasures would prevent the formation of the asphalt pavement such as that which developed in Bay 11.

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