

Design and Operation of Oil Discharge Systems and Characteristics of Oil Used in the Baffin Island Oil Spill Project

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ABSTRACT. As part of the Baffin Island Oil Spill (BIOS) Project, two experimental oil discharges were made into bays at Cape Hatt at the northern end of Baffin Island. The objective was to allow the comparison of the nearshore fate and effects of an untreated surface oil slick and oil chemically dispersed into the water column. Weathered Lagomedio crude oil (15 m^3) was discharged onto the water surface in one bay, and most of the slick became stranded on the intertidal zone under the influence of an onshore wind and ebb tide. The oil thickness averaged about 1 mm on the beach face. The same volume and type of oil premixed with Corexit 9527 in a ratio of 10:1 was pumped into a second bay through a perforated diffuser pipe lying on the bottom sediments. The cloud of chemically dispersed oil contacted the bottom sediments and benthic organisms in the second bay and an adjacent third bay. The total exposure in the water column in the second bay was about $300 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ and about $30 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ in the third bay.

Key words: BIOS Project, oil spill, Arctic, oil discharge system, dispersant

RÉSUMÉ. Deux déversements expérimentaux de pétrole ont été faits dans des baies au cap Hatt, à l'extrémité nord de l'île Baffin, dans le cadre du projet de déversement de pétrole à l'île Baffin (BIOS). Le but des essais était de comparer le comportement près de la côte et les effets du pétrole non traité répandu en surface, à ceux du pétrole chimiquement dispersé dans la colonne d'eau. Du pétrole brut Lagomedio vieilli (15 m^3) a été répandu à la surface dans une baie, et la plus grande partie s'est échouée sur la laisse sous l'effet d'un vent du large et de la marée descendante. La couche de pétrole sur la plage avait environ 1 mm d'épaisseur. Un volume égal du même pétrole prémélangé avec du Corexit 9527 dans un rapport de 10 pour 1 a été pompé à l'intérieur d'une deuxième baie grâce à un tuyau diffuseur perforé reposant sur les sédiments du fond. Le panache de pétrole chimiquement dispersé s'est trouvé en contact avec les sédiments du fond et les organismes benthiques de la deuxième baie et d'une troisième baie adjacente. L'exposition totale dans la colonne d'eau était d'environ $300 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ dans la deuxième baie et d'environ $30 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ dans la troisième.

Mots clés: projet BIOS, déversement de pétrole, Arctique, système de déversement de pétrole, agent de dispersion

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INTRODUCTION AND OBJECTIVES

This paper is one of a set published in this issue of *Arctic* reporting the results of the Baffin Island Oil Spill (BIOS) Project. One objective of the project was to examine and compare the fate and effects of untreated oil and oil treated with dispersant released into a representative nearshore arctic environment. A general description of the project and its findings is provided by Sergy and Blackall (1987). The purpose of this paper is to discuss the design and operation of the oil discharge systems used and to describe the characteristics of the released oil.

The selection and preparation of the oil and the methods chosen for the oil releases originated in a preliminary statement of objectives for the study of oil in nearshore arctic environments (Environment Canada, 1979). Conceptual design of the BIOS Project oil releases was concerned with achieving a balance between the desired level of real spill simulation and limitations imposed by field conditions. Critical questions involved site selection, oil volumes, discharge rates and methods for dispersant application.

The preferred experimental site would have a series of relatively sheltered bays with beaches several hundred metres in length. Small bays were considered as the most appropriate environment, because their biological standing crop is high enough to facilitate observations of the effects of spilled oil. They are also appropriate because they offer more opportunity to achieve oil concentrations similar to those encountered after actual spills, while maintaining an acceptable degree of control of released oil.

The original conceptual design anticipated one bay receiving oil as a surface slick, one bay receiving an oil-dispersant mixture

and one bay remaining uncontaminated to serve as a control. As much as possible, the bays were to be isolated from each other in terms of water movements to minimize cross-contamination. At the same time, the bays had to be close enough to facilitate the use of a common base camp and to increase the likelihood of physical and biological similitude.

Realistic target oil concentrations were derived for both the untreated and chemically dispersed oil as follows. It was decided that each discharge would be completed within a 6 h period. For the surface spill, this decision meant that, starting at high tide, the oil would be left stranded on the shore during a falling tide. For the dispersed oil, 6 h represented the maximum period during which current patterns could be expected to remain relatively constant. Identical volumes, discharge periods and discharge rates were chosen for each spill to provide equal doses and dosing rates in the test areas. To minimize cross-contamination, any oil remaining on the water surface after the 6 h release periods would be recovered with skimmers.

An oil slick moving onshore from a 100 d blowout at $1000 \text{ m}^3\cdot\text{d}^{-1}$ would result in an average linear shoreline concentration in the range of $10\text{-}100 \text{ l}\cdot\text{m}^{-1}$ (if 10% of the oil reached a shoreline 100-1000 km long). If the upper one-third of a 30 m wide intertidal zone was most heavily contaminated, this linear concentration would result in an average oil thickness of between 1 mm and 1 cm. A 200 m long test bay would require 2-20 m^3 of oil to achieve the above-mentioned linear concentrations.

At the time of the BIOS Project design, available data on typical oil concentrations beneath dispersed oil slicks indicated peak values several hours after dispersant application of $0.1\text{-}10 \mu\text{g}\cdot\text{g}^{-1}$ (McAuliffe, 1980). With onshore currents and winds, oil from a slick chemically dispersed several km offshore would take several hours to impact the shoreline. Peak values of

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dispersed oil concentrations in the nearshore could be close to the values reported by McAuliffe. On this basis, it was decided to aim for average dispersed oil concentrations close to $10 \mu\text{g}\cdot\text{g}^{-1}$ (about $10 \text{mg}\cdot\text{l}^{-1}$) within the test bay.

In a static situation, $10 \text{mg}\cdot\text{l}^{-1}$ oil concentration in a wedge of water 200 m (alongshore) by 200 m (offshore) and 10 m deep would require 4m^3 of oil. In a dynamic situation, however, the concentration would depend on the oil release rate and the water exchange rate through the bay. Assuming that water was moving through the bay at a speed of $1\text{--}10 \text{cm}\cdot\text{s}^{-1}$, a discharge of $4\text{--}40 \text{m}^3$ of oil over a 6 h period would be required to generate an average oil concentration of about $10 \mu\text{g}\cdot\text{g}^{-1}$ in the moving wedge of water in the bay.

Based on order of magnitude estimates for the surface and dispersed oil concentrations, the possible range of oil volumes was $4\text{--}20 \text{m}^3$. Erring toward a "worst case" scenario, the government permits were set at 15m^3 for each oil discharge.

The surface spill could easily be carried out by pumping from a moving source offshore. The dispersed oil spill, on the other hand, involved a series of calculations and laboratory evaluations to establish the most reliable means of contacting the nearshore sediments with the desired oil concentrations.

It was decided that spraying dispersant on a surface slick ran the risk of partial dispersion, followed by loss of control of the experiment. The BIOS Project was not intended to evaluate dispersant effectiveness or to simulate real dispersant application techniques. The primary objective was to achieve an even distribution of oil at depth in the dispersant test bay. To accomplish this objective, a decision was made to discharge premixed oil and dispersant at a 10:1 ratio with water through a submerged perforated discharge pipe (diffuser). The optimum field location of the diffuser pipe depended strongly on local oceanography and was chosen only after a series of dye tests and current observations (see Buckley *et al.*, 1987).

METHODOLOGY

Oil and Dispersant Characteristics

Lagomedio, a Venezuelan crude oil, was selected for the experiment because of its medium density, ready availability and anticipated use in cold water dispersant effectiveness studies planned for the east coast of Canada. The dispersant selected for the experiment was Corexit 9527 in the concentrate form.

In a real spill, oil weathers on the surface of the ocean, as lighter components evaporate into the atmosphere. In order to simulate oil approaching a coastline, the Lagomedio crude was artificially weathered before being shipped north. The weathering was accomplished by bubbling $2.3 \text{m}^3\cdot\text{min}^{-1}$ of air through the oil in a 38m^3 tank for several days. After the original oil was reduced in volume by approximately 8%, the oil properties included an API gravity of 29.6, a pour point of -20°F and a flash point of 72°F (an important consideration for shipping and handling).

A number of other characteristics of similarly weathered oil samples were also determined. Measurements of absolute kinematic viscosity (ASTM method D445), interfacial (oil/water) tension (ASTM method D971) and density were made for three temperatures and oil/dispersant mixtures (see Table A1 in the Appendix).

Of particular concern to the project was the apparent non-Newtonian behaviour of the oil and oil/Corexit 10:1 mixture at 0°C and -5°C , likely caused by the formation of waxy deposits

in the viscometer orifices. These waxy precipitates necessitated the homogenization of all the oil prior to use and the maintenance of the oil and oil/Corexit mixtures above the critical temperature range during the experiment.

Organic analysis showed that the weathered oil had lost most of the saturated hydrocarbon components that were more volatile than *n*-decane (10 carbon atoms). There was a 70% reduction in *n*-decane itself, and there were progressively smaller reductions with increasing molecular size up to about *n*-tetracosane (24 carbon atoms). The aromatic hydrocarbons were reduced in a similar manner.

The organic analysis provided a basis for assessing the changes in composition of the oil and oil/Corexit mixtures during the course of the experimental nearshore oil releases (see Table A2 in the Appendix). Samples obtained before and during the oil releases showed differences in organic chemical characteristics, suggesting some degree of inhomogeneity between different batches of oil. Values of three indexes used to measure post-release biodegradation and weathering of the oil did not change significantly during the releases. Also, the concentrations of the naphthalenes, representative of the more soluble, volatile and toxic components of the oil, remained essentially unchanged by the release process (see Table A2, and a detailed discussion of post-spill oil samples in Humphrey *et al.*, 1987).

METHODS

Discharge Systems Design

The two BIOS Project nearshore discharges required two very different systems: a simple surface spill plate for the untreated oil release, and a complex submerged discharge pipe for the dispersed oil release. The success of the dispersed oil release depended on being able to create a cloud of dispersed oil particles whose size distribution would closely approximate that thought to result from the application of dispersant to oil on the sea surface. Laboratory measurements were made of particle size distributions resulting from pumping premixed oil and dispersant through an orifice with and without the addition of water (Mackay *et al.*, 1982). Particle size distributions produced by the jets had median diameters of $5\text{--}20 \mu\text{m}$, similar to dispersed oil particles produced in the Mackay Nadeau Effectiveness Apparatus (Mackay *et al.*, 1978). The introduction of water produced a lower fluid viscosity and higher Reynolds Number but did not appreciably affect the distribution of particle sizes within the dispersed oil plume. It was concluded that the dispersed oil drops were produced primarily in turbulence at the tee pipe junction, where water met the premixed oil/dispersant stream, rather than at the pipe orifice, as occurred without addition of water.

The laboratory tests confirmed the concept of pumping premixed oil/dispersant, with or without addition of water, through a submerged diffuser pipe to create a dispersed oil cloud in the water column. Laboratory results pointed to a 3 mm jet orifice operating at $10\text{--}20 \text{cm}^3\cdot\text{s}^{-1}$ flow rate as the desired operating condition (Mackay *et al.*, 1982). With straight oil/dispersant, a pressure drop of $9\text{--}15 \text{kPa}$ across the orifices was required to produce the required median droplet size. With the introduction of seawater, the fluid viscosity at 0°C dropped from about 450 centipoise to 3.5 centipoise. The pressure drop across the orifices then became less of a critical design consideration. Without the introduction of seawater into the system, the attainment of an even discharge along the entire pipe length was

affected by minor variations in oil viscosity, pipe length, pipe slope and water depth. With a water/oil ratio of 5:1, the fluid viscosity was relatively insensitive to unpredictable variations in oil viscosity, and a uniform jet discharge could be maintained over a wide range of pipe slopes (1:5-1:10) and pipe submergence (10-20 m). A series of iterative calculations was carried out to investigate the different effects of flow rate, fluid viscosity, slope, depth, pipe diameter, orifice diameter and orifice spacing (Thornton, in Dickins, 1982).

The final dispersed oil discharge system is shown as a schematic in Figure 1. The submerged diffuser consisted of 100 m of 7.6 cm diameter aluminum irrigation pipe. Fifty-one orifices of 6 mm diameter were drilled at a variable spacing, decreasing with water depth to maintain a constant discharge volume per unit volume of receiving water. The dispersant was mixed with the oil in an onshore holding tank fabricated from a conventional above-ground swimming pool with a special oil-resistant liner. The dispersant/oil mixture was pumped from the tank by a positive displacement pump. Seawater was pumped from offshore and injected into the oil line at a 5:1 water/oil ratio, after which the oil/dispersant/water mixture was pumped out to enter the diffuser pipe at the submerged seaward end, 100 m offshore.

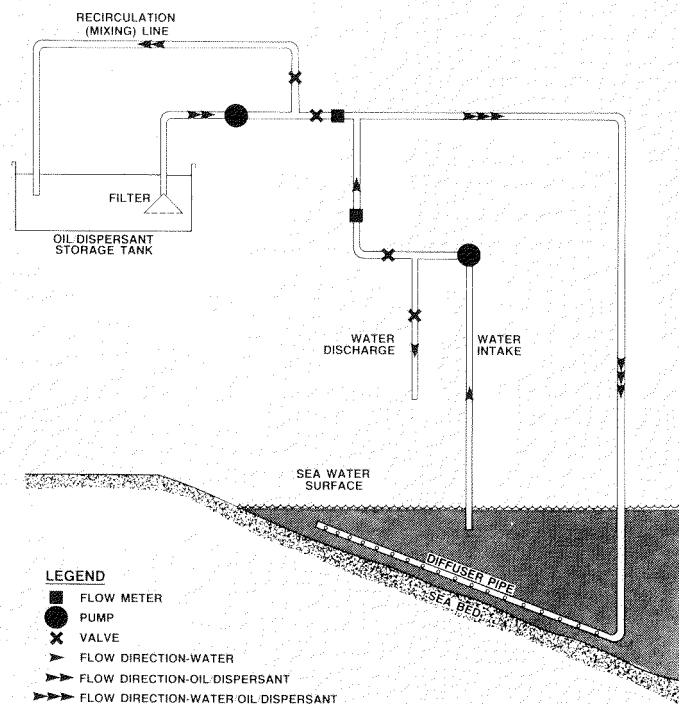


FIG. 1. Schematic of dispersed oil discharge system.

In contrast to the diffuser system development, the surface oil discharge system was extremely simple in concept and execution. Design objectives were to provide a smooth, gentle flow of oil directly onto the water surface, minimizing entrainment of oil droplets in the water column. The device had to be easily towed across the width of the test bay to enable a uniform beach fouling with different onshore winds.

The final design for the surface discharge device consisted of a standard foam-filled mooring buoy, modified to allow connection of the neoprene discharge hose at the base of the buoy. Oil

flowed up through the centre, over the buoy's upper surface and onto the water (Fig. 2). With a tether line and small boat, the "spill plate" could be swung through a wide arc offshore from the supply tank.

Prior to shipment north, a dye test was used as a full-scale demonstration of the diffuser and water column monitoring programs planned for the BIOS Project. This test confirmed that the major challenge was going to be exposing the benthos to a uniform, well-defined concentration of dispersed oil without contaminating surrounding areas. The pumping systems and diffuser pipe performed as expected in the southern dye test (Green, 1981). Dye plumes were observed by divers to rise after mixing with surrounding water. Concerns about plume buoyancy eventually led to placement of the pipe directly on the seabed, rather than suspending the pipe off the bottom, as originally planned.

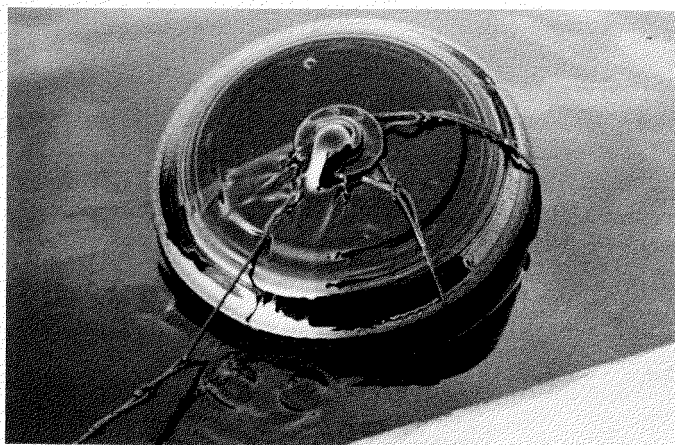


FIG. 2. Surface oil spill plate.

Discharge Systems Deployment

General criteria for the selection of test bays were discussed in the introduction to this paper. In the Cape Hatt area chosen for the BIOS Project, Ragged Channel offered the best selection of possible test bays, with Bays 9, 10 and 11 being most favoured in terms of environmental similarity and potential for control and containment of spilled oil. The critical decisions that had to be made prior to deploying the discharge systems centred around the optimum utilization of the three favoured bays (see location map in Sergy and Blackall, 1987).

The primary consideration in selecting the experimental bays was the possibility of cross-contamination. In order of priority, the cross-contamination mechanisms initially considered were: transportation of oil dispersed/dissolved in the water column; movement of oil on the water surface; and redeposition of contaminated sediments. The first mechanism, transportation of oil dispersed/dissolved in the water column, offered the potential of severe, almost immediate cross-contamination and no control over the oil following discharge. The second mechanism, movement of oil on the water surface, offered the potential of severe, almost immediate cross-contamination, but provided the opportunity for post-discharge control through the use of oil spill booms. The final mechanism, sediment movement, offered the potential of only very minor contamination in the long term and was not ultimately a factor in the decision regarding the choice of the experimental bays.

Oceanographic studies had indicated that there was a reasonable chance of surface or subsurface cross-contamination between immediately adjacent bays but that the probability of oil exchange between Bays 11/12 and Bay 9 was very small. Hence, these two bay areas were chosen to receive the oil discharges. This choice implied a relatively high chance of Bay 10 becoming contaminated. If this occurred, the remote Bay 7 was available as a control bay, and Bay 10 would serve as a secondary contaminated bay and still provide useful information.

The subsurface current patterns were more regular and predictable in Bay 9 than Bays 11/12. The rather protected nature of Bays 11/12 offered a greater chance of controlling surface slicks using booms. Further, onshore winds, necessary for the release of untreated oil, were more frequent in Bay 12. Hence, it was decided to release untreated oil in Bay 12 and chemically treated oil in Bay 9.

The field experience confirmed the choice of test bays as being the best compromise, but unexpected problems developed in selecting the best location of the diffuser pipe in Bay 9. The expected southerly water flow at depth proved to be unreliable during two dye tests with the discharge pipe at the north end of the bay. Ongoing oceanographic work confirmed the presence of a strong northerly jet at depth along the east side of Ragged Channel. This jet was present throughout the entire tidal cycle, with both northerly and southerly winds. Surface currents were highly variable (Buckley *et al.*, 1987).

The final installation of the discharge pipe at the south end of

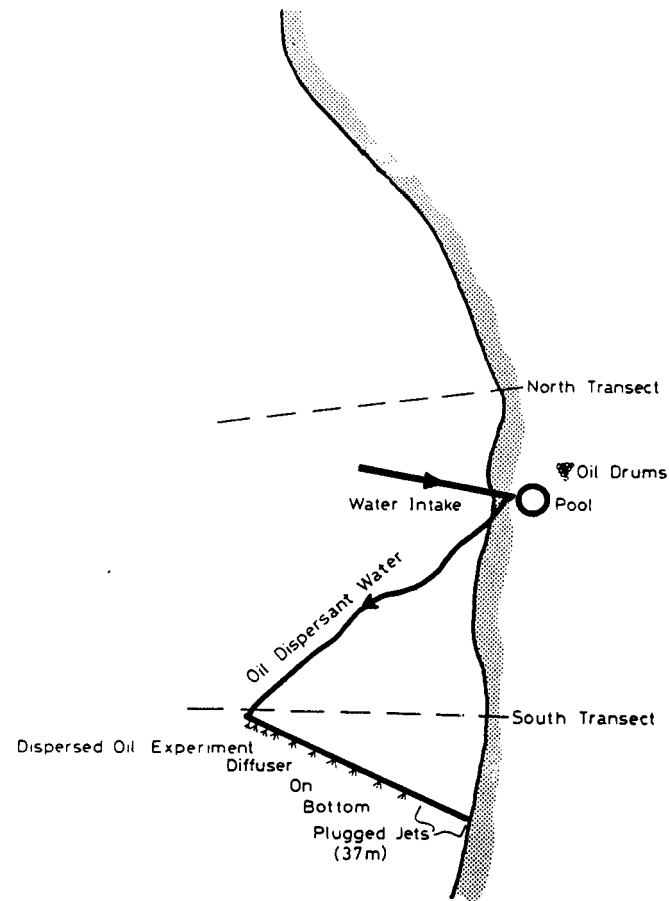


FIG. 3. Plan of Bay 9 test site.

Bay 9 is shown in schematic view in Figure 3. Note that the jets were pointed into the expected current flow at depth, an arrangement observed to promote mixing of the individual plumes during previous dye tests. Two final dye tests immediately prior to the oil release showed satisfactory results, with the dye contacting the bottom sediments throughout the biological test areas. Dye from 11 jets in shallow water less than 2 m deep tended to move south out of the test area in response to surface currents. These nearshore jets were plugged, leaving 40 active orifices for the oil release.

The pipe in its final installation was laid directly on the bottom, with lengths of steel reinforcing bar attached to each joint to prevent the pipe rolling with current or wave action nearshore. Figures 4 and 5 show views of the oil storage pool in the Bay 9 backshore and the diffuser pipe being positioned prior to sinking at the location shown in Figure 3.

The storage pool shown in Figure 4 was filled with 75 drums of oil on 26 August 1981, one day prior to the release. (Note: one drum of oil contains nominally 45 imperial gallons.) The



FIG. 4. View from the shore of Bay 9 showing the oil storage pool.

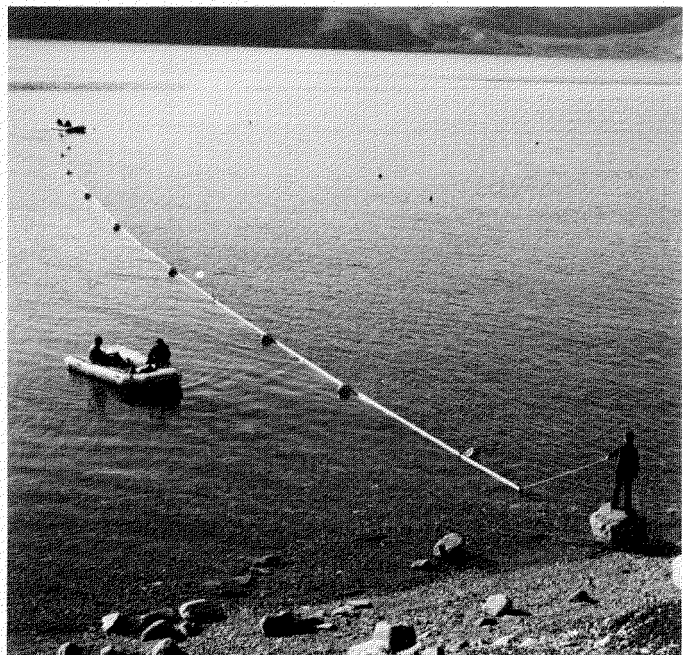


FIG. 5. Diffuser pipe being floated into position.

total volume of dispersant (7.5 drums) was added after 25 drums of oil had been loaded. The tank was covered to minimize evaporative losses. Oil and dispersant in the tank were pumped through a recirculation loop for 4 h on 26 August (2000 h to 2400 h) and again for 2 h on the morning of the test. Circulation of the tank was stopped 40 min prior to discharge on 27 August 1981.

Deployment and testing of the spill plate used for the surface oil release in Bay 11 was a relatively simple exercise. Figure 6 shows a plan view of Bay 11, with the oil booms in place, oil storage pool in the backshore and the flexible discharge hose leading to the floating spill plate (see Figure 2). The spill plate was tested by pumping water while towing with a small boat.

Contingency

Every precaution was taken to ensure adequate control of any surface slick resulting from either oil release. The Canadian Coast Guard developed a detailed contingency plan that addressed potential problems of spills during transport or storage and loss of control during the experimental spills (Transport Canada, 1981).

The contingency equipment was prepared and deployed prior to the oil releases. Deflector booms were positioned in Bay 9 to collect any recoalescing oil (Fig. 10). The test area in Bay 11 was boomed off to collect oil that did not strand immediately on the beach and to protect other bays and test areas from cross-contamination. These booms were left in place for several weeks to contain sheens from oil being naturally redistributed within the test area. These minor quantities of oil were not recovered, as they represented a normal redistribution of the oil expected in a real spill incident.

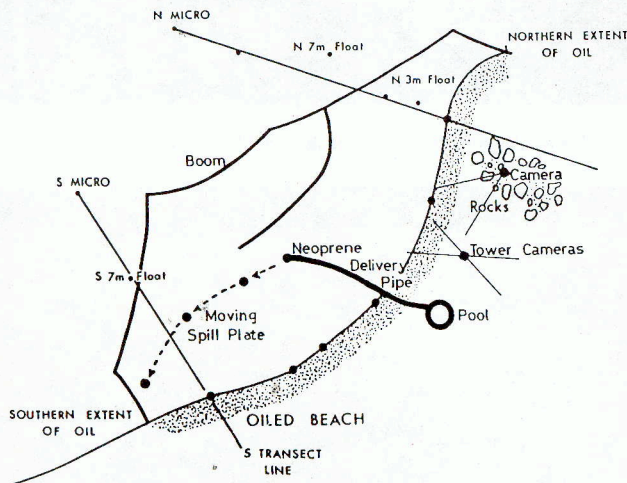


FIG. 6. Plan of Bay 11 test site.

Sampling Procedures

Oil concentrations in the water column during and after the dispersed oil discharge were measured with five flow-through fluorimeters. Three bottom pumps were monitored for 36 h to determine oil concentrations from the surface discharge near the bottom sediments. A vessel-mounted fluorometer provided vertical water column profiles during both oil releases (see Humphrey *et al.*, 1983 for a full description of the BIOS water sampling procedures).

In addition to the water column sampling, regular samples were extracted from the shoreward end of the discharge pipe. These samples of dispersed oil in water were placed in glass

tubes and allowed to settle. Periodic Polaroid photographs against a gridded background were used to establish oil particle settling times. Particle size distributions were then estimated from these times by applying Stokes law for particle velocities. For example, within 4 min all particles greater than 100 μm would have settled out, within 40 min all particles greater than 30 μm and after 6 h all particles greater than 10 μm (Mackay *et al.*, 1982).

RESULTS

Surface Oil Release

The release of 15 m³ of crude oil onto the surface waters of Bay 11 occurred on 19 August 1981, beginning at 1540 h (local time). The oil carried ashore by a light northwesterly breeze was left stranded by the ebb tide over a mixed sand and gravel beach



FIG. 7. Aerial view of Bay 11, 45 min after the start of pumping.

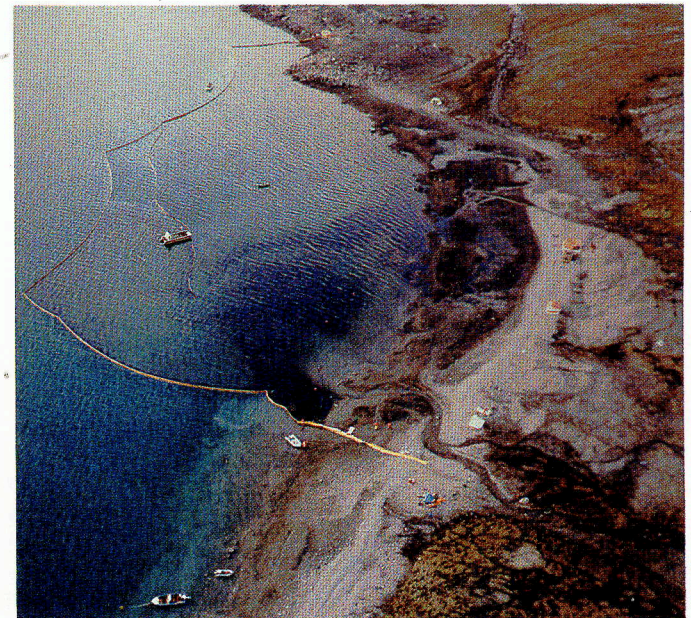


FIG. 8. Aerial view of Bay 11, 4 h after the start of pumping. Oil coating the intertidal area is clearly visible.

some 360 m in length. Figures 7 and 8 are aerial views of Bay 11 at the beginning and about halfway through the oil release. Figure 9 shows the oil-saturated intertidal zone immediately following the oil release.

After completion of the discharge at 2140 h, operations commenced to remove any oil left floating on the water surface. This operation was considered representative of a real spill situation, where any oil that had not stranded during the first ebb tide might normally move offshore or alongshore. Recovery operations continued to 1600 h, 21 August, when it was decided that there was insufficient oil remaining on the water surface to continue skimming. Recovery operations collected a total of 58 drums of 47% oil-in-water emulsion, representing 27.2 drums of crude (5.5 m^3).



FIG. 9. Bay 11 beach appearance immediately following completion of the surface oil release.

Within 48 h following the oil release, relatively stable conditions were reached in Bay 11, with the oil no longer lifting off the beach. By this time the total estimate of oil losses through natural processes was 2.66 m^3 , made up of 0.26 m^3 through dissolution during the release, 1.95 m^3 through evaporation on the water surface during release, and 0.45 m^3 through evaporation during the first 18 h following release.

While there was direct oil saturation of the intertidal zone, the short-term oil exposure for the subtidal inhabitants was minimal during the surface oil release. Oil concentrations in the water column below the slick ranged between 0.006 and $3.0 \mu\text{g}\cdot\text{g}^{-1}$ confined to the upper 1 m of water (Humphrey *et al.*, 1987). Oil exposures at the two Bay 11 biological transects at 3 and 7 m depths were below fluorometer detection limits of $0.05 \mu\text{g}\cdot\text{g}^{-1}$ during the oil release.

Dispersed Oil Release

The release of dispersant-treated oil began at 1310 h, 27 August 1981, and continued for 6 h 23 min over an ebb tide. The total volumes spilled were 14.4 m^3 of crude oil and 1.6 m^3 of Corexit dispersant. Seawater was injected into the oil/dispersant flow as planned at a ratio of 4.9:1 water/oil. The oil temperature in the storage pool during the release averaged 3.5°C . Water temperature offshore was 2.6°C at 5 m depth and 2.3°C at 12 m depth.

The movements of the dispersed oil through the test areas in Bays 9 and 10 were controlled by the complex nearshore oceanography of Ragged Channel. Shallow oil released between 3 and 7 m depth moved with eddy currents to the far southerly limits of Bay 9 and eventually looped back to reach the experimental areas 6 h after the start of the release. The extended oil journey was considered advantageous, since it allowed the oil to spread into a uniform cloud prior to reaching the test site. Most of the deep oil released between 8 and 15 m depth became entrained in the north-flowing coastal jet and continued past Bay 9 to either circulate in Bay 10 or move off into Ragged Channel (described in Buckley *et al.*, 1987, and in Humphrey *et al.*, 1987). Figure 10 is an aerial view of Bay 9 showing the shallow dispersed oil cloud visible in the water column.



FIG. 10. Aerial photograph of Bay 9 showing the dispersed oil cloud.



FIG. 11. Underwater photograph showing one of the dispersed oil clouds during the oil release. (Photo credit: W. Cross.)

Diver observations during the release in Bay 9 describe the dispersed oil as dense, billowy, light-brown clouds. Movement of the dispersed oil was similar to that observed with the dye tests, i.e., rapid southward movement from nearshore jets and slower northerly movement from deeper orifices. Dispersed oil was seen to impinge on the sediments in water depths from 3 to 18 m (N. Snow, pers. comm. 1981). Figure 11 shows the visual appearance of the dispersed oil plume in an underwater photograph.

Peak oil concentrations reached at the monitoring stations after the release in Bay 9 showed maximum values at the seabed greater than or equal to $55 \mu\text{g}\cdot\text{g}^{-1}$. An exception was the south microbiology station directly in the path of deep oil moving north; here the concentrations reached $160 \mu\text{g}\cdot\text{g}^{-1}$ during the release. Bay 10 test areas also received a considerable amount of dispersed oil, with peak concentrations around $5\text{--}7 \mu\text{g}\cdot\text{g}^{-1}$ being reached during the ebb tide on 28 August 1981, the day following the oil release. During the actual release, Bay 10 concentrations were typically less than $0.5 \mu\text{g}\cdot\text{g}^{-1}$. Overall exposures at the seabed were about $300 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ in Bay 9 and $30 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$ in Bay 10 (see Humphrey *et al.*, 1987, for a detailed discussion of the water column monitoring results).

Following the dispersed oil release, crews recovered approximately 60 l of re-coalesced oil trapped by the deflector boom at the south end of Bay 9 (visible in Fig. 10). There was no oil visible along the shorelines of Bays 9 and 10 following release. A light sheen was observed to contact the shore during the release.

The dispersed oil cloud continued to spread after release, until on the fourth day (30 August) it could be found throughout Ragged Channel at levels of $30\text{--}50 \text{ ng}\cdot\text{g}^{-1}$ (parts per billion), at depths of 5–15 m (Humphrey *et al.*, 1987). Over a 36 h period, Bay 7 also received total exposures of approximately $0.5 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$, three orders of magnitude below Bay 9, the primary dispersed oil test bay.

DISCUSSION AND CONCLUSIONS

The discharge systems met the design requirements and objectives of the BIOS Project.

In Bay 11, 66% of the intertidal surface area was covered with oil to a mean thickness of 1.2 mm (Owens and Robson, 1987). The bulk of the oil not removed from the water or lost through natural weathering remained on the beach, achieving the primary objective of producing a uniform contamination of the intertidal area through stranding of an oil slick.

In Bay 9, the diffuser system produced oil particles in the $5\text{--}15 \mu\text{m}$ size range, as predicted (Mackay *et al.*, 1982). The primary objective of exposing the sediments within the biological test areas to significant concentrations of dispersed oil was achieved. The duration of exposure and peak concentrations proved to be largely beyond any reliable experimental control. Current eddies initially transported oil away from Bay 9, before finally sweeping the oil back over the biological test sites at exposure levels averaging $300 \mu\text{g}\cdot\text{g}^{-1}\cdot\text{h}$, a value five times higher than originally projected. The adjacent Bay 10 received dispersed oil exposures an order of magnitude less than Bay 9, or approximately equal to the original exposure targets for the primary test bay. The unpredictable behaviour of the dispersed oil cloud provided two separate dispersant tests from a single release separated by an order of magnitude in oil exposure

levels. Peak oil concentrations in Bay 10 were comparable to those values measured in previous trials where dispersants were applied to actual oil slicks (McAuliffe, 1980; Myers and Corry, 1984). Despite the complex oceanography and unpredictable field conditions at Cape Hatt, the dispersed oil discharge system met its design objectives.

In conclusion, the discharge systems used in the BIOS Project provided results that met or exceeded expectations and enabled comparison between the nearshore fate and effects of surface slicks and chemically dispersed oil.

ACKNOWLEDGEMENTS

The authors acknowledge individual contributions to the design, testing and field operation of the discharge systems at Cape Hatt. Donald Mackay, of the University of Toronto, worked with one of the authors (D.E. Thornton) to develop the concepts and basic design for the discharge systems. Howard Smith, of Swan Wooster Engineering Ltd., in Vancouver, performed a hydraulics evaluation of the diffuser system and selected the actual hardware components. The Institute of Ocean Sciences in Sidney, B.C., loaned boats and operators for the southern field trial of the discharge system. Blair Humphrey contributed to the conceptual design and construction of the mooring system for the diffuser pipe. At Cape Hatt, many people assisted with the assembly of the oil storage tanks and diffuser pipe, in particular, Peter Blackall, Gary Sergy, Ernie Reimer, Bodo de Lange Boom, Joe Buckley and Donald Mackay. Doug Kittle, Norm Snow, Claude Rivet and William Cross provided invaluable assistance through diving to deploy the pipe and observe its performance underwater.

APPENDIX. TABULATED PHYSICAL AND CHEMICAL CHARACTERISTICS OF LAGOMEDIO CRUDE OIL AND COREXIT 9527 DISPERSANT By W.J. Cretney

Prior to the oil release experiments, a number of physico-chemical characteristics of 8% artificially weathered oil samples were determined. Measurements of absolute kinematic viscosity (ASTM method D445), interfacial (oil/seawater) tension (ASTM method D971) and density were made for three temperatures and oil/dispersant mixtures (Table A1). Of particular concern to the project was the apparent non-Newtonian behaviour of the oil and oil/Corexit (10:1) mixture at 0°C and -5°C , which appeared to be caused by the formation of waxy deposits in the viscometer orifices. The precipitation of waxy components, also previously observed in barrels of oil stored at Cape Hatt, necessitated the homogenization of all the oil prior to use in the experiments and maintenance of the oil and oil/Corexit mixtures above the critical temperature range during the experiment.

Metal analysis of the weathered Lagomedio crude oil confirmed what was expected from knowledge of the original oil: it was distinctive compared to most other crude oils in having a particularly high vanadium content and elevated nickel content. Organic analysis showed that the oil being weathered had lost most of its saturated hydrocarbon components more volatile than *n*-decane. There was a 70% reduction in the amount of *n*-decane (10 carbon atoms) itself and progressively smaller reductions with increasing molecular size from *n*-decane to about *n*-tetracosane (24 carbon atoms). Similarly, the aromatic hydrocarbon components were reduced in concentration so that there was a 70% reduction in the concentration of three carbon-containing alkylbenzenes (9 carbon atoms), with little or no loss indicated for components of larger molecular size or less volatility than the three carbon-containing alkylnaphthalenes (13 carbon atoms).

The organic analysis also provided a basis for assessing the changes in composition of the oil and oil/Corexit mixtures during the course of the experimental nearshore oil releases (Table A2). Indeed, the composition of the oil, as shown by the relative amounts of different

TABLE A1. Absolute viscosities, interfacial tensions and densities of mixtures of artificially weathered Lagomedio crude oil and Corexit 9527 dispersant

Weathered ^a Lagomedio: Corexit ratios ^b	Temperature (°C)	Viscosity (centistokes)	Interfacial tension ^c (dynes·cm ⁻¹)	Density (g·cm ⁻³)
1:0	-5	(1626, 3351) ^d	n.d. ^e	0.8990
10:1		(9801, 20960) ^d	1.7	0.9118
1:1		218	1.3	0.9586
1:0	0	(1420, 2640) ^d	16.7	0.8958
10:1		(880, 1288) ^d	1.3	0.9082
1:1		144.6	1.3	0.9586
1:0	5	154.1	19.8	0.8923
10:1		120.0	3.4	0.9045
1:1		100.3	2.0	0.9551

^aWeathered by air bubbling to give a volume reduction of 8%.

^bVolume:volume ratio.

^cVs. standard sea water (35‰).

^dThe samples appeared to precipitate waxy components at 0°C and -5°C. These components clogged the orifice of the viscometer. The values in brackets are the "viscosities" measured in the first and second sections of the reverse flow viscometers.

^en.d. = not determined.

TABLE A2. Organic chemical characteristics of Lagomedio crude oil and dispersant mixtures used for the BIOS nearshore oil releases

Oil sample	Composition ^a (%)			Weathering indexes ^b			Conc. ^c (mg·g ⁻¹)		
	Saturates	Aromatics	Polars/residuals	Alk/Iso	SHUR	AWR	N	C ₁ N	C ₂ N
Unweathered Lagomedio	59.1	35.2	6.3	2.36	2.87	4.29	n.a. ^d	n.a.	n.a.
Weathered ^e Lagomedio	58.8	30.0	14.8	2.50	2.28	3.47	0.3	2.0	3.4
Bay 11 pool ^f (1600 h)	49.8	30.0	20.2	3.41	2.20	3.42	0.3	1.7	3.0
Bay 11 pool ^f (1800 h)	39.8	29.2	31.0	2.42	2.20	n.a.	0.2	1.2	2.9
Weathered ^e Lagomedio Corexit 9527 (10:1)	44.2	27.5	28.3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Bay 9 diffuser ^g (1600 h)	37.7	24.1	38.8	2.41	2.02	3.47	0.2	1.0	2.0
Bay 9 diffuser ^g (1830 h)	43.7	36.8	19.5	2.45	1.91	n.a.	n.a.	0.7	2.8

^aDetermined from silica gel column chromatographic fractionation: saturates (f₁) elute in hexane, aromatics elute in hexane: dichloromethane (60:40), polars elute in methanol and residuals remain on column.

$${}^b\text{Alk/Iso} = \frac{\sum[n - \text{alkanes}; n - C_{14} \text{ to } n - C_{18}]}{\sum[\text{five isoprenoids in } n - C_{13} \text{ boiling range}]}$$

$$\text{SHWR} = \frac{\sum[n - \text{alkanes}; n - C_{10} \text{ to } n - C_{25}]}{\sum[n - \text{alkanes}; n - C_{17} \text{ to } n - C_{25}]}$$

$$\text{AWR} = \frac{[\text{Benzenes}] + [\text{Naphthalenes}] + [\text{Fluorenes}] + [\text{Phenanthrenes}] + [\text{Dibenzothiophenes}]}{[\text{Phenanthrenes}] + [\text{Dibenzothiophenes}]}$$

^cN = Naphthalene; C₁N = methylnaphthalenes, C₂N = dimethylnaphthalenes.

^dn.a. = not analyzed for.

^eWeathered by air bubbling to volume reduction of 8%.

^fDrawn from the swimming pool used as a reservoir for the 8% artificially weathered Lagomedio crude oil.

^gDrawn from the nearshore end of the diffuser pipe and consisting of a 5:1 water:oil/dispersant mixture. The analysis refers to the oil phase only.

compound classes, did show differences between the samples obtained in the two sampling periods for each oil release experiment, suggesting that there were inhomogeneities despite efforts to remove them. Nevertheless, the three indexes primarily to be used to indicate post-release biodegradation and physico-chemical weathering of the oil were acceptably unchanged during the releases. Also, the naphthalenes, representative of the more soluble, volatile and toxic components of the oil, remained acceptably unchanged in concentration, although some loss of these components was indicated.

The analyses reported in this Appendix were performed at Energy Resources Co. Inc. (ERCO), Cambridge, Massachusetts (Boehm, 1981; Boehm *et al.*, 1982).

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