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The Feasibility of Oil Spill Dispersant Application in the Southern Beaufort Sea

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**THE FEASIBILITY OF OIL SPILL DISPERSANT APPLICATION
IN THE SOUTHERN BEAUFORT SEA**

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A Report Submitted to:

Research and Development Division
Environmental Emergency Branch
Environmental Impact Control Directorate
Environmental Protection Service
Department of Fisheries and the Environment

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This report has been reviewed by the Environmental Impact Control Directorate, Environmental Protection Service, and approved for publication. Approval does not necessarily signify that the contents reflect the views and policies of the Environmental Protection Service. Mention of trade names and commercial products does not constitute endorsement for use.

FOREWORD

This study was undertaken by Dames and Moore Consulting Engineers under contract to the Environmental Emergency Branch of the Department of Fisheries and the Environment. Mr. C.W. Ross of this Branch supervised the work outlined in this report. Mr. P.B. Hildebrand, currently of The Environmental Applications Group Limited, headed this study on behalf of Dames and Moore. Contributions are acknowledged from Mr. A.A. Allen of Crowley Environmental Services Corporation, Mr. P. Martin and Mr. D. Ragle of Dames and Moore, Mr. R.E. Nash of Evergreen Air of Montana Inc., Mr. K. Owens of Bell Aerospace, and Mr. A.B. Stellards of Globe Air Inc.

ABSTRACT

This study addresses the feasibility of dispersant application in the Southern Beaufort Sea. A review of application techniques and physical environments is presented, and on the basis of this review, three application platforms appear to be worthy of further study: a heavy-lift helicopter, such as the Sikorsky S-64, the Canadair CL-215, and the Lockheed L-100-30. Dispersants were analyzed for their applicability to the Arctic environment and on this basis, it is recommended that concentrate dispersants be examined further. A cost and time analysis of using dispersants in the Southern Beaufort Sea is performed. Under "best-case" conditions the total cost to disperse 20,000 m³ of oil is calculated to be \$10,000,000 over an 8-day operational period. These costs relate only to dispersant purchase, shipping and application, and do not include manpower or ancillary support, such as shelter, food, waste disposal and recovery of empty drums.

RÉSUMÉ

La présente étude traite de la faisabilité de l'application des dispersants d'hydrocarbures dans le sud de la mer de Beaufort. À l'examen des techniques d'application et des milieux physiques, trois moyens d'application semblent mériter une étude plus poussée: les hélicoptères de transport lourd S-64 de Sikorsky, CL-215 de Canadair et L-100-30 de Lockheed. Après avoir analysé les dispersants pour voir s'ils pouvaient être appliqués à l'environnement arctique, on recommande d'en étudier plus à fond les préparations concentrées. D'après l'analyse des coûts et de la durée d'application, il faudrait 10 millions de dollars, au total, pour disperser 20 000 m³ d'hydrocarbures dans le sud de la mer de Beaufort, dans des conditions "idéales", sur une période de 8 jours de travail. Ces coûts ne comprennent que l'achat, l'expédition et l'application et n'incluent ni la main-d'oeuvre ni les services auxiliaires tels que logement, nourriture, élimination des déchets et récupération des fûts vides.

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1 INTRODUCTION

1.1 Study Background

Dispersants are chemical compounds which create an oil-in-water emulsion when applied to an oil slick. The resulting small droplets of oil and dispersant are spread throughout the water column. Dispersants apparently do not alter the chemical composition of the oil, they merely emulsify it. Once distributed throughout the water column, the droplets of oil are more amenable to biological degradation. Furthermore, the oil is removed from the water surface and hence results in less readily apparent ecological damage.

Dispersants would be a very attractive oil spill countermeasure if it were not for a number of factors, the most significant one being the reported ecological damage resulting from their use. They were first used extensively during the Torrey Canyon incident and later in such major spills as the Santa Barbara blowout. When used extensively, dispersants invariably drew the ire of conservationists. Frequently they were used in the nearshore littoral zones and even on beaches. In such cases severe ecological damage and other consequences could be observed. In the littoral zone dispersants can result in the coating of marine mammals and the ingestion through the gills of fish or into filter-feeding invertebrates such as oysters and clams.

Over the years the chemical formulations for dispersants have changed dramatically. Current generation products are much more efficient in removing oil from the water surface, and while at the same time have a lower toxicity. These new generation dispersants, many of which are called concentrates, have not yet been developed to the point where they would be readily approved for use in Canada. However, the achievements to date indicate that highly efficient, low-toxicity products can be manufactured and may soon be available commercially.

The new dispersant concentrates can be so efficient that they spontaneously emulsify oil without the application of mechanical mixing energy supplied from a surface vessel. Thus, spraying these products from aircraft becomes a technique warranting further consideration, particularly in areas where surface vessels have limited applicability.

Offshore exploration in the Southern Beaufort Sea has been underway for a number of years. Until recently drilling was based on artificial islands constructed in the shallow nearshore areas of the continental shelf. This activity has now been extended to deeper water using drillships. Due to inadequate basic knowledge of the Southern Beaufort Sea area, an extensive environmental program called the Beaufort Sea Project was undertaken. Results of this program, published in Beaufort Sea Technical Reports, are an invaluable source of basic input data to the current study. One of these technical reports addressed oil spill countermeasures and concluded that traditional methods which were effective in temperate climates were, at best, only marginally useful in this area due primarily to ice infestation. Hence, the search for innovative oil cleanup techniques was begun.

Within the past few years the literature on oil spill cleanup has indicated that new generation dispersants could be aerially applied. Given the problems of inaccessability in the Beaufort Sea area, it was natural to undertake a study of the feasibility of using this oil spill countermeasure method.

The current study addresses the practicality of using aircraft to disperse oil resulting from a hypothetical blowout at an actual offshore drill site. It is recognized that ecological problems from such activities may be substantial and could arouse public opposition. Dispersants, if used, would be applied in the leads and open water particularly in the spring period. In view of the importance of these leads to migratory seabirds, geese and shorebirds, as well as bearded seals, mammals, whales and fishes, severe ecological damage is possible. No information is available on the long-term alterations to the food chain. It has been postulated that oil alone resulting from an offshore blowout would not result in permanent ecological damage, but that recovery in some cases could take 10 years (Beaufort Sea Technical Report No. 39). Ecological concerns are beyond the present terms of reference for this study.

The question of the acceptability of dispersants to environmental regulatory agencies is also not addressed in this report. In early May, oil resulting from an October offshore blowout in Canadian waters could be well within the territorial waters of the United States. The program discussed in this report involves applying dispersants within these waters and it is recognized that, at present, the United States Environmental Protection Agency would not approve the use of these products. As stated, however, regulatory issues are not considered in this conceptual study.

1.2 Study Approach

In view of the lack of basic data on physical environmental conditions in the study area, as well as uncertainty concerning the crude oil reserves in the continental shelf of the Beaufort Sea, many of the input parameters in this study are best-guess assumptions. To the extent possible such estimates are taken directly from those used in the Beaufort Sea Technical Reports.

The study is based on an assumed blowout at an offshore drill site on October 5, 1976 running unrelieved at a standard Beaufort Sea blowout rate for 12 months. The standard blowout rate assumed is 2,500 barrels per day (b/d) (398 m³/d) for the first month, decaying to 1,500 b/d (239 m³/d) until relieved. Previously made assumptions concerning the interaction of the subsequent oil with ice and the resulting oil fate and behaviour are extended to give an oil cleanup scenario, one component of which is an aerially applied dispersant program.

Numerous potential dispersants are considered and evaluated for use in the program. While it was originally intended to recommend one dispersant for this application program, it was eventually decided to recommend a small number of products with final selection being based on further laboratory and field tests. It is felt that this is required in view of the data gaps concerning their requisite properties. An extensive test program on the set of potential dispersants is given in a later section of the report.

A large number of both fixed and rotary winged aircraft is considered for spraying platforms. These crafts are initially screened on the basis of availability, flexibility, proven local Arctic experience, payload and several other parameters to arrive at a reduced set of aircraft for detailed analysis.

Based upon the above data, mathematical formulations are developed to evaluate dispersant application platforms. These formulations are valid for most craft, including surface-based vessels, and enable the selection of craft on a common, non-subjective basis.

After the optimum dispersant application platform, including a spraying system, is selected, a logistical program is developed for the Arctic conditions to be encountered. Time and cost estimates for the entire oil dispersal program are developed for the basic scenarios.

2 PHYSICAL ENVIRONMENT

The success of a dispersant program utilizing aerial operations in the Southern Beaufort Sea depends upon the amenability of the developed program to the area's environmental conditions. Considerable data have been developed on the physical environmental conditions in this area (Beaufort Sea Technical Reports, Burns 1973). The following sections draw heavily on these reports and are presented in order for the present study to stand as an independent document. Only those environmental conditions affecting the success of an aerial application program are presented. Particular emphasis is given to the physical environmental conditions during the month of May, since this is a critical time for the aerial application program presented.

2.1 Meteorological Conditions

Meteorological conditions, particularly air temperature, visibility and wind speed, are critical elements which affect any proposed aerial operation in northern environments.

2.1.1 Air Temperature. Information on air temperatures offshore is scarce and does not include continuous readings over an extended time period. In winter, temperatures onshore and offshore are similar due to the virtually complete ice cover. In the summer months temperatures offshore are usually lower than onshore due to open-water conditions. Long-term temperature records at Komakuk Beach and Tuktoyaktuk (Figure 2) show a maximum daily mean temperature of about 7°C which is reached during July. Winter temperatures fall to extremes of -57°C with a daily mean temperature during the coldest winter months of about -32°C. During May the daily mean temperature ranges from -7°C in the beginning of the month to over 4°C towards early June. Sea ice deterioration, which begins when air temperatures rise above -2°C, can be expected soon after mid-May.

2.1.2 Precipitation. The Southern Beaufort Sea area can be referred to as a "polar desert". Annual mean precipitation along the coastal areas is only about 12.7 cm of water and is subject to wide variations from year to year. The majority of the annual precipitation occurs in the months of July and August and the mean monthly total precipitation for each of these months is between 2.5 and 3.8 cm. The coastal areas receive very little precipitation prior to June and after October. Virtually all precipitation

prior to May is snow, and the mean aggregate rainfall during all of May is only 0.1 cm. The monthly maximum precipitation in a 24-hour period over the Beaufort Sea during May is less than 1.3 cm.

The mean annual snowfall along the coastal areas is about 63.5 cm. Maximum snowfall occurs during the late fall and early winter months. During May the total monthly snowfall is only about 5.1 cm.

During the spring months freezing precipitation is common along the coastal areas and occurs most often in the early morning hours. Although no information is available for coastal stations west of Tuktoyaktuk, the Cape Parry station records indicate that during May there may be upwards of 3% of the time with freezing precipitation.

2.1.3 Wind. Aerial operations involving the spraying of dispersants would be greatly affected by wind speed and direction during the program. Also, the wind chill factor index of energy loss affects the performance of men and equipment, as well as the viscosity of dispersants used.

Mean hourly wind speeds are higher along the Beaufort Sea coast than in areas further south. Although no such records are apparently available for coastal stations west of Tuktoyaktuk, Cape Parry records indicate mean hourly wind speeds of about 19 kph consistently throughout the year, including May. Extreme high winds during May can reach hourly speeds of 64 kph. These speeds, combined with temperatures during May, result in a comfort class of II for about two-thirds of the time, hence work and travel only require reasonable protection.

Wind direction over the Southern Beaufort Sea varies considerably throughout the season. During the winter the prevailing wind directions are from the west and east with frequent incursions from the north. Wind directions during May, based upon Inuvik records for the period 1961-1966, are predominantly from the east and north-east (Ministry of Transport, undated). Given these prevailing directions, runway alignments for any dispersant program should be oriented in a parallel direction to eliminate crosswind take off and landing problems.

2.1.4 Visibility. Visibility in the Arctic varies greatly, and frequently is severely limited due to the prevalence of fog in summer months and blowing snow in winter months. Summer fog is common in the coastal areas of the Beaufort Sea. With the advent of fall and growth of sea ice, fog becomes more prevalent at the edges of the ice.

Between October and April blowing snow constitutes a hazard to air operations. Where snow surfaces are not hard packed, winds frequently blow snow into drifts that may obliterate poorly defined runways. Blowing snow usually is confined to heights of less than 15 m above the ground and frequently is a local anomaly lasting a short time. Whiteout conditions are frequent in the autumn-to-early-spring period.

Based upon records at Inuvik and Tuktoyaktuk, the visibility should be less than 4.8 km for less than 15% of the time during May and less than 9.7 km for about 80% of the time during May in coastal areas.

Between May and early August the region experiences daylight or twilight throughout the entire day. From mid-November until the end of January virtual darkness prevails.

2.1.5 Flying Conditions. For safety reasons and because of visibility requirements for dispersant application, aircraft operations would probably need to be confined to those periods when Visual Flight Rules (VFR) are in effect. The weather minima for VFR are based primarily on visibility and ceiling criteria dependent upon whether the airspace is controlled or not. For areas outside of controlled airspaces and aerodrome traffic zones, flight visibility must be 1.6 km and vertical distance to cloud must be at least 153 m. Low flying rotary wing craft are special cases and are allowed to operate below 214 m from ground or water when flight visibility is less than 1.6 km.

Along coastal areas a weather ceiling of at least 305 m combined with a visibility greater than 4.8 km during the spring, occurs primarily with easterly winds and should prevail for about 70% of the time. Figure 1 shows the probability of flying VFR missions from three airports in the region. As seen, the probability of success is considerably lower in coastal areas. These estimates do not include flying time reductions due to icing. Such reductions would be particularly significant for helicopters which cannot safely operate in conditions of freezing precipitation.

2.2 Oceanographic Conditions

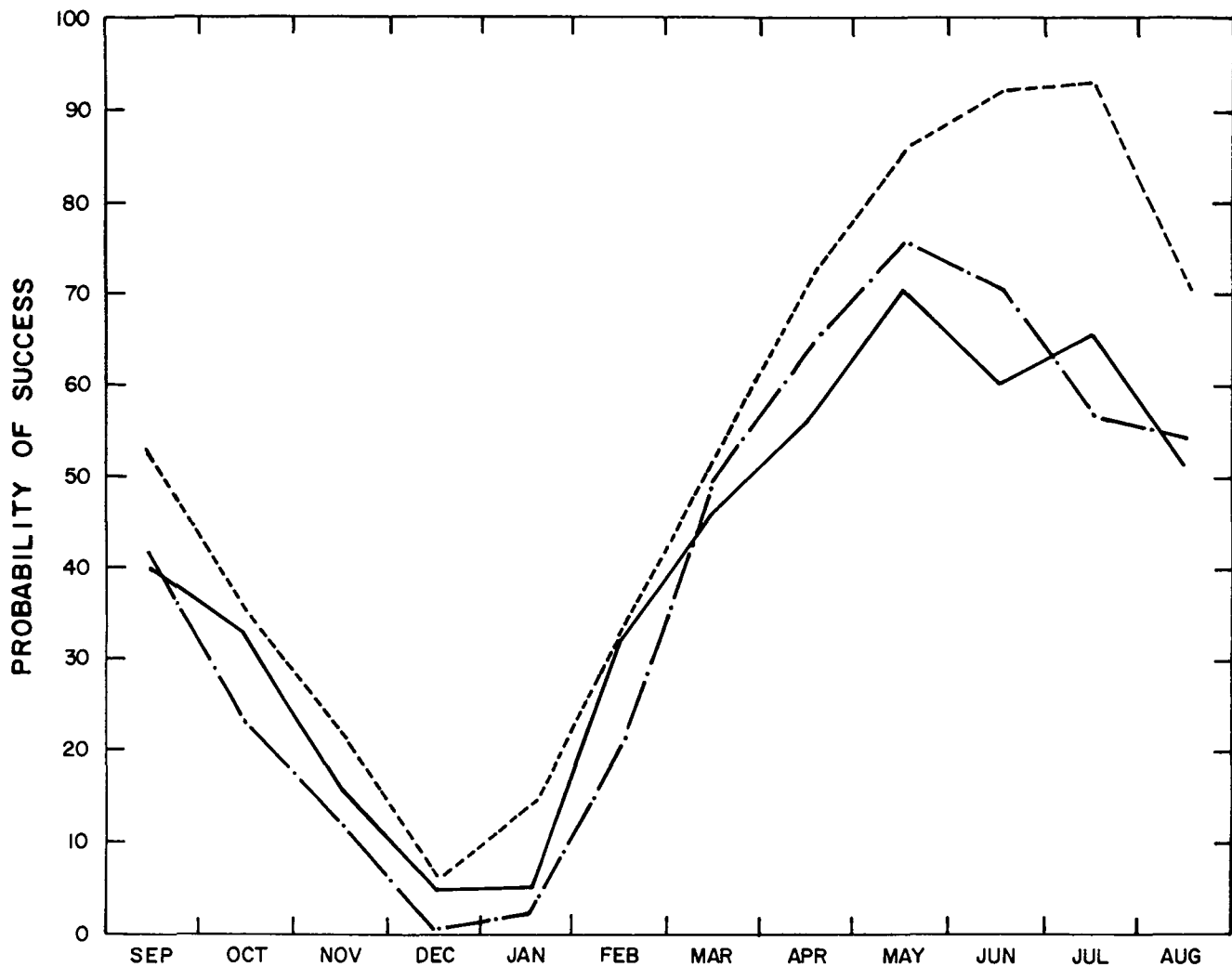
Oceanographic conditions affect the success of a dispersant program primarily in that they alter the fate and behaviour of the oil spill and the dispersant effectiveness. While the knowledge level of physical and chemical changes of oil under Arctic conditions is limited, certain oceanographic characteristics are known to be significant.

2.2.1 Water Temperature. During winter months, surface temperatures in the open leads or polynyi are about -2°C. During summer months these temperatures reach a maximum of about 5°C in nearshore areas, decreasing to 1°C for offshore areas. Surface temperatures generally reach a maximum in August and decrease rapidly with the coming of fall. Water temperatures below a depth of 20 metres tend to remain fairly constant throughout the year at about -1°C.

2.2.2 Salinity. The salinity content in parts per thousand of near-surface waters in the Beaufort Sea is as low as 15. However, in deeper areas and presumably offshore surface areas, not subject to surface water runoff, salinity increases to the more normal seawater levels of 30 to 35 parts per thousand.

2.2.3 Surface Currents. During periods of high ice infestation, oil movement and spreading is strongly influenced by the percentage of ice cover and its direction of movement. Under open-water conditions oil slick movement is often strongly influenced by wind. However, since ice is more strongly influenced by oceanographic currents rather than by wind, the fate of oil spilled in periods of ice infestation is difficult to predict. Once encapsulated in ice or trapped in leads and interstices between floes, oil movement is primarily determined by ice dynamics.

Beyond the continental shelf, oceanographic currents are strongly influenced by the clockwise Beaufort Gyre and move in a westerly direction. Current speeds, although highly variable, are



LEGEND:

----- INUVIK
———— CAPE PARRY
- · - · - SACHS HARBOUR

NOTE:

THIS FIGURE BASED ON VFR CONDITIONS
NO ALLOWANCE IS MADE FOR POSSIBILITY
OF ICING.

SOURCE: BEAUFORT SEA PROJECT TECHNICAL REPORT 31

Fig. 1 — Comparative Probability of Flying VFR Missions

generally in the range of 1-5 cm/sec. On the continental shelf in areas not influenced directly by one gyre, surface currents are highly variable and depend upon wind, freshwater input from the Mackenzie River and other factors. Based on the mean annual surface wind, an easterly setting coastal surface current along the Alaskan coast has been postulated, but insufficient data are available to confirm this hypothesis. Surface water velocities over 60 cm/sec in both easterly and westerly directions have been observed.

2.3 Ice Zones

2.3.1 Landfast Ice. The landfast ice zone is normally a smooth ice sheet stretching from the shore to an outer edge corresponding to the 18-20 m bathymetric contour. The landfast ice zone begins to form along the entire coastline in early October and generally reaches a maximum thickness of about 200 cm by early May. The outer edge of the landfast ice zone frequently includes rubble fields and heavy ridging frozen in place after early winter storms. This ice zone may include isolated remnants of second and multi-year ice.

The landfast ice zone begins to deteriorate after mid-May as temperatures rise. Generally the ice begins to clear north of Cape Bathurst after mid-May and in the southern part of Mackenzie Bay by mid-June. The landfast ice has normally been completely removed by early June.

2.3.2 Transition Ice Zone. The transition or seasonal pack ice zone is found from the northern edge of the landfast ice zone to roughly the edge of the continental shelf. It is a zone of rapidly deforming, heavily ridged and highly irregular ice acting as a boundary layer between the stationary landfast ice and the circulating ice of the Beaufort Gyre. The ice movement in this zone is predominantly westerly.

The transition ice zone varies considerably in width, but can be upwards of several hundred kilometres. During summer months the seasonal pack is generally driven against the polar pack by offshore winds, while in winter it is forced against the landfast ice.

The transition ice zone is the most dynamic one in the Southern Beaufort Sea. The zone is composed predominantly of first-year ice, but includes some multi-year flows and ice island fragments in various stages of consolidation. The mean net long-term winter ice velocity is about 2.5 to 3.0 cm/sec., but is usually considerably higher in the spring.

2.3.3 Polar Pack Zone. The polar pack ice zone extends beyond the continental shelf onwards into the Arctic Basin, but can be driven towards shore at any time by high winds. In winter the zone is composed of multi-year ice flows with first-year ice growing and being compressed between these floes. The ice thickness in this zone varies from thin, refrozen leads to multi-year pressure ridges greater than 45 m in total thickness. The intensity of ridging varies depending on the season, area and year. Although ridging will generally be less severe in the Southern Beaufort Sea than in the Arctic Basin, conditions vary considerably from year to year. Typical spatial density of ice ridges is reported to be in the range of 10 to 20 ridges/km, their average heights about 3 m, and the height ratio of keel to sail about 3 to 1. If caught in the zone of seasonal ice flow during late summer and early fall, keels may become grounded.

3 OIL SPILL SCENARIOS

The development of an oil spill countermeasure program of any type requires that knowledge on the oil properties, as well as the temporal and spatial spill characteristics, be considered. Application of dispersants from aircraft would be one countermeasure to be used along with numerous others and would have to be co-ordinated with all oil spill response methods. The following sections extend information contained in the Beaufort Sea Project Technical reports to outline the oil spill and cleanup scenarios and their relation to the dispersant application program.

3.1 Hypothetical Blowout

Due to severe ice infestation in the seasonal pack ice zone for the majority of the year, drilling is allowed for only a relatively short time each season. Drillships are generally prevented from operating in the area outside of two months or so between early August and October.

Studies undertaken in the Beaufort Sea Project are based on a postulated blowout on October 5, 1976. Due to the curtailed drilling season, it is unlikely that a blowout could be relieved until at least the following summer. Unless it is naturally bridged and sealed by debris, the blowout could run unrelieved for a year or possibly longer. For the purposes of this study it is assumed that the well continues unrelieved for 12 months.

The standard Beaufort Sea blowout has been agreed upon based upon the expected offshore geological formation. It consists of an initial flow rate of 2,500 barrels of oil per day (b/d) (398 m³/d) for the first month, decaying to 1,500 b/d (239 m³/d) until relieved. Included with the oil is gas equivalent to 22.7 m³/barrel at atmospheric pressure.

The oil released from a hypothetical blowout is postulated to be a light oil with a specific gravity between 0.821 and 0.833 (API = 38.4-40.9) and a pour point of -40°C.

3.2 Oil/Ice Interactions

Oil released into an open-water environment (whether instantaneously or continuously) immediately spreads under the influence of gravity to form a layer, the area of which depends on the volume released and, to a lesser extent, on the properties of the oil. During this initial period low-boiling fractions of oil begin to evaporate and dissolve, thereby causing the properties of the atmospheric residual oil slick to change with time. The slick grows in area and is moved along the sea surface by a combination of meteorologic and oceanographic driving forces.

The visual disappearance of a coherent oil film may take several forms. This is especially true in the Arctic where the degradation and dispersion of oil are complicated by a number of oil/ice interactions.

Under open-water conditions evaporation of lighter hydrocarbon molecules depends primarily on vapor pressure and surface area and may be enhanced by higher sea states. After the lighter ends have been given off to the atmosphere, a residue of higher specific gravity and viscosity remains.

Occasionally these heavier hydrocarbons have specific gravities greater than seawater and sink. The oil slick may emulsify into a water-in-oil emulsion popularly called "chocolate mousse". In this form, the oil is in a continuous stable liquid phase containing 30 to 80% water.

Eventually the slick loses its coherence, begins to break up and undergoes a process whereby it is physically assimilated by the marine environment. At this point in time the properties and physical state of the oil have been influenced by a wide variety of factors resulting in possible emulsification, sediment uptake, tar ball formation, and chemical and biological oxidation.

A blowout within the inner portion of the landfast ice would likely spread outward from the blowout site forming a semi-coherent slick across the bottom surface of the ice. Rarely would there be pressure ridges within this inner belt to constrain spreading of oil; nor are there likely to be leads or open cracks into which oil could collect. The only vent would be immediately above the blowout site should the initial gas and oil plume be forceful enough or the ice thin enough at the time of blowout to yield a fracture.

The outer-fast ice belt is topographically characterized by fields of ridges and hummocks, although the ice itself remains almost stationary. During the fall freeze-up, areas of rafted rubble or hummocky ice are generated in the outer belt by pressure from the seasonal and polar pack pushing southward on the young, first-year fast ice. In these areas the relatively rough bottom surface of the ice sheet would tend to consolidate and contain oil in pools and pockets.

An oil plume in the shallow coastal waters of the Beaufort Sea (< 60 m) will rise from its source on the seabed to the ice-water or air-water interface in a conical plume with a half-angle of approximately 25° to 30° (Beaufort Sea Technical Report No. 33). An oil and gas mixture, however, will rise as a conical plume initially and then become nearly cylindrical. The distance at which the conversion occurs depends upon such variables as the ratio of oil to gas, blowout pressure, oil density, and any current or wave action which may be present. As far as known to date, experiments at depths greater than 60 m have not been attempted, thus whether there is any additional change in shape of the plume is unknown.

After being discharged oil quickly breaks into small, nearly spherical particles which, depending upon gas flow, may rise at rates that vary from approximately 0.3 to 1 m/sec. At the ice-water interface most crude oil will first coalesce to form sessile drops. In the process of spreading out many of these drops will in turn coalesce and develop into rivulets, which for most crude oils will spread at a radial velocity approaching 0.5 to 0.7 m/sec. Under an ice sheet that is flat the rivulets will travel outward unimpeded. If the underside undulates, the oil will tend to pool in concavities.

The topography of the bottom of an ice sheet is the most important factor in the natural containment of oil. However, ice movement that is generated by wind, current, tide and lateral forces resulting from the pressures of surrounding ice will also have a marked effect on the spreading and movement of oil.

The underside of an ice sheet approximately reflects its surface topography. Projections beneath the ice usually indicate hummocks or ridges on the surface. Concavities along the under surface

of the ice generally indicate a snow-free surface above; convexities, on the other hand, may signify that a snow drift or dune is an insulating cover above.

In all cases the spatial distribution and ultimate entrainment of oil into an ice cover strongly depends upon the nature and extent of any gas layers between the oil and the ice. Large volumes of gas typically associated with a blowout could provide an expanding oil/gas interface below the ice which would allow the oil to spread rapidly. Such spreading would be relatively unhampered by the usual pooling effects of an even modest surface roughness beneath the ice.

It is likely, however, that any trapped gas would soon find a crack or ice flaw through which it could escape to the surface. Some oil would probably escape to the surface as well, resulting in a relatively small spread due to surface roughness and absorption in snow. The oil below would then come into contact with the ice and become entrained within a matter of days, particularly during conditions of rapid ice formation.

Several excellent discussions have been presented on the interactions of oil and ice (Beaufort Sea Technical Reports No's. 31 and 37). Suffice it to say here that the important mechanism for long-range response planning is the process of the oil entrainment in ice. This capture of oil, combined with the predicted movements of ice, is fundamental to the basic concerns of where and when oil will first be exposed during the following spring.

Oil trapped beneath the sea ice or encapsulated in it experiences little weathering. It is only when the crude is exposed to air that the lighter hydrocarbon fractions can evaporate and the weathering process occur. It is the behaviour of oil under open-water conditions that is most critical for the planned aerial application program since only then can it be readily dispersed.

Evaporation rates of up to 40% by volume in two weeks have been reported for Norman Wells and Swan Hills crudes at freezing temperatures. Oil from the hypothetical Beaufort Sea blowout is assumed to lose 40% of its volume in 13 hours.

3.3 Spatial and Temporal Factors

The fate and behaviour of oil released from the hypothesized blowout is complex and not well understood. Depending upon ice cover, drift rate, oceanographic currents and other factors, discharged oil could move along many pathways. However, only oil exposed to open-water conditions either in summer or in ice leads during late spring is amenable to aerial-based chemical dispersion. The beginning of landfast ice breakup in this area is in early to mid May.

It is estimated that by May 5, 1977 the 53,500 m³ of oil released from the October 5, 1976 blowout would be located as shown in Figure 2 (Beaufort Sea Project Technical Report No. 39). As shown, the oil would be distributed as:

3,500 m ³ on the Tuktoyaktuk coast
5,000 m ³ south of Banks Island
22,000 m ³ in the landfast ice zone north of the Tuktoyaktuk Peninsula
23,000 m ³ in a 400-km long swath along the northern edge of the landfast ice off the north coast of Alaska
<hr/>
53,500 m ³ Total

This estimate makes no allowance for the volume reduction resulting from weathering of the crude oil or from movement of oil under the polar ice pack.

The above volume estimates represent the oil location at only one date during the assumed 12-month period until relieved. Figure 3 is presented to show the approximate distribution of oil from this blowout over the entire year period, in particular that exposed in open water. As shown, the volume of crude oil released increases according to the upper curve in this figure.

The volume of oil that is unreachable for dispersant application due either to being under ice or on shore areas has been shown. During winter months virtually all oil is unreachable. However, as the ice breaks up much more, but not all, is available for dispersion.

In view of the rapid weathering rate for this oil when exposed to the air, it can be assumed that only 60% of the total oil potentially available for dispersion may actually be available. This reduction due to natural causes has been estimated in Figure 3.

Based upon the figure, the oil actually available for dispersion at any time during the year after a blowout is shown as the lower-bound curve. This value increases from about 90,000 barrels (14,300 m³) in early May to about 200,000 barrels (31,800 m³) in early October. These volume estimates include an allowance for weathering.

3.4 Oil Spill Cleanup Alternatives

In order to determine the best dispersant application methods and develop the logistical program, it is necessary to estimate the oil volumes and their locations over time. Based upon these estimates and assumed volumes to be cleaned up by alternative countermeasures, estimated volumes amenable to dispersant applications can be determined. One of the basic assumptions implicit in the following analysis is that dispersant application from a aircraft would be attempted only after all other less exotic techniques have been considered or employed. Hence, the oil volume dispersed is only that which has not been handled by other countermeasures. This is likely a realistic assumption in view of the high costs involved in using dispersants, as well as the possible ecological problems associated with their use.

As discussed in Section 3.3, on May 5, 1977, oil from the hypothetical blowout is assumed to be distributed over a larger area, but can be classified into four principal locations. Between the assumed October 5, 1976, blowout and May 5, 1977, oil would have been transported by various

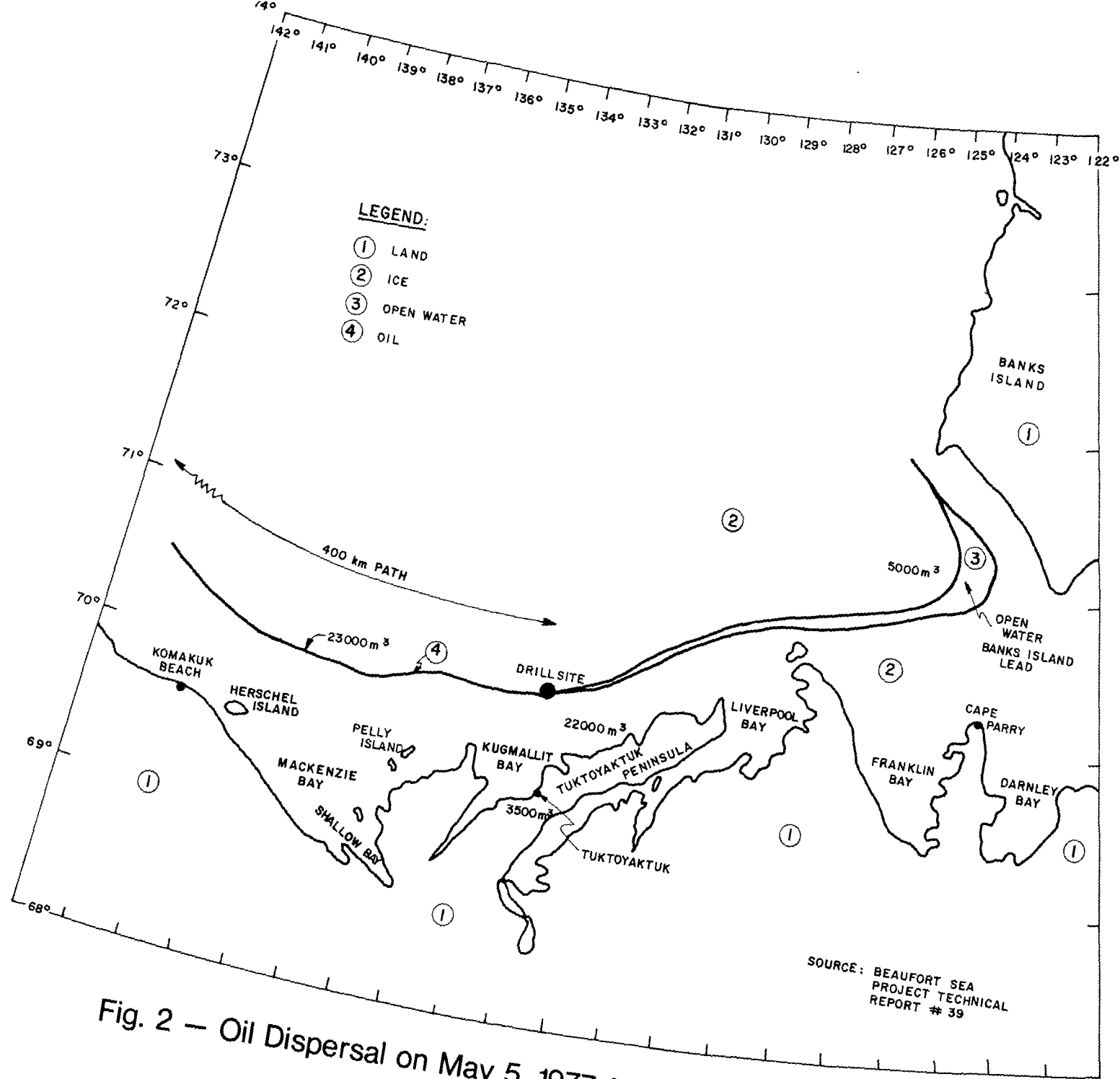


Fig. 2 — Oil Dispersal on May 5, 1977 from an October 5, 1976

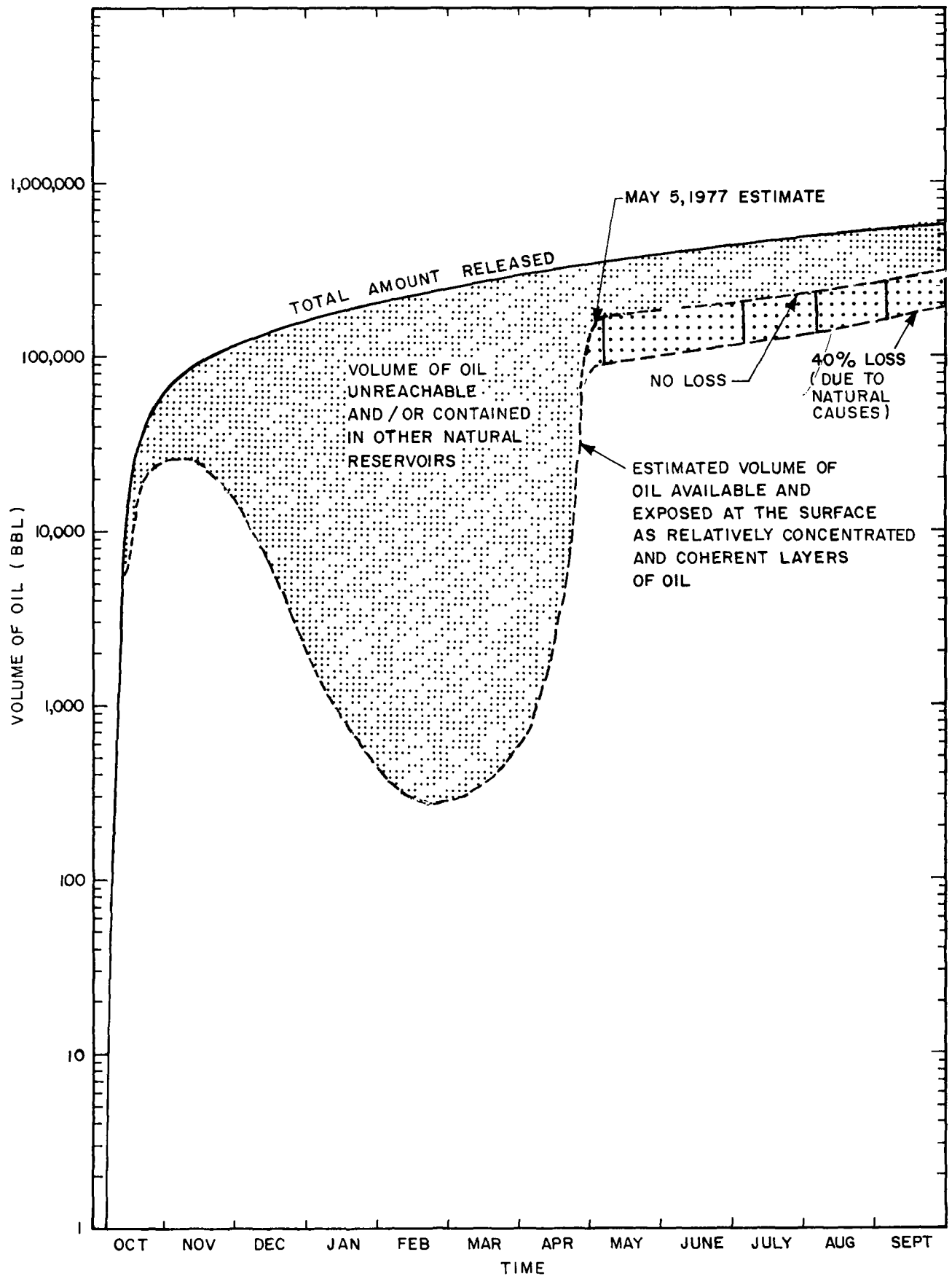


Fig. 3 — Estimated Amount of Oil Available for Dispersant Application

pathways from the drill site to these locations. Hence, to present a useful picture of the oil volumes and their locations over the entire 12-month period could involve many more than the four locations affected in early May.

Since the base of operations for most standard oil spill countermeasures will likely to Tuktoyaktuk, it is convenient to present oil volumes classified according to distances relative to this support base. Table 1 presents monthly volume estimates on the basis of three geographical locations. These estimates are based on projections for optimum cleanup using physical removal techniques. Lower estimates have been made by other sources. Variations between estimates result primarily from the uncertainties of future cleanup technologies. It is recognized that this table is only a rough estimate not based on detailed analysis. However, it is useful in giving a first-order approximation on the amount and location of oil, the method of cleanup and its rate.

October 5 to November 1, 1976: Total oil volume released during this period is 10,500 m³; all of this oil is within 100 km of Tuktoyaktuk. Surface vessels are capable of operating for part of this month and skimmers could therefore be deployed. In addition, when using oil cleanup techniques such as burning, oil booms would be employed. It is assumed that 5,000 m³ of oil are cleaned up during this period.

November 1 to December 1, 1976: Due to unstable ice conditions, no sea-ice-based operations are assumed during this period. Furthermore, it is assumed that additional logistical and equipment requirements are being organized during this period and little, if any, oil cleanup actually occurs. As a result it is assumed that no oil is removed during this period. This is, no doubt, a conservative assumption.

December 1, 1976 to January 1, 1977: During this period the 1,000 m³ of oil is assumed to arrive in the area south of Banks Island, and the first 4,000 m³ moves west of the drill site outside of the 100 km radius from Tuktoyaktuk. It is assumed that 11,000 m³ of oil are cleaned up in this period, all of it under the landfast ice adjacent to Tuktoyaktuk. Removal of 11,000 m³ during December represents 73% of the available oil and exceeds the capabilities of available technology.

January 1 to February 1, 1977: During this period an additional 1,000 m³ and 5,000 m³ of oil arrived in the Banks Island and west of the drill site beyond 100 km³ respectively. The only oil cleaned up during this period is in the landfast ice zone adjacent to Tuktoyaktuk. However, oil could likely be removed from the area south of Banks Island.

February 1 to March 1, 1977: This period is similar to the previous ones with only slightly modified volume estimates.

March 1 to April 1, 1977: This period is similar to the previous ones with only slightly modified volume estimates.

April 1 to May 1, 1977: This period is similar to the previous ones with only slightly modified volume estimates.

May 1 to June 1, 1977: This is the critical period for aerial dispersant application. It is assumed that in early May the westward lead along the northern landfast ice area opens up exposing 23,000 m³ of

TABLE 1 ASSUMED OIL TRANSPORT AND REMOVAL SCENARIO

Location	Oct 1 to Nov 1	Nov 1 to Dec 1	Dec 1 to Jan 1	Jan 1 to Feb 1	Feb 1 to Mar 1	Mar 1 to Apr 1	Apr 1 to May 1	May 1 to June 1	June 1 to July 1	July 1 to Aug 1	Aug 1 to Sept 1	Sept 1 to Oct 1
TOTAL												
Cumulative total to end of period (m ³)	10,500	17,500	25,000	32,500	39,000	46,500	53,500	61,000	68,000	75,500	83,000	90,000
Previously cleaned up (m ³)	0	5,000	5,000	16,000	17,500	19,000	21,500	22,500	55,500	64,500	71,500	84,000
Total available to clean up (m ³)	10,500	12,500	20,000	16,500	21,500	27,500	32,000	38,500	12,500	11,000	11,500	6,000
Actual amount cleaned up (m ³)	5,000	0	11,000	1,500	1,500	2,500	1,000	33,000	9,000	7,000	11,500	6,000
Residual (m ³)	5,500	12,500	9,000	15,000	20,000	25,000	31,000	5,500	3,500	4,000	0	0
BANKS ISLAND AREA												
Cumulative total to end of period (m ³)	0	0	1,000	2,000	3,000	4,000	5,000	6,000	6,000	6,000	6,000	6,000
Previously cleaned up (m ³)	0	0	0	0	0	0	0	0	4,000	6,000	6,000	6,000
Total available to clean up (m ³)	0	0	1,000	2,000	3,000	4,000	5,000	6,000	2,000	0	0	0
Actual amount cleaned up (m ³)	0	0	0	0	0	0	0	4,000	2,000	0	0	0
Residual (m ³)	0	0	1,000	2,000	3,000	4,000	5,000	2,000	0	0	0	0
WITHIN 100 km RADIUS OF TUKTOYAKTUK												
Cumulative total to end of period (m ³)	10,500	17,500	20,000	21,500	23,000	25,500	25,500	32,000	39,000	46,500	54,000	61,000
Previously cleaned up (m ³)	0	5,000	5,000	16,000	17,500	19,000	21,500	22,500	28,500	35,500	42,500	55,000
Total available to clean up (m ³)	10,500	12,500	15,000	5,500	5,500	6,500	4,000	9,500	10,500	11,000	11,500	6,000
Actual amount to clean up (m ³)	5,000	0	11,000	1,500	1,500	2,500	1,000	6,000	8,000	7,000	11,500	6,000
Residual (m ³)	5,500	12,500	4,000	4,000	4,000	4,000	3,000	3,500	2,500	4,000	0	0
WEST OF DRILLSITE BEYOND 100 km OF TUKTOYAKTUK												
Cumulative total to end of period (m ³)	0	0	4,000	9,000	13,000	17,000	23,000	23,000	23,000	23,000	23,000	23,000
Previously cleaned up (m ³)	0	0	0	0	0	0	0	0	23,000	23,000	23,000	23,000
Total available to clean up (m ³)	0	0	4,000	9,000	13,000	17,000	23,000	23,000	0	0	0	0
Actual amount to clean up (m ³)	0	0	0	0	0	0	0	23,000	0	0	0	0
Residual (m ³)	0	0	4,000	9,000	13,000	17,000	23,000	0	0	0	0	0

NOTE: 1 m³ = 6.28 barrels

oil for aerial dispersal, all of which is assumed to be dispersed by this countermeasure. It is further assumed that prior to May 1, 1977, 22,500 m³ of oil have been cleaned up (37% of total to date) all of this being from the landfast ice adjacent to Tuktoyaktuk. This is an optimistic estimate. Due to the initial exposure of oil in leads during this period, a total of 33,000 m³ is assumed to be cleaned up. This results in a total cleanup or dispersal to June 1 of about 80%. During this period it is assumed that 4,000 m³ is removed by aerial dispersant applications from the Banks Island area in the open leads.

June 1 to July 1, 1977: No further cleanup is required in the area 100 km west of Tuktoyaktuk since all oil is presumed to be removed closer to the blowout. During this period it is assumed that the remaining 2,000 m³ in the Banks Island area is removed by aerial dispersant application. This completes the cleanup activities in this area.

August 1 to September 1, 1977: During this period all activities occur in relatively open water within 100 km of Tuktoyaktuk. Dispersants could be applied aerially, but such efforts would likely be insignificant due to the viability of other less expensive means.

September to October 1, 1977: This period is similar to the previous one with modified volume estimates.

Based upon the above scenario, which is only one of many likely ones that would be developed, the critical time for aerial application techniques is in May. Only a relatively small oil volume is dispersed outside of this period using this method. In summary, the following are the oil volumes dispersed by such means:

Period	Volume of Oil (m ³)	Location
May 1 – June 1	23,000	Beyond 100 km west of Tuktoyaktuk
May 1 – June 1	4,000	South of Banks Island
June 1 – July 1	2,000	South of Banks Island
	<hr/> 29,000	

Hence, it is assumed that about 29,000 m³ of oil are dispersed. This volume represents 32% of the entire 90,000 m³ released during the hypothetical 1-year, unrelieved blowout.

4 DISPERSANT CONSIDERATIONS

4.1 Physical-Chemical Properties

Water emulsifying degreasers have been commonly used for about 50 years. They were developed to clean oily and greasy materials and were frequently used aboard ships to clean out cargo

tanks. As formulated, these emulsifying agents were primarily a mixture of soap and solvent and were originally referred to as soaps or detergents. The term dispersant has evolved only recently.

Application of a chemical dispersant to an oil slick reduces the interfacial tension between the oil and water. This reduction results in the formation of globules which disperse throughout the water column when sufficient mixing energy is supplied. The globules are then likely to degrade biologically within the water column. At present, knowledge of the kinetics of oil dispersion, particle sizes and the resulting ultimate fate and ecological significance of oil dispersion is incomplete. In spite of these and other major knowledge gaps, dispersants are a powerful oil spill countermeasure tool.

The two principal components of any oil spill dispersant are surfactants (surface active agent) and solvents. However, numerous other additives such as stabilizers, agents to prevent recoalescing of the particles, etc., are added by each manufacturer.

Surfactants are active ingredients with an affinity to both water and oil. There are two broad classes of surfactant, ionic and non-ionic. Ionic surfactants can be anionic or cationic. Ionic surfactants are colloidal electrolytes and form ions when in solution. The newer surfactants, such as polyoxyethylene alkylphenols, alcohols, esters, mercaptans or alkylamines, are non-ionic and owe their solubility to the combined effect of weak solubilizing groups in the molecule. (Sittig, 1974; Canevari, September 1976).

Solvents, which generally constitute the bulk of any dispersant, are used in the formulation to alter the physical properties of the mixture and enable more efficient utilization of the surfactant. There are numerous types of solvents commonly used. Early generation dispersants such as those used in the Torrey Canyon cleanup were hydrocarbon-based solvents with upwards of three-quarters of the formulation being highly toxic aromatic hydrocarbons. Recently developed dispersant formulations have utilized a wide variety of solvents and where hydrocarbon solvents are used, have relied upon less toxic, higher boiling fractions. Solvents currently used vary from petroleum hydrocarbons through alcoholic compounds to water or water-solvent compounds.

Some recently developed dispersants, referred to as "concentrates", contain relatively high concentrations of surfactant compared to solvent. During a dispersal operation, at sea for example, seawater can be mixed with the "concentrate" dispersant prior to application on the oil slick. In this way, for a given vessel with a certain payload, overall dispersal time can be significantly extended. More importantly, as related to aerial application methods, these concentrates are very effective when applied undiluted.

4.2 Recommended Dispersants

In an attempt to obtain information on a broad cross section of available dispersants, letters were sent to all 102 manufacturers of oil spill treating agents listed in a recent survey (American Petroleum Institute, 1972) and several major, well-known manufacturers. In addition, letters were written to all manufacturers of dispersants approved by the Warren Spring Laboratory. Those manufacturers whose products warranted further investigation were recontacted to solicit further

information. Information was also solicited from numerous individuals involved in the chemical treatment of oil spills.

From these contacts it became readily apparent that in spite of severe data gaps concentrate dispersants would likely be the best for aerial application. Whether or not all such concentrates are truly "self mixing", and hence "spontaneously" emulsify oil, is not considered important. What is considered important is that for all concentrates to be effective, quite low mixing energy levels appear to be required and these are generally available under normal meteorologic and sea state conditions found in the study area.

The laboratory test programs used to evaluate the toxicity and effectiveness of dispersants have changed relatively little over the years. While modifications have been made to the original U.S. Navy Simulated Environmental Tank (SET) test MIL-S-22864 (S.S. Navy, 1961, 1966), these represent relatively minor variations. The SET test modified by the Environmental Protection Service is currently used to assess the effectiveness of dispersants in Canada, although alternate test methods are acknowledged (EPS, 1973).

Based upon the EPS modified SET test, a dispersant is considered ineffective for a particular oil or product if it cannot disperse 65% of the oil or if the dispersant/oil ratio is greater than unity. In addition, dispersants must have a minimum dispersion stability.

The toxicity acceptance of a dispersant is based on lethal toxicity of the dispersant and a dispersant/oil mixture in fresh water. Toxicities are based on rainbow trout (*Salmo gairdneri* Richardson) although other species may be substituted.

To be acceptable a dispersant must have:

1. 96-hour LC50 \geq 1,000 mg/litre using dispersant only; and
2. 96-hour LC50 \geq 100 mg/litre using a 1:1 mixture of dispersant and No. 2 fuel oil.

Sufficient information is not available for a proper ranking of concentrate dispersants. At best, it is recommended that the dispersant used for testing and planned for actual oil spill treatment be a concentrate. The "concentrate" dispersants are made by known, reputable, large manufacturers and are commercially available.

These products are:

Exxon:	Corexit, 9517, Corexit 9527, Corexit 19-L-50 (not commercially available);
Petrofina:	Finasol OSR5;
B. P. Oil Ltd:	BP1100WD (identical to Imperial Chemical Industries Ltd's Synperonic OSD 20).

The key physical and chemical properties of these dispersants are listed in Table 2, while a graphical presentation of the Environmental Protection Service (EPS) test results is shown in Figure 4.

Effectiveness Ratio as shown in Figure 4 is defined as the minimum dispersant/oil ratio required to disperse 65% of the oil under test conditions (EPS, 1973).

TABLE 2 SELECTED PHYSICAL AND CHEMICAL PROPERTIES OF DISPERSANTS

Dispersant	Specific Gravity @ 15.5°C	Pour Point ASTM (°C)	Viscosity	Flash Point (Pensky Martens Closed Cup)
Corexit 9517	0.998	-37	CS @ 38°C = 28 @ 0°C = 175 @ -18°C = 635	57°C
Corexit 9527	0.998	-37	CS @ 38°C = 25 @ 0°C = 175 @ -18°C = 635	93°C
19-L-50	0.903	<-37	CS @ 38°C = 39 @ 0°C = 613 @ -18°C = 5234	43°C
OSR5	1.024	<-27	CS @ 0°C = 238 @ 21°C = 66	
BP 1100WD	0.875	-58	CS @ 0°C = 50 @ 21°C = 20	88°C

4.2.1 Corexit 9517: This is a new generation concentrate dispersant specially formulated for use in seawater and is manufactured by Exxon in Houston, Texas. The product can be used in undiluted form, pre-mixed with water (either fresh or salt) or diluted during spraying by means of an eductor system. The manufacturer recommends that Corexit 9517 be mixed with a hydrocarbon-based solvent such as kerosene or other aliphatics when dispersing viscous crude oil or crude residues.

Tests by EPS, while incomplete, have shown Corexit 9517 to be an effective product in seawater for medium and heavy bunker. No laboratory tests were performed with crude oil, but it has always been assumed that a product which is effective on heavy bunker is also effective on crude oil.

4.2.2 Corexit 9527: This is a new generation concentrate dispersant with a higher flash point than Corexit 9517. The manufacturer claims that in all other aspects the physical-chemical properties of these two dispersants are similar. Unfortunately, there is inadequate information available to determine whether or not dispersant effectiveness is also similar.

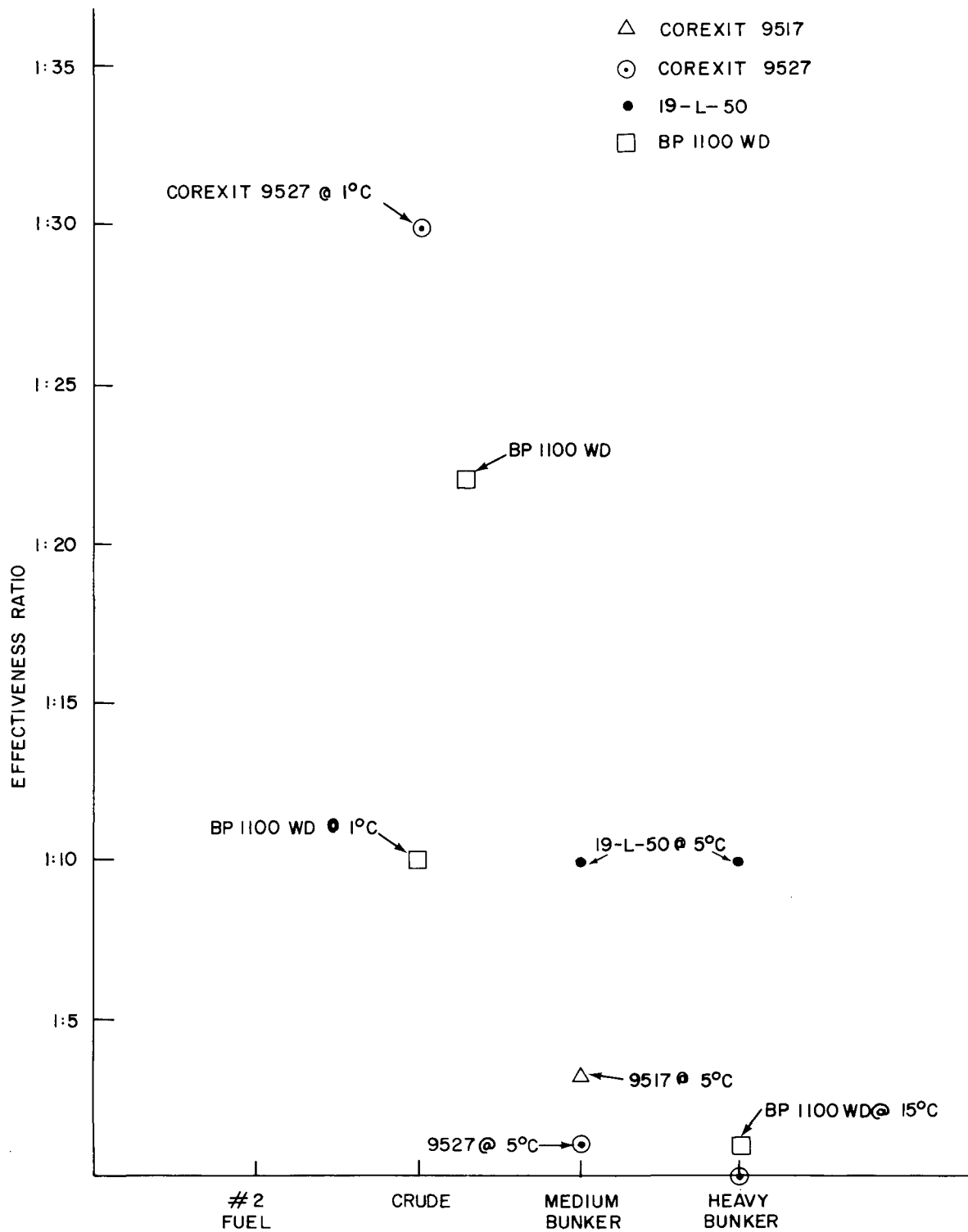


Fig. 4 — Summary of E.P.S., SET Effectiveness Tests
on Selected Concentrate Dispersant in Seawater
(All Tests Use Undiluted Dispersants)

Tests by EPS show Corexit 9527 to be a highly effective product for use on crude oil in cold seawater. In addition to laboratory tests, this product has been tested in field trials undertaken by Transport Canada using the Warren Spring Laboratory format (Gill, S.D. undated).

Corexit 9527 was found to be effective on crude oil in seawater at 17°C down to an oil/dispersant ratio of 8.5:1.

4.2.3 *Corexit 19-L-50:* This is an experimental concentrate dispersant, the commercialization of which is still under consideration. Although little quantitative information is available on the relevant properties of the product, the few results available indicate it to be a very effective, relatively low-toxicity dispersant.

Incomplete tests on Corexit 19-L-50 have been run by EPS and the product has been shown to be effective on medium and heavy bunker oils in seawater at 5°C. Indications are that Corexit 19-L-50 would be very effective on crude oil.

4.2.4 *Finasol OSR5:* This is a new generation concentrate dispersant manufactured in Europe and available in Canada through Petrofina. It is similar to most concentrates in that it may be diluted with water (fresh or salt) or with a hydrocarbon solvent.

No laboratory effectiveness or toxicity tests have been performed by EPS on this product. However, field tests by Transport Canada using the Warren Spring Laboratory format have shown the product to be effective in 4°C seawater up to an oil/dispersant ratio of 5.4:1.

The manufacturer of Finasol OSR5 has published information on the effectiveness and toxicity of this product. Utilizing the SET test, the non-diluted concentrate had an efficiency of 67%, with oil/dispersant ratios of 20:1. The efficiency was greater than 95% for lower oil/dispersant ratios. Tests have shown the efficiency to be fairly insensitive to water temperatures in the range of 12°C to 25°C. The efficiency of the product has also proven to be fairly insensitive to levels of mixing energy, given that at least some energy is provided or available.

4.2.5 *BP1100WD:* This is a concentrate dispersant marketed in Canada by Canadian Industries Limited and known here as Synperonic OSD 20.

Several effectiveness and toxicity tests have been performed on this product and it has been shown to be a very effective, slightly toxic dispersant. Tests by the EPS have shown an SET effectiveness of 30:1 on crude oil in seawater at 5°C. This value falls to 10:1 at 1°C.

Transport Canada has performed field trials in 17°C and 4°C seawater with BP1100WD using the standard Warren Spring Laboratory format. The tests show the dispersant to be effective at oil/dispersant ratios of 7.8:1 in 17°C and 6.0:1 in 4°C water.

4.3 Concentration Considerations

It is relatively straightforward to show that if an oil slick of thickness t_o (cm) is dispersed vertically into water volume to a depth d_p (metres) the concentration C (ppm) is:

$$C_o = \frac{\rho t_o 10^4}{d_p} \quad (1)$$

where

C = concentration of hydrocarbon molecules in ppm
 ρ = density of oil gm/cm³
 d_p = penetration depth m
 t_o = slick thickness cm

If the dispersion results from the application of a dispersant, the molecular concentration in the water column increases depending upon the effectiveness of the dispersant applied. This concentration increases when less efficient dispersants are used and decreases for more efficient products. It is straightforward to show that when a dispersant is applied to an oil slick:

$$C_d = \frac{\rho_d t_o 10^4}{d_p} (1 + ER) \quad (2)$$

where

C_d = concentration of oil and dispersant molecules ppm
 ρ_d = density of oil/dispersant mixture gm/cm³
 ER = effectiveness ratio of dispersant =

$$\frac{\text{volume of dispersant}}{\text{volume of oil}}$$

This equation is presented in graphical form in Figure 5.

Equation 2 is based on the simplifying assumption that either the oil/dispersant mixture is instantaneously emulsified to depth d_p or that the water velocity is zero, relative to the oil slick. In real conditions during the time required to spray the oil spill, the volume of water contaminated will be greater than previously assumed due to the continuous movement of uncontaminated water into the affected area. It can be shown that:

$$C_v = \frac{C_d}{1 + \frac{\nu w}{S_d}} \quad (3)$$

$$= \frac{\rho_d t_o 10^4 (1 + ER)}{d_p (1 + \frac{\nu w}{S_d})}$$

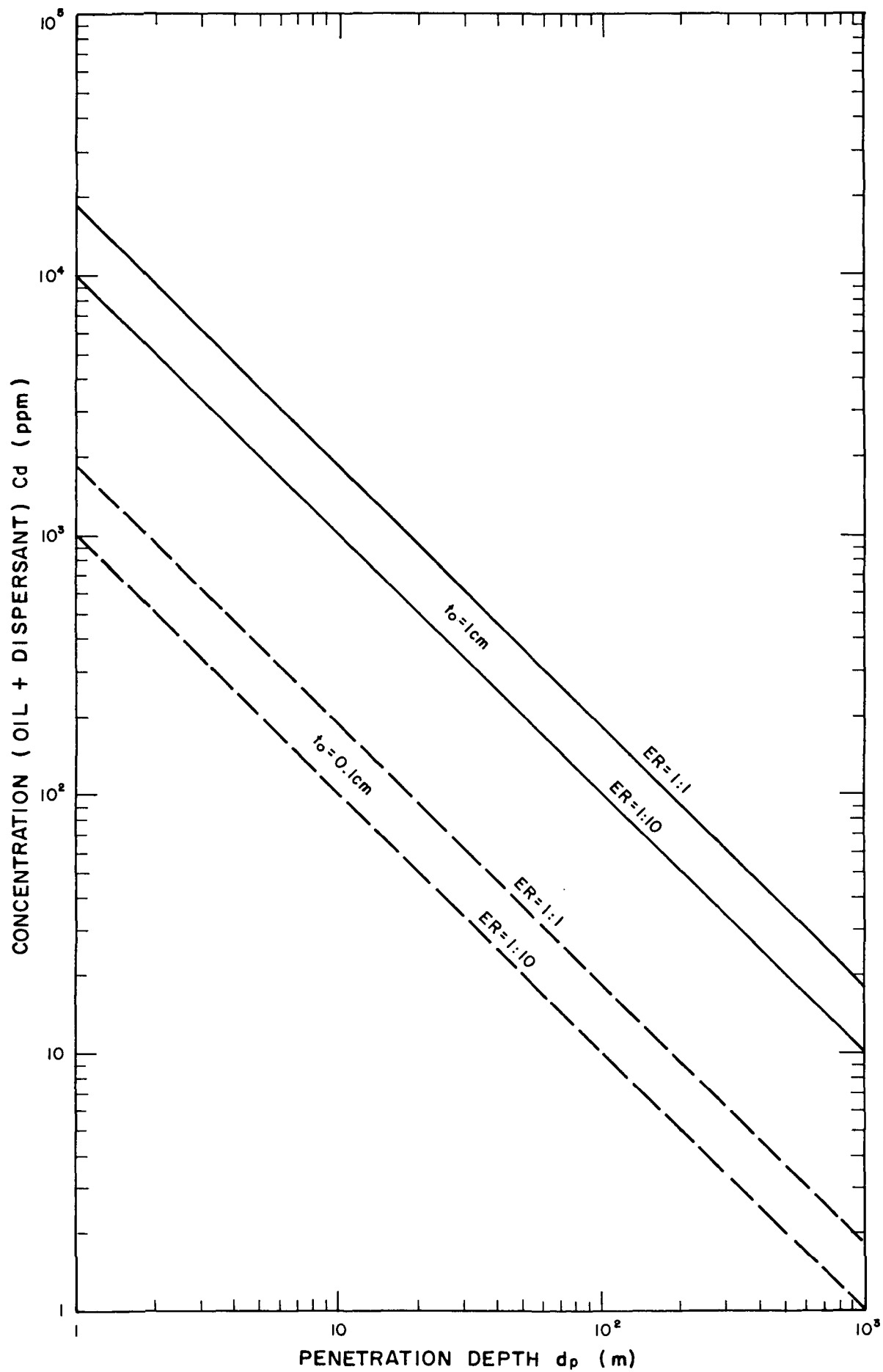


Fig. 5 — Molecular Concentration vs Dispersion Depth

where

C_v = concentration of oil and dispersant mixture ppm
 v_w = current velocity
 S_d = velocity of dispersant application craft

In the Southern Beaufort Sea area, the normal range of ocean current velocities is very small relative to the speed of aircraft which could be used for dispersant application. Hence $C_v \approx C_d$.

Much of the previous information on oil slick volume area relationships and dispersion depths can be related together as shown in Figure 6.

This figure provides a readily useful means of predicting molecular concentrations in the water column upon dispersion of an oil spill by simply inputting basic variables in their most convenient units.

For example, an oil spill of 40,000 barrels occurring in the Beaufort Sea would have a mean thickness between 0.25 and 1.0 cms. If dispersed in water 100 metres deep, $d_p \leq 100$ m and with a dispersant whose ER = 1:10, as shown C_d is between 25 and 100 ppm. The actual C_d may be greater than this range since it is based on $d_p = 100$ m, which assumes a uniform molecular dispersion throughout the entire water column. Depending upon the particular oceanographic conditions the actual depth of dispersion could be less than this. Furthermore, the above range is based on the simplifying assumption that the molecular concentration is uniform through out the depth of dispersion. Having obtained C_d it is straightforward to calculate C_v based on the relative velocities of the current and dispersant application craft (Equation 4.3).

It can also be seen from Equation 2 and Figure 6 that for fixed d_p and ER, the concentration of molecules C_d depends only upon slick thickness t_o . For example, if $d_p = 100$ m, ER = 1:10 dispersing a slick 0.25 cm thick results in a $C_d = 25$ ppm, regardless of the size of the spill. These values are all considerably greater than acceptable levels for sublethal effects.

4.4 Critical Unknowns

At present very little is known about many of the critical characteristics necessary to discuss adequately the usefulness of dispersants in the envisioned Arctic conditions. The following section attempts to point out many of the more critical unknowns and their significance. Recommendations are given in Section 10 on a possible field and laboratory program to fill in some of these data gaps.

Temperature Effects: Available data indicate that dispersant effectiveness decreases at lower temperatures. To some extent this indication is borne out in recent field trails (Gill, S.D. undated) and EPS laboratory tests. This reduction in efficiency has as yet not been adequately documented, but will be of considerable relevance in the Southern Beaufort Sea where water temperatures are frequently less than 0°C.

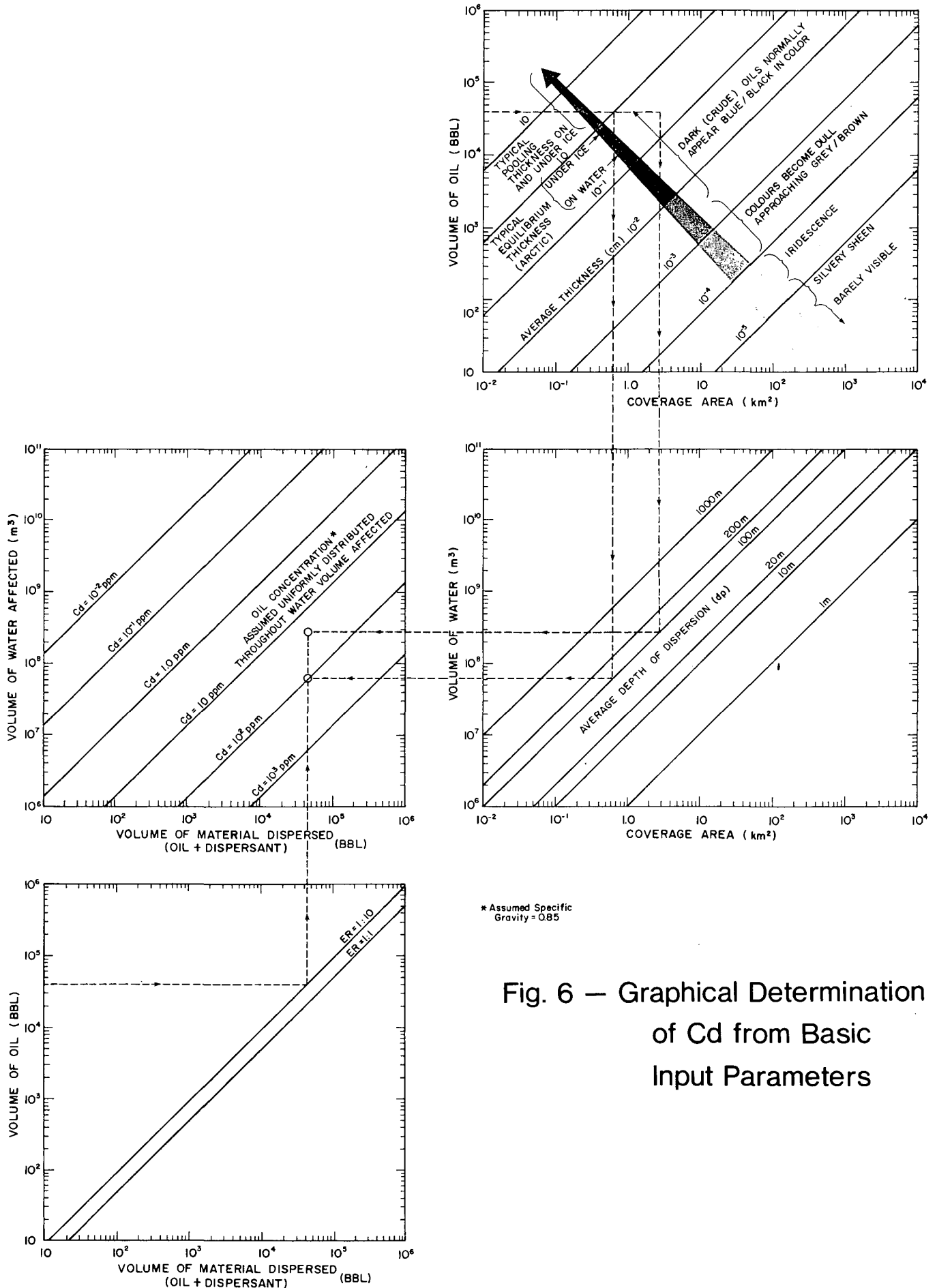


Fig. 6 — Graphical Determination of Cd from Basic Input Parameters

Slick Thickness Effects: For dispersant to be effective in field conditions, it must penetrate the oil slick down to the oil-water interface. When mixing energy is applied, problems related to penetration are minimized. However, in the field conditions envisioned, these problems are maximized due to the low temperatures and consequent thick, highly viscous slicks. It is projected that slick thicknesses will be in the range of 0.25 to 1.0 cms with localized pooling in leads of up to 10 cms or more. Slick thicknesses of this magnitude may behave differently from those of thickness in the range of 0.001 cm more commonly found in temperate climates.

Dispersant Aerosol Effects: As early as 1968, problems related to the evaporation of dispersant solvent when using aerial methods were identified. This problem is particularly significant when fine sprays are used with droplets of maximum surface area to volume ratios (Section 6.2). Although the problem may be reduced with better nozzle designs, no information is available on the significance of this effect for different dispersant formulations.

Inadequate Effectiveness Tests: To date, virtually all quantitative data on effectiveness are based on methods that impart mixing energy. These methods are not particularly useful in evaluating dispersants to be applied in field conditions. Although progress is being made, particularly between U.S.A. and U.S.S.R., to standardize simpler tests, such as the swirling beaker test, these have not gained wide acceptance.

5 APPLICATION PLATFORMS

The study is directed at assessing the feasibility of aerial methods for dispersant application, and hence focusses on fixed and rotary winged aircraft. However, the mathematical formulations developed in Section 7 enable all types of application systems to be compared readily. For completeness, both aerial and surface-based methods are compared using these formulations. The following sections present data on the relevant operational characteristics of various craft that could be used as an application platform. Selected craft are subsequently evaluated in Section 8.

5.1 Fixed Wing Aircraft

Virtually all fixed wing aircraft could be modified for use as an airtanker for dispersant application. In addition, there are aircraft available which have been originally designed as airtankers and could therefore be used in an unmodified condition. Tankers are becoming increasingly common in view of their usefulness for forest fire fighting, agricultural spraying, forestry spraying and other operations. Such craft offer the capability of discharging large volumes of liquid at a wide range of application rates. Most airtankers are conversions of aircraft primarily designed for other purposes, either cargo or personnel. As such, the aircraft are not always ideal, but offer the "best fit" to a set of given circumstances.

In order to screen the number of potential aircraft down to a reasonable number for further consideration, several required and desirable aircraft properties were selected. Aircraft were then reviewed

on the basis of these characteristics and a short list of potential aircraft was then determined. These properties were classified into two categories as discussed below.

Required Properties

The aircraft must meet all of the following requirements or it is rejected from further consideration:

- multiple engines for safety
- proven reliability under harsh conditions
- useful payload must be greater than 5,000 lbs
- proven performance as an airtanker used for spraying or bulk dumping operations
- available for use in Canada

Desirable Properties

In order to be considered further, aircraft should have as many of the following properties as possible:

- experience in the Arctic ideally in the Beaufort Sea – Mackenzie Delta area
- able to land on Beaufort Sea ice
- low cost of operation (if known)
- available from non-government organizations
- offering flexible dumping and spraying techniques

Comparison of performance characteristics on airtankers is frequently done using conflicting information. These conflicts result not necessarily from error, but because each airtanker frequently has been built or modified uniquely. Capacities, operating characteristics and drop patterns all may differ widely.

Based upon this selection criteria, the following aircraft were considered for use as a dispersant application platform.

<i>Manufacturer</i>	<i>Aircraft</i>
Boeing	B-25 (Mitchell)
Canadair	CL-215
Consolidated Vultee	PBY5A (Canso)
Douglas	A-26 (Invader), DC-6
Lockheed	C-130 (Hercules) P 2V-7 (Neptune)
Martin	JRM-3 (Mars)

The principal operating characteristics of these aircraft are listed in Table 3. These aircraft are considered as common representatives of the types of aircraft that could be considered further. No doubt, some aircraft meeting the required and desired properties have not been included.

In addition to the aircraft listed in Table 3, there are numerous other fixed wing aircraft that have successfully been converted to airtankers and are commonly used for aerial spraying operations. These include aircraft such as the Lockheed L-188 (Electra), L-749 Constellation and L-1049 Super Constellation, as well as the Douglas DC-3 and DC-4. However, none of these aircraft have been used to any extent in Canada, although they could be made available. Plans are currently underway between a major petroleum company and a large firm specializing in aerial spraying to utilize one of the above aircraft for an aerial dispersant application test program in the near future.

Smaller agricultural spraying aircraft have been used for applying dispersants to both real spills and for test spills. In October, 1976 the Warren Spring Laboratory in England undertook such field trials using a Piper Pawnee. In view of the problems concerning reliability, payload and aerosol effects, these small aircraft are not considered further in this report.

5.2 Rotary Wing Aircraft

Rotary wing aircraft are an attractive alternative to fixed wing aircraft for the application of dispersants to an oil slick in ice leads. These aircraft are extremely maneuverable, can vary speeds over a wide range and can disperse the chemicals from very low heights. However, they are generally much more expensive to operate than a fixed aircraft and have a sharply reduced range for even moderate payload. The following section presents the characteristics of several rotary wing aircraft that have been selected for further consideration.

The screening process used to reduce the number of rotary wing aircraft to a manageable number is much simpler than that used for fixed wing aircraft due to the relatively small number of rotary wing aircraft available. As an initial screening criterion, it was decided to consider only rotary wing aircraft with payloads greater than about 3,600 kg, and those having proven reliability in remote areas in North America.

Based upon the required payload criterion, the following rotary wing aircraft are selected for further consideration:

<i>Manufacturer</i>	<i>Aircraft</i>
Boeing	CH-47 (Chinook)
Bell	214
Sikorsky	S-61
	S-64 (Skycrane)
Sud Aviation	SA 330 (Puma)

The list was further reduced based on the question of availability in the private sector. Since all Boeing CH-47's are owned and operated by the military primarily in Canada and the United States,

TABLE 3 CHARACTERISTICS OF SELECTED FIXED WING AIRCRAFT FOR POTENTIAL USE

		Boeing B-25 Mitchell	Canadair CL-215	Consolidated Vultee PB5A Canso	Douglas A-26	Douglas DC-6	Lockheed C-130 Hercules	lockheed P2V-7 Neptune	Martin JRM-3 Mars
Speed:									
Maximum	kph	483	370	315	555	572	589	463	354
Cruise	kph	338	296	233	450	504	539	346	246
Stall	kph	137	117	122	160	-	185	124	124
Weights:									
Empty	kgs	9,571	10,878	7,967	9,072	23,358	33,067	19,936	34,836
Payload (max)	kgs	4,082	5,171	2,352	4,536	11,227	18,144	1,985	4,082
Gross take-off	kgs	15,196	19,278	15,422	15,876	44,089	70,308	32,659	65,772
Fuel:									
Capacity	Litres	2,346	4,337	6,637	2,909	17,798	25,321	8,319	48,915
Consumption	Litres/hr	636	636	364	682	1,546	2,819	1,182	2,409
Tank Capacity:									
Total Litres		4,319	5,455	3,637	4,546	13,638	11,365	11,820	27,276
With Full Fuel-load	Litres	4,319	5,182	2,318	4,546	11,251	11,365	6,524	4,091
Minimum Take-off									
Roll:	Metres	1,220	775	1,373	1,266	1,007	1,159	763	915
Dimensions:									
Length	Metres	16.3	19.4	19.5	15.5	30.7	29.8	23.4	35.8
Wingspan	Metres	20.6	28.6	31.8	21.4	35.8	40.5	30.5	61.0
Availability and Experience in Canada									
General Comments:		Used in Canada for fighting fires.	Used in Canada by Quebec Govt. only. Good, versatile aircraft.	Used extensively in Canada. A good airtanker.	About 9 are in Canada for fire-fighting.	Used for Spraying Operations.	Used extensively in Arctic, not as airtanker.	Recently used in Canada as airtanker.	Used for forest fighting in B.C.
General Comments:		Not a well accepted conversion.	High costs could have availability problems, but excellent aircraft.	Generally used as amphibious. Would need conversion.	Generally considered a good aircraft, would need conversion, but needs a long runway.	Generally considered a good aircraft, would need conversion.	High cost to acquire.		High capacity air tanker.
(Source: Simard & Forester, 1972)									

they are not considered further. Based upon their performance specifications however, they did appear to be a potentially good dispersant application platform.

The Sud Aviation SA-330 (Puma) is also considered to be an excellent aircraft, but is excluded from further consideration due to limited North American availability.

There are other rotary wing aircraft such as the Sikorsky S-65 and S-78 or the Sud Aviation SA 321F (Super Frelon) that were originally dropped from further consideration due to their use primarily as a military aircraft, limited experience or unsuitability due to design factors.

The principal characteristics of the rotary wing aircraft selected for further consideration are given in Table 4.

TABLE 4 CHARACTERISTICS OF SELECTED ROTARY WING AIRCRAFT FOR POTENTIAL USE (1)

		Bell 214B	Sikorsky S-61	S-64
<i>Speed:</i>	Maximum (kph)	259	241	200
	Cruise (kph)	-	225	177
<i>Weight:</i>	Max. gross take-off (kg)	6,260 - 7,258	8,626	17,237
	external payload (kg)	3,808	3,901	8,618
	internal payload (kg)	2,760	-	-
<i>Fuel:</i>	capacity (litres)	927	1,863 - 2,973	-

Source:

(1) Manufacturer's Specifications

The Sikorsky S-64 (Skycrane) is a unique aircraft capable of lifting much greater loads than any other rotary wing aircraft. This aircraft is no longer commercially available and only about six are available in North America. However, they are used in Canada primarily to install large transmission towers in remote areas. One of the S-64's is stationed in Alaska.

The Sikorsky S-61 has been used in the Mackenzie Delta area and is a proven reliable aircraft for remote area operations. The Bell 214 model is relatively new and apparently has not been used extensively in remote areas of Canada. However, other Bell Helicopter models are common in the

Mackenzie Delta and it is likely that the 214 would operate successfully in this area using existing logistical support.

5.3 Air Cushion Vehicles

Although the terms of reference of this study pertain to aerial methods for dispersant application, air cushion vehicles (ACV's) frequently called surface effect vehicles (SEV's) offer a unique technology with potential applicability to this problem. Consequently, information is provided on these craft for later evaluation.

ACV's have a very significant potential for Arctic application, but at the present stage in their evolution, their use is limited. It is likely that applications will develop and grow on the basis of their potential of providing a new transportation mode in conditions where no other one is viable. These vehicles offer a significant advantage over aircraft because of their high payload and ability to operate in low visibility conditions.

The two principal ACV types are sidewall and peripheral seal. The former type, which can operate only on water, is constructed with two rigid sides which penetrate into the water with a bow and stern skirt seal. The fully amphibious ACV's have a skirt around the entire vehicle and can clear any surface obstacle less than the skirt depth.

While it is likely that at sufficiently slow speeds an ACV can cross broken ice fields, the ability of the craft to operate on an oil slick or to disperse chemicals is unknown. No information is available on the question of flammability or the effect of spraying dispersant underneath the vehicle. Also, downwash may displace oil from under the craft. When operating, the downwash from the air cushion creates considerable agitation of the water surface. This agitation would likely impart high levels of mixing energy, and hence improve dispersant effectiveness. It appears feasible and appropriate to mount spray booms in the aft section of an ACV. When operating at even low speeds, however, considerable spray is blown upwards at the bow which would result in loss of large volumes of material, visibility problems and ingestion of material into the engines. Injecting the dispersant beneath the craft within the skirts may be possible if flammability is not a problem. Spray booms mounted aft would need to be below the horizontal thrust propellers.

ACV's operating under Arctic conditions have proven to be reasonably reliable and to have suitable performance specifications. However, references have cited several drawbacks such as:

- poor maneuverability
- inability to climb or traverse slopes
- greatly reduced combined man and machine efficiency at very low temperatures
- low-temperature chill factor effects on skirt
- high maintenance
- corrosion
- sever icing and ice impact damage

- noise and vibration
- sensitivity to winds
- must greatly reduce speed in heavy seas (Peterson , Orgill, Swift, Loscutoff, March 1975)

Elimination or alleviation of the above problems is within the realm of current technology, but could require a few years before being realized.

ACV's have been recommended and used for numerous Arctic activities ranging from cargo and personnel carriers to scientific and operational platforms. One ACV that was recommended by several manufacturers was the Bell Aerospace Canada Textron Voyageur (Arctic Institute of North America, May 1972).

In order to assess fully the potential of ACV's as a dispersant application platform, information was gathered on several vehicles. In particular, the Bell Aerospace Textron Voyageur was considered in detail.

The Voyageur has been tested and used under Arctic conditions including trials in the Mackenzie Delta. There are only four Voyageurs in the world at present; three are owned by Bell Textron and one is currently owned by Transport Canada for ice breaking in the St. Lawrence River.

The vehicle's principal operating characteristics are listed as follows:

Maximum Calm-Water Speed	= 87 kph
Vertical Obstacle Clearance	= 1.1 metres
Endurance with Maximum Fuel	= 10 - 12 hours
Operable in Waves up to	= 1.4 metres
Payload (max.)	= 21,909 kgs

A higher capacity militarized version of the Voyageur called the LACV-30 has been developed. This craft can carry a payload of 27 million kgs. The commercial version of the LACV-30, the AL-30, has yet to be manufactured.

5.4 Surface Vessels

Under conditions of normal accessibility, surface vessels would be used as dispersant platforms. This is the traditionally used application platform due to its advantages of cost dispersal effectiveness and efficiency. Although beyond the limits of present technology, a highly reinforced ice breaker could be developed to operate outside the narrow, ice-free time currently possible. Currently surface-based operations in the Southern Beaufort Sea are only possible from July to October. For example, presently available supply vessels for offshore drilling meet the Type A Standards of Construction of the Canadian Arctic Shipping Pollution Prevention Regulations, but are incapable of operating beyond October. As discussed in Section 3.3, the optimum time for oil spill cleanup from the hypothesized blowout is in May.

Should an adequate surface vessel be designed it is likely that its deployment would result in greatly lowered costs for dispersing an oil slick. As a basis of comparing time and cost estimates, a hypothetical surface vessel is assumed with the following capabilities:

Maximum Speed	46 kph
Normal Speed	37 kph
Dimensions: LOA	113 m
Beam	12.8 m
Standard Displacement	2.7×10^6 kgs

6 AERIAL APPLICATION CONSIDERATIONS

Existing aerial application methods have been developed primarily from experience gained in fire fighting operations and agricultural spraying. Considerable research and field testing have been undertaken to understand the mechanics of droplet behaviour, design aircraft and develop new methods for aerially applying water and chemical retardants. Much of this information is directly relevant to aerial dispersant application. For the purposes of the following discussions the simplifying assumption is made that dispersants have properties similar to water.

6.1 Droplet Behaviour

When a liquid is allowed to fall through the air it erodes into smaller droplets. This erosion is accelerated when the liquid is dropped from a platform having a horizontal velocity. After release from an aircraft the bulk liquid volume continues in a horizontal direction. As it falls it loses the horizontal momentum due to air friction and begins to become unstable and to erode into smaller droplets. After the liquid breaks up it falls in a droplet form to a steady state vertical direction with little or no horizontal component. A droplet reaches a terminal velocity depending upon its diameter, specific gravity and other properties.

The mean diameter of water droplets formed varies between:

$$\delta_{\max.} = \frac{77.1}{V^2} \quad (4)$$

and

$$\delta_{\min.} = \frac{2.07}{V} \quad (5)$$

where

δ = mean droplet diameter (cm)

V = velocity of aircraft relative to wind velocity m/sec.

This expression is plotted in Figure 7.

The terminal velocity of a spherical droplet can be estimated based upon the liquid characteristics and the droplet diameter. Figure 8 shows the relationship for water between terminal velocity and droplet diameter. Terminal velocities are reached very quickly for droplets. For example, a water droplet will reach this velocity in only about one second in free air.

Based upon these two figures, one major difference between fixed and rotary winged aircraft is apparent. A fixed wing aircraft travelling at 160 kph would yield water droplets with a mean diameter of about 0.07 cm, and a terminal velocity of about 2.4 m/sec. A rotary wing aircraft travelling at 65 kph would yield water droplets with a mean diameter 0.17-0.51 cm and a terminal velocity of between 6.1 m/sec. and at least 9.2 m/sec. The kinetic energy of the droplets from the rotary wing aircraft is up to 5,000 times greater than that from the fixed wing, and hence there is a much greater penetration through to the oil-water interface. This is assuming there is no rotary wash which could modify the above estimates.

6.2 Evaporation Problems

The problem of evaporation loss for small diameter droplets is well known. For forest fire fighting activities chemical thickening agents are frequently added to fire retardants to increase droplet surface tension and minimize the formation of near aerosol particles. Such reformulations are possible for concentrate dispersants, but apparently none have been developed yet.

Problems related to the loss of solvent and other chemicals when dispersants are aerially sprayed have been known for some time:

“Utilizing crop-spraying aircraft has the advantage of speed and flexibility, but also has severe restrictions. These include the limited payload of light aircraft, the inadequate agitation of the oil dispersant mixture, the loss of solvent before the detergent reaches the sea surface and the tremendous dispersion of the material being applied especially in high winds”. (Stander, 1968).

In October 1976, the Warren Spring Laboratory in Great Britain used a Piper Pawnee crop-spraying aircraft to apply dispersants to a test oil slick. The spray in this test was extremely fine being virtually atomized and at least one report estimated that over 50% of the concentrate was lost into the atmosphere.

For water there is a relatively narrow range of droplet sizes depending on drop height over which evaporation losses are great. Scott (1964) presents the following formula for droplet lifetime:

$$t_o = \frac{\pi \rho}{2B} \int_0^{\delta_o} \frac{\delta^2 d\delta}{A(\delta)} \quad (6)$$

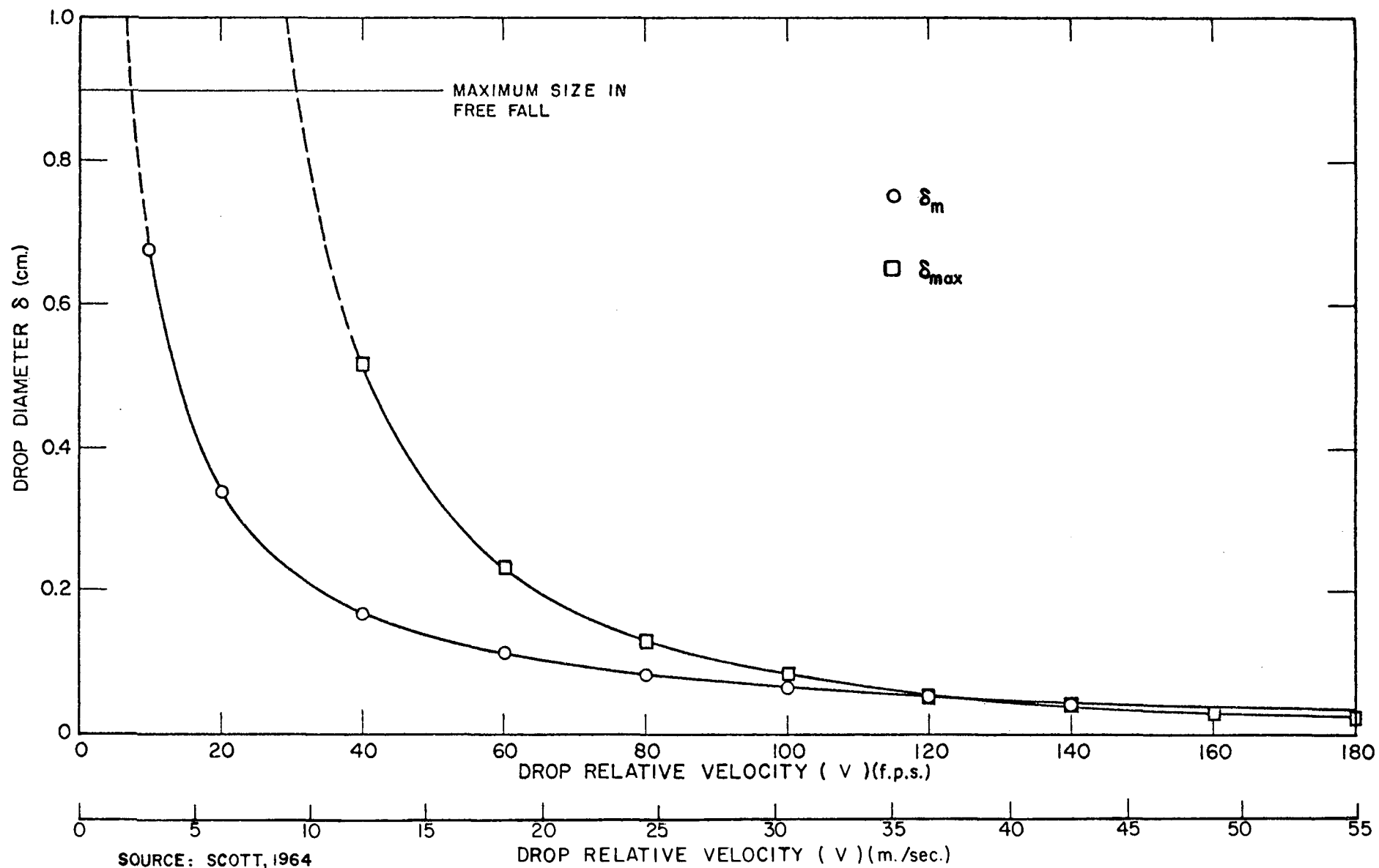


Fig. 7 — Effect of Velocity on Mean Drop Size
(For Water Drops in Air)

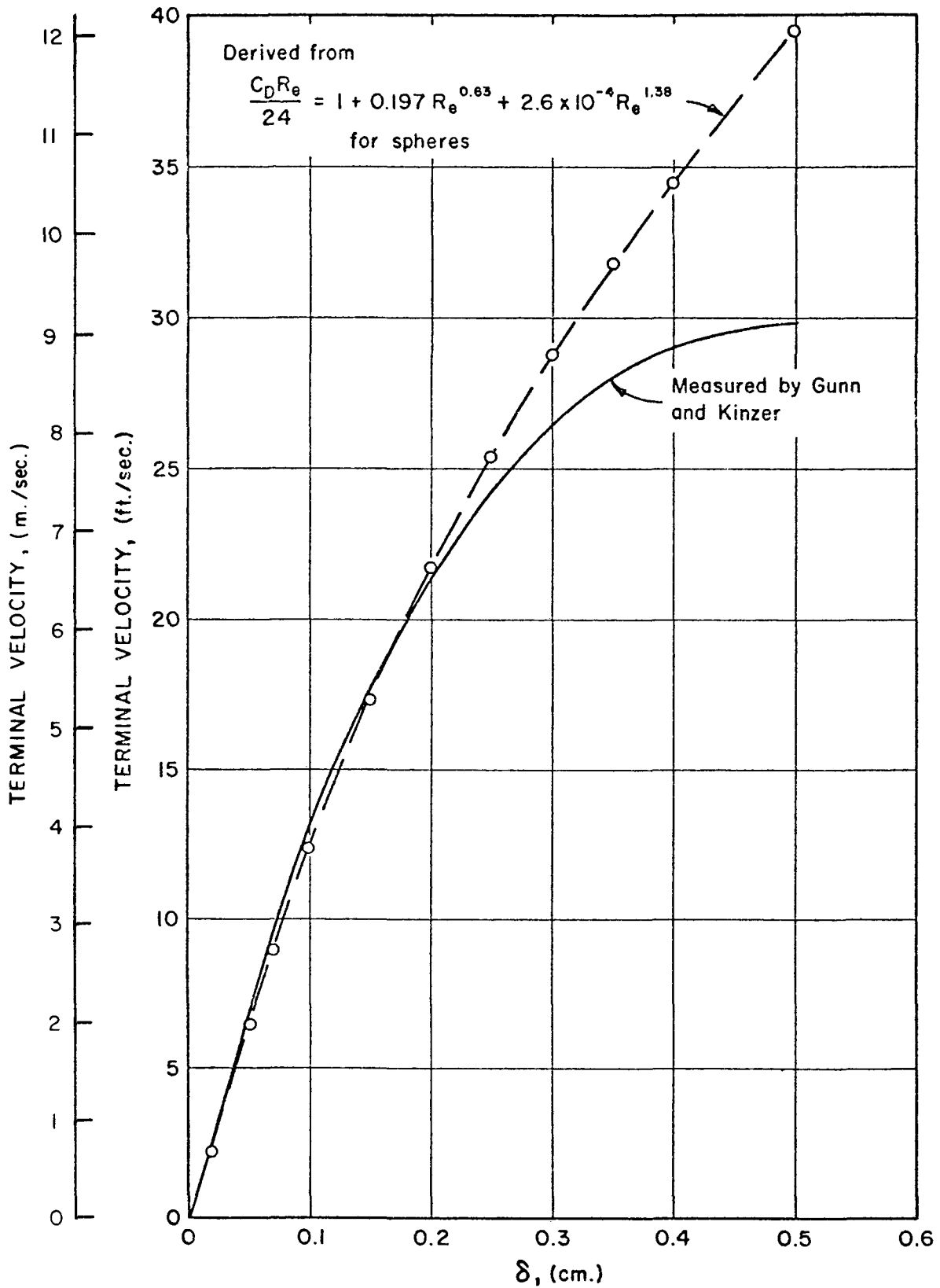


Fig. 8 — Terminal Velocities of Free Falling Water Droplets

SOURCE: SCOTT, 1964

where

- t_o = droplet lifetime (sec.)
- ρ = liquid density gm/cm³
- δ = droplet diameter cm
- A = a function of δ and ambient temperature
given in (Scott, 1964)
- B = a function of ambient temperature and
relative humidity given in (Scott, 1964)

By numerically integrating this expression, droplet lifetimes for given diameters, and meteorological conditions can be determined. Based upon this formula, the lifetime for a droplet $\delta = 0.08$ cm is about 1,200 seconds, while for a larger droplet, e.g. $\delta = 0.22$, $t_o = 5,680$ seconds.

6.3 Available Aircraft Delivery Systems

Dispersants could be delivered from aircraft in a number of ways. The most frequent methods currently used for aerially applying material are to gravity release or to pressure eject it.

The classical discharge method from airtankers is to gravity release liquid using doors under the aircraft. Such aircraft are frequently converted military bombers. When liquids are discharged in bulk from an aircraft, they result in coverage at ground level that is non-uniform. The greatest concentration of liquid is found along the centre line of the aircraft's flight path forward of the point of release. Coverage decreases forward and backward from this area, as well as on either side of the centre line. Consequently, ground distribution contours may be highly irregular, thus resulting in an inefficient use of liquid. In view of the considerable per-unit-dispersant cost, no gravity release methods are considered further in this study.

For aft-loading aircraft such as the Lockheed L-100-30 Hercules, modular, high-flow-rate pressure release systems are available. These systems increase the effective utilization of liquids over bulk release systems since the material is more uniformly applied at ground level. One such patented system is the Modular Airborne Fire Fighting System (MAFFS) developed by the FMC Corporation in U.S.A. This system will fit virtually any large fixed or rotary wing aircraft without any modification to the vehicle. The MAFFS is a self-contained pneumatic unit capable of deploying 10,600 litres from a L-100-30 at application rates of up to 172,000 litres/min. It requires approximately two hours to initially load the system into an L-100-30. After the initial load has been discharged the time required for subsequent filling of the retardent tanks is eight minutes and the time required to refill the pneumatic container is 10 minutes. This system can be used to discharge dispersants.

For aerial application uses other than fire fighting, liquids are frequently pressure ejected from aircraft using spraying systems. Such spray systems are used for insecticide and herbicide applications and have been presented as a means of applying dispersants.

For fixed wing aircraft, spray booms are generally attached under the wings and liquid is pumped from on board tanks through specially selected nozzles in the spray boom. The swath width of application depends upon the width of the spray boom and the elevation of the aircraft.

For rotary wing aircraft, the tank and pumping unit may be either internally mounted or externally mounted on a sling system. The spray bar can be mounted either attached to the aircraft or supported by an external sling. However, fins or other features would be required to prevent rotation of the spray boom system due to rotary wash.

6.4 Innovative Aircraft Delivery Systems

Concepts have been developed to improve the application effectiveness of aerial systems. These concepts are directed at containing the liquid to make it less susceptible to evaporation and wind drift. These concepts have generally been developed with a view toward improving the effectiveness of forest fire fighting operations. Apparently not one ever been developed beyond the concept stage to actual implementation. The following section draws heavily on ideas contained in the report High Altitude Retardant Drop Mechanization Study published by the Northern Forest Fire Laboratory in 1973.

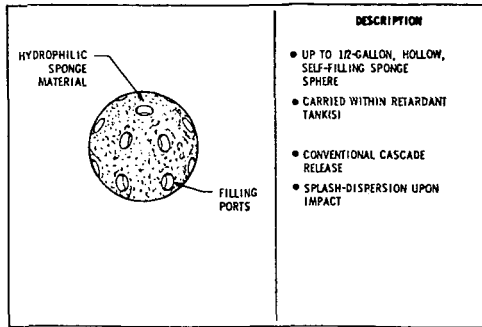
Containment systems can be classified as natural dispersion or forced dispersion systems. Natural systems break on impact without an energy input to break it up or impose some initial velocity. Forced systems include an energy source to increase the horizontal speed of the liquid. Nine such concepts from the above report are presented in Figure 9.

All containment concepts are more complex than bulk dump or spray systems. Furthermore, they are expensive and involve a heavy reduction in effective payload due to their shape and construction material. Only two of the nine liquid-based concepts were considered worthy of more detailed study. These were the polyethylene thinwall capsule and the airburst bulk disperser.

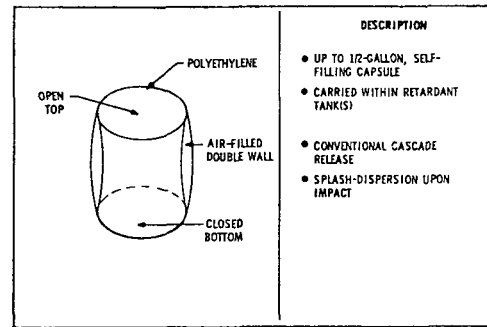
Delivery of dispersants in plastic bags requires either a central packing facility or an on-line pouching operation. Current maximum rates for filling and sealing plastic bags is limited to a maximum of about 400 per minute with this rate decreasing rapidly for larger volume containers. The limiting factor from a time point of view is that required to heat, weld and cool the seal. Based upon payload capabilities of various aircraft and the surface coverage of each pouch on impact, the required pouch production rate would have to be about 1,500 per minute to supply a moderately sized aircraft with enough pouches to disperse material at a rate comparable to that which could be sprayed or bulk dumped. The logistics and cost problems in supplying bagged dispersants are sufficiently higher and the methods too complex to warrant further analysis at this time.

Airburst containers that create a salvo dump at an altitude some distance below the aircraft were evaluated in the above report. These systems offer advantages such as minimizing evaporation losses, and wind drift; in addition they can be deployed from unmodified aft loading aircraft.

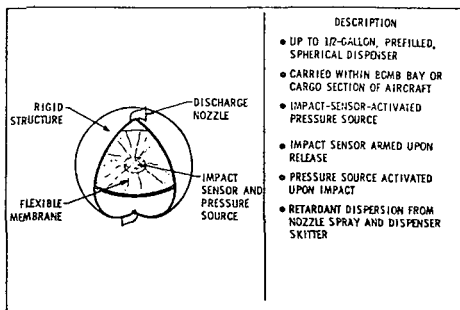
They were rejected because they do not yield a uniform pattern of distribution and accuracy of application is not increased substantially over lower flying discharge methods. In addition, there are safety problems at the ground base storage area that require expensive, failsafe



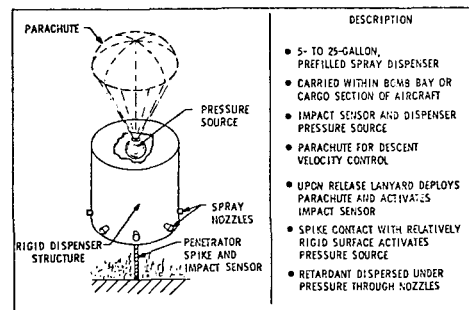
Impact Burst, Sponge Sphere



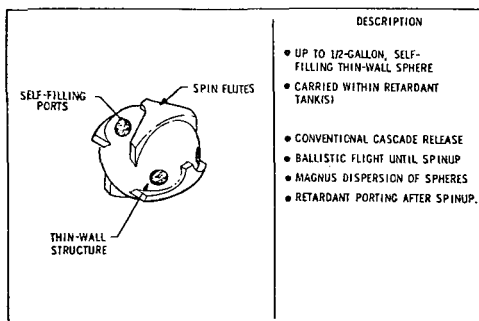
Impact Burst, Thin-Wall Capsule



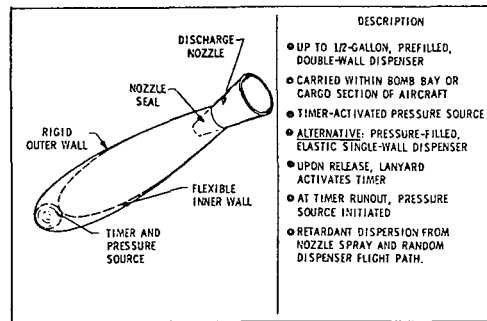
Impact Burst, Skittering Dispenser



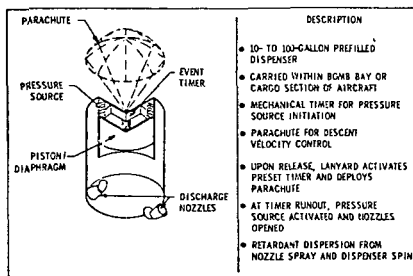
Impact Burst, Spray Generator



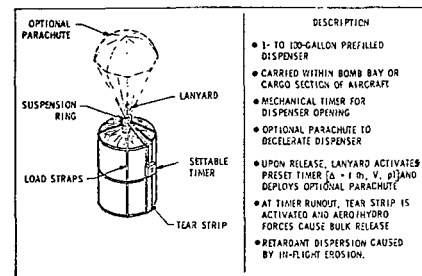
Airburst, Spinning Sphere



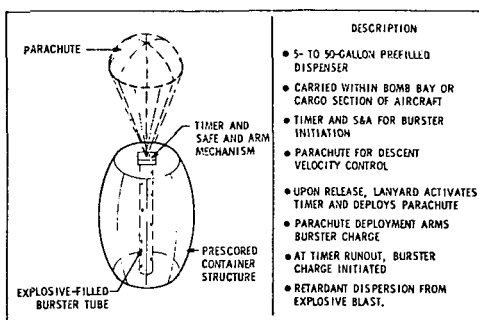
Airburst, Skittering Dispenser



Airburst, Pressure/Nozzle Dispenser



Airburst, Bulk Dispenser



Airburst, Explosive-Activated Dispenser

Fig. 9 — Innovative Aircraft Delivery Systems

explosion prevention systems that could be difficult to ensure in remote operations. The concept of airburst containers is not pursued further at this time.

7 AERIAL RESPONSE SCENARIO

7.1 Basic Considerations

The aerial application of dispersants to oil slicks in the Beaufort Sea must be considered within a broad range of environmental, logistical, financial, and even socio-political constraints. This section is primarily aimed at the logistical aspects of the problem, and at the same time addresses those real-world environmental and operational factors, which in the end may dominate any financial considerations.

The mathematical treatment of key variables and the subsequent graphic analysis of their relationships are made deliberately general here. The results can be employed in the evaluation of both fixed and rotary wing aircraft, air cushion vehicles and surface vessels. Mathematical expressions are formulated to permit an examination of parameter sensitivities to ultimate time and cost considerations, and to examine the feasibility of utilizing state-of-the-art system components.

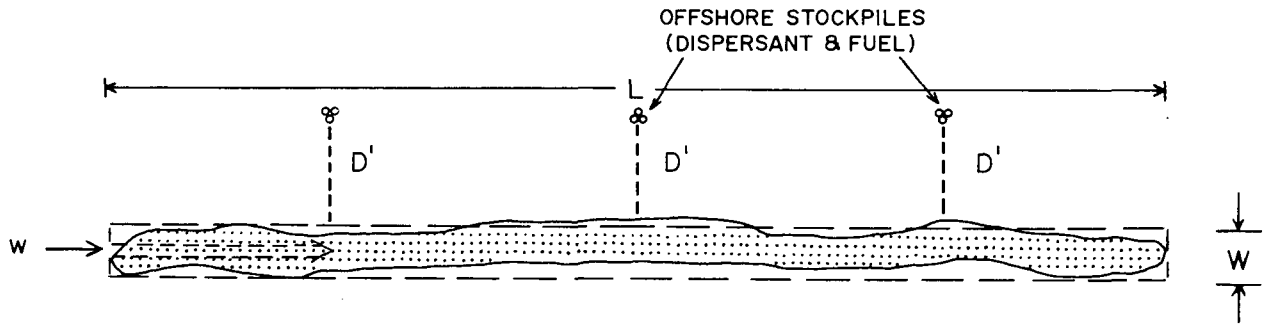
It should be noted that the treatment contained herein does not deal with the logistics of initially transporting and stockpiling aircraft, dispersant, fuel, and other materials to/at the stockpile site. These aspects of the problem are addressed in Section 9. Instead, this section focuses on the most efficient storage, movement, and application of dispersant material at the scene of a hypothetical spill similar to that described in Section 3.3.

7.2 Response Formulation

As discussed in earlier sections, the actual size and shape of exposed oil slicks during and after a major blowout in the Beaufort Sea will depend upon a number of complex and unpredictable factors. It is reasonable to assume, however, that most oil spill configurations in open (or partially open) water could be approximated by a rectangle (or several rectangles) of a length, L , and width, W . This geometric simplification, for mathematical purposes, does not introduce any significant error to the analysis contained in this section. It should be recognized, however, that the actual anticipated irregularity of a slick (e.g., the leeward edge of a lead) could place stringent maneuverability constraints upon a desired aircraft.

Figure 10 illustrates and lists most of the parameters used to develop the mathematical expressions in this section.

To begin with, the actual amount of dispersant that would be required per unit area of oil slick (d) can be expressed as:



	SYMBOL	UNITS	DESCRIPTION
	GEOMETRY		
	L	km	average length of oil slick
	W	m	average width of oil slick
	t_o	cm	average thickness of oil slick
	D_o	km	distance to permanent onshore support base
	D'	km	distance to temporary offshore stockpiles
	PLATFORM		
	S	km/hr	speed to and from oil slick
	S_d	km/hr	speed while dispersing
	p_d	litres	dispersant payload volume for aircraft
	t_f	hr	time to refuel aircraft
	t_a	hr	time aircraft can fly without refueling
	t_u	hr	time for aircraft to negotiate a 180° turn
	α	--	proportion of normal operating time required for aircraft maintenance activities
	SPRAY SYSTEM		
	d	litres/hectare	dosage of dispersant to completely disperse an oil slick
	\dot{d}	litres/min.	actual dosage (or emission) rate out of aircraft
	w	m	dispersed swath width (assumed uniform dispersant application)
	ER	--	efficiency ratio for dispersant (volume dispersant/volume oil)
	n	--	number of dispersant refills need to disperse entire oil slick
	n_p	--	number of passes with aircraft to disperse entire oil slick (multiple applications)
	t_r	hr	time to refill dispersant tanks, including landing and takeoff
	t_p	min.	time to deplete a single dispersant payload
	TOTAL OPERATING TIMES		
	T_D	hr	total time required for releasing dispersant only
	T_C	hr	total time required to travel between dispersant stockpile(s) & the oil slick
	T_F	hr	total time required for all aircraft refueling activities
	T_M	hr	total time required for all maintenance of aircraft
	T_R	hr	total time required to refill dispersant units
	T_U	hr	total time required for all 180° turns
	T_{UD}	hr	total time required for all oil dispersal activities
	M_r	--	a dimension less multiplier associated with aircraft refueling & dispersant refilling activities

Fig. 10 — Hypothetical Spill Configuration and List of Symbols

$$d = ER t_o 10^5 \quad (7)$$

where

- ER = efficiency ratio for the dispersant (i.e., ratio of volume of dispersant required to the volume of oil actually dispersed)
 t_o = oil slick thickness (cm)
d = dosage required (litres/hectare)

The actual dosage under Arctic conditions may differ greatly from standard dispersant tests carried out under warmer conditions. Thicker, more viscous oil slicks may make it difficult for the dispersant to penetrate to the oil-water interface.

It is interesting to note that the dosage requirements for oil spills in more temperate climates with slick thicknesses of thousandths of a centimetre will clearly require much lower dosage rates than Arctic spills where thicknesses of 0.25 to 1.0 cm could be expected. A dispersant dosage rate of 5 gallons/acre (45 litres/hectare) is frequently discussed in the literature. For a dispersant with $ER = 0.1$, such a rate would be adequate for slicks with $t_o \leq 0.0045$ cm. This rate is clearly inadequate for the slick thicknesses encountered in the Arctic.

By multiplying Equation (7) by the rate of coverage for a dispersant application platform (speed S_d and swath width w) an expression can be derived for the rate at which dispersant should be applied to an oil slick. A more meaningful expression, however, would account for the fact that multiple passes might be desired, depending upon the actual dosage rate (or pumping rate) that can be achieved. Such an expression, with the proper adjustment of multipliers for unit homogeneity, is:

$$\dot{d} = \frac{1.67 ER t_o w S_d 10^2}{n_p} \quad (8)$$

where

- ER = efficiency ratio
 t_o = slick thickness (cm)
 w = swath width (m)
 S_d = dispersing platform speed (km/hr)
 n_p = number of passes made by the dispersing platform over the oil slick
 \dot{d} = the actual dosage rate (litres/minute) required to disperse the slick in n_p passes

A useful set of illustrations is provide in Figure 11, which graphically presents the relationships between the parameters of Equation (8) when n_p is equal to one (i.e., single-pass mode of dispersal). Dosage rates for multiple-pass operations can simply be achieved for any point on the plots by dividing the single-pass dosage rate at that point by the number of passes desired.

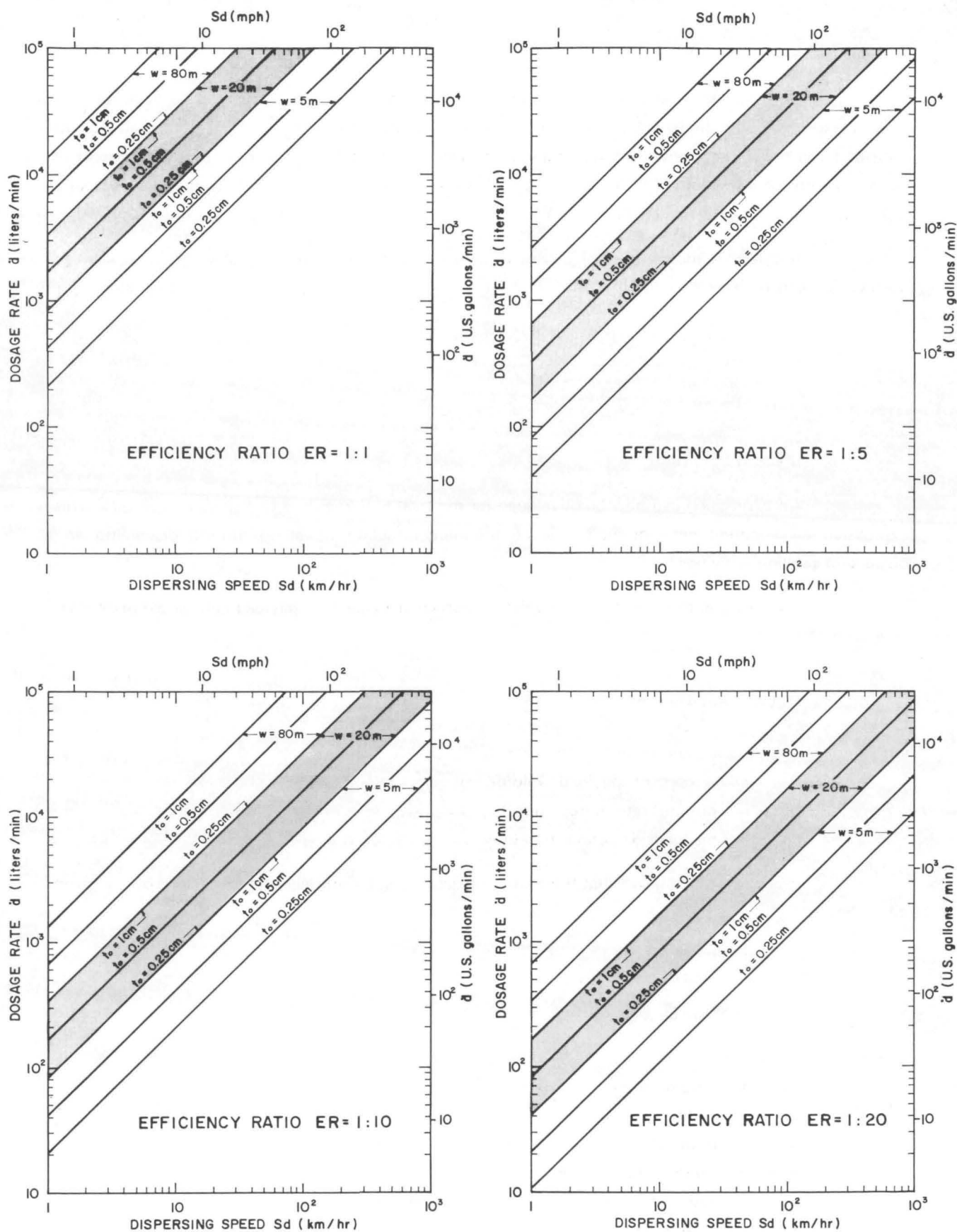


Fig. 11 — RELATIONSHIP BETWEEN S_d , w , t_o AND d FOR $n_p=1$
(Equation 8)

Note that for single-pass operation, the application craft would be forced to travel at very slow speeds and with high dosage rates in order to treat the rather thick oil slicks to ≥ 0.25 cm anticipated in the Arctic. For example, an aircraft travelling at speeds slightly in excess of 30 km/hr (≈ 20 mph) with a swath width of 20 metres on a spill 0.25 cm thick, would require a dosage rate of nearly 2,700 litres/min (≈ 700 U.S. gallons/min) for $ER = 1:10$.

Recall that the number of passes required to disperse an oil slick of width w at a given dosage rate can be expressed (from Equation 8) as:

$$n_p = \frac{1.67 ER t_o w S_d 10^2}{\bullet d} \quad (9)$$

where

$$n_p \geq 1$$

An expression can now be developed for the total time required to disperse an oil slick. This expression involves the times required for each of the many refueling, travelling, turning, dispersing, and dispersant refilling activities.

It is obvious that the time to deplete a particular dispersant payload can be expressed as:

$$t_p = \frac{P}{\bullet d} \quad (10)$$

where

$$\begin{aligned} P &= \text{dispersant payload volume (litres)} \\ \bullet d &= \text{dosage rate (litres/min.)} \\ t_p &= \text{payload depletion time (min.)} \end{aligned}$$

It is also easily shown that the total time actually spent in releasing dispersant over a given oil slick is:

$$T_D = \frac{L W n_p}{w S_d} \quad (11)$$

where

$$\begin{aligned} L &= \text{length of oil slick (km)} \\ W &= \text{width of oil slick (m)} \\ n_p &= \text{number of passes required for dispersal} \\ w &= \text{swath width during dispersal (m)} \\ S_d &= \text{speed of craft during dispersal (km/hr)} \\ T_D &= \text{total dispersing time (hr)} \end{aligned}$$

Note that T_D does not include the time required for other related activities such as travel to and from the spill site, refueling, etc. These activities depend upon the frequency with which a particular dispersing platform must return to refill its dispersant tanks and refuel.

The number of times that a particular dispersant application system must be refilled can be expressed as:

$$\begin{aligned}
 n &= \frac{\text{total time required to disperse an oil slick}}{\text{time to deplete a single payload}} \\
 &= \frac{\text{Equation (11), expressed in minutes}}{\text{Equation (10)}} \\
 &= \frac{60 L W n_p \cdot d}{w S_d P} \\
 &= \frac{ER t_o L W 10^4}{P} \tag{12}
 \end{aligned}$$

Knowing the number of times (n) that a particular dispersing platform will have to travel to and from a dispersant stockpile, we can express the time spent in travel as:

$$T_c = \frac{2 n D'}{S} \tag{13}$$

where

- n = number of refill trips
- D' = the average one-way distance from slick to stockpile (km)
- S = platform's cruising speed (km/hr)
- T_c = total travel time for dispersant refills (hr)

The time to negotiate a 180° turn (t_u) depends upon the particular platform being used (nearly zero for helicopters), as well as the spraying equipment and techniques utilized with each system. Assuming that there is one 180° turn for each refill of the dispersant tank and one for each pass over the oil slick, the total time for all turns can be expressed as:

$$T_u = t_u (n + \frac{W}{w}) \tag{14}$$

where

- t_u = turning time per 180° turn (hr)
- n = number of dispersant refills
- W = width of oil slick (m)
- w = swath width during dispersal (m)

(Note: if $w > W$, use $w = W$)

If t_r is the time allowed for transferring dispersant from the stockpile to the dispersing system and for landing, taxiing and taking off again, then the total time for refilling (or exchanging) dispersant tanks would be:

$$T_R = t_r (n - \frac{T}{24}) \quad (15)$$

where

- t_r = time to refill dispersant tanks, land, taxi, and takeoff again (hr)
- n = number of dispersant refills
- T = total time for all operations (hr)(see Equation 18)
- T_R = total time for refilling operations (hr)

Note that T_R allows for the refilling of dispersant once each 24-hour day during a daily maintenance of all engines and equipment. Note too that T has not been fully defined at this point in the discussion.

Recognizing that the sum of T_D , T_C , T_U and T_R is an approximation of the total operating time for the dispersing platform, we can define the total time for refueling activities as follows:

$$T_F = t_f \left(\frac{T_D + T_C + T_U + T_R}{t_a} - \frac{T}{24} \right) \quad (16)$$

where

- t_f = time required to refuel platform (hr)
- t_a = time aircraft can fly without refueling (hr)
- T = total time for all operations (hr)
- T_F = total time for all refueling activities (hr)

Again, note that T_F allows for the refueling of the dispersing platform once each 24-hour day in conjunction with a daily maintenance of equipment.

The input of a proper value for t_a , the time a platform might operate without refueling, must of course reflect an awareness of the different rates of fuel consumption during different activities (e.g., cruising, dispersing, taxiing, etc.). A study of several types of aircraft and their range versus payload and

safety margins (fuel) has shown that a reasonable value for t_a can be identified for the operational scenarios envisioned in this study.

A final component of the total time to carry out the dispersing activities involves the time required for maintenance throughout the program. Since α is used to denote the proportion of normal operating time required for dispersant platform maintenance activities, the total time for maintenance can be expressed as:

$$T_M = \alpha (T_D + T_C + T_U + T_R + T_F) \quad (17)$$

where

α = proportion of operating time for maintenance

T_D = time spent dispersing (hr)

T_C = time spend to and from stockpile (hr)

T_U = time spent in 180° turns (hr)

T_R = time spent refilling dispersant, landing, taxiing and taking off (hr)

T_F = time spent in all refueling activities (hr)

T_M = time spent for maintenance (hr)

Now, since the total time for all operations can be expressed as:

$$T = T_D + T_C + T_U + T_R + T_F + T_M \quad (18)$$

We can simplify the previous equation. Using Equation (18), the expression for T_M can be written as:

$$\begin{aligned} T_M &= \alpha (T_D + T_C + T_U + T_R + T_F) \\ &= \alpha (T - T_M) \\ &= \frac{\alpha T}{1 + \alpha} \end{aligned} \quad (19)$$

It should be noted here that the total maintenance time (T_M) divided by the number of days for the whole operation ($T/24$) results in a daily maintenance time which must be equal to or greater than some minimum time required for each maintenance service. Mathematically, this requirement can be expressed as:

$$\frac{T_M}{T/24} \geq \text{minimum maintenance time per service}$$

Using the previous expressions for each of the time factors contained in Equation (18), the total time for all activities (T) in hours can be written as:

$$T = T_D + T_C + T_U + t_r (n - \frac{T}{24}) + t_f (\frac{T_D + T_C + T_U + T_R}{t_a} - \frac{T}{24}) + \frac{\alpha T}{1 + \alpha}$$

By substituting and gathering common factors, the above expression can be reduced further to:

$$T = M_r (T_D + T_C + T_U + nt_r) \quad (20)$$

$$M_r = \frac{1 + \frac{t_f}{t_a}}{1 + \frac{t_r}{24} + \frac{t_f}{24} + \frac{t_r t_f}{24 t_a} - \frac{\alpha}{1 + \alpha}}$$

and, from earlier derivations,

$$T_D = \frac{L W n_p}{w S_d}$$

$$T_C = \frac{2 n D'}{S}$$

$$T_U = t_u (n + \frac{W}{w})$$

7.3 Example Problem and Discussions

The following example is provided to help illustrate the simplicity and the utility of the mathematical expressions developed in the previous section. In this example, the Sikorsky S-64 helicopter is assumed to be used with the following operation and spraying characteristics on a long narrow stretch of oil.

Basic Assumptions:

Spill Configuration -

$$\begin{aligned} \text{Volume} &= 20,000 \text{ m}^3 \\ L &= 400 \text{ km} \\ W &= 20 \text{ m} \\ t_o &= 0.25 \text{ cm} \end{aligned}$$

Dispersant Stockpiles -

$$D = 20 \text{ km}$$

Aircraft Characteristics -

$$\begin{aligned} S &= 145 \text{ km/hr} \\ S_d &= 65 \text{ km/hr} \quad (\text{minimum normal safe operating} \\ &\quad \text{speed for helicopter at low} \\ &\quad \text{altitude with high payload}) \\ P &= 6,500 \text{ litres} \\ t_f &= 0.17 \text{ hr } (\approx 10 \text{ minutes}) \\ t_a &= 1.0 \text{ hr} \\ t_u &= 0 \text{ (helicopter)} \\ \alpha &= 0.15 \end{aligned}$$

Spraying Characteristics -

$$\begin{aligned} w &= 20 \text{ m} \\ ER &= 1:10 \text{ (or, } 0.1) \\ t_r &= 0.1 \text{ hr (6 minutes)} \end{aligned}$$

The spill could be envisioned as a 20-m wide, 0.25-cm thick slick running in an east-west direction for approximately 400 km. Such a spill scenario is similar to that which is discussed in Section 3.3. Dispersant stockpiles are spaced uniformly along the apparent lead (with entrapped oil) such that the average distances from stockpiles to dispersing start and stop points are approximately 20 km.

It is interesting to note that the dosage required (Equation 7) in this example is:

$$d = (0.1) (0.25) 10^5 = 2,500 \text{ litres/hectare}$$

This dosage (equivalent to 267 U.S. gallons/acre) is what would theoretically be required to disperse the entire 20,000 m³ of oil. The 8 km² involved with this hypothetical spill would therefore require a total dispersant volume of nearly 2 million litres ($\approx 527,800$ U.S. gallons).

Interestingly, the dosage rate (\dot{d}) from Equation (8) also poses mechanical problems. The dosage rate for single-pass operation would be:

$$\dot{d} = \frac{1.67 (0.1) (0.25) (20) (65) 10^2}{1} \approx 5,430 \text{ litres/min.}$$

This dosage rate would only drop to 1,086 litres/min. (or about 290 U.S. gallons/min.) for a 5-pass operation. The time to deplete a single payload would be about 6 minutes for the 5-pass mode of operation (Equation 10), thus dispersant every 6.5 km along the slick (i.e., 60 or more caches would be required).

Using Equation (11) and a 5-pass operation, the total time spent in actually releasing dispersant can be shown to be:

$$T_D = \frac{(400) (20) (5)}{(20) 65} = 31 \text{ hours}$$

$$(T_D = 6.2 \text{ hrs. for single-pass mode})$$

It is important to recognize that the number of passes (n_p) and the dispersing speed (S_d) in Equation (11) must be consistent with the related dosage rate, efficiency ratio, slick thickness, and swath width of Equation (8). In other words, the physical limitations of a spraying platform and its equipment (principally d and S_d) normally dictates the number of passes required to deliver the requisite volume of dispersant. This number may well be impractical operationally.

Noting that the number of dispersant refills is independent of the number of passes, Equation (12) can be used to show that for the example under consideration:

$$n = \frac{(0.1) (0.25) (400) (20) 10^4}{6,500} = 308 \text{ refills}$$

This number, in turn, leads to the fact that it would take 85 hours for travel between the oil slick and the many stockpiles of dispersant (see Equation 13). The travel time, T_C , would remain at 85 hours for single-pass operation as well.

Equation (14) would normally be used to calculate the time spent in negotiating 180° turns; however, t_u has been set equal to zero in this example since a helicopter is being used.

Turning now to Equation (20) for the total time required to conduct all dispersing activities, the multiplier (M_r) can be shown to be:

$$M_r = \frac{1 + 0.17}{1 + \frac{0.1}{24} + \frac{0.17}{24} + \frac{(0.1) (0.17)}{24} - \frac{0.15}{1.15}}$$

$$= 1.33$$

which leads to a total time (T) of:

$$T = 1.33 (31 + 85 + 0 + 308 (0.1))$$

$$= 195 \text{ hours (approximately 8 days) (for 5-pass operation)}$$

$$(T = 162 \text{ hours single-pass mode})$$

Referring back to Equation (15), (16) and (19) we can now calculate the remaining total times for refilling dispersant (T_R), refueling aircraft (T_F), and for aircraft maintenance (T_M). These are:

$$T_R = (0.1) \left(308 - \frac{195}{24} \right) = 30 \text{ hours}$$

$$T_F = (0.17) \left(\frac{31 + 85 + 0 + 30}{1.0} - \frac{195}{24} \right) = 23.5 \text{ hours}$$

($T_F = 20$ hrs. for single-pass mode)

$$T_M = \frac{(0.15) (195)}{1 + 0.15} = 25.5 \text{ hours}$$

($T_M = 21$ hrs. for single-pass mode)

A check of the total times shows that:

$$\begin{aligned} T &= T_D + T_C + T_U + T_R + T_F + T_M \\ &= 31 + 85 + 0 + 30 + 23.5 + 25.5 \\ &= 195 \text{ hours (for single-pass operation)} \end{aligned}$$

In the final analysis, of course, additional time would also have to be allowed for bad weather, mechanical failures, etc.

7.4 Parametric Sensitivity

As can be seen from other previous equations, the total cleanup time for all activities (T), can be reduced by altering the variables in the following manner:

<i>Increase</i>	<i>Decrease</i>
S	D'
P	t_r
$\cdot d$	t_f
t_a	α
ER	

Many of the key variables are, to a great extent, fixed (e.g., S and t_u) given the type of aircraft and its dispersant unit. However, investigating the sensitivity with regard to selected variables enables an optimum type of aircraft and logistical plan to be developed. The following subsections include a look at the significance of variations in key parameters. The example given in Section 7.3 is used as a basis for comparison.

7.4.1 Variation in D' . Under actual field conditions considerable flexibility in the location of stockpiles would be required depending upon the location of ice leads and the strength of neighbouring

ice masses. It is clear that minimization of D' results in a reduction in the total cleanup time, primarily as a result of reducing T_c , the time for travel to and from stockpiles. Figure 12 shows the relationship between total cleanup time (T) broken into its major components and D' for a dispersant with $ER = 1:10$.

As seen from Figure 12, when $D' = 0$, $T = 49$ hours and increases linearly. In this example (with single-pass operation), T can be expressed as:

$$T = 5.65 D' + 49$$

That is, for every 10 km increase in D' , T increases about 56 hours. It is clear from this figure that D' should be minimized to the extent possible.

In Figure 13 the previous example is presented for a dispersant with $ER = 1:20$. The significance of D' in this example is proportionately reduced; that is:

$$T = 2.83 D' + 29$$

The effect of improving the efficiency ratio (ER) is discussed in the following subsection.

7.4.2 Variation in ER . The use of a dispersant with an improved efficiency ratio (i.e., smaller ER value) reduces the total time for dispersing operations. The reduction results from a decrease in the number of dispersant refills required (n) and therefore in the total travel time T_c .

It should be recognized that an improved efficiency ratio can also reduce the dispersing time T_D , since triple-pass mode of operation) the number of passes required over a slick (n_p) could be reduced for a given aircraft speed (S_a) and pumping rate (\dot{d}). Since this subsection is dealing with the single-pass mode of operation in the example problem, T_D does not change with an improved ER . Under this condition, however, the dispersing speed could be increased (because of the improved ER) for the same dosage rate. This increase in speed would also shorten the time for dispersal T_D .

Figure 14 shows the relationship between ER and T and its major components. It is apparent that a major reduction in total operation time is possible by using efficient dispersants. In the limit with a dispersant of $ER = 0$ (i.e., an infinitely effective product), the example problem would require a total operations time of $T = T_D = 6$ hours. The increase in total time T is again linear and, in this example only, could be expressed as:

$$T = 1,538 ER + 6$$

7.4.3 Variation in Payload Volume P . Using an aircraft with maximum possible payload volume reduces the number of times that the dispersant units must be filled. This results in a proportionate reduction in T_c and a non-linear reduction in the total time for dispersing activities, T . As seen in Figure 15, there is a dramatic reduction in T for payloads up to about 2,000 to 3,000 litres. For larger aircraft the reduction in T is much less per unit increase in P .

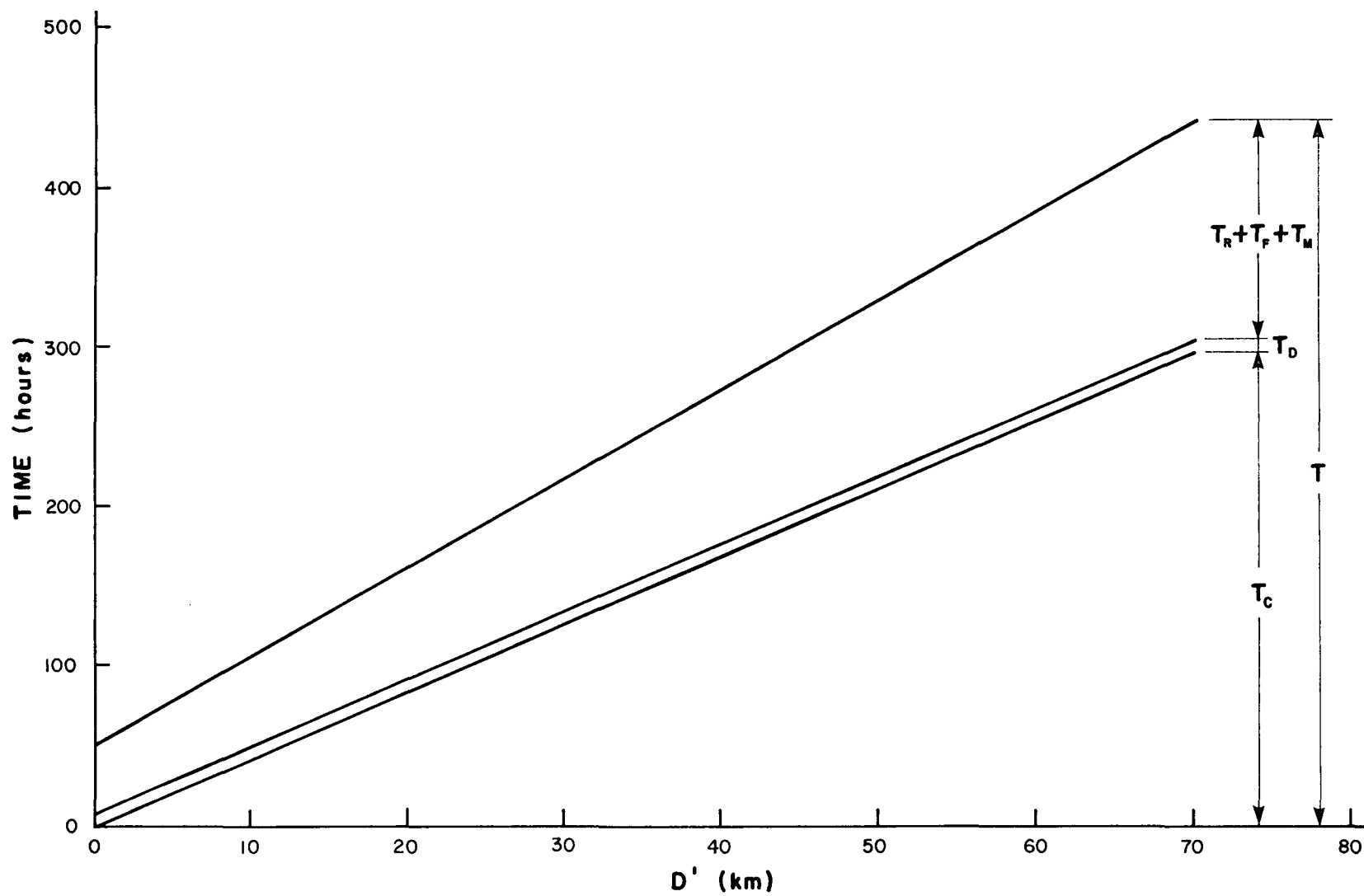


Fig. 12 — T vs D (Example Problem Single-Pass Operation)

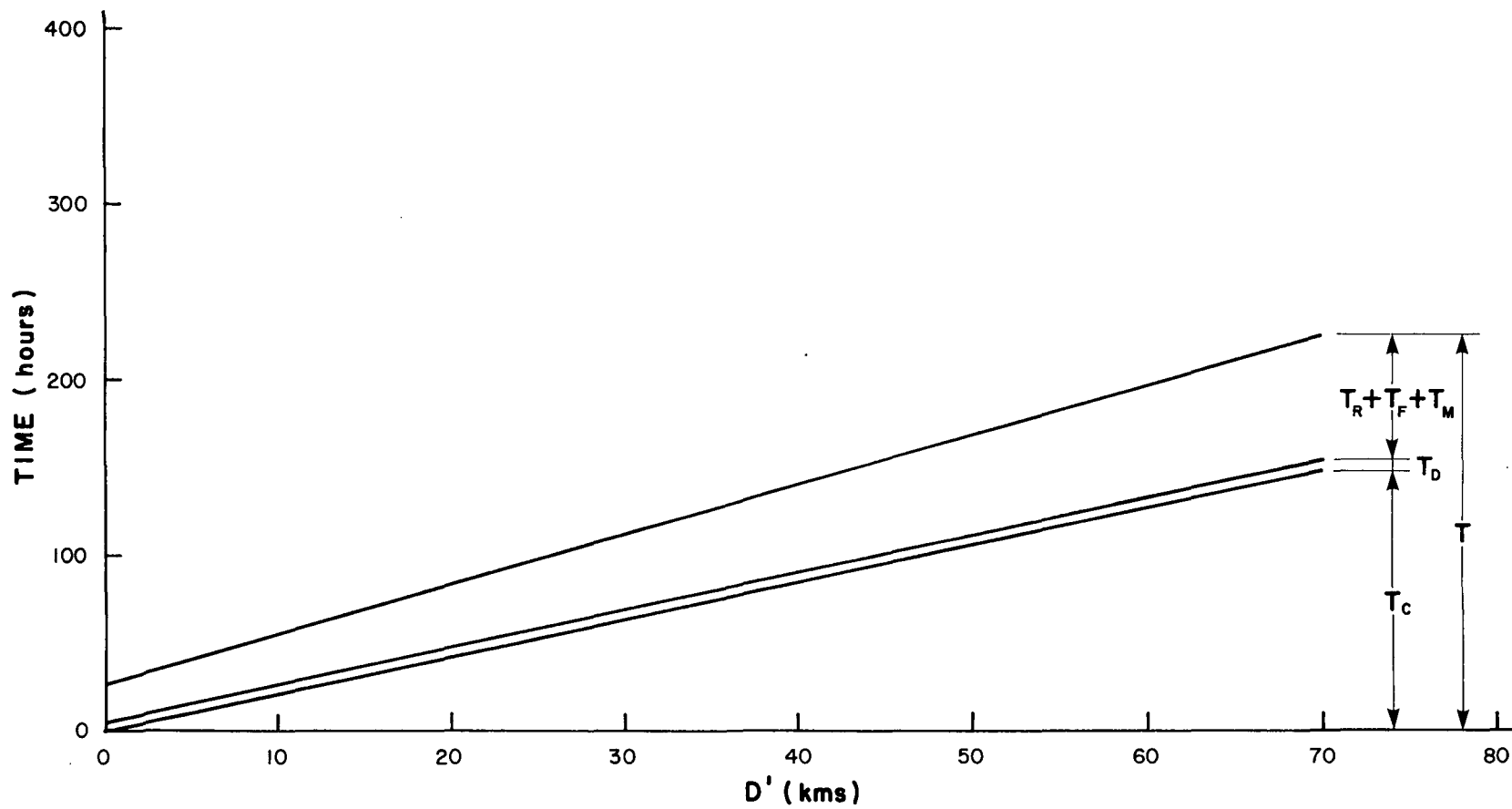


Fig. 13 — T vs D'

(Example Problem with ER=1:20 Single - Pass Operation)

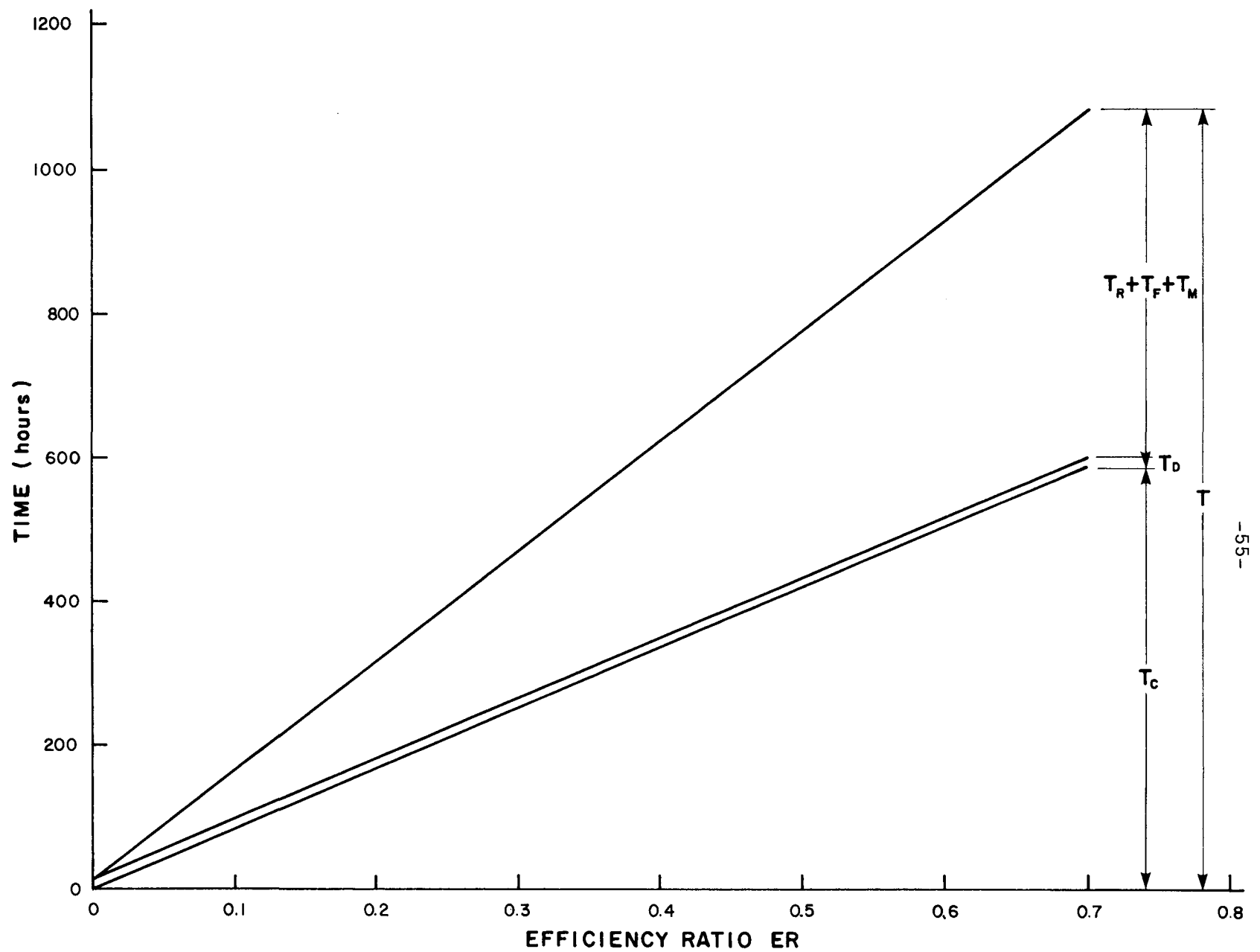


Fig. 14 — T vs ER (Example Problem Single-Pass Operation with $D^i=20\text{km}$)

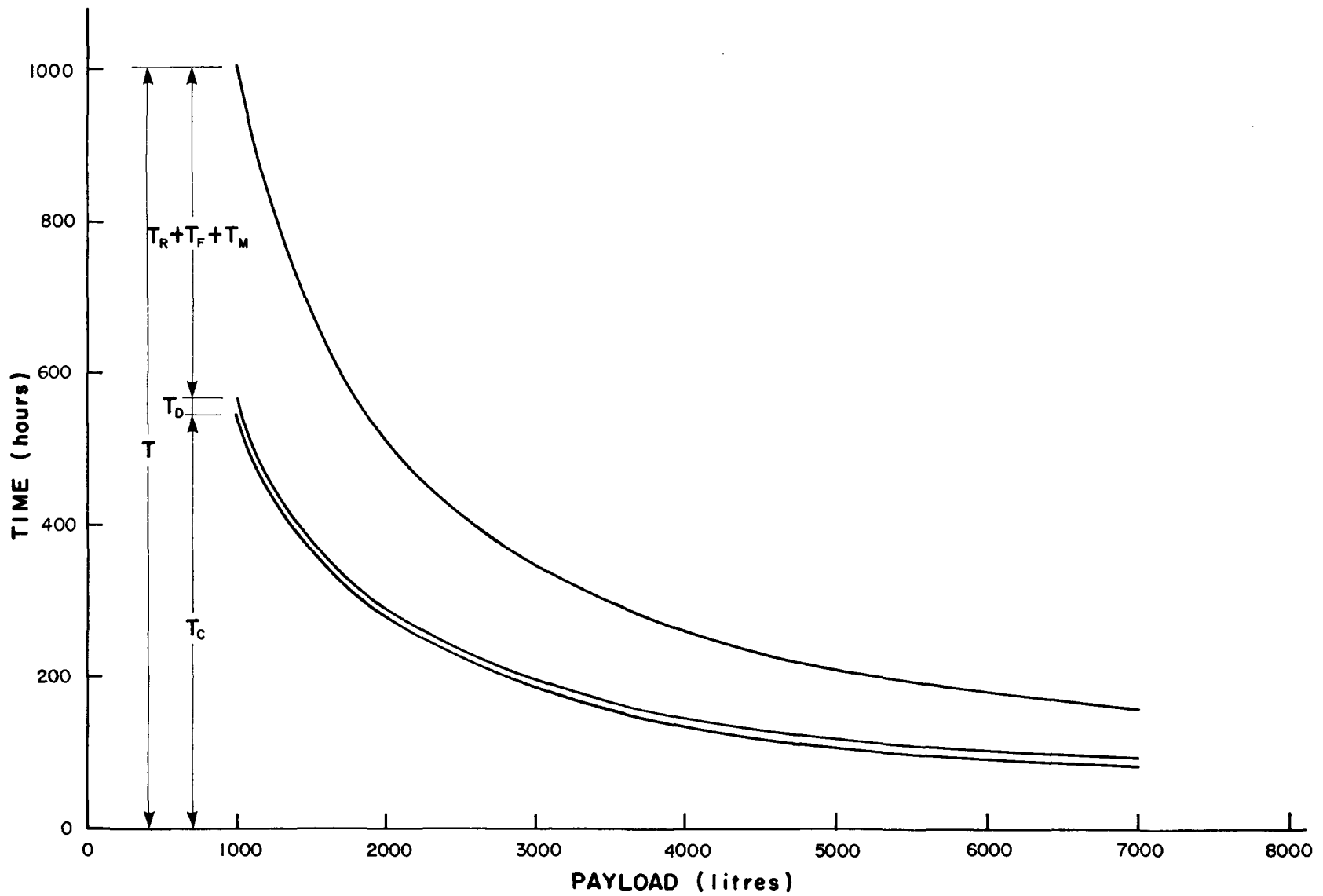


Fig. 15 — T vs P (Example Problem Single—Pass Operation)

7.4.4 Variation in Number of Passes, n_p . All calculations thus far have been based on single-pass operation. As can be seen from Equation (8), single-pass operation frequently requires high dosage rates $\cdot d$ and consequently large volume pumps.

$$\text{That is, } \cdot d \propto \frac{S_d}{n_p}$$

For a fixed $\cdot d$, S_d can increase if the number of passes is allowed to increase as well. Conversely, for a given S_d , the dosage rate can decrease if n_p is increased. Depending upon the minimum allowable S_d for the particular aircraft and dispersing system, and upon the maximum dosage rate (or pump size) achievable, the required number of passes can be determined.

Figure 16 illustrates the relationship between T and its major components and the number of passes, n_p , for the example problem. For increasing n_p , the total travel time, T_c , remains constant; the dispersing time, T_D , increases in direct proportion to n_p (assuming that the increase in n_p is due to a decrease in $\cdot d$). The total time for all operations would then increase according to the function:

$$T = 8.2 n_p + 154 \quad n_p = 1, 2, 3 \dots n$$

Note that at $n_p = 5$, the total time, T , for all operations equals 195 hours, compared to $T = 162$ hours for single-pass operations. The additional 33 hours for completion of all activities, however, allowed a dosage rate reduction of from 5,430 litres/min. to 1,086 litres/min. (see Section 7.3).

One critical simplifying assumption made is that n_p passes at a dosage rate $\cdot d$ is equivalent to one pass at a dosage rate $n_p \times \cdot d$. It is recognized that this assumption may be invalid. However, there is no currently known way to verify its validity.

7.4.5 Significance of S_d , w and $\cdot d$ Relationship. These variables are related as shown in equation (8) and Figure 11. The two principal aircraft types considered (i.e., rotary and fixed wing) have major performance differences which would influence these parameters.

As discussed in Section 5, the normal cruising speed for a fixed wing aircraft with a payload of at least 680 kg is about 270 km/hr. The stall speed on such aircraft generally is in the range of 110 to 130 km/hr. For normal safe operation at low altitude, a minimum possible S_d of about 190 km/hr is typical. Depending on the aircraft elevation, the swath width w is at least 20 metres, but is more likely to be greater.

Based upon an $S_d = 170$ km/hr, $w = 20$ m, $t_o = 0.25$ cm, and single-pass operation, $\cdot d$ would range from about 7,000 litres/min. for $ER = 1:20$, to about 142,000 litres/min. for $ER = 1:1$. Such high dosage rates, even with efficient dispersants, would require enormous pumping systems. In this example, numerous passages over the slick would be required to reduce the dosage rate to a reasonable level.

A rotary wing aircraft can travel with S_d very close to zero; however, due to low altitudes of the craft, a normal safe dispersing speed is considered to be about 65 km/hr. Propellor downwash

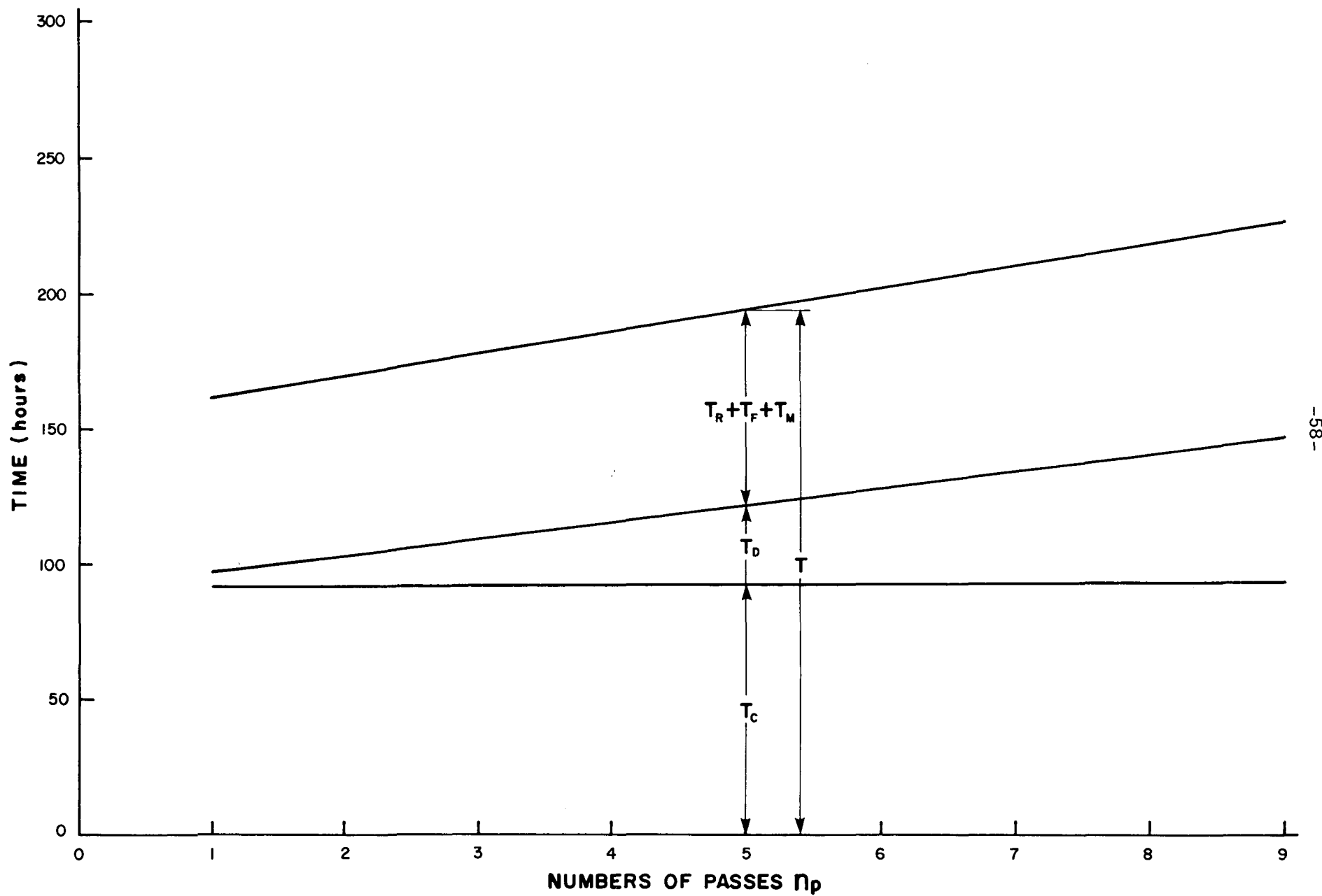


Fig. 16 — T vs n_p (Assuming n_p Increases Due to a Decrease in d)

tends to rotate any device connected by a single cable beneath the helicopter unless a suitable forward speed is maintained as well. Fins can be installed on the suspended device (i.e., spraying system in this case) to further retard any rotation at slower speeds.

Since a helicopter can fly very close to the water surface, w can be made as small as required. At values of $S_g = 65$ km/hr and $w = 20$ m, \dot{v} ranges from about 2,700 to 5,500 litres/minute for efficiency ratios between 1:20 and 1:1.

7.4.6 Operational Constraints. In Section 5 the characteristics of various aircraft are presented. Based on the preceeding sensitivity analyses, several operational requirements for the optimum vehicle, as well as a desirable spraying method, become apparent.

Important aspects of any planned aerial application program involve the minimization of time and costs required for the overall operation. These two objectives can be met, in part, by the development of response packages and procedures, which to the extent feasible: 1) reduce D' ; 2) improve ER (i.e., smaller value); 3) increase P ; and 4) involve appropriate combinations of S_g and \dot{v} so that n_p is kept as low as possible.

As discussed earlier, these latter parameters should be selected and field tested to provide a safe and reliable dispersing system (i.e., platform and spray equipment) which is both cost effective and responsive to the potential impacts of acute toxicity and sublethal concentrations following dispersal. For example, dosage rates may well be determined from maximum allowable concentration considerations rather than from speed and pumping limitations on equipment. In turn, similar concentration requirements may dictate an operational mode consisting of numerous (low-dosage) passes properly spaced in time.

8 COMPARISON OF SELECTED DISPERSANT APPLICATION PLATFORMS

The comparison of dispersant platforms and spraying systems is based primarily upon characteristics required to disperse a major oil slick 400 km by 20 metres at the edge of the landfast ice westward from the drill site as discussed in Section 3. This spill is assumed to be dispersed during May following an early October blowout. This slick is the most inaccessible one resulting from the hypothesized blowout and requires the most complex logistical program. Other than a comparatively small oil volume southwest of Banks Island, it is assumed that the rest of the oil is cleaned up by other countermeasures (Section 3.4).

The principal purpose of this chapter is to compare aerial-based systems to disperse the oil slick. However, for completeness, subsequent parts of this section will investigate ACV's and surface vessels.

8.1 Fixed and Rotary Wing Aircraft

The summary data provided in this section relate to the known and, in some cases, estimated performance characteristics of specific fixed and rotary wing aircraft. These data, combined with

comparative dispersant application packages, provide the input to assess each system using the previously described mathematical model and example from Section 7.

While numerous aircraft and dispersant application packages could be considered for a broader comparison of aerial application systems, the dispersing platforms selected here are felt to be representative of those which are both credible and presently available. The operational requirements and times for completion presented in this section should not be interpreted as indicators of the "best" aerial dispersant application system. Rather, they should provide a basis for comparison of typical fixed and rotary wing aircraft (for the defined spill configuration) and for subsequent comparison of air cushion vehicles and surface vessels in the following subsections.

The spill configuration from Section 7.3 is used to compare the total times resulting from the use of several application platforms and spraying systems. For comparison, four aircraft and three application methods are considered:

- 1) Sikorsky S-61 using a spray boom system;
- 2) Sikorsky S-64 using a spray boom system;
- 3) Canadian CL-215 using a spray boom system;
- 4) Lockheed L-100-30 using the MAFFS.

Each aircraft is assumed to operate from a sea ice base with $D' = 20$ km and the spill and dispersant characteristics are as in Section 7.3.

Due to unstable, deteriorating ice conditions after mid-May, a maximum total time for all dispersal activities T of 400 hours is assumed. Aircraft with \dot{v} such that $T > 400$ hours could be used, but more than one would then be required. Clearly T decreases in direct proportion to the number of aircraft of a particular type employed. Also, in order to keep the number of passes to a reasonable level, a maximum $n_p = 10$ is arbitrarily assumed.

Table 5 presents the operating characteristics and total times for these aircraft for various dispersing conditions. The results of Table 5 are graphically presented in Figure 17. The fixed wing aircraft are assumed to operate at a constant $S_d = 170$ km/hr., and variations in the total times result from changes in \dot{v} and n_p . Rotary wing aircraft allow wide variations in S_d . The example includes values of $S_d = 32.5$ km/hr. and 65 km/hr. As shown in Figure 17, all four aircraft are capable of dispersing this oil slick provided adequately large dosage rates are used. With the exception of the MAFFS for which very large pumping rates are claimed, a normal maximum $\dot{v} = 1,000$ litres/min. is reasonable, although rates higher than this are possible. For example, the CL-215 system described in the manufacturer's literature is based on a $\dot{v} = 1,360$ l/min.

Using these four aircraft and spray systems as typical, the following points are significant:

- 1) The lines in Figure 17 are dependent only upon the performance characteristics of each aircraft. For higher dosage rate \dot{v} the actual operating point is closer to the left end of each line.

TABLE 5 OPERATING CHARACTERISTICS OF SELECTED AIRCRAFT*

DISPERSING SYSTEM					OPERATING CHARACTERISTICS										
Variable	S	P	t_u	S_d	*d	n_p	t_p	n	T_D	T_C	T_U	T_R	T_F	T_M	T^{**}
Units	km/hr	litres	hr	km/hr	litres/min	-	min	-	hr	hr	hr	hr	hr	hr	hr
CL-215															
	280	5,346	.02	170	1,000	15	5.3	374	35	53	8	91	4	19	210
	280	5,346	.02	170	500	28	11	374	66	53	8	91	4	22	245
	280	5,346	.02	170	100	142	53	374	334	53	8	88	10	49	542
L-100-30 MAFFS															
	290	10,600	0.03	170	1,000	14	11	189	33	26	6	31	3	10	109
	290	10,600	0.03	170	500	28	21	189	66	26	6	31	2	13	146
	290	10,600	0.03	170	100	142	106	189	334	26	6	29	11	41	446
	290	10,600	0.03	170	14,200	1	0.75	189	2	26	6	32	2	7	74

*Assume: L = 400 km, w = W = 20m, t_o = 0.25 cm, D' = 20 km, ER = 1:10

PLATFORM: L-100-30 MAFFS

t_f = 0.20 t_r = 0.17
 t_a = 5.2 α = 0.1
 M_r = 1.12

PLATFORM: CL - 215

t_f = 0.33 hr t_r = 0.25 hr
 t_a = 9.4 hr α = 0.1
 M_r = 1.11

TABLE 5 (b) OPERATING CHARACTERISTICS OF SELECTED AIRCRAFT*

DISPERSING SYSTEM					OPERATING CHARACTERISTICS										
Variable	S	P	t _u	S _d	*d	n _p	t _{pp}	n	T _D	T _C	T _U	T _R	T _F	T _M	T**
Units	km/hr	litres	hr	km/hr	litres/min	—	min	—	hr	hr	hr	hr	hr	hr	hr
Aircraft 1															
170	6,500	0	65.0	1,000	1,000	6	6.5	380	37	73	0	30	22	24	187
170	6,500	0	65.0	500	500	11	13.0	308	68	73	0	30	27	30	228
170	6,500	0	65.0	100	100	55	65.0	308	339	73	0	28	71	77	589
170	6,500	0	32.5	1,000	1,000	3	6.5	308	37	73	0	30	22	24	187
170	6,500	0	32.5	500	500	6	13.0	308	74	73	0	30	28	31	236
170	6,500	0	32.5	100	100	29	65.0	308	357	73	0	28	74	80	613
Aircraft 2															
224	2,220	0	65.0	1,000	1,000	6	2.2	901	37	161	0	89	32	38	357
224	2,220	0	65.0	500	500	11	4.4	901	68	161	0	88	36	42	396
224	2,220	0	65.0	100	100	55	22.2	901	339	161	0	87	66	78	732
224	2,220	0	32.5	1,000	1,000	3	2.2	901	37	161	0	89	32	38	357
224	2,220	0	32.5	500	500	6	4.4	901	74	161	0	88	36	43	403
224	2,220	0	32.5	100	100	29	22.2	901	357	161	0	87	68	81	754

* Assume: L = 400 km, w = W = 20 m, $t_o = 0.25$ cm, D' = 20 km, ER = 1:10

II Total time differs slightly from the sum of its parts due to rounding off values.

PLATFORM 2		PLATFORM 1	
$t_f = 0.17$ hr	$t_r = 0.1$ hr	$t_f = 0.17$ hr	$t_r = 0.1$ hr
$t_a = 1.4$ hr	$\alpha = 0.12$	$t_a = 1.0$ hr	$\alpha = 0.15$
	$M_f = 1.24$		$M_f = 1.33$

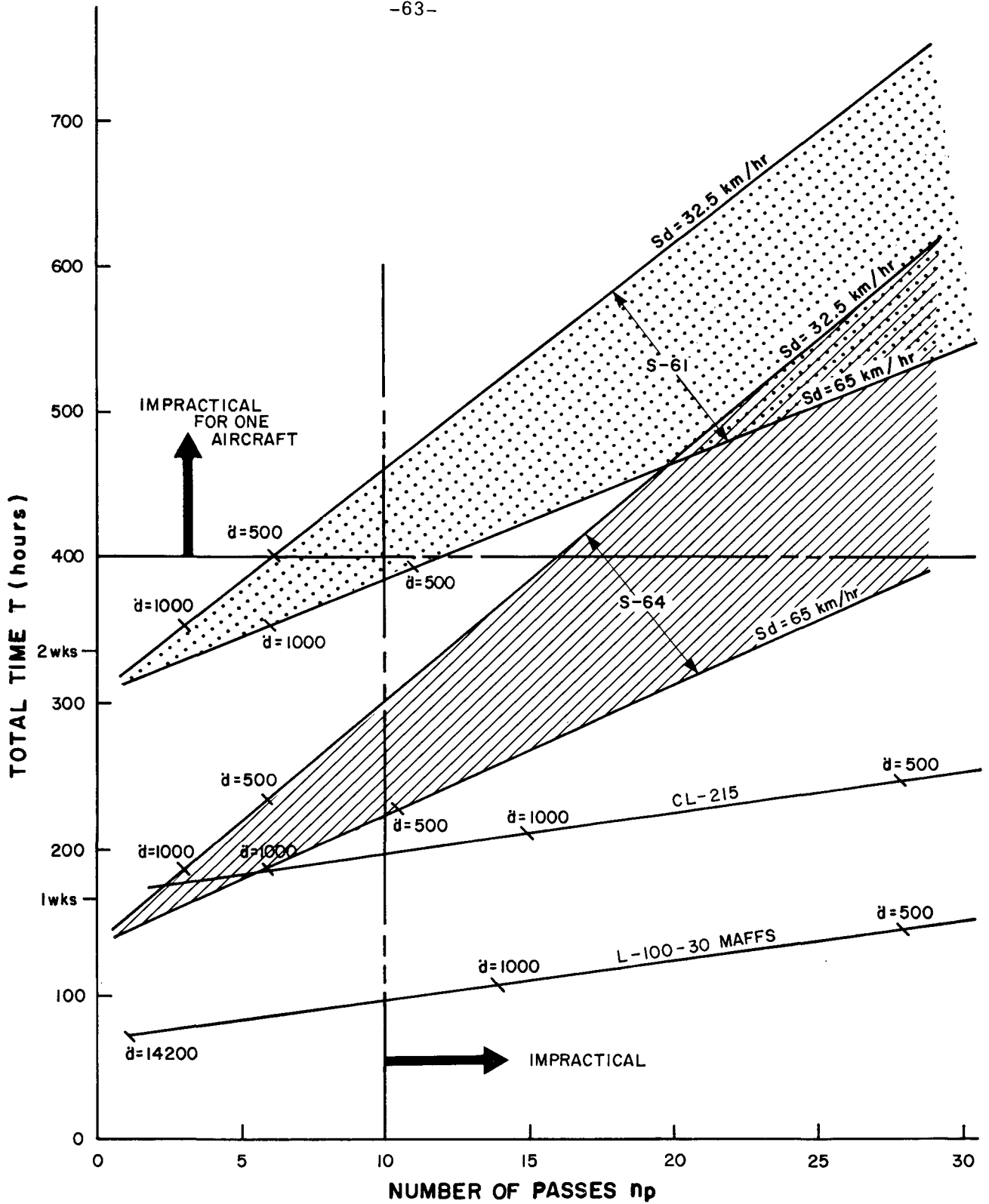


Fig. 17

Relationship of \dot{d} , T and n_p for
Selected Aircraft using Example Problem

- 2) In terms of ability to apply large dispersant volumes and minimize time the MAFFS is excellent. In an L-100-30 it is particularly effective in view of the aircraft's high payload. Since the system apparently fits other unmodified aircraft, similar time reductions are likely. For example, on a CL-215 using the MAFFS, the CL-215 line shown in Figure 17 would remain approximately the same. It would be shifted slightly upwards due to a reduced effective P (from the large parasitic weight of the MAFFS and other changes in times) but the operating point would be considerable to the left of d as per the current CL-215 dispersant package.
- 3) The CL-215 with the currently proposed system saves considerable time over either of the two rotary winged aircraft, but requires high pumping rates to keep the number of passes within reason.
- 4) At a very low number of passes the S-64 is marginally better than the CL-215, while the CL-215 is much better than the S-61.
- 5) The S-64 is much better than the S-61 in terms of time and required number of passes.
- 6) At lower speeds, all other variables being constant, a rotary wing aircraft significantly reduces the number of passes required while only slightly reducing the time to completely disperse the oil slick.

It is reiterated that these comments are only valid for the particular example chosen and the assumed operating conditions.

The previous comparison of aircraft is based on a common stockpile distance D' . For large capacity rotary wing aircraft it is important to minimize D' particularly for the S-64, which have a large payload drop for increased range. However, fixed wing aircraft, particularly a heavy L-100-30, may have difficulty operating safely from sea ice thicknesses expected to exist (Section 9.5). For these craft it is more likely that operations would be based from neighbouring onshore locations.

The following comparison is made between the S-64 and S-61 operating as before ($D' = 20$ km) and a MAFFS-equipped L-100-30 and a CL-215 as per manufacturer's description operating from onshore basis with $D' = 150$ km. The T , n_p , and d curves for this example are shown in Figure 18.

8.2 Air Cushion Vehicles and Surface Vessels

The practicality of using an ACV or surface vessel to disperse the example oil spill is questionable. However, should these craft be able to operate successfully in the leads which open in May, or should dispersant application be delayed until more open-water conditions exist, considerable time and cost savings would result from their use. Based upon the example problem previously used, the time for these craft to disperse the oil slick is less than 100 hours.

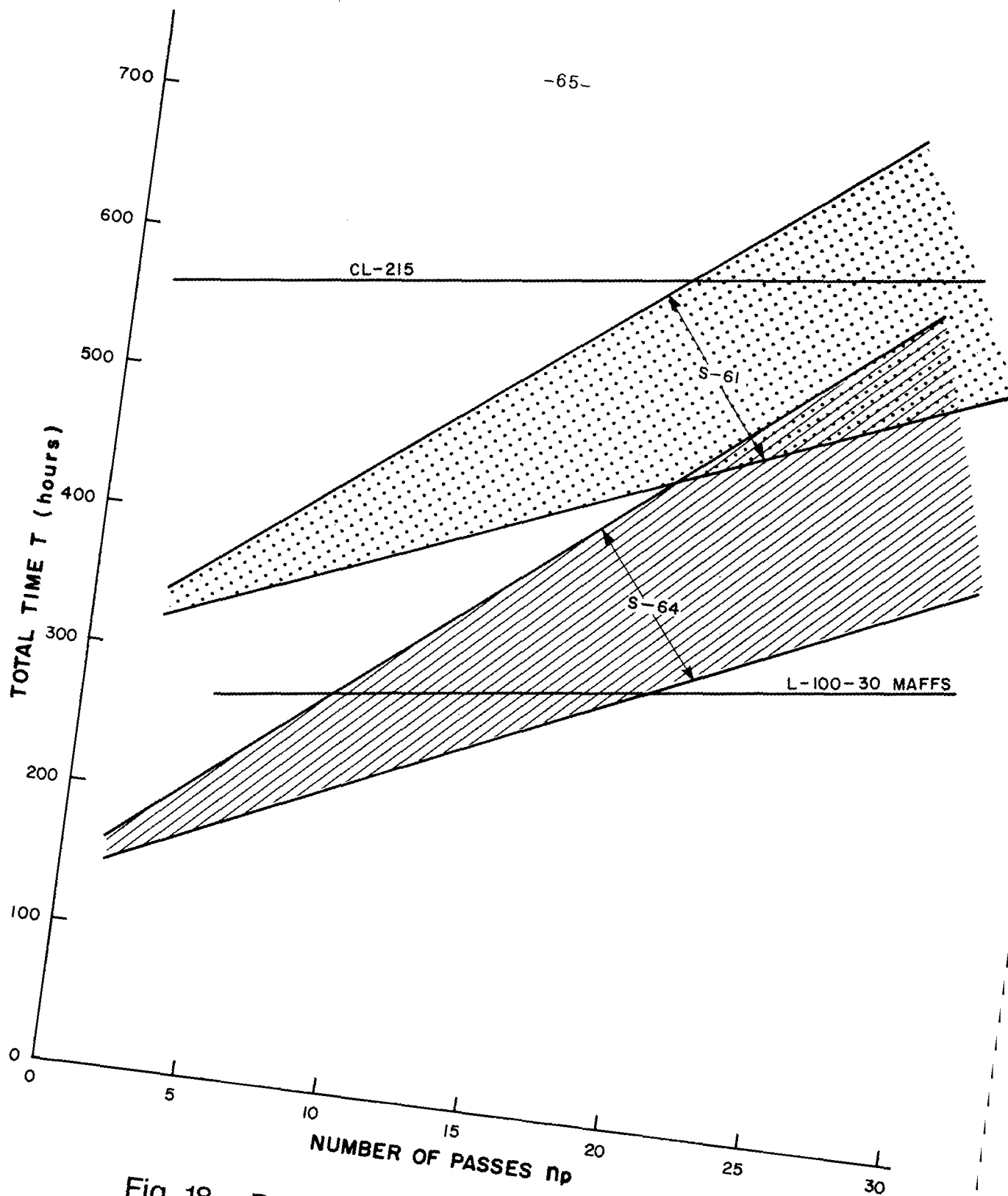


Fig. 18 — Relationship of \dot{d} , T and n_p for
 $D' = 20\text{km}$ Rotary Wing
 $D' = 150\text{km}$ Fixed Wing

At a dispersant application rate $\dot{d} = 1,000$ l/min. a Voyageur ACV operating on a single-pass could disperse the spill in about 80 hours (Table 6). This time estimate is based on a stockpile distance $D' = 20$ km. Due to the craft's large payload, the dispersant tanks on the ACV only need to be refilled six times. Such a few number of refills results in a very small T_c , and hence a larger percentage of the total time T is spent dispersing and not refilling dispersant and fuel tanks.

The ice-reinforced surface vessel is likely capable of carrying all the required dispersant in one payload, and hence no time is required for dispersant tank refills. Also due to the very high potential time that the vessel can travel without refuelling, virtually all the total time is spent dispersing chemicals (i.e. $T_d = T$). In this case no stockpiles are required other than at the vessel's home base. The total time required for such an operation based on $n_p = 1$ is merely L/S_d . That is, given the shape of the slick, all the surface vessel has to do is travel the length of the spill once at a speed S_d and the oil is assumed to be dispersed.

The normal operating mode for dispersant application from surface vessels involves a spray bar and use of surface breaker boards to impart mixing energy to the oil/dispersant mix. There could be considerable difficulty in effectively deploying breaker boards in the brash ice within the lead. In addition, the oil would likely pool to considerable thickness along the northern edge of the landfast ice and surface vessels would have difficulty reaching it. Such thick oil slicks could possibly be burned or pumped out using equipment that could readily be carried on the vessel.

9 RECOMMENDED DISPERSANT APPLICATION SYSTEM

9.1 Response Scenario

One of the critical elements in developing an actual dispersant application program is a knowledge of whether to stockpile sufficient dispersant material at a northern location before a blowout or whether to respond after its occurrence. If material is stockpiled during the previous open-water season or sooner, there are considerable transportation economies realized. The dispersants considered for use are either manufactured in Houston, Texas or Europe. Hence, it is assumed that Houston and P.O.E., Montreal are the source points for dispersant delivery. It is likely that Canadian sources would manufacture the material if required; however, the volumes which could be supplied are unknown at present and these potential sources are not considered further. Figure 19 shows several possible means of transporting dispersants from Montreal and Houston to the three key staging areas: Tuktoyaktuk, Coastal Sites and the Shorefast Ice.

These three sites are considered to be the principal ones from which dispersant platforms would operate. Tuktoyaktuk would likely be used only for surface vessels and possibly ACV's. Both the coastal and landfast ice sites would only be used by aircraft or ACV's.

In order to compare the costs for alternative responses, three possible scenarios are postulated. Time, manpower and cost estimates are subsequently derived for each of these:

TABLE 6 OPERATING CHARACTERISTICS OF ACV AND SURFACE VESSEL*

DISPERSING SYSTEM					OPERATING CHARACTERISTICS										
Variable	S	P	t _u	S _d	*d	n _p	t _p	n	T _D	T _C	T _U	T _R	T _F	T _M	T
Units	km/hr	litres	hr	km/hr	litres/min	-	min	-	hr	hr	hr	hr	hr	hr	hr
Voyageur ACV															
	87	360,000	0	10	835	1	430	6	40	3	0	25	2	14	83
	87	360,000	0	12	1,000	1	360	6	33	3	0	28	2	13	78
Surface Vessel															
	37	2 x 10 ⁶	0.3	10	835	1	2,355	0	40	-	-	-	-	-	40

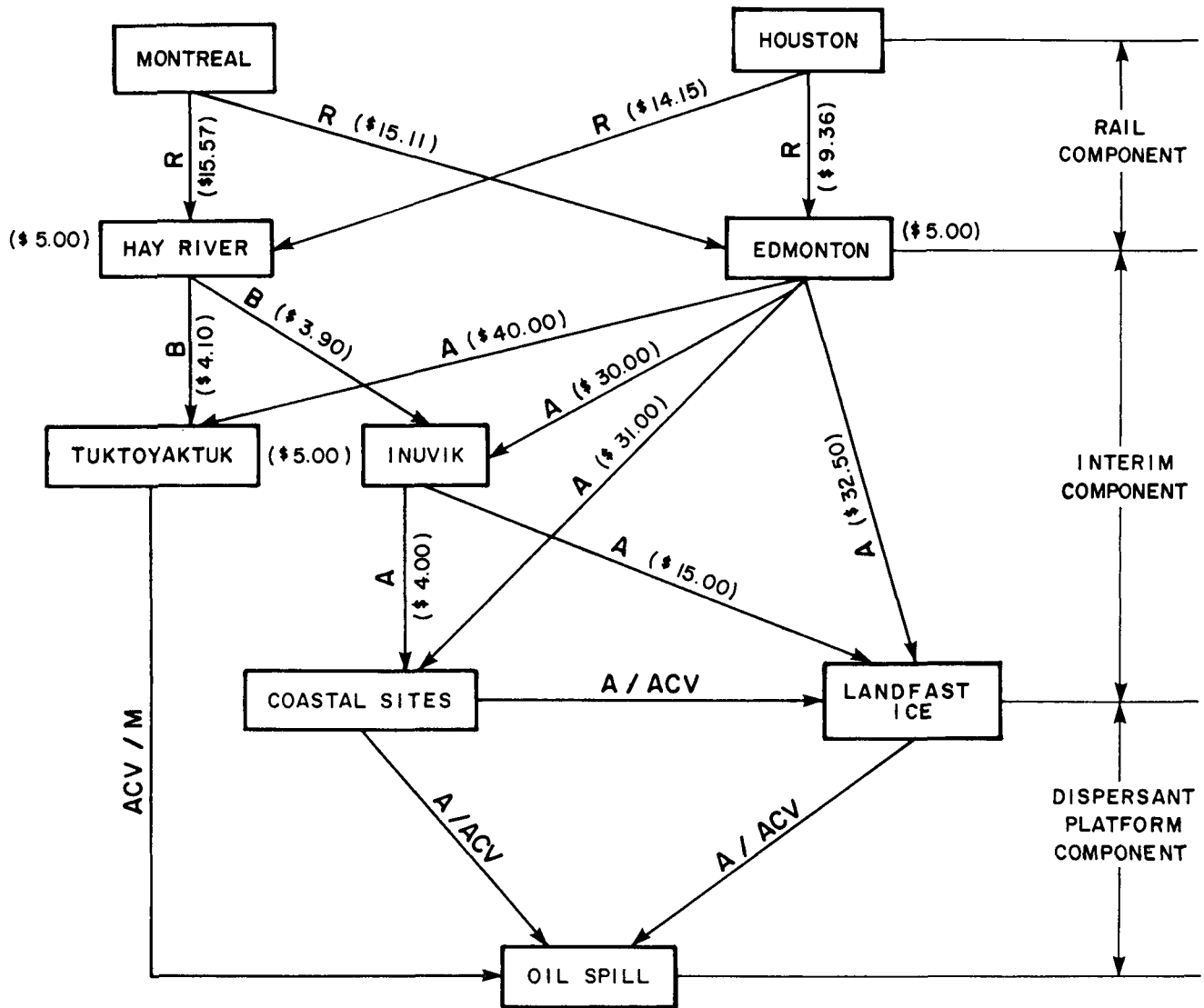
*Assume: L = 400 km, w = W + 20m, t_o = 0.25cm, D' = 20 km, ER = 1:10

PLATFORM: Surface Vessel

t_f = 0 t_r = 0
t_a = 1,000 α = 0
M_r = 1.0

PLATFORM: Voyageur ACV

t_f = 0.3 t_r = 10
t_a = 7.0 α = 0.20
M_r = 0.81



CODE :

- R - RAIL
- A - AIRCRAFT
- B - BARGE
- ACV - AIR CUSHION VEHICLE
- M - MARINE

NOTE: COST ESTIMATES ARE PER HUNDRED WEIGHT

Fig. 19
Dispersant Delivery Network

Scenario I

This scenario is based on responding after a blowout. Material is ordered from European and United States dispersant manufacturers as soon after an October blowout as possible. The material is railed to Edmonton and stockpiled there until mid-April.

At this time men and materials would begin mobilizing to clear landing sites on the landfast ice about 20 km away from the impending lead containing the oil spill. By late April, L-100-30's would deposit dispersant and fuel at these ice bases. A LAPES (Low Altitude Parachute Extraction System), which does not require a L-100-30 to land, could be used to deposit the material on the ice. The S-64 and other ancillary aircraft would move out onto the ice surface in early May. This operation would be complete and all men and equipment removed from the landfast ice by late May when the surface could be expected to begin deterioration.

Scenario II

This scenario is based on responding after a blowout. Material is ordered as soon after the October blowout as possible. It is railed to Edmonton for air delivery to coastal airports. Delivery can occur as soon as adequate coastal landing facilities are assured. It is likely that two or three major operations based would be required. In early May when the oil contaminated lead opens up, fixed wing aircraft, such as a CL-215 or MAFFS-equipped L-100-30, operate from these onshore bases and disperse the oil spill. Since all operations are land based, deterioration of the landfast ice by late May is not significant.

Scenario III

This scenario is similar to the above one except fixed wing aircraft double handle the dispersant and fuel from coastal sites to stockpile sites very close to the leads where an S-64 is used as the dispersant platform. Material is moved daily from coastal sites to the area of operation of the S-64, and hence the distance D' can be minimized.

9.2 Response Scenario Requirements

Each of the three response scenarios requires a unique combination of manpower and equipment. In order to estimate time and costs for such scenario, some estimate is required of the aircraft and ancillary equipment requirements. Aircraft other than the dispersant application platform would be required to move men, equipment and dispersant. Also, a spotter aircraft would likely be required to direct the application platform and ensure that activities are efficiently carried out. Such aircraft would be useful in view of the likely discontinuities in the slick and thick pool sections.

The following assumptions are made concerning each scenario:

Scenario I

The following aircraft are assumed to be required:

- | | | |
|----|----------------------------|--|
| -1 | Sikorsky S-64: | dispersant platform |
| -2 | Bell 206B's: | spotter aircraft and
moving materials on
ice . |
| -1 | DeHavilland DHC-3 (otter): | moving men back and
forth to onshore
areas . |

Scenario II

The following aircraft are assumed to be required:

- | | | |
|----|----------------------------|---------------------|
| -1 | Lockheed L-100-30 or | |
| -1 | Canadair CL-215: | dispersant platform |
| -1 | DeHavilland DHC-3 (otter): | spotter aircraft |

Scenario III

The following aircraft are assumed to be required:

- | | | |
|----|--------------------|--|
| -1 | Sikorsky S-64: | dispersant platform |
| -1 | Bell 206B: | spotter aircraft |
| -1 | Lockheed L-100-30: | movement from onshore
to landfast ice . |

9.3 Evaluation of Response Scenarios

In addition to presenting potential transportation modes, Figure 19 shows the estimated costs per hundred weight to transport material (dispersant plus containers) along any particular pathway. This figure also contains estimated transfer costs at certain interim unloading and loading points. These cost estimates are based and extrapolated from current (1976) charges. Rail freighting is assumed to be in standard box cars with a capacity of 10,886 kgs. Transportation via barge from Hay River is based on Northern Transportation Company Ltd. tariffs for barging and palletizing costs. Airfreight costs are based on Pacific Western Airlines tariffs for transportation from Edmonton to coastal or landfast ice sites. All costs are considered approximate only.

These are the three delivery pathways most likely dependent upon whether or not dispersants are stockpiled prior to a blowout:

	Delivery From		
Delivery To	Montreal	Houston	Comments
(cost per hundred weight)			
Tuktoyaktuk	\$ 14 . 67	\$ 23 . 25	Surface travel only
Coastal Sites	51 . 11	45 . 36	Edmonton – coastal sites direct
Shorefast Ice	52 . 60	46 . 86	Edmonton – landfast ice sites direct

The surface mode is viable only if material is stockpiled north of Hay River during an open-water season. For the purposes of this study, it is assumed that stockpiling before a blowout is not done.

Assuming for conservatism that dispersants are shipped in 45-gallon drums with a tare weight of 34 kgs, approximately 15% of the weight transported is non-useful material. Hence, the estimated delivery cost per hundred weight of dispersant via Edmonton is between about \$52.00 and \$60.00. Assuming that the required aircraft fuel is also airfreighted to the coastal or landfast ice sites, the cost per hundred weight to deliver it is about \$37.00. Hence, for cost estimating the following loaded costs are assumed:

Dispersant:	\$ 1 . 21 per litre
Fuel:	\$ 0 . 62 per litre

Table 7 presents an estimate of the costs for aircraft rental and fuel for each of the three scenarios. The total operating time for each dispersant platform is calculated using the formulae from Chapter 7. The times for ancillary aircraft are estimates based on that required for the dispersant platform. As seen, Scenario III is about 20% less costly than Scenario I. It should be borne in mind that these cost estimates are very approximate and the differences between scenarios are likely not significant. To these costs must be added those to purchase and deliver the dispersant. Table 8 gives the estimated costs for the entire dispersant application program for each scenario. As seen, the costs are virtually the same for each scenario. The difference between the upper and lower values is only 4%. Hence for estimating purposes, a per-cubic-metre dispersing cost of about \$510 is estimated (\$83 per barrel). These costs do not include several ancillary requirements which would add considerable cost to the overall program. No allowance has been made for clearing of airstrips, removal of empty drums, waste disposal, shelter, food, maintenance, etc. Therefore, cost estimates presented here are for optimal situations only.

TABLE 7 EQUIPMENT AND FUEL COSTS SCENARIOS I, II AND III

Aircraft Operations						Fuel			Total Equipment Cost
Scenario	Type	Number	Approx. Total Operating Time (hrs)	Per Hour Rental Cost	Total Cost	Consumption Rate (depends on payload) litres/hour	Amount Required litres x 10 ³	Fuel Cost @ \$0.62/litre	
I	S-64	1	190	\$5,000	\$950,000	2,046	388.6	\$241,000	\$1,376,000
	206B	2	380	\$310.	\$118,000	151	60.5	\$ 38,000	
	DHC-3	1	100	\$220.	\$ 22,000	114	11.4	\$ 7,000	
	Otter								
II (a)	C-130	1	280	\$2,500	\$700,000	227	636.4	\$395,000	\$1,177,000
	DHC-3	1	280	\$220.	\$ 62,000	114	31.8	\$ 20,000	
II (b)	CL-215	1	580	\$1,200	\$696,000	773	450.1	\$279,000	\$1,144,000
	DHC-3	1	580	\$220.	\$128,000	114	65.9	\$41,000	
III	S-64	1	100 ⁽¹⁾	\$5,000	\$500,000	2,046	204.6	\$127,000	\$1,047,000
	206B	1	100	\$220.	\$ 22,000	114	11.4	\$ 7,000	
	C-130	1	100	\$2,500	\$250,000	227	227.3	\$141,000	

(1) Based on D' = 2km

TABLE 8 ESTIMATED TOTAL COST FOR SCENARIOS I, II, and III

Scenario	Dispersant					Aircraft and Fuel Cost	Total Cost Dispersant Program	Cost Per M ³ of Oil Dispersed
	Delivery Point	Volume Required litres x 10 ⁶	Purchase Cost (per litre)	Delivery Cost (litre)	Total Cost			
I	Landfast Ice	2.00 ⁽¹⁾	\$2.16 ⁽²⁾ 3.21	\$1.21	\$8.85 x 10 ⁶	\$1.37 x 10 ⁶	\$10.22 x 10 ⁶	\$511
II	Coastal Sites	2.00	\$2.16 3.21	\$1.21	\$8.85 x 10 ⁶	\$1.17 x 10 ⁶	\$10.02 x 10 ⁶	\$501
						\$1.14 x 10 ⁶	\$9.99 x 10 ⁶	\$499
III	Coastal Sites	2.00	\$2.16 3.21	\$1.21	\$8.85 x 10 ⁶	\$1.05 x 10 ⁶	\$9.9 x 10 ⁶	\$495

NOTES:

(1) Based on 2×10^7 l. of oil and a ER of 1:10

(2) This is F.O.B. Houston Price of Corexit 9527 with 24% of Excise Tax + 12% Fed. Sales Tax.

9.4 Conceptual Designs

As discussed previously, the three dispersant platforms evaluated based on the previous analysis are essentially identical with regard to cost and these are:

1. Sikorsky S-64 with spray boom;
2. Canadair CL-215 equipped as per manufacturer's specifications;
3. Lockheed L-100-30 equipped with MAFFS

Conceptual designs for each of the aircraft are now presented.

9.4.1 Conceptual Design Sikorsky S-64 Skycrane: the S-64 is an aircraft which is uniquely designed to carry large payloads. The fuselage of this aircraft enables the dispersant tank to be externally mounted yet rigidly attached to the frame of the aircraft (Figure 20). Based upon the operating characteristics of the particular S-64 used, the dispersant tank could have a capacity of approximately 6,500 litres (230 ft³).

The design considered best for the planned operation is a fiberglass tank which, due to its lack of structural rigidity, should be mounted inside of a steel cradle. Fiberglass is selected since it can be simply repaired in field conditions without resulting in a major loss of time. The tank interior would be equipped with baffles to minimize the movement of dispersant, and hence increase the stability of the aircraft when in flight. If required, the tank would be equipped with an emergency door in the bottom for rapid dumping of the dispersant. A heater would also likely be underneath the cockpit in an exposed locations for rapid repair or replacement should it develop problems. A 35-horsepower, variable-speed, air-cooled, four-cycle engine should be adequate to pump dispersants at rates up to 1,000 litres per minute.

The spray boom would be mounted across the wheels of the S-64 and be at least 20 metres long. Nozzles on the spray boom should be designed to produce large uniform droplets for minimum evaporative and drift losses. A spray boom system, such as the Microfoil .060 system manufactured by Amchem Products Inc., is worthy of consideration.

Figure 21 presents a conceptual scheme for a tank, pump and spray system as described below. The cost to design and build such a system would be about \$ 150,000 and would require several days flying and spraying to test.

9.4.2 Conceptual Design Canadair CL-215. Canadair Ltd. has designed a spray system for the CL-215 which is described in detail in Appendix A.

9.4.3 Conceptual Design MAFFS-Equipped Lockheed L-100-30 (Hercules). FMC Corporation has designed the MAFFS for a Lockheed Hercules which is described in Appendix B.

9.5 Logistical Considerations For Ice-Based Operations

Considerable information has been published on criteria related to operating aircraft on sea ice. The usual sources for these data are the Transport Canada and the U.S. Army Cold Region Research

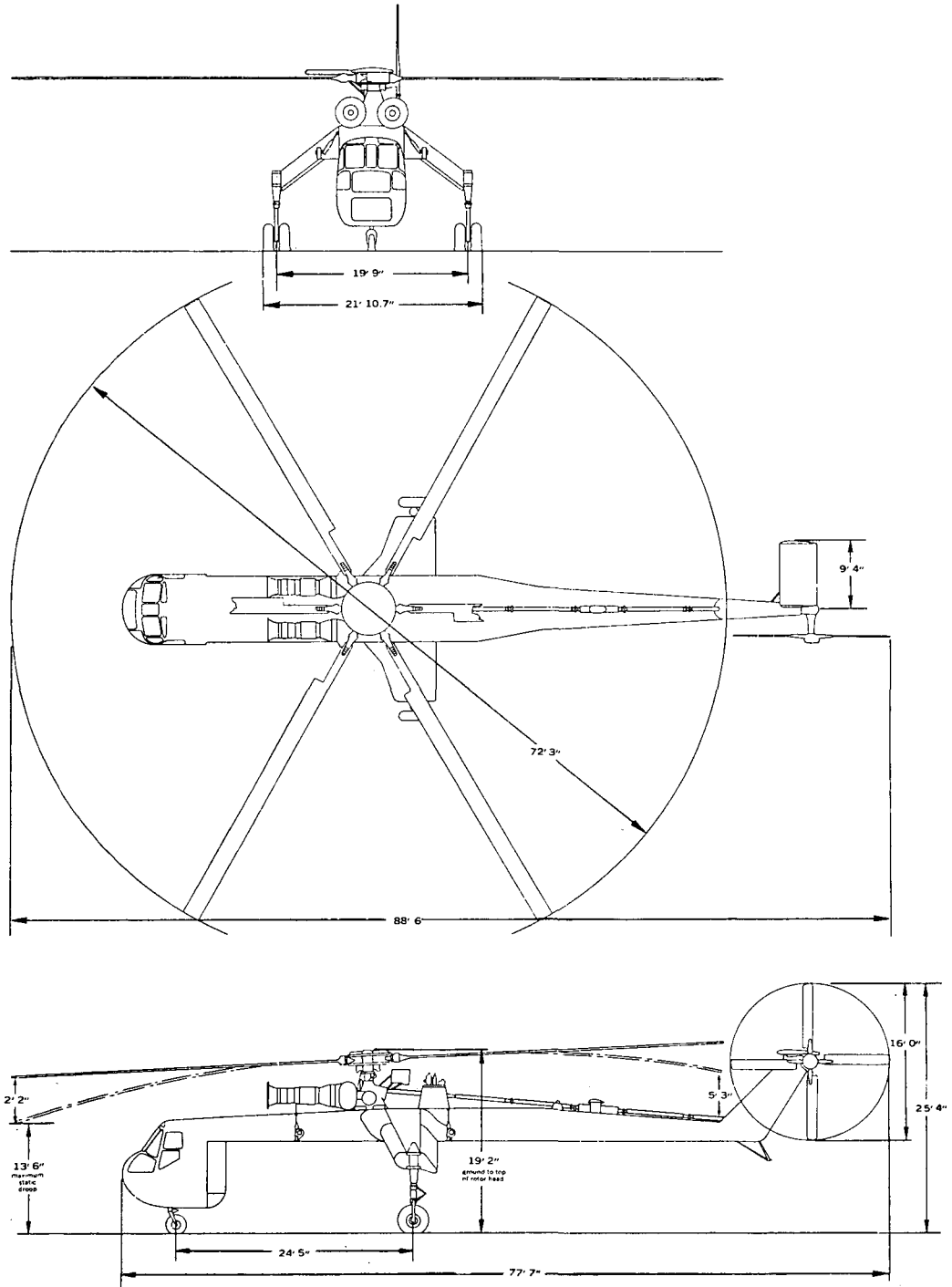


Fig. 20
Three View Dimensional Drawing S-64 SKYCRANE

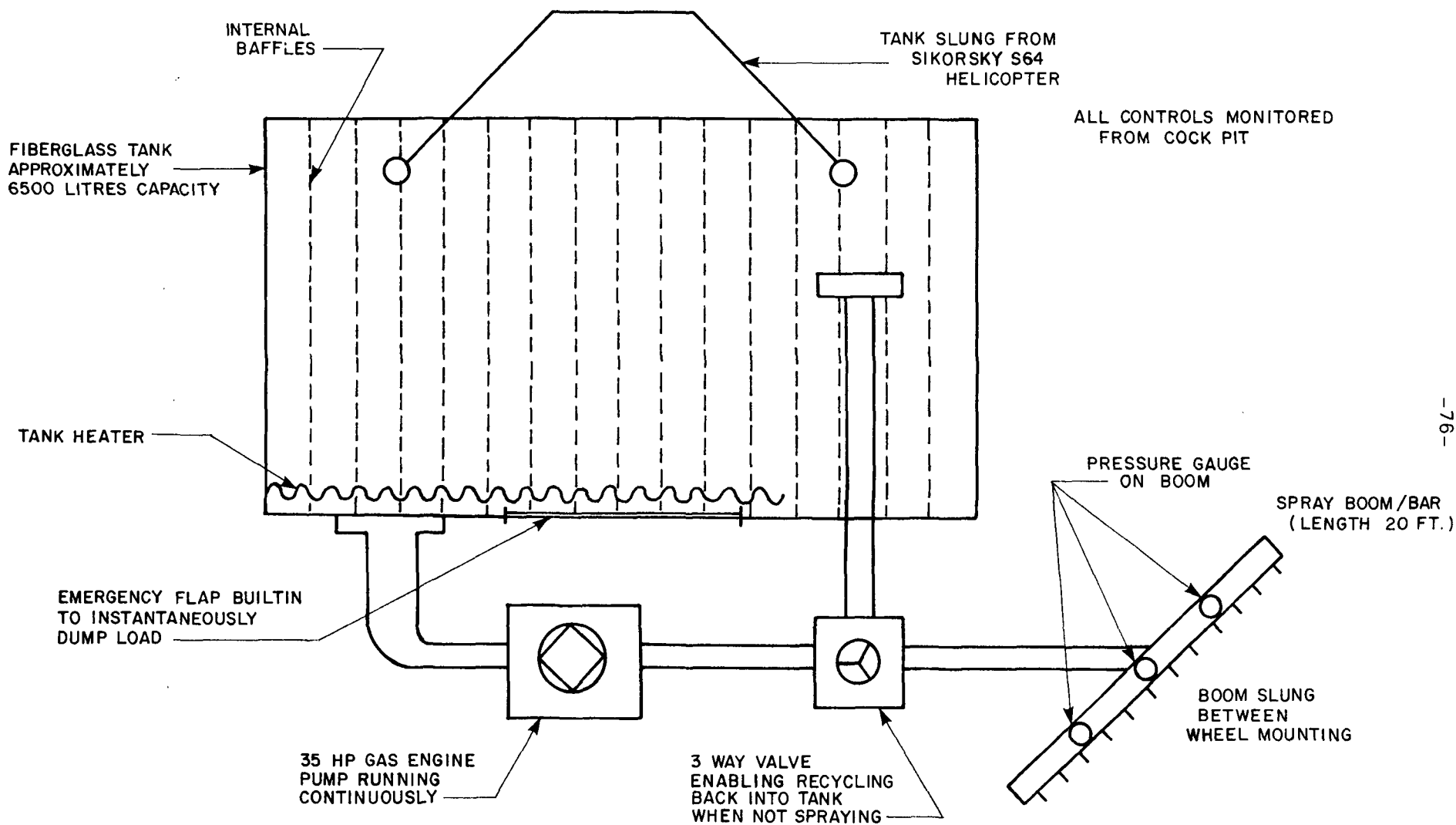


Fig. 21 — Conceptual Scheme S-64 Dispersant Application System

Engineering Laboratory (CRREL). The following discussion is based upon information from these sources supplemented by recent work done in the private sector primarily in Alaska.

Aircraft operations on ice depend upon a number of factors, the primary ones being ice thickness, salinity and climatic conditions. Salinity is an important factor in determining the required ice thickness for aircraft landings, since ice formed in seawater is considerably weaker than fresh water ice formed under similar conditions.

Studies by Transport Canada, CRREL and others have resulted in relatively simple criteria relating sea ice thicknesses which are suitable for various aircraft types and wheel or ski loads. Table 9 shows sea ice thicknesses required for regular operations of various fixed wing aircraft. Rotary wing aircraft would require similar but somewhat lower ice thicknesses due to smaller landing impacts. If aircraft operations on sea ice proceed at temperatures over -2°C , the required ice thicknesses should be increased up to 20% until there is deterioration of the ice surface due to slush or candling. All operations must cease for air temperatures over 4°C .

Graphs have also been developed to relate ice thickness to safe allowable bearing loads. Figure 22 shows such a relationship.

For aircraft parking over one hour, sea ice thicknesses allowed should be increased by 25 percent. For air temperatures greater than -2°C prolonged aircraft parking over one hour is not recommended unless ice thicknesses are considerably greater than indicated in Table 9.

Ice surfaces can be flooded to thicken them if minimum thickness requirements in Table 9 are not met. Generally for moderately low temperatures, e.g. -18°C , ice lifts of about 5 cms per 24-hour period are possible.

In addition to minimum thickness requirements it is important to exercise caution in the parking of aircraft, stockpiling of fuel and dispersant to ensure no problems arise from overlapping zones of influence of loads. Radii of influence of loads on sea ice are approximately:

Ice Thickness (cms)	Zone of Influence (metres)
25	24
51	43
76	55
102	70
127	82
152	95
178	107
203	116

New landfast ice begins to form in about early October and reaches a thickness of about 100 cm by late December. The maximum ice thickness reached is usually about 200 ± 50 cm by mid-May.

TABLE 9 SEA ICE THICKNESSES FOR SAFE LANDING OF SELECTED AIRCRAFT FOR REGULAR OPERATION

Aircraft Type	Gear	Assumed Gross Weight (kgs)	Ice Thickness (cms)		
			Air Temperature (°C)		
			-12	-7	-2
Otter	Wheels	3,266	36.8	41.9	50.8
	Ski	3,266	33.0	38.1	48.3
Dakota	Wheels	11,794	63.5	73.7	88.9
	Ski	11,794	53.3	63.5	78.7
G123	Wheels	25,402	88.9	96.5	119.4
G119	Wheels	32,795	94.0	101.6	124.5
CL-44	Wheels	83,916	142.2	165.1	195.6
C-130	Wheels	86,184	144.8	167.6	198.1

Source: CRREL & D&M

The first signs of deterioration are normally evident in early June and most areas are clear of ice by mid-July.

As discussed previously, air temperatures are critical in determining the time when ice-based operations are unsafe since all operations should cease at temperatures greater than 4°C. Air temperatures in the Southern Beaufort Sea do not normally reach 4°C until early June (Tuktoyaktuk data, Burns, 1973). This is about the general commencement of deterioration of the sea ice surface, and hence when normal ice-based operations would be terminated. Air temperatures normally reach about -2°C in mid-May and therefore after mid-May the required ice thicknesses given in Table 3 would need to be increased for safe operation.

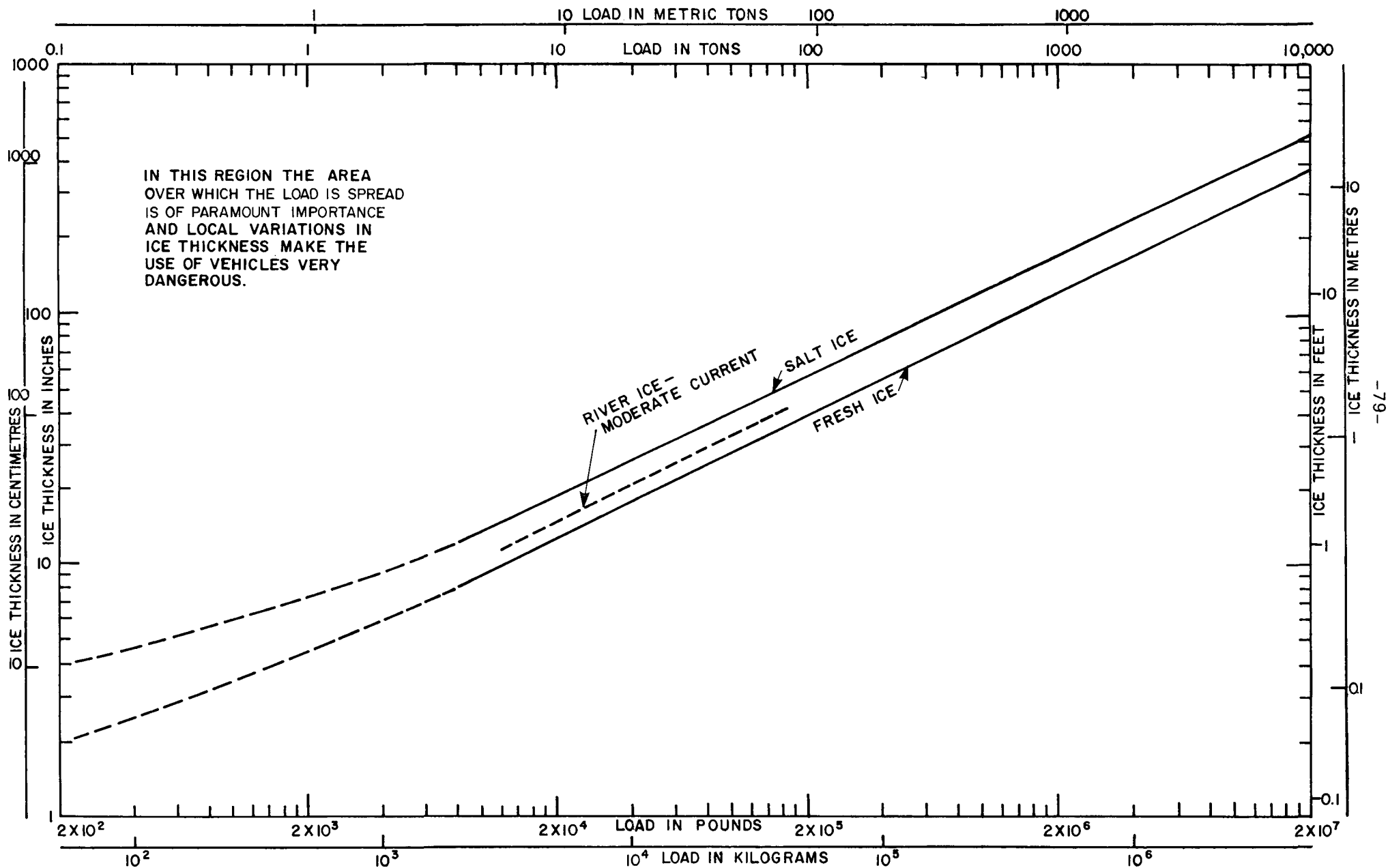


Fig. 22 — Relationship Between Allowable Load and Ice Thickness

Based upon the previous discussions it is concluded that under normal conditions with mid-May ice thicknesses of 200 cm and the commencement of temperatures greater than -2°C , and hence initial ice deterioration, that large capacity Hercules aircraft can operate on the ice until shortly after mid-May. Smaller capacity aircraft could be used until early June. All rotary wing aircraft types can safely operate under these conditions until well beyond early June possibly into the third week of the month.

Based upon Figure 22 and an assumed ice thickness in May of 200 cm (79 inches) surface loadings up to 136,000 kgs are acceptable, provided such loads are about 116 metres apart.

10 LABORATORY AND FIELD TEST PROGRAMS

There are numerous unknowns affecting the viability of an aerial application program as discussed. Several major unknowns relate to the characteristics of dispersants employed and to the properties of oil to be dispersed. In addition, there are more scenario specific questions that would need to be answered to select confidently one application system over another. In order to fill in the major data gaps, a co-ordinated laboratory and field testing program is suggested.

10.1 Laboratory Tests

It is apparent from discussions in Sections 3 and 8 that the toxicity and effectiveness of dispersants will be critical factors in determining the viability of the application program. While important, toxicity-related laboratory tests are considered beyond the scope of the current study and not discussed further. The following points focus on effectiveness related issues specific to aerial application.

10.1.1 Static Effectiveness Tests. The effectiveness tests used to evaluate all dispersants discussed in Section 4.2 are dynamic and require the application of high levels of mixing energy. It is recommended that low-energy tests, such as the swirling beaker test, be considered. Discussions are currently underway between United States Environmental Protection Agency representatives and their Soviet counterparts, relating to the development of a standard, low-cost test of this type.

10.1.2 Temperature Effects. Most SET tests run by the EPS use minimum water temperatures of 5°C , although a few at 0°C have been run. It is recommended that tests in saltwater be performed at temperatures in the order of -2°C , which would be common in the Beaufort Sea ice leads and polynyi.

10.1.3 Saline Effects. The surface waters of the Southern Beaufort Sea are brackish (salinity as low as 15 parts per thousand). These reduced salt levels are likely due to surface water runoff, freshwater input from the Mackenzie River and ice melt. Dispersant effectiveness varies widely depending upon water salinity and most are more effective in seawater than in freshwater.

It is recommended that effectiveness tests to select or develop a dispersant for use in the Beaufort Sea include lowered salinity water.

10.1.4 Slick Thickness Effects. The problem of penetration of dispersant droplets through a viscous, crude oil slick has apparently not been studied adequately to date. It is one of the most critical issues in determining the viability of the planned program. While dispersants generally are less efficient at lower temperatures, the reasons for this decline are not fully known. Penetration through viscous slicks rather than lowered chemical reaction rates could be the major reason for reduced effectiveness.

As discussed in Section 6.1, the kinetic energy differences for droplet sizes to be expected from aerial platforms vary widely and could strongly influence the suitability of a given platform. This is a problem that is much more critical in Arctic climates than in temperate areas where most applications have been considered to date.

10.1.5 Dispersant Aerosol Effects. Evaporation of solvents with the resulting alteration of chemical properties is a major problem when considering the aerial application of dispersants. It is recommended that a test program be set up to assess the true chemical properties of the various dispersants when they have free fallen in air of given temperature, humidity, horizontal wind speed, for varying periods of time. The program should cover a range of droplet sizes.

10.1.6 Multiple-Pass Effects. Throughout the discussions to this point, it has been tacitly assumed that from a dispersal point of view the dosage rate $\cdot d$ is the only critical variable. That is, it has been assumed that it makes no difference if the number of passes n_p is increased by some multiple, as long as the dosage rate $\cdot d$ is decreased by the same multiple. This is clearly an oversimplification.

It is recommended that tests be undertaken to simulate varying combinations of $\cdot d$ and n_p to assess their effect on the efficiency of various dispersants.

10.1.7 Weathered Beaufort Sea Crude. No effectiveness tests have been run on crude oil from the Beaufort Sea. If and when such crude becomes available, it is recommended that it be used in weathered conditions as a test oil.

10.1.8 Frozen Dispersants. When operating in the area as planned, dispersants may be exposed to several freeze-thaw cycles before being used. Data are insufficient to assess the effect of such cycles on their chemical characteristics.

10.1.9 Water-in-Oil Emulsions. Beaufort Sea crude oil may under the action of waves in ice leads, form stable water in oil emulsions. The probability of this happening is, of course, unknown. However, if such a mousse is created, it may be difficult if not impossible using aerial methods, to disperse this into the water column. If possible, the significance of this problem should be addressed in laboratory tests.

10.2 Field Tests

The field test program would enable a site specific determination to be made on the suitability of various critical components of the program. For cost minimization it is recommended that selected components of this program be deferred until completion of certain laboratory tests.

10.2.1 Performance of Potential Aerial Platforms. It is not possible to justify selection of one particular application platform based on current information. While the rotary wing platform appears best

in view of its lower cost, minimized aerosol problems and flexibility, an oil dispersing scenario based on fixed wing aircraft offers several advantages.

It is suggested that each of the three basic platforms considered, namely the S-64, CL-215 and the MAFFS-equipped L-100-30, be tested in the Southern Beaufort Sea. The test should be run as a simulated oil spill response. However, it is likely that using oil or dispersants would not be acceptable. The test should assess each craft's capability with regard to:

- low altitude flying and dispersal;
- control of application patterns, aerosol and wind drift;
- flexibility concerning swath widths. to this point, it has been assumed that the swath width for fixed wing aircraft can be very narrow ($w = 20$ m); this may not be feasible;
- ability to operate from landfast ice;
- the values of t_r , t_a , t_u , α , as well as t_r , should be determined for each craft under true field conditions;
- suitability of the LAPES for ice-based operations;
- more detailed cost estimates including manpower and support equipment requirements.

10.2.2 Air Cushion Vehicles. The Bell Voyager offers a number of potential advantages over aerial platforms. These potential advantages are balanced by several critical unknowns concerning the suitability of this vehicle as a dispersant platform. In addition to the areas listed in Section 10.2.1 that apply to an ACV, a field test program of this vehicle should include an evaluation of:

- ability to operate in ice conditions, particularly in leads, broken ice fields and over oil slicks;
- location of dispersant spray system - i.e., whether aft under the craft's skirts or off the sides.

11 SUMMARY AND CONCLUSIONS

11.1 Summary

The study has taken a detailed look at selected components involved in establishing the feasibility of aerially applying dispersants on oil resulting from a Beaufort Sea blowout. The approach has purposely focussed on those areas affecting operational feasibility only. Little attention has been given to other critical areas such as ecology, comparisons with alternative countermeasures or even a detailed comparison with alternative dispersant platforms.

The study has purposely been based on general assumptions and mathematical formulae that can be used to evaluate other spill configurations, volumes, locations or even other dispersant platforms. The mathematical formulations are critical elements in this study. It is possible to extend these equations and eventually computerize them to develop an exact optimization of the delivery and

application systems. In this study, however, the formulae are simply used to discuss a few scenarios related to the dispersing of the main oil slick resulting from a blowout.

Based on the developed scenarios, the total cost to disperse 20,000 m³ of oil is in the neighbourhood of \$10 million or \$510 per m³. This figure consists of about \$1.3 million for equipment rental and fuel and \$8.85 million for dispersants. No allowance has been made for other costs such as manpower, ancillary logistics such as shelter, food, waste disposal, developments of airstrips, etc. These costs could be considerable.

While there are numerous critical unknowns which could be further investigated in a laboratory and field test program, application platforms appear worthy of further study and these are:

1. A heavy-lift rotary wing aircraft such as the Sikorsky S-64 Skycrane using a spray boom;
2. A Canadair CL-215 using the manufacturer's recommended spray boom system;
3. A Lockheed L-100-30 using the high-volume MAFFS.

Each of these with ancillary aircraft appears to cost approximately the same to disperse the oil volumes discussed. Approximately 13% of the total program cost is for aircraft.

It is not possible to recommend particular dispersants due to lack of knowledge concerning their properties. However, concentrate dispersants are recommended for further study. In particular, the following products are considered: Corexit 9517, 9527 and 19-L-50, Finasol OSR5 and BP1100WD (Synperonic OSD 20).

11.2 Conclusions and Recommendations

The use of dispersants as an oil spill countermeasure in the Beaufort Sea will involve very high costs both in economic terms and potentially in ecological terms. Regardless of the application method, a cost to purchase and deliver dispersants to a spill is at least \$445 per m³. To this must be added the cost of dispersing, which for aerial platforms would be in the neighbourhood of \$65 per m³. These costs do not include ancillary equipment and manpower.

Applying dispersants to oil slicks in the neighbourhood of 0.25 to 1.0 cm thick in shallow water depths found on the Southern Beaufort Sea continental shelf will result in concentrations of hydrocarbon molecules, hundreds or thousands of times greater than those considered safe on a sublethal toxicity basis.

If the anticipated costs are not considered prohibitive and aerial-based methods are to be further pursued, it is recommended that a comprehensive laboratory and field test program be undertaken. It is recommended that a detailed laboratory program be performed to ensure selection of the most efficient, low-toxicity product. Manufacturers have not invested in the development of products specially formulated for Arctic waters and it is likely that entirely new dispersant formulations may be required.

If laboratory tests indicate the suitability of further testing, it is recommended that a comprehensive field simulation be performed to test all phases of the selected countermeasure scenario in particular those facets related to operation of dispersant platforms on sea ice.

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APPENDIX A

THE CL-215 SPRAY SYSTEM

APPENDIX A: THE CL-215 SPRAY SYSTEM

This system is designed to:

1. perform a wide range of spray operations involving low, medium and high-application rates.
2. be installed in any CL-215 aircraft with minimum modification by making maximum use of existing structure and equipment.
3. be capable of rapid installation and removal.
4. have little or no effect on the aircraft's performance in its other roles.

The system consists of a system package mounted on a pallet 89 cm by 89 cm (35 in by 35 in); a hydraulic power supply system; suction, recirculating and boom feed lines and a full-span boom.

The chemical to be sprayed is carried in the aircraft's internal tanks, which have a total capacity of 5,346 litres (1,176 Imp. gallons). However, in order to avoid spillage through the tank overflow vents during manoeuvring, the load is usually limited to 5,000 litres (1,100 Imp. gallons) in practice.

The system package includes two hydraulically powered spray pumps, one 5 cm (2 in.) and one 7.62 (3 in.); spray system control valves, hydraulic control panel and spray system filter. The package pallet is attached to cargo tie downs in the cabin floor to the rear of the wheel well. The pallet can be installed or removed in about 30 minutes.

Hydraulic power to drive the spray pumps is supplied by an engine-driven pump on the left engine. A hydraulic reservoir is located in the left nacelle.

The boom is attached to the bottom of the flap hinges and to support attachments from the underside of the wing.

Operation

Normal procedure is to actuate the spray system immediately after engine start and to circulate the chemical through the pump and back to the tanks to achieve a homogeneous mix prior to spraying.

Performance

Installation of the spray system has no effect on the fire fighting capability of the aircraft apart from a reduction in maximum water load of approximately 225 kg, the weight of the spray system. The added drag of the boom reduces the cruise speed by roughly 3 knots.

The system is highly flexible in operation and can apply chemicals at application rates ranging from 1.1 litres per hectare (16 fl ozs/acre) to 50 litres per hectare (4 Imp. gal/acre). Maximum

system output is 870 litres per minute (190 Imp. gal/min). System pressure can be regulated from 0.28 kg per sq m to 2.8 kg per sq cm (4 psi to 40 psi). A total of 120 spray nozzles can be installed in the boom.

Calibration

The system must be calibrated for each type of operation to achieve the desired application rate for that particular job. Calibration involves arriving at the optimum arrangement of flow rate (for low and medium-volume application the 5-cm (2-in.) pump is used and for higher volumes the 7.62-cm (3-in.) pump is used) system pressure, the number of nozzles and the type of nozzle tip.

For example, the Government of the Province of Quebec uses CL-215's to spray insecticide on budworm infestations in spruce and balsam-fir forests. The objective of the spray operation is to apply a large number of very small droplets over the widest possible swath.

After conducting a series of tests, the Quebec Air Service established that the most effective swath is obtained using a flow rate of 200 litres per min (44 Imp. gal/min), a system pressure of 1.12 kg per sq cm (16 psi), and 74 open nozzles with no tips. This combination gives an application rate of 1.1 litres per hectare (16 fl oz/acre). A swath width of 500 metres (1,600 feet) is achieved by use of the cross-wind application technique. This technique, also termed the height/draft technique or the Porton method, enables the effective swath width to be doubled or even tripled by using the factor of aircraft height and wind velocity to control the pattern of spray droplets. When the wind speed is low the aircraft flies at an altitude of around 100 metres (300 feet) and the altitude is decreased progressively to a minimum of about 30 metres (100 feet) as the wind speed increases to its maximum allowable of about 22 km/hr (12 knots).

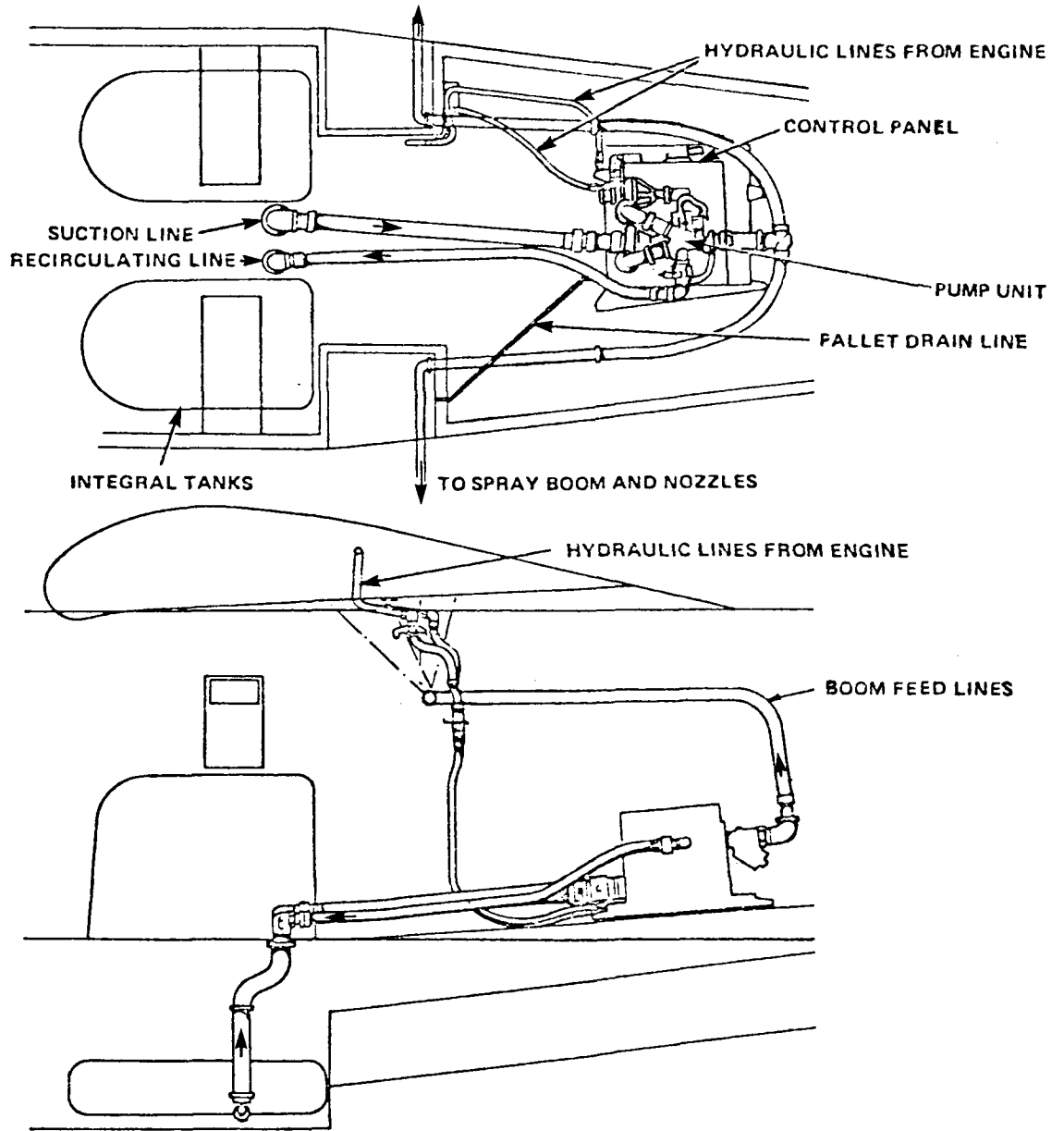


Fig. 23 — CL-215 Spray System

APPENDIX B

THE MAFFS CONCEPT

APPENDIX B: THE MAFFS CONCEPT

The FMC MAFFS (Modular Airborne Fire Fighting System) is a self-contained system designed to quickly convert an unmodified cargo aircraft (fixed or rotary wing) into a highly effective aerial tanker. As the name implies, MAFFS systems in present usage have been designed and built to carry and discharge fire-retardant chemicals for use in fighting forest fires.

The basic system, however, is quite well suited for conversion into an aerial delivery tool for oil spill dispersants. As such, it would offer the following benefits:

1. A MAFFS unit may be installed in any unmodified aircraft (fixed or rotary wing) of the type for which it is designed, normally during a time period of one hour or less. This gives the user a capability of rapid disaster response without the associated cost of procuring (or contracting) a permanently modified standby aircraft.
2. Due to the size of cargo planes in which the MAFFS is normally used, the system provides high payload capability, usually between 1,500 and 4,000 gallons. This is a valuable asset, especially because the oil spills on which self-mixing dispersants would most likely be used, will be of large magnitude requiring delivery of substantial amounts of dispersant chemicals.
3. The MAFFS is a fully self-contained system requiring no additional equipment onboard the aircraft. Ground support equipment to recharge pneumatic and fluid systems between airdrop missions is available.
4. Due to its self-contained nature, MAFFS is well suited to a multi-function role. For example, when not being utilized to deliver fluids from an aircraft, the system could be installed on shipboard to render it an effective system for marine delivery of fluids. A single system could also be configured to deliver either oil dispersant or fire-retardant chemicals by using alternate discharge modules.

Principal of Operation

MAFFS was conceived to be simple while effective. Self-stored pneumatic pressure is introduced into the fluid storage tanks prior to fluid delivery to provide regulated, uniform fluid discharge rates without requirement of onboard pumps or other complex equipment. All system functions are controlled from a central panel, and major system functions can be controlled from the aircraft flight station. Control interlocks are provided to assure correct operational sequence, and backup and emergency provisions are made to deal with system or aircraft malfunctions.

Current Systems

Over 150 successful retardant drops have been made over forest fires by the U.S. Forest Service using Air Force C130's and eight MAFFS systems. The Forest Service has also successfully flight-tested a MAFFS in a CH 47 Helicopter at Apalachicola Army Test Facility in Florida. A prototype

MAFFS for Aeritalia's newly developed G-222 Aircraft was recently delivered and has successfully completed ground and flight testing in Italy.

In addition to the above units, concept design work has been done in preparation of proposals for C119, C123, and L-100-30 Aircraft. The MAFFS design is also highly adaptable to a wide variety of other aircraft.

Converting MAFFS to the Role of Oil Dispersant Delivery

MAFFS exists at this time as a successful system for aerial fluid delivery. Major component designs and purchased hardware components have been proven in past and current customer usage. Although system modifications and/or revised system layout (i.e., to tailor size, weight, and CG to the aircraft desired) will be required, basic system elements will continue to exist as successful, proven components.

The primary requirements which must be met to convert the MAFFS from its forest-fighting role to one of dispensing dispersants are twofold:

1. Provide for even distribution of fluids at flowrates which are greatly reduced in comparison to those currently employed during fire-retardant delivery (these range up to 38,000 gpm).
2. Provide a means of payload center-of-gravity control during gradual reduction of this payload through fluid discharge.

The first requirement can be best met by redesign of the discharge portion of the system to handle properly the reduced flow required. Meeting the second requirement, payload center-of-gravity control by proper fluid management, will be a relatively simple matter since engineering to achieve this result is already well underway on a current U.S. Forest Service contract. It should be reemphasized that neither of the above modifications involve substantial change to the basic system design. The MAFFS, as it exists today, is suitable for successful, effective conversion into a practical oil spill dispersant delivery system.

System Description

The MAFFS is a self-contained, airborne, modular, reusable system capable of deploying water and fire retardant chemicals while in flight. The system, as seen in Figure 24, consists of five tank modules, one control module, and one dissemination module. These seven basic units contain retardant reservoirs, a power source, controls, nozzles, and miscellaneous plumbing.

The pneumatic power source provides the energy necessary to expel the retardant from the reservoirs and the transfer lines. The master controls located on the control module in the aircraft cargo compartment are operated by the loadmaster. The copilot is provided with a control box of duplicate controls for actuating both a normal drop and an emergency dump. A manual emergency dump unit can be activated by the loadmaster. The system's electrical power is provided by the aircraft or by a 24-volt battery located on the control module.

Each tank module includes a retardant tank and two 18-inch diameter tubes with provisions for center of gravity and slosh control. These palletized modules also have a retardant filling line, overboard vent, full-tank sensor, check valves, rupture disk, air pressure reservoirs, regulator, and the necessary system arming valves.

The control module, located immediately aft of the five tanks, contains the two 18-inch diameter discharge valves. The operator's seat, the master control panel, the retardant loading lines, and the pneumatic charging lines are attached to the control module. The dissemination module is designed to permit the aircraft to fly to and from the fire with the aircraft in a buttoned-up condition. On approaching the fire site, the aft cargo door and ramp are opened, and the nozzles are extended over the ramp for deployment of retardant. The dissemination module contains the mechanism for lowering and lifting the dual nozzles and the interlocks to prevent dissemination of the retardant until the nozzles are lowered and locked.

System Parameters

The following parameters apply to MAFFS as installed in the C-130 aircraft:

Total system capacity at current float settings	2,800 gal (10,600 liters)
Tank module capacity	528 gal
Tank	402 gal
Tubes	126 gal
Control module discharge tubes capacity	160 gal
Deployment rate	to 38,000 gpm
Pressure range	0 to 40 psig
Retardant fill time (using both lines) (ground-station dependent)	8 min
Pneumatic fill time (ground-station dependent)	10 min
Manual emergency dump time (1/2 payload)	45 sec
Electrical system (from aircraft power or system battery)	28 vdc
Dump-valve diameter	18 in
Dump-valve type	Butterfly
Nozzles	Parabolic
Arming valves	Electrically actuated
Pressure-bottle pressure	1,500 psig
Initial aircraft loading time	2 hrs
Total empty weight	10,550 lbs
Empty weight, tank module 5	1,420 lbs
Empty weight, tank modules 1, 2, 3, 4, each	1,405 lbs
Empty weight, control module	1,595 lbs
Weight, dissemination module	1,825 lbs

Weight, power cable 90 lbs

Component Description

The MAFFS comprises the following major subassemblies:

- Tank module assembly
- Control module assembly
- Dissemination module assembly
- Branched cable assembly
- Flight-station control box
- Cable assembly flight-station control box
- Power cable assembly
- Cap assembly
- Cap adapter
- Ground support equipment

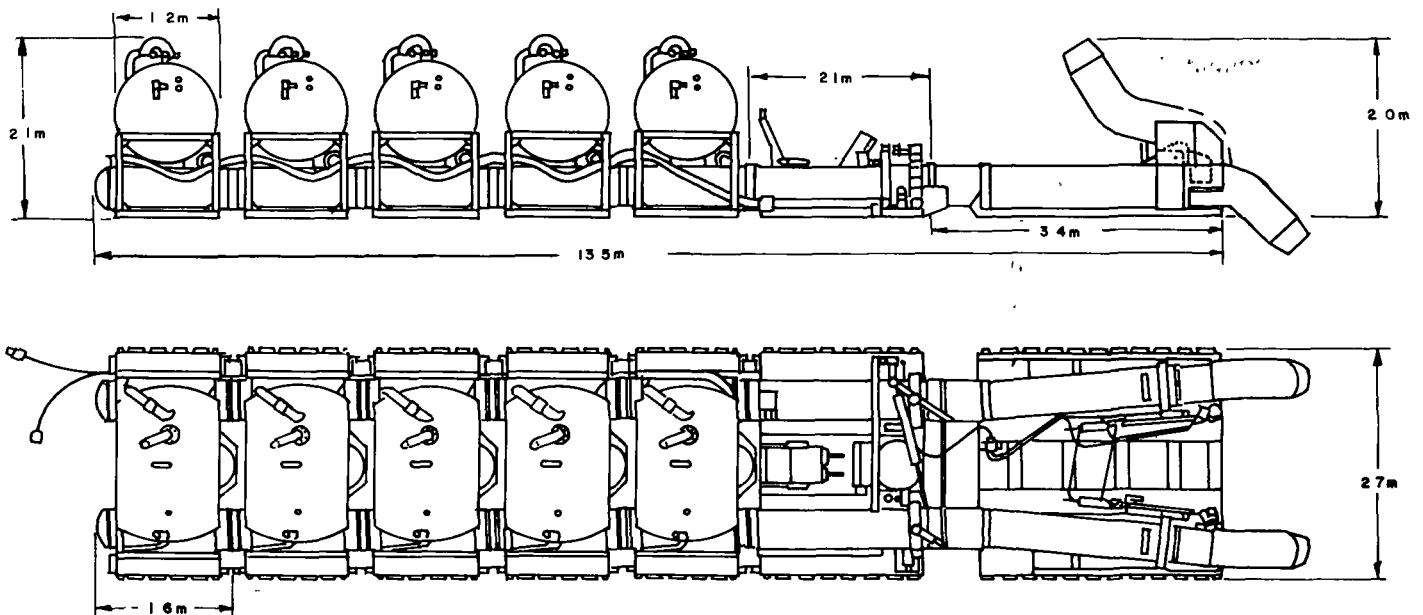


Fig. 24 — The Maffs System

Capacity

Modular in 500 gallon (1893 liter) increments, dependent upon aircraft

Power Supply

Air - individual reservoirs on each module

Pumping Rate

Up to 40,000 gallons (151,416 liters) per minute

Pumping Characteristics

Constant flow rate at any discharge setting Volume and pressure evenly maintained by automatic regulators

Installation

Completely integrated system

- Emplaced as cargo
- No aircraft modification
- No special tools
- Initial installation less than two hours

Ground Deposition in Unbroken Lines

With thickened thixotropic retardants and 3000 gallon (11,356 liter) system

- At C-130 Hercules drop speed of 140 knots (259 kilometers per hour)
- Altitudes effective 100 to 500 feet (30 to 152 meters)
- Line widths of 40 to 200 feet (13 to 61 meters)
- Line length to 2000 feet (610 meters)
- Concentrations of 1 to 4 gallons (3.8 to 15 liters) per 100 ft² (9.3 m²)

Resupply Time

Ground supply dependent - 10 minute turnaround with standard supply system to 3000 gallon capacity (11,356 liters)

Weights

-	Tank module	
	including pallet and controls	1400 lbs (635 kg)
-	Control module	
	pallet and controls	1600 lbs (725 kg)
-	Dissemination module,	
	pallet and controls	1800 lbs (816 kg)
-	Power cable	100 lbs (45 kg)
	Total weight of empty system	10,500 lbs (4750 kg)