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Characteristics of Atmospheric Emissions from an In-Situ Crude Oil Fire

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CHARACTERISTICS OF ATMOSPHERIC EMISSIONS FROM AN IN-SITU CRUDE OIL FIRE

by

Tom Day
Donald Mackay
Stuart Nadeau
Robert Thurier

Department of Chemical Engineering
and Applied Chemistry
University of Toronto
Toronto, Ontario M5S 1A4

for the

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

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ABSTRACT

The characteristics and behaviour of smoke generated from in-situ burning of crude oil in the Beaufort Sea are examined. From a review of previous work on the likely magnitude and distribution of spilled oil from a winter blowout, a scenario is postulated giving the amount of oil which could be burned, the size of burned oil pools, the individual burn durations and the number and frequencies of pools burned over the time period in question. Two time periods are considered: early June, when oil migrates to the surface of first year sea ice, and September, when it is believed oil may migrate to the surface of multiyear sea ice.

Available information about oil combustion characteristics is reviewed - particularly as it relates to (a) emissions, (b) the atmospheric conditions likely to prevail in the Beaufort Sea during the time periods in question and their effect on smoke plume dispersion, and (c) possible oil compositions. It is suggested that it is best to treat the emission behaviour during cleanup as a multiple number of "unit burns" in which a standard quantity of oil is burned. The total behaviour is obtained by superimposing the required number of "unit burns". The plume rise and dispersion of a unit burn are calculated and these calculations yield data on the concentration of particulates (soot), SO_2, CO_2, CO, hydrocarbons and metals at various distances downwind. Laboratory and field studies which were undertaken to provide data on the emission characteristics of crude oil fires are described.

It is concluded that the atmospheric concentrations of CO and SO_2 will be acceptably low and usually below National Air Quality Objective levels. Concentrations of soot which may be achieved within a few kilometres of the fires will often be above National Air Quality Objective levels; but at distances greater than about 10 km, the air quality will be comparable to that of urban areas in Canada. Since there are no generally accepted tolerable concentrations for airborne polynuclear aromatic hydrocarbons or metals, both of which will be emitted from the fires, it is recommended that human exposure to the smoke plume be minimized by appropriate deployment of countermeasures personnel, and by avoiding burning under weather conditions during which plumes will reach communities. Recommendations are made for some further studies.

RÉSUMÉ

Nous examinons les caractéristiques et le comportement de la fumée engendrée par la combustion du pétrole brut sur les lieux des déversements, dans la région de la mer de Beaufort. Grâce aux travaux antérieurs portant sur la quantité et la répartition probables du pétrole déversé à l'occasion d'une éruption survenant en hiver, nous pouvons élaborer un scénario donnant des indications sur la quantité de pétrole qui pourrait être brûlée, l'importance des flaques brûlée, la durée de combustion de chacune d'elles et le nombre et la fréquence des brûlages pendant la période étudiée. Notre étude porte sur deux périodes distinctes: le début de juin, alors que le pétrole se répand à la surface de la glace de l'année; et septembre, où on croit savoir que le pétrole aboutit à la surface de la glace de plusieurs années.

Nous passons en revue les données accessibles concernant les caractéristiques de la combustion du pétrole, surtout dans la mesure où elles se rapportent aux émissions. Nous indiquons quelles seraient les conditions atmosphériques probables dans la mer de Beaufort pendant les périodes considérées et quels seraient leurs effets sur la dispersion du panache de fumée. Nous traitons finalement de la composition possible du pétrole déversé. Nous pensons qu'il serait préférable de considérer le comportement des émissions provenant des opérations de nettoyage comme la somme de plusieurs "unités de combustion" d'une quantité normalisée de pétrole. Le comportement d'ensemble serait obtenu en superposant le nombre requis de ces "unités". Le calcul de l'élévation et de la dispersion du panache engendré par une unité de combustion fournit des données sur la concentration des particules (suie), du SO_2, du CO_2, du CO, des hydrocarbures et des métaux en fonction de la distance sous le vent. Nous décrivons les études entreprises en laboratoire et sur le terrain afin d'obtenir des précisions sur les caractéristiques des émissions de la combustion du pétrole brut.

Nous concluons que les concentrations de CO et de SO_2 dans l'atmosphère seront acceptables et qu'elles n'enfreindront généralement pas les objectifs nationaux de la qualité de l'air. Les concentrations de suie observées à quelques kilomètres du lieu de combustion seront souvent supérieures à celles qui sont fixées par les objectifs nationaux; mais au-delà d'environ 10 km, la qualité de l'air sera comparable à celle des régions urbaines du Canada. Comme il n'existe pas de seuil généralement accepté pour les concentrations d'hydrocarbures aromatiques polycycliques ou de métaux qui découlent de la combustion, nous recommandons de limiter l'exposition des équipes de nettoyage au

panache de fumée en les disposant de façon appropriée et en évitant la combustion lorsque les vents risquent de pousser les panaches en direction des collectivités. Nous formulons des recommandations pour les études qui restent à faire dans ce domaine.

FOREWORD

This study was undertaken by the Department of Chemical Engineering and Applied Chemistry of the University of Toronto under contract to the Environmental Emergency Branch, Department of the Environment. The scientific authority was Mr. Peter Blackall, Environmental Emergency Branch, Edmonton, Alberta.

The objective was to undertake a preliminary study of air pollution arising from crude oil burning in the Beaufort Sea, with a view to determining if further more detailed studies are warranted. Since there was no extensive experimentation (and none in the North), a large number of assumptions were necessary, particularly with regard to atmospheric conditions. Consequently, the findings of the report must be qualified in the light of these assumptions.

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A scenario has been established that describes a time and space distribution for oil burning in the Beaufort Sea. A mass balance on the blowout suggests that the oil may burn in pools of about one m^3 of oil; the pools are in clusters of from nine to 10. About 1000 clusters may be ignited.

The atmospheric concentrations of SO_2, CO particulate matter and metals have been estimated for locations close to the fire, at distances of about 10 and 40 km. These concentrations have been compared with National Air Quality Objectives and typical levels in Canadian urban areas. It is concluded that in the immediate vicinity of the fire, the concentration of particulates (soot) will be undesirably high and such areas should be avoided. The concentrations at distances of 10 to 40 km and beyond are judged to be sufficiently low that no adverse air quality problem exists.

Since there is doubt about the toxicity of metals and polynuclear aromatic hydrocarbons in the oil soot, it is prudent to minimize exposure of personnel and communities to these substances. This should be accomplished by careful planning of the burning operations, taking into account short range weather forecasts.

It is recommended that further research work be done on the issue of whether or not burning increases the emission of polynuclear aromatic hydrocarbons. Additionally, further research work should be done on the fundamental mechanism of burning, including measurements of soot formation and soot properties such as particle size and metal behaviour. A full-scale experiment of oil burning with concurrent air quality measurement is recommended in order to provide a general validation of these calculations.

Further, in order to improve the dispersion calculations, it would be useful to obtain relevant atmospheric data (especially mixing heights and stability classes) for the Beaufort Sea for times when burning may occur. Finally, as Arctic oil samples become available, they should be subjected to appropriate chemical and physical analyses.

1 INTRODUCTION

1.1 Oil Spill Countermeasures in the Beaufort Sea

The Mackenzie Delta-Beaufort Banks sedimentary basin is one of the most promising frontier oil provinces. Discoveries have been made on land on the Tuktoyaktuk Peninsula and on artificial islands during drilling programs in the shallow nearshore region. In 1976, offshore drilling from drillships commenced, and this program continued during 1977 with promising results. A number of studies of possible environmental impacts of oil exploitation in this region have been undertaken; for example, the early critical review of Pimlott et al (1976), and the several technical and summary reports arising from the Beaufort Sea Project, notably the reviews of Logan et al (1975, 1975a) and of Ross et al (1977).

Conventional oil spill countermeasures equipment such as booms and skimmers may prove to be very difficult to deploy in the Beaufort Sea because of ice, hostile weather and lack of a local labour force. One of the most attractive countermeasures options is in-situ burning, which has been demonstrated to be capable of destroying oil as it accumulates on the ice surface in early June (Norcor, 1975). Accordingly, considerable effort has been devoted to developing ignition devices and to reviewing the feasibility of burning (Purves, 1977).

One possible undesirable effect of burning is the emission of substantial quantities of combustion products into the atmosphere, with consequent adverse effects on air quality downwind. The report addresses the problem of assessing, in an approximate and exploratory manner, the effect of burning on air quality, with a view to determining if further experimentation is justified.

There can be several adverse impacts. Undesirably high concentrations of particulate or gaseous pollutants could reach human settlements, notably Tuktoyaktuk, which is about 70 km and 140 km from the two 1976 drilling sites. Inhaled air quality and visibility would be affected adversely. The emissions could result in deposition of soot on snow and ice, reducing the albedo and leading to an early melt, with possible influences on local weather (Walker, 1975). The emissions could result in deposition of chemical compounds that are not normally present in the area in marine, littoral or terrestrial ecosystems. These depositions could have a disruptive effect.

Examples of these undesirable compounds are heavy metals and polynuclear aromatic hydrocarbons. This report attempts to place some of these potential problems in perspective by making quantitative estimates of exposure to these pollutants.

1.2 Oil Spill Scenario

In assessing the environmental impact of oil burning, it is first necessary to make some assumptions about the volume, nature and location of the oil to be burned. The approach adopted in this report has been to assume the "standard" Beaufort Sea oil and gas blowout scenario. The location is defined as the general area indicated in Figure 1. Ice movement in this area was studied by Norcor (1977) and the probable behaviour of a winter blowout was postulated. This postulate forms the basis of the present scenario.

It is assumed that a blowout starts late in the drilling season (i.e., August or September); this is too late to permit a relief well to be drilled. Oil discharges from the well at an average rate of 2500 barrels/day (398 m^3/day) for the first 30 days, falling to 1000 barrels/day (159 m^3/day) during the remaining months of the winter period. It is assumed that natural gas associated with the oil (usually assumed to be a 150:1 gas to oil volume ratio) is vented through the ice, and thus does not play a role in the burning process.

First year sea ice usually starts to form in the Beaufort Sea in late September. This ice grows in thickness to about two metres by May of the following year and generally remains landfast. Between the polar pack (usually 300 to 400 km offshore in summer) and the landfast ice is a "transition" region, in which it is impossible to predict ice conditions accurately. There may be regions of first-year ice, multiyear ice, and open water, with the entire pack moving in an irregular manner, driven by winds and currents.

In the event of an oil well blowout, the oil will "paint" the under-surface of the moving ice. The thickness of the oil layer will depend on the oil plume lateral spreading (believed to be to a maximum of about 200 m), the oil release rate, and the ice velocity (varying from zero to about 10 km/day; an average of about one km/day). During the months from October to May inclusive, there is a probability that a strip of ice about 240 km long and about 100 m wide will be painted with oil. The total volume spilled during this eight-month period will be 45 700 m^3(287,000 barrels) (i.e. 31 x 2500 + 210 x 1000 barrels) (10,000,000 gallons (UK)). The area affected will be about 24 km^2; thus, the average oil film thickness will be 1.9 mm. In practice, it is believed that only about 35 percent of the oil will achieve a thickness greater than five mm, which is about the thickness necessary to permit ignition and combustion. A pictorialization of an oiled area is given in Figure 2, which is reproduced from Norcor (1977).

During the winter, the oil is encapsulated in the growing ice and remains intact until melting starts in the spring. As the snow on the ice melts, and the albedo

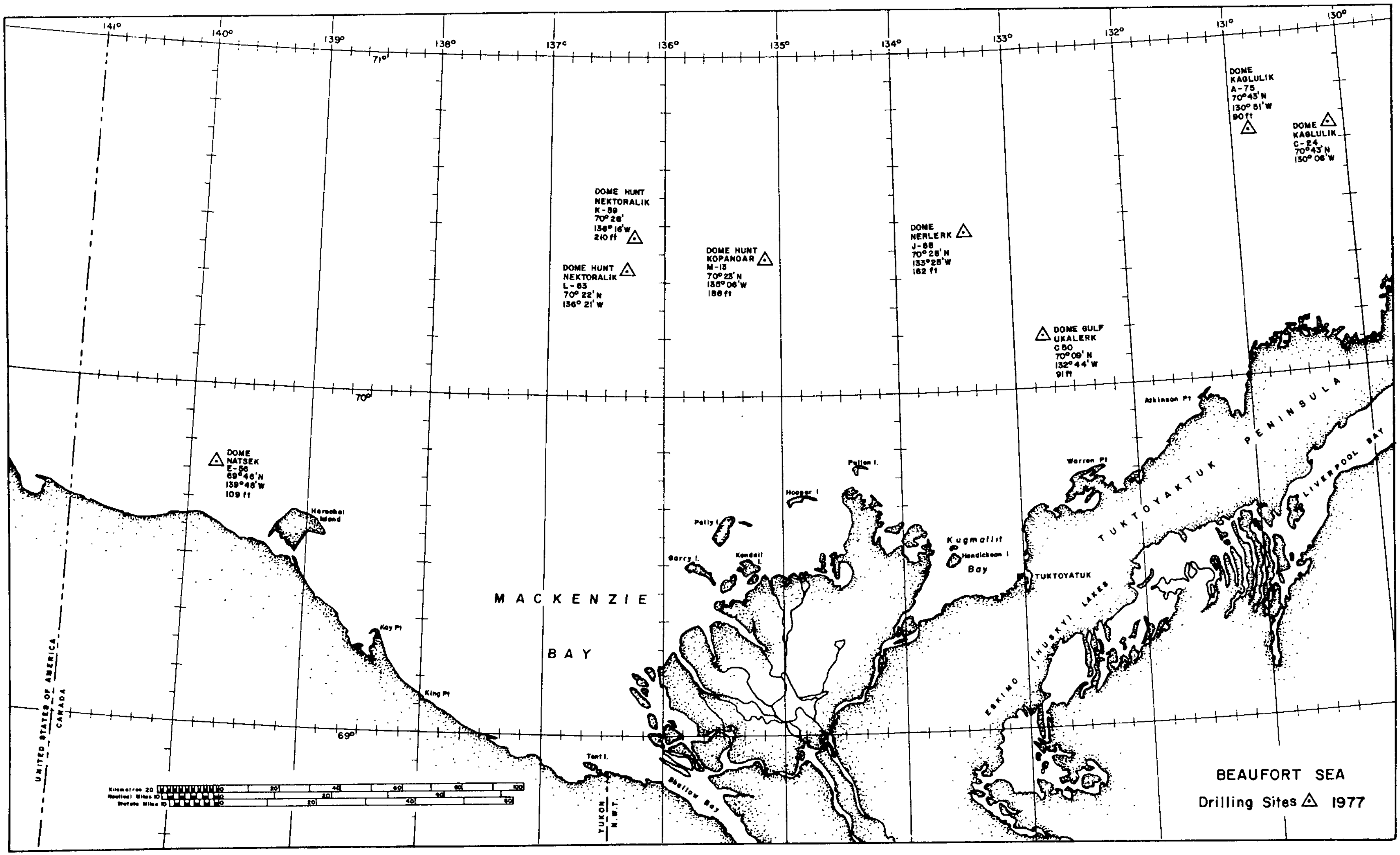


FIGURE 1 MAP OF THE STUDY AREA

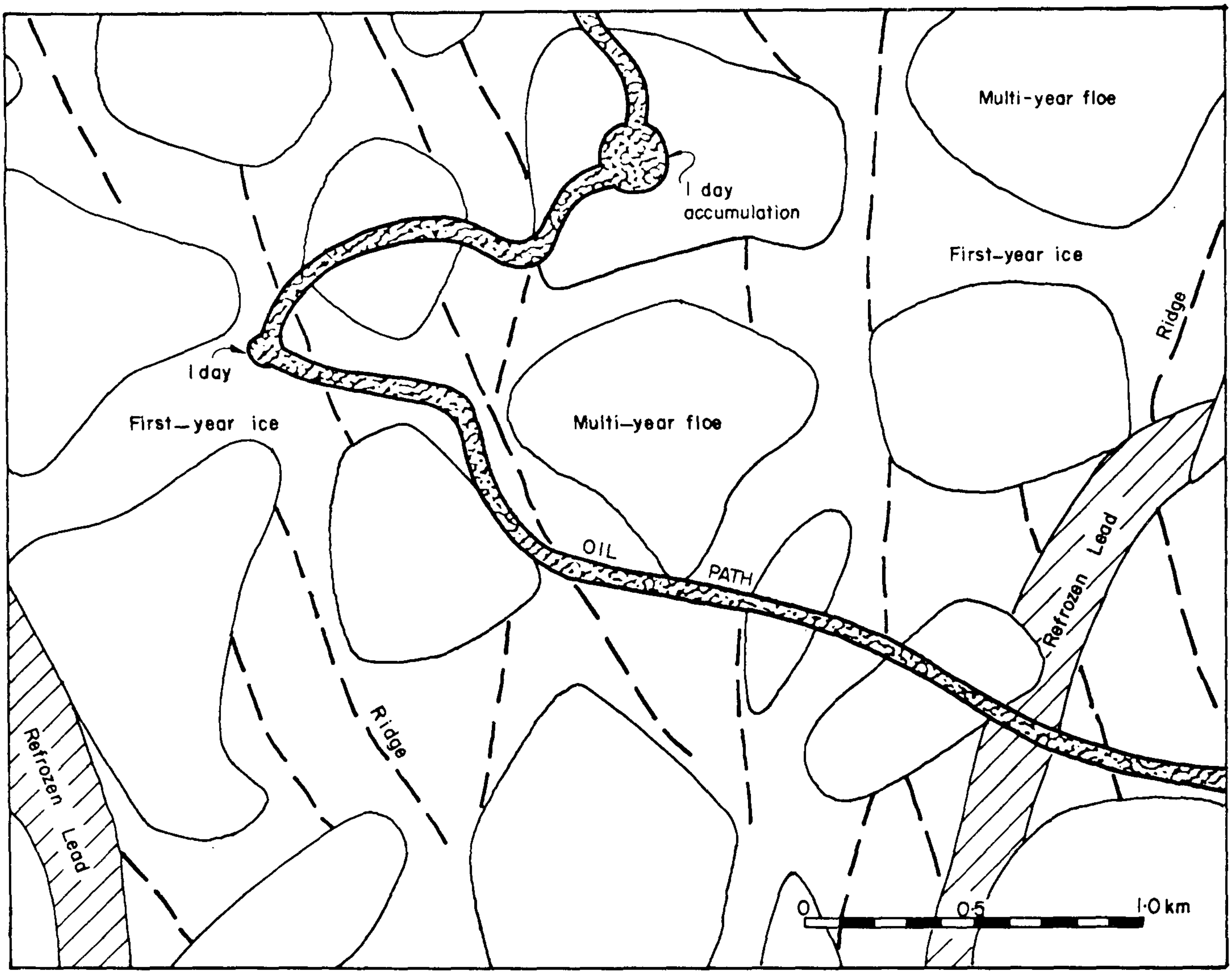


FIGURE 2 OILED TRACK IN A TYPICAL MIXTURE OF ICE CONDITIONS
N.B. This diagram is a pictorial presentation of measured means; it does not represent a specific area.
Source: NORCOR (1977).

falls, the upper regions of the ice warm, and the oil begins to migrate up brine channels, forming oil pools on the surface. This process is self-accelerating. As soon as oil reaches the near-surface region, it absorbs solar radiation more efficiently (by albedo reduction), and thus the rate of local melting is enhanced. This can be regarded as advantageous; the uncontaminated ice melts more slowly and can therefore serve as a working platform from which contaminated ice can be subjected to clean-up measures, such as burning. In addition, the ice surrounding the oil pools retains its integrity longer than the oiled ice, this localizes the oil-contaminated area.

For the purposes of this report, it is assumed that the oil reaches burnable thickness on the first year ice surface about June 1, and continues to flow for about 20 days. This date will vary yearly depending on weather, especially snowfall and solar insulation. Oil flow will probably start about May 10.

Little is known about oil migration in multiyear ice, but some recent work by Milne (1977) suggests that the oil may reach the surface in September. It is assumed that about 30 percent of the oil is trapped under multiyear ice, leaving 70 percent under first-year ice.

It is now possible to assemble an approximate mass balance for the oil in this scenario. Of the oil that reaches the surface, about 30 percent may evaporate if exposed to the atmosphere for about 10 days. It seems likely that the oil which will be burned will be ignited on the average about five days after reaching the surface. At that time, about 10 percent may be evaporated.

The remaining problem is to assume a fraction of the oil which can be burned. It is arbitrarily assumed that about 35 percent of the oil reaching the surface is in a condition in which burning is feasible. The total assumed oil mass balance is presented in Figure 3, which shows that 9500 m^3 of oil is subjected to burning in June, and 3800 m^3 in September. This yields 2100 m^3 of unburned residue; and 11 200 m^3 of oil is converted into CO_2, CO, unburned hydrocarbon or soot. Although these figures are approximate, it seems unlikely that they are in error by more that ± 50 percent. This assumes that 16 percent of the burned oil remains as residue.

It is assumed that as the oil reaches the surface over this 20-day period (either in June or September), the growing pools are ignited by deployment of ignition devices from fixed-wing aircraft, helicopters, or by hand from the ice surface.

Although the configuration of the pools and the sequence of burning is unknown, some estimate has to be made. It is suggested that the oil reaches the surface in

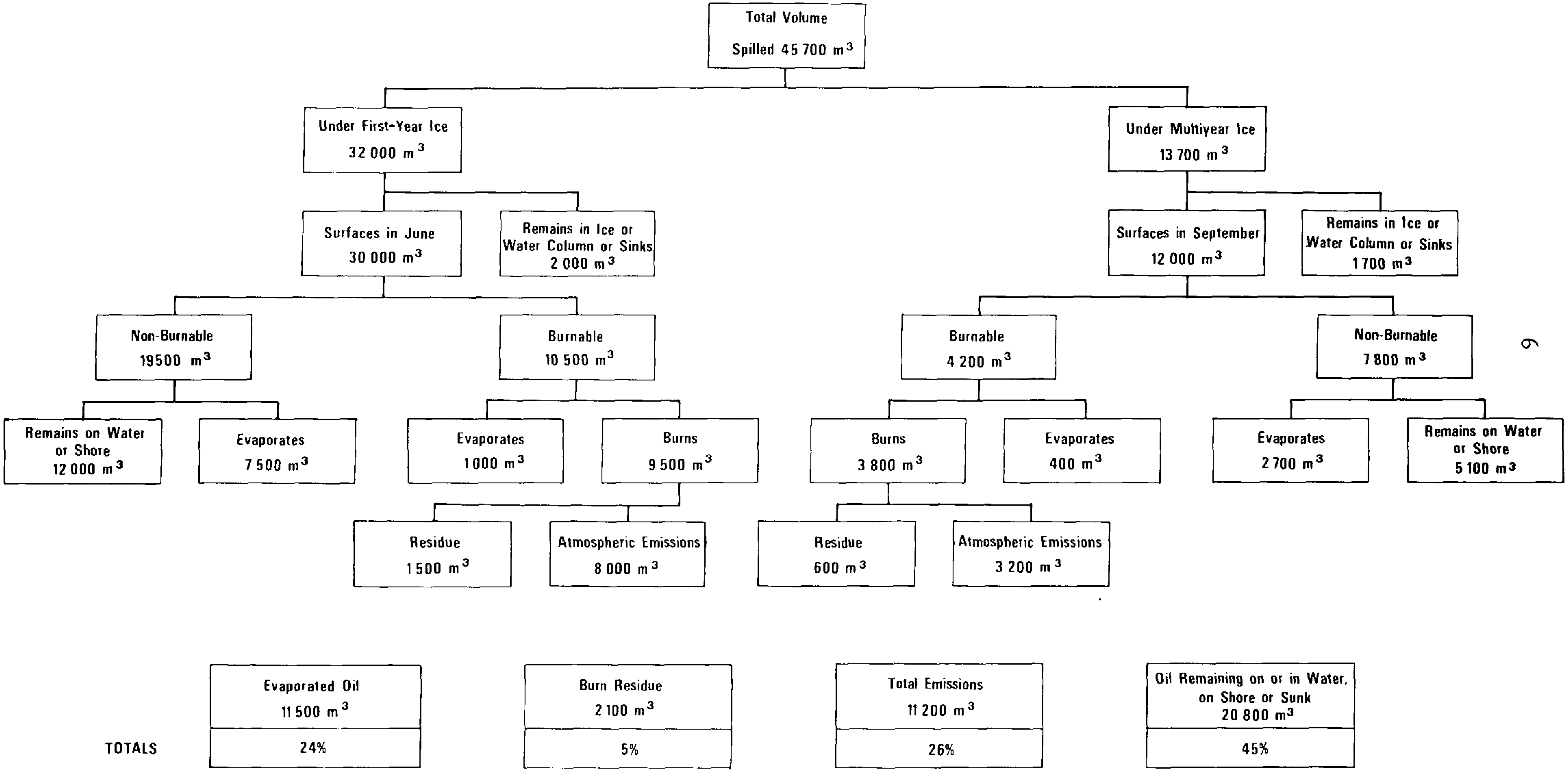


FIGURE 3 OIL MASS BALANCE

pools, each pool containing about 1.0 m^3 of oil in an area of 10 to 15 m in diameter. These pools are clustered in groups of approximately 10, which are ignited at one time.

An approximate mass balance for the oil is assembled by making the following assumptions:

- Seventy percent of the oil lies under first-year ice and 30 percent under multiyear ice (Norcor, 1977).
- Approximately six percent of the oil under first-year ice and 12 percent of the oil under multiyear ice does not reach the surface. It sinks, dissolves, disperses or becomes trapped in the ice (Norcor, 1977).
- Thirty-five percent of the oil which surfaces gathers in pools of sufficient thickness so that burning is feasible (Norcor, 1977).
- The oil which is burned gathers in pools; 10 percent evaporates prior to burning, leaving 1.0 m^3 of oil of average thickness of seven mm, covering an area of 143 m^2 or 13.5 m in diameter (Norcor, 1977).
- The average pool burns for 10 minutes, leaving a residue of 0.16 m^3 (Coupal, 1976). This event is used as a "unit burn" in the dispersion calculation.
- During the burning operation, an average of 9.5 pools are ignited at approximately the same time; some pool-to-pool fire spreading occurs. This "cluster" of pools contains 9.5 m^3 of oil and is assumed to burn for one hour, with a maximum of three pools burning at any one time.
- There are 9500 pools in 1000 clusters in June and 3800 pools in 400 clusters in September.
- Since the total length of the contaminated strip is 240 km, each of the 1400 clusters occupies a length of 171 m and is 100 m wide (i.e., the width of the strip).
- The oiled strip is tortuous and lies entirely in a rectangle 80 by 30 km, i.e., in a total area of 240 km^2. This is based on Norcor's (1977) observations that net ice movement is considerably less than total distance travelled, especially during the "static" period of February and March.

The time distribution of cluster burns is given in Table 1. This table has been assembled speculatively; it has no real statistical basis. The important feature that it suggests is that at no time are more than 10 clusters burning simultaneously. This is regarded as conservative (pessimistic); the average number of simultaneous burns in June will be three. For September, these quantities should be multiplied by 0.4.

TABLE 1 BURN-TIME DISTRIBUTION IN JUNE

Number of Simultaneous Burns of 1.0 Hour*	Duration of Burn (number of hours)	Total Number of Cluster Burns
10	18	180
9	18	162
8	18	144
7	18	126
6	18	108
5	18	90
4	18	76
3	18	54
2	19	38
1	22	22
0	151	0
Total	336 (14 days)	1000

* It is assumed that 9.5 pools burn for ten minutes each, with some overlap, to give a total burning period of one hour.

In many cases these assumptions are arbitrary; they are regarded as being reasonable and they provide a basis for calculation of the disperison behaviour. A summary of the mass balance is given in Figure 3.

The logistical problem of igniting these pools is worth considering. If it is assumed that 15 ignition devices are required to ignite a cluster (allowing for failure due to maloperation of the device, excessive wind, missed targets or lack of ignitable volatiles), this would imply the deployment of a total of 15 000 devices during June. This could be accomplished by three helicopters flying on 14 of the 20 days (the other days being unsuitable for flying), spending six hours per day over the target area, and deploying devices at an average rate of one per minute.

In September, flying conditions are worse but there is less oil to be ignited; therefore, the logistical problem is similar in severity.

1.3 Oil Burning Characteristics

A complete discussion of the process of oil combustion is beyond the scope of this report; however, it is useful to outline the principal processes since they have a bearing on the emission characteristics of an oil fire. The processes occurring in a ground level oil fire have been discussed in a number of sources, notably Purves (1977) and in various texts on combustion. Some of the more salient points are reviewed as follows.

The combustion reaction of hydrocarbons with oxygen from air occurs in the vapour phase in a flame region above the oil spill. The exothermic heat of reaction from the combustion processes is dissipated in the form of radiation in all directions and as sensible heat in the combustion plume. Radiation from the flame heats the oil pool and evaporates the volatile hydrocarbons, which then enter the flame region and react with the incoming air. The fire is thus a self-sustaining process; heat generated maintains the supply of gaseous fuel for combustion.

The problem of igniting crude oil fires arises from the initial difficulty of generating a sufficient quantity of vapour to achieve combustion. Various ignition devices, which essentially have the objective of heating part of the oil pool to a temperature higher than the fire point of the oil, have been proposed.

Combustion continues until the rate of vapour evolution from the oil pool drops, either because the oil is becoming depleted of volatile material, or because the oil pool has become sufficiently thin that its temperature drops below the fire point, in this case because of heat transfer to the water or ice. Clearly, thicker oil films are more able to support combustion, since they have a superior thermal resistance.

Observations of oil combustion suggest that the oil pool may become very hot and cause melting of underlying ice, and even boiling of underlying water. There may be considerable sputtering of oil into the flame region, and thus material which is normally non-volatile may be physically conveyed in droplet form into the combustion region. This is of particular importance as a mechanism for transporting non-volatile chemical species containing metals into the combustion zone; it results in the presence of metals in the emissions.

In an ideal combustion system (as occurs in a furnace or jet engine), a very high proportion of the hydrocarbon fuel (i.e., greater than 99 percent) is converted into carbon dioxide. In the case of a ground-level fire, there is insufficient oxygen to convert all hydrocarbon vapour into carbon dioxide. This results in the formation of carbon particles which are visible as the characteristic black smoke or soot of oil fires.

An important characteristic of oil fires is the percentage of the carbon in the oil that is converted into soot and other solid particulate material, as distinct from gaseous carbon dioxide and carbon monoxide. No data could be found on this topic and as a result a number of simple, small-scale experiments were conducted to determine the likely magnitude of the percentage of carbon in the oil converted into soot. Similarly, no data could be found on the fate of metals present in the oil and this necessitated additional experimentation.

The sulphur compounds in oil are present in part as hydrogen sulphide, which will undoubtedly be converted into sulphur dioxide in the flame, and in part as complex sulphur containing compounds, which tend to accumulate in the higher boiling residues of the oil. For the purposes of this report, it has been assumed that all the sulphur present in the oil is converted into the gaseous state in the form of sulphur dioxide. This is possibly a pessimistic assumption, as it is expected that a fraction of the sulphur will remain in the unburned residue. The assumption, however, provides a basis for calculation; and the resulting sulphur dioxide concentrations can be scaled down appropriately if other assumptions are believed to be more valid.

1.4 Atmospheric Dispersion Conditions in the Beaufort Sea

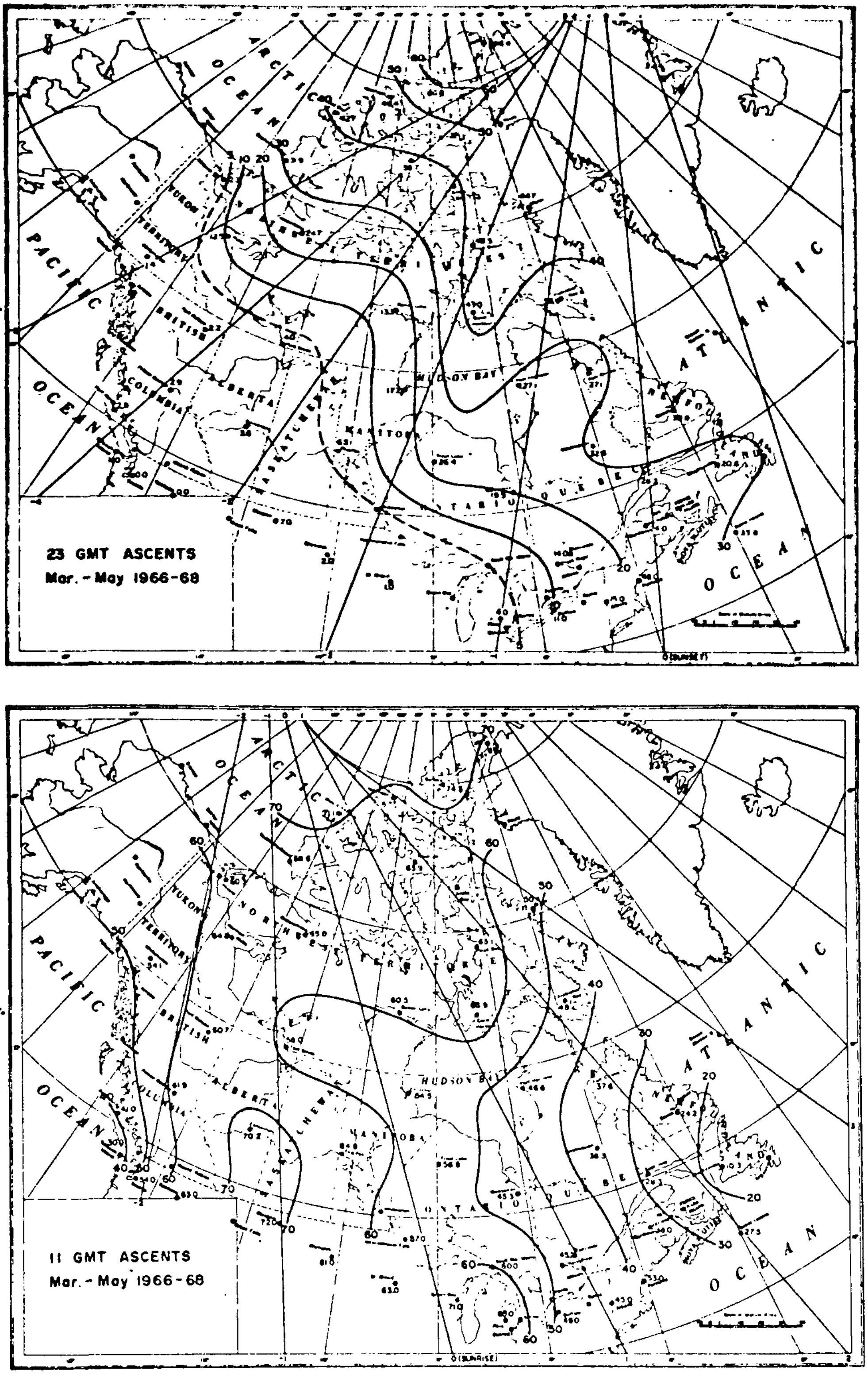
The most comprehensive accounts of climate and weather in the Mackenzie Valley-Beaufort Sea region have been provided by Burns (1973), Walker (1975) and Berry et al (1975). In addition, some relevant statistics relating to the air pollution protection climatology of the region have been published by Munn et al (1970), Shaw et al (1972) and Portelli (1977). A complete discussion of the weather and climate of this region is beyond scope of this report; however, a few general comments are necessary as background to the calculations.

It is generally accepted that there is a poorer understanding of the climate, weather and atmospheric conditions existing in the Beaufort Sea region than of the conditions existing in the more populous, temperate Canadian South. However, a considerable volume of weather data has been accumulated in recent years at stations such as Inuvik, Sachs Harbour, and Cape Parry and from vessels in the Beaufort Sea. Doubt remains, however, about the average and extreme conditions in the region. Of particular importance is the atmospheric condition known as inversion. Inversion results in the localization or trapping of emissions, and creates the potential for the establishment of unusually high concentrations of pollutants in a given area. A few words of explanation about this phenomenon are appropriate.

Normally, the air temperature drops with increasing altitude at a rate of about $6^{o}C/km$. A parcel of air propelled from the land surface, for example, emitted from a polluting source into the atmosphere, while rising will expand and cool due to adiabatic expansion. If the atmosphere surrounding the parcel of air proves to be colder than the parcel of air, the parcel will remain buoyant and will tend to be carried to greater heights. This "unstable" condition occurs when the atmosphere cools more rapidly than the "adiabatic lapse rate", which is about $9.5^{o}C/km$. On the other hand, if the atmosphere is warmer than the expanding and cooling parcel of air, the parcel will experience negative buoyancy and will tend to slow and stabilize, and vertical diffusion rates are thereby substantially reduced. This condition is particularly pronounced when the atmospheric temperature increases with height, i.e., inverts. This condition has the effect of trapping parcels of pollutant air, thus preventing them from diffusing vertically by large scale eddy motion.

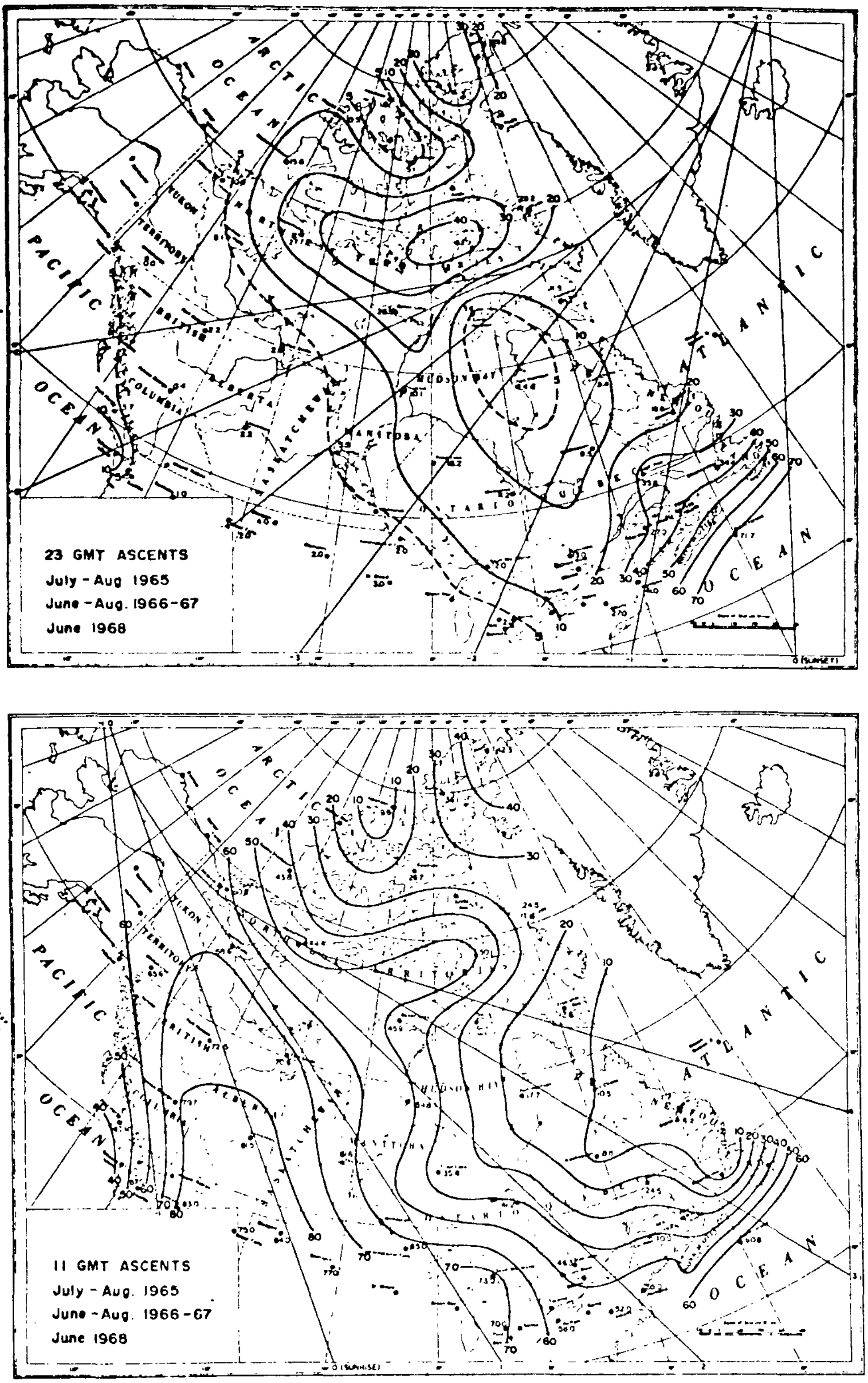
Severe inversions occur relatively infrequently in southern climates and are usually attributable to unusual weather conditions or to night-time cooling of the lower layers of the atmosphere. In the Arctic, inversions are very common in winter because of the low level of solar radiation. The ground, and the air in immediate contact with it, become much colder than the air mass above and the air temperature thus increases with height. This condition is particularly serious during periods of low wind speed. Munn et al (1970) have reviewed the frequency of ground-based inversions at various stations in Canada. Their findings, illustrated in Figures 4, 5 and 6, suggest that at the times of rawinsonde ascents, there is relatively little difference in inversion frequency in the Beaufort Sea region from that in the South. There is, however, a possibility that inversions persist longer in the Arctic; the mixed height achieves a relatively lower altitude because of the less intense insulation, especially in winter. The adverse pollution conditions experienced in urban areas of Alaska, such as Fairbanks, during winter add support to this contention. A complementary study by Shaw et al (1972) shows the persistence of light surface winds, which also contribute to severity of the air pollution incidents.

A particularly relevant recent publication is one by Portelli (1977), who has compiled data on mixing height and ventilation coefficients throughout Canada. The concept of mixing height is essential to this study and a few words of explanantion are necessary. The maximum or afternoon mixing height is calculated as the height above ground at which the dry adiabatic extension of the maximum surface temperature intersects the vertical temperature profile observed at 1200 GMT. The maximum surface temperature is determined from local observations and the vertical temperature profile is obtained from rawinsonde data. A low value for this mixing height, for example, 300 m, implies that the atmospheric characteristics in the lower 300 m are such



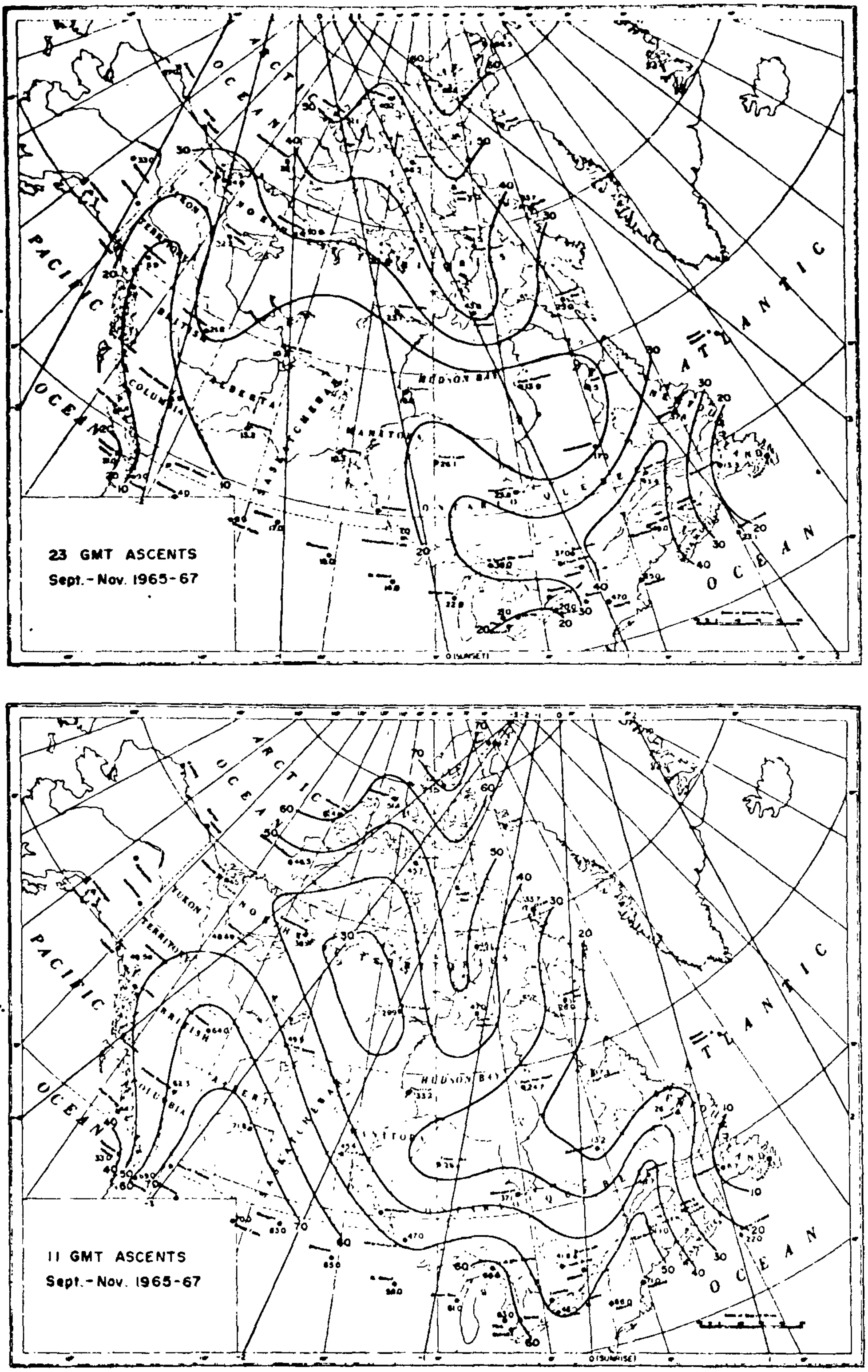
Hours of day, relative to sunset or sunrise, are given by thin, straight lines in upper or lower figure, respectively.

FIGURE 4 PERCENTAGE FREQUENCIES OF GROUND-BASED INVERSIONS
Source: Munn et al (1970)



Hours of day, relative to sunset or sunrise, are given by thin, straight lines in upper or lower figure, respectively.

FIGURE 5 PERCENTAGE FREQUENCIES OF GROUND-BASED INVERSIONS
Source: Munn et al (1970)



Hours of day, relative to sunset or sunrise, are given by thin, straight lines in upper or lower figure, respectively.

FIGURE 6 PERCENTAGE FREQUENCIES OF GROUND-BASED INVERSIONS
Source: Munn et al (1970)

transported by its own buoyancy beyond a height of 300 m. Therefore, it is effectively trapped by a "ceiling" or "lid" at this height. It may, of course, be able to penetrate this barrier by virtue of high buoyancy because of heat, a high stack, or a high emission velocity. In essence, the mixing height gives the effective height of the layer below which inversion conditions serve to trap smoke plumes. The smaller this height, the more confined the smoke, and the higher the concentrations. The concept is illustrated in Figure 7.

The second criterion provided by Portelli (1977) is the ventilation coefficient, which is computed as the product of the maximum mixing height and the mean wind speed through the mixed layer. The units of this quantity are $m^3 \bullet s^{-1} \bullet m^{-1}$ or m^2/s, and they represent the rate at which air is ventilated from the area. A low value implies that atmospheric conditions are such that the contaminated air will persist longer in the region, and thus higher concentrations of pollutants will be achieved because of slow dilution.

Figures 8 to 13, taken from Portelli (1977), show mixing height and ventilation coefficient data for Canada. It is immediately apparent that the Beaufort Sea region suffers from very much more difficult and potentially troublesome air pollution conditions than most regions in Canada. The mean summer mixing heights of the region are generally about 400 to 600 m, in contrast to areas such as Ontario, which are about 1300 m. Similar conditions exist in the fall. Mean spring and fall wind speeds in the Beaufort Sea and Ontario are similar; thus, the ventilation coefficients in the Beaufort Sea are correspondingly smaller as a result of the smaller mixing height. Although it is an oversimplification, it can be stated that conditions in the Beaufort Sea are generally such that the area is less ventilated by a factor of three to four than areas such as Ontario or mid-Alberta.

Another atmospheric parameter essential for calculation of smoke dispersion is wind speed. It is impossible to predict with any certainty the prevailing wind conditions during a period of oil burning. However, the probability is that during June the wind will be from the ESE with about a 25 percent frequency or from the WNW with about a 15 percent frequency, and with somewhat lower probability from other directions. During the month of September, a similar situation applies, however, there is a greater probability that wind will be from the WNW (Burns, 1973).

The mean wind speed at Cape Parry in June is about 19 km/h (12 mph) with a slightly higher wind speed of about 21 km/h (13 mph) prevailing in September. The

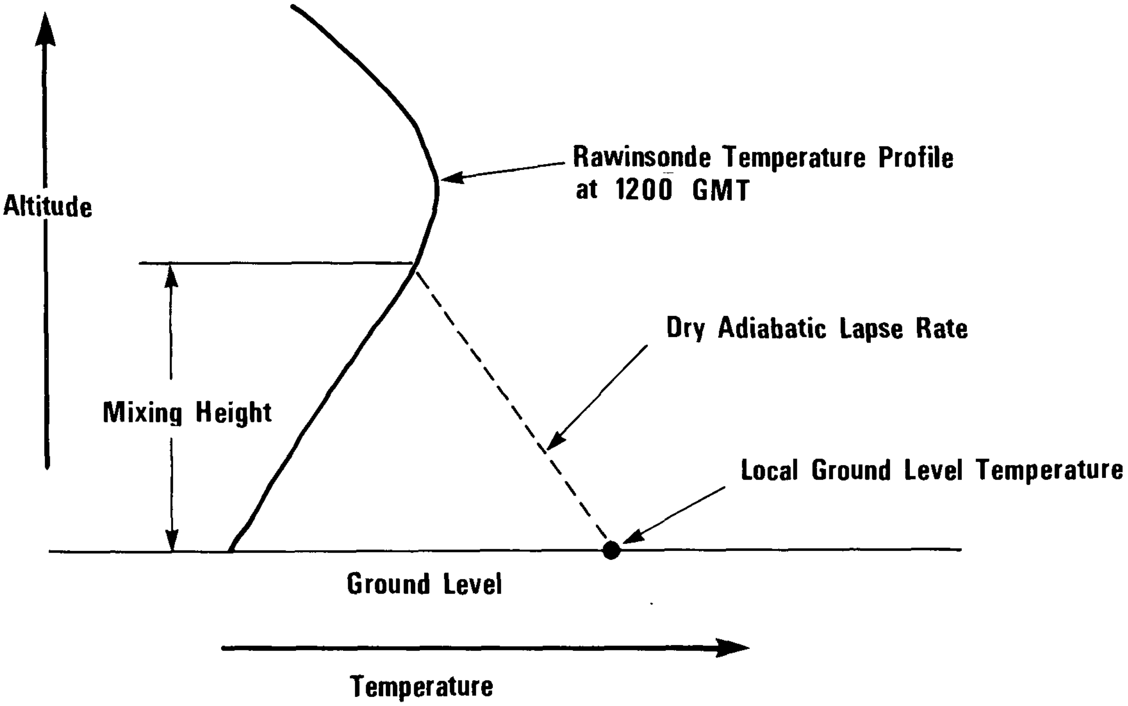


FIGURE 7 CONCEPT OF MIXING HEIGHT

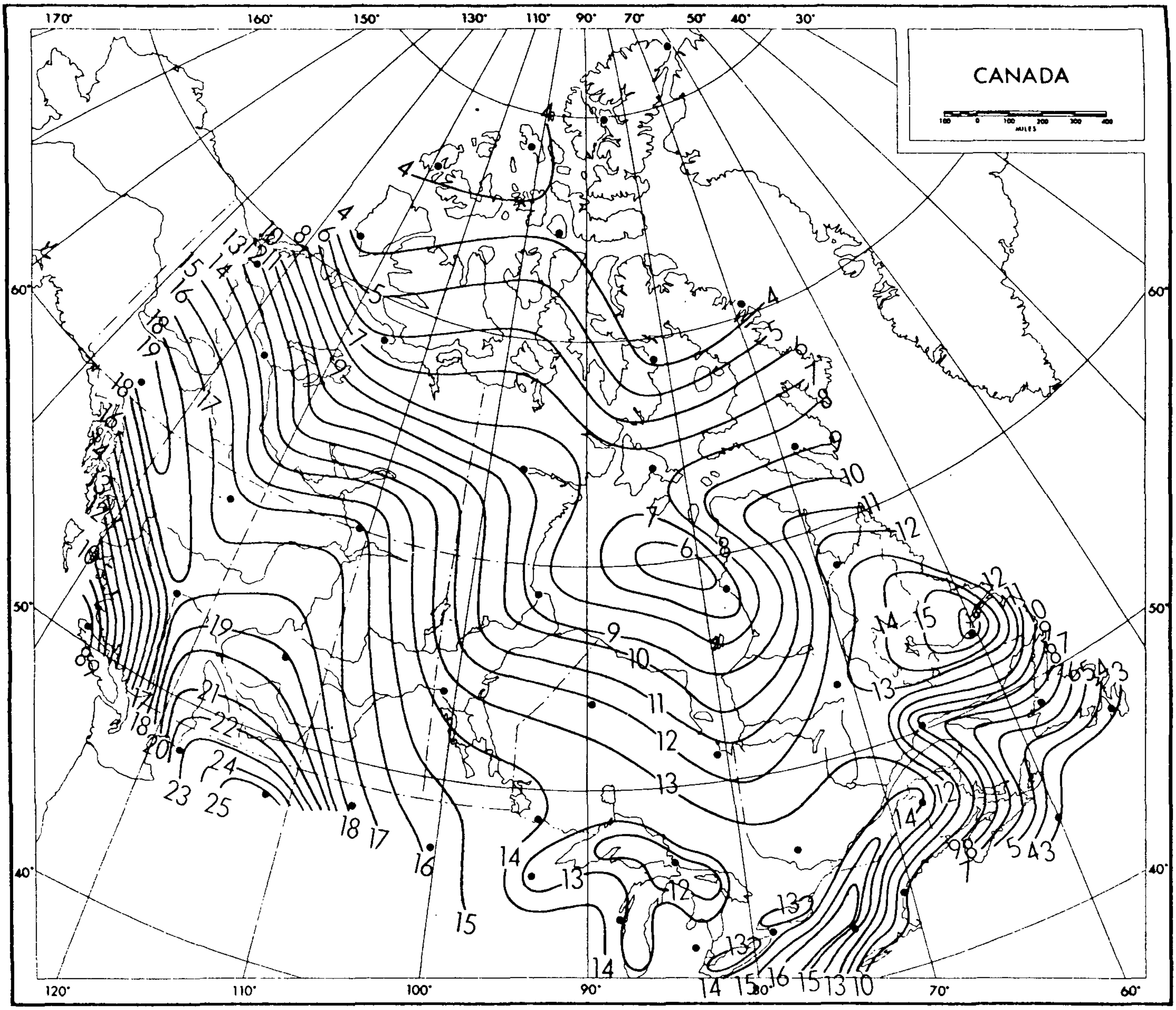


FIGURE 8 ISOPLETHS (m x 10^2) OF MEAN SUMMER MAXIMUM (AFTERNOON) MIXING HEIGHTS
Source: Portelli (1977)

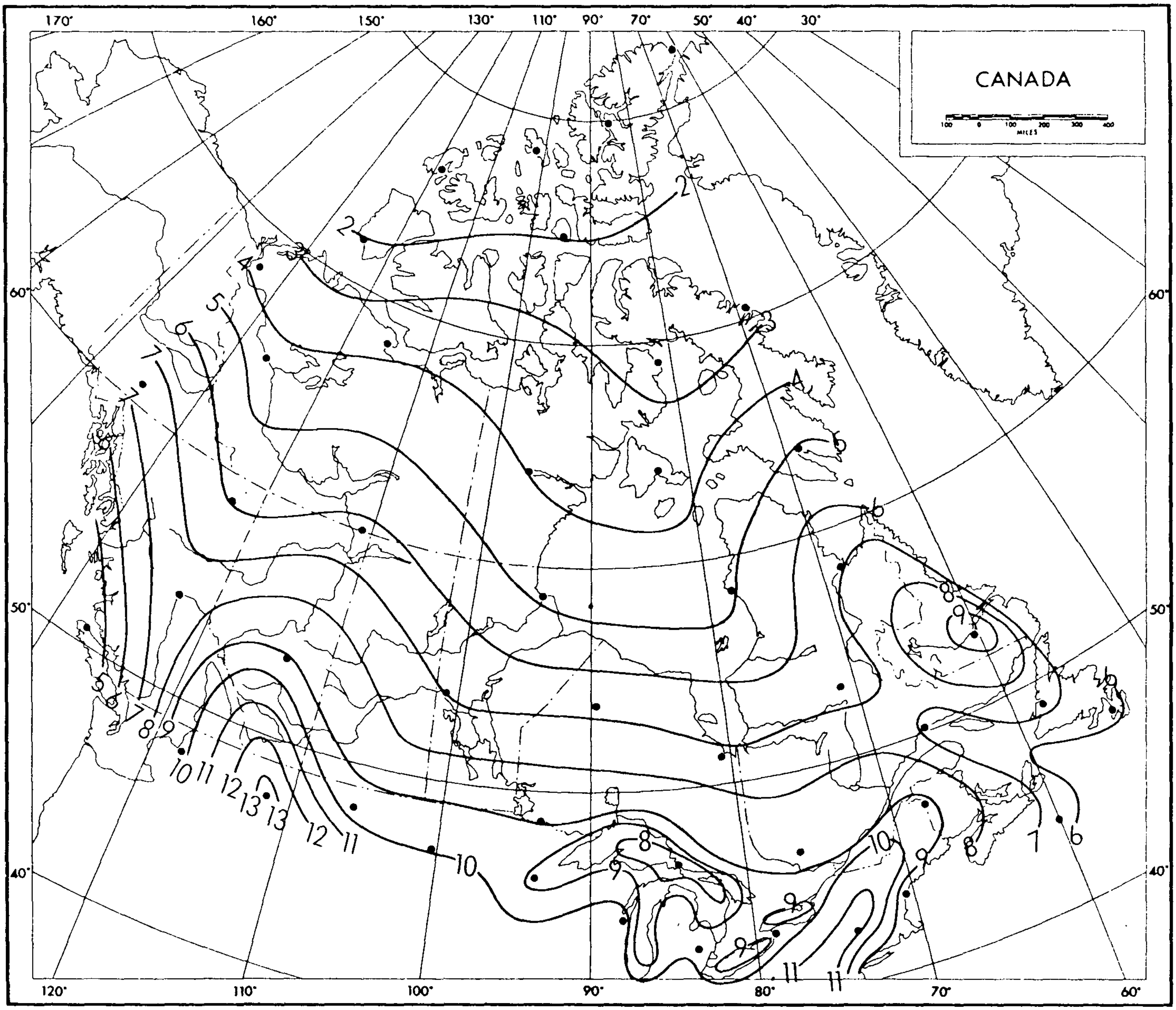


FIGURE 9 ISOPLETHS (m x 10^2) OF MEAN AUTUMN MAXIMUM (AFTERNOON) MIXING HEIGHTS
Source: Portelli (1977)

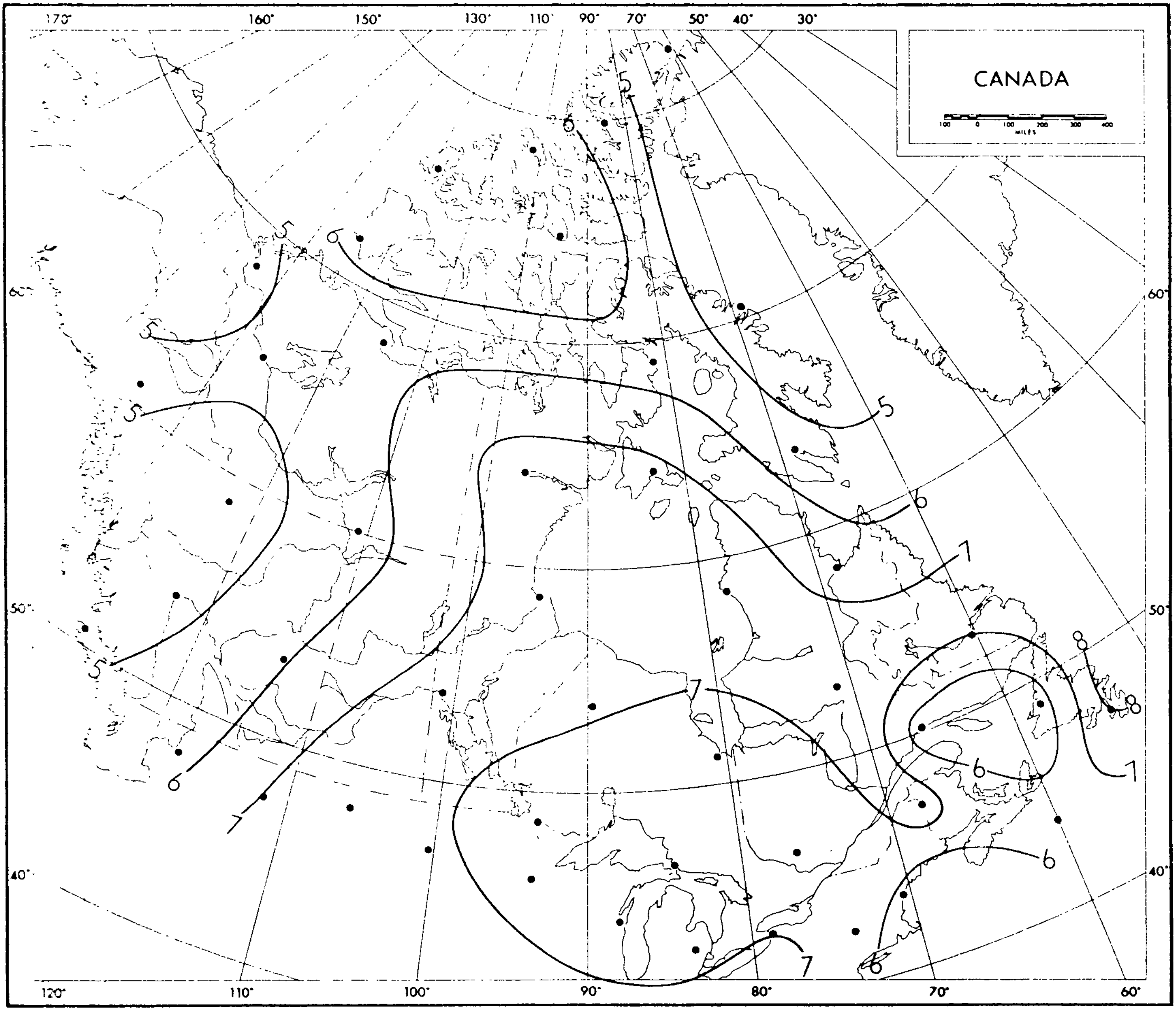


FIGURE 10 ISOPLETHS ($m \cdot s^{-1}$) OF MEAN SUMMER WIND SPEED AVERAGED THROUGH THE MAXIMUM (AFTERNOON) MIXING LAYER
Source: Portelli (1977)

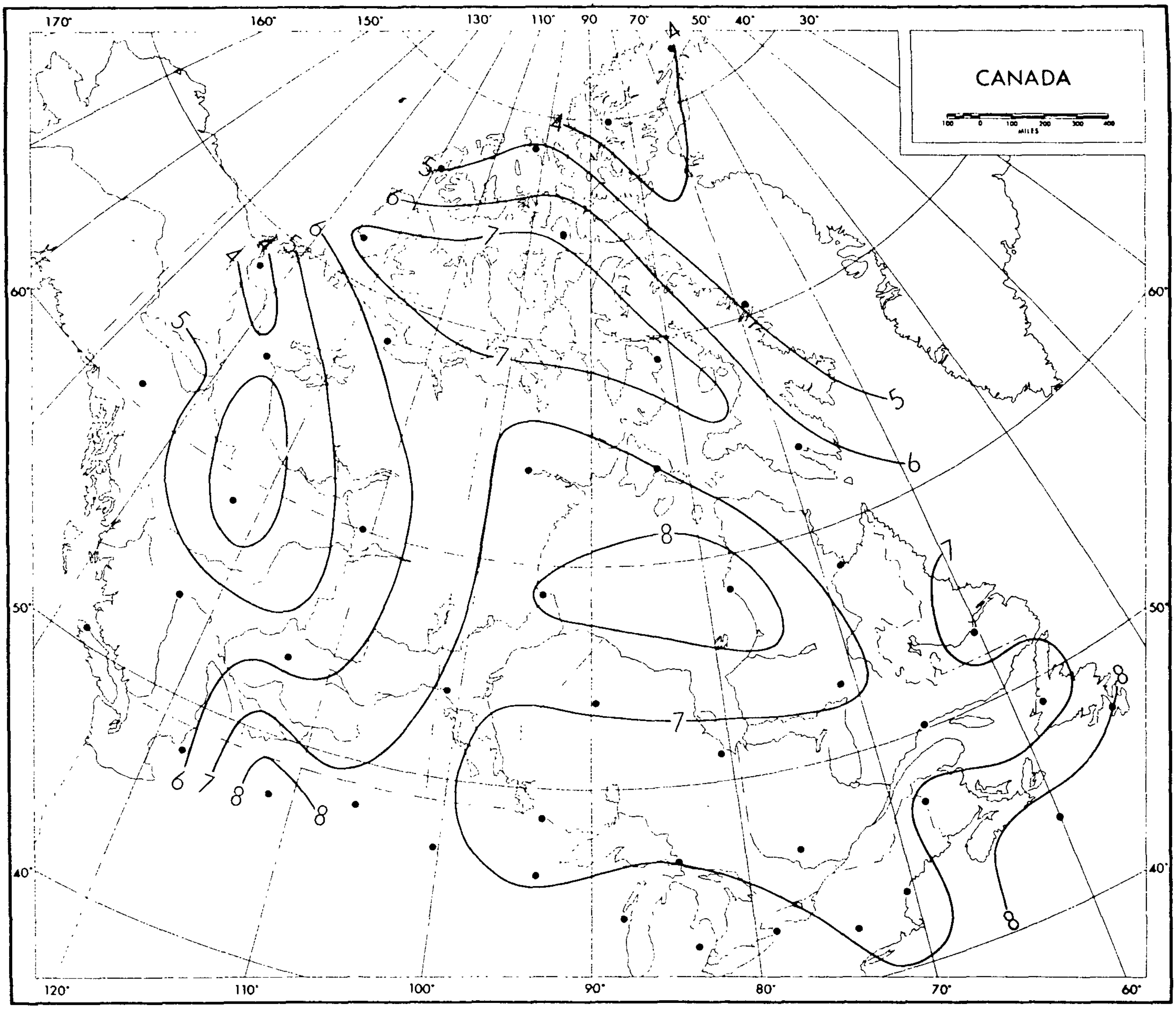


FIGURE 11 ISOPLETHS (m• s^{-1}) OF MEAN AUTUMN WIND SPEED AVERAGED THROUGH THE MAXIMUM (AFTERNOON) MIXING LAYER
Source: Portelli (1977)

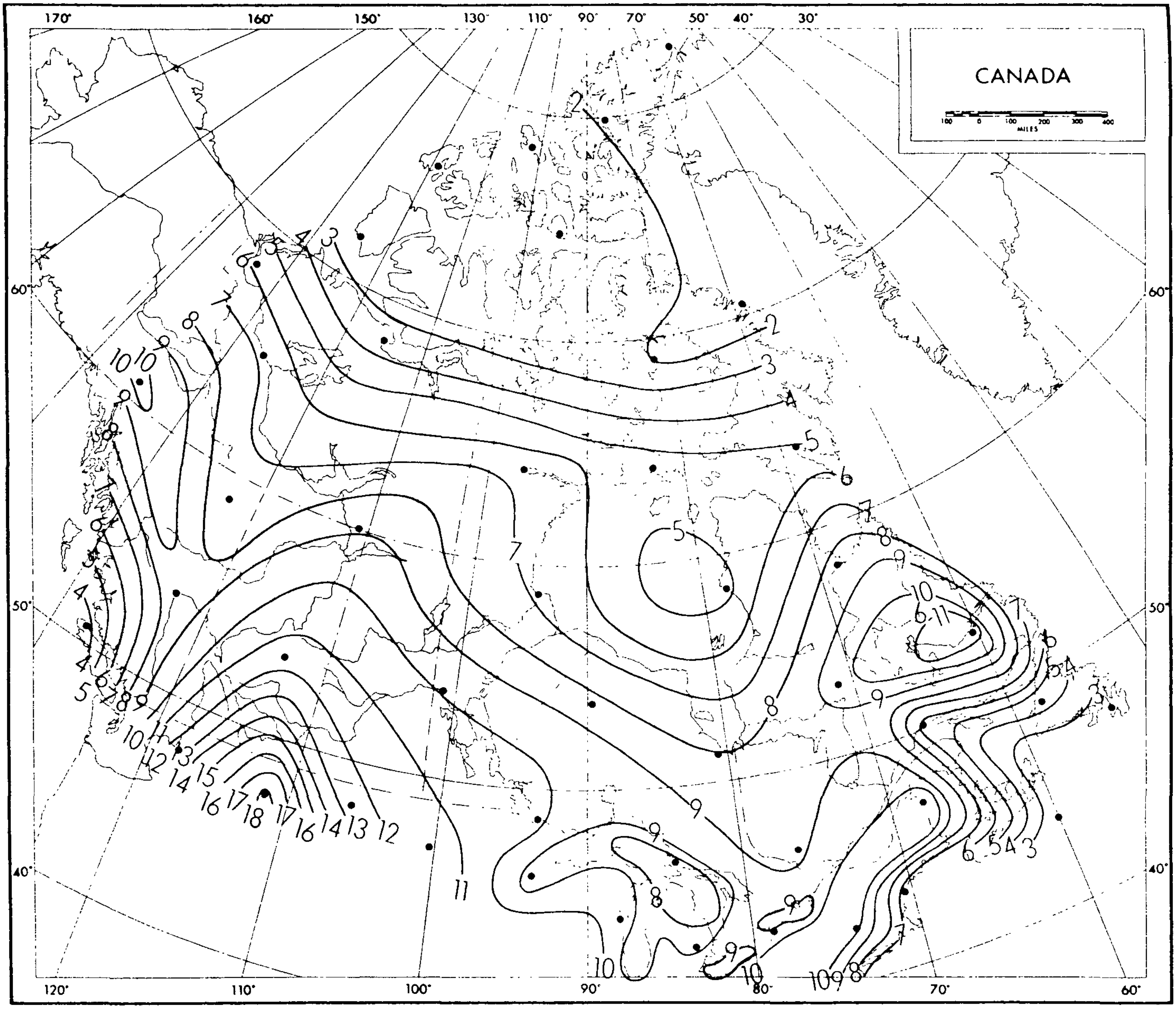


FIGURE 12 ISOPLETHS ($m^2 \cdot s^{-1} \times 10^3$) OF MEAN SUMMER MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS
Source: Portelli (1977)

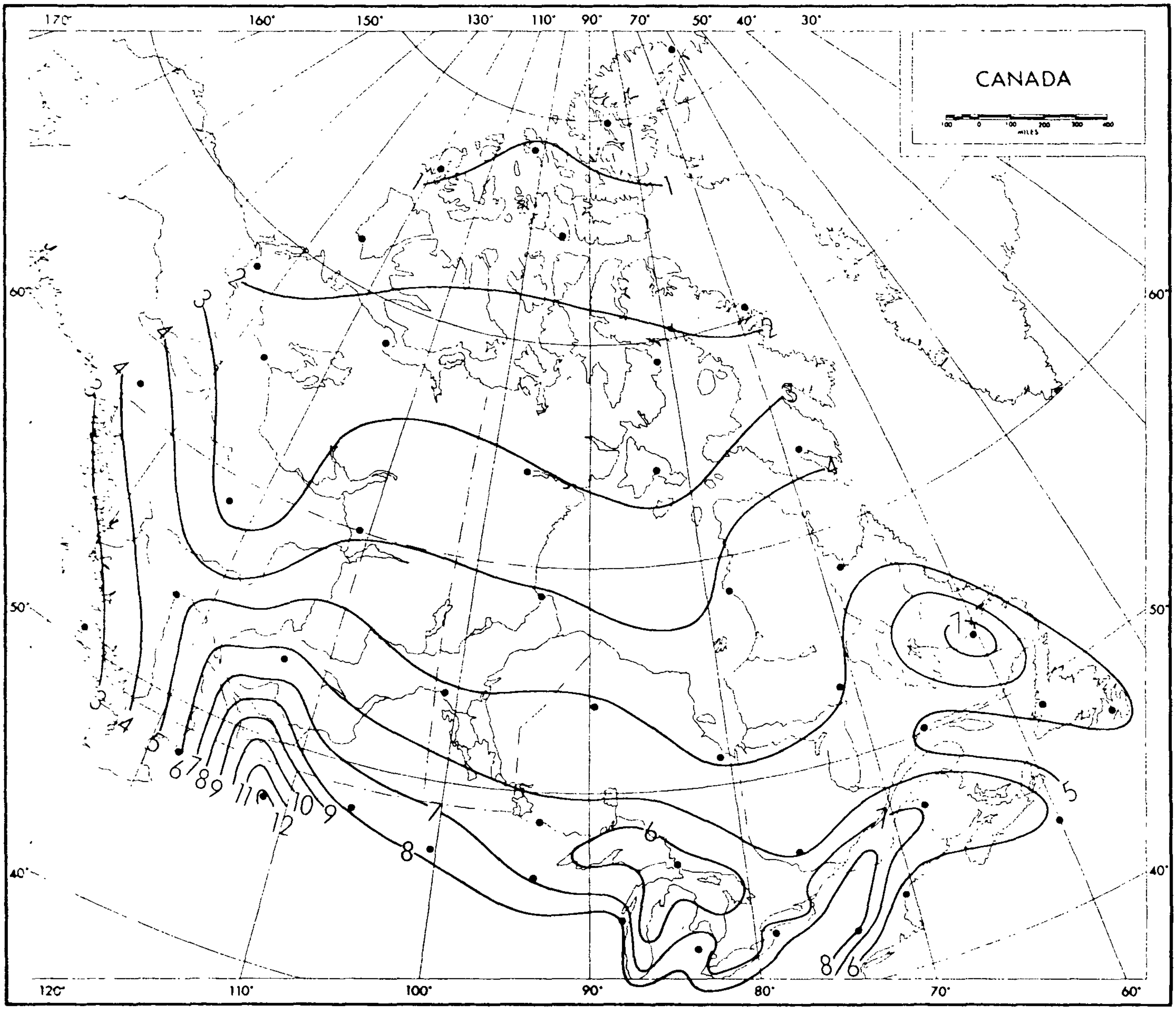


FIGURE 13 ISOPLETHS ($m^2 \cdot s^{-1} \times 10^3$) OF MEAN AUTUMN MAXIMUM (AFTERNOON) VENTILATION COEFFICIENTS
Source: Portelli (1977)

corresponding figures for Inuvik are lower: 13 km/h (8 mph) and 11 km/h (7 mph), respectively. The standard deviation on wind speed at Cape Parry is about 13 km/h (8 mph); at Inuvik, it is 7 km/h (4 mph). Therefore, it seems likely that during June the wind speed will lie between about 7 and 32 km/h (4 and 20 mph) if the conditions at Cape Parry are assumed to be typical of the Beaufort Sea.

In calculating the downwind concentrations of pollutants from an emitting source, it is necessary to make two separate calculations, a plume rise calculation and a plume dispersion calculation. The smoke and combustion gases from the fire are propelled vertically by their buoyancy relative to the surrounding atmosphere. They may rise to a height of several hundred metres. This height depends on the buoyancy of the plume and the strength of the prevailing wind. A number of equations are available that can be used to calculate the plume rise. These have been reviewed in standard texts on air pollution, for example, Seinfield (1975), Williamson (1973), and in the workbook by Turner (1974). The equations used in this work are described in detail in Appendix A. The assumed plume rises are presented in Figure 14.

When the plume has reached a condition of neutral buoyancy, it is carried in a generally downwind direction by the prevailing wind. The plume is subject to horizontal, vertical and lateral diffusion. The mathematics of plume dispersion are fully reviewed in texts such as those previously mentioned; a full treatment of this topic is beyond the scope of this report. The usual procedure is to assure that the plume expands in a Gaussian manner with an increasing "standard deviation", σ. The values of σ which apply vertically and laterally are different and depend on the distance downwind (i.e., the duration of the diffusion period) and on the inherent turbulence present in the atmosphere. This latter quantity is difficult to characterize, but the generally accepted approach is to consider five stability criteria designated from A (very unstable with fast diffusion) to F (very stable). In this work, examination of the behaviour under B, D, E and F conditions has been elected. The values of σ used here were obtained from Turner (1974).

The equations used take into account the plume rise height, the wind direction, stability criterion (B to F), and the amounts emitted; they can be used to calculate the concentration of the gaseous pollutant at any point in a generally downwind direction.

Figure 15 shows the likely plume dispersion if the plume rise height (H) is less than the mixing height. The plume is effectively trapped below the inversion "lid" and will spread vertically and laterally to fill the entire mixed volume. Figure 16 shows the likely behaviour if the plume has sufficient buoyancy to penetrate the top of the mixed layer.

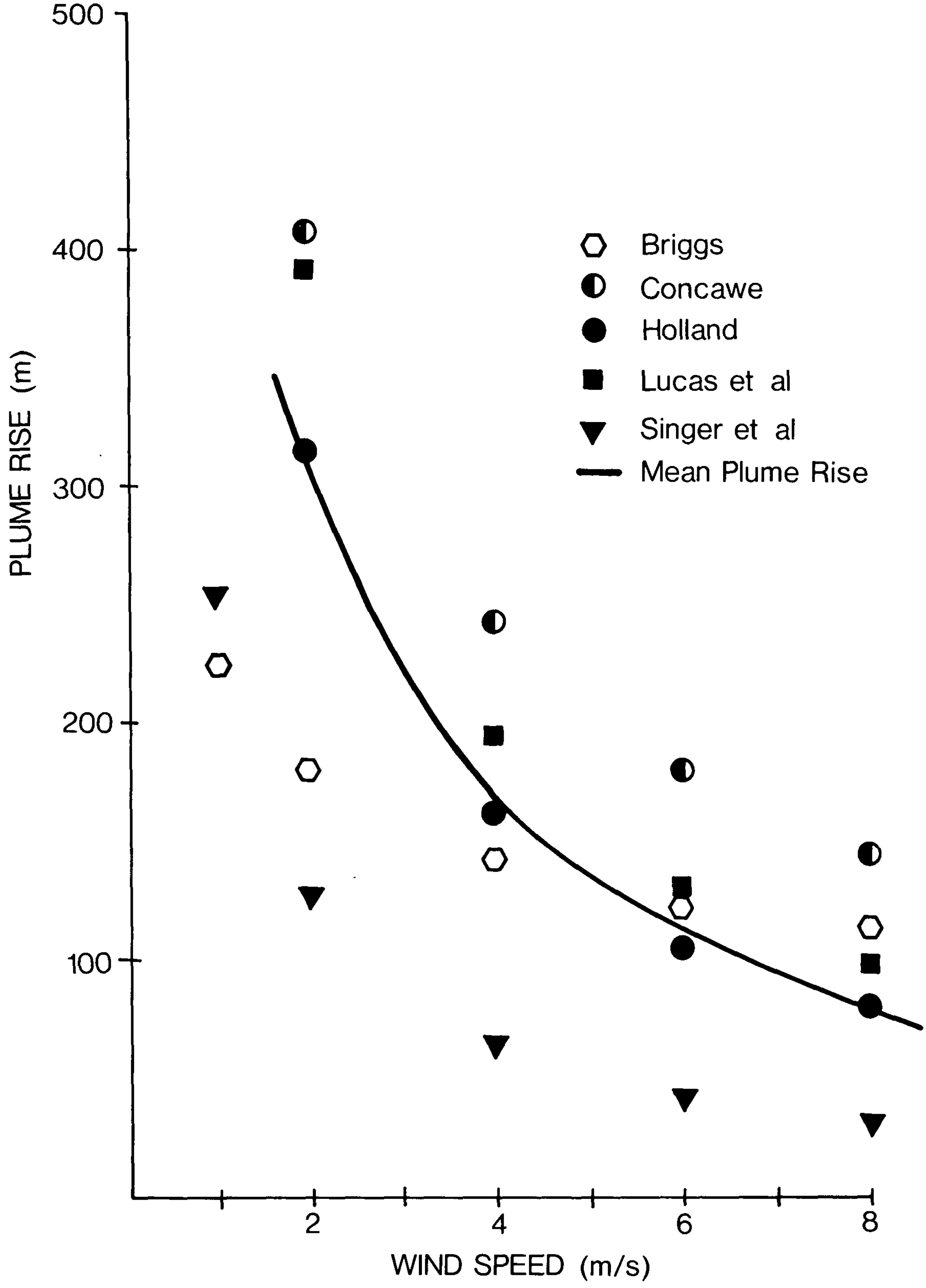


FIGURE 14 PLUME RISE VS. WIND SPEED

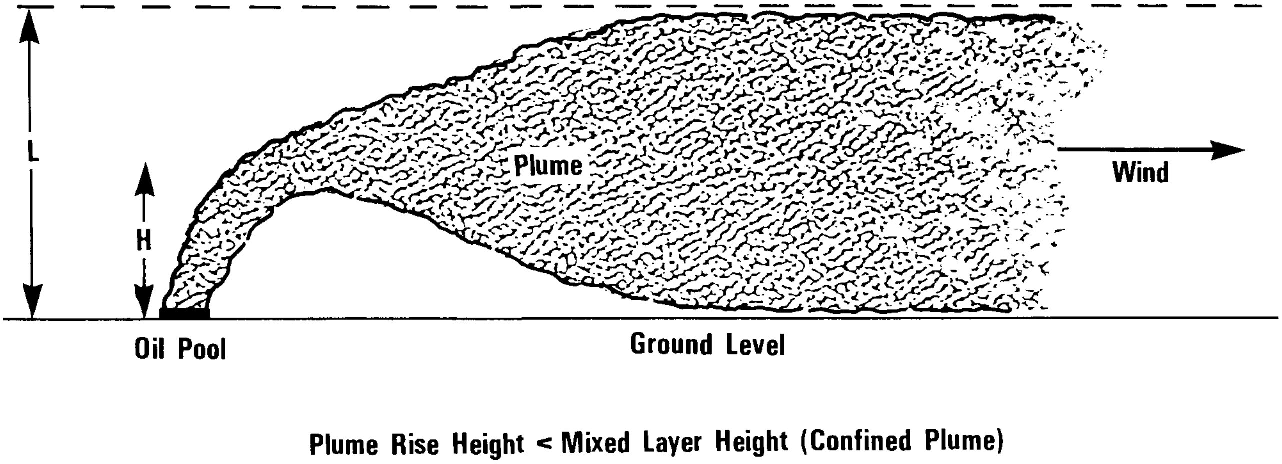


FIGURE 15 CONFINEMENT OF A PLUME IN A MIXED LAYER

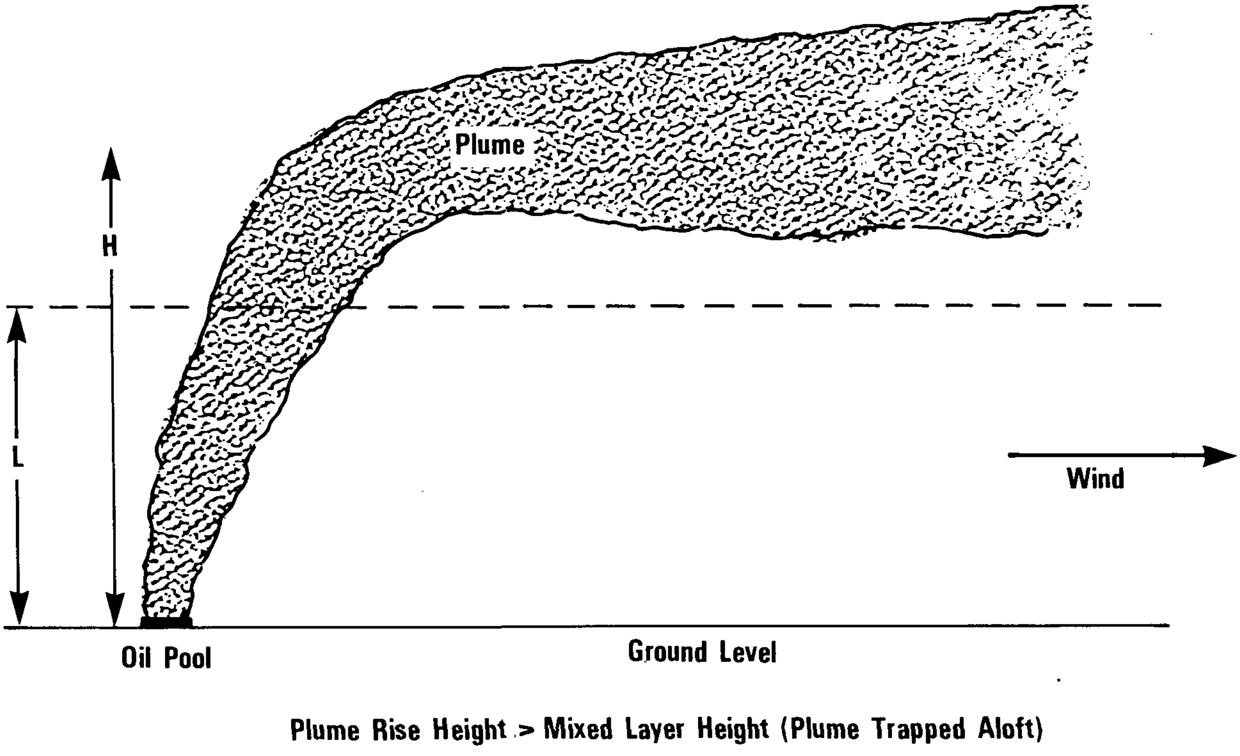


FIGURE 16 PENETRATION OF A MIXED-LAYER CEILING BY A PLUME

The plume may then spread vertically, but largely in an upward direction, since the "lid" will prevent or reduce downward diffusion. In the event that the plume height 'H' and mixing height 'L' are equal, it is likely that the plume will fan out at the top of the layer, with some vertical downward diffusion.

Another interesting and important case is the zero wind situation. The existing equations for plume diffusion break down for zero wind. Figure 17 gives a possible behaviour with a mushroom cloud forming and subsequently dissipating slowly. Conditions in the vicinity of the plume will probably be quite unpleasant.

In this calculation, a steady state or continuous source is assumed in the interests of mathematical simplicity. This implies that there is no upwind-downwind diffusion and that a "puff" of smoke is formed in 60 minutes (1.0 h) burning of length 1.0 'U' km, where 'U' is the wind speed (km/h). This would then be 15 km long in a 15 km/h wind and would drift across the area, continuously expanding vertically (until it reaches the lid) and laterally.

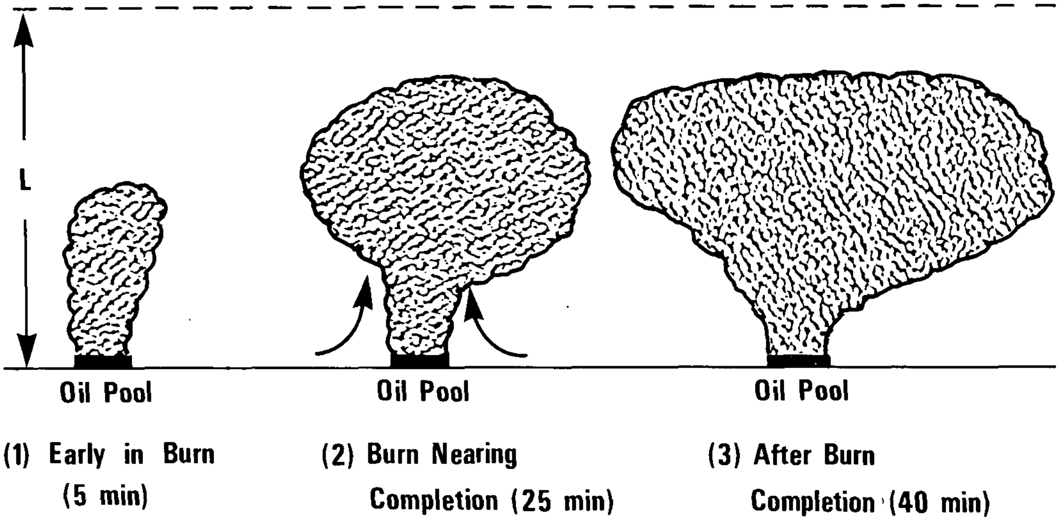


FIGURE 17 POSSIBLE PLUME BEHAVIOUR IN ZERO WIND

An additional complication is that the particulate matter (soot) is subject not only to diffusion, but also to a downward settling velocity dependent on the particle density and size. No information could be obtained on the characteristics of crude oil soot. Some laboratory experiments were undertaken to determine the approximate soot characteristics (Section 2.1.2). The deposition of soot was included in the computation by the method outlined in Appendix C.

It is emphasized that the results of these computations are subject to a considerable number of assumptions. However, it is believed that a valid approach at this stage is to make the assumptions, obtain conclusions, and then test the sensitivity of the conclusions to the assumptions. This is done with a view to determining whether more accurate experimental data was required.

The concentrations predicted by the dispersion model are based on a continuously emitting source and half-hour sampling times. The emission time used in the calculation is less than the sampling time and the concentrations that are predicted are considered to be conservative (high) estimates of pollutant levels.

1.5 Oil Composition

The exact chemical nature of crude oils obtained from the Canadian Arctic will, of course, remain uncertain until such time as the reservoirs are delineated and typical oils are analyzed. It is necessary, however, to make some oil composition assumptions.

The volatility distribution or "lightness" of the oil has a bearing on the ease of ignition and on the percentage of the oil that will remain unburned; however, this property is of little interest in the present study. Of more importance are the quantities of non-hydrocarbon materials present, notably sulphur and heavy metals. Table 2, which is a reproduction of Table B6 of the Norcor (1977) report, gives sulphur and metal analyses of unweathered crude oil samples from Norman Wells and Swan Hills. These data suggest that the significant non-hydrocarbon elements present are sulphur, which could be present at about 2 percent; vanadium, which could be present at about three parts per million (ppm); lead and zinc, 20 ppm; and nickel, one part per million. Other elements such as calcium, iron, sodium, aluminum, barium and magnesium are not normally regarded as toxic.

Information was also provided by Imperial Oil Limited on Norman Wells crude oil; this information indicated that sulphur was present at about 0.34 percent by weight. Additionally, H_2S was present at a concentration of about 21 lb/1000 barrels (i.e., less than 0.01 percent). No metal analyses were available.

TABLE 2 METAL ANALYSIS OF UNWEATHERED CRUDE OIL SAMPLES

	Norman Wells		Swan Hills	
Sulphur	1.76	percent	2.90	percent
Aluminum (Al_2O_3)	< 0.5	ppm	<0.5	ppm
Barium	< 0.5	ppm	<0.5	ppm
Calcium (CaO)	< 0.5	ppm	5	ppm
Copper	< 0.5	ppm	<0.5	ppm
Iron (Fe)*	0.3	ppm	0.3	ppm
Lead	0.5	ppm	20	ppm
Magnesium (MgO)	< 0.5	ppm	<0.5	ppm
Nickel	1	ppm	<0.5	ppm
Silicon (SiO_2)	< 0.5	ppm	<0.5	ppm
Sodium (Na_2O)	< 1	ppm	1	ppm
Tin	< 0.5	ppm	<0.5	ppm
Vanadium	3	ppm	<0.5	ppm
Zinc*	-		20	ppm

* Values for iron and zinc may be suspect as a result of contamination from metal containers.

The most significant metals normally found in crude oil are vanadium and nickel. The American Petroleum Institute research project 56 "Trace Metal Constituents in Petroleum" (Sugihara, 1962) has resulted in a number of studies in which a number of metals have been identified and their concentrations determined. Vanadium may be present at concentrations up to about 1000 ppm; nickel is present at considerably lower concentrations.

There is very little information about the chemical state of these metals. It is probable that they are combined in some complex metal-organic form with the asphaltene fraction of the oil, and thus the metals will tend to accumulate in the non-volatile fraction. This does not necessarily imply that the metals will not be vapourized since, as earlier discussed, some of the liquid hydrocarbon will be propelled into the combustion zone during the combustion process. Metals contained in this oil undoubtedly will be converted into particulate form and will be deposited with the particulates downwind of the fire. Fortunately, neither vanadium nor nickel are regarded as particularly toxic elements. The oxidation state of these metals as they are emitted from the burn is presently unknown. Whether or not the high lead and zinc concentrations in Swan Hills oil are typical should be investigated.

2 EXPERIMENTAL

2.1 Laboratory Studies of Oil Burning

2.1.1 Equipment and Procedure. A small laboratory apparatus was assembled in order to undertake some studies of the characteristics of oil burning. The apparatus was designed and constructed so that a known quantity of oil could be subjected to combustion with a known air supply rate and the combustion products collected. A schematic diagram of the apparatus is shown in Figure 18.

The apparatus consisted of a 15.2 cm diameter by 45.7 cm high glass column fitted at the bottom with a hemispherical end. Contained in this end was a sand bed which supported a circular brass dish; the dish was 8.9 cm in diameter and 1.3 cm thick. A quantity of oil, to a maximum depth of approximately 0.75 cm, could be contained in this dish. A nichrome wire was used to ignite the oil. Air was supplied by a pump at a controlled rate that was determined by passing the air through an orifice meter. Chromel-alumel thermocouples were used to record temperatures of the dish, the oil and various other locations in the column. A suction filter was connected to the top of the apparatus to collect the soot produced. Provision was made to vary the temperature of the dish by circulating temperature controlled water through a coil on the dish base.

A known quantity of oil was placed in the dish. By passing water through the coils of the brass dish, the temperature of the dish and the oil were adjusted to the required temperature. The oil was then ignited using the nichrome wire. During the burning process, pool temperatures of the oil, the dish, and various locations in the flame were recorded. When the burning was complete, the weight of the residue in the dish was measured. The mass of soot collected in the filter was measured by subtracting the weight of the filter paper plus soot from the preweighted paper, and an approximate mass balance was calculated. Photomicrographs were also taken of the soot particles to obtain data on particle size necessary for calculating settling velocities.

Samples of the original oil, the residue and the soot were analyzed for vanadium content in order to determine the extent to which such metals are present in the emissions. Analysis was by instrumental neutron activation analysis.

Seven gas composition determinations were made in the apparatus during the oil burning for O_2, N_2, CO_2, CO and other peaks. The peak areas on a GC thermal conductivity detector showed an average 21.2:1 ratio of CO_2 to CO, although the ratio varied widely from 7.9:1 to 43.1:1. A mole ratio of 20:1 is assumed. The CO

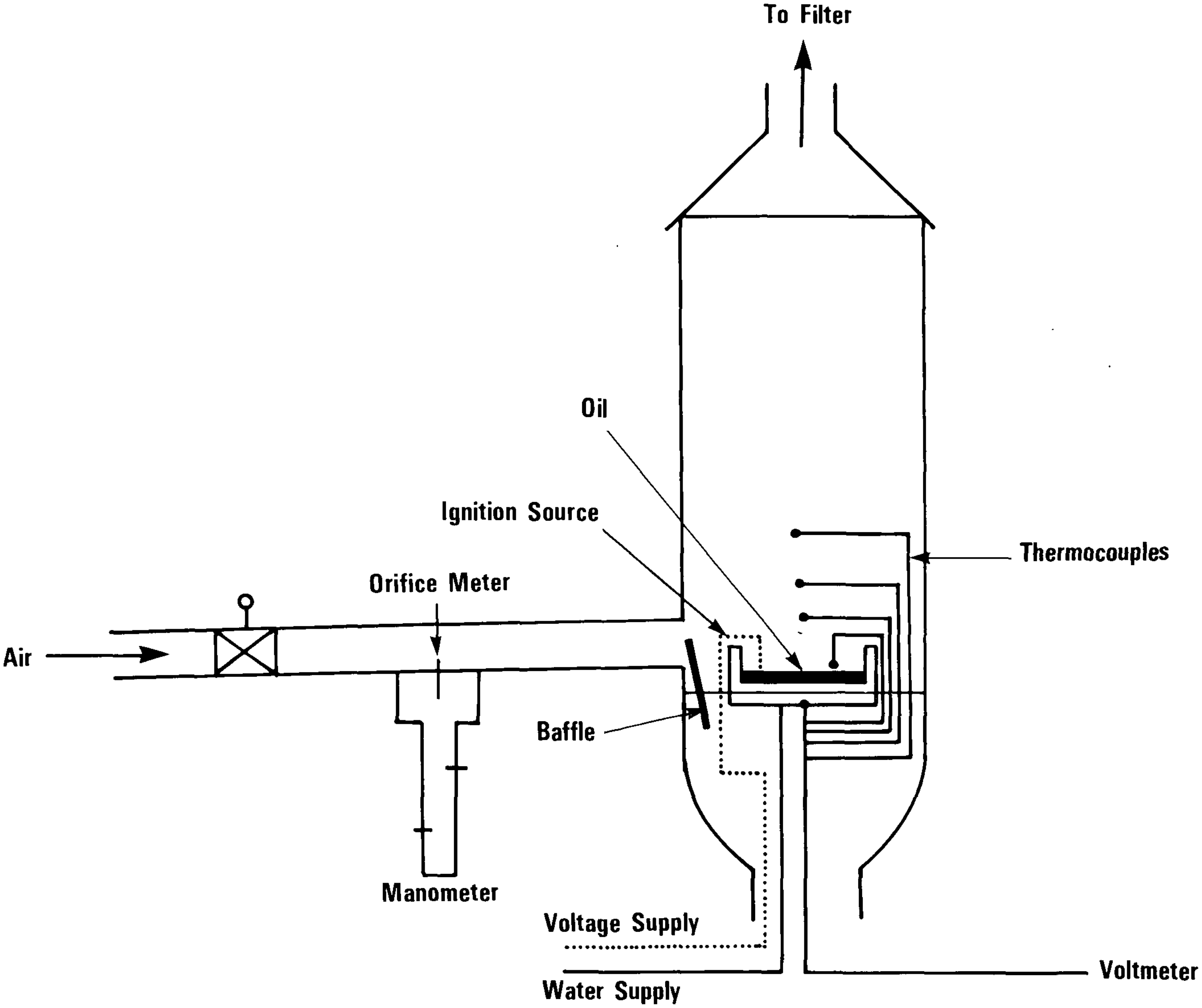


FIGURE 18 APPARATUS

produced will behave similarly to the SO_2 during dispersion, thus the CO concentrations can be estimated as a ratio to the SO_2.

2.1.2 Photomicrography of Soot. In the dispersion calculations, it is essential to define a settling velocity for the particulate matter. This velocity largely controls the location and concentration at which the soot is deposited. Large, heavy particles settle faster and thus will fall to the ground closer to the source in greater concentrations. It proved to be impossible to measure the settling velocity directly; thus, photomicrographs of soot from the laboratory appparatus were taken to enable diameters to be estimated. Both light and electron microscope photographs were taken.

The results are illustrated in Figure 19. The soot consisted basically of a large number of very small particles ranging in diameter from one to 100 nm; most were about 100 nm (0.1 µm). These particles were agglomerated into larger particles, which were often about one µm but occasionally 10 µm in "diameter". The photomicrograph shows this range in size. The large particle cluster is about 10 µm (0.01 mm) and would be easily visible in a light microscope. These findings are in accord with values reported by Ledbetter (1972), who gives a size range for oil smoke of 30 nm to one µm.

Examination of the soot by a light microscope showed particles up to 40 µm in diameter. It appears, therefore, that soot consists of a spectrum of particle sizes ranging from possibly one nm to 40 µm and even larger particles may form by clustering. This observation makes the selection of a settling velocity almost meaningless, but some selection is necessary. Probably the most realistic approach is to postulate that the soot forms in the flame as particles of size one to 100 nm (so small that they have effectively zero settling velocity), gradually clustering in the rising plume to form particles which range from one µm to 10 µm. The clustering, coagulation, or agglomeration process is discussed in texts on air pollution such as that by Williamson (1973).

Assuming that the particles have the density of carbon (2.3 g/cm^3), the free fall or settling velocity of the soot particles can be calculated from the Stokes equation for low Reynolds numbers and using a drag coefficient at high Reynolds numbers. The approximate velocities are as follows (Ledbetter, 1972):

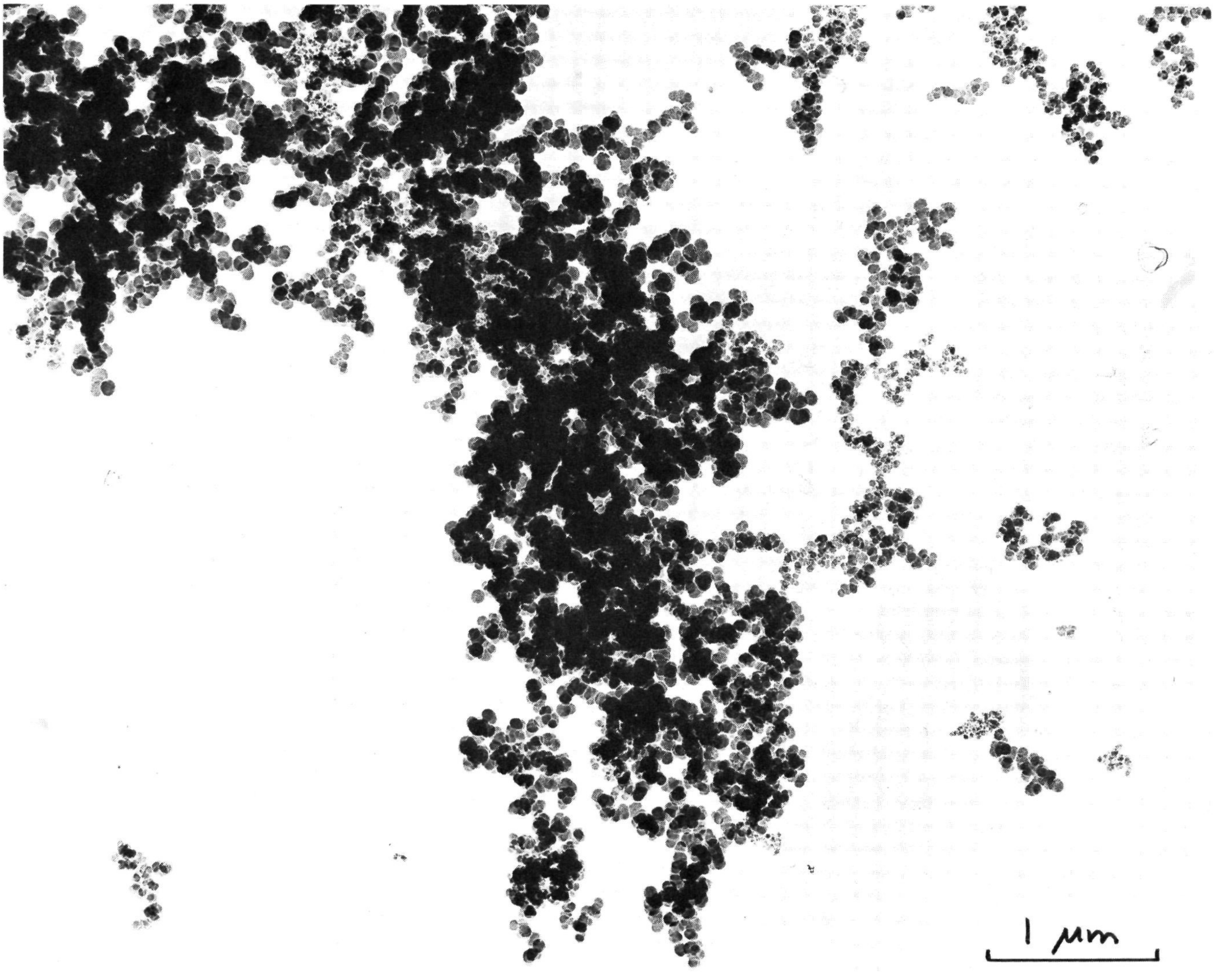


FIGURE 19 ELECTRON PHOTOMICROGRAPH OF SOOT
(Scale 1.25 in = 1 μm)

Particle Size (μm)	Free Fall Velocity (cm/s)	Time to Fall 100 Metres		
1000	600	17 s		
100	50	200 s		
30	5	2000 s	~	0.6 h
10	0.6	$1.7\text{x}10^4$	~	4.7 h
3	0.06	$1.7\text{x}10^5$	~	47 h
1	0.007	$1.43\text{x}10^6$	~	400 h

Thus, particles of less than 10 μm fall at very slow velocities and will take several hours or days to fall from the plume, by which time the plume is probably tens of kilometres from the source.

2.1.3 Laboratory Burning Results. The results of the oil burning experiments are shown in Table 3. It was found that the fraction of the oil burned and the amount of soot formed depended on the dish temperature (which influences the oil temperature), the air flow rate and the quantity of oil. As expected, the colder the oil, the less efficient the burn; for example, at 198°C, 81.6 percent of the oil burned, whereas as 31°C, only 34.4 percent burned.

These conditions are far removed from a full-scale burn but the same trends probably apply. The air flow results indicate an optimum. At too low air flows there is a decrease in combustion rate and at too high flows the flame is blown out. The greater the quantity of oil, the greater the burning efficiency, probably as a result of the insulating effect of the deeper oil pool.

The amounts of soot formed were generally two to five percent of the original oil mass. For calculation of the full-scale dispersion, a figure of six percent is suggested as being appropriately pessimistic.

2.1.4 Metal Analysis. The metal analyses are given in Table 4. It proved difficult to obtain a satisfactory mass balance on the metal due to analysis errors, and possibly due to loss of metal in vapour form. The laboratory tests with vanadium typically showed that one to three percent of the metal was present in the soot, but that as much as 38 percent was emitted.

It is believed that the best interpretation of the data is that typically one-third of the metal is emitted. Similar results were obtained using oil with added cobalt octanoate. In the field trial, the mass of soot could not be determined; thus the mass of

TABLE 3 LABORATORY OIL BURNING EXPERIMENTS (RESULTS)

(i) Variable dish temperature; constant quantity of oil; constant air flow.

Oil Quantity (g)	Air Flow (l/min)	Dish Temperature (^oC)	Burn Efficiency (%)	Soot as Fraction of Oil Lost (%)
12.5	190	198	81.6	-
13.0	190	148	60.0	1.2
12.0	190	147	63.3	4.3
12.5	190	98	44.8	-
12.1	190	39	33.9	2.9
12.5	190	31	34.4	2.8

(ii) Variable air flow; constant quantity of oil; constant dish temperature.

Oil Quantity (g)	Air Flow (l/min)	Dish Temperature (^oC)	Burn Efficiency (%)	Soot as Fraction of Oil Lost (%)
13.2	0	22	35.6	1.8
12.4	100	35	53.2	2.7
12.5	150	24	36.8	-
12.5	190	31	34.4	2.8

(iii) Variable quantity of oil; constant dish temperature; constant air flow.

Oil Quantity (g)	Air Flow (l/min)	Dish Temperature (^oC)	Burn Efficiency (%)	Soot as Fraction of Oil Lost (%)
16.6	190	13	57.8	2.1
12.5	190	31	34.4	2.8
12.1	190	39	33.9	2.9
8.3	190	21	24.1	4.5

TABLE 4 RESULTS OF METAL ANALYSES

	1	2	3	4	5	6	7	8	9	10	11	12
Original Oil Mass (g)	12.8	12.8	12.4	12.7	12.7	12.8	100	100	100	12.7	12.7	12.8
Metal Concentrations (μg/g)	3.7	3.7	3.6	2.1	2.2	2.1	2.1	2.1	2.1	22.8	22.8	22.7
Metal Mass (μg) (A)	47.4	47.4	44.6	26.7	27.9	26.9	210	210	210	290	290	291
Residue Mass (g)	4.6	7.0	6.0	4.4	7.8	4.2	10.8	10.8	10.8	4.4	7.8	4.2
Metal Concentrations (μg/g)	8.3	8.2	7.8	3.8	3.3	4.0	4.1	3.0	3.8	35.1	30.5	40.6
Metal Mass (μg) (B)	38.2	57.4	46.8	16.7	25.7	16.8	44.3	32.4	41.0	154	238	171
Soot Mass (g)	0.193	0.126	0.136	0.196	0.120	0.199	-	-	-	0.20	0.12	0.20
Metal Concentration (μg/g)	4.1	6.0	3.6	4.1	2.9	1.9	14.6	22.6	17.8	8.9	2.5	0
Metal Mass (μg) (C)	0.8	0.8	0.5	0.8	0.3	0.4	-	-	-	1.7	0.3	0
Mass Balance (%) 100(B + C)/A	82	123	106	66	93	64	-	-	-	53	83	59
Apparent Percent Metal in Soot (1)	2	2	1	3	1	1	-	-	-	1	< 1	0
Apparent Percent Metal in Soot (2)	19	-	-	37	8	38	79	84	80	47	18	41

(1) Calculated as 100C/A

(2) Calculated as 100(A - B)/A

Runs 1 through 6 are laboratory tests with naturally occurring vanadium

Runs 7 through 9 are field tests with naturally occurring vanadium

Runs 10 through 12 are laboratory tests with added cobalt octanoate metal emitted could only be calculated as a difference between the original metal mass and that present in the residue. These results indicate a much higher emission percentage of 79 to 80 percent, which is a reflection of the much higher fraction of the oil burned, i.e. 90 percent compared to 50 to 70 percent in the laboratory.

Apparently, the metal is concentrated in the residue during the early stages of burning; about 30 percent is emitted during the burning of the first 60 percent of the oil. As more residue burns and sputters into the flame, more metal is emitted, until at 90 percent burning about 80 percent of the metal has been emitted.

It is believed that for the present purposes, assuming 84 percent burning, a reasonable assumption is that 67 percent of the metal is emitted, and that it all eventually becomes associated in the plume. An oil containing nine ppm metal will therefore yield a residue containing the equivalent of three ppm (at a concentration of 19 ppm) and the equivalent of six ppm will be emitted. This is a factor of 10^4 less than the soot mass, thus the soot will have an ultimate average concentration of about 100 ppm metal.

2.1.5 CO Analysis. A sulphur and carbon mass balance suggests that if 100 g of oil are burned to give six g of soot, then the remaining approximately 94 g will yield about four g SO_2, 9 g CO and 280 g CO_2. The CO concentrations are estimated as 2.25 the time the SO_2 mass concentrations. If desired, the CO_2 mass concentrations can be calculated as 70 times the SO_2 concentrations.

2.2 Field Studies of Oil Burning

Permission was obtained from the Metropolitan Toronto and Region Conservation Authority to undertake an oil burn in the Glen Major Conservation Area near Claremont, Ontario. This site is fortunately fairly remote. Forty gallons (UK) (0.204 m^3, 146 kg) of mixed sour blend Alberta crude oil obtained from BP Oil Ltd. were spilled on a level ice surface in a pool about one cm thick and five m in diameter. At the time of the burn, the air temperature was -4^oC and the wind speed was eight km/h. The burn took place at 11:00 am on February 3, 1978. The oil was ignited using an oil rag soaked in 7.5 litres of a kerosene/gasoline mixture. The flames spread rapidly over the entire area, emitting a dense cloud of black smoke. The burn lasted for six minutes.

An attempt was made to measure temperatures in the flame and plume by locating ceramic-insulated thermocouples on a Dexion pyramid located in the fire (Figures 20 to 25). The output from these thermocouples was to be read on a Thermoelectric MultiMite. In addition, a portable thermometer-probe system was used; the probe was mounted at the end of a three m long, hand-held aluminum pole.

No meaningful temperature measurements were obtained. Most thermocouple readings went off scale immediately. The flames engulfed the pyramid and no readings could be taken of the temperature above the flame. This would have required mounting a thermocouple at a height of at least 10 m; but even if this could have been done, there is no guarantee that the centre of the plume would have been close to the thermocouple. The intense heat from the fire prevented successful use of the hand-held thermocouple.

It is apparent that to measure temperatures in and above oil fires requires either (i) very small fires of about 20 l of oil, or (ii) construction of a very sophisticated tower assembly over the fire.

An attempt was made to measure the amount of soot formed in the flame by drawing part of the plume of combustion gases through a tube (Figure 21) to a Precision Scientific air sampler fitted with a preweighed Whatman number 40 filter paper. The velocity of rise of the plume and its diameter were determined approximately by cinematography. From a knowledge of the air sampling rate and the total volume of the plume formed, an estimate could be made of the fraction of the total amount of the material emitted, which was sampled. This, coupled to the weight of the material collected, would result in an approximate value for the amount of soot generated in the flame.

This also proved unsuccessful, as the sampling tube could not be located properly above the flame in the plume because of the intense heat. The generator driving the air sampler also failed during the test. Some soot was collected for analysis but no quantitative calculations of soot were possible. No attempt was made to analyze the plume for hydrocarbons, carbon dioxide, or carbon monoxide.

Again, it is concluded that either the work must be done on a small scale or with very sophisticated equipment. Aerial plume sampling is preferable.

The original oil and the soot were both analyzed for heavy metal contents using instrumental neutron activation analysis. The mass of residual oil was also determined by collection and direct weighing and was found to be 16 kg or 10 percent of the original oil mass.

The plume rose at an angle of about 30 degrees to the vertical but this varied with wind speed and direction. The plume rise velocity was estimated from cinematography to be about five m/s and it increased in diameter steadily, doubling at a height of about 20 m. The total plume rise could not be measured accurately but it was believed to be about 150 m.

The vigour with which the oil burned was impressive and suggested that once a fire is established it may spread rapidly to nearby pools. The ice under the oil melted and the water boiled, sputtering through the burning oil layer, and probably conveying quantities of non-volatile material into the flame and plume. There is a tendency for the flame to spread by transport of burning oil on flowing water; this may be very useful in a practical clean-up situation. There is obviously some danger to personnel in the area, particularly if they are surrounded by ignitable oil. For this reason, the use of helicopters for remote ignition is very desirable.

The oil residue was thick tar, which was easily collected. The relatively small amount of residue, 10 percent, may reflect the unweathered nature of the oil. If the same residue had been left after approximately 30 percent of the oil had evaporated (as would occur in a few days), the residue would be 14 percent of the weathered oil.

The burning experiment was useful in providing some information on the nature of the burning process and on the plume rise characteristics. Figures 20 to 25 illustrate the experiment.

If further, large experimental burns are to be undertaken to obtain temperature and soot quantity data, it is clear that a much more sophisticated instrumental and sampling system is required - at a correspondingly greater expense. Probably the most economical approach is to undertake a number of small burns that can be readily instrumented to obtain data. There data can be analysed and used to design a subsequent, large-scale experiment. Also, it is still not entirely clear what parameters should be measured or how they should be measured. Since burning is one of the most attractive clean-up approaches, further experimental work is clearly justified.

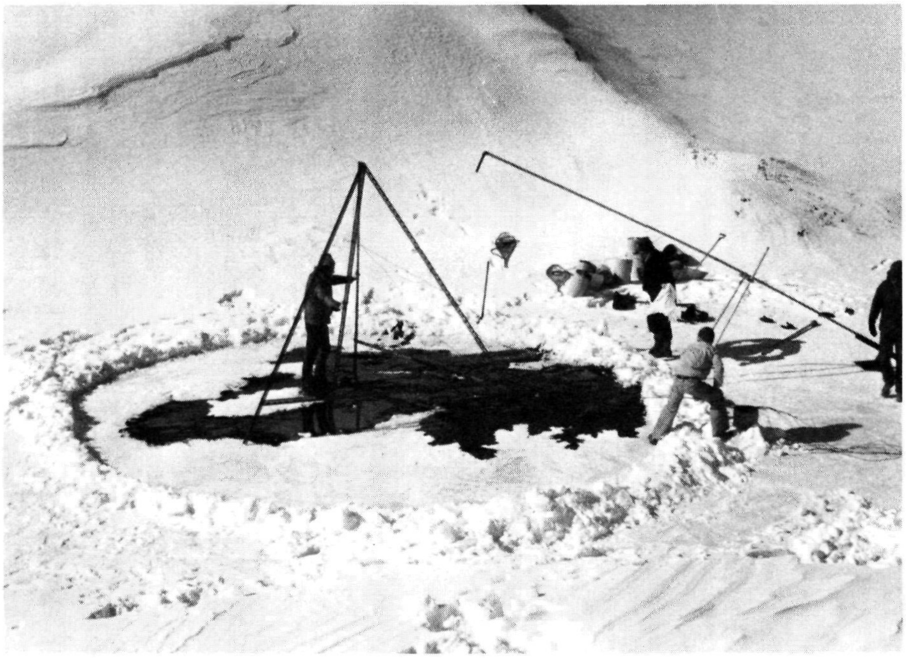


FIGURE 20 PREPARATION OF BURN SITE

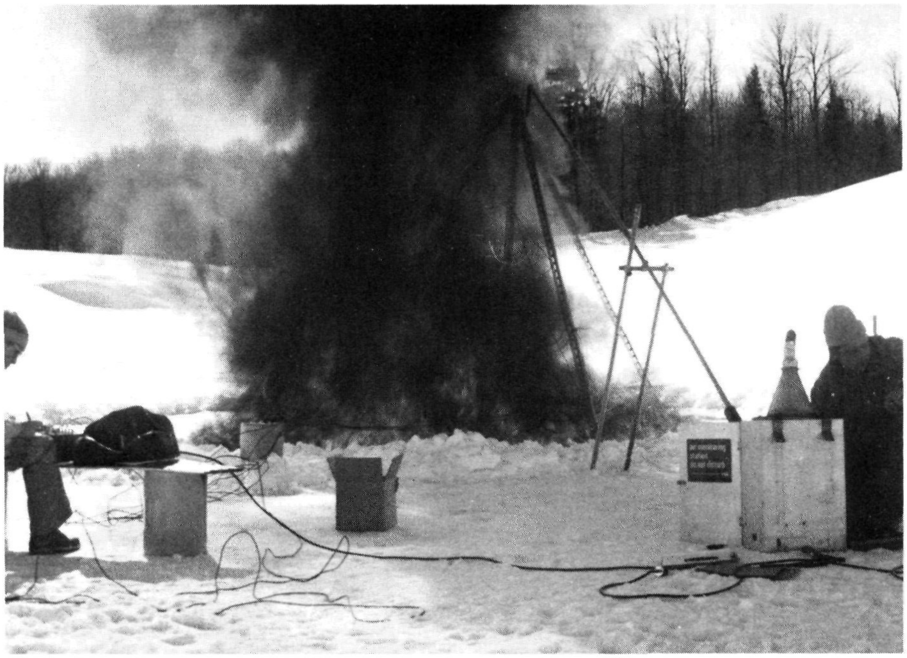


FIGURE 21 COMMENCEMENT OF BURN

FIGURE 22 DEVELOPED BURN TWO MINUTES AFTER IGNITION

FIGURE 23 DEVELOPED BURN FOUR MINUTES AFTER IGNITION

FIGURE 24 DEVELOPED BURN FIVE MINUTES AFTER IGNITION

FIGURE 25 END OF EXPERIMENTAL BURN

3 DISPERSION CALCULATIONS

3.1 Unit Burns

3.1.1 Assumptions. It is assumed that each pool consists of 1.0 m^3 of oil that contains two percent sulphur (all of which forms SO_2). The oil burns in 10 minutes to form six percent of the original oil mass as soot at a rate of 83 g/s, and it forms SO_2 at 55 g/s. It is assumed that metal is present at a concentration of 10 ppm, of which six ppm is emitted as particulate matter. The emission rate is 8.3×10^{-3} g/s, or 1/10,000 that of the soot rate.

Although hydrocarbons are emitted, a consideration of the overall oil mass balance in Section 1.2 shows that the amount of hydrocarbon emitted in the burns will be negligible compared to the amounts emitted by direct evaporation. If, for example, it is assumed that one percent of the burned oil is emitted as hydrocarbon, this corresponds to about one percent of the total hydrocarbon emissions by evaporation. Clearly, the ambient hydrocarbon levels arise from evaporation, rather than from burning. Burning serves to reduce hydrocarbon emissions. Thus, no hydrocarbon dispersion calculations were undertaken. Fortunately, hydrocarbons are not regarded as a particularly noxious pollutant in areas that are not subject to photochemical smog.

The weather conditions considered are two, four, six, and eight m/s wind speeds, which cover the expected range. The zero wind speed case is considered separately later. A mixed layer height of 310 m is assumed.

3.1.2 Plume Rise Calculation. A number of calculations are available for calculating plume rise as a function of wind speed, heat emission rate, burn area, exit velocity, etc. The equations used were those of Holland, Concawe Lucas et al, and Singer et al. Not surprisingly, the results showed considerable discrepancies, as illustrated in Figure 14. Details of the calculations are given in Appendix A. A mean plume rise was calculated, as shown in Figure 14. It should be recognized that the data are probably subject to a ± 50 percent error.

These equations can not be used to predict a plume rise at zero speed, but experimental results suggest that a rise of about 500 m is likely.

3.1.3 SO_2 Dispersion. The equation used in the dispersion calculation is described in Appendix B, and is taken from Turner (1970). It gives the ground level concentration at the centreline (i.e., exactly downwind: the worst case) as a function of source strength, wind speed, stability class (B to F), plume rise height and mixing height. The horizontal and vertical dispersion coefficients are taken from the stability class - downwind distance diagrams given by Turner (1970). The equation assumes reflection at the ground and at the top of the mixing layer.

A number of computations were undertaken for varying combinations of the variables and the centreline ground level concentration calculated as a function of distance from the fire. Typical profiles in Figures 26 and 27 show the effect of stability and wind speed. The ordinate is SO_2 concentration (g/m^3) and the abscissa is the downwind distance (km).

The general behaviour is as expected, with a near-zero concentration in the immediate vicinity of the fire as a result of the plume rise. The vertical, downward diffusion starts to bring the SO_2 back to ground level about one km downwind for the fast diffusion, Class B, resulting in maximum ground level concentrations of above 100 $\mu g/m^3$. At more stable conditions, (Classes D and E), the maximum is reached further downwind at five to 20 km typically at lower concentrations of 30 to 70 $\mu g/m^3$. The worst conditions tend to be at locations close to the fire, under Class B conditions, at low wind speeds. The results are given in Table 5.

Increasing the wind speed decreases the plume height and usually tends to cause greater exposure close to the fire. The concentrations at 10 and 40 km downwind are reduced by dilution. Below two m/s, the plume penetrates the top of the mixed layer; it will probably be diluted at heights of 300 to 500 m, thus causing little exposure at ground level.

It is suggested that a unit burn will cause maximum concentration exposures, as summarized below. If it is assumed that three pools burn simultaneously, then the maximum cluster concentrations can be estimated by multiplying by 3.

	From a Pool	From a Cluster
Maximum SO_2 concentration close to fire $\mu g/m^3$	100	300
Concentration at 10 km	30	90
Concentration at 40 km	10	30

The significance of these concentration levels is discussed in more detail later. Sulphur contents other than the two percent assumed here will linearly change the emission concentrations; for example, if one percent sulphur is assumed, the concentrations should be halved.

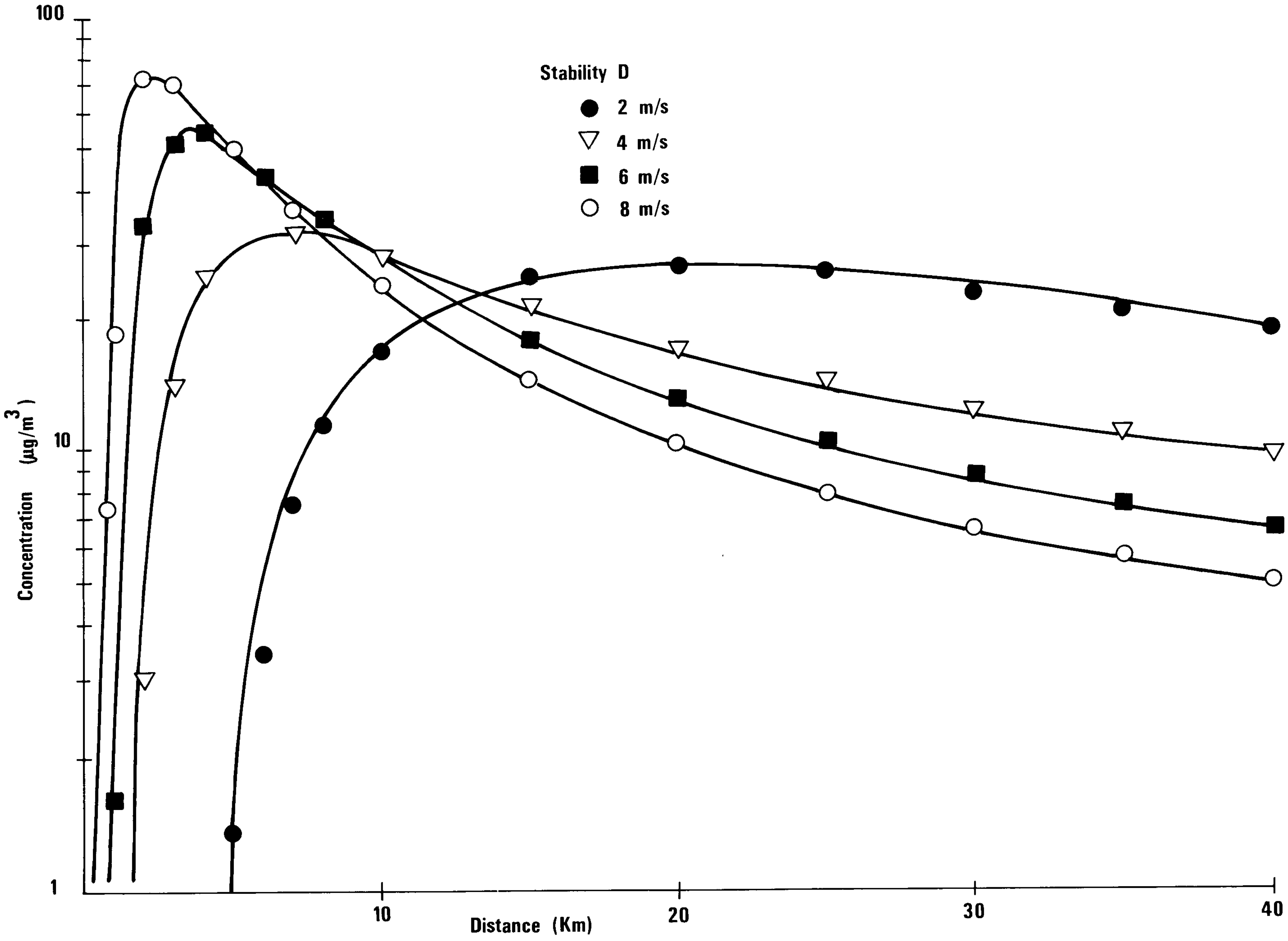


FIGURE 26 SULPHUR DIOXIDE CONCENTRATION VS. DISTANCE

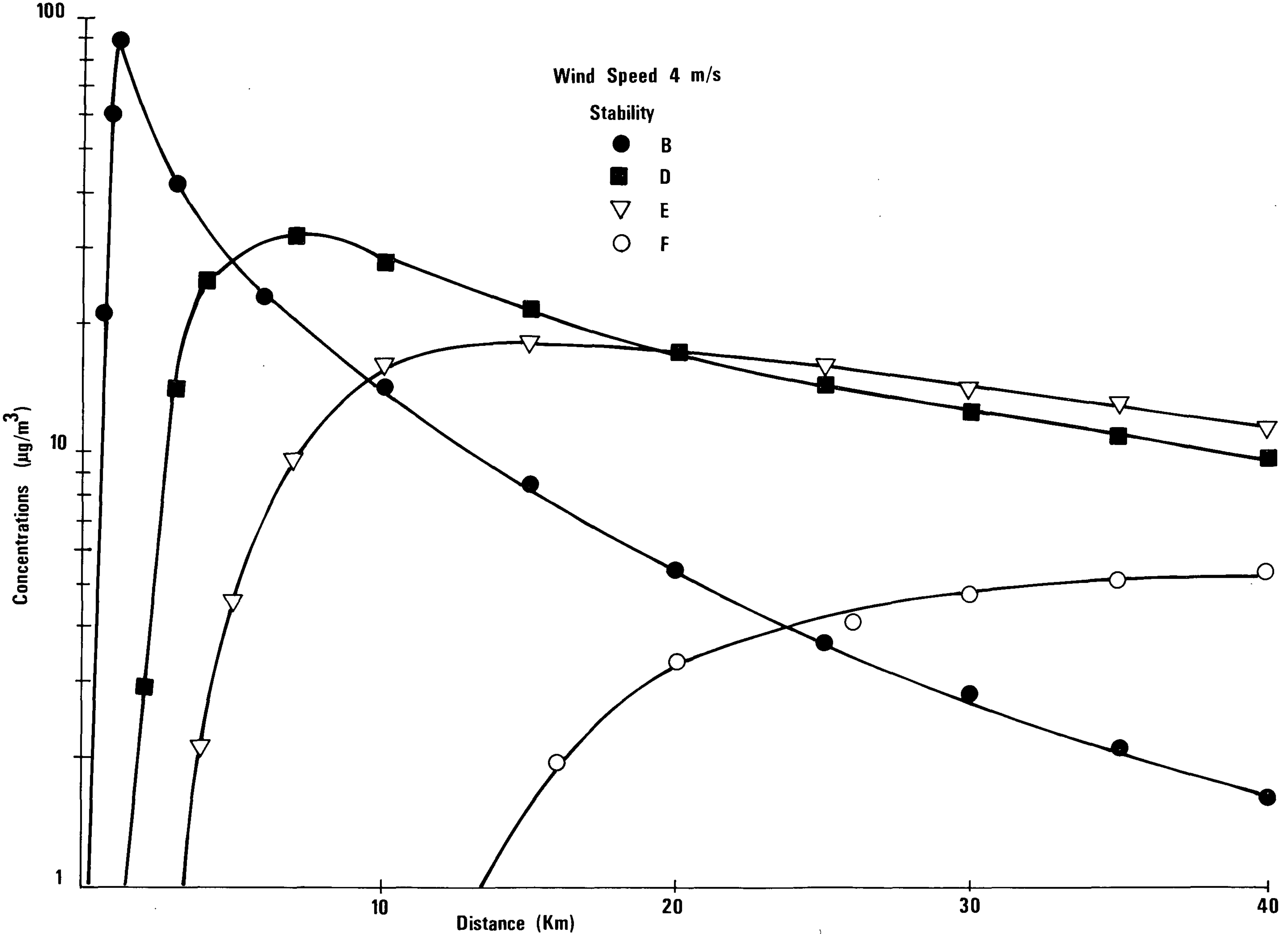


FIGURE 27 SULPHUR DIOXIDE CONCENTRATION VS. DISTANCE

TABLE 5 SO_2 CONCENTRATIONS ($\mu g/m^3$) AT STATED DOWNWIND DISTANCES (km)

Wind Speed		Plume Rise	Stability Class			
m/s	km/h	m	B	D	E	F
2	7.2	310	102 at 2 28 at 10 3.2 at 40	26 at 20 17 at 10 19 at 40	8 at 35 0.3 at 10 8 at 40	no maximum <<1 at 10 0.04 at 40
4	14.4	165	89 at 1 14 at 10 2 at 40	32 at 7 28 at 10 10 at 40	18 at 15 16 at 10 12 at 40	no maximum 1 at 10 5 at 40
6	21.6	114	----	54 at 4 28 at 10 7 at 40	33 at 7 32 at 10 11 at 40	----
8	57.6	88	----	72 at 2 24 at 10 5 at 40	52 at 5 32 at 10 9 at 40	----

N.B. The first entry is the maximum concentration.

It is noteworthy that at distances of greater than 10 km downwind, the equation reduced to the approximate form:

(Mixing height m) x (plume width m) x (wind speed m/s)
x (concentration g/m^3) ≈ (emission rate g/s)

Since the plume width is typically about 10 percent of the downwind distance D(m), the equation becomes a 300 m mixing height and U (m/s) wind speed.

Concentration ≈ Emission Rate/(30 UD)

For the cluster of burns, the total emission rate averages about 90 g/s for one hour. Thus, at three m/s, the downwind concentration will reach about (1/D) g/m^3; i.e., 100 $\mu g/m^3$ at 10 km, 50 $\mu g/m^3$ at 20 km, and 20 $\mu g/m^3$ at 40 km.

3.1.4 Particulate Matter (Soot). The equation used to calculate the downwind concentrations of soot is given in Appendix C. It is similar in principle to the equation used for the SO_2 calculation in that it has a simlar functionality for emission rate, wind speed and stability class and it assumes reflection at the top of the mixing height.

The equation used to calculate soot concentrations contains two significant differences from the equation used to calculate SO_2 concentrations. First, it assumes no reflection at the ground, i.e., any particles reaching ground level are deposited; therefore, the concentrations tend to be lower than in the SO_2 case. Secondly, the particles are assigned a settling velocity that tends to cause higher concentrations close to the fire and lower concentrations at greater distances from the fire. The approach used is the "tilted plume", in which the plume is (fictitiously) assigned a downward tilt amounting to a height reduction of wx/u, where w is the settling velocity (m/s), x is the downwind distance (m), and u is the wind speed (m/s). The quantity x/u is essentially the time of fall, which when multiplied by the velocity, gives the fall distance. The settling velocity is thus included as an input variable.

The results are given in Figures 28, 29 and 30, which show the effect of particle size, wind speed and stability, and in Tables 6, 7, 8, and 9. Two additional quantities can be calculated. The first is the centreline deposition rate G_C ($g/m^2.s$), which is the ground level concentration (g/m^3) multiplied by the settling velocity (m/s). The second is the mean ground level deposition rate G_M ($g/m^2.s$), over a strip of ground one m wide in a downwind direction and 2.67 standard deviations (σ_z) long in a lateral direction (perpendicular to the wind direction); this is the area in which about 95 percent of all the particulate matter falls. It can be shown that G_M is 0.63 G. These quantities are linearly related to the concentration. Also of interest is the downwind distance at which most of the particulate matter reaches the ground.

Figure 28 shows that for particles larger than 50 µm, i.e., settling velocity greater than 10 cm/s, there is appreciable deposition in the first few km from the fire. Between 50 and 15 µm, the particles are carried further from the fire; and below 15 µm (1 cm/s velocity), the particles fall so slowly that they behave similarly to gases under these conditions.

From Tables 6 to 9, it is apparent that the exposures will be as follows.

	From a Pool	From a Cluster
Maximum Soot Concentrations Close to Fire µg	700	2100
Concentration at 10 km	200	600
Concentration at 40 km	15	45

3.1.5 Metal Concentrations. The metal concentrations and deposition rate can be estimated by simply dividing the particulate quantities by a factor of 10^4.

3.1.6 Carbon Monoxide. The carbon monoxide concentrations can be estimated by multiplying the SO_2 concentrations by a factor of 2.25.

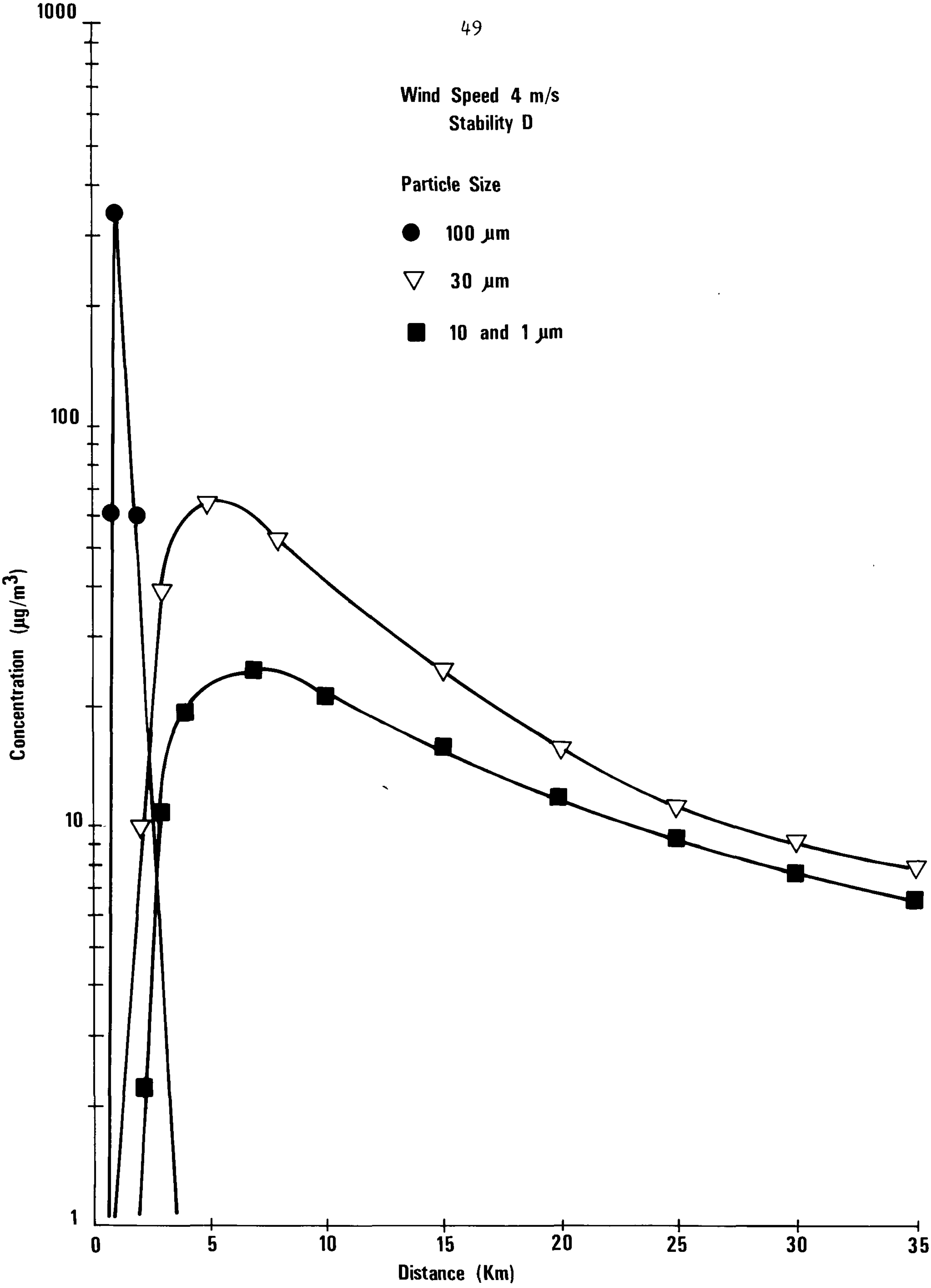


FIGURE 28 SOOT CONCENTRATION VS. DISTANCE

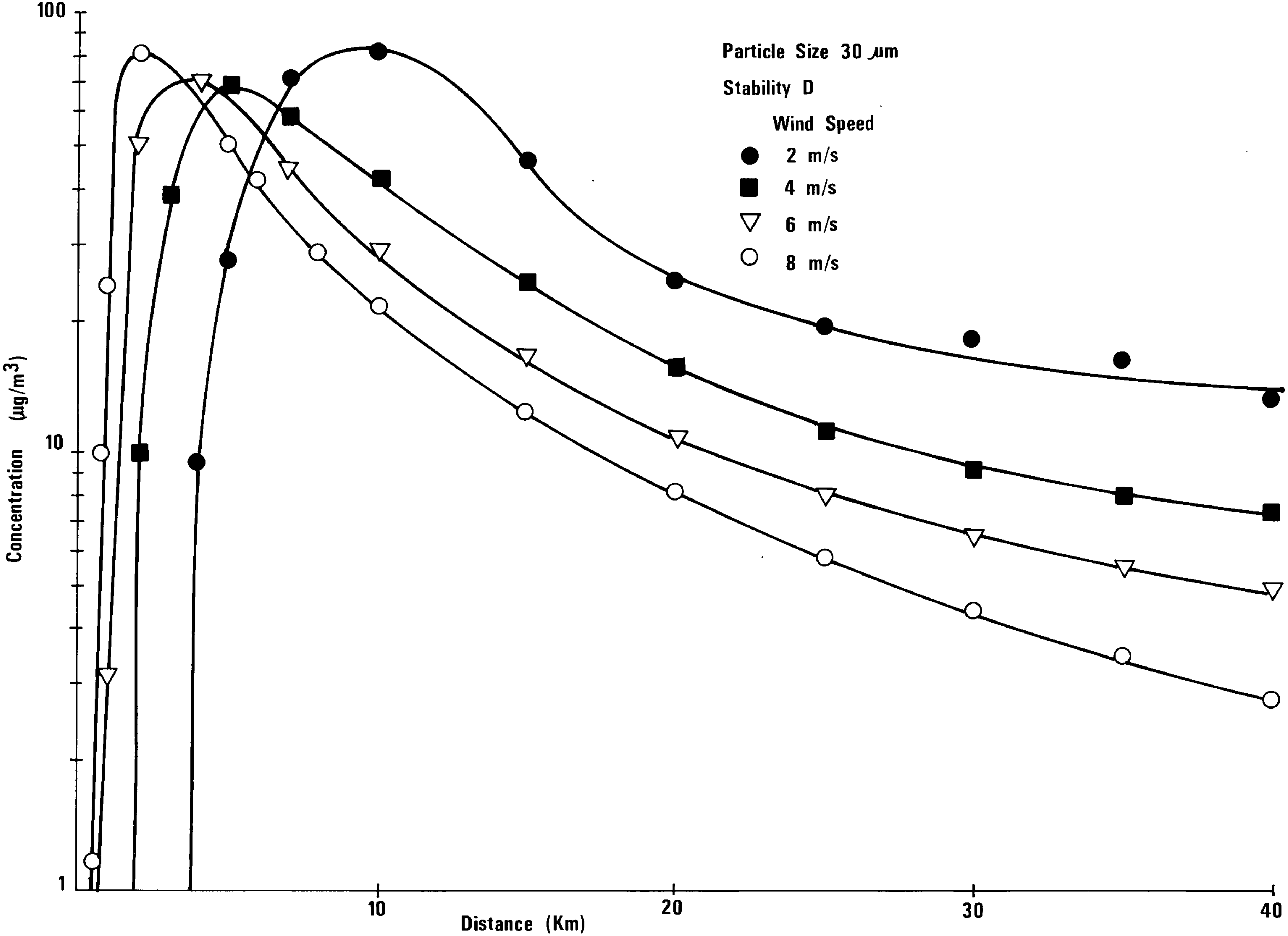


FIGURE 29 SOOT CONCENTRATION VS. DISTANCE

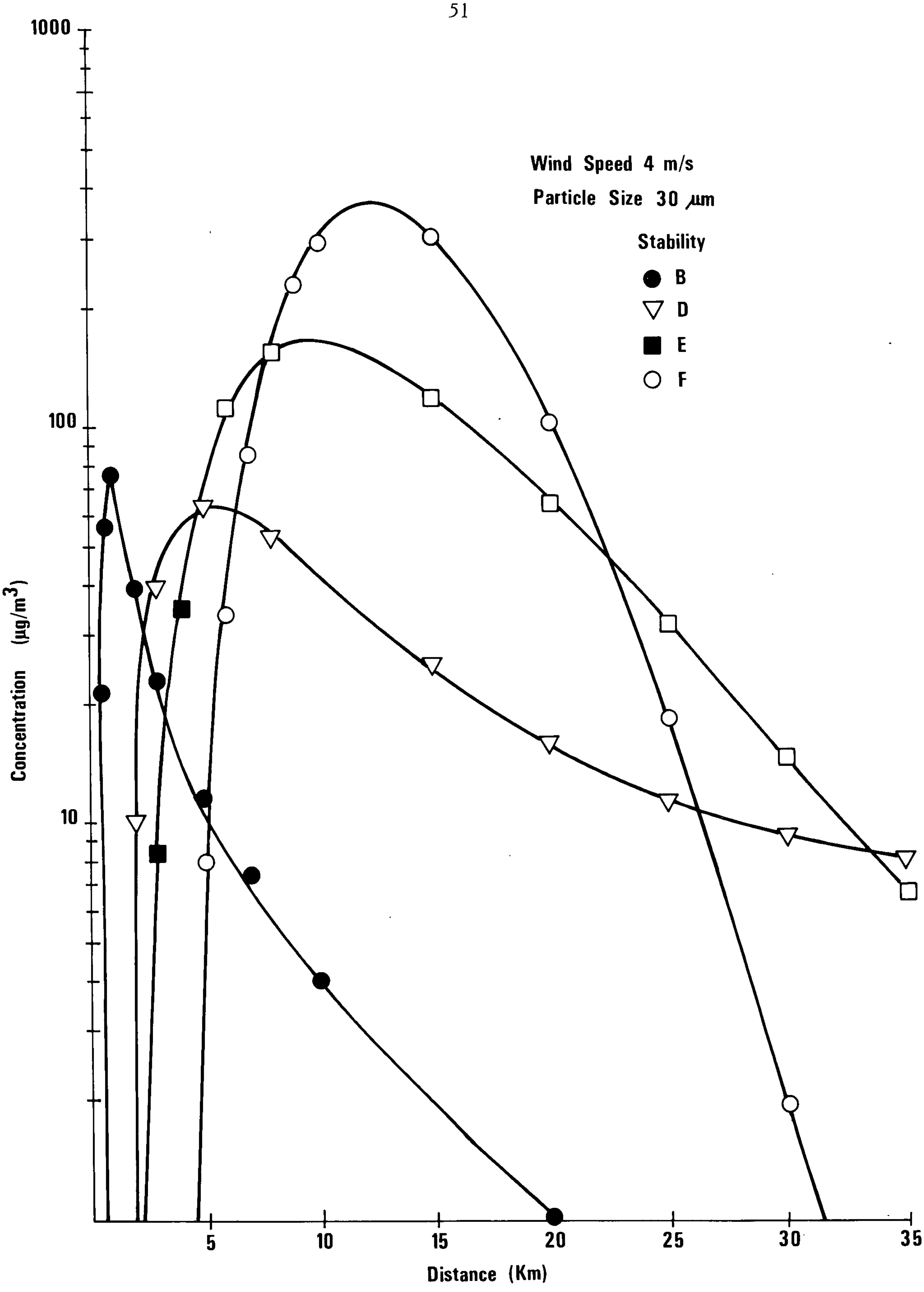


FIGURE 30 SOOT CONCENTRATION VS. DISTANCE

TABLE 6 SOOT CONCENTRATIONS (μg/m^3) AT STATED DOWNWIND DISTANCES (km)
(Particle Size: 100 μm)

Wind Speed		Plume Rise	Stability Class			
m/s	km/h	m	B	D	E	F
2	7.2	310	304 at 1 1 at 10 <1 at 40	482 at 1 0 at 10 0 at 40	106 at 1 0 at 10 0 at 40	143 at 1 0 at 10 0 at 40
4	14.4	165	223 at 0.8 2 at 10 0.1 at 40	682 at 1 0 at 10 0 at 40	513 at 1 0 at 10 0 at 40	171 at 1 0 at 10 0 at 40
6	21.6	114	- - -	640 at 1 0 at 10 0 at 40	722 at 1 0 at 10 0 at 40	- - -
8	57.6	88	- - -	559 at 1 <1 at 10 0 at 40	752 at 1 0 at 10 0 at 40	- - -

N.B. The first entry is the maximum concentration.

TABLE 7 SOOT CONCENTRATIONS (μg/m^3) AT STATED DOWNWIND DISTANCES (km)
(Particle Size: 30 μm)

Wind Speed		Plume Rise	Stability Class			
m/s	km/h	m	B	D	E	F
2	7.2	310	38 at 3 8 at 10 0.6 at 40	82 at 9 80 at 10 13 at 40	152 at 10 30 at 40	297 at 15 290 at 10 <1 at 40
4	14.4	165	77 at 1 4 at 10 0.3 at 40	63 at 5 42 at 10 7 at 40	164 at 10 3 at 40	223 at 10 62 at 40
6	21.6	114	- - -	70 at 3 29 at 10 5 at 40	80 at 6 62 at 10 4 at 40	- - -
8	57.6	88	-		83 at 4 43 at 10 4 at 40	- - -

N.B. The first entry is the maximum concentration.

TABLE 8 SOOT CONCENTRATIONS ($\mu g/m^3$) AT STATED DOWNWIND DISTANCES (km) (Particle Size: 10 μm)

Wind Speed		Plume Rise	Stability Class			
m/s	km/h	m	B	D	E	F
2	7.2	310	39 at 2	10 at 20	no maximum	no maximum
			7 at 10	7 at 10	0.1 at 10	0 at 10
			0.6 at 40	8 at 40	4 at 40	0.03 at 40
4	14.4	165	67 at 1	25 at 7	14 at 15	no maximum
			4 at 10	21 at 10	12 at 10	0.5 at 10
			0.3 at 40	6 at 40	9 at 40	5 at 40
6	21.6	114	-	41 at 4	25 at 7	-
			-	21 at 10	25 at 10	-
			-	4 at 40	8 at 40	-
8	57.6	88	-	54 at 2	60 at 5	-
			-	18 at 10	48 at 10	-
			-	3 at 40	13 at 40	-

N.B. The first entry is the maximum concentration.

TABLE 9 SOOT CONCENTRATIONS ($\mu g/m^3$) AT STATED DOWNWIND DISTANCES (km) (Particle Size: 1 μm)

Wind Speed			Plume Rise	Stability Class			
m/s	km/h		m	B	D	E	F
2	7.2	310	39 at 2	19 at 20	no maximum		no maximum
			7 at 10	11 at 10	0.1 at 10	0 at 10	
			0.6 at 40	14 at 40	3 at 40	0.02 at 40	
4	14.4	165	7 at 1	24 at 7	14 at 15	no maximum	
			4 at 10	21 at 10	12 at 10	0.4 at 10	
			0.3 at 40	6 at 40	9 at 40	4 at 40	
6	21.6	114	-	40 at 4	25 at 7	-	
			-	21 at 10	24 at 10	-	
			-	4 at 40	8 at 40	-	
8	57.6	88	-	54 at 2	60 at 5	-	
			-	18 at 10	48 at 10	-	
			-	3 at 40	13 at 40	-	

N.B. The first entry is the maximum concentration.

3.1.7 Dispersion in Zero Wind. All commonly used dispersion equations contain the implicit assumption that the turbulent diffusion which disperses the emissions is generated by wind. The equations fail under zero wind conditions. It is possible to set up a suitable cloud diffusion equation for stagnant conditions to express concentration as a function of time, position source strength and diffusivity, but there is no information about the value of the diffusion coefficient. The molecular diffusivity is obviously too small. Since this is probably the condition in which highest concentrations are likely to be encountered, it is recommended that some theoretical and experimental work be undertaken to elucidate the behaviour and to quantify the concentrations.

Fortunately, these conditions are fairly rare. Burns (1973) presents data for Cape Parry for the months from June to August which show that there is only a two percent probability that the wind speed will be less than four mph (1.8 m/s). Even if such conditions do occur, they are unlikely to persist for longer than one day.

3.2 Superposition of Cluster Plumes

The final problem addressed here is the extent to which smoke plumes or "puffs" from differenct clusters may superimpose and thus expose an area to multiples of the concentrations calculated for a cluster of pools.

If a cluster burns for one hour in a wind speed U m/s, it will generate a puff 3600 U m or 3.6 U km long. Typically, at 4 m/s or 14.4 km/h, this will be 14.4 km long. It will increase in width due to horizontal diffusion and will typically have a width about 20 percent of the downwind distance from the fire; for example, at 10 km it may be two km wide. The worst conditions are likely to occur within 10 km of the fire; the puffs at this distance will be typically 15 km long and two km wide, covering an area of 30 km^2.

Each puff will sweep out an area about two km in width. The sweep distance can be taken as 50 km, which will take the puff to the edge of the spill area or will dilute it to a negligible concentration. The area swept will be 100 km^2 over a time period of about three hours or 33 km^2 in one hour. From Table 1, it is assumed that a maximum of 10 clusters are burning at any time in the total spill area of 2400 km^2. There would be one cluster alight over each 240 km^2 and this maximum condition will only apply for 18 hours.

Since the puffs will all be moving in the same direction (they are subject to the same wind field) there is little possibility of one puff "catching up" with another. Superposition will only occur when a puff is blown over an alight cluster. Changing the wind speed does not change the probability much, since it increases the area swept but decreases the residence time. It does, however, increase the puff length, but this is accomplished with a reduction in concentration.

A simple statistical analysis leads to the conclusion that approximately one-third of all fires will be swept over by a plume from another fire. The justification is that if three of 10 fires encounter a plume, seven single plumes and three double plumes will be formed during each hour; the 13 plumes will comprise a total area of 300 km^2. Since there are 30 plumes in the area, their total area will be 700 km^2 or 30 percent of the total spill area of 2400 km^2. There is thus 30 percent probability that a fire will occur in the area of a plume. Alternatively, each plume that sweeps an area of 30 km^2/h will have a probability of (10x30/2400) or 12 percent of encountering one of the 10 fires in the total area of 2400 km^2 each hour, and thus a 36 percent probability in three hours. Superposition of a "double" plume on a fire will occur to one fire in 10.

This analysis is necessarily approximate in that the superposition probability is very sensitive to the alignment of the clusters with respect to wind direction. Superposition of the two near-fire concentrations of, for example, 300 μg/m^3 of SO_2 will be infrequent. The worst common condition will be superposition of a 10 km concentration with a near-fire concentration, which will occur in five to 10% of the plumes; and more frequently, i.e., in 20 to 25% of the plumes, one would expect doubling of the 10 km or 30 km concentrations. These superimposed concentrations are shown in Table 4. These conditions, with approximately one-third superposition, will occur only during the most intense burning period.

4 DISCUSSION

In considering the severity of the impact of these atmospheric conditions, it is first instructive to examine the National Air Quality Objectives and typical levels in urban areas of Canada. The objectives for SO_2, particulate matter, and CO and average 1975 annual levels for several Canadian cities are given in Table 10. These quantities can be compared with the expected levels in Table 11 from a cluster of burns derived in the previous section and allowing for some superposition.

For SO_2, it is apparent that the levels are not undesirably high. The concentrations close to the fire are below the one hour acceptable and desirable concentrations, and those at some distance from the fire (10 km) are about the 24 hour average desirable levels. The concentrations that are likely to be experienced in the general area (40 km) are actually lower than the levels encountered in Canadian urban areas. It is concluded that SO_2 levels likely to be achieved with a two percent sulphur oil are well below the levels that give cause for concern.

For particulate matter, the concentrations are somewhat higher than those of SO_2, due to the higher emission rate and the tendency to fallout closer to the fire. There are no one hour average standards against which the expected concentrations can be compared. It appears that the concentrations achieved in areas remote from the fire (beyond 40 km) will be about the concentration of existing standards and of urban areas. It is noteworthy that "particulates" can include a variety of chemical species with very diffent toxicities; thus, comparision on this basis is possibly misleading. This issue is addressed later.

For CO, which is arbitrarily assumed here to be 2.25 times the SO_2 concentrations, the levels are below the standards by a factor of 10 and no problem is likely.

No standards exist for metals, which can be taken as about 10^{-4} times the particulate levels. Thus, no definite statement can be made, although some of the comments made later about components in the particulate matter will apply.

For hydrocarbons, the principal source is the evaporating unburned oil, not the burned oil. No standards exist for hydrocarbons, and these compounds are not normally regarded as noxious at the low concentrations expected. Only in areas subject to photochemical smog and at concentrations where an explosion hazard exists is there need for concern.

TABLE 10 ATMOSPHERIC LEVELS OF SO_2, PARTICULATE MATTER AND CO IN CANADA (µg/m^3)

		SO_2	Particulate Matter	CO
Maximum Acceptable	1 h	900	-	35000
Concentrations*	8 or 24 h	300 (24)	120 (24)	15000 (8)
	1 yr	60	70	-
Maximum Desirable	1 h	450	-	15000
Concentrations*	8 or 24 h	150 (24)	-	6000 (8)
	1 yr	30	60	-
Actual Annual	Ottawa (Slater/Elgin)	52	77	3.6×10^3
Concentration	Sudbury (Ash)	73	32	-
1975**	Edmonton (109/98)	-	73	1.5×10^3
	Toronto (College)	39	71	-
	Montreal (Drummond)	96	101	-
	Average	65	71	2.5×10^3

*Source: "Criteria for National Air Quality Objectives". (Department of Fisheries and the Environment, 1976)

**Source: Annual Summary National Air Pollution Surveillance Report 1975, EPS-5-AP-76-16.

TABLE 11 EXPECTED CONCENTRATIONS DURING BURNING (µg/m^3)

	SO_2			Particulates			CO		
	Pool	Cluster	SP*	Pool	Cluster	SP	Pool	Cluster	SP
Concentration close to fire	100	300	390	700	2100	2700	225	675	875
Concentration at 10 km	30	90	180	200	600	1200	67	200	400
Concentration at 40 km	10	30	60	15	45	90	22	67	120

*Superimposed concentration obtained by adding the 10 km figure to the concentration close to the fire, doubling the 10 km concentration, and doubling the 40 km concentration.

4.1 Polynuclear Aromatic Hydrocarbons

One of the most difficult issues in assessing the environmental impact of oil burning lies in assigning a severity to the polynuclear aromatic (PNA) emissions. PNA's are of concern because some have been established as potent carcinogens and they are regarded as being only slowly biodegradable. There is no conclusive evidence that they are biomagnified in food chains, but the suspicion remains. They are not generally regarded as very active ecologically; the main concern is that of human health.

Because of the brief and exploratory nature of this program, we are unable to reach any definite conclusions, but a few comments are appropriate. PNA's are undoubtedly present in the oil. Some are probably burned to CO_2, thereby reducing the amount introduced into the environment. Some are probably transported from the oil by sputtering into the atmosphere with particulate matter; and although the amount may not be increased, the distribution will change. Additionally, some PNA's may be formed in the combustion zone and emitted in particulate and/or gaseous form. The chemical nature of PNA's and soot are such that one would expect rapid and irreversible adsorption of gaseous PNA's on soot particles. The problem is to assign approximate magnitudes to these three routes: i.e., construct a mass balance, and determine the location of the deposition from the atmosphere.

The only way in which these quantities can be determined is by a carefully designed experiment in which PNA's are analyzed in an oil; the oil is burned; and the soot and residue collected and each analyzed for PNA content. This would determine if burning increases or decreases PNA amounts. Some experimental work on this topic is recommended.

There are reasons to suspect that oil smoke will contain higher concentrations of PNA's than smoke from conventional combustion operations. The direct comparison of suspended particulate concentrations in the plume and in urban areas may be misleading in terms of exposure to PNA's.

The does-response relationships for PNA-induced environmental concerns are far from clear. Consequently, it is probably prudent to minimize human exposure to these toxicants.

There may be a concern that the population of communities such as Tuktoyaktuk are exposed to soot as a result of oil burning, whereas they would not be exposed if burning did not occur. The soot fallout calculations suggest that most of the particulate matter will deposit within 10 km of the fire. The remainder will be highly diluted by the time it reaches the community. It should be noted that this is not a case of exposure from burning versus no exposure; there is already considerable exposure to PNA's from stationary and mobile combustion sources and dump burning.

Further south, there may be considerable PNA emissions from forest fires; and to the east, the Smoking Hills have been emitting substantial quantities of SO_2 and soot from the naturally burning lignite beds.

Any pronouncement about the seriousness of the human PNA exposure problem would be premature and subjective until quantitative data are available about natural and anthropogenic sources, quantities and exposures. In the interests of prudence, it is recommended that human exposure to oil smoke be minimized by avoiding situations in which clean-up crews are located downwind of a fire and in which prevailing winds carry smoke plume directly into communities. This implies a coordination of igniting activites with short term weather forecasts.

4.2 Metals

Although the metal concentrations are low in soot and the most prevalent metals are not regarded as being particularly toxic, it is recommended that some prudence is justified in exposing humans to these metal emissions. Some toxic metals such as mercury or chromium may be present. The valency state or chemical speciation is unknown; and since toxicity is a strong function of these quantities, it is possible (though improbable) that an unusual and unforeseen combination of circumstances may result in an unappreciated exposure.

Again, it is recommended that measures be taken to minimize human exposure to the plumes. There remains some uncertainty about the fate of the metals (eg., fraction emitted). Some further work in this area would be worthwhile.

4.3 Properties of Northern Oils

The concentrations of SO_2 and metals considered in this report are linearly dependent on the amounts present in the oil. The behaviour of the oil in the environment is also dependent on its volatility, density, etc.

It is probable that the same general conclusions as were reached for the June situation will apply in September. There will be a lower probability of superposition of plumes in September. Consequently, the concentrations achieved will be slightly lower.

It is recommended that when new oil reserves are established in the North, samples be obtained and analyzed for all relevant physical and chemical properties to assist assessment of the environmental impact of burning. Specifically, volatility, density, rheology, chemical nature (saturates, aromatics, etc., sulphur, nitrogen, oxygen and metals) should be measured.

4.4 Further Research

This report has resulted in the calculation of atmospheric concentrations of the relevant contaminants. This was accomplished by making a large number of assumptions. It would probably be worthwhile to undertake an experimental oil burn in the Beaufort Sea area and to make appropriate concentration measurements in order to attempt to validate the calculations presented here. It is recommeded that the feasibility and cost of this experiment be investigated.

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APPENDIX A

PLUME RISE

APPENDIX A

Plume Rise

Estimates of plume rise for a ground level burn were obtained using plume rise formulae described by Seinfield (1975), Singer et al (1964) and Lowry (1967). It is difficult to specify the best plume rise formula. Therefore, plume rise was calculated using four formulae and an average plume rise was used in subsequent calculations. Table 12 gives the equations used in making the estimates.

TABLE 12 PLUME RISE FOMULAE

H(metres)	Name
$1.5(\frac{2rw}{u}) + 4 \times 10^{-5} (\frac{Q}{u})$	Holland
$\frac{0.175\ Q^{1/2}}{u^{3/4}}$	Concawe
$\frac{12.4\ Q^{1/4}}{u}$	Lucas, Moore, and Sparr
$\frac{1.02\ Q^{1/3}}{u}$	Singer, Frizzola, and Smith

Q	heat emission, calls
u	mean horizontal wind speed (m/s)
r	radius of burn (m)
w	vertical velocity of plume (m/s)

An estimate of the vertical velocity rise of the plume can be obtained by a formula outlined by Lowry (1967).

$$w = \frac{Q}{(Cp/R)\pi r^2 pB}$$

where		
	Cp	specific heat of air at constant pressure, 1.0 joule/g^{o}K
	R	gas constant for dry air, 0.29 joule/g^{o}K
	πr^2	burn area = 143 m^2; r = 6.75 m
	p	barometric pressure, atmospheres
	B	$\frac{Ts-Te}{Ts}$ dimensionless buoyancy
	Ts	mean temperature in the plume
	Te	ambient temperature

Plume rise estimates were made assuming complete combustion of 1.0 m^3 of oil (5.8 x 10^6 BTU/barrel) in a period of 10 minutes, which results in a heat emission of 1.53 x 10^7 cal/s. Assuming a dimensionless buoyancy of 0.6 and a barometric pressure of one atmosphere, a vertical plume velocity of 2.1 m/s was obtained. Substitution of these estimated burn site values into the plume rise formulae at different wind speeds gave the results shown in Table 13.

TABLE 13 CALCULATED PLUME RISE H (metres)

Wind Speed (m/s)	1	2	4	6	8
Holland	629	315	162	105	79
Concawe	685	407	242	179	144
Lucas et al	781	391	195	130	98
Singer et al	254	127	63	4	32
Briggs	226	179	142	124	113

The results of the calculations suggest that there may be a 50 percent error in the plume rise estimates. The above mean values for plume rise of wind speeds of one, two, four, six and eight m/s were used in the dispersion calculations.

APPENDIX B

CALCULATION OF GROUND-LEVEL SO_2 CONCENTRATIONS

APPENDIX B

Calculation of Ground-Level SO_2 Concentrations

The calculation of ground-level concentrations of sulphur dioxide resulting from a 1.0 m^3 oil burn were estimated using atmospheric dispersion formulae outlined in Turner (1974). Since the mixing heights in the Arctic region are low (approximately 300 to 400 m), a dispersion formula which accounts for the reflection of pollutants between the ground and a stable layer was used. The dispersion formula used is as follows:

$$\chi(X,0,0;H) = \frac{Q}{\pi u \sigma_y \sigma_z}\left[\exp\left[-1/2(H/\sigma_z)^2\right] + \sum_{N=1}^{N=4}\exp\left[-1/2\frac{(H+2NL)^2}{\sigma_z{}^2}\right] + \exp\left[-1/2\frac{(H-2NL)^2}{\sigma_z{}^2}\right]\right] \qquad (1)$$

where

$\chi(X,0,0;H)$ - is the centre line ground-level concentration (g/m^3)
Q - source strength (g/s)
u - wind speed (m/s)
σ_y - horizontal dispersion coefficient (m)
σ_z - vertical dispersion coefficient (m)
H - effective plume rise (m)
L - mixing height (m)

A mixing height of 310 m was chosen for the calculation. The burn time used was 10 minutes. It was assumed that all of the sulphur (two percent wt) was converted to sulphur dioxide, resulting in a pollutant source strength of 55 g/s.

$$\frac{1.0\ m^3 \times 10^6 \times 0.83\ \frac{g}{cm^3} \times 0.2 \times \frac{64\ \text{mole.wt.}}{32\ \text{mole.wt.}}\ \frac{SO_2}{S}}{600s} = 55\ \frac{g}{s}$$

The plume rise for various wind speeds was taken from Appendix A. The dispersion coefficients for the various stability classes are shown in Table 14 and the key to the stability classes are shown in Table 15.

Table 14 STABILITY CLASSES

Downwind Distance	B		D		E		F	
km	σ_y	σ_z	σ_y	σ_z	σ_y	σ_z	σ_y	σ_z
0.2	36	20	15	8.5	11	6.4	7.5	4
0.4	68	40	29	15	23	11	15.5	7
0.6	98	62	42	22	32	15	22	9.8
0.8	130	85	55	27	40	18	27.5	12
1	160	120	68	31	50	21	34	14
2	300	230	130	50	96	33	64	22
3	420	360	190	65	140	43	94	27
4	550	500	240	78	180	50	120	31
5	670	650	300	88	220	56	146	34
6	780	780	350	98	260	61	170	37
7	880	920	400	110	300	66	200	40
8	1000	1100	460	120	340	70	225	42
9	1100	1200	500	130	380	75	250	44
10	1200	1300	550	135	410	80	275	46
15	1700	2100	780	170	580	96	395	54
20	2200	2900	1000	200	760	110	500	60
25	2600	3800	1200	230	920	120	620	64
30	3000	4400	1400	250	1080	130	720	68
35	3500	5000	1600	270	1200	138	820	71
40	3900	6000	1800	290	1380	143	925	74

TABLE 15 KEY TO STABILITY CLASSES

Surface Wind speed (at 10 m), m sec^{-1}	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or	
	Strong	Moderate	Slight	$\geq 4/8$ low cloud	$\leq 3/8$ cloud
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night. Source: Turner (1974).

An APL computer program, listed below, was used to calculate sulphur dioxide concentrations and to plot centreline concentration versus distance. The results of the calculations for different meteorological conditions are presented in tabular and graphic formats.

```
∇Burn O Σ∇
  ∇ U Burn Q

(1)   ' plume rise (meters) '; H←0
(2)   ' mixing height (meters) '; L←0
(3)   X←  0.2  0.4  0.8  1  5  10  15  20  30 40
(4)   Y←  15  29  55  68  300  550  780  1000  1400  1800
(5)   Z←  8.5  15  27  31  88  135  170  200  250  290
(6)   N←0
(7)   S←  0  0  0  0  0  0  0  0  0  0
(8)   A←Q÷(3.1416 x U x Y x Z)
(9)   B←*(-0.5 x ( (H÷Z)*2) )
(10)  N←N+1
(11)  C←*(-0.5 x ( ( (H+(2 x N x L) )÷Z)*2) )
(12)  D←*(-0.5 x ( ( (H-(2 x N x L) )÷Z)*2) )
(13)  E←C+D
(14)  S←S+E
```

```
(15)  ←(N<4)/9
(16)  Conc←A x (B+S)
(17)  '              '
(18)  ' Source Strength (grams/sec)' ;Q
(19)  ' Wind Speed (meters/sec)' ;U
(20)  M←X, conc
(21)  Data←ϕ 2 10 pM
(22)  '        '
(23)  Data
(24)  50 Plot conc vs X
   ∇
```

This program calculates concentrations at ten downwind locations. It was found that the maximum concentrations in most runs occurred within a 10 km distance. To obtain a finer grid, the number of points calculated was increased to 20. This was done by changing X, σ_y and σ_z in lines three, four and five of the above paragraph.

APPENDIX C

CALCULATION OF GROUND-LEVEL SOOT CONCENTRATIONS AND DEPOSITION RATES

APPENDIX C

Calculation of Ground-Level Soot Concentrations and Deposition Rates

The calculation of downwind concentrations of soot were estimated using a dispersion formula outlined by Somers (1971). Dispersion of particulates emitted differs from that of gaseous pollutants in that particles settle by gravity. Generally, when they reach the ground, they are not reflected from the ground by the wind. The ground-level concentration of soot particles can be calculated using a "tilted plume" model, which takes into account particle settling velocities, and is outlined below.

$$(X,0,0;H) = \frac{Q_p}{2\pi\sigma_y\sigma_z}\left[\exp\left(-\frac{1}{2}\left(\frac{(H-XW/u^2)}{\sigma_z^2}\right)\right) + \exp\left(-\frac{1}{2}\left(\frac{(H+2L-XW/u)^2}{\sigma_z^2}\right)\right)\right]$$

where Q_p is the particle source strength g/s and
W particle settling velocity m/s.

The other is the terms are described in Appendix B.

The first exponential term is the primary emission source. The second exponential term takes into account reflection of soot particles from the inversion layer.

The procedure is valid for gases and particles with very low settling velocities, for example, particles less than 20 μm. Large particles with fast setting velocities are unlikely to diffuse to the top of the mixed layer. Thus, no reflection term is necessary. Indeed, a reflection term results in an overestimate of soot deposition by about a factor of two, as a result of the mathematical approach used, if including a fictitious second source above the mixed layer. Inclusion or exclusion of the reflecting term is thus dependent on settling velocity. The approach taken in this study was generally to include the reflection term but to interpret the results recognising the deposition and concentration overestimate likely for large particles. Settling velocities for particles 100, 30, 10 microns and one micron in size were taken from Ledbetter (1973). It was assumed that six percent (wt) of the oil was converted to soot (Appendix A), resulting in a soot source strength of 83 g/s. The concentration multiplied by the particle settling velocity gives a centreline deposition G_C, mass per unit area-time.

$$G_C = \chi \times w$$

The average ground level, centreline deposition rate G_M can be shown to be equal to

$$G_M = \frac{\sqrt{\pi}}{2\sqrt{2}} G_C = 0.626\, G_C$$

An estimate of the fall-out fraction F, soot that settles within a downwind distance increment, ΔX, can be obtained from;

$$F = \frac{G_M \times 2.67\sigma_y X \Delta X}{Q_p}$$

Two-thirds of the range $4\sigma_y$ contains 95 percent of the settled material. The division of burn area into increments is shown in Figure A3.

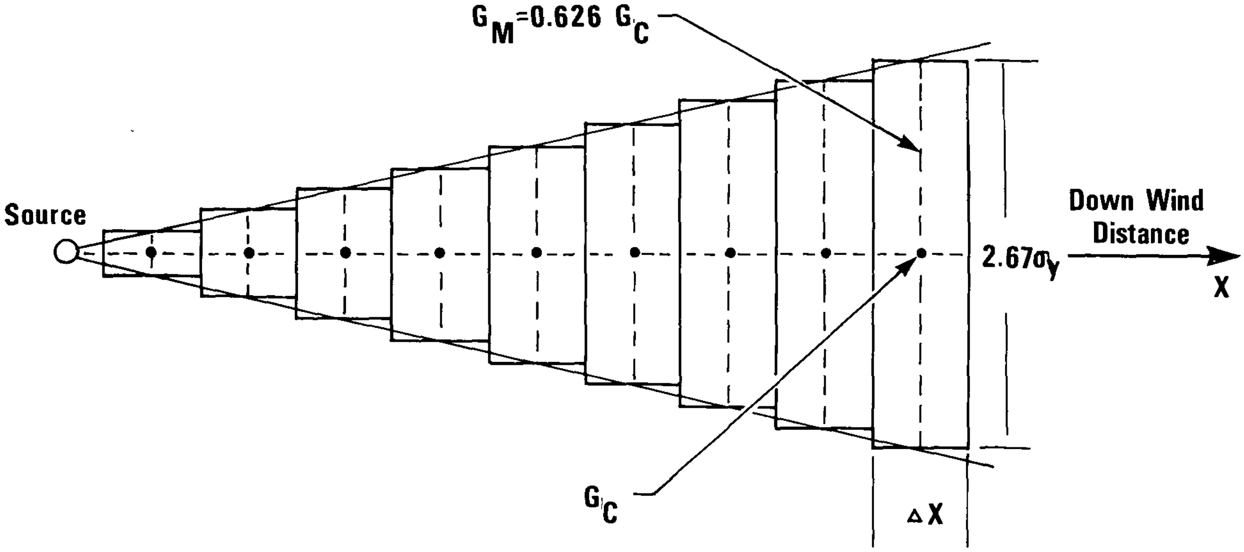

FIGURE 31 DIVISION OF BURN AREA INTO INCREMENTS

An APL computer program listed below was used to calculate concentrations, deposition rates, fall-out fractions and total fall-out for distances up to 40 km. The results of the calculations for different meteorological conditions are presented in a tabular and graphical form.

```
        ∇    U Soot Q
(1)          ' Plume rise (meters) ' ;H←0
(2)          'Mixing height (meters) ' ;L←0
(3)          'Settling velocity (meters/sec) ' ;W←0
(4)          'Source strength (grams/sec) ' ;Q
(5)          'Wind speed (meters/sec) ' ;U
(6)          X← 0.2  0.4  0.6  0.8  1  2  3  4  5  6  7  8  9  10  15  20  25  30  35  40
(7)          ΔX← 200  200  200  200  600  1000  1000  1000  1000  1000  1000  1000
                        1000  3000  5000  5000  5000  5000  5000  5000
(8)          Y← 36  68  98  130  160  300  420  550  670  780  880  1000  1100  1200
                        1700  2200  2600  3000  3500  3900
(9)          Z← 20  40  62  85  120  230  360  500  650  780  920  1100  1200  1300
                        2100  2900  3800  4400  5000  6000
(10)         X1←1000 x X
(11)         A←Q÷(6.283 x U x Y x Z)
(12)         B←H-(W x X1)÷U)
(13)         C←*(-0.5 x ( (B÷Z)*2) )
(14)         D←*(-0.5 x ( ( (B+(2 x L) )÷Z)*2) )
(15)         Conc←A x (C+D)
(16)         GCL←Conc x W
(17)         GAVG←GCL x 0.62666
(18)         QS←GAVG x 2.67 x Y x ΔX
(19)         FRACTION←QS÷Q
(20)         'Integrated source strength (grams/sec) ' ;(+/QS)
(21)         'sum of fractions' ;(+/Fraction)
(22)         N←X, Conc, GCL, GAVG, Fraction
(23)         Data←ϕ  5  20  pN
(24)         '         '
(25)         ' Distance    Conc    GCL    GAVG    Fraction    '
(26)         Data
(27)    ∇    25  72  Plot  Conc  VS  X
```