

# CHARACTERISTICS OF SMOKE FROM IN SITU CRUDE OIL FIRES

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## 1.0 INTRODUCTION

Concurrent with increased petroleum exploration offshore in the Canadian Arctic have been studies of the environmental impacts of oil and gas blowouts and discharges resulting in reviews of the feasibility of cleaning up oil spills in this hostile environment (Logan et al. 1975, 1975a, Pimlott et al. 1976, Ross et al. 1977). Since it may be difficult to deploy conventional oil spill countermeasures equipment in the Beaufort Sea, one of the most attractive options is in situ burning of oil, either as it reaches the water surface directly or when it migrates to the surface through melting ice in the spring. Burning would result in the emission of substantial quantities of combustion products into the atmosphere with adverse effects on downwind air quality. This work is an exploratory assessment of the effect on air quality. The approach is to establish a scenario for burning, estimate emissions, calculate downwind concentrations of combustion products using conventional plume dispersion equations, and examine the issue of superposition of plumes in time and space from a number of burning pools. In support of this calculation some laboratory and field experiments were performed.

## 2.0 OIL SPILL SCENARIO

The scenario adopted here is based on the behaviour of a winter blowout postulated by Norcor (1977). It is assumed that a blowout starts late in the drilling season, eg. August, too late to permit a relief well

to be drilled. Oil discharges from the well at a rate of  $398 \text{ m}^3/\text{day}$  (2500 barrels/day) for the first 30 days, then  $159 \text{ m}^3/\text{day}$  (1000 barrels/day) until the following summer. The total volume discharge is  $45700 \text{ m}^3$ . The gas is assumed to vent through the ice, but much of the oil remains trapped under the growing and moving ice sheet. The ice is assumed to move with an average velocity of 1 km/day, thus, a strip of ice about 240 km long and about 100 m wide will be "painted" with oil. The strip is tortuous and is probably contained in an area of 80 km by 30 km. Most of the oil is encapsulated in the growing ice in an oil layer about 1 cm thick. Oil trapped under first year ice migrates to the surface and achieves a burnable thickness about June 1 and flow continues for 20 days. Oil trapped under multi-year ice reaches the surface in September. It is assumed that 30% of the oil is trapped under multi-year ice and 70% under first year ice.

An estimated mass balance for the oil was assembled which allows for about 10% evaporation of the burnable oil prior to ignition, and assumes that 35% of the oil reaching the surface is in a burnable condition. About 15% of the burned oil remains as residue and 85% is converted into combustion products. The non-burnable oil evaporates and is probably stranded on shore.

An estimate must be made of the configuration and sequence of the oil burns. It is suggested that the burnable oil reaches the surface in pools containing about  $1 \text{ m}^3$  of oil. These pools are clustered in groups of about 10 which will be ignited using aerial incendiary devices, all at one time. In June, there are 1000 clusters of pools, and in September, 430 clusters. Each cluster, which is assumed to burn for a period of 1 hour, consists of 9.5 individual pools, each of which burns for 10 minutes. At any given time, a maximum of 3 pools are burning.

Each pool is assumed to be 7 mm deep covering an area of  $143 \text{ m}^2$  (diameter 13.5 m) and a cluster of 9.5 pools covers a strip of contaminated ice, 100 m wide by 170 m long.

It is assumed that of the 20 days when burning is feasible in June, only 14 will be suitable for flying and aerial oil ignition. Most of the burning will probably be concentrated in a short period of about 8 days with favourable wind conditions. It is speculated that rarely will more than 10 clusters of pools be actively burning at any one time.

### 3.0 OIL PROPERTIES

The important oil characteristics are the sulphur and metal contents and the percentage of the oil which is emitted as soot. This latter quantity depends on the nature of the combustion process. Since no experimental data could be located for soot formation, some laboratory work was undertaken to obtain an estimate. The chemical nature of Arctic crude oils is of course not known, however, data are available on the sulfur and metal analysis of Norman Wells (NWT) and Swan Hills (Alberta) crude oils (Norcor, 1977). For the present purposes, it is assumed (pessimistically) that sulfur is present at a concentration of 2%, and metals (principally vanadium) are present at a concentration of 6 ppm. No information could be located on the fraction of the metal emitted during combustion, thus some experimental work on this topic was undertaken. It is assumed that all the sulfur is converted to  $\text{SO}_2$ . Measurements were made of CO to  $\text{CO}_2$  ratio in the experiments.

### 4.0 WEATHER

Comprehensive accounts of climate and weather in the Beaufort Sea region have been provided by Burns (1973), Walker (1975) and Barry et al (1975) with statistics relevant to the air pollution climatology having been published by Munn et al (1970), Shaw et al (1972) and Portelli (1977). The Beaufort Sea region suffers from lower mixing heights and ventilation coefficients than do most regions of Canada. Generally, the mean summer and fall maximum (afternoon) mixing heights in the region are from 200 to 500 m. For purposes of this study, a figure of 310 m is assumed. The mean wind speed in June and September is about 20 km/h (5.6 m/s) and is variable in direction, but tending to be from the ESE in June and the WNW in September.

### 5.0 EXPERIMENTAL

A small laboratory apparatus was assembled to study oil burning. It consisted of a 15.2 cm diameter by 46 cm long glass column with a hemispherical bottom containing a sandbed supporting a circular brass dish 9 cm in diameter and 1 cm thick containing oil to a maximum depth of 0.75 cm. The oil was ignited by a nichrome wire and air was supplied by a pump at a

known flow rate, Thermocouples were used to measure temperatures in the dish, flame and plume. A suction filter was connected to the top of the apparatus to collect all the soot. The temperature of the dish could be varied by circulating water through a coil molded in the dish base. In a typical test, a known weight of oil was placed in the dish, the temperatures and air flow rate set, the oil ignited, and the temperatures measured. The weight of the residue and soot was measured. Photomicrographs were taken of the soot particles to obtain data on soot particle size. Metal analysis of the oil and soot was by instrumental neutron activation analysis. Samples of the gas were also analyzed to obtain the  $\text{CO}_2$  to CO ratio using a thermal conductivity detector gas chromatograph.

The oil burning experiments showed that the fraction of the oil burned depended strongly on the dish temperature and air flow rate. From 2 to 6% of the original oil mass was converted to soot, being appropriately pessimistic. A mass balance on the vanadium showed that some of the metal was emitted in the soot, probably as a result of sputtering of oil particles into the combustion zone. The ratio of  $\text{CO}_2$  to CO varied from 8 to 43 with a mean mole ratio of 20:1.

A field study was also undertaken in which  $0.204 \text{ m}^3$  of oil were spilled on an ice surface in a pool 1 cm thick and about 5 m diameter. The oil was ignited using a rag soaked in kerosene. The burn lasted for 6 minutes. The air temperature was  $-4^\circ\text{C}$  and the wind speed was 8 km/h. Attempts to measure the temperatures of the flame and to sample the plume failed because of the high flame height (ca 5 m) and the intense heat from the fire which prevented close access to the burn. The oil burned very vigorously and left a residue of only 10% (weight). The plume rising velocity was about 5 m/s and it rose about 150 m.

The soot photomicrographs showed that it consisted of a large number of very small particles of diameter 6 nm to 100 nm with most being about 100 nm. These particles were agglomerated into larger particles often about  $1 \mu\text{m}$ , but occasionally about  $10 \mu\text{m}$  in diameter. Examination with a light microscope also showed particles of up to  $100 \mu\text{m}$  in diameter. Selection of a mean particle size and corresponding settling velocity is therefore almost meaningless since the particles are presumably continuously

agglomerating in the plume. In calculating the deposition rate of the soot, three particle sizes are assumed: 10, 30 and 100  $\mu\text{m}$  with corresponding free-fall velocities of 0.6, 5 and 50 cm/s (Ledbetter, 1977).

## 6.0 DISPERSION CALCULATIONS

It is assumed that each pool consists of 1.0  $\text{m}^3$  of oil, density 0.85  $\text{g}/\text{cm}^3$  containing 2% sulfur (all of which forms  $\text{SO}_2$ ) 6% of the original oil mass is emitted as soot and 6 ppm metal is also emitted with the soot. This corresponds to emission rates of 86 g/s of soot and 55 g/s  $\text{SO}_2$  for 10 minutes. The metal content of the soot is conveniently calculated as  $10^{-4}$  times that of the soot, corresponding to emission of 6 ppm. A carbon mass balance shows that the CO emissions should be about 2.25 times those of the  $\text{SO}_2$ . The wind velocities investigated were 2, 4, 6 and 8 m/s with a mixing layer height of 310 m. Soot deposition velocities of 0.6, 5 and 50 cm/s were used.

The plume rise was calculated using the equations of Holland, Concawe, Lucas et al., Singer and Briggs. The results show considerable disagreement and a mean plume rise was selected for each velocity. These quantities which could be in error by  $\pm 50\%$  are given in Table 1.

The dispersion equations used are the conventional Gaussian distribution equations as reviewed by Turner (1973). Calculations were made for stability classes A - F at these wind speeds and the centre line concentrations calculated at distances of 1 to 40 km downwind.

The equations assume for  $\text{SO}_2$  and CO total reflection at the ground and at the top of the mixing layer. For soot, reflection at the top of the mixing layer and deposition at the ground is assumed. The settling velocity of the soot was included by using a tilting plume model.

## 7.0 RESULTS

Figure 1 is a typical concentration profile for sulfur dioxide. From a series of such figures, maximum typical concentrations were arbitrarily selected as in Table 1. For a cluster of pools with a maximum of 3 burning pools at any time, the concentrations are arbitrarily multiplied by a factor of 3. For  $\text{SO}_2$ , the maximum concentration close to the fire is

Table I

Expected Concentrations During Burning ( $\mu\text{g}/\text{m}^3$ )

	SO <sub>2</sub>			Particulates			CO		
	Pool	Cluster	SP*	Pool	Cluster	SP	Pool	Cluster	SP
Concentration close to fire	100	300	390	700	2100	2340	225	675	875
Concentration at 10 km	30	90	180	80	240	580	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.

Atmospheric Levels of SO<sub>2</sub>, Particulate Matter and CO in Canada ( $\mu\text{g}/\text{m}^3$ )

		SO <sub>2</sub>	Particulate Matter	CO
Maximum Acceptable Concentrations*	1 hr	900	-	35000
	8 or 24 hr	300 (24)	120 (24)	15000 (8)
	1 yr	60	70	-
Maximum Desirable Concentration*	1 hr	450	-	15000
	8 or 24 hr	150 (24)	-	6000 (8)
	1 yr	30	60	-
Actual Annual Concentration 1975**	Ottawa (Slater/Elgin)	52	77	$3.6 \times 10^3$
	Sudbury (Ash)	73	32	-
	Edmonton (109/98)	-	73	$1.5 \times 10^3$
	Toronto (College)	39	71	-
	Montreal (Drummond)	96	101	-
	Average	65	71	$2.5 \times 10^3$

\* from "Criteria for National Air Quality objectives" (Department of Fisheries and Environment, 1976)

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

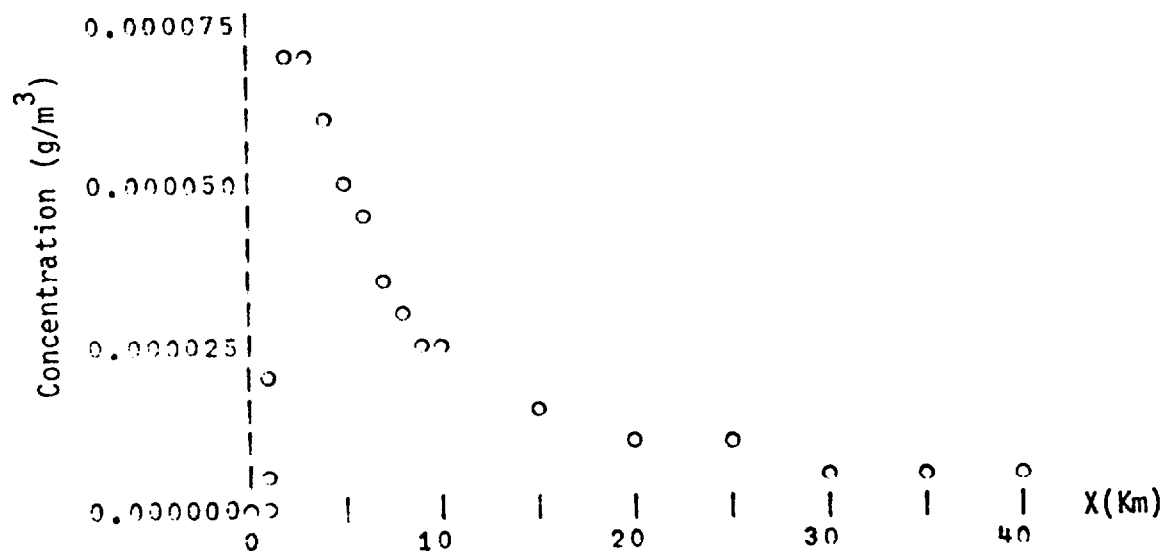


Figure 1. SO<sub>2</sub> Concentration Profile at  
8 m/s Wind Speed, Stability D,  
Plume Rise 88 m

300  $\mu\text{g}/\text{cm}^3$  with figures of 90 and 30  $\mu\text{g}/\text{m}^3$  at 10 and 40 m distance downwind respectively. A similar procedure was followed for soot. For particles less than 30  $\mu\text{g}$  in diameter, the settling velocity is so slow that it has little effect on the atmospheric concentration. The maximum concentrations from a pool and a cluster of pools are given in Table 1. The metal concentrations can be estimated by dividing the particulate concentrations by  $10^4$ . Carbon monoxide concentrations in the plume can be estimated by multiplying  $\text{SO}_2$  concentrations by 2.25.

Under very calm conditions (which fortunately occur very rarely in the Beaufort Sea), the plume will presumably remain stationary forming a cloud which will diffuse slowly horizontally and vertically between the ground and the top of the mixing layer. Meaningful calculation of this situation was impossible, but assuming a horizontal dispersion rate equivalent to that at a very low wind speed of 1 m/s, it can be postulated that a cluster of pools will generate a plume of about 1 km diameter and about 300 m high after 1 hour. The average  $\text{SO}_2$  and soot concentration in this plume will be about 1300 and 200  $\mu\text{g}/\text{m}^3$  (assuming zero settling velocity) which are somewhat higher than the maximum concentrations which will occur under wind conditions. Clearly, it is desirable to avoid entering the immediate area of the fire under calm conditions.

It is also necessary to estimate the extent to which the plumes from different clusters may superimpose and thus expose an area to multiple concentrations. At a wind speed of 4 m/s, the plume from a cluster which burns for 1 hour will typically be about 15 km long and about 2 km wide, covering an area of 30  $\text{km}^2$ . In moving across the region, it will "sweep out" an area of 30  $\text{km}^2$  per hour. If it is assumed that a maximum of 10 clusters are burning at any time in the total spill area of 2400  $\text{km}^2$ , then there will be 1 cluster burning in each 240  $\text{km}^2$ . Superposition of the plumes can only occur when a plume is blown over a burning cluster. Each plume will thus have about 33/240 or 14% probability of superposition on a burning cluster. Typically, it will take plumes about 3 hours to drift to the edge of the spill area or to be diluted to very low concentrations, thus about 30 plumes will be drifting over the area under the worst conditions. There is, therefore, a 30 x 14% or 420% probability of 2 plumes



superimposing, i.e., out of 30 plumes, 4 will encounter a fire.

Superposition of plumes will, therefore, be a rare event and when it does occur, the concentrations experienced will increase by relatively small amounts. It is quite unlikely that two near-fire high concentrations of, for example,  $300 \mu\text{g}/\text{m}^3$  of  $\text{SO}_2$  could superimpose. The worst condition is likely to be the superposition of a 10 km concentration with a near fire concentration and it is more likely that the 10 km or 40 km concentrations will about double. Using this argument, the concentrations in Table 1 can be deduced for superimposed plumes. It is emphasized that this will occur in about one-seventh of the plumes and these conditions will persist for a short period of time.

## 8.0 DISCUSSION

It is interesting to compare in Table 1 these concentrations with the Canadian National Air Quality Objectives and typical levels in urban areas of Canada.

For  $\text{SO}_2$ , the concentrations are all below the 1 hour desirable concentrations, thus exposure of personnel or communities to sulfur dioxide from a 2% oil is not regarded as serious.

For soot concentrations close to the fire and at distances up to 10 km are clearly undesirably high.

There are reasons to suspect that oil smoke will contain higher concentrations of polynuclear aromatic hydrocarbons (PNAs) than will particulate emissions from conventional sources. The direct comparison of suspended particulate concentrations in the plume and with the acceptable or desirable concentrations or urban area concentrations may, therefore, be misleading. Since PNAs have been established as potent carcinogens, it is clearly desirable to be prudent; therefore, it is recommended that human exposure to oil smoke be minimized by avoiding situations where clean-up crews enter plumes or when prevailing winds carry smoke plumes directly over communities. This can be accomplished by careful coordination of igniting activities with short term weather forecasts. The use of aerial ignition techniques also reduces exposure.

Although the metal concentrations are low, and the prevalent metals

vanadium and nickel are not regarded as being particularly toxic, some prudence is also justified in exposing humans to these metal emissions. There is a possibility that toxic metals such as mercury or chromium may be present in the oil or gas. The chemical speciation is not known and an unforeseen combination of circumstances could result in unexpected exposure. This is an additional incentive for avoiding exposure to smoke.

The carbon monoxide concentrations are an order of magnitude less than the desirable concentrations; thus, no problem is likely.

The principal source of hydrocarbons is evaporation of unburned oil rather than the burned oil. Volatile hydrocarbons are not regarded as noxious at low concentrations in regions not subject to photochemical smog. The only cause for concern may be the occasional, local, high concentration in which an explosion hazard exists.

## 9.0 CONCLUSIONS AND RECOMMENDATIONS

A scenario has been established to describe the time and space distribution of oil burning in the Beaufort Sea. The atmospheric concentrations of  $\text{SO}_2$ , CO, soot and metals have been estimated for locations close to the fire and at distances of 10 km and 40 km. Comparison of these concentrations with Air Quality Objectives and typical levels in urban Canada, shows that the  $\text{SO}_2$  and CO concentrations will be acceptably low. The principal concern is the high soot concentration in the immediate vicinity of the fires. Human entry into such areas should be avoided. Since there is doubt about the effects of polynuclear aromatic hydrocarbons and metals which will be present in the soot, it is prudent to minimize the exposure of personnel and communities to these substances by careful planning of the burning operations using short-range weather forecasts.

It is emphasised that these calculations are exploratory in nature and include a large number of assumptions about atmospheric conditions, applicability of diffusion and plume rise equations, the time and space distribution of the burning operation, the quantities of  $\text{SO}_2$ , CO, soot and metals emitted and the probability of plume superposition. Experimental validation (or otherwise) of the calculations by undertaking a controlled oil burn in the Beaufort Sea with aerial plume sampling would be desirable.

This work should not be regarded as an accurate calculation of concentrations, but rather as a quantitative assembly of the relevant factors in a reasonably logical framework to permit calculation of concentrations. The probable accuracy is no better than a factor of 2 or 3,

It is recommended that further research is justified on oil burning mechanisms, on northern oil compositions, on oil evaporation rates and on soot deposition characteristics.