

**AN INVESTIGATION OF ATMOSPHERIC EMISSIONS**  
**FROM THE**  
**ROYAL OAK GIANT YELLOWKNIFE MINE**

Environmental Protection Division  
Department of Renewable Resources  
Government of the Northwest Territories  
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## INTRODUCTION

An investigation of arsenic and sulphur dioxide emissions from the roaster stack at the Royal Oak Giant Yellowknife Mine was undertaken by the Department of Renewable Resources after a request for an investigation under the Environmental Rights Act was filed with the Government of the Northwest Territories on April 22, 1991. This report contains the technical findings of that investigation.

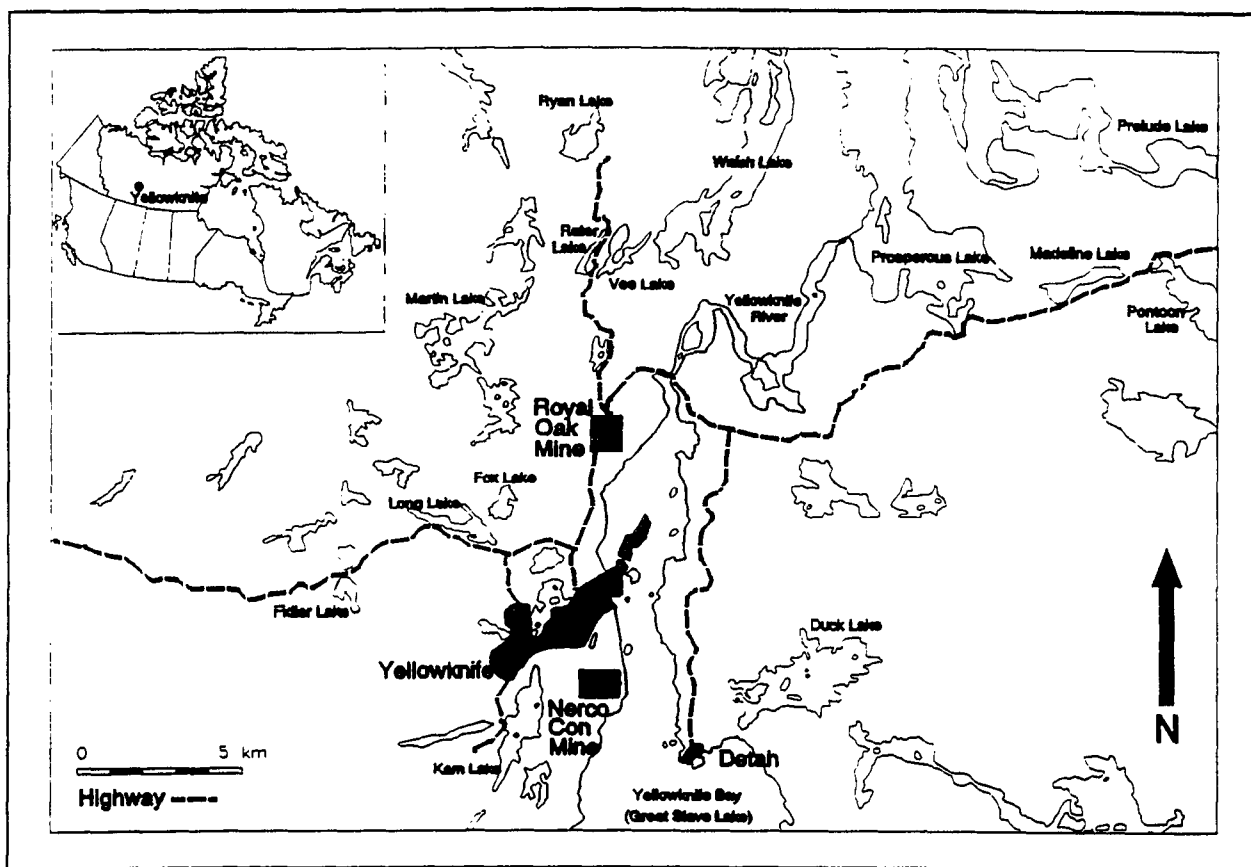
The objective of the investigation was to measure pollutant levels resulting from arsenic and SO<sub>2</sub> emissions from the Royal Oak roaster stack and to determine the degree of impact these pollutants may be having on vegetation.

Specific objectives for the investigation are listed below.

- A Determine as closely as possible roaster stack emission rates for arsenic and SO<sub>2</sub>.
- B Determine the fate of arsenic and SO<sub>2</sub> dispersed to the environment and estimate the concentrations and total loading within the dispersal zone.
- C Determine the cause of vegetation damage observed in the vicinity of the Royal Oak Giant Yellowknife Mine.

The City of Yellowknife, capital of the Northwest Territories (see Figure 1), was established shortly after gold was discovered in the area in 1936. Yellowknife is now a modern city with a population of over 15,000 residents. Gold mining continues to play an important role in the local economy and is presently mined and smelted at two mines, the Royal Oak Giant Yellowknife Mine located about 5 kilometres north of the city and the Nerco Con Mine at the southeastern edge of the city.

The rocky Precambrian Shield landscape of the northern shore of Great Slave Lake, on which Yellowknife is situated, is covered by boreal forest. At this latitude (62° N), there are about 20 hours of sunlight per day in June and about 4 hours a day in December. The treeline lies about 150 kilometres to the northeast of Yellowknife. With a dry sub-arctic climate, the mean annual temperature in Yellowknife is -5.4° C. The monthly mean temperature is 16.3° C in July, the warmest month and -28.8° C in January, the coldest month of the year. Total precipitation averages 267 millimetres per year. The prevailing wind direction is from the east, except in June, July and August when the prevailing direction is from the south and in January when it is from the northwest.



**Figure 1** Map of Yellowknife and surrounding area.

### Arsenic and Sulphur Dioxide Emissions

Both sulphur dioxide and arsenic have been released into the Yellowknife environment since gold mining activities started, and in past years, emission rates were considerably higher than they are now. Presently, the Royal Oak Giant Mine contributes the bulk of arsenic and sulphur into the Yellowknife environment.

Royal Oak roaster stack emissions of arsenic trioxide ( $As_2O_3$ ) and sulphur dioxide ( $SO_2$ ) are by-products of the roasting process used to produce gold. Pulverized ore burns in the roaster at high temperatures fuelled by the high sulphur content of the ore.  $SO_2$  emissions from the 45 metre high Royal Oak roaster stack have not been controlled and are released directly into the atmosphere.

The first electrostatic precipitator was installed in 1951 to control arsenic emissions from the Royal Oak Giant Yellowknife mine. A number of improvements since that time,

including the installation of a baghouse dust collector, have further reduced the rate of arsenic emitted from the roaster stack. Dust captured by the electrostatic precipitator is processed to remove the gold it contains, and then the  $\text{As}_2\text{O}_3$  wastes from it and the baghouse are stored underground.

Nerco Con Mine started controlling arsenic emissions in 1949 when a wet scrubber system was installed on their roaster stack and improvements to their arsenic control system were made on a number of occasions in later years. Roaster stack emissions of  $\text{As}_2\text{O}_3$  and  $\text{SO}_2$  from the Nerco Con Mine ceased in 1970 when, due to reduced sulphur content in the ore as the mine extracted ore from greater depths, the roasting equipment was no longer needed.

Arsenic is emitted from gold roasters in a fully oxidized form, principally as  $\text{As}_2\text{O}_3$ . Below temperatures of  $193^\circ\text{C}$ ,  $\text{As}_2\text{O}_3$  is a solid and exists in the atmosphere as suspended particulate matter. Small amounts of other forms of arsenic are emitted, and a number more forms are found in the environment including the natural forms. Usually total arsenic is measured in environmental studies because  $\text{As}_2\text{O}_3$  can be difficult to isolate and analyze in the laboratory.

Arsenic in the environment is of concern because at high enough concentrations, some forms of arsenic are toxic.  $\text{As}_2\text{O}_3$  is one of these toxic forms and is also a suspected carcinogen.

Some  $\text{SO}_2$  is emitted in Yellowknife through the combustion of fossil fuels for heating, vehicle operation and electricity generation. These emissions are estimated to be low, but do create detectable background levels of  $\text{SO}_2$  in Yellowknife air. The Jackfish Lake power plant has an annual  $\text{SO}_2$  emission rate (estimated to be 30 tonnes/year based on fuel consumption rates and average sulphur content of fuel) that is less than the daily emission rate from the Royal Oak roaster stack.

$\text{SO}_2$  is a very reactive gas that corrodes many materials including living tissues. The total dose received by a particular receptor is determined by ambient  $\text{SO}_2$  levels and exposure times. Studies in other parts of Canada and the world have shown that  $\text{SO}_2$  can be carried hundreds of kilometres away from the source when it dissolves into water droplets. In the atmosphere,  $\text{SO}_2$  tends to be converted within a few hours or days to the sulphate ion ( $\text{SO}_4^-$ ) when it dissolves in water droplets in the atmosphere. Sulphate ions contribute to the "acid rain" problems being experienced in many parts of the world.

### **Task Force on Arsenic**

During the mid 1970's, a Canadian Public Health Association (CPHA) Task Force conducted a comprehensive study of the short and long term effects of arsenic exposure in Yellowknife. All sources of arsenic in Yellowknife were reviewed along with all routes of human exposure, including air, water, soil, vegetation and fish. The broadly focused study also reviewed occupational exposure to arsenic. CPHA released their report outlining the activities, findings, conclusions and recommendations in 1977.

It was the opinion of the Task Force that, with respect to arsenic, the quality of ambient air in the Yellowknife area at that time was acceptable. They made a number of recommendations regarding arsenic in Yellowknife air.

1. THAT a continuing atmospheric monitoring program be conducted by the Government of the Northwest Territories, in cooperation with the Environmental Protection Service (Environment Canada).
8. THAT Giant Yellowknife take immediate steps to reduce arsenic air emissions by commencing application of the best available technology even before this application becomes mandatory.
9. THAT Giant Yellowknife obtain appropriate stack testing equipment as soon as possible and that baseline stack monitoring be conducted.

### **Regulatory Limits for Arsenic and Sulphur**

There are no regulations or standards in place to limit emission rates of air pollutants from the Royal Oak Giant Yellowknife Mine, including emissions of arsenic and SO<sub>2</sub>. Arsenic emission rates from gold roasters were reviewed in 1979 and regulated limits under Environment Canada's Clean Air Act were considered but were never promulgated (emission rates of arsenic from the Royal Oak stack have been below the proposed limits since a major retrofit of control equipment was voluntarily undertaken in the mid 1970's).

Arsenic and its compounds are presently being assessed by Environment Canada and Health and Welfare Canada to determine whether these substances are "toxic" according to the definition under the *Canadian Environmental Protection Act (CEPA)*. If arsenic and its compounds are found to be "toxic" according to the definition under the Act then they are

to be placed on Schedule 1 of the Act which allows for the making of regulations to control any aspect of their life cycle, from the research and development stage through manufacture, use, storage, transport and ultimate disposal.

At the present time there are no national ambient air quality objectives for arsenic. Ontario is the only jurisdiction in Canada that has set a limit for arsenic in ambient air, a 24 hour average of 0.3 micrograms of total arsenic per cubic metre ( $\mu\text{g}/\text{m}^3$ ).

National  $\text{SO}_2$  ambient air quality objectives have been established under the *CEPA* and are listed in Table 1. These objectives provide guidance only and are not legally enforceable.

**Table 1:** Ambient air quality objectives for  $\text{SO}_2$  under the *Canadian Environmental Protection Act*.

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Sulphur dioxide $\mu\text{g}/\text{m}^3$	one hour	24 hour	annual
Desirable	450	150	30
Acceptable	900	300	60
Tolerable	-	800	-

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The maximum desirable level is the long-term goal for air quality and provides a basis for an antidegradation policy for unpolluted parts of the country, and for continuing development of pollution control technology.

The maximum acceptable level is intended to provide adequate protection against effects on soil, water, vegetation, materials, animals, visibility, personal comfort and well-being.

The maximum tolerable level denotes time-based concentrations of air contaminants beyond which, due to a diminishing margin of safety, appropriate action is required without delay to protect the health of the general population.

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## STACK EMISSION RATES

Roaster stack arsenic emission rates for the years 1949 to 1974 were reported by the CPHA (1977) and those emission rates are shown in Table 2. Results from stack emission surveys conducted from 1975 to 1991 are provided in Table 3. Emission rates from the mine are considered to vary over time because of the variability in production rates and ore concentrations.

Significant decreases in reported arsenic emission rates occurred following control equipment improvements made in 1951, 1954, 1958 and 1974. Prior to 1951 when a cold electrostatic precipitator was installed at the mine there was no arsenic control equipment. A hot electrostatic precipitator was added in 1955 to take some of the load. A Dracco baghouse gas filter was installed in 1958 and the original cold electrostatic precipitator was converted to a hot mode of production in 1962. Starting in the mid 1970's a major retrofit of the control equipment was undertaken and improvements were made in operation and maintenance procedures.

Stack sampling is a commonly used technique for determining stack emission rates although the results are accurate for the period of sampling only. Stack sampling was conducted at the Royal Oak roaster stack in 1991 under contract to the Department of Renewable Resources by Western Research in August and by Entech Environmental Services Ltd. in October. The purpose of these surveys was to determine the emission rates of arsenic and  $\text{SO}_2$  from the gold roaster stack. Results from these stack emission surveys conducted in 1991 are included in Table 3.

Sampling and analysis for arsenic in August and October were conducted as per the Environment Canada standard reference method, *Measurement of Emissions of Arsenic from Gold Roasting Operations, Report EPS 1-AP-79-1*. In this method, an integrated sample of particulate and gaseous arsenic stack emissions are withdrawn isokinetically from a number of traverse points along the stack cross section. This provides a representative sample from within the stack where flow rates and temperatures vary across the width.

In August,  $\text{SO}_2$  was sampled in an absorption train utilizing 6% hydrogen peroxide solution. The subsequent analysis of these samples was performed on an ion chromatograph. In October the  $\text{SO}_2$  determination was conducted as per the Environment Canada method *EPS 1-AP-74-3*. On both occasions the sample was extracted isokinetically from a point near the centre of the stack.



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**Table 2:** Arsenic emission rates from the Royal Oak Giant Yellowknife Mine roaster stack, 1949 to 1974.

YEAR	ARSENIC kg/day	SOURCE	YEAR	ARSENIC kg/day	SOURCE
1949	7,300	estimate	1962	150	estimate
1950	7,300	estimate	1963	150	estimate
1951	7,300	estimate	1964	310	company
1952	-		1965	-	
1953	-		1966	240	company
1954	5,500	company	1967	130	company
1955	2,900	company	1968	230	company
1956	2,700	company	1969	300	company
1957	3,000	company	1970	220	company
1958	1,500	estimate	1971	880	company
1959	52	company	1972	400	company
1960	75	company	1973	400	company
1961	150	estimate	1974	220	company

Table from CPHA 1977.

**Table 3:** Roaster stack emission surveys, 1975 to 1991.

DATE	ARSENIC kg/day	SO <sub>2</sub> t/day	SOURCE
Aug. 1975	76.1	-	EPS
Aug. 1981	17.5	-	EPS
Aug. 1981	17.8	-	company
Dec. 1982	13.2	-	company
July 1983	27.1	32.2	EPS
Nov. 1985	24.2	-	company
Nov. 1986	24.3	-	company
Sept. 1988	185.0 <sup>1</sup>	-	company
Oct. 1988	232.8 <sup>1</sup>	-	company
Oct. 1989	26.4	-	company
July 1990	-	35.0	Contract
Aug. 1990	37.1	-	company
July 1991	15.2	-	company
Aug. 1991	59.0	82.9	Contract
Oct. 1991	25.9	49.5	Contract

**NOTE:** 1. High emission rates for arsenic measured by mine personnel in 1988 likely resulted from bag house operational difficulties being encountered during the testing periods.

## ARSENIC MONITORING

### High volume air sampling

Table 4 contains a summary of measurements made of total arsenic levels in downtown Yellowknife air from 1973 to 1992. The annual geometric mean total arsenic levels from 1973 to 1992 are shown in Figure 2. Daily levels of total arsenic measured since 1984 have been below the Ontario standard of  $0.3 \mu\text{g}/\text{m}^3$  except for two occasions in 1988, the year that baghouse malfunctions and high arsenic emission rates were reported.

From 1973 to 1975, Environment Canada conducted an ambient air monitoring program in the Yellowknife area (see Hazra and Prokopuk 1977). Three high-volume air samplers were operated in all 3 years and 6 more samplers were added in 1975. The levels reported in Table 4 and Figure 2 for 1973-75 are for samples which were collected at the station in downtown Yellowknife. Elevated arsenic levels were detected more frequently at stations in closer proximity to the roaster stack. Hazra and Prokopuk concluded that the mine was the main source of arsenic emissions to Yellowknife ambient air.

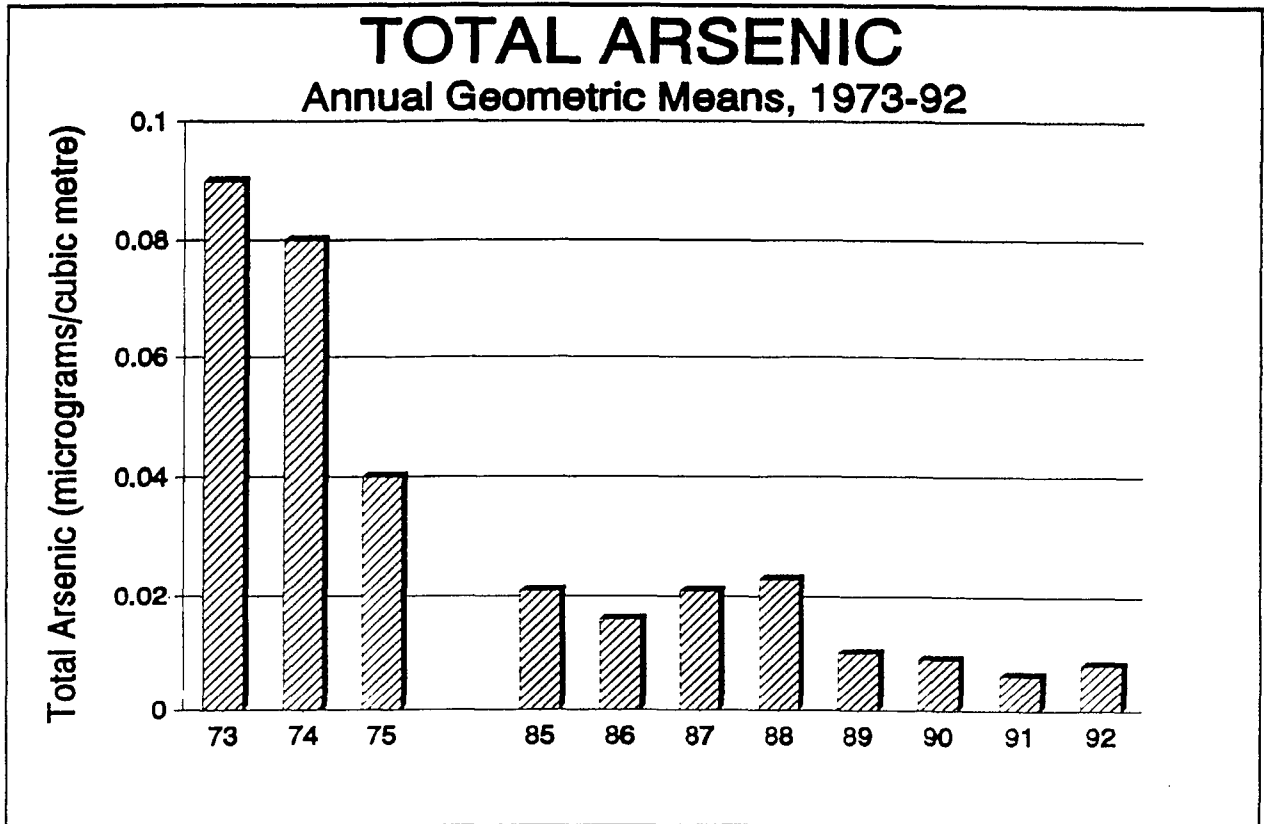
High-volume samples were collected by Environment Canada in downtown Yellowknife between July 1978 and June 1979. Edwards and Kent (1979) reported that there had been a substantial reduction in total arsenic levels in ambient air from 1975 to 1978.

Atmospheric levels of total arsenic have been monitored in downtown Yellowknife since 1984 in conjunction with Environment Canada's National Air Pollution Sampling (NAPS) network. The Environmental Protection Division took over operation of the sampler at the end of 1986. The high-volume air sampler in downtown Yellowknife is operated every six days. Samples are collected over a 24 hour period by "vacuuming" a measured volume of air through an 8 by 10 inch fibreglass (PALLFLEX) filter that collects particles from the passing air. Exposed filters are sent to the River Road Environmental Technology Centre (RRETC) Chemistry Division in Ottawa for analysis of total arsenic by acid extraction of the sample filter followed by hydride generation and detection by atomic absorption.

Declines in total arsenic detected in Yellowknife air correspond with equipment and operational improvements at the mine. Levels in Yellowknife dropped in the mid 1970's after the control equipment was extensively overhauled. A further reduction in levels detected since 1988 is thought to be the result of improved maintenance and operation of control equipment.

**Table 4:** Total arsenic levels in downtown Yellowknife, 1973-75 and 1984-92. Results expressed in  $\mu\text{g}/\text{m}^3$ .

YEAR	HIGHEST 24 hr level	LOWEST 24 hr level	ANNUAL GEOMETRIC MEAN
1973	0.42	<0.01	0.08
1974	0.54	<0.01	0.09
1975	0.59	<0.01	0.06
1978/79	0.11	n/a	<0.02
1984	0.182	0.005	n/a
1985	0.288	0.002	0.021
1986	0.176	0.001	0.016
1987	0.238	0.005	0.021
1988	1.819	0.004	0.023
1989	0.047	0.003	0.010
1990	0.039	0.003	0.009
1991	0.037	0.002	0.006
1992	0.083	0.002	0.008



**Figure 2**

### **Snow surveys**

In 1975, Environment Canada conducted a survey to determine total arsenic deposition rates to snow in the Yellowknife area (Hazra et al 1977). Snow core and snow scoop samples were taken in March and April 1975. From these samples it was estimated that the mean deposition rate of total arsenic to snow in the Yellowknife area was  $2.23 \text{ kg/km}^2/\text{month}$ .

Arsenic levels in snow were highest in close proximity to the mine and decreased with distance in 1975. Hazra et al found that the average concentration of total arsenic in melted snow core samples was 0.17 milligrams per litre (mg/l). Many of the snow water samples collected in 1975 exceeded the maximum permissible level of 0.05 mg/l of total arsenic under the Canadian Drinking Water Standards and Objectives. The Canadian Public Health Association (1977) concluded that the use of snow at that time from the Yellowknife area as a source of drinking water could constitute a serious health hazard.

In 1986, Stanley Associates Engineering Ltd. carried out a snow core survey under contract to the Department of Renewable Resources. Approximately the same sites as those used in the 1975 survey were visited and a considerable reduction in total arsenic deposition rates was found. Average deposition rates of total arsenic to snow at sites sampled in March 1986 were  $0.40 \text{ kg/km}^2/\text{month}$  and average snow water concentrations were 0.028 mg/l. Sites where samples exceeded the Canadian Drinking Water Standard were located to the south and southeast in close proximity to the mine and did not extend to populated areas.

## **SO<sub>2</sub> MONITORING**

### **Lead candle network**

In October of 1990, a SO<sub>2</sub> monitoring network consisting of 16 lead candles located within 4 km of the Royal Oak roaster stack was established by mine personnel under a one year cost sharing agreement between the Department of Renewable Resources, Environment Canada's Conservation and Protection Branch and Royal Oak. The locations of lead candle network sampling sites were selected by mine personnel and they installed and changed the candles every month. All sampling stations in the network were located on the mine site except for one which was 4 km north of the mine along the Vee Lake Road (see Figure 3).

Lead candles operate on the principle of exposing filters impregnated with a known amount of lead dioxide (PbO<sub>2</sub>) to the atmosphere for a period of time. PbO<sub>2</sub> reacts with SO<sub>2</sub> at a

uniform rate to form  $\text{PbSO}_4$ . At the end of the exposure period the devices are returned to the laboratory and the level of total sulphation is determined. Total sulphation is measured as sulphite equivalents in milligrams per day per 100 square centimetres ( $\text{SO}_3$  eq. mg/day/100  $\text{cm}^2$ ).

Lead candles are used as a simple and inexpensive method to assess if high ambient levels of  $\text{SO}_2$  in the air may be occurring. They provide a relative indication of ambient  $\text{SO}_2$  levels at the sampling site over the exposure period. In Alberta, readings greater than 0.5  $\text{SO}_3$  eq. mg./day/100  $\text{cm}^2$  trigger further investigation to determine ambient  $\text{SO}_2$  levels using more accurate techniques. Lead candles are also useful for identifying deposition trends over seasons or years and for identifying geographical patterns of sulphur deposition.

Results for all stations in the lead candle network during the year it was in place are provided in Table 5. Readings higher than 0.5  $\text{SO}_3$  eq. mg./day/100  $\text{cm}^2$  for at least one month were reported at 6 stations. Overall, the lowest readings occurred during the months of December, January and February. Readings at some individual stations did deviate from this general rule, especially station 5 (0.7 km SE) which had high readings in most months.

The annual average sulphation readings for all stations are plotted against distance in Figure 4. Stations in the lead candle network that had the highest annual average readings were between 0.4 to 1.0 km from the roaster stack. Peak readings (i.e. >0.5) also occurred within this range.

Figure 5 is a graphical presentation of monthly readings for 6 lead candle stations shown here to demonstrate differences in readings from distance and direction. The stations at 0.7 km had higher readings and showed more variability in monthly levels over the year than the readings obtained at about 1.5 km. Lead candles located in different directions but at the same distance from the stack received different levels of  $\text{SO}_2$ . This variation is likely due to wind patterns and other changeable weather conditions.

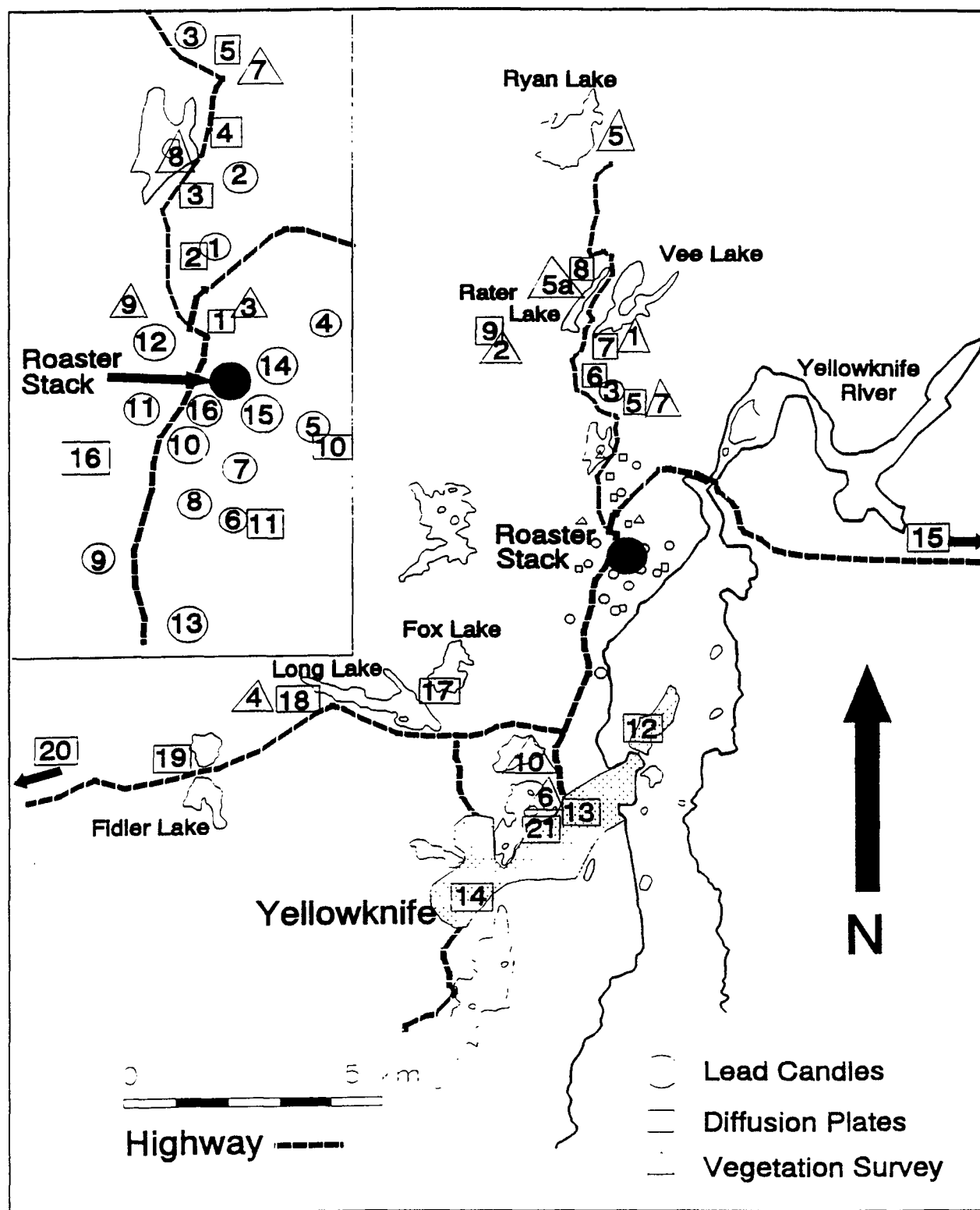


Figure 3 Location of sampling sites for the lead candle network, diffusion plates and vegetation survey.

**Table 5:** Lead candle network results, October 1990 to September 1991.  
Results expressed as total sulphation ( $\text{SO}_3$  eq.  $\text{mg}/100 \text{ cm}^2$ ) per day.

Stn #	Dir.	Dist. (km)	Oct 1990	Nov 1990	Dec 1990	Jan 1991	Feb 1991	March 1991	April 1991	May 1991	June 1991	July 1991	Aug 1991	Sept 1991	Stn Avg
1	N	1.5	0.02	0.02	0.02	0.02	0.01	0.01	0.14	0.17	0.18	0.09	0.13	0.05	0.07
2	N	2.5	0.03	0.01	0.02	0.02	0.01	0.08	0.11	0.13	0.04	0.04	0.08	0.03	0.05
3	N	4.0	0.03	0.01	0.02	0.02	0.02	0.09	0.21	0.46	0.31	0.24	0.21	0.13	0.15
4	ENE	0.7	0.03	0.01	0.02	0.02	0.27	0.01	0.02	0.11	0.04	0.09	1.00	0.05	0.14
5	SE	0.7	1.15	0.46	1.90	0.94	0.98	0.52	0.02	0.49	1.06	1.03	0.40	0.54	0.70
6	S	1.0	0.94	0.13	0.02	0.06	0.07	0.08	0.10	0.10	0.14	0.08	0.60	0.15	0.21
7	S	0.5	2.10	0.54	0.02	0.02	0.18	0.13	0.14	0.33	0.70	0.08	0.60	0.11	0.41
8	SSW	0.7	0.54	0.25	0.02	0.02	0.03	0.16	0.25	0.60	0.80	0.08	0.18	0.18	0.25
9	SSW	1.4	0.30	0.25	0.02	0.02	0.02	0.08	0.18	0.22	0.18	0.07	0.13	0.08	0.13
10	SW	0.4	0.41	0.62	0.02	0.02	0.02	0.12	0.61	0.93	0.63	0.19	0.17	0.07	0.32
11	WSW	0.3	0.03	0.28	0.02	0.02	0.02	0.13	0.12	0.36	0.15	0.14	0.16	0.06	0.12
12	N	0.2	0.11	0.01	0.02	0.02	0.01	0.05	0.07	0.11	0.10	0.11	0.15	0.09	0.07
13	S	1.7	0.47	0.18	0.02	0.02	0.26	0.28	0.21	0.15	0.10	0.04	0.18	0.14	0.17
14	E	0.1	0.04	0.02	0.02	0.02	0.04	0.07	0.03	0.04	0.05	0.05	0.04	0.02	0.04
15	S	0.1	0.18	0.01	0.02	0.02	0.02	0.04	0.18	0.13	0.16	0.09	0.23	0.04	0.09
16	SSW	0.2	0.21	0.28	0.02	0.02	0.02	0.08	0.04	0.45	0.43	0.07	0.06	0.03	0.14

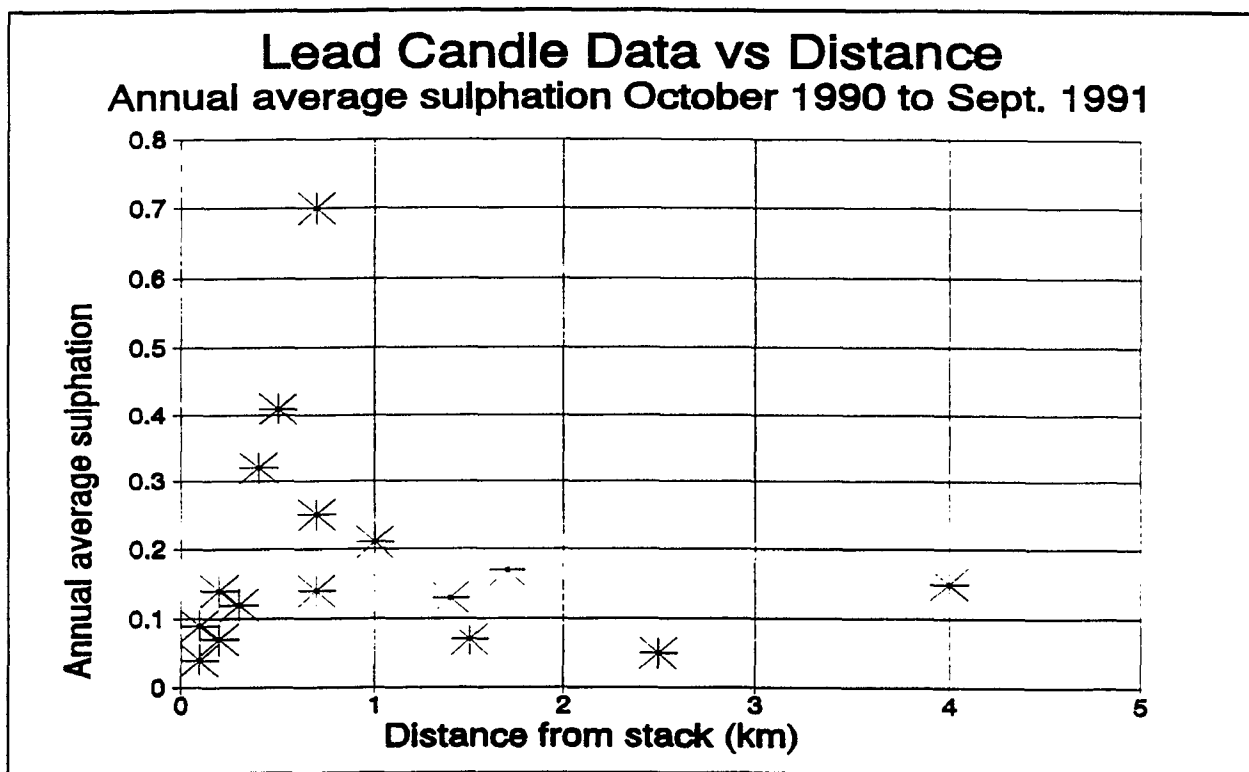


Figure 4

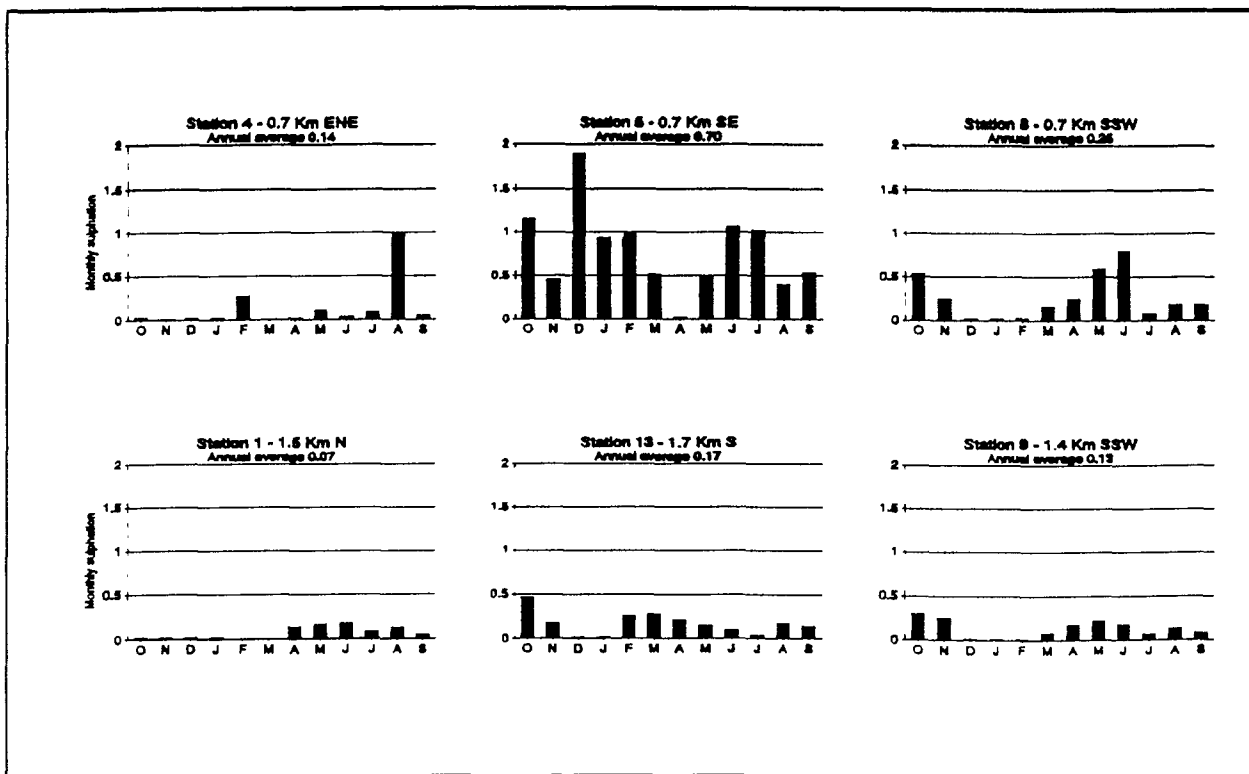


Figure 5 Monthly lead candle readings showing differences in levels resulting from distance and direction from stack.



### Diffusion Plate Network

Following completion of the lead candle network program, a network of 20 diffusion plates was established by the Department of Renewable Resources and was operated from November 1991 until November 1992. The diffusion plate network was positioned to cover a larger area than the lead candle network, with sampling sites as far away as 34 kilometres from the roaster stack (see Figure 3). Computer model (ADEPT2) calculations of ambient  $\text{SO}_2$  levels were used to guide selection of sampling site locations.

The diffusion plate technique used in this study was developed by the Alberta Environmental Centre and is a more accurate method for measuring monthly  $\text{SO}_2$  levels than lead candles. The plates are based on the same principle as lead candles but use potassium carbonate ( $\text{K}_2\text{CO}_3$ ) instead of lead dioxide ( $\text{PbO}_2$ ) as a reactive substrate to eliminate sources of laboratory error. Diffusion screens used in these devices minimize the effect of wind velocity on  $\text{SO}_2$  uptake and these devices have been shown to be independent of air temperature between minus  $40^\circ$  to plus  $40^\circ$  C (see Bertram et al 1988 for a more complete description).

Diffusion plate holders were placed 2 metres above the ground at sites generally located on rock outcrops. Care was taken to avoid locating sample sites within heavily wooded areas because vegetation will intercept air pollutants and reduce ambient levels. Diffusion plates were changed monthly, as soon as possible after the 20<sup>th</sup> of each month for operational reasons. Thus, the plates did not measure levels in exactly the month for which the results are reported, but rather include the last week of the previous month and exclude the last week of the reported month, i.e. August = July 20 to August 20.

Diffusion plates used in Yellowknife were calibrated at the Alberta Environmental Centre in Vegreville by exposing a set of diffusion plates from the same batch adjacent to an annular denuder, a very accurate device for measuring ambient concentrations of  $\text{SO}_2$ . The ambient  $\text{SO}_2$  level measured by the annular denuder (in  $\mu\text{g}$  per litre) was compared to the level for that same period measured by the diffusion plate (in  $\mu\text{g}$  per minute) allowing calculation of the diffusion plate draw rate in litres per minute. The draw rate calculated by the Alberta Environmental Centre for the diffusion plates used in Yellowknife was determined to be 0.288 litres/minute. Using this measured draw rate, the monthly plate readings provided by the laboratory (measured in milligrams of  $\text{SO}_4$  per plate) were converted into monthly ambient average levels of  $\text{SO}_2$  in  $\mu\text{g}/\text{m}^3$ .

The ambient SO<sub>2</sub> levels detected by the diffusion plate network are provided in Table 6. Data is missing in some cases because the diffusion plates were blown out of the holders by high winds. April was the worst month for wind when 6 plates were lost. Wind losses after April were eliminated when clips were installed to anchor the plates in the holders. Plates at stations 1, 10, 11 and 16 were exposed for 2 continuous months for June/July and September/October. The plate at station 2 for June/July was spoiled and the station was deleted from the network after August so that the plate could be installed at the new station 21 for the remainder of the study.

In general, SO<sub>2</sub> levels were found to be highest during the warm months of May, June, July and August although this trend was not as distinct at stations 11 to 14 which were located to the south of the roaster stack.

The annual average SO<sub>2</sub> levels measured by the diffusion plates are plotted against distance from the roaster stack in Figure 6. The highest levels measured by the diffusion plates were within 3 km of the roaster stack. Between 3 to 5 km a middle range of levels was detected and beyond 5 km levels were much lower.

SO<sub>2</sub> levels along 3 transects are displayed in Figure 7. To the south and southwest, peak SO<sub>2</sub> levels were measured at 1 km and were much lower at 4 km. To the north the pattern was different with levels at 4 km found to be higher than at 1 km. Peak concentrations to the north occurred farther from the roaster stack, and higher SO<sub>2</sub> levels persisted farther than they did in other directions. This difference in deposition patterns may be due to different characteristics of winds coming from the south off Great Slave Lake, compared to winds coming over land from the other directions.

Table 6: Diffusion plate network results, December 1991 to November 1992. Results expressed as  $\mu\text{g}/\text{m}^3$  of  $\text{SO}_2$ .

STN	LOCATION	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	AVG
1	1 km N	2	8	11	27	-	90	139	139	192	52	52	21	66
2	1.5 N	2	16	11	24	-	47	-	-	132	-	-	-	39
3	2.0 N	2	184	108	73	268	383	947	384	800	168	19	191	294
4	2.5 N	2	76	55	61	-	291	491	221	396	108	16	60	162
5	3.0 N	2	5	13	31	29	81	123	74	131	34	6	10	45
6	4.0 N	2	45	48	44	99	204	265	123	254	48	6	79	97
7	5.0 N	2	21	34	31	84	105	183	65	176	36	5	40	65
8	6.75 N	2	16	13	11	29	66	79	45	65	23	5	11	31
9	5.0 NNW	3	40	29	-	-	57	71	52	111	16	10	42	44
10	0.7 E	320	409	166	701	179	226	126	126	614	740	740	153	375
11	1.0 S	45	23	113	236	-	412	76	76	326	79	79	234	155
12	3.6 SSE	37	13	90	55	65	39	6	6	36	29	21	23	36
13	5.4 S	5	6	71	23	32	18	5	8	16	23	11	16	19
14	7.4 SSW	19	15	73	44	52	19	6	11	5	19	5	19	24
15	20.0 ENE	2	5	6	3	6	2	2	2	3	2	2	2	3
16	1.0 SW	81	52	120	155	-	359	596	596	447	2	2	189	231
17	4.0 SW	42	29	82	-	103	69	29	102	19	60	8	61	55
18	6.0 SW	34	39	60	44	124	26	16	39	16	39	8	42	40
19	10.0 SW	11	31	39	16	78	16	11	26	8	19	5	27	24
20	34.0 WNW	13	6	11	5	5	2	2	2	2	2	3	10	5
21	5.4 SSW	-	-	-	-	-	-	-	-	-	26	11	34	-

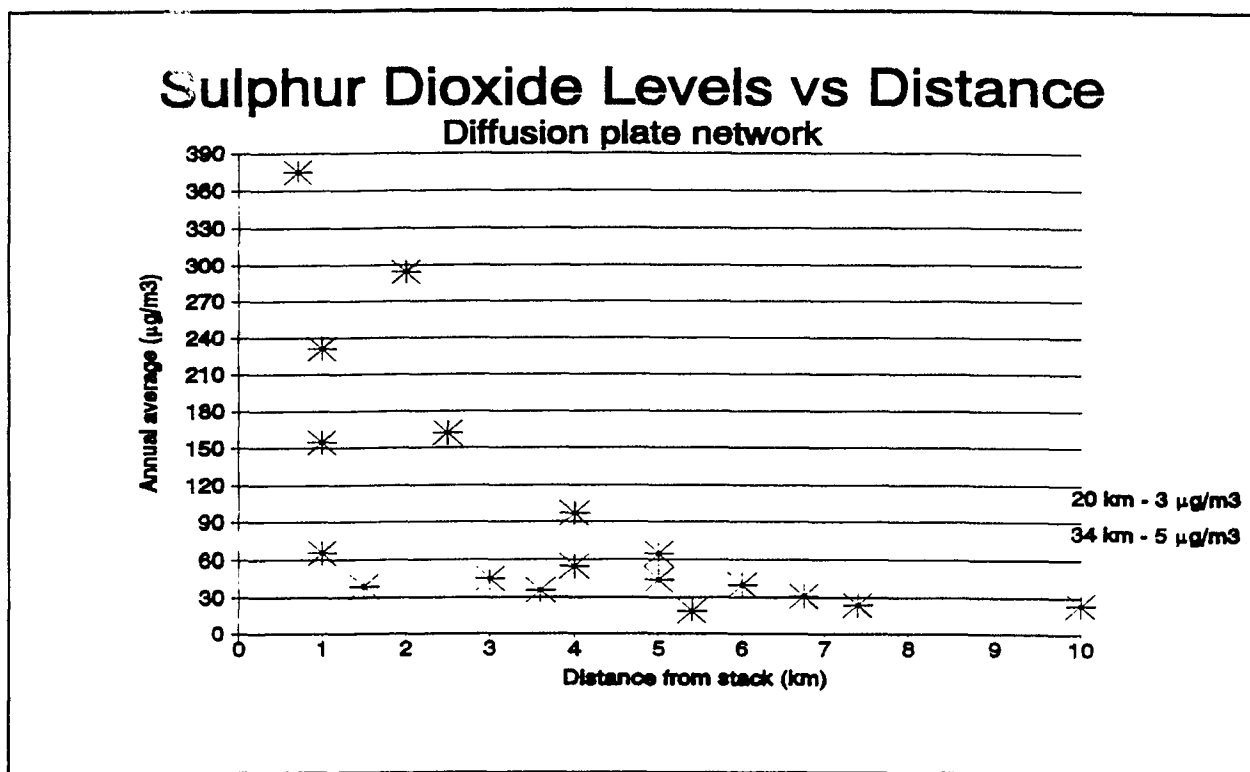
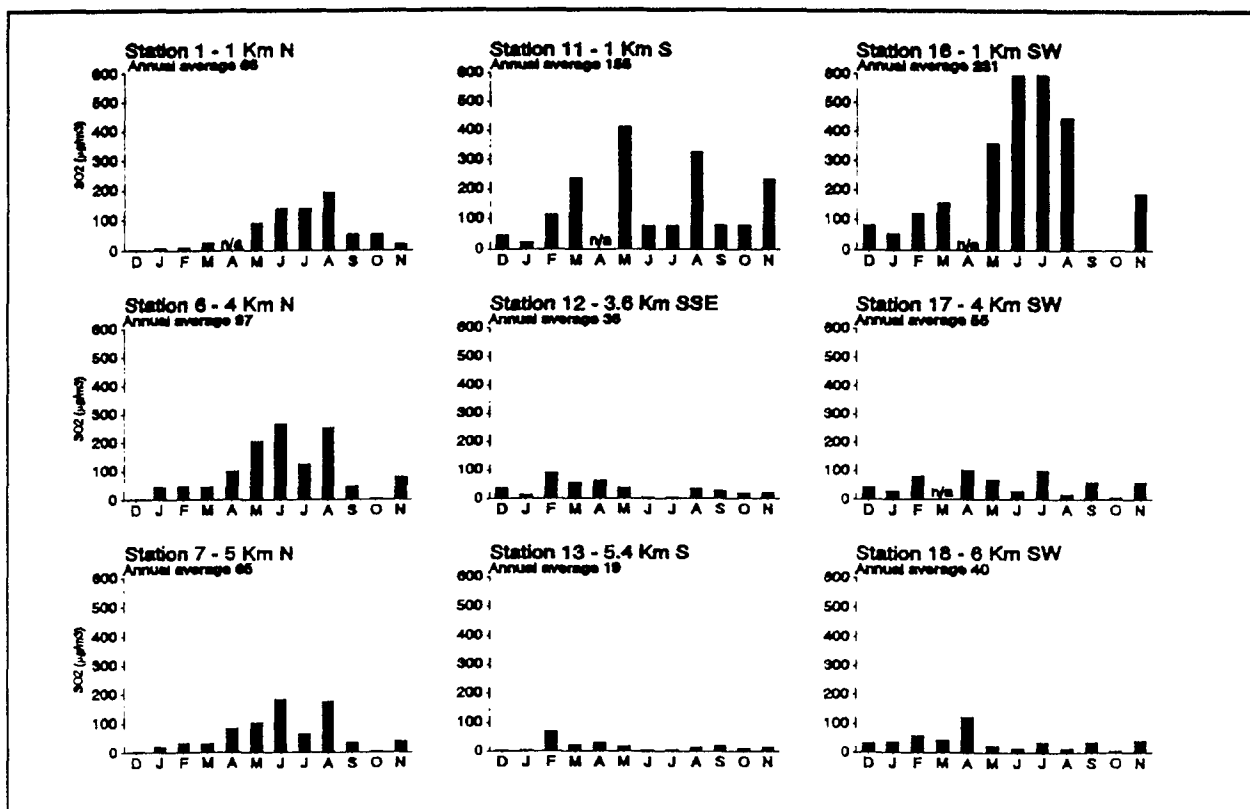


Figure 6

Figure 7 Monthly SO<sub>2</sub> levels measured by diffusion plates along 3 transects.

### Ambient monitoring

Continuous ambient air monitoring for SO<sub>2</sub> was conducted in downtown Yellowknife by Environment Canada from 1973 to 1975. Two more monitors were operated during the summer of 1975, one on Latham Island and another 2 km north of the roaster stack. The results of this monitoring were reported by Hazra and Prokopuk (1977). Analysis of monitoring results and wind patterns led Hazra and Prokopuk to conclude that the roaster stack was clearly the major source of SO<sub>2</sub> emissions in the Yellowknife area.

Hazra and Prokopuk reported that SO<sub>2</sub> concentrations in ambient air around Yellowknife during the study period did not exceed the annual arithmetic mean *Maximum Desirable National Air Quality Objective* of 30 µg/m<sup>3</sup> although one hour ambient concentrations occasionally exceeded the one hour *Maximum Desirable Level* (450 µg/m<sup>3</sup>) and rarely exceeded the one hour *Maximum Acceptable Level* (900 µg/m<sup>3</sup>). Individual one hour values were higher than 450 µg/m<sup>3</sup> 0.12% of the time in 1973, 0.25% in 1974 and 0.48% in 1975.

In the fall of 1990, Western Research was hired by the mine to monitor ambient SO<sub>2</sub> levels on the mine site 1.5 kilometres north of the roaster stack on a tailings pond. Between September 19 to October 22, a Monitor Labs 8850 SO<sub>2</sub> analyzer was operated. SO<sub>2</sub> was nearly always detected when a direct south wind blew during this period, was generally detected when winds blew from approximately a 90° sector between SSE and WSW and was not detected when winds blew from the north. During the sampling period, SO<sub>2</sub> levels rose above the 24 hour *Maximum Desirable Level* (150 µg/m<sup>3</sup>) once. The one hour *Maximum Desirable Level* was exceeded 7 times and the one hour *Maximum Acceptable Level* was exceeded once when the one hour SO<sub>2</sub> level rose to 1.678 µg/m<sup>3</sup>.

During the months of August to November 1992, the Environmental Protection Division operated a Monitor Labs 8850 SO<sub>2</sub> analyzer in downtown Yellowknife through the cooperation of the Pollution Measurement Division (PMD), Environment Canada, Ottawa. The analyzer was calibrated in Ottawa by the PMD before being shipped to Yellowknife and was recalibrated by the PMD in Ottawa at the end of the survey. Materials and equipment used for the calibrations were traceable to the National Institute of Standards and Technology (NIST) standards. During the survey the analyzer zero and span were verified on a weekly basis to ensure that readings remained accurate.

**Table 7:** Summary of SO<sub>2</sub> monitoring results in downtown Yellowknife for August, September, October and November 1992.

One hour levels exceeding the desirable limit (450 µg/m<sup>3</sup> SO<sub>2</sub>):

Date	Time	SO <sub>2</sub> (µg/m <sup>3</sup> )	Wind Direction
August 26	00:00	469	east
September 2	06:00	511	NNE
September 2	07:00	764	north
September 2	20:00	538	north
September 2	22:00	623	north
September 3	08:00	637	north
October 26	16:00	511	NNE
October 26	17:00	474	NNE
November 1	21:00	610	north
November 2	07:00	895	north
November 6	10:00	554	NNE
November 13	13:00	493	NE
November 17	11:00	455	north
November 18	14:00	517	NNE
November 18	15:00	900	north
November 21	18:00	490	north

One hour levels exceeding the acceptable limit (900 µg/m<sup>3</sup> SO<sub>2</sub>):

Date	Time	SO <sub>2</sub> (µg/m <sup>3</sup> )	Wind Direction
September 26	21:00	1516	south
November 13	12:00	924	NE
November 16	12:00	1057	north
November 21	19:00	1212	NNW

24 hour levels exceeding the desirable limit (150 µg/m<sup>3</sup> SO<sub>2</sub>):

Date	SO <sub>2</sub> (µg/m <sup>3</sup> )	Wind Direction
September 2	168	north

The 1992 monitoring results are summarized in Table 7. On 16 occasions (0.68% of the time) between August to November, the one hour *Maximum Desirable Level* (450 µg/m<sup>3</sup>) was exceeded and on 4 occasions the one hour *Maximum Acceptable Level* (900 µg/m<sup>3</sup>) was exceeded. The 24 hour *Maximum Desirable Level* (150 µg/m<sup>3</sup>) was exceeded once.

Wind measurements taken at the Yellowknife airport by Environment Canada's Atmospheric Environment Service were used to evaluate the source(s) of  $\text{SO}_2$ . One hour  $\text{SO}_2$  levels measured over 4 months were sorted according to wind direction for 36 points on the compass. Measured levels for each of the 36 wind directions were then averaged. The results of this evaluation are shown in Figure 8.

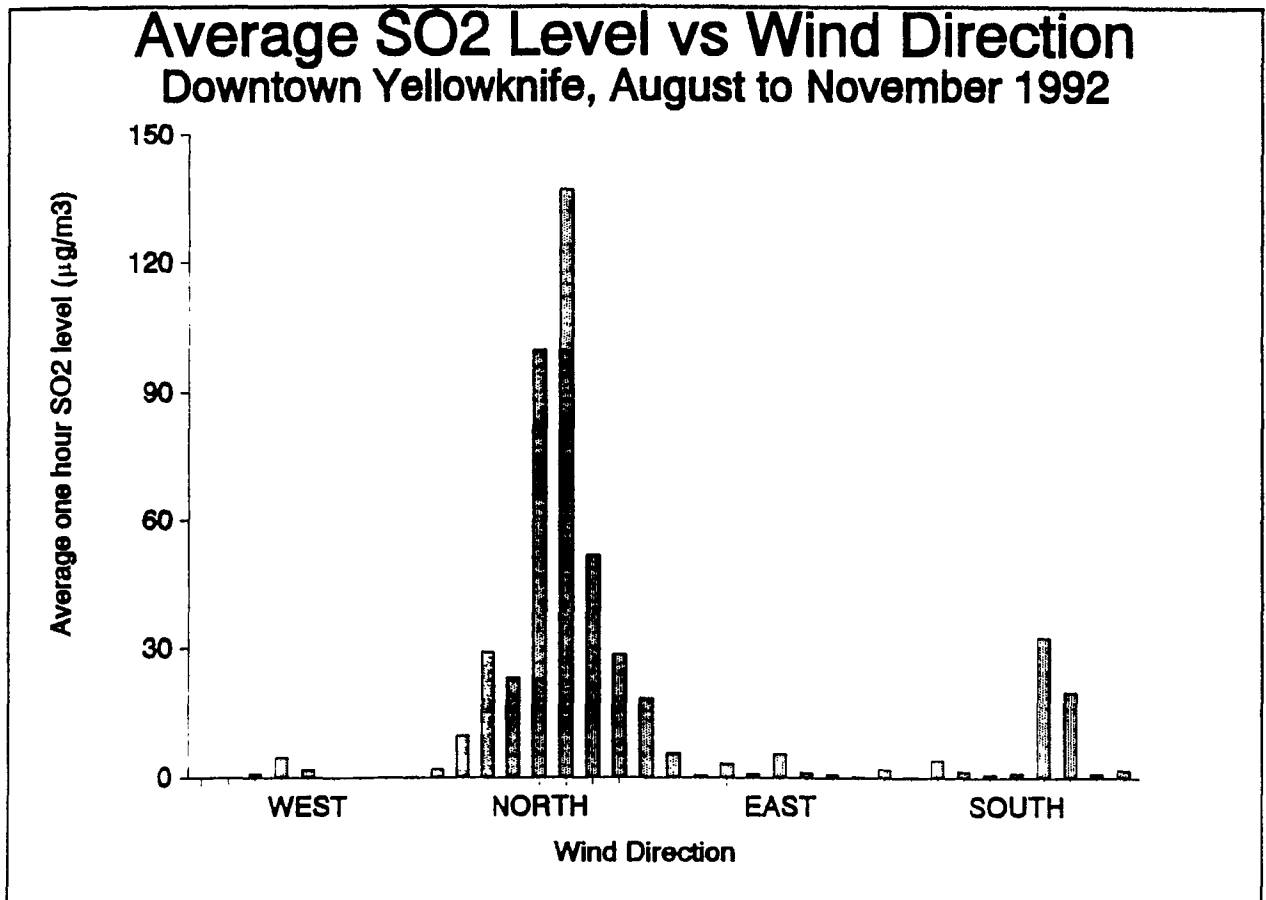


Figure 8

The highest average  $\text{SO}_2$  levels occurred when winds carried emissions from the roaster stack at  $10^\circ$  north directly to the monitoring site. Winds from this direction carried detectable levels of  $\text{SO}_2$  64% of the time compared to 30% for all directions. As the emission plume travels downwind from the roaster stack it spreads out and Figure 8 shows that northerly winds in general carried higher levels of  $\text{SO}_2$  than winds from other directions.

$\text{SO}_2$  from the south was rarely detected, but it was the direction from which the highest hourly level detected came during the 4 month monitoring period ( $1,516 \mu\text{g}/\text{m}^3$  on

September 26, see Table 7). The source(s) of infrequent bursts of high SO<sub>2</sub> levels from the south have not been identified. SO<sub>2</sub> from the east was rarely detected during August through October but by November low levels were frequently detected when winds blew from the east. Low levels from the east, west and south appear to originate from fuels burned in furnaces and vehicles in Yellowknife.

When the SO<sub>2</sub> analyzer was installed, the diffusion plate from station 2 was relocated adjacent to the sample intake. Diffusion plate readings from this station, renumbered station 21, are compared in Table 8 with average SO<sub>2</sub> concentrations measured by the analyzer over the same periods. There was reasonable agreement between the two detection methods. Average levels measured by the analyzer are expected to be somewhat lower than levels measured by the plates because the analyzer does not measure below the detection limit of 2.7 µg/m<sup>3</sup> (0.001 ppm) whereas the diffusion plates will react with and measure SO<sub>2</sub> present at any level.

**Table 8:** A comparison of diffusion plate readings and SO<sub>2</sub> analyzer readings (µg/m<sup>3</sup>).

	Sept	Oct	Nov	Average
SO <sub>2</sub> analyzer	19	11	19	16
Diffusion plate	26	11	34	24

## COMPUTER MODELLING OF SO<sub>2</sub> DEPOSITION

The Alberta Deposition Model with Terrain (ADEPT2) computer model developed by Alberta Environment was used to estimate long term (seasonal) average concentrations and deposition of SO<sub>2</sub> within 100 km from the roaster stack. The model inputs include meteorological data measured by the Atmospheric Environment Service of Environment Canada and emission rates determined from stack emission surveys. The model calculates SO<sub>2</sub> and SO<sub>4</sub> ambient concentrations in µg/m<sup>3</sup> and deposition rates in kg/hectare for 16 points on the compass, broken into seasonal and yearly rates.

Meteorological information used in the model were averages of measurements (STAR data) taken over the 5 year period of 1984 to 1989 at the Yellowknife airport by the Atmospheric



Environment Service. A number of stack emission scenarios were considered, including stack testing results obtained in August and October of 1991.

Although the local terrain is quite hilly, the maximum relief within the study area is only about 50 metres. The topography in the Yellowknife area has not been mapped at the detailed scale that would be necessary for use in the ADEPT2 model. The model can and was used without the input of topographical information but the results thus obtained are insensitive to terrain effects.

In general the patterns calculated by the model are in agreement with the results from the lead candle and diffusion plate networks. These patterns include calculations that the highest ambient SO<sub>2</sub> levels occur in the summer season and that the highest levels do not occur immediately at the base of the stack but do occur within less than 3 kilometres from the roaster stack.

Measured SO<sub>2</sub> levels at some of the diffusion plate network stations were much higher than ADEPT2 calculations for those locations. This was especially true for stations within a few kilometres of the roaster stack where the highest SO<sub>2</sub> levels were detected and for stations to the north. Similarly, the range of SO<sub>2</sub> levels detected by the lead candle network was much greater than the model calculations.

From reviewing the diffusion plate measurements and model results it appears that at least two factors must receive further attention before model calculations can be refined. Terrain factors are affecting SO<sub>2</sub> dispersion around Yellowknife but have not yet been included in model inputs. Second, Great Slave Lake is having an influence on meteorological conditions and dispersion patterns that are not accounted for in the ADEPT2 model.

## VEGETATION SURVEYS

At the request of the Department of Renewable Resources, Forestry Canada investigated vegetation damage in 1990 after the Department received inquiries from the public about yellowing leaves and premature leaf drop along the Vee Lake Road as far north as Ryan Lake. Leaf and soil samples collected in the affected area were analyzed by Forestry Canada at the Northern Forestry Centre in Edmonton. The results of the 1990 survey were reported by Maynard and Malhotra (1990). Samples were collected again in 1991 by Renewable Resources personnel and submitted to the Northern Forestry Centre for analysis and interpretation of results. The 1991 survey was reported by Maynard (1991).

In both years leaf samples were collected from the tree species present at each site. Soil samples were split into surface organic material and mineral soils. In 1990, 8 sites were sampled (see Figure 3 for sampling locations). In 1991 10 sites were sampled. Seven of these were the same sites sampled in 1990. Because of a road washout, an alternative site (5A) to the Ryan Lake site (5) was selected and 2 new sites (9 and 10) were added.

In 1990, Maynard and Malhotra observed that at the Vee Lake Road intersection all species had discoloured leaves but that farther to the north of the mine drought tolerant species appeared less affected. The visual symptoms observed in 1990 included the effects of a drought which masked any SO<sub>2</sub> damage that might have occurred.

In 1991 when drought was not a factor, Maynard found that visual symptoms typically associated with SO<sub>2</sub> pollution were found on birch leaves collected up to 3.2 km north of the mine along the Vee Lake Road. The most obvious signs of SO<sub>2</sub> damage were found at site 9, about 1.5 km north of the roaster stack. Site 9 was located in a "streak" of trees with coppery coloured browned leaves that continued in a widening line extending directly away from the roaster stack at least as far as 2.5 km from the mine. This streak was first noticed in June of 1991. Birch leaves from site 9 were either completely necrotic or showed severe interveinal chlorosis, symptoms typical of an acute SO<sub>2</sub> fumigation event. The black spruce sample from site 9 showed severe yellowing and necrosis of the older needles.

The sulphur content of birch leaves in 1990 and 1991 provided evidence that sulphur deposition was occurring north of the mine and followed a gradient with the highest concentrations closest to the stack and the lowest concentrations at Ryan Lake. In 1990, Maynard and Malhotra found sulphur in birch leaves at levels where SO<sub>2</sub> damage would be expected within 4 km of the roaster stack. In 1991, elevated sulphur concentrations were found in leaf samples collected at sites north of the mine along the Vee Lake Road as far as 3 to 5 km north of the mine.

Soil analyses conducted in both 1990 and 1991 were found to have soil sulphur and pH levels characteristic of this area, although sulphur levels along the Vee Lake Road were slightly higher than at the sites to the south and west.

Maynard and Malhotra concluded in 1990 that drought conditions contributed to the observed symptoms, and that within 5 km of the Royal Oak mine stack SO<sub>2</sub> may be contributing to the symptoms. Maynard found that visual symptoms and chemical analyses of the 1991 samples provided further confirmation that SO<sub>2</sub> deposition along the Vee Lake

Road extended at least 3 to 5 km north of the mine. Visual symptoms of damaged tree leaves typically associated with exposure to  $\text{SO}_2$  were observed by Forestry Canada on samples collected within this range.

## DISCUSSION

Arsenic in the Yellowknife environment has been a public health issue for a long time. The first medical survey of arsenic effects in Yellowknife was conducted in 1951 (see CPHA 1977 for a description of these earlier studies). Since 1951, reviews have been carried out about every ten to fifteen years and were often followed by measures undertaken at the two mines to reduce atmospheric arsenic emission rates. Arsenic emission rates to the atmosphere have never been regulated by the territorial or federal governments.

Sulphur dioxide has been emitted from gold roasters along with arsenic over the years but never received the attention as an environmental contaminant that arsenic did.  $\text{SO}_2$  emissions in Yellowknife have never been controlled and there are no territorial or federal regulations in place to limit emission rates.

### Roaster Stack Emission Rates

Arsenic emission rate measurements are available since 1949 and show that emission rates have been reduced over the years as a result of the voluntary control programs implemented by the mines. It is considered that total arsenic emission rates from the Royal Oak roaster stack at the present time fluctuate but are generally in the range of 20 to 30 kg/day. At these emission rates, the removal efficiency of the baghouse and electrostatic precipitator is about 99%.

$\text{SO}_2$  emission rates during the earlier years of mine operation are not available. Table 3 shows the results of 4 stack tests conducted at the Royal Oak roaster stack since 1983, including 2 tests conducted under contract to the Department in 1991. It is considered that  $\text{SO}_2$  emission rates fluctuate and are now in the range of 50 to 65 tonnes/day.

### Arsenic and $\text{SO}_2$ in the Environment

Snow surveys and other deposition studies in the 1970's showed that the highest total arsenic levels were found closest to the mine and led Hazra and Prokopuk (1977) to conclude that the Giant mine roaster stack was the main source of arsenic emissions to the ambient air.

In 1986, Stanley and Associates Eng. Ltd. found that the highest arsenic levels in snow continued to be close to the mine but levels were considerably lower than levels reported in the 1970's.

Total arsenic levels measured in downtown Yellowknife air have declined since the 1970's (see Figure 2). Lower total arsenic levels in the 1980's follow improvements to emission controls made at the mine in the late 1970's. The slightly higher levels detected in 1988 correspond with baghouse operation difficulties in that year. A further decline in levels measured in the 1990's correspond with operational improvements at the mine made after 1988. Total arsenic levels in Yellowknife air have remained at levels well below the Ontario 24 hour limit of  $0.3 \mu\text{g}/\text{m}^3$  since 1988.

As the emission plume from the roaster stack is carried downwind, it begins to disperse and mix into the atmosphere so that pollutant levels on the ground decrease with distance. Terrain influences, different weather conditions typically associated with each wind direction and seasonal changes in the weather affect dispersion patterns of  $\text{SO}_2$ .

$\text{SO}_2$  levels on the ground are low up to about 0.5 km away from the 45 metre high roaster stack. The lead candle network, with all sampling sites located within 4 km of the mine, showed that the highest annual average levels occurred between about 0.5 to 0.7 km and it is believed that it is in this range where the emission plume begins reaching the ground. The diffusion plate network showed that to the south and the southwest the peak  $\text{SO}_2$  levels were at about 0.5 to 0.7 km and levels decreased rapidly beyond that distance. The pattern to the north was quite different. Levels to the north did not peak until about 2 km away from the roaster stack and higher levels persisted over a greater distance. The different dispersion patterns are most likely due to wind and stability conditions.

Terrain characteristics affect the surface winds that carry  $\text{SO}_2$  and play a role in determining  $\text{SO}_2$  levels at any particular site. For example, the diffusion plate at 3 km north (station 5) of the roaster stack consistently had monthly readings that were lower than the plates at 4 and 5 km north (stations 6 and 7). The number of diffusion plates in this survey was too sparse to fully describe the influence terrain is having on  $\text{SO}_2$  levels.

The deposition plate network showed that higher  $\text{SO}_2$  levels persisted a greater distance from the mine to the north than in other directions. Winds from the south cross Great Slave Lake before reaching Yellowknife and the Royal Oak mine. After travelling over the flat surfaces of lakes, winds close to the surface tend to be "smoother" than winds from other

directions that travel over the rougher surface of the Precambrian Shield. It may be that the smoother, less turbulent surface winds coming off the lake from the south do not mix the roaster stack plume with fresh, unpolluted air as quickly, and could account for the higher SO<sub>2</sub> levels measured at greater distances to the north of the mine.

Seasonal differences in SO<sub>2</sub> levels were evident from both the lead candle and diffusion plate networks. During the warmer months levels in all directions tend to be higher. This phenomena was also predicted by the ADEPT2 model. The plume rising from the roaster stack is at 80-90° C. It is postulated that when the plume enters cold winter air it rises higher and then disperses into winds at higher elevations. The plume is not carried as high when it enters warmer air so that in the summer, less SO<sub>2</sub> is carried away by higher elevation winds and more of the SO<sub>2</sub> reaches the ground in the vicinity of the minesite.

The occurrence of detectable levels of SO<sub>2</sub> measured by the continuous analyzer located in downtown Yellowknife were found to be episodic. Winds from 10° north carried higher average SO<sub>2</sub> levels than winds from any other direction. In wind from 10° north, SO<sub>2</sub> was detected 64 % of the time (compared to 30 % of the time for all directions). When winds were blowing from the north, SO<sub>2</sub> levels would rise from undetectable, peak and then drop back to undetectable levels. Although continuous monitoring was only conducted at one location, it is expected that this episodic pattern occurs in any direction downwind from the mine. The streak of browned leaves north of the mine identified by Forestry Canada as the result of an acute (high level) SO<sub>2</sub> fumigation event provides evidence that peak levels of SO<sub>2</sub> occur episodically in the Yellowknife area.

### **Causes of Vegetation Damage**

Analysis of vegetation samples conducted by Forestry Canada in 1990 and 1991 showed that SO<sub>2</sub> damage to trees was occurring along the Vee Lake Road at least as far away from the mine as 5 km. In 1990 damage caused by drought conditions was also evident and in 1991 insect damage was found on samples from some of the stations.

## CONCLUSIONS

Royal Oak Giant Yellowknife mine roaster stack emissions of arsenic are the most significant source of arsenic found in Yellowknife air. Since the late 1940's when operation of the roaster started, improvements have been made at the mine to control and reduce arsenic emission rates. At this time total arsenic emission rates are considered to be in the range of 20 to 30 kilograms per day.

Presently, total arsenic levels in Yellowknife air are below the Ontario 24 hour average limit of  $0.3 \mu\text{g}/\text{m}^3$ . Since 1978, exceedences of this level have only been measured on two occasions in 1988. Following the 1988 exceedences, total arsenic levels in Yellowknife decreased and have remained at an annual geometric mean level of less than  $0.01 \mu\text{g}/\text{m}^3$ . Continued maintenance and operation of arsenic emission control equipment remains of critical importance if the lower levels of arsenic in Yellowknife are to be sustained.

The Royal Oak Giant Yellowknife Mine roaster stack is the major source of  $\text{SO}_2$  in Yellowknife air. Presently,  $\text{SO}_2$  emission rates from the roaster stack are considered to be in the range of 50 to 65 tonnes per day. It was the only identified source contributing to  $\text{SO}_2$  levels found to the north of the mine. In Yellowknife to the south of the mine, the roaster stack is the major source of  $\text{SO}_2$  but there are also minor sources that contribute to detected background levels.

Continuous monitoring to the south of the mine in downtown Yellowknife using an  $\text{SO}_2$  analyzer showed that levels of  $\text{SO}_2$  in populated areas periodically exceed national air quality objectives when the wind blows from the north. Monthly average  $\text{SO}_2$  levels detected by the diffusion plate network indicate that elevated levels are also occurring in other directions. When elevated  $\text{SO}_2$  levels do occur these episodic events usually only last for a short period. Elevated  $\text{SO}_2$  levels are more likely during warmer months. To the north,  $\text{SO}_2$  is carried greater distances from the roaster stack than to the south.

Damage to trees from high levels of  $\text{SO}_2$  was found along the Vee Lake Road as far north of the roaster stack as 5 kilometres. This is within the range where elevated  $\text{SO}_2$  levels were measured.

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