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PLUME DISPERSION RESEARCH AT NATURAL-GAS SULPHUR-EXTRACTION PLANTS

G. K. Lee, H. Whaley and J. G. Gainer*
Canadian Combustion Research Laboratory
FUELS RESEARCH CENTRE
*Gulf Oil Canada Limited-Calgary, Alberta.

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PLUME DISPERSION RESEARCH AT NATURAL GAS SULPHUR EXTRACTION PLANTS[1]

by

G. K. Lee[2], H. Whaley[2] and J. G. Gainer[3]

ABSTRACT

The rise and dispersion have been determined for four plumes emitted by three natural-gas sulphur-extraction plants in Alberta. This report describes the data acquisition techniques employed and gives a preliminary evaluation of the results. At one plant, two plumes were studied, one under inversion conditions and the other under limited mixing conditions. One plume from each of the other two plants was studied under neutral conditions. The results indicate that the standard deviations of plume spread cannot be reliably estimated for limited mixing conditions and that plume behaviour is strongly influenced by local topography.

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[2] Research Scientists, Canadian Combustion Research Laboratory, Fuels Research Centre, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

[3] Senior Engineer, Exploration and Production Department, Gulf Oil Canada Ltd., Calgary, Alberta.

Direction des mines

Rapport de recherches R 265

LA RECHERCHE SUR LA DISPERSION DE FUMÉE EN FORME DE PLUME DES USINES D'EXTRACTION DE SOUFRE DU GAZ NATUREL*

par

G.K. Lee**, H. Whaley** et J.G. Gainer***

RÉSUMÉ

Les auteurs ont déterminé la montée et la dispersion de quatre émissions de fumée en forme de plume de trois usines d'extraction de soufre du gaz naturel. Dans ce rapport, ils décrivent les techniques employées dans l'acquisition des données et ils donnent aussi une évaluation préliminaire des résultats. A une des usines, les auteurs ont étudié deux émissions de fumée en forme de plume, une sous conditions d'inversion et l'autre sous conditions de mélange limité. Ils ont aussi étudié une émission de fumée en forme de plume de chacune de deux autres usines sous conditions neutres. Les résultats indiquent que les déviations normales d'étendue de fumée en forme de plume ne peuvent être évaluées avec certitude dans des conditions de mélange limité et la topographie influence fortement le comportement de la fumée en forme de plume.

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*Présenté à l'Association des producteurs canadiens de gaz naturel, Calgary, Alberta, le 2 mars 1973.

**Chercheurs scientifiques, Laboratoires canadien de recherches sur la combustion, Centre de recherche sur les combustibles, Direction des mines, ministère de l'Énergie, des Mines et des Ressources, Ottawa, Canada.

***Ingénieur supérieur, Département d'exploration et de production, "Gulf Oil Canada Ltd." Calgary, Alberta.

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INTRODUCTION

Historically, studies of the plumes generated by the sulphur incinerator stacks at sour gas plants in Alberta have been limited to:

(a) direct measurements of the source strengths based on temperature, exit velocity and contaminant concentration;

(b) both direct and indirect measurements of the ground level concentration at the points of impingement.

With the exception of some studies conducted with the aid of visible tracers, and the occasional natural trace suggested by water vapour during certain combinations of stack and atmospheric conditions, plume investigations have been limited to the head (source study) and tail (point of impingement) measurements listed above.

Using an aerial probing methodology, investigations were conducted at each of four plant sites to bracket, in so far as practicable, the influence of source strengths, meteorological conditions and topographic features encountered in central and southwestern Alberta on hot plume dispersion. Altogether, 19 studies were completed during the period April 17-27, 1972.

This report describes a technique for determining dynamic plume behaviour by direct measurement of the concentration and distribution of SO_2 in space and gives a preliminary evaluation of 4 of the 19 plume studies to show the effect of selected meteorological and topographical conditions on both plume rise and the standard deviations of plume spread.

DATA ACQUISITION

Scope

The four plume studies described in this report were conducted at three natural gas sulphur-extraction plants operated in Alberta by Gulf Oil Canada Limited. Two studies, conducted over hilly country around the Strachan Gas Plant on April 24th, show the contrast between atmospheric dispersion during an early morning inversion and limited mixing condition which had developed by midday. The other two studies, conducted under neutral conditions on April 25th and 27th respectively, compare the influence on plume behaviour of the flat terrain around the Rimbey Gas Plant and of the steep river valley adjacent to the Nevis Gas Plant.

Aerial Probing

Aerial probing of the plumes was done by means of a helicopter equipped to measure SO_2, temperature, pressure height and wet bulb depression continuously. The instrument package is shown in Figure 1, the sensing probe in Figures 2 and 3, and the flow system for the SO_2 analyzer is illustrated in Figure 4. During each flight, the location of the helicopter was accurately and continuously determined by a radar navigation system which measures the distance between a base unit on the helicopter and any two of four remote stations on the ground. Figures 5, 6, and 7 respectively show the base unit mounted on the helicopter, the distance measuring unit located in the cockpit, and a remote station on the ground. The sensing probe is mounted on the helicopter skid forward of any rotor downwash and clear of engine contrails as shown in Figure 8.

Each flight was planned to terminate within 2 hr 30 min of take-off, in order to minimize the influence of meteorological changes during the selected sampling period. In general, the following flight patterns were used to obtain quantitative data on plume characteristics:

1. temperature soundings were taken upwind and downwind of the main stack at each plant at the beginning and termination of each flight; upwind soundings consisted of climbing in a 200-m-dia helical path from 10 m to 1800 m above ground, whereas downwind soundings consisted of descending through the plume in a similar helical path from 1800 m to 10 m above ground at about 4 km downwind; the latter sounding, which also provided data on both the vertical plume boundaries and the concentration of SO_2 within the plume, assisted in determining the vertical limits for the crosswind traverses described below; and

2. three crosswind traverses were flown downwind of the main stack and essentially normal to the plume axis to determine the lateral and vertical spread of the plume; these traverses, which were flown at distances ranging from 0.3 km to 7 km from the main stack, consisted of a series of level passes through the plume at vertical intervals of 30 m to 200 m depending on the vertical spread of the plume.

Ground Traversing

Concurrently with the helicopter flights, an automobile equipped with instruments similar to those in the helicopter was used to traverse along highways and roads over areas of ground-level plume impingement.

Wind Measurements

Before and during each flight, pilot balloons were released at the plant site to measure wind speed and direction between ground surface and 1500 m up. Any significant changes in the wind gradient during a flight were communicated to the helicopter and the automobile via a field radio system.

DATA REDUCTION

Meteorological Conditions

Synoptic weather maps, supplied by the Atmospheric Environment Service, were used first to predict and subsequently to accurately assess the weather conditions during a study. The synoptic surface maps for the April 24 to 27, 1972 are shown in Figure 9.

On April 24th at Strachan, a low, centred in central British Columbia, resulted in south easterly winds at the surface. During the early morning, a ground-based inversion extended up to about 600 m. However, by midday, this had been partially destroyed by solar heating of the ground, leaving a ground-based neutral layer capped by an elevated inversion. By the evening of April 24th, the low had passed east of Alberta.

At Rimbey on April 25th, the winds aloft were from the west with a northerly component near the surface. The air was cooler than on April 24th with neutral conditions prevailing up to 800 m.

By April 27th a high over Montana and a low over northwestern British Columbia resulted in light winds at Nevis that were southwesterly aloft but variable near the surface. Near neutral conditions developed in the surface layer late in the morning after the break-up of a severe overnight inversion.

Plume Dispersion Measurements

Figure 10 (Table 1) summarizes the emission parameters and the atmospheric conditions that prevailed during each study. It also demonstrates the effectiveness of various atmospheric turbulence levels in promoting massive dilution of hot waste gases from stacks of adequate height. At Strachan, during poor dispersion conditions, the hot gases had been diluted by a factor of 2900 at 2.6 km downwind while, under favourable dispersion conditions at Rimbey, the stack gases had been diluted by a factor of 81,300 at 3.2 km downwind.

The vertical temperature gradients measured downwind of the source during each of the four studies are plotted in Figures 11, 14, 18, and 22 and the plan and side views of these plumes are shown in Figures 12, 13, 15, 16, 17, 19, 20, 21, 23, 24, and 25. Figures 17, 21 and 25 also include profiles of plume impingement as measured by ground-level traversing on April 24th, 25th, and 27th.

COMPARISON OF DERIVED AND EMPIRICAL DATA

The spatial location of the plume axis and the standard deviations of plume spread (σ_y and σ_z) for each plume were derived from spatial measurements of SO_2 by the method of finite differences(1). This numerical method, which eliminates errors due to arbitrary assumptions and subjective interpretations of data, yields plume rise and σ values based on the first and second moments of the total mass flow respectively about the y and z axes at given downwind distances; this procedure is outlined in Figures 26 and 27.

Plume Rise

Plume rise values, as determined by numerical analysis, are given in Figure 28 (Table 2) together with the corresponding values estimated by the Briggs equation(2).

During inversion conditions at Strachan, the plume axis tended to gradually decrease and approach the value predicted by the Briggs equation for stable conditions. However, at midday under limited-mixing conditions, the derived plume rise values tended to level off at downwind distances greater than 6 km, as would be expected for this situation.

In the case of neutral conditions, the plume rise values over flat terrain at Rimbey and the river valley topography at Nevis agreed reasonably well with the Briggs equation, particularly at downwind distances greater than 1 km.

Standard Deviations of Plume Spread

The standard deviations of plume spread, σ_y and σ_z, derived from the four plumes studied are plotted in Figure 29 together with the curves for the Pasquill stability classes that fall closest to the plotted points. The Pasquill stability classes, which range from A (extremely unstable) to F (moderately stable), provide an estimate of the lateral and vertical spread of a plume under various degrees of atmospheric turbulence.

During the early morning inversion at Strachan, the fairly wide but thin plume was transported downwind for a considerable distance without any indication of impingement on the gradually receding terrain. As shown in Figure 29 (a), the derived σ_y and σ_z values for this plume fall closest to stability Classes C and F respectively. Therefore, this plume was much wider than would be estimated by assuming Class F stability for a moderately stable atmosphere.

Under the limited-mixing conditions that persisted during the midday study at Strachan, the elevated inversion prevented upward dispersion and resulted in an extremely wide plume having a derived σ_y value that was slightly greater than Class A stability. At the same time, vertical turbulence throughout the 600 m thick mixing layer produced ground-level plume impingement close to the source and, as shown in Figure 29 (b), the derived σ_z value for the plume was almost constant; this effect is consistent with a limited-mixing height.

Neutral conditions fall in the C to D stability range of Pasquill. However, under the neutral conditions at both Rimbey and Nevis the derived σ_y values were roughly equivalent to Class A stability, as shown in Figure 24 (c) and 29 (d). These large values of σ_y can be attributed to the line-source effect of the main stack and the flare stack, which at both sites, was off-parallel to the wind direction. The derived σ_z values for the Rimbey plume, at distances greater than 2 km, corresponded to Class C stability as shown in Figure 29 (c), but, close to the source, the exceptionally deep vertical spread of the plume was probably caused by merging of the waste gas emissions from the flare stack with those from the higher main stack. On the other hand, the derived σ_z value close to the source at Nevis, Figure 29 (d), was in the C stability range, but, at distances greater than 1 km, the vertical spread of the plume was greatly increased by winds being deflected upward by the steep river bank upwind from the plant. This situation resulted in (a) abnormally high values of σ_z which showed fair agreement with Class B stability and (b) very low ground-level concentrations of SO_2, as shown in Figure 21.

SUMMARY

1. In all four plumes, massive dilution of the stack gases occurred within 3 km of the source. Even under stable (inversion) conditions while dispersion was poor, the stack gas concentration had decreased by a factor of 2900 at 2.6 km downwind.

2. The derived plume rise values showed good agreement with the Briggs equations for stable and neutral conditions. For limited-mixing conditions, the plume tended to level off at a constant height.

3. The lateral plume spread, in each of the four cases, was much wider than would be estimated from empirical data.

4. The vertical plume spread was strongly influenced by both the flare stack emissions and topographic effects close to the source; however, farther downwind ($>$ 3 km) atmospheric stability had a major effect.

REFERENCES

1. Whaley, H., The Derivation of Plume Dispersion Parameters from Measured Three-Dimensional Data, Department of Energy, Mines and Resources, Mines Branch Research Report R 254, 1972.

2. Briggs, G. A., Plume Rise, USAEC TID 25075, 1969.

ACKNOWLEDGEMENT

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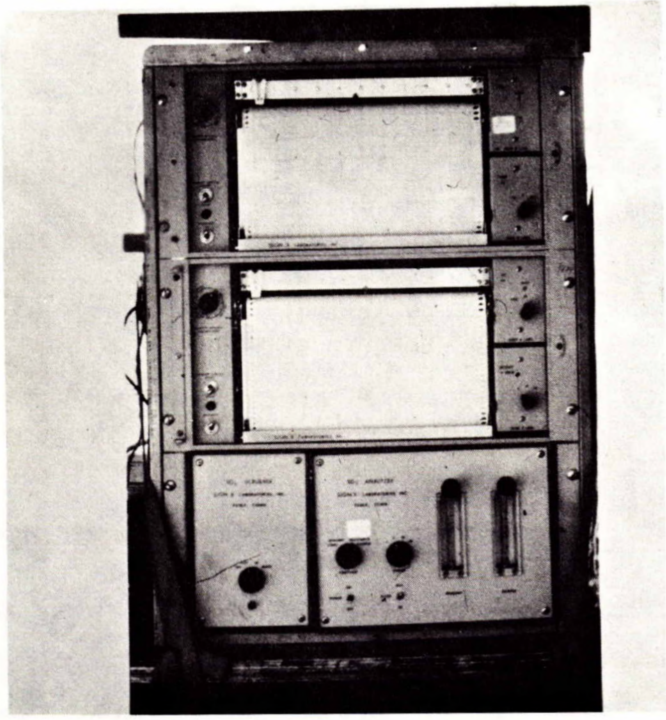
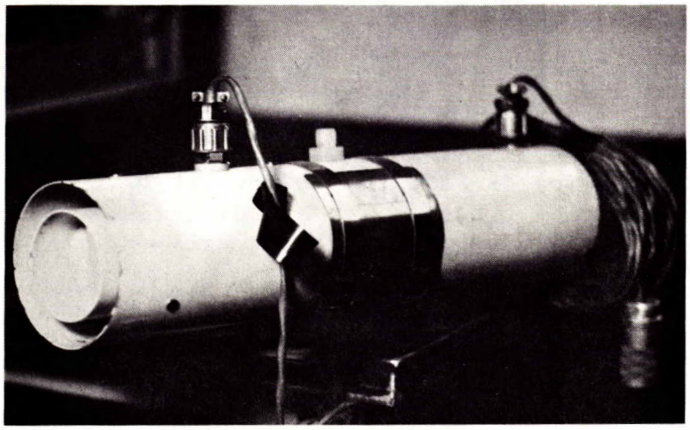
Gulf Oil Canada Limited would further recognize the assistance of R. H. Holbrook of the Atmospheric Environment Service of Environment Canada, and O. Johnson of Defense Research Board - Suffield, in the acquisition of meteorological data throughout the 21-day survey period.



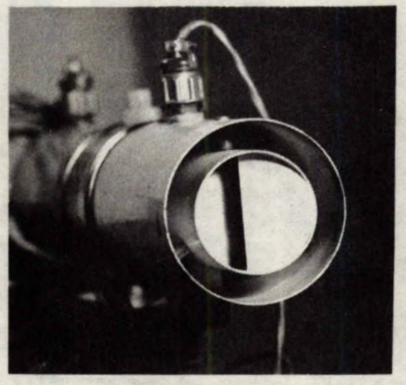
Air quality and meteorological instrument package installed in helicopter.

FIGURE 1

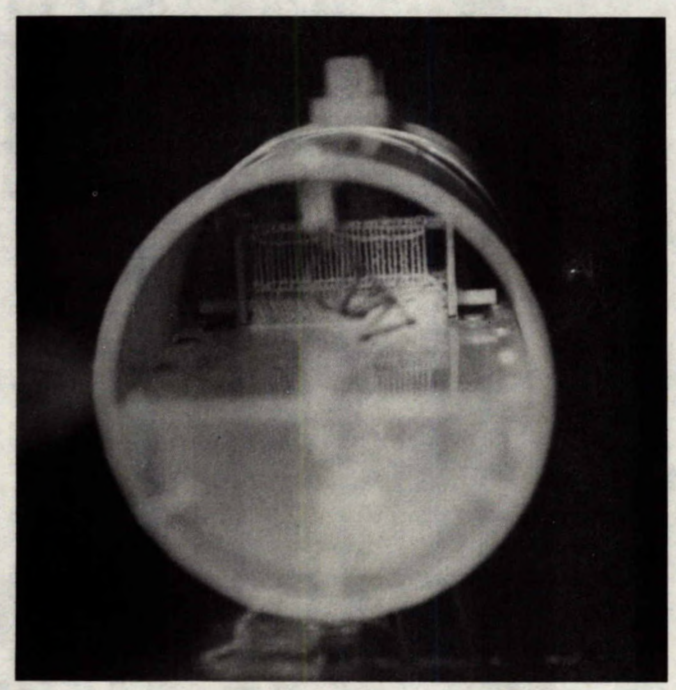


Sensing probe showing connections for temperature dewpoint depression and SO_2 sample inlet.

FIGURE 2



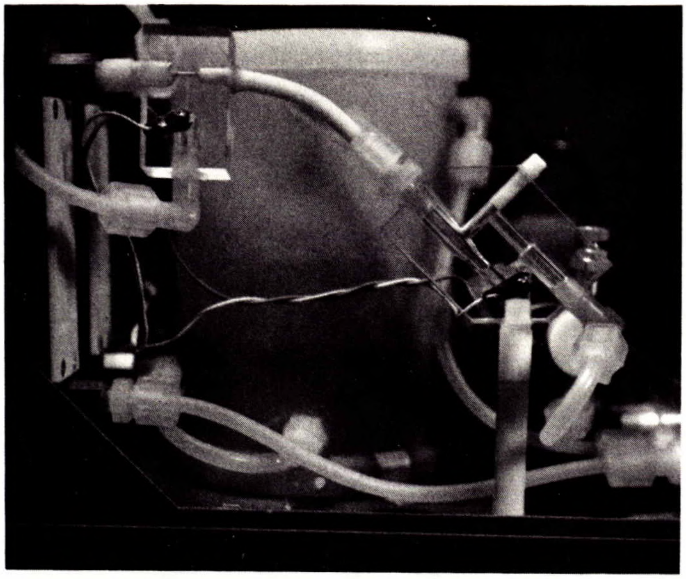
(a) Front view showing baffled air inlet and concentric shields.



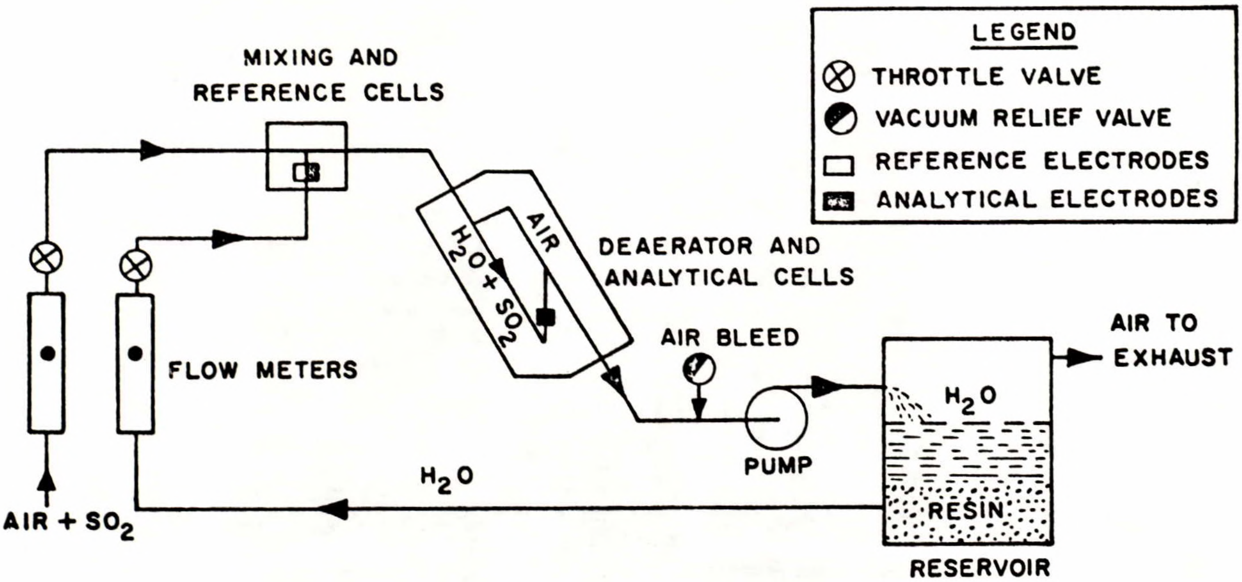
(b) Rear view showing dewpoint depression thermopiles and distilled water reservoir.

End views of the 3 x 12-in. sensing probe.

FIGURE 3



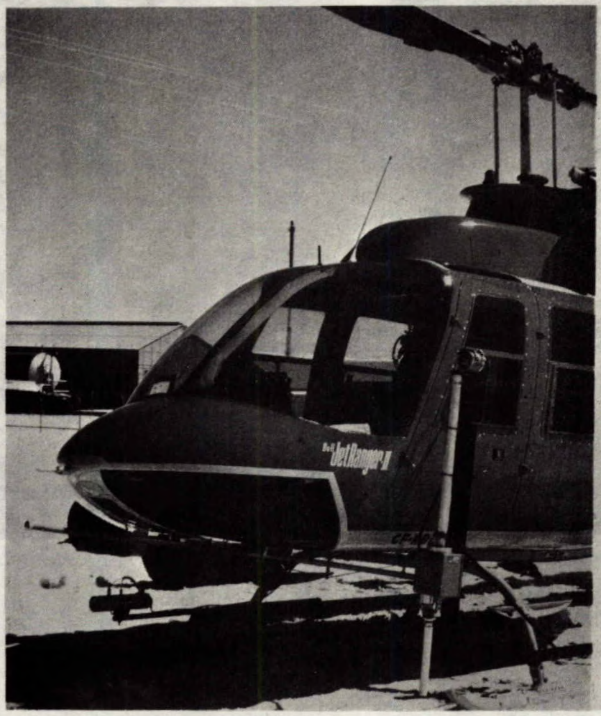
(a) Pictorial view.



(b) Flow diagram.

SO_2 analyzer.

FIGURE 4

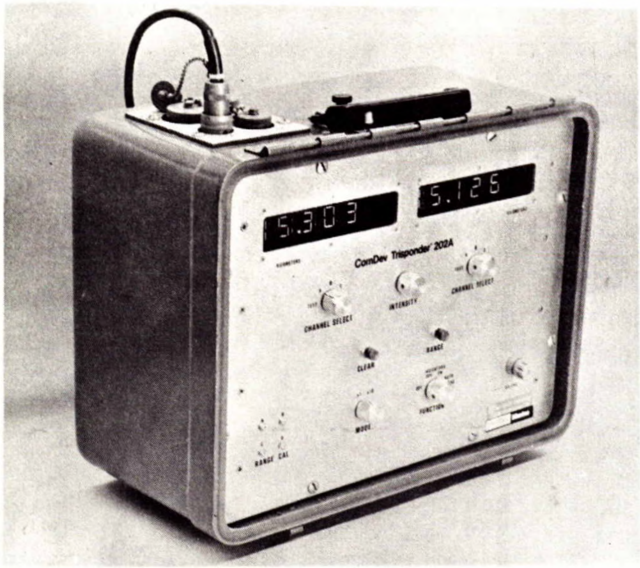


(a) Landing position.

(b) Flight position.

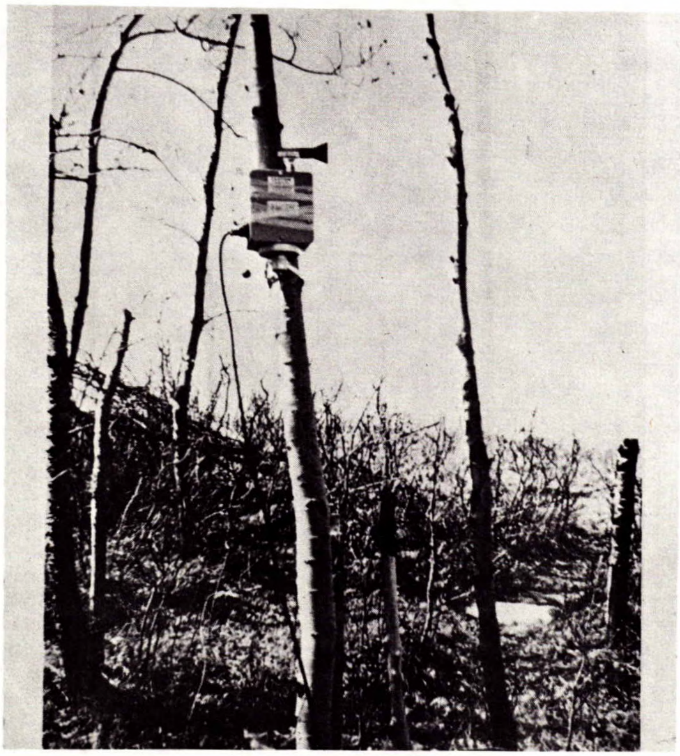
Radar base unit mounted on helicopter undercarriage.

FIGURE 5



Distance measuring unit of radar navigation system.

FIGURE 6



Fixed remote radar beacon.

FIGURE 7

HELICOPTER PROFILE SHOWING LOCATION OF INSTRUMENTS

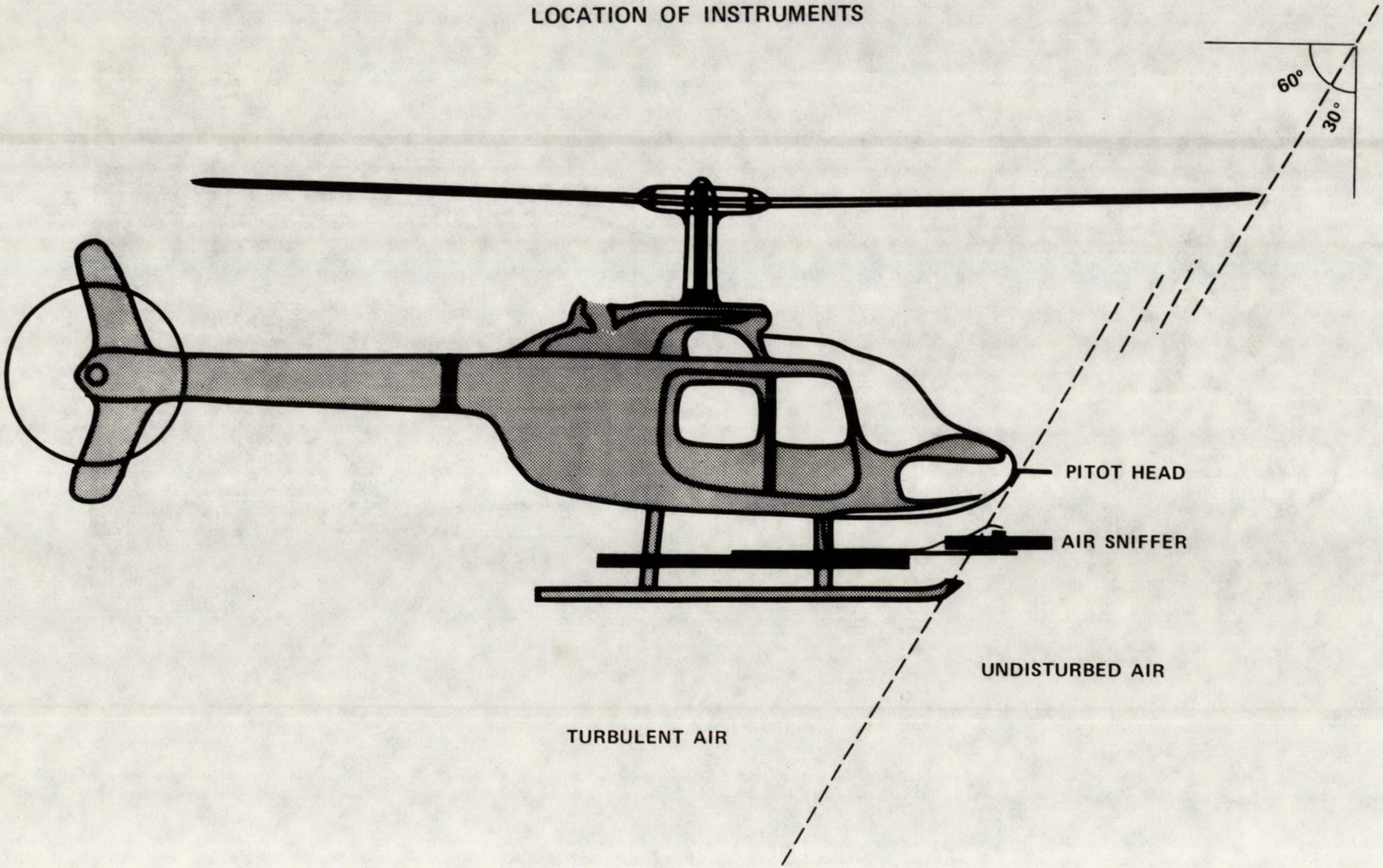
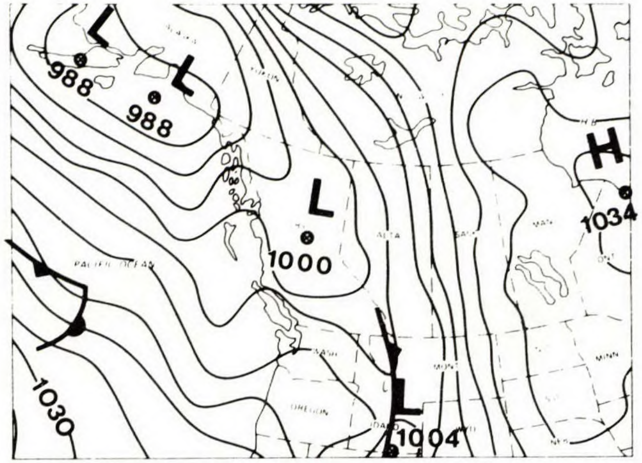
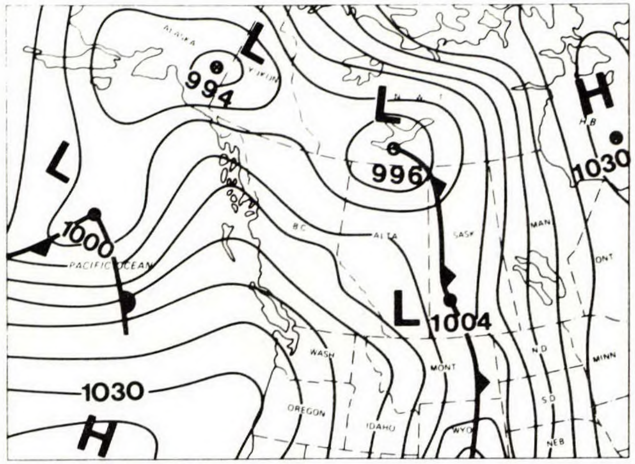


FIGURE 8

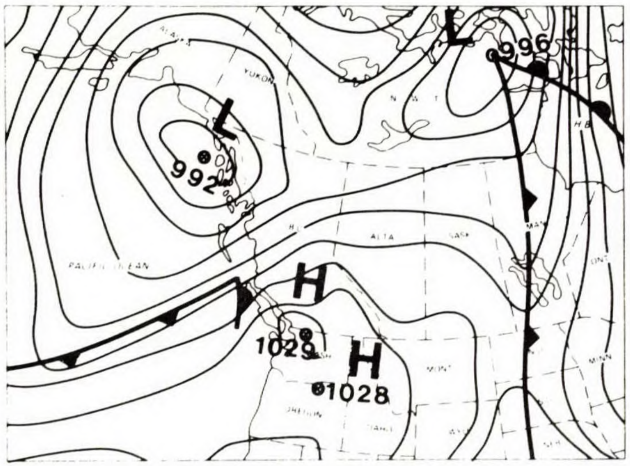
APRIL 24th 1972



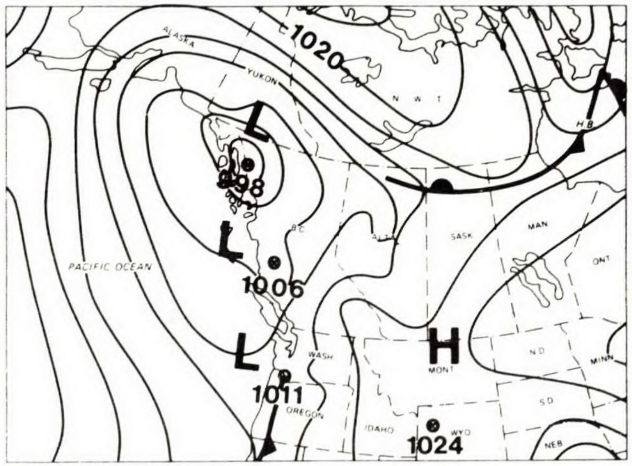
APRIL 25th 1972



APRIL 26th 1972



APRIL 27th 1972



SYNOPTIC WEATHER MAPS

SURFACE ANALYSIS 1100 MST

FROM DATA BY CENTRAL ANALYSTS OFFICE ENVIRONMENT CANADA

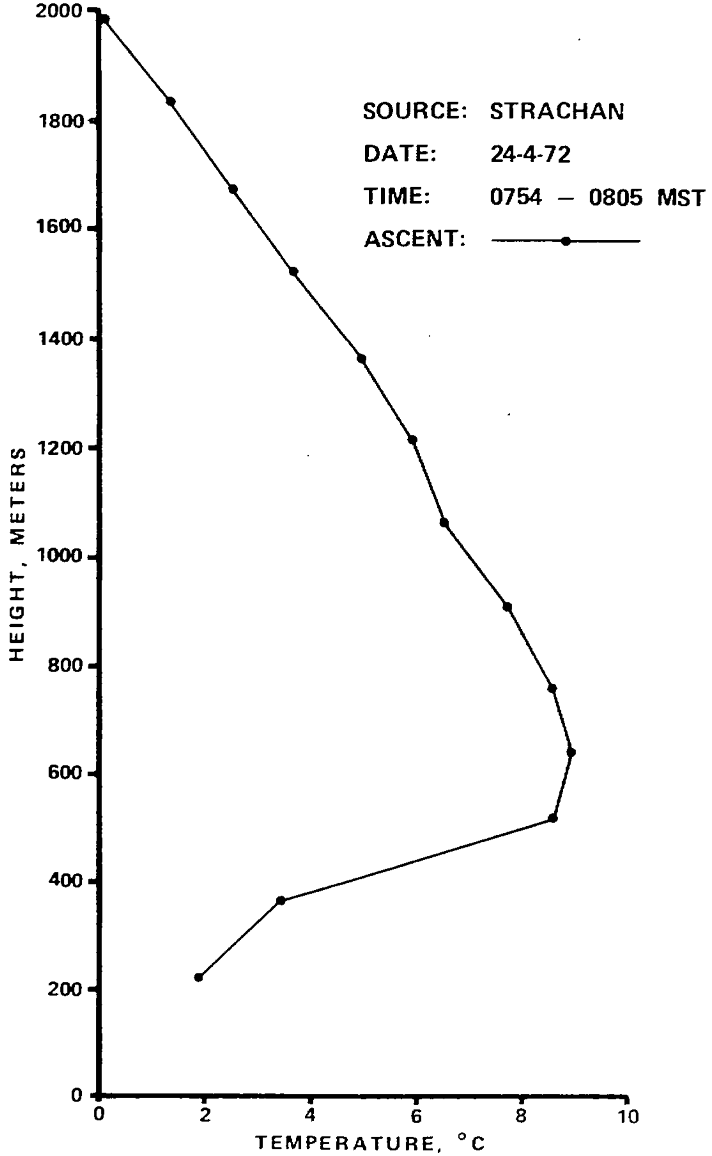
FIGURE 9

TABLE 1

SOURCE DATA AND ATMOSPHERIC CONDITIONS

Date Time MST	Source Stack Ht. m	Sulphur Emission ppm	Mean Wind		Elevation of Atmospheric Layers, m	dT/dz °C/100 m	Minimum Plume Dispersion
			Speed m/s	Direction deg			
24-4-72 0805 to 0926	Strachan 135	7,900	9.3	155	0 - 550	+ 2.2 Inversion	2,900 x @ 2.6 km
1126 to 1250	Strachan 135	4,400	9.2	145	0-560 560-760	− 0.9 Neutral + 0.2 Isothermal	7,000 x @ 3.1 km
25-4-72 1021 to 1203	Rimbey 66	13,000	6.0	310	0-1000	− 0.9 Neutral	81,300 x @ 3.2 km
27-4-72 0955 to 1054	Nevis 101	8,250	5.2	202	0-1000	− 0.9 Neutral	37,500 x @ 2.1 km

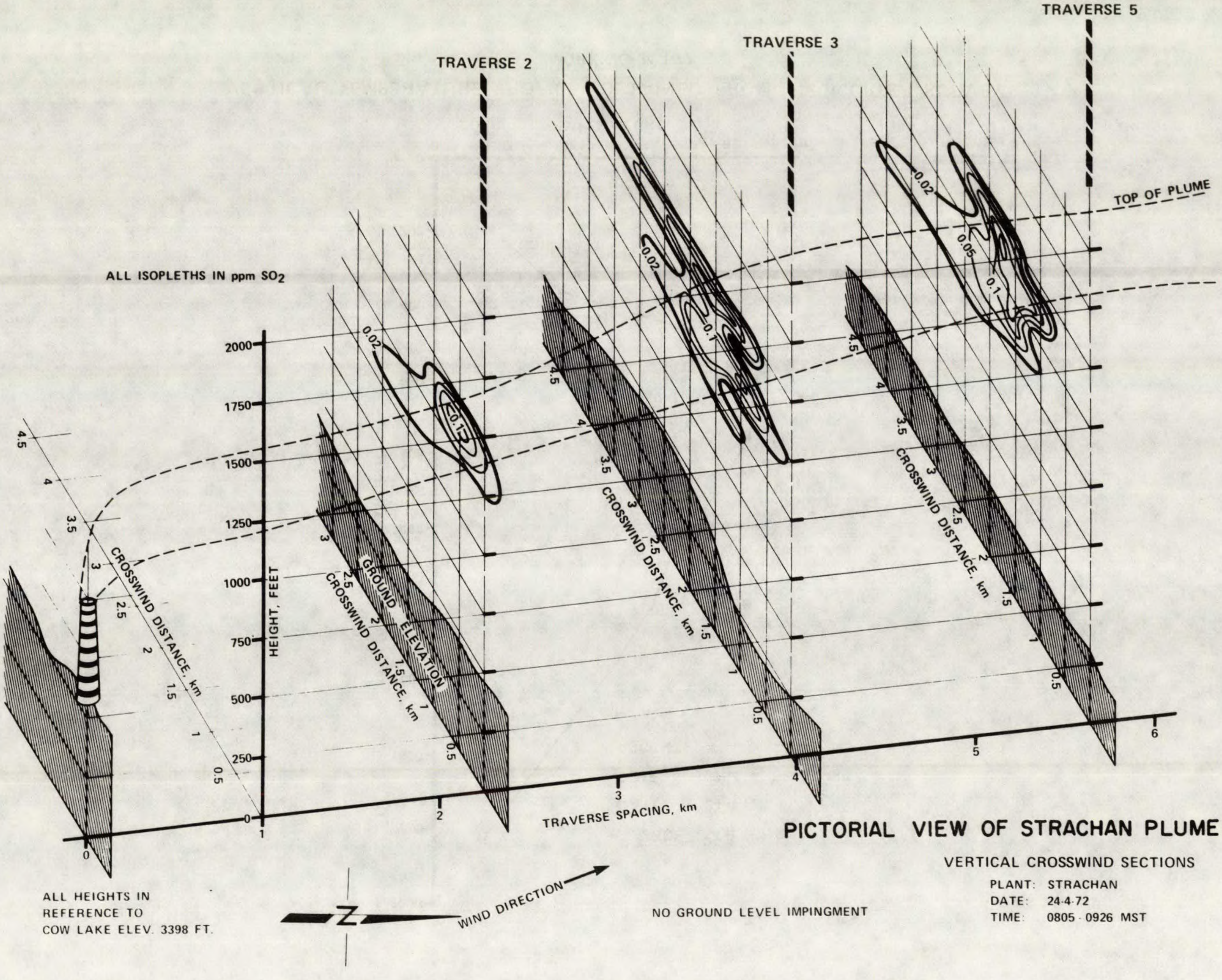
FIGURE 10



VERTICAL TEMPERATURE PROFILE OBTAINED FROM HELICOPTER SURVEY

MORNING 24-4-72

FIGURE 11

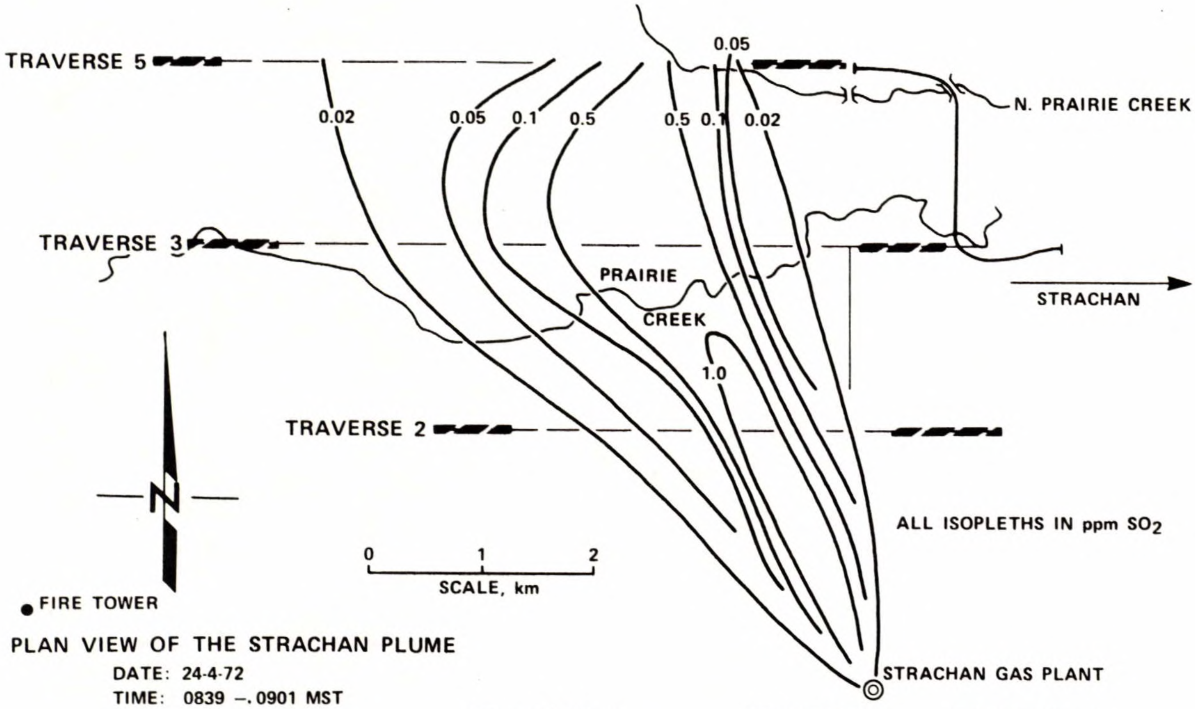


PICTORIAL VIEW OF STRACHAN PLUME

VERTICAL CROSSWIND SECTIONS

PLANT: STRACHAN
DATE: 24-4-72
TIME: 0805 - 0926 MST

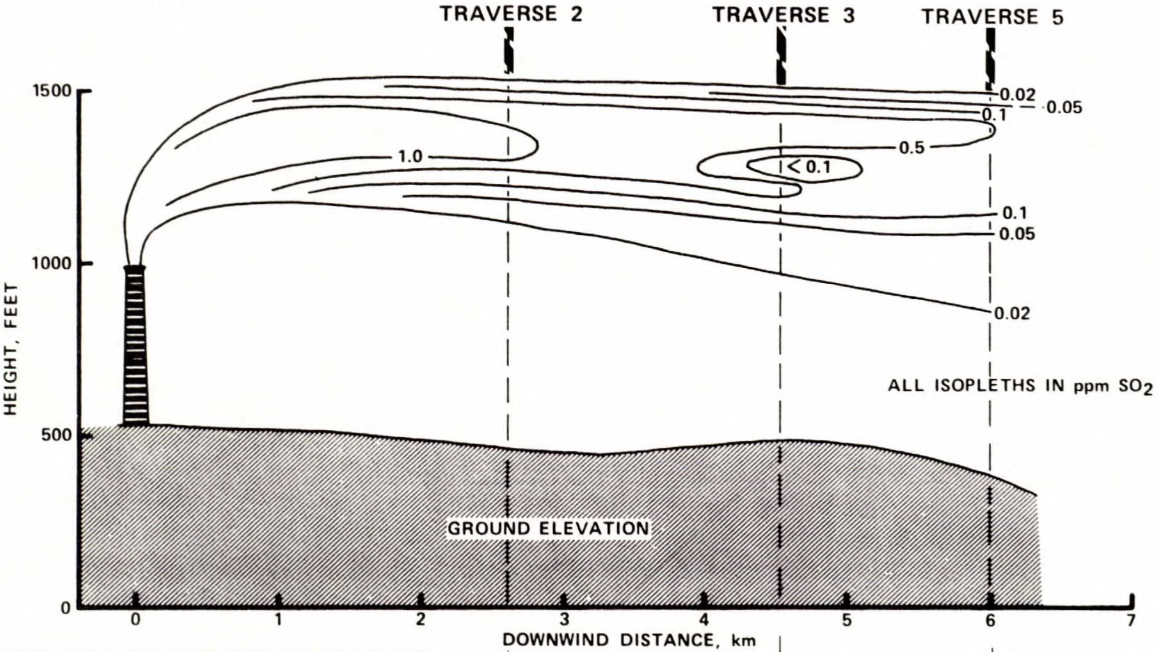
FIGURE 12



PLAN VIEW OF THE STRACHAN PLUME

DATE: 24-4-72

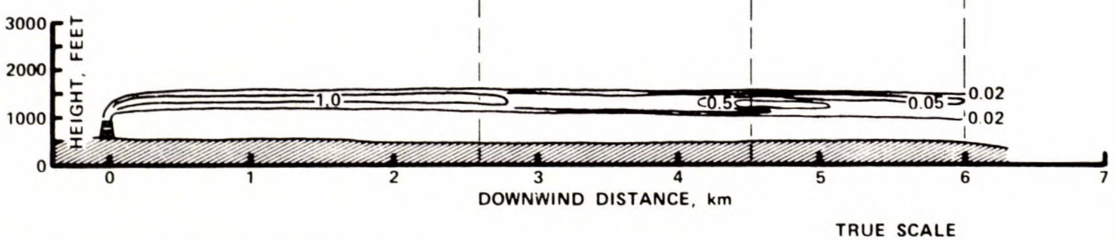
TIME: 0839 –. 0901 MST



SIDE VIEW OF THE STRACHAN PLUME

DATE: 24-4-72

TIME: 0839 – 0901 MST

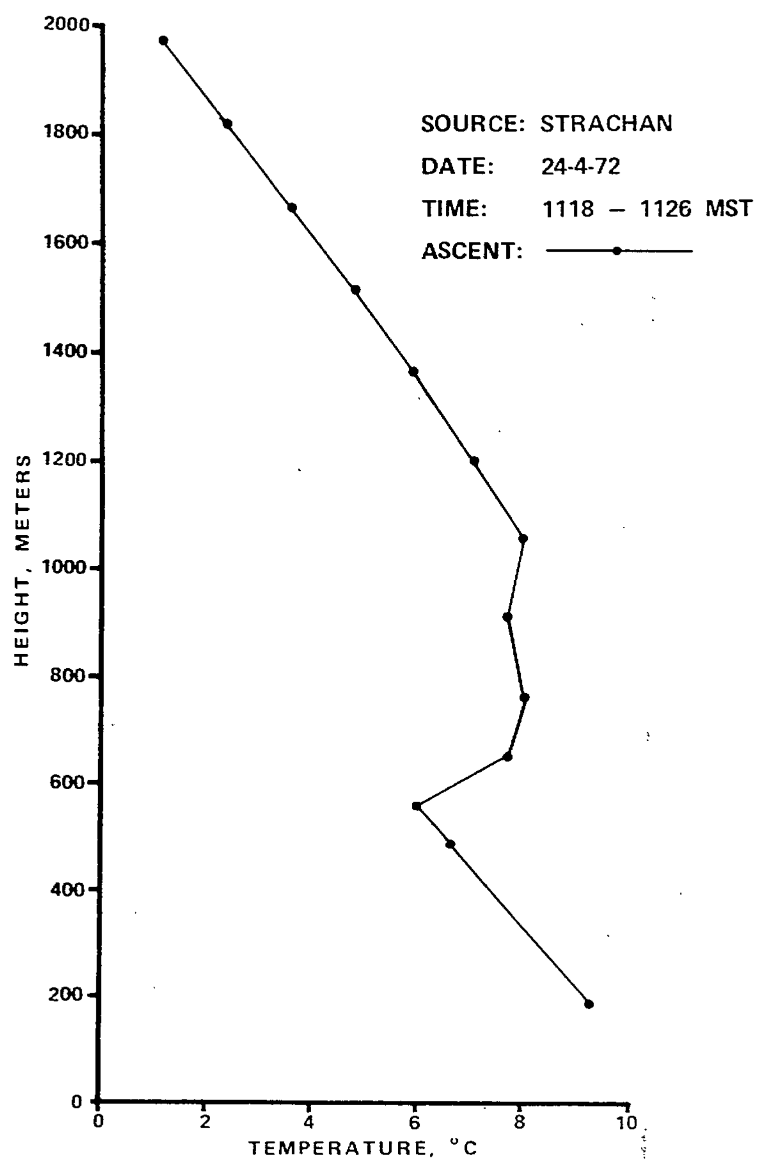


SIDE VIEW OF THE STRACHAN PLUME

DATE: 24-4-72

TIME: 0839 – 0901 MST

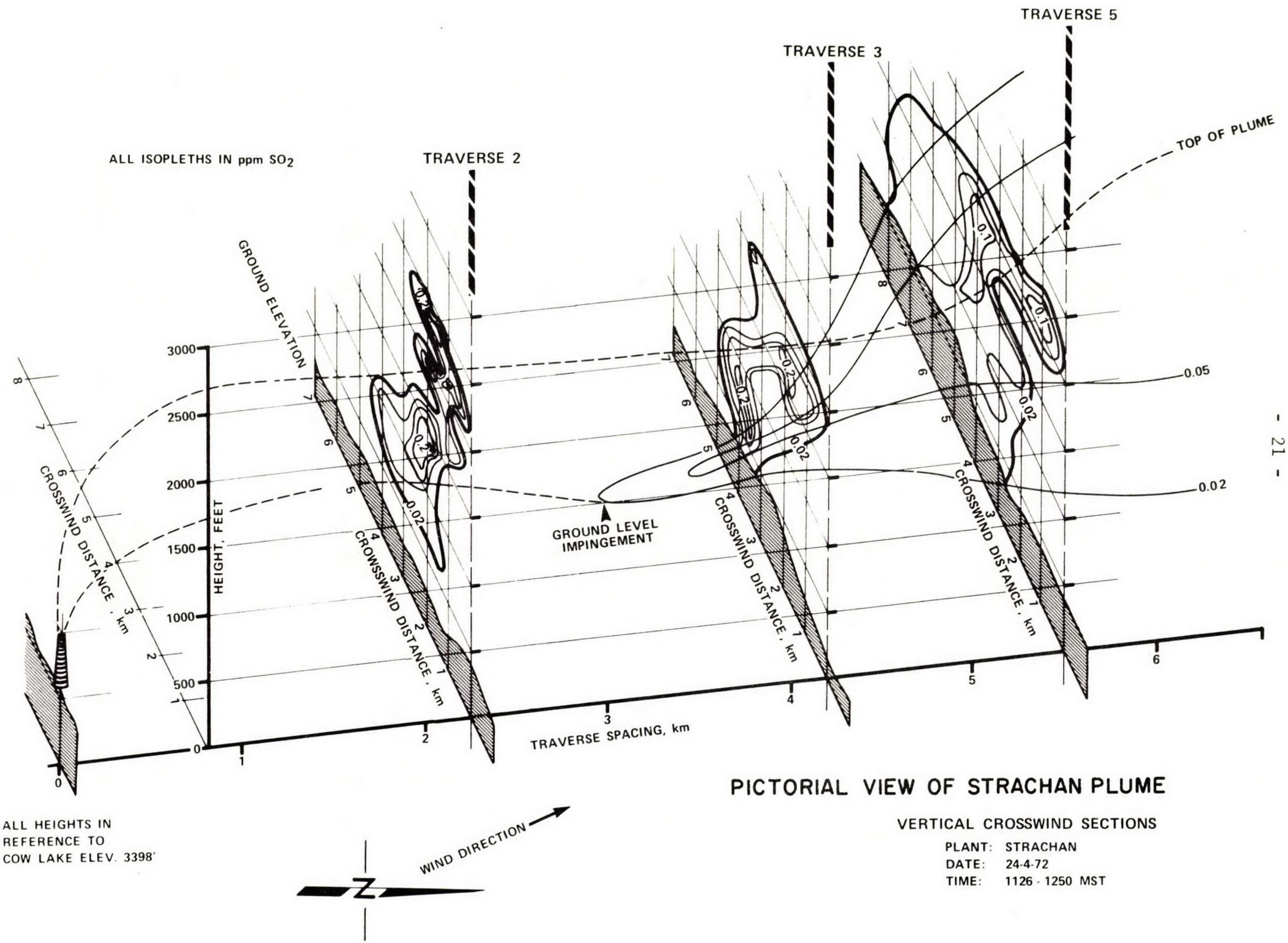
FIGURE 13



VERTICAL TEMPERATURE PROFILE OBTAINED FROM HELICOPTER SURVEY

MIDDAY 24-4-72

FIGURE 14



PICTORIAL VIEW OF STRACHAN PLUME

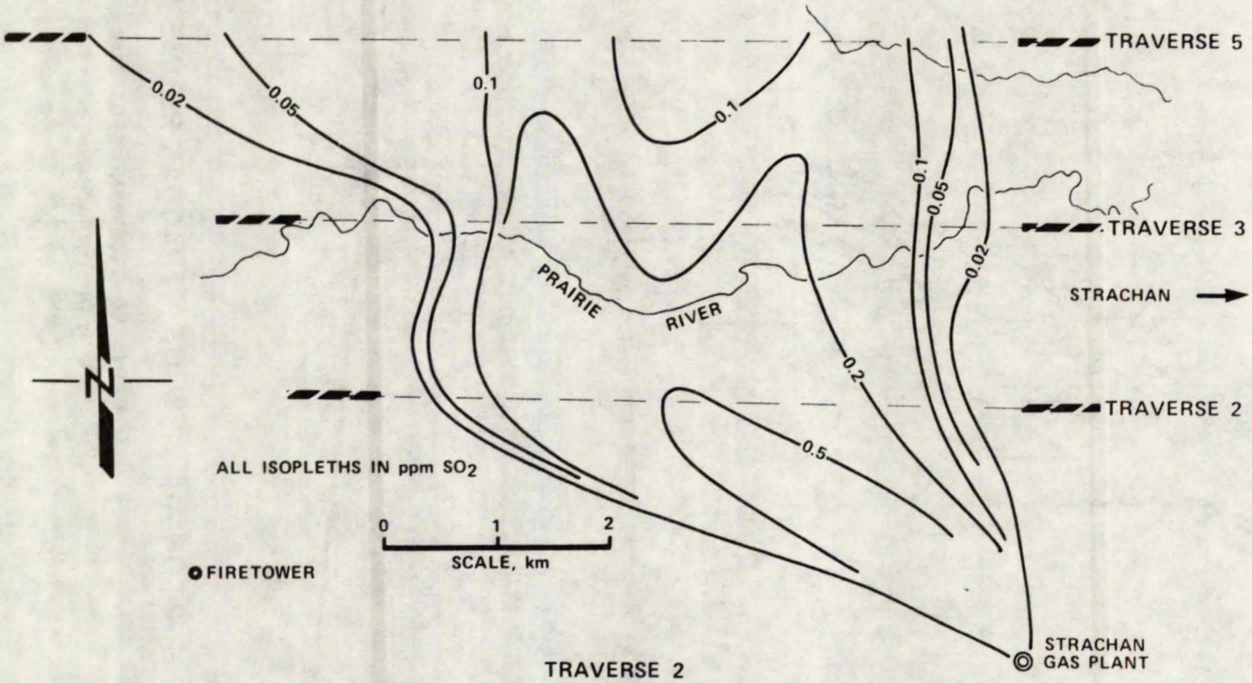
VERTICAL CROSSWIND SECTIONS

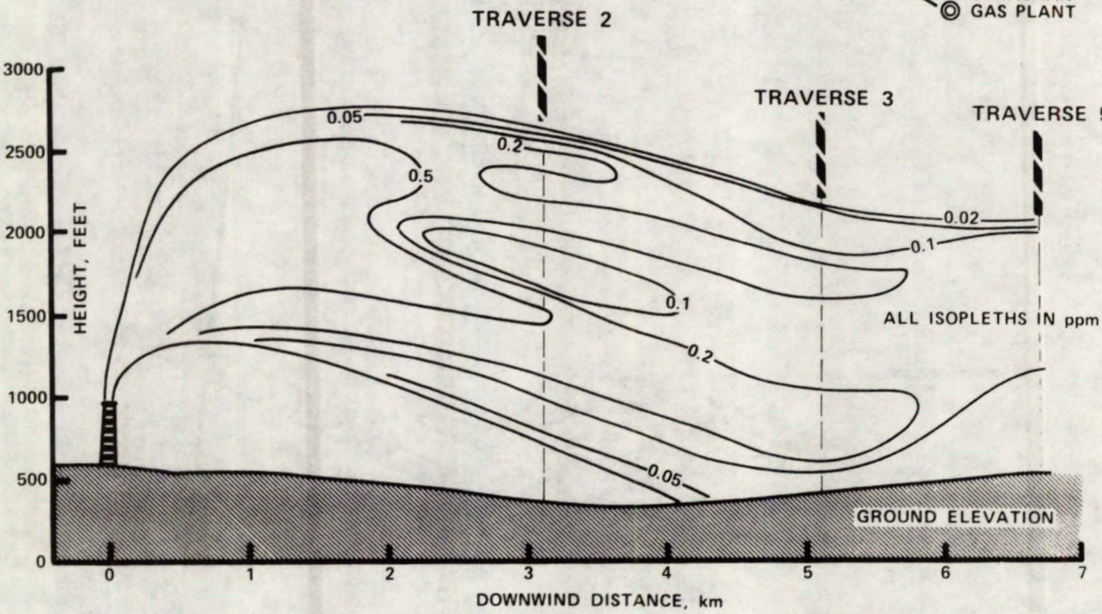
PLANT: STRACHAN
DATE: 24-4-72
TIME: 1126 - 1250 MST

FIGURE 15

PLAN VIEW OF THE STRACHAN PLUME

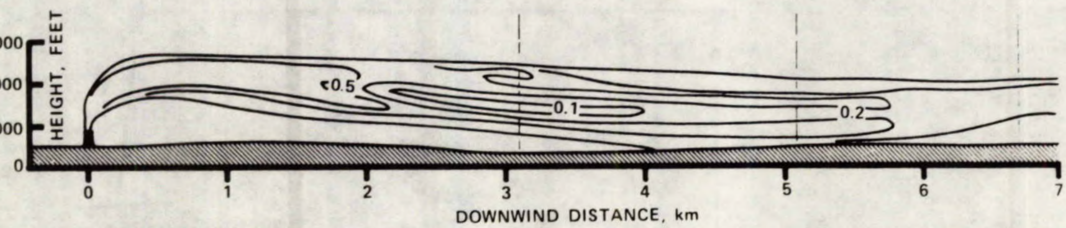
DATE: 24-4-72
TIME: 1126 – 1250 MST





SIDE VIEW OF THE STRACHAN PLUME

DATE: 24-4-72
TIME: 1126 – 1250 MST



SIDE VIEW OF THE STRACHAN PLUME

TRUE SCALE

DATE: 24-4-72
TIME: 1126 – 1250 MST

FIGURE 16

PLAN VIEW OF THE STRACHAN PLUME

DATE: 24-4-72
TIME: 1126 – 1250 MST

AREA OF GROUND-LEVEL PLUME IMPINGEMENT

DATE: 24-4-72
TIME: 1126 – 1150 MST

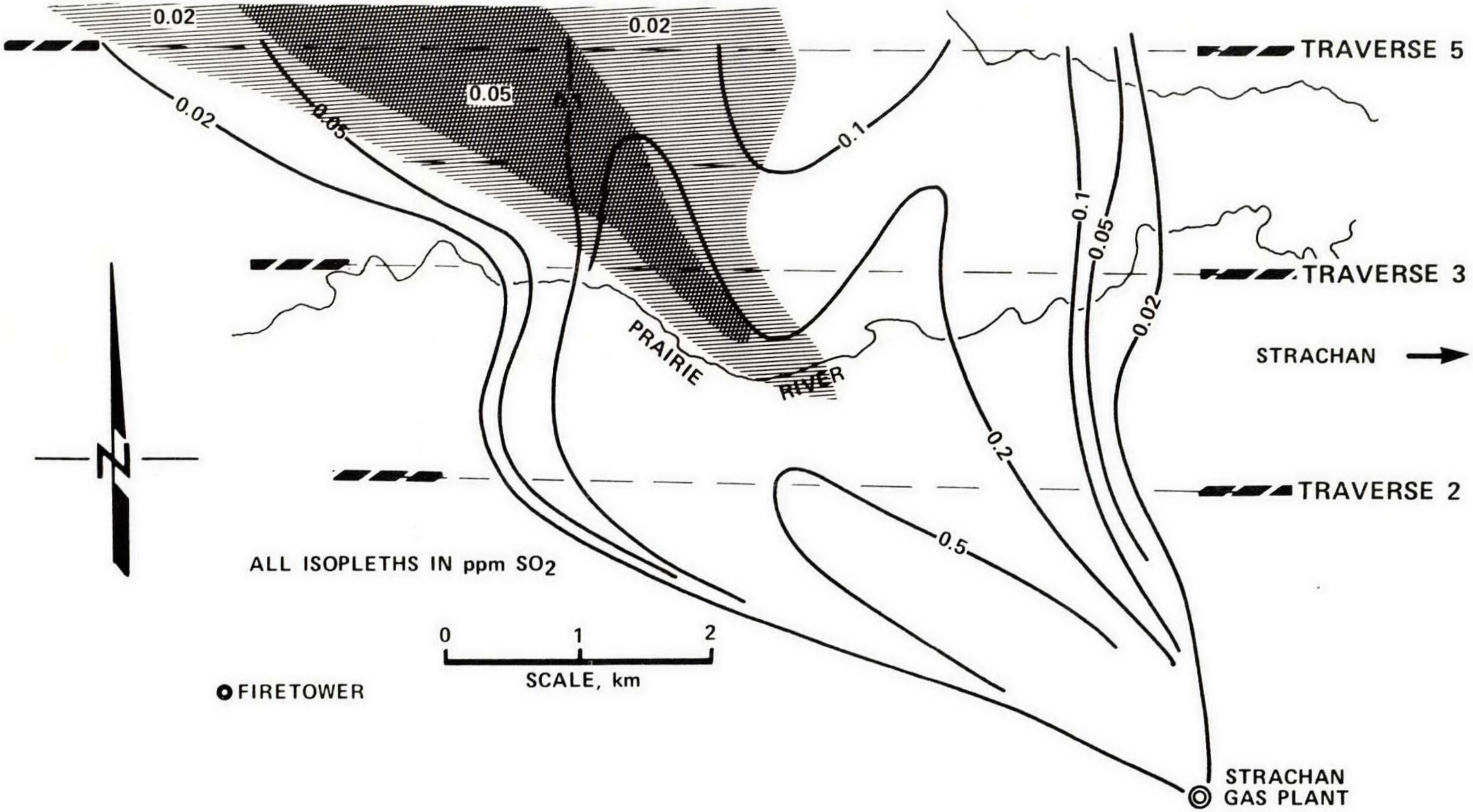
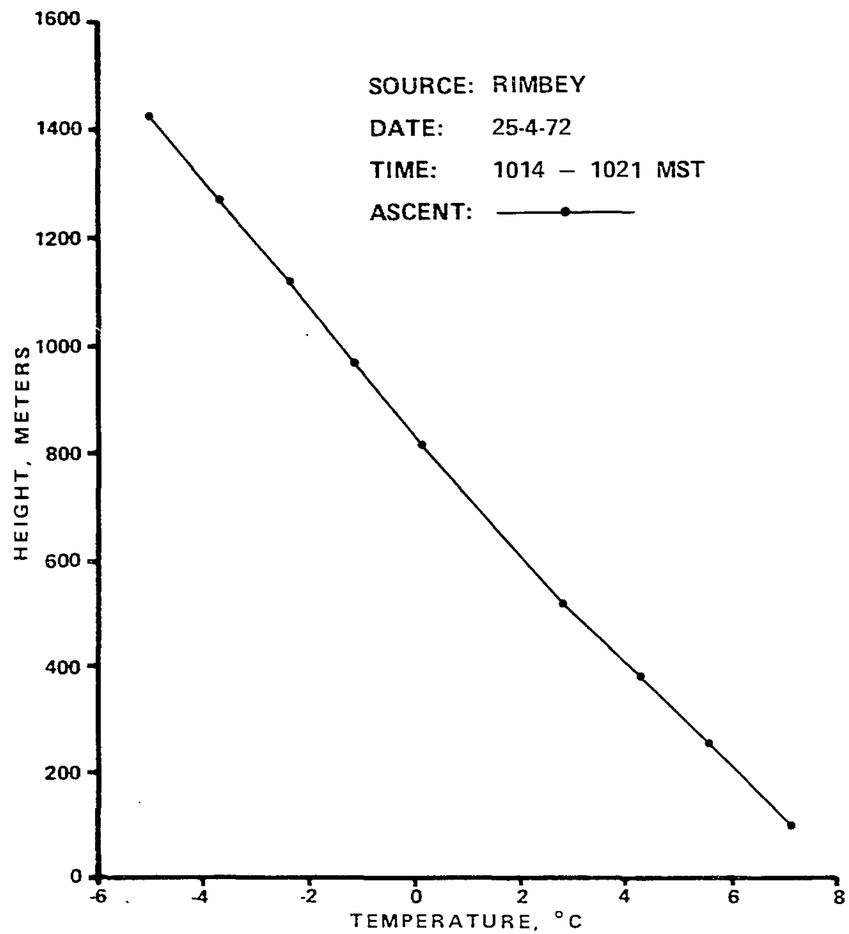


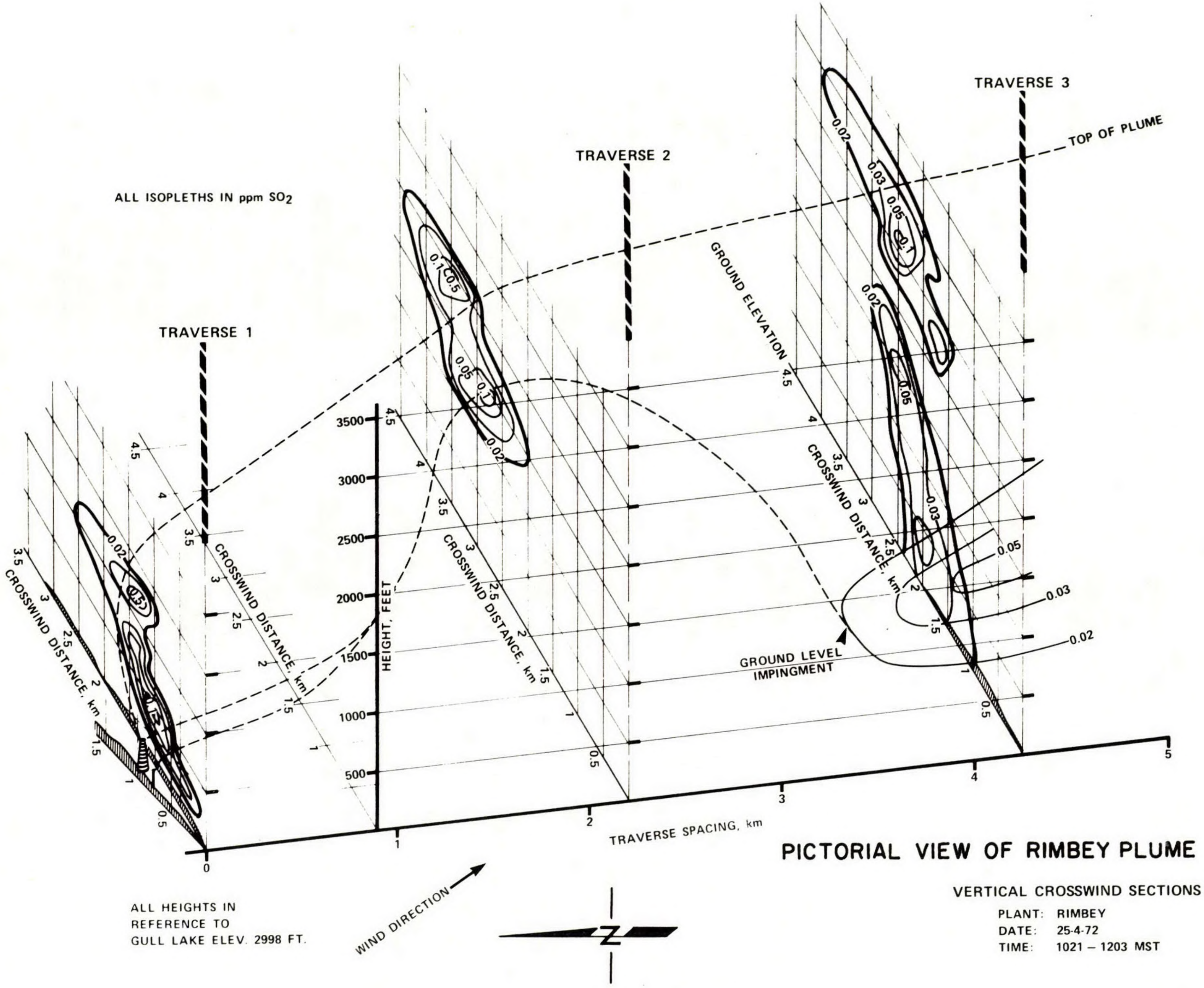
FIGURE 17



VERTICAL TEMPERATURE PROFILE OBTAINED FROM HELICOPTER SURVEY

MORNING 25-4-72

FIGURE 18



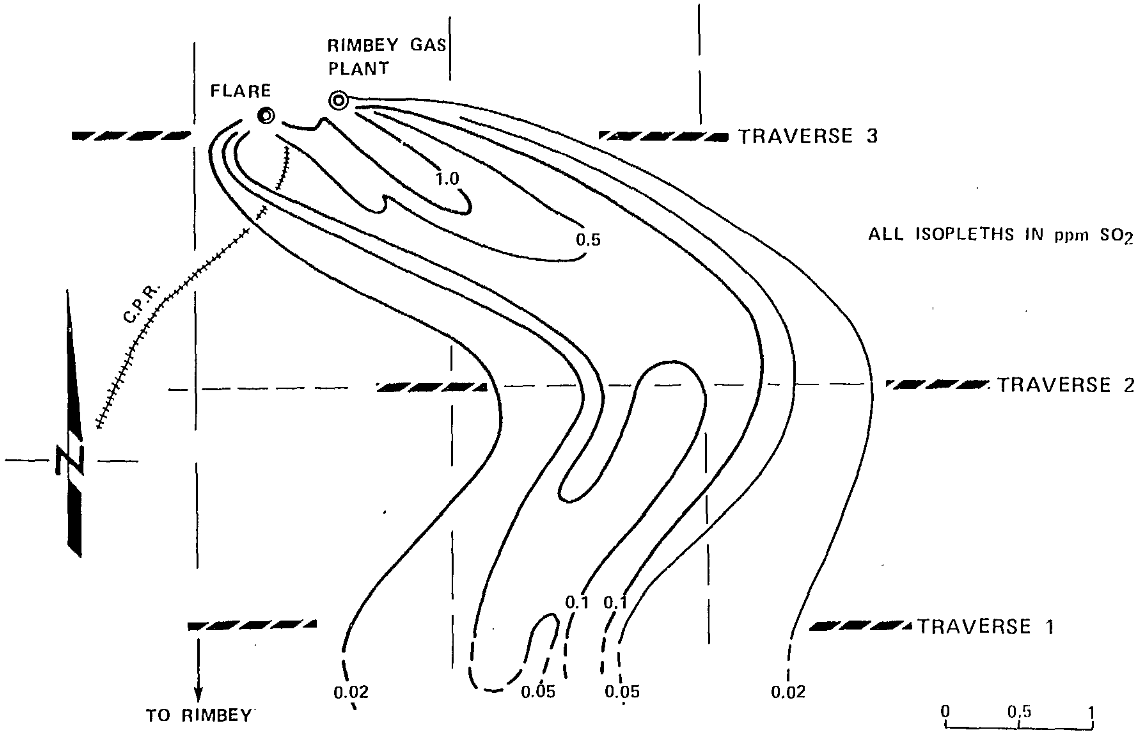
ALL HEIGHTS IN
REFERENCE TO
GULL LAKE ELEV. 2998 FT.

PICTORIAL VIEW OF RIMBEY PLUME

VERTICAL CROSSWIND SECTIONS

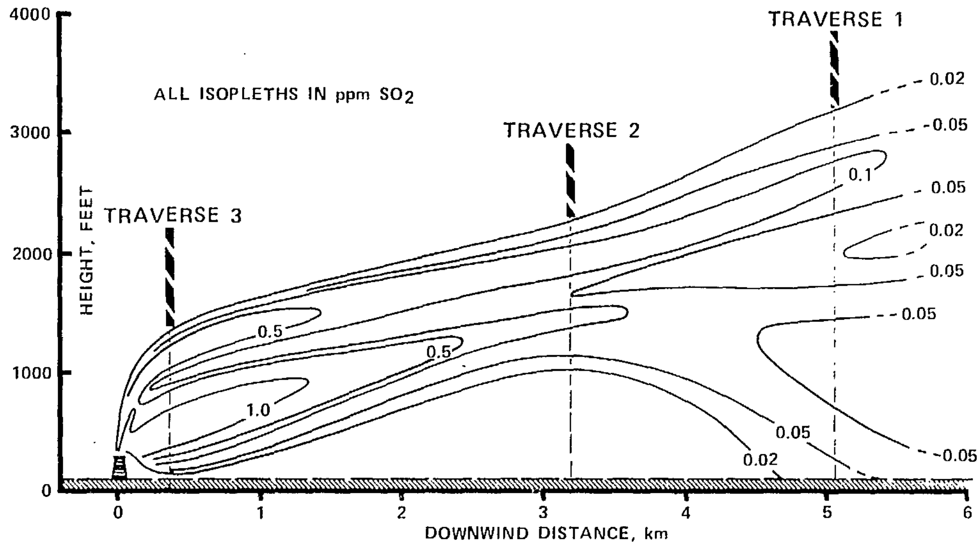
PLANT: RIMBEY
DATE: 25-4-72
TIME: 1021 – 1203 MST

FIGURE 19



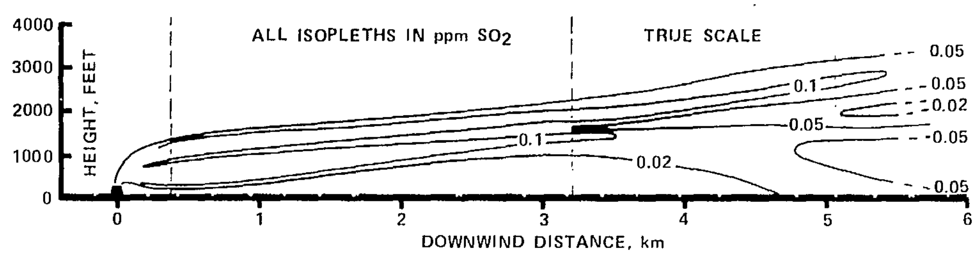
PLAN VIEW OF THE RIMBEY PLUME

DATE: 25-4-72
TIME: 1021 – 1203 MST



SIDE VIEW OF THE RIMBEY PLUME

DATE: 25-4-72
TIME: 1021 – 1203 MST



SIDE VIEW OF THE RIMBEY PLUME

DATE: 25-4-72
TIME: 1021 – 1203 MST

FIGURE 20

PLAN VIEW OF THE RIMBEY PLUME

DATE: 25-4-72
TIME: 1021 – 1203 MST

AREA OF GROUND-LEVEL IMPINGEMENT

DATE: 25-4-72
TIME: 1021 – 1203 MST

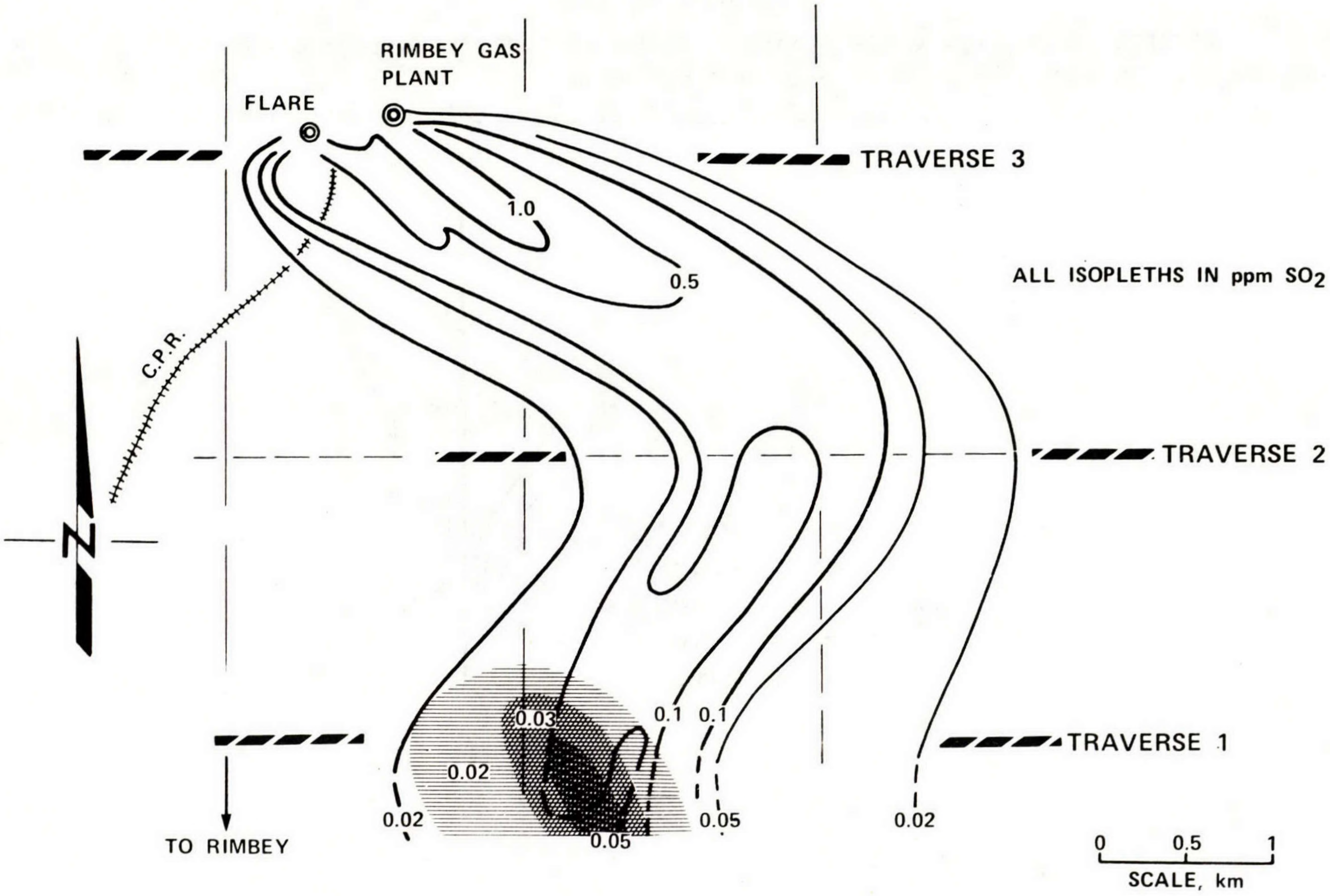
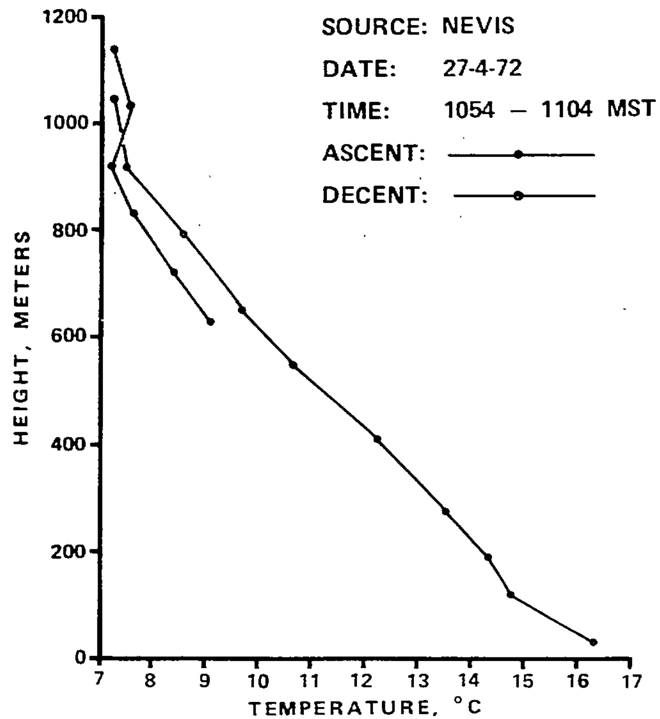


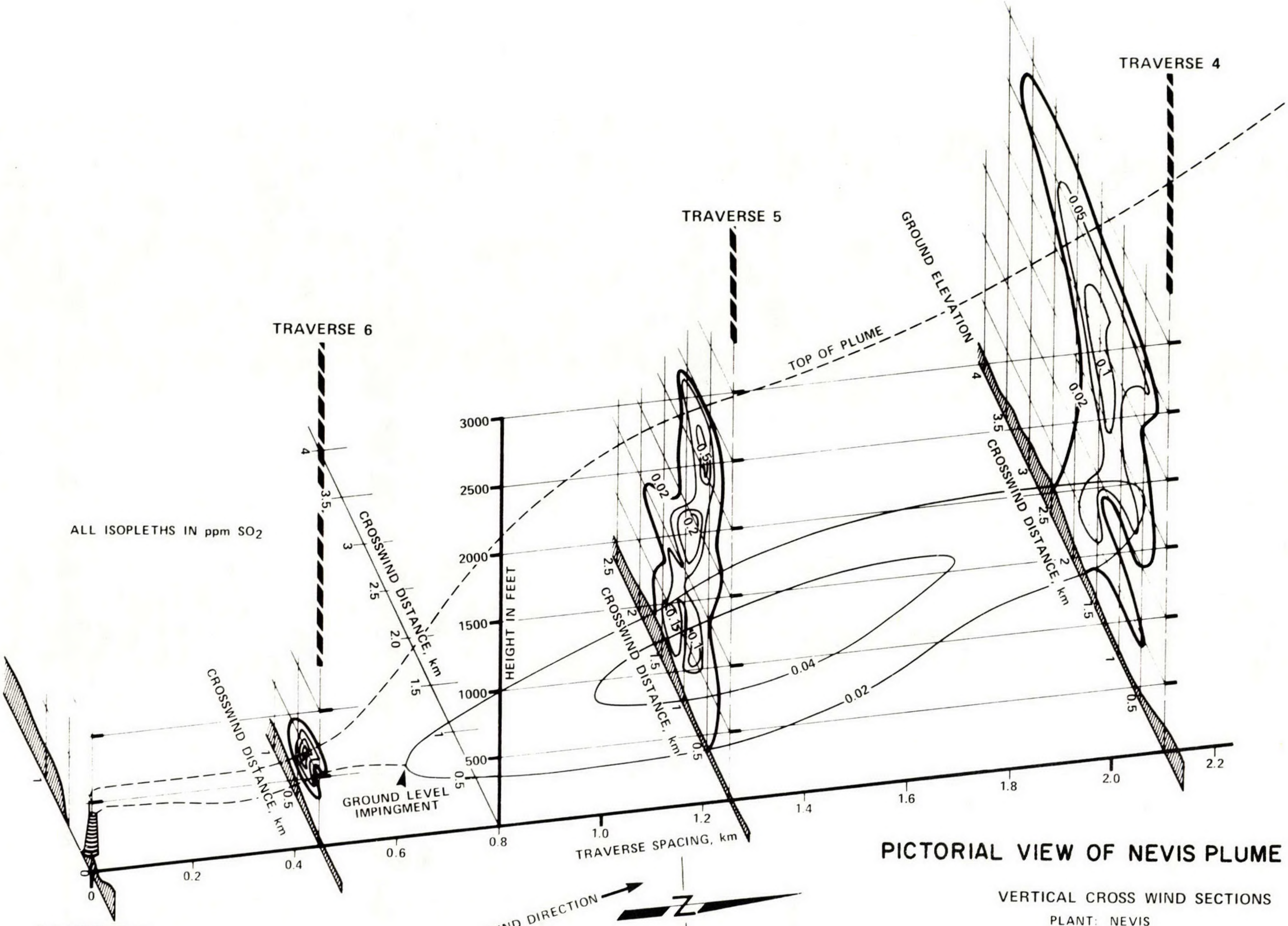
FIGURE 21



VERTICAL TEMPERATURE PROFILES OBTAINED FROM HELICOPTER SURVEY

LATE MORNING 27-4-72

FIGURE 22



ALL HEIGHTS IN
REFERENCE TO
RED DEER RIVER NEAR PLANT
ELEVATION 2440 FT.

PICTORIAL VIEW OF NEVIS PLUME

VERTICAL CROSS WIND SECTIONS

PLANT: NEVIS
DATE: 27-4-72
TIME: 0955 - 1054 MST

FIGURE 23

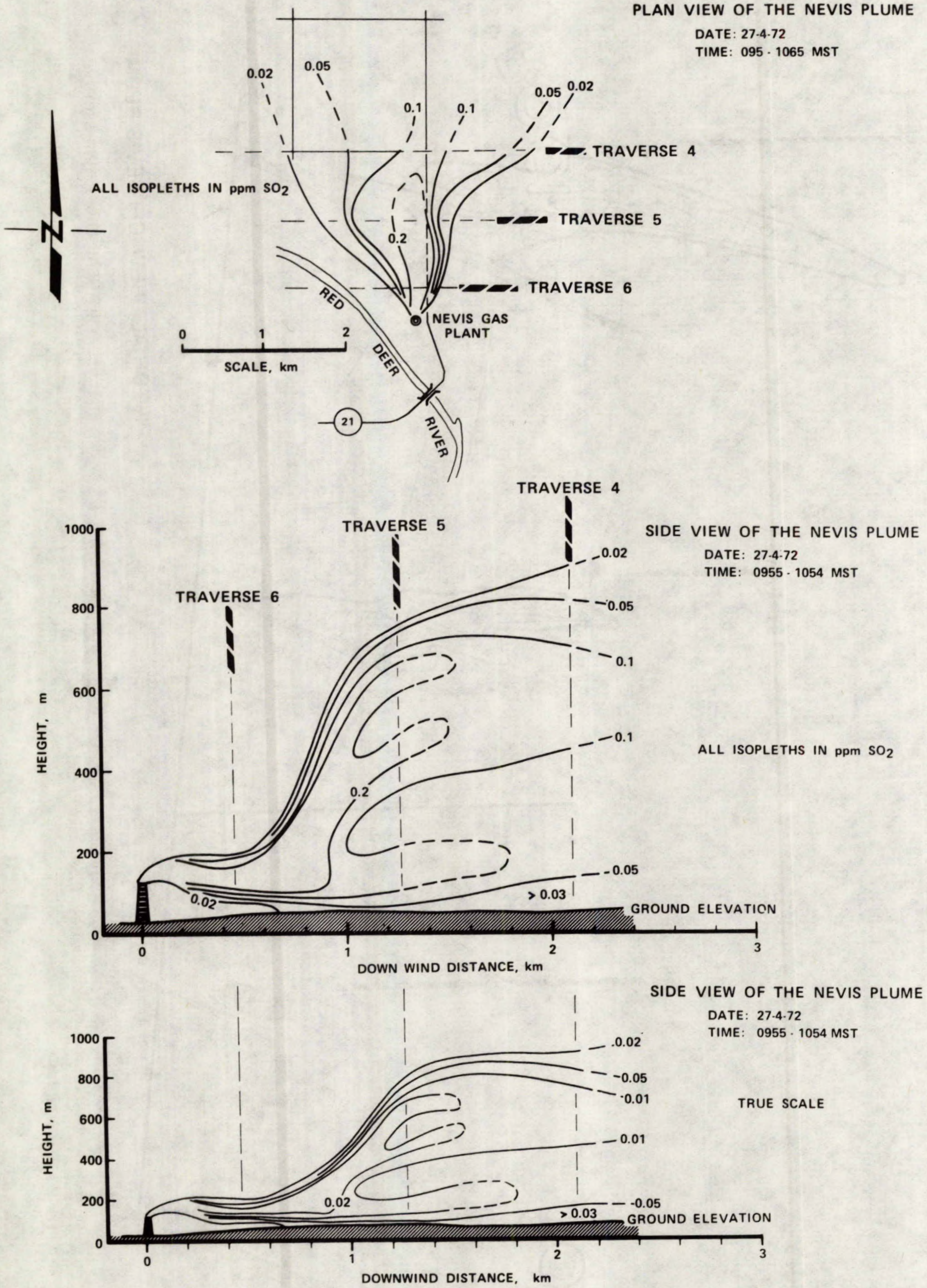

PLAN VIEW OF THE NEVIS PLUME
DATE: 27-4-72
TIME: 095 - 1065 MST
0.02
0.05
0.1
0.1
0.05
0.02
TRAVERSE 4
ALL ISOPLETHS IN ppm SO2
TRAVERSE 5
0.2
TRAVERSE 6
RED
DEER
RIVER
NEVIS GAS
PLANT
0
1
2
SCALE, km
21
TRAVERSE 4
TRAVERSE 5
TRAVERSE 6
SIDE VIEW OF THE NEVIS PLUME
DATE: 27-4-72
TIME: 0955 - 1054 MST
0.02
0.05
0.1
0.1
0.2
0.05
> 0.03
0.02
GROUND ELEVATION
ALL ISOPLETHS IN ppm SO2
1000
800
600
400
200
0
HEIGHT, m
0
1
2
3
DOWN WIND DISTANCE, km
SIDE VIEW OF THE NEVIS PLUME
DATE: 27-4-72
TIME: 0955 - 1054 MST
.0.02
-0.05
-0.01
0.01
0.02
-0.05
> 0.03
GROUND ELEVATION
TRUE SCALE
1000
800
600
400
200
0
HEIGHT, m
0
1
2
3
DOWNWIND DISTANCE, km

FIGURE 24

PLAN VIEW OF THE NEVIS PLUME

DATE: 27-4-72
TIME: 095 - 1065 MST

AREA OF GROUND-LEVEL IMPINGEMENT

DATE: 27-4-72
TIME: 0933 - 1104 MST

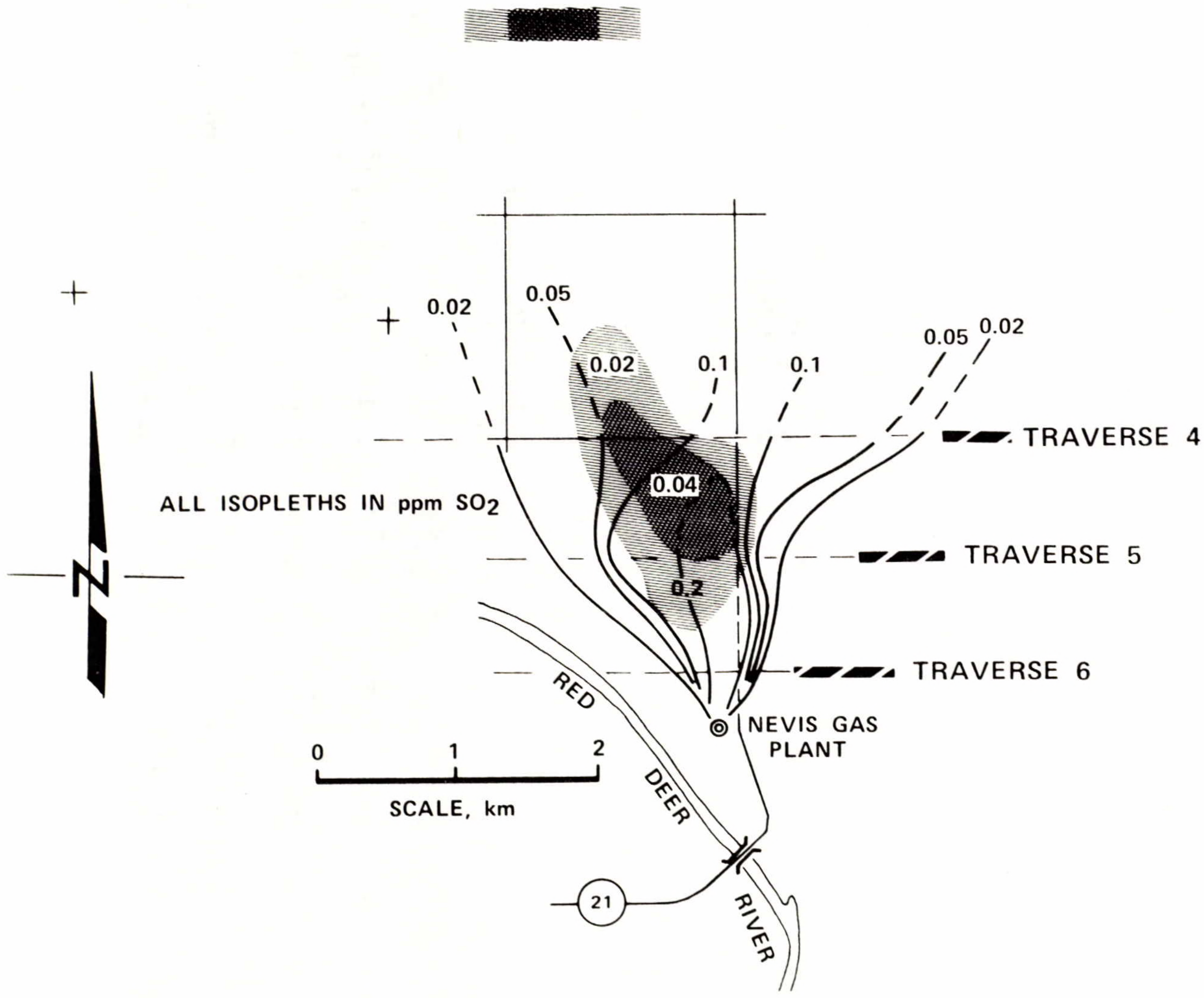


FIGURE 25

THE MASS OF POLLUTANT FLOWING ACROSS THE AREA A OCCUPIED BY THE PLUME CROSS SECTION IS

$$q = \iint_A C \, dy . dz, \quad (1)$$

THE CENTRE OF POLLUTANT MASS FLOW IS THE FIRST MOMENT:

$$\bar{y} = \frac{1}{q} \iint_A Cy \, dy . dz, \quad (2)$$

AND THE VARIANCE IS THE SECOND MOMENT ABOUT THE AXIS

$$\sigma_y^2 = \frac{1}{q} \iint_A C (y - \bar{y})^2 \, dy . dz. \quad (3)$$

SIMILARLY FOR THE VERTICAL DIMENSIONS,

$$\bar{z} = \frac{1}{q} \iint_A Cz \, dz . dy, \quad (4)$$

AND

$$\sigma_z^2 = \frac{1}{q} \iint_A C (z - \bar{z})^2 \, dz . dy \quad (5)$$

INTEGRAL EQUATIONS DEFINING THE CENTRE OF MASS FLOW AND THE STANDARD DEVIATION OF PLUME SPREAD

FIGURE 26

IF THESE INTEGRAL EQUATIONS ARE TRANSLATED INTO FINITE DIFFERENCE FORM THEN (1) BECOMES

$$Q = \sum \Delta c \sum Y \Delta Z \qquad (6)$$

AND CO-ORDINATES OF THE CENTRE OF MASS FLOW (2) AND (4) RESPECTIVELY BECOME

$$\bar{Y} = \frac{1}{2Q} \sum \Delta c \sum Y^2 \Delta Z \qquad (7)$$

$$\bar{Z} = \frac{1}{2Q} \sum \Delta c \sum Z^2 \Delta Y \qquad (8)$$

LIKEWISE THE VARIANCES (4) AND (5) RESPECTIVELY BECOME

$$\sigma_Y{}^2 = \frac{1}{3Q} \sum \Delta c \sum (Y - \bar{Y})^3 \Delta Z \qquad (9)$$

AND

$$\sigma_Z{}^2 = \frac{1}{3Q} \sum \Delta c \sum (Z - \bar{Z})^3 \Delta Y \qquad (10)$$

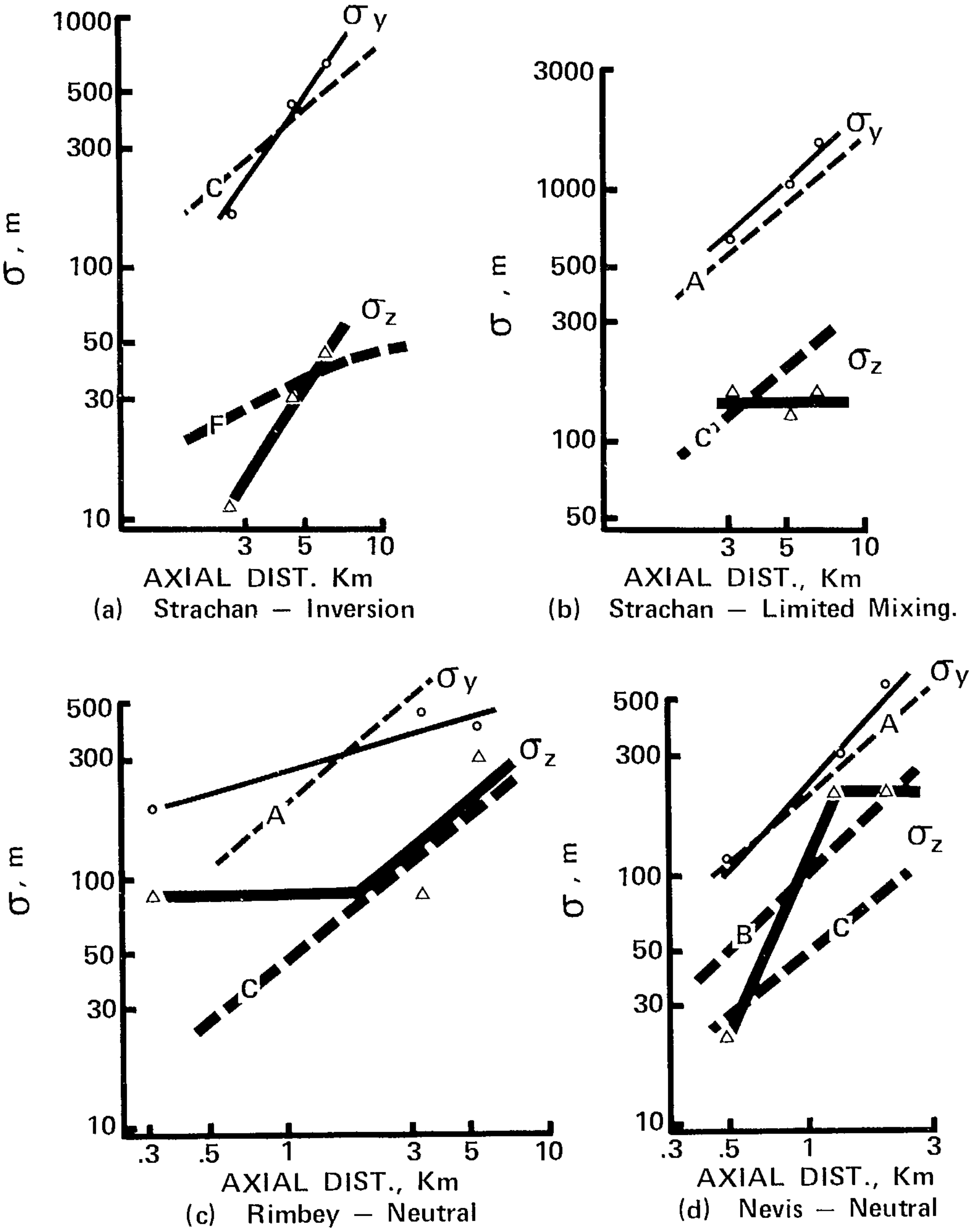
FINITE DIFFERENCE FORM OF THE INTEGRAL EQUATIONS GIVEN IN FIGURE 26

FIGURE 27

TABLE 2

COMPARISON OF DERIVED AND EMPIRICAL PLUME RISE

SOURCE	STRACHAN			STRACHAN			RIMBEY			NEVIS		
STABILITY	INVERSION			LIMITED-MIXING			NEUTRAL			NEUTRAL		
Mean Heat Flux, Mcal/s	11.22			11.22			5.14			3.07		
Mean Wind Speed, m/s	9.3			9.2			6.0			5.2		
Axial Dist., Km	2.6	4.5	6.0	3.1	5.1	6.7	0.3	3.2	5.1	0.5	1.3	2.1
Plume Rise, m $\overline{\Delta z}$ (finite diff.)	164	143	131	213	103	101	137	412	423	- 6	217	289
Briggs	98	98	98				69	332	453	94	178	244



DERIVED STANDARD DEVIATIONS OF PLUME SPREAD.

BROKEN LINES SHOW CLOSEST PASQUILL STABILITY CLASS.

FIGURE 29