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PLUME DISPERSION FROM A NATURAL-GAS SULPHUR-EXTRACTION PLANT UNDER A PERSISTENT ELEVATED INVERSION

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DISPERSION DU PANACHE DE FUMEE PRODUIT PAR UNE INSTALLATION D'EXTRACTION DU SOUFRE DU GAZ NATUREL, LORS D'UNE INVERSION ELEVEE ET PERSISTANTE

PLUME DISPERSION FROM A NATURAL GAS SULPHUR EXTRACTION PLANT UNDER A PERSISTENT ELEVATED INVERSION

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SUMMARY

Natural gas frequently contains high concentrations of hydrogen sulphide which must be removed before admission to the pipeline. The sour gas treating plants extract and convert the hydrogen sulphide to elemental sulphur by reacting it with sulphur dioxide over an alumina catalyst. The required sulphur recovery efficiencies of these plants range from about 93% for small plants (10-100 tonnes of sulphur recovered per day) to about 99% for large plants (1,000-4000 tonnes/day). The unrecovered sulphur is burned, giving rise to relatively small emissions of SO_2; nevertheless, high ground-level concentrations may occur during adverse meteorological conditions.

Using a unique aerial probing methodology, plume dispersion research studies were conducted to measure the behaviour of hot plumes from a natural-gas sulphur-extraction plant located in the foothills of western Canada. These studies, which were conducted during a persistent elevated inversion in early spring, permitted an evaluation of the influence of topography and mixing height on plume rise and dispersion. Numerical analysis of the dispersion data indicate that presently accepted procedures cannot be used with confidence to estimate dispersion parameters for limited-mixing conditions over hilly terrain.

RESUME

Le gaz naturel contient fréquemment de fortes concentrations de sulphure d'hydrogène, lequel doit être enlevé avant l'entrée dans le gazoduc. Les installations de traitement du gaz acide extraient le sulphure d'hydrogène et le transforment en soufre en le faisant réagir avec de l'anhydride sulfureux à l'aide d'un catalyseur d'alumine. L'efficacité de récupération requise s'échelonne d'environ 93% pour les petites installations (10 à 100 tonnes de soufre par jour) jusqu'a vers 99% pour les grandes installations (1,000 à 4,000 tonnes par jour). Le soufre non récupéré est brûlé, ce qui donne lieu à des dégagements relativement faibles de SO_2, néanmoins il peut se produire des fortes concentrations au niveau du sol lorsque les conditions météorologiques sont défavourables.

A l'aide d'une méthode aérienne unique de sondage, des études sur la dispersion d'un panache de fumée ont été effectuées pour mesurer le comportement des panaches de fumée chaude produits par une installation d'extraction du soufre du gaz naturel. L'installation est située dans les avants-monts, dans l'ouest du Canada. Ces études ont été menées pendant une inversion élevée et persistante au début du printemps. Elles nous ont permis de faire une évaluation de l'influence de la topographie et d'un mélange en hauteur sur la montée et la dispersion d'un panache de fumée. Les données numériques de l'analyse de la dispersion indiquent que l'on ne peut faire confiance aux méthodes classiques pour évaluer les paramètres de dispersion dans des conditions de mélange limité au-dessus d'un terrain accidenté.

INTRODUCTION

A research project was carried out during two successive days in April 1972 to study the dispersion of hot (600°C) plumes from a natural-gas sulphur-extraction plant located in the eastern slopes of the Canadian Rocky Mountains

During normal plant operation, relatively small amounts of unrecoverable sulphur are incinerated to SO_2 and emitted to atmosphere through a tall stack. However, if a major breakdown occurs in the plant most of the inlet sour gas is automatically flared from the top of a short, high-pressure stack.

The project consisted of six two-hour aerial studies conducted during morning, midday and early afternoon of each day. In four of the six studies normal operating conditions prevailed but, during the midday and afternoon studies on the first day, extensive flaring released some ten times the normal amount of sulphur to the atmosphere at temperatures in excess of 1300°C. This provided a unique opportunity for the first known aerial studies of a sour gas plant under emergency dumping conditions. These two studies demonstrated how large volumes of sour (9.3% H_2S) inlet gas can be flared under limited-mixing conditions for up to eight hours without exceeding critical ground-level concentrations.

This paper describes the dispersion characteristics of the emissions throughout the two-day study period and presents data indicating that a limiting condition can be predicted for both the plume axis elevations and the standard deviations of plume spread during limited-mixing conditions.

1 - SOURCE AND METEOROLOGICAL DATA

1.1 - SOURCE DATA

The Strachan Gas Plant is situated 1204m above mean sea level about 175 km southwest of Edmonton, Alberta. The surrounding topography, which is hilly and forested in all directions, slopes upward from east to west. Sour natural gas is processed at the plant at the rate of 7.1 x 10^6 sm^3/day with sulphur recovery efficiencies exceeding 97%.

On both days of the dispersion study, the total mass of sulphur emitted to atmosphere was relatively constant at about 35 tonnes/day, except between 1100 h and 1830 h on April 23rd when inlet sour gas was flared because of a mechanical failure in the gas treating system. Table 1 summarizes the plant [redacted] parameters as well as the stack and flare emission data for each study.

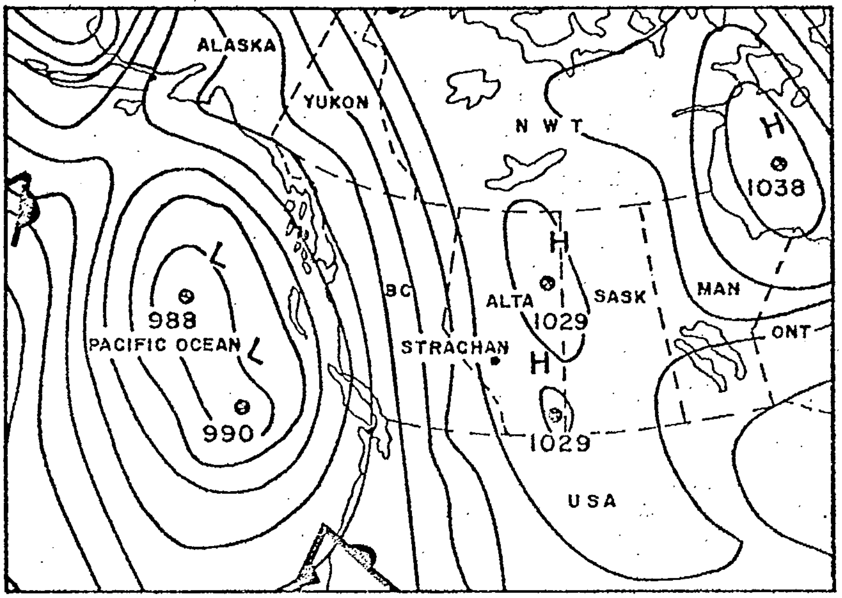
TABLE 1

Date	Time Period MST	SO_2 Emission		Heat Emission Mcal/s
		sm/s	ppm	
23-4-72	0834-1020	0.206	4400	28.9
	1120-1321*	2.023	40,000	223.0
	1444-1627*	2.850	40,000	319.0
24-4-72	0805-0926	0.238	4900	30.3
	1126-1250	0.166	3400	29.6
	1516-1636	0.207	4300	28.1

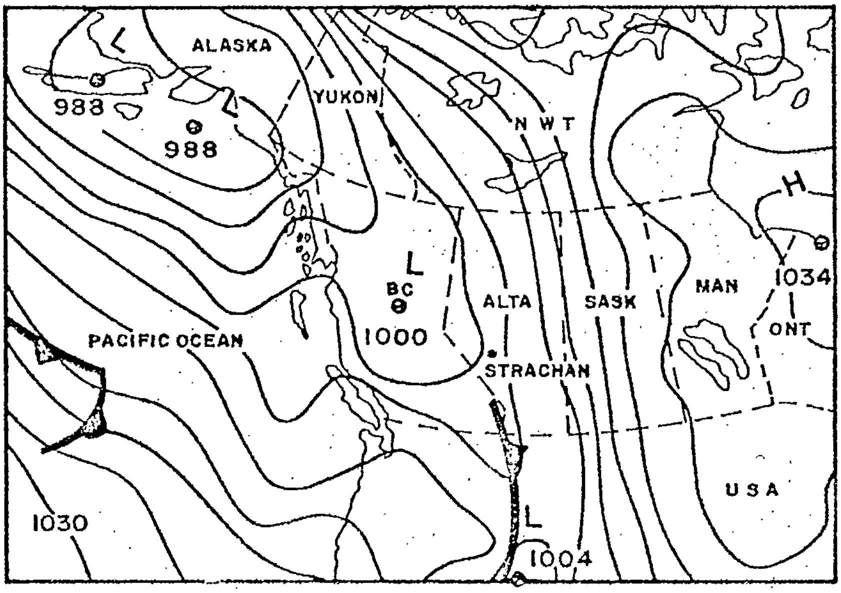
*Emissions dominated by flaring of inlet sour gas.

1.2 - METEOROLOGICAL CONDITIONS

On April 23rd a ridge of high pressure along the Alberta-Saskatchewan border and a low-pressure region centred off the Pacific coast resulted in strong southerly winds over all of western Alberta. At Strachan, this situation created a flow of dry air at all levels that was down slope. A subsidence inversion, based at about 1100m above ground,persisted all day with near-neutral conditions between the surface and the inversion base; considerable warming of the neutral layer occured during the day.



SURFACE ANALYSIS 1100 MST APRIL 23 rd 1972



SURFACE ANALYSIS 1100 MST APRIL 24 th 1972

FIG. 1 SYNOPTIC WEATHER MAPS, APRIL 23-24, 1972.

TABLE 2

Date	Time Period MST	Wind Speed m/s	Height Interval m	$\frac{\partial\theta}{\partial Z}$ °C/100m	Atmospheric Stability	Minimum Plume Dispersion Ratio
23-4-72	0834-1020	7.3	0-1150 1150-1450	0.15 1.39	Neutral Inversion	31300 at 5.8 km
	1120-1321*	6.4	0.-1150 1150-1450	0.03 1.39	Neutral Inversion	40300 at 5.5 km
	1444-1627*	10.8	0-1150 1150-1650	0.08 1.08	Neutral Inversion	175000 at 5.6 km
24-4-72	0805-0926	8.7	0-300	3.02	Inversion	5310 at 6.4 km
	1126-1250	9.5	0-575 575-735	0.08 2.12	Neutral Inversion	17200 at 5.2 km
	1516-1636	10.5	0-575 576-665	-0.04 1.40	Neutral Inversion	21500 at 4.9 km

*Emissions dominated by the flaring of inlet sour gas.

By April 24th the centre of low-pressure had moved from the Pacific Ocean eastward into central British Columbia resulting in the wind direction shifting from south to southeast near the surface. The air layer next to the surface was topped by a warmer air mass aloft with a marked front between the two layers at a height of about 600m. Near-neutral conditions existed in both air masses until late in the afternoon when super-adiabatic conditions developed in the surface layer. By the evening of the 24th the centre of low-pressure had passed east of Alberta.

The synoptic surface maps for 1100 h MST on both days are shown in Fig. 1 and a summary of the local atmospheric temperature gradients that existed during each study is given in Table 2.

2 - PLUME DISPERSION MEASUREMENTS

During each study, detailed SO_2 distributions across the plume at three or more downwind traverses were measured by an immersion probing technique[1]. With these data, crosswind sectional maps of the SO_2 concentration gradients within the plume were plotted as illustrated in Fig. 2. Each crosswind section was then analyzed by a rigorous finite difference method to obtain the plume axis elevation, ΔZ, the downwind distance, X, and the standard deviations of plume spread σ_y and σ_z for the traverses selected[2]. In addition, these crosswind sections can be used to produce a pictorial view of each plume as shown in Figs. 3 to 7 inclusive.

2.1 - PLUME AXIS ELEVATIONS

2.1.1 - Limited-Mixing Conditions

The rise of the plume axis in all five studies conducted under limited-mixing conditions was restricted by an elevated inversion which was based about 1100m and 600m above ground on April 23rd and 24th respectively. With only the incinerator stack operational it can be assumed that a top hat or plug flow concentration profile will eventually exist in the vertical and that the plume axis will then reach a limiting elevation midway between the ground and the inversion base. Hence, the limiting elevation of the plume axis is given by:

$$\Delta Z = kh_m - h_s \quad \text{where } k = 0.5$$

In the two studies when emergency flaring of sour gas occurred, an analysis of the measured SO_2 plume profiles showed that the flow paths of the flare and incinerator stack emissions remained separate due to buoyancy differences with the flare emissions quickly rising to the inversion base and dispersing over the top of those from the incinerator. For this situation, concentrations in each part of the dual-layer or bifurcated plume were also assumed to reach a plug-flow profile. But, because of extensive downward diffusion from the lower part of the high concentration flare-stream into the upper part of the low concentration incinerator stream, k was determined to be 0.7 in the above equation.

Thus, for each study conducted under limited-mixing conditions, it is possible to estimate the limiting elevation of the plume axis. These limits are given together with the derived data points on the dimensionless plots shown in Fig. 9. These plots show that most of the data points fall close to the estimated limit for the plume axis

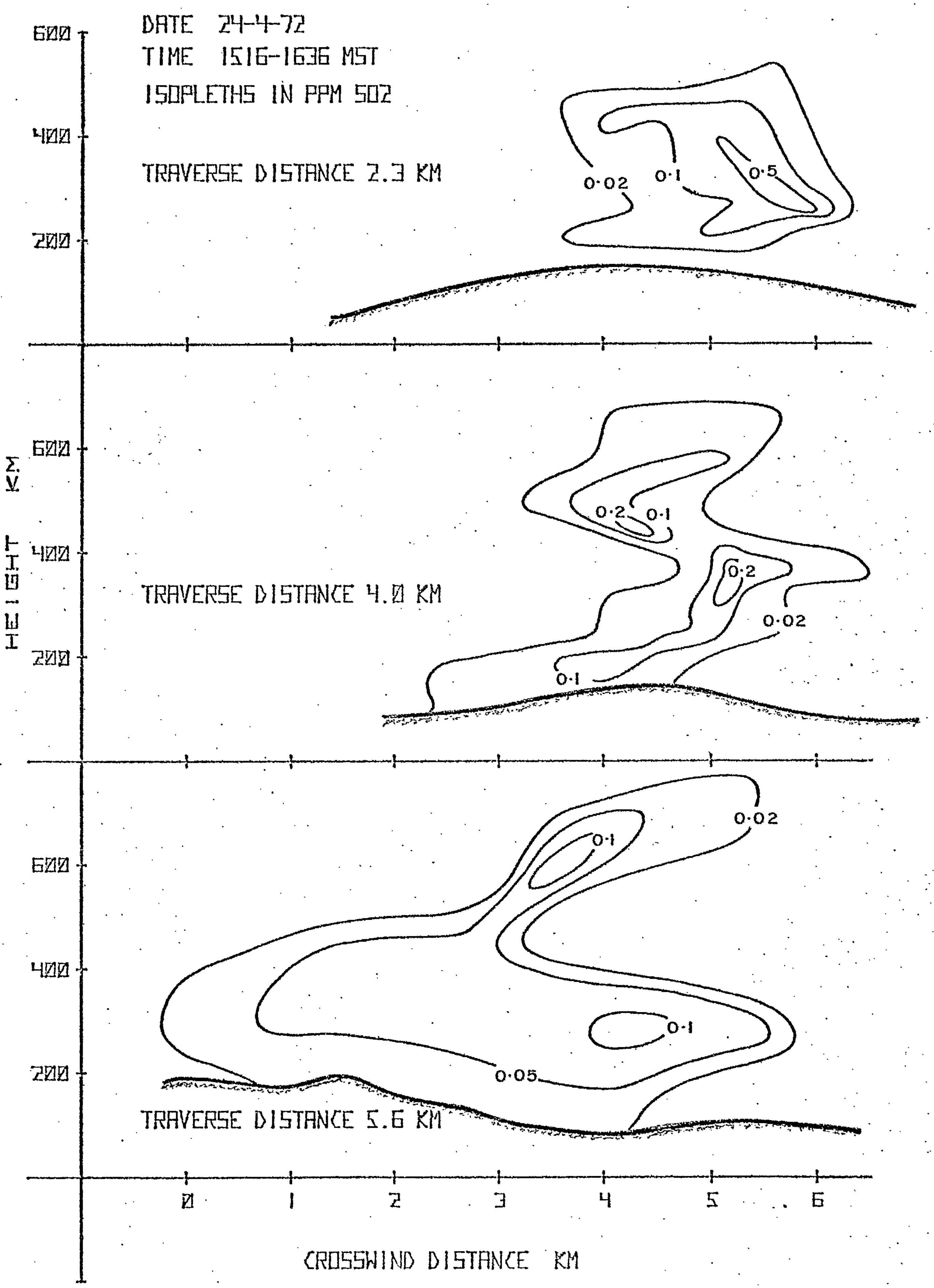


FIG. 2 CROSSWIND SECTIONS OF THE PLUME, AFTERNOON 24-4-72.

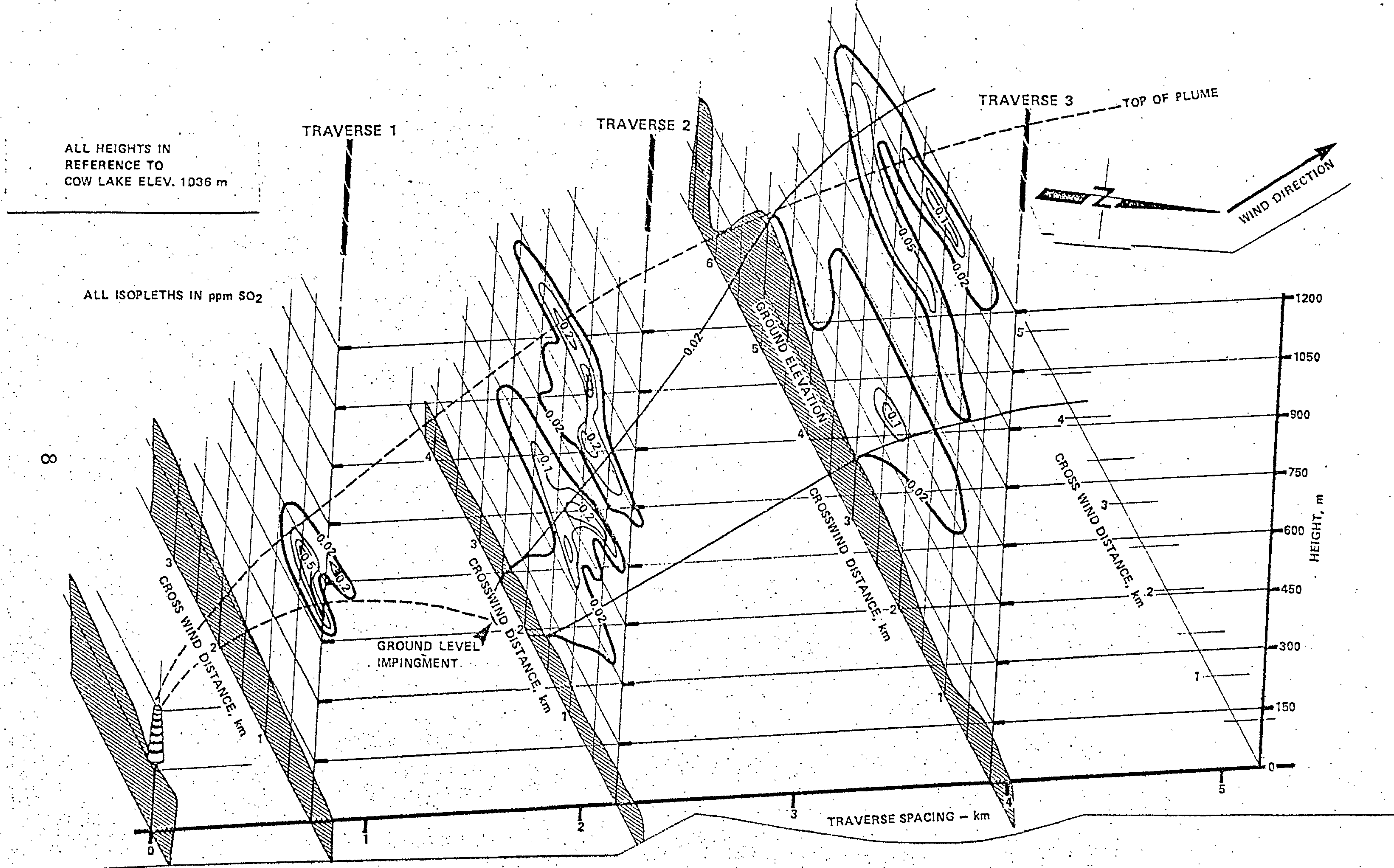


FIG. 3 PICTORIAL VIEW OF THE PLUME, MORNING 23-4-72.

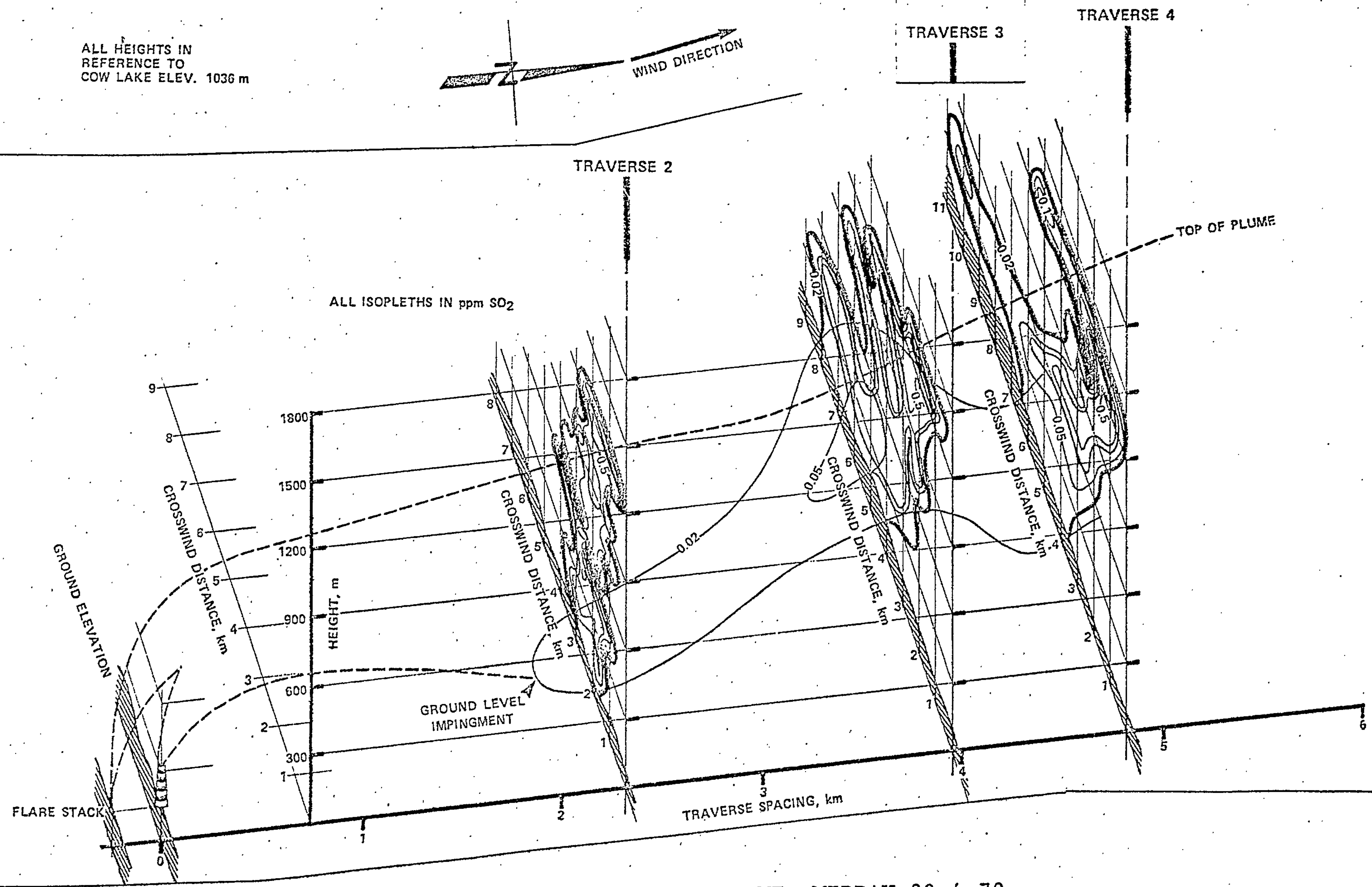


FIG. 4 PICTORIAL VIEW OF THE PLUME, MIDDAY 23-4-72.

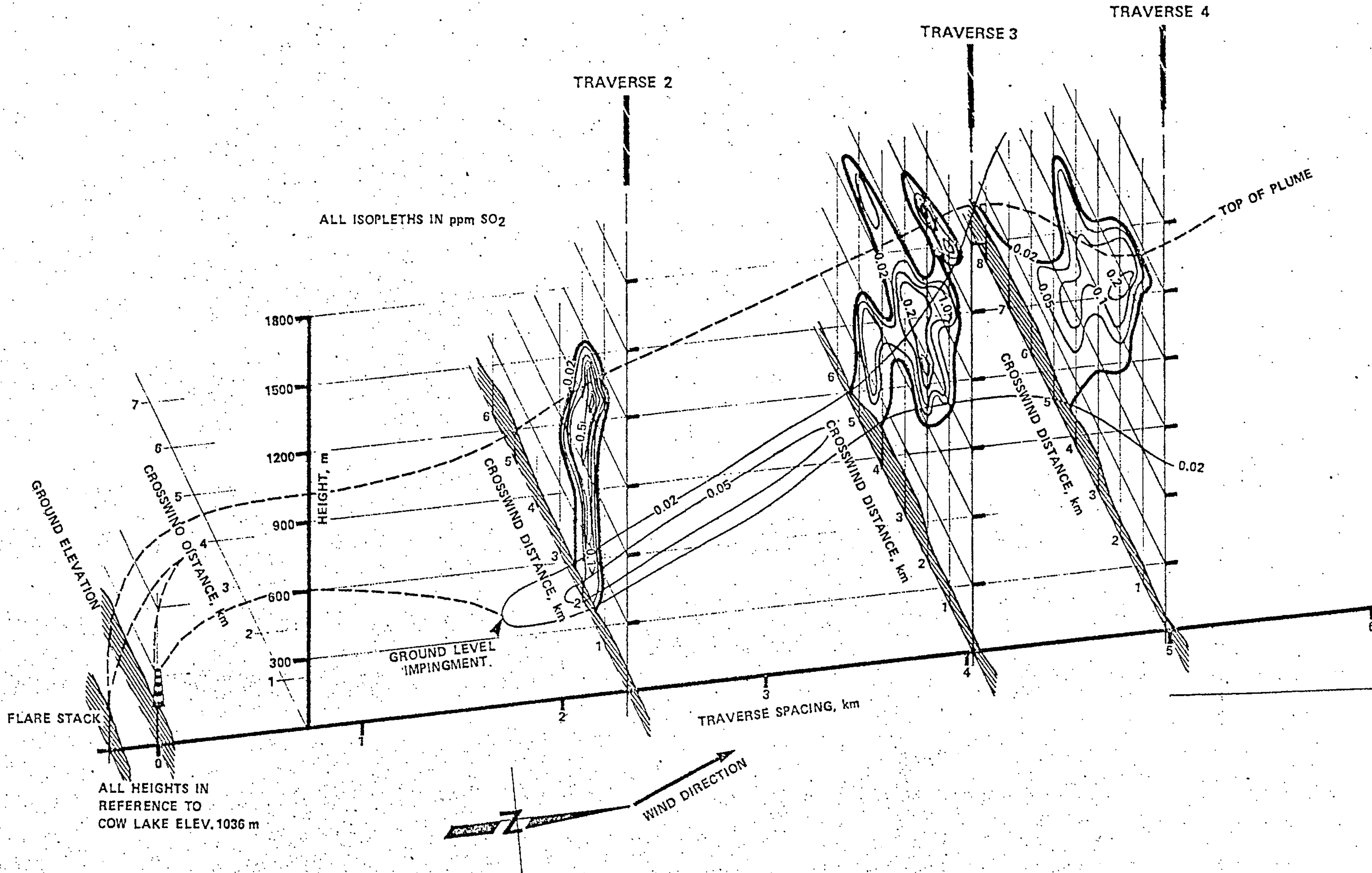


FIG. 5 PICTORIAL VIEW OF THE PLUME, AFTERNOON 23-4-72.

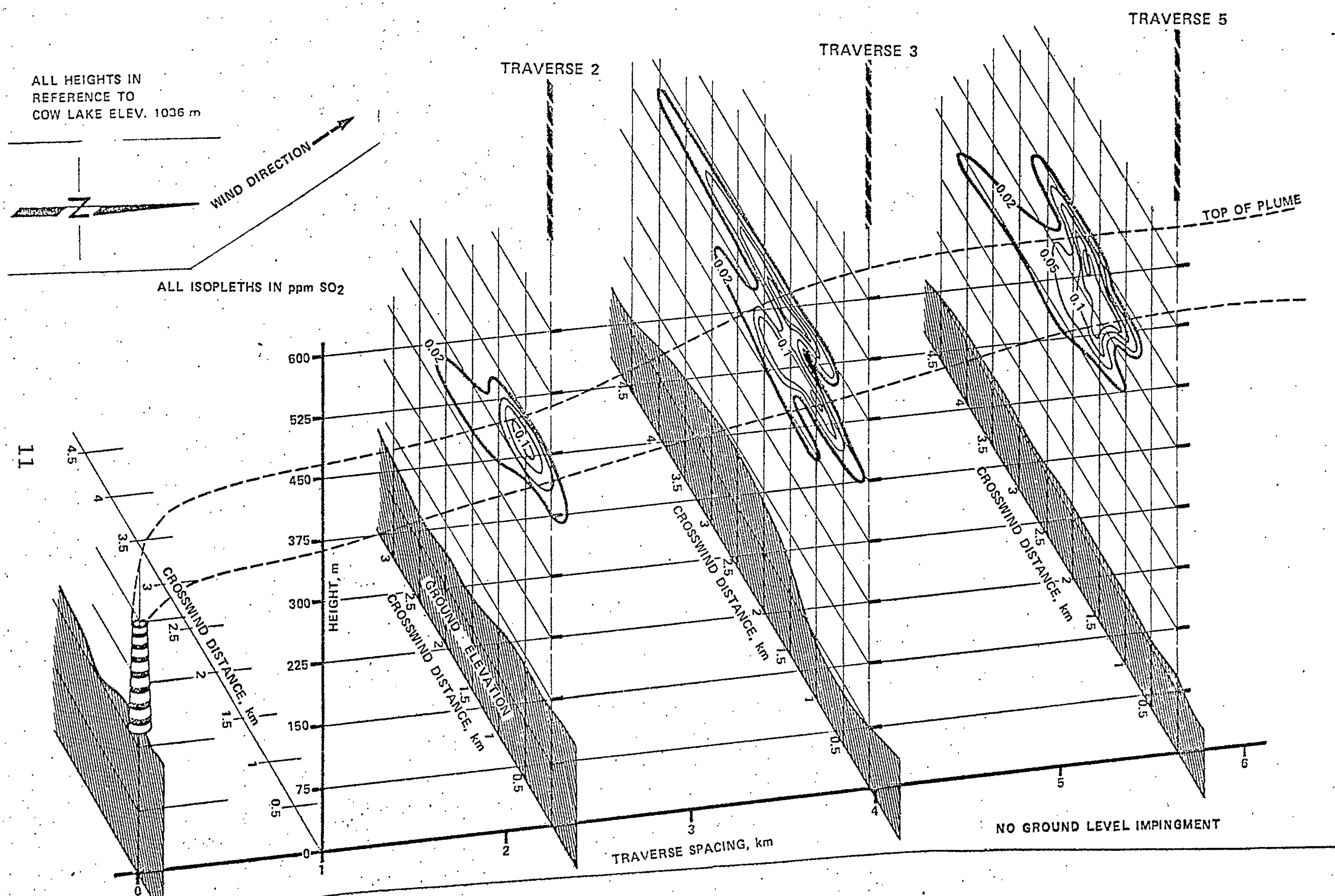


FIG. 6 PICTORIAL VIEW OF THE PLUME, MORNING 24-4-72.

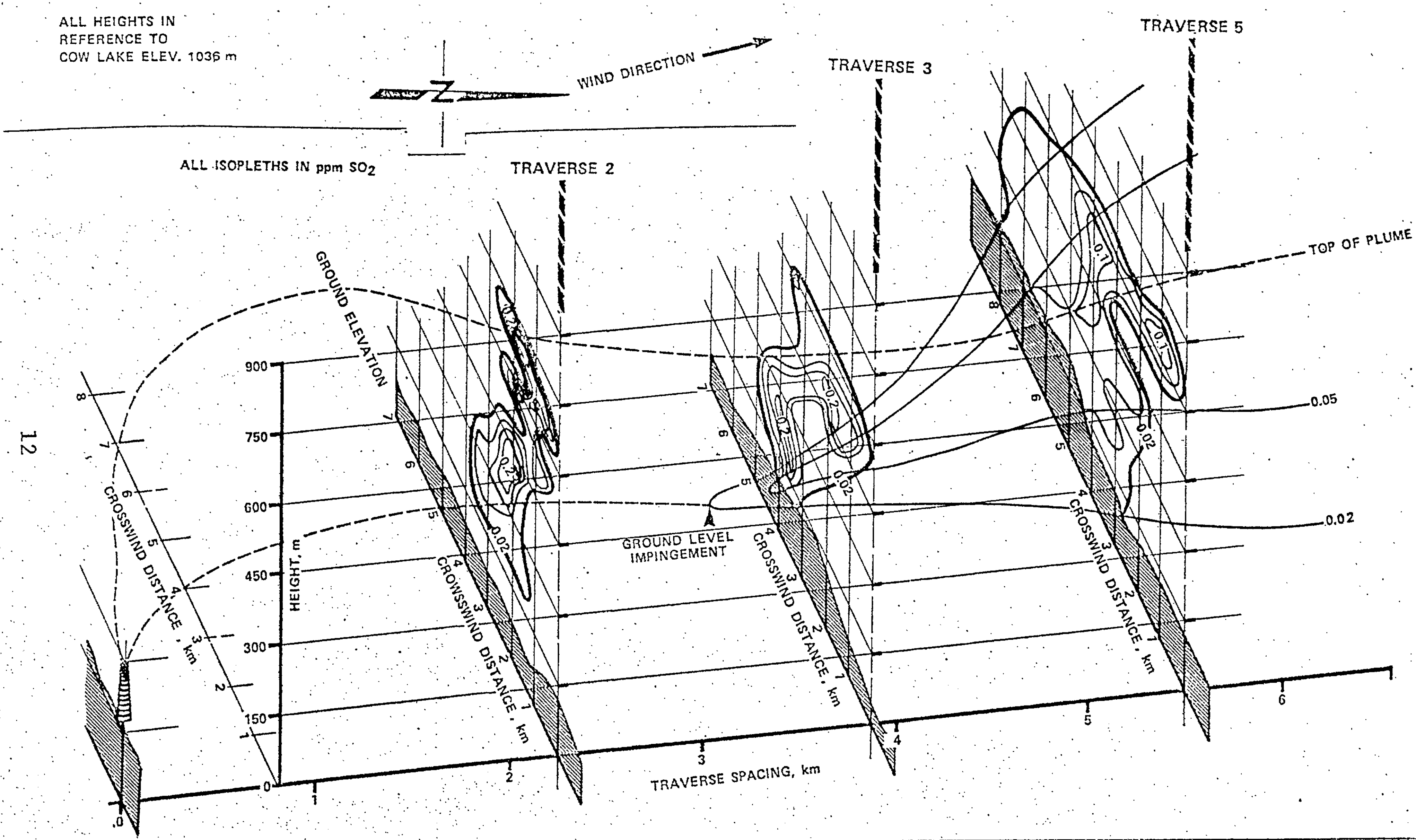


FIG. 7 PICTORIAL VIEW OF THE PLUME, MIDDAY 24-4-72.

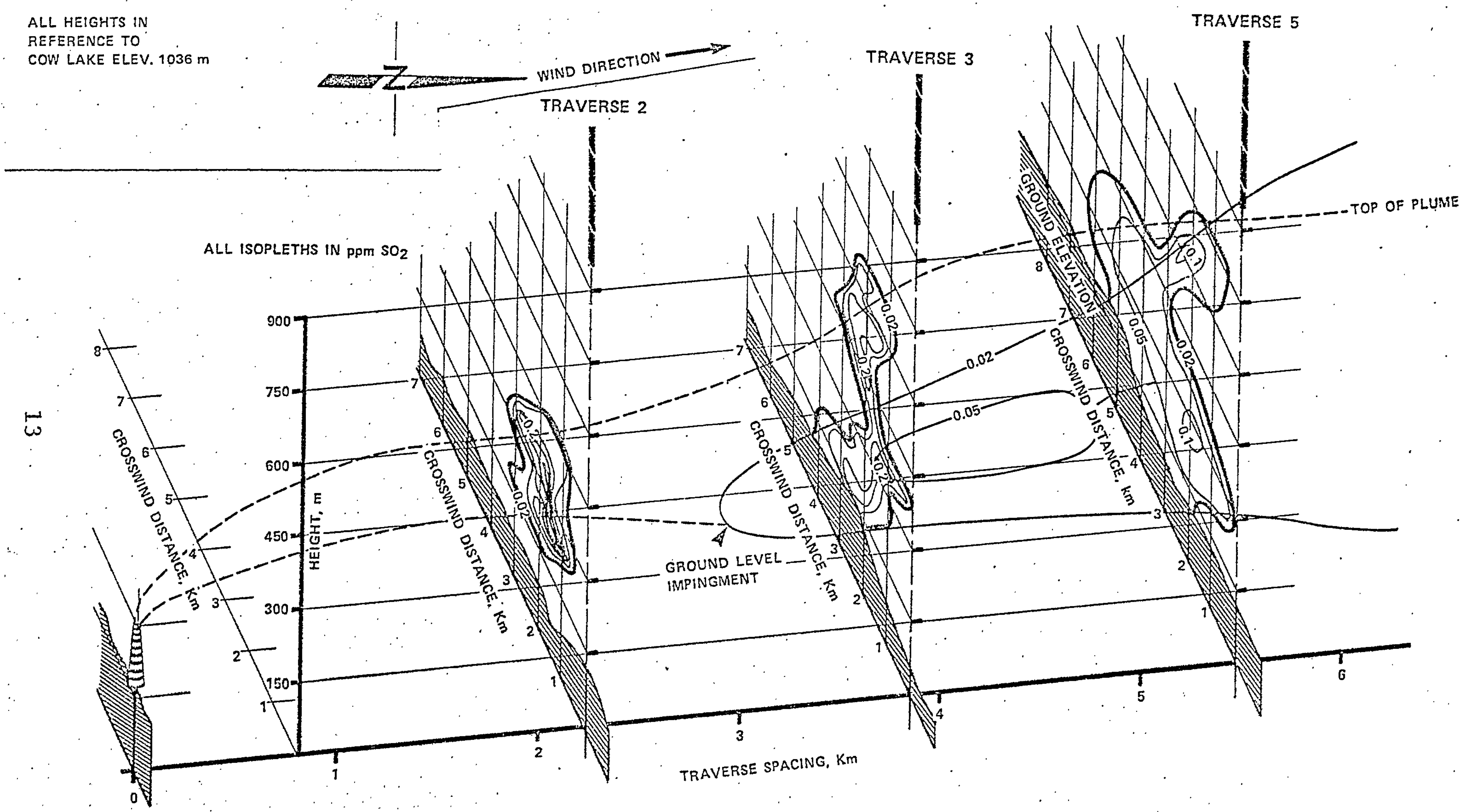


FIG. 8 PICTORIAL VIEW OF THE PLUME, AFTERNOON 24-4-72.

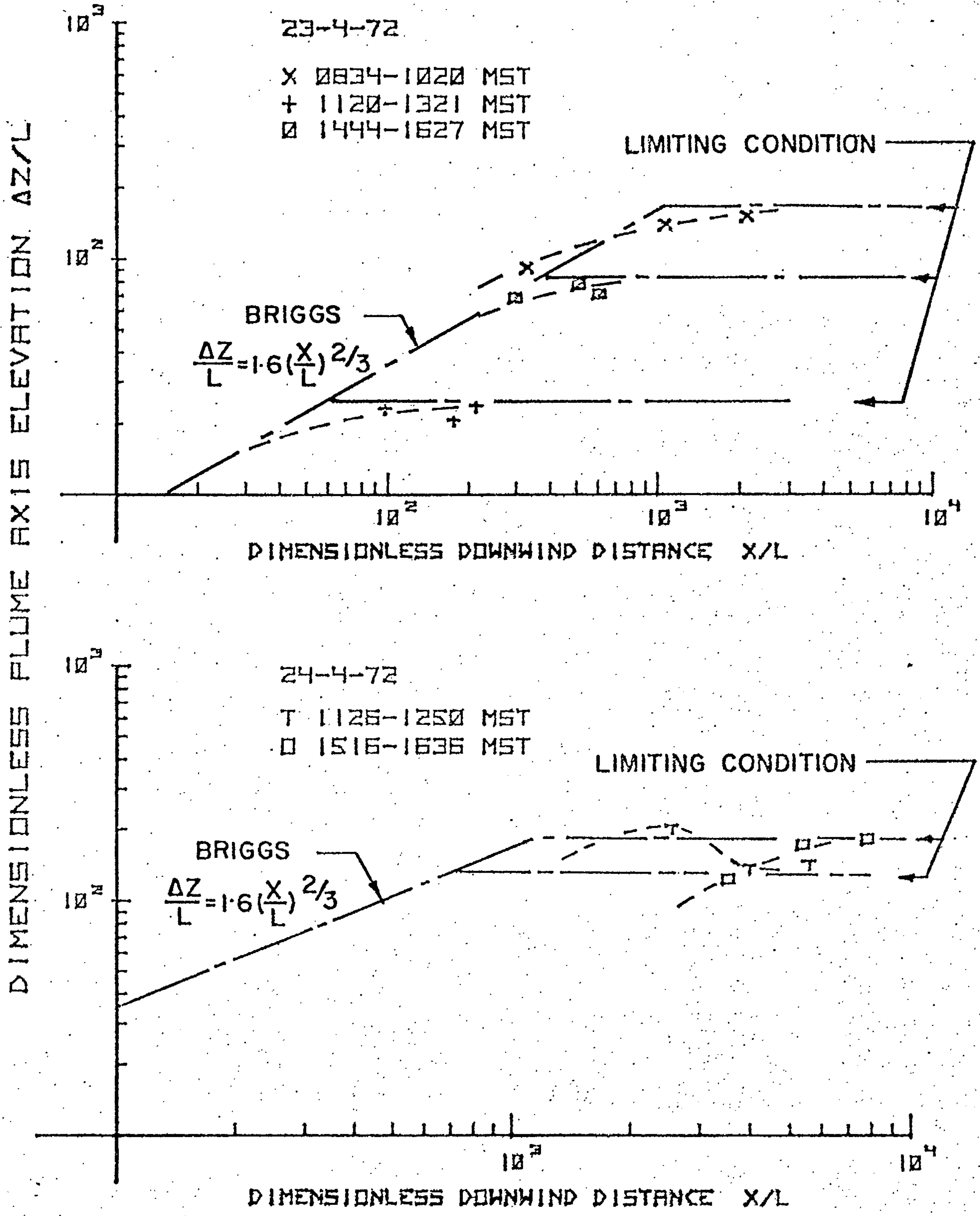


FIG. 9 DIMENSIONLESS PLUME AXIS ELEVATIONS DURING LIMITED-MIXING CONDITIONS.

elevation. As a matter of interest, the measured data are all beyond the downwind distance suggested by Briggs[3] as the levelling-off point for plumes in unrestricted neutral atmospheres.

2.1.2 - Stable Conditions

On the morning of April 24th, the plume was embedded in a ground-based inversion which had a mean thermal gradient of +2°C/100m. As shown in Fig. 10 the derived axis elevations for this plume were found to agree with the Briggs equation for stable conditions, although the data points extend well beyond the range of dimensionless downwind distances used to develop this equation.

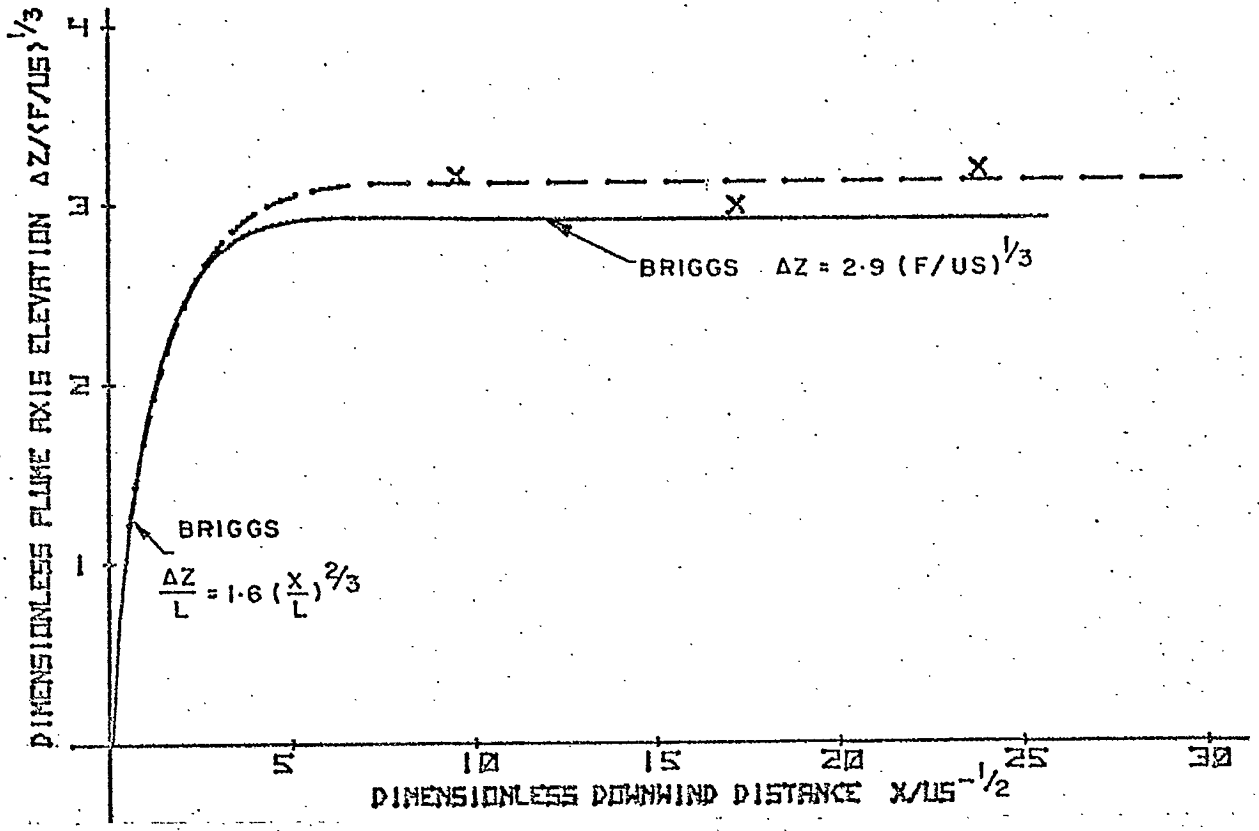


FIG. 10 DIMENSIONLESS PLUME AXIS ELEVATIONS DURING STABLE CONDITIONS.

2.2 - PLUME SPREAD PARAMETERS

2.2.1 - Limited-Mixing Conditions

Fig. 11 shows the derived values of σ_Y and σ_Z for the five studies carried out under limited-mixing conditions. Although the mixing height on April 23rd was about 500m thicker than on April 24th the plume was exceptionally wide on both days with the σ_Y values showing close agreement with stability Class A after Pasquill[4]. This indicates that lateral dispersion is much better than suggested by the neutral temperature gradient of the dispersion zone and that mixing heights between 600m and 1100m had no measurable effect on plume width under an elevated inversion. On the other hand, vertical dispersion was severely restricted on both days with the σ_Z values falling in the region of stability Class F.

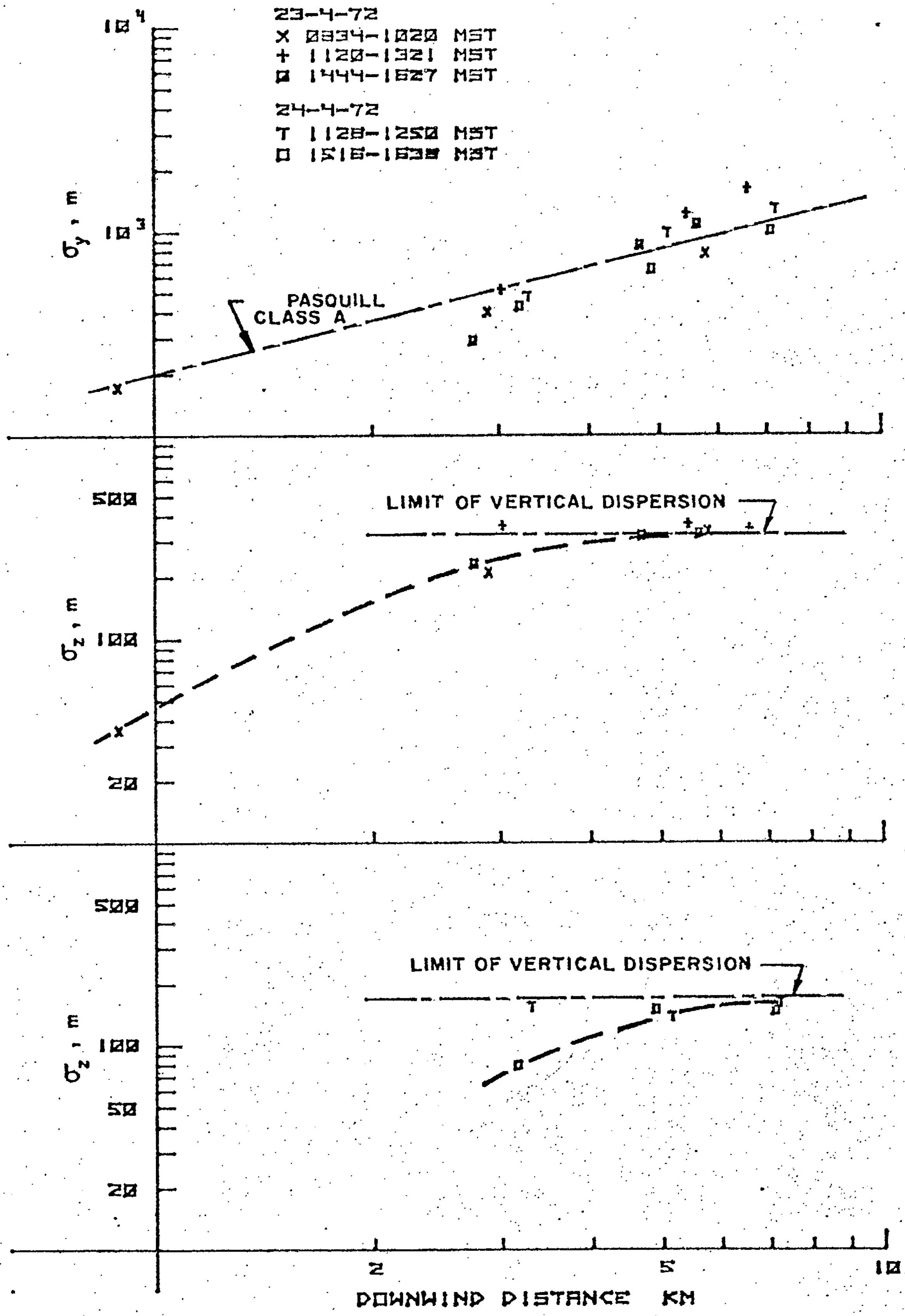


FIG. 11 STANDARD DEVIATIONS OF PLUME SPREAD DURING LIMITED-MIXING CONDITIONS.

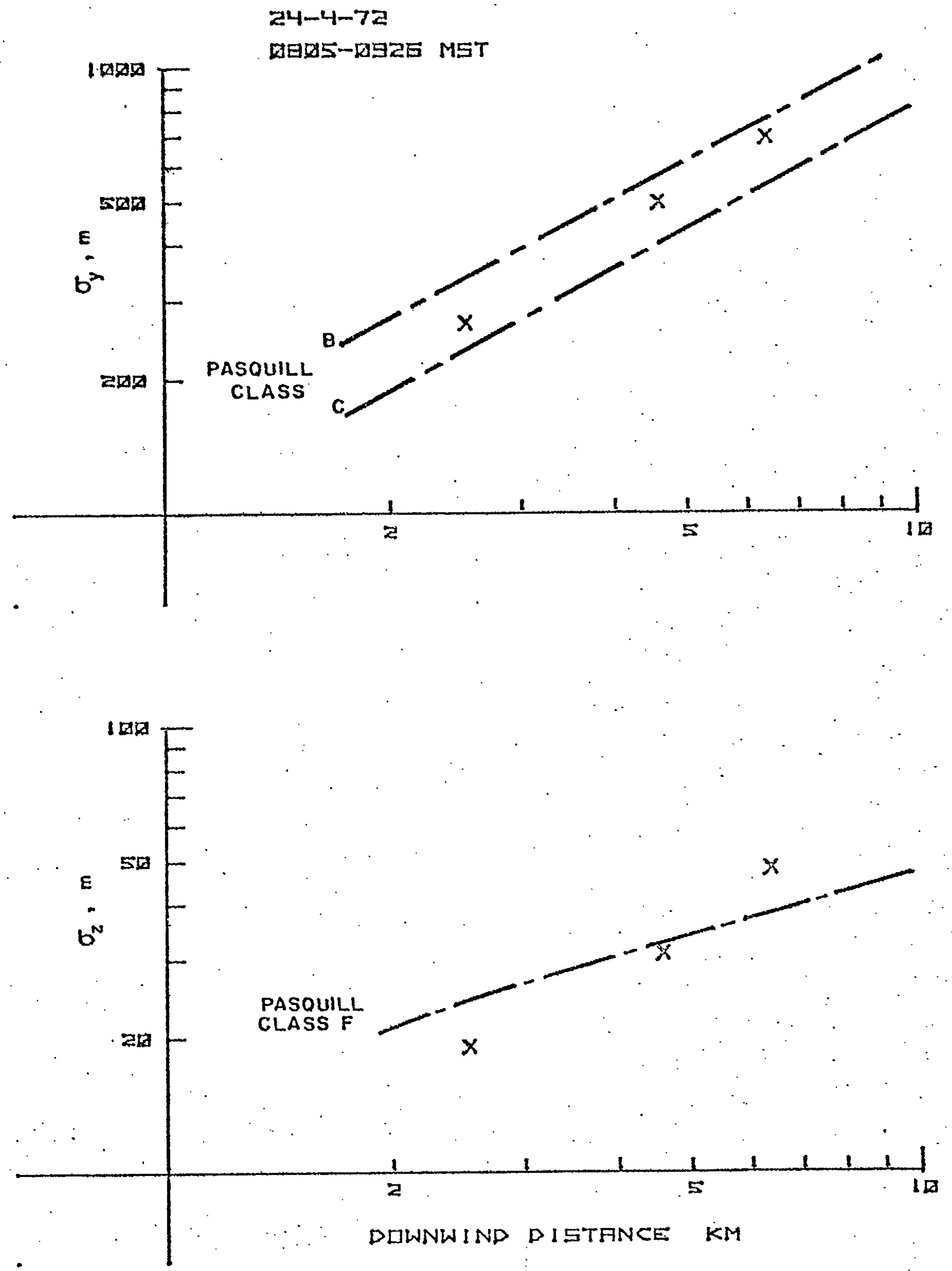


FIG. 12 STANDARD DEVIATIONS OF PLUME SPREAD UNDER STABLE CONDITIONS.

A good indication of the limiting value for σ_z under an elevated inversion can be obtained for plumes during both normal operation and emergency flaring by estimating the equivalent standard deviation for both conditions after plug-flow profiles have developed. As previously described in Section 2.1.1, the two limiting conditions give single and bifurcated plumes having uniform and dual-layered concentration profiles respectively.

For both of these profiles the limiting conditions for σ_z are given by $h_m/2\sqrt{3}$ because the flare emissions are either virtually non-existent or effectively occupy most of the mixing height. As shown in Fig. 11 the derived σ_z values appear to approach this limit for all five studies.

It is evident from the vertical concentration profiles through these plumes and the ground-level plume impingement patterns that emergency flaring under an elevated inversion based at about 1100m above ground does not contribute significantly to ground-level SO_2 concentrations, which were all well below the allowable regional air quality standard for both normal operating and emergency flaring conditions. The fact that the extremely hot flare emissions migrate into the upper levels of the mixing layer suggests that emergency flaring of inlet sour gas for short periods, i.e. less than 8 h, has only a marginal effect on the assimilative capacity of the atmosphere.

2.2.2 - Stable Conditions

One study, on the early morning of April 24th, was conducted with the plume embedded in a ground-based inversion. Under this condition, the plume was very thin as would be expected in a stable atmosphere, but its lateral dispersion characteristics were more consistent with a neutral rather than a stable atmosphere. As shown in Fig. 12 the derived σ_y and σ_z values for this plume correspond approximately to stability Classes B and F respectively. Since the σ_z values for this plume conform fairly well with the stability class for stable atmospheres, this finding demonstrates that plume dispersion was much better than indicated by the Pasquill class for the thermal regime of the atmosphere. Furthermore, this improvement in dispersion occurs without any increase in the possibility of ground-level plume impingement.

CONCLUSIONS

1. The derived values for σ_y and σ_z during stable conditions correspond to stability Classes B to C and F respectively. This agrees with data obtained under similar conditions on the Canadian prairie which showed that σ_y values were generally about two stability classes higher than would be expected from the thermal gradient of the atmosphere. Therefore, concentrations within the plume will decrease more rapidly than would be calculated using stability Class F for both σ_y and σ_z without increasing the possibility of ground-level plume impingement.

2. Under limited-mixing conditions the derived values of σ_z were found to approach the limiting value of σ_z calculated for a plug-flow profile over the mixing height. The derived σ_y values, which correspond to stability Class A and appear to be independent of mixing height, are extremely large due to plume impingement on the inversion base;consequently, measured ground-level SO_2 concentrations were very low.

3. The limiting value for plume axis elevations in the Canadian foothills are predicted reasonably well by the equation $\Delta Z = kh_m - h_s$ during limited-mixing conditions and by the Briggs equation during stable conditions.

4. Although the potential for adverse environmental impact occured while inlet sour gas was being flared under limited-mixing conditions, it was found that the concentration and distribution of ground-level SO_2 remained well below the allowable regional air quality standard. This strongly suggests that vertical turbulence in the mixing layer was too weak to bring the flare emissions, which occupied the upper part of the plume, to ground-level and that emergency flaring of inlet sour gas for up to 8 h can be assimilated by the atmosphere when the mixing height is 1100m or more.

5. Measured ground-level SO_2 concentrations established that emergency flaring of raw gas into a 1100m thick mixing layer will disperse equally as well as normal controlled plant emissions into a 600m thick mixing layer.

6. It would appear that current design criteria and height requirements for safe operation of flare stacks are also effective in maintaining maximum ground-level concentrations of SO_2 within desirable limits, despite adverse atmospheric conditions.

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NOMENCLATURE

c	specific heat at constant pressure, Mcal/kg-°C
F	buoyancy flux = $gQ/\pi cpT$, m^4/s
g	gravitational constant, m/s^2
h_s	stack height, m
h_m	mixing height, m
L	characteristic length for a buoyant plume = F/U^3, m
Q	heat emission from stack, Mcal/s
S	stability parameter = $\frac{g}{T}\left(\frac{\partial\theta}{\partial Z}\right)$
T	absolute temperature of ambient air, K
U	mean wind speed over the plume height, m/s
X	downwind distance, km
ΔZ	elevation of plume axis above stack top, m
θ	potential temperature of ambient air, °C
ρ	density of ambient air, kg/m
σ_y, σ_z	horizontal and vertical standard deviations of plume spread, m