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HIGH VOLUME FLARING OF SOUR GAS UNDER LIMITED MIXING CONDITIONS

H. WHALEY AND G. K. LEE
CANADIAN COMBUSTION RESEARCH LABORATORY
AND J. G. GAINER
GULF OIL CANADA LIMITED

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H. WHALEY and G.K. LEE, Research Scientists, Canadian Combustion Research Laboratory, Energy, Mines and Resources, Canada, and
J.G. GAINER, Senior Environmental Advisor, Exploration & Production, Gulf Oil Canada Limited

ABSTRACT

In April 1972, an extensive series of Sulphur Incinerator Stack Plume surveys were conducted by Canadian Combustion Research Laboratories using helicopter transported rapid response instruments for Gulf Oil Canada at each of their four major gas plants. The primary objective of the project was to investigate the influence of regional topography on plume rise and dispersion at each site under the prevailing meteorological conditions for morning, midday and afternoon periods. In all but one case, the aerial probes were conducted under optimum plant throughput volumes to evaluate the respective plants' waste management programs.

The exception occurred in the late morning of the first of a two day study at the Strachan plant, where some six hours of emergency flaring provided a unique opportunity to measure the combined incinerator and flare stack plumes, in the midday and afternoon traverses under limited mixing conditions.

Extended surveys were conducted at the Gulf Pincher Creek plant over a two week period in the spring of 1974, but throughout these studies, no emergencies arose to prompt excess flaring and the Strachan aerial probe remains unique in the wide experience of the CCRL staff. This experience includes major thermal power generating stations, Tar Sands plants and smelter operations.

This paper presents a review of the abnormal plant flaring conditions, and the results of dispersion studies conducted under these unique plant emission rates.

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 at Strachan, Alberta in the eastern slopes of the Rocky Mountains.

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.

The paper further describes the dispersion characteristics of the emissions throughout the two-day study period and presents data indicating that a limited 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. 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%. The surrounding topography, which is hilly and forested in all directions, slopes upward from east to west.

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 design parameters as well as the stack and flare emission data for each study, while Figures 1 and 2 respectively, provide profiles of the gas volumes handled and the weight of sulphur emitted under the emergency conditions that prevailed from 1100 h to 1830 h.

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

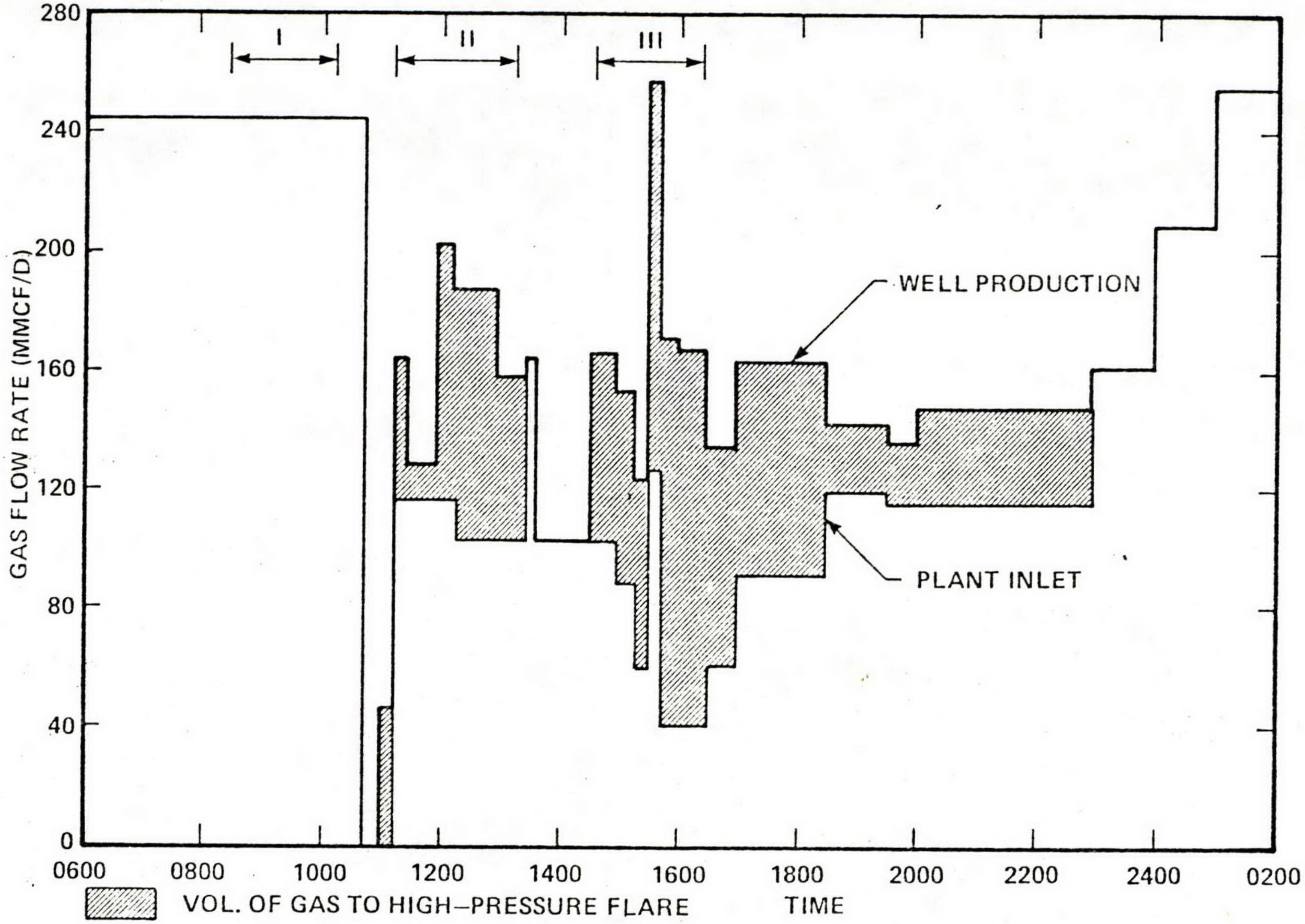


FIGURE 1

GULF STRACHAN GAS PLANT

INLET VOLUMES

(4/23/72 – 4/24/72)

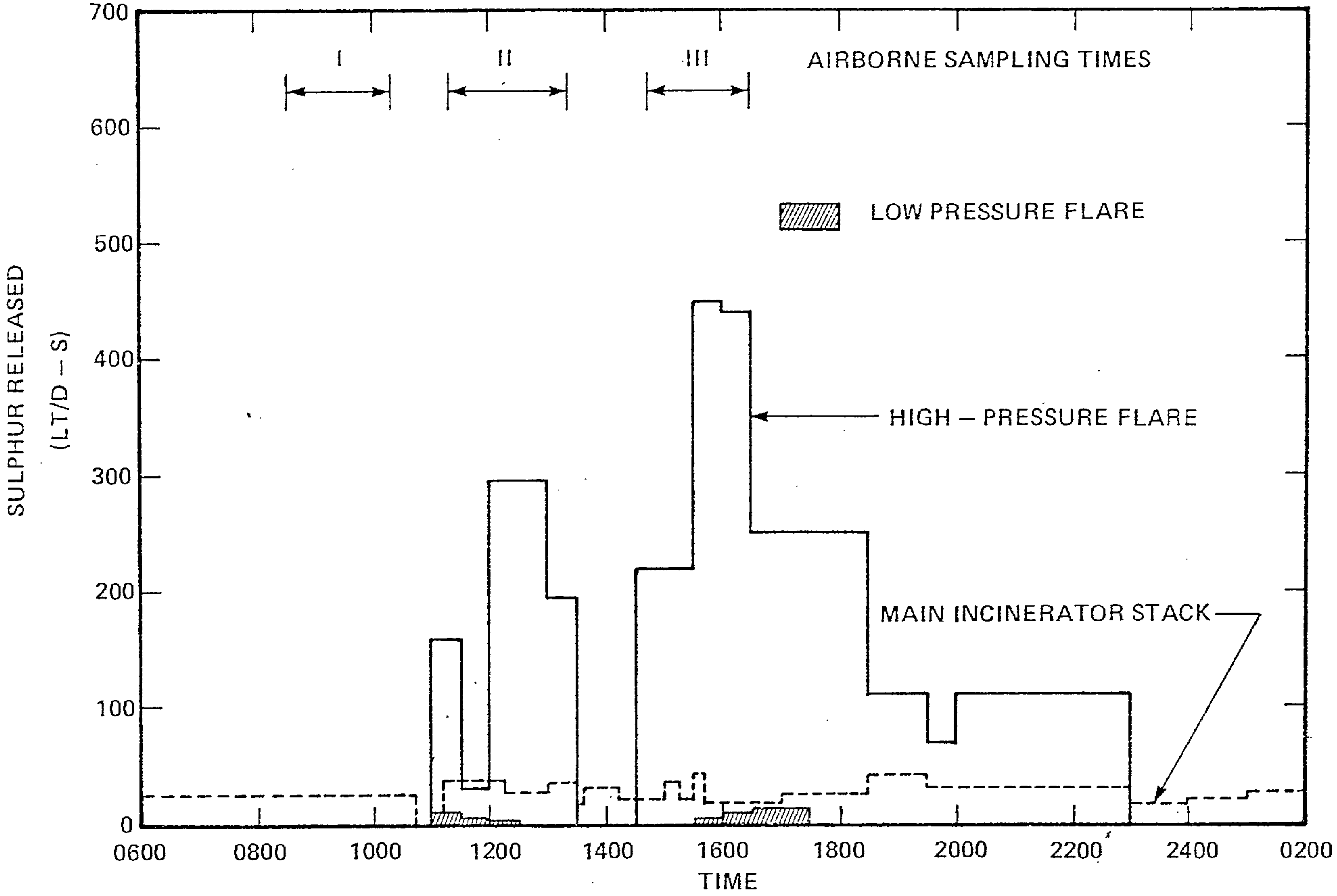


FIGURE 2

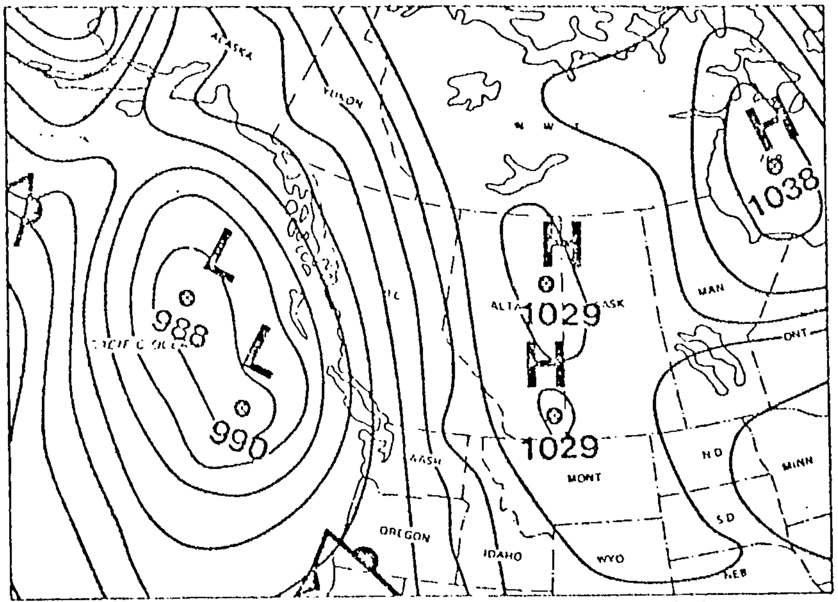
GULF STRACHAN GAS PLANT

EMERGENCY FLARE RATES

(4/23/72 — 4/24/72)

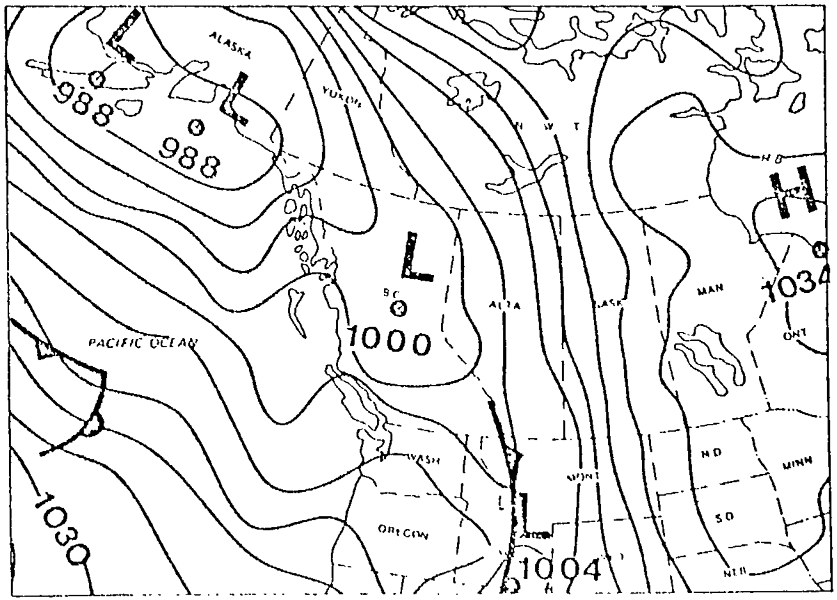
1.2 METEOROLOGICAL CONDITIONS

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 were down slope. A subsidence inversion, based at about 1100m above ground persisted all day with near neutral conditons between the surface and the inversion base; considerable warming of the neutral layer occurred during the day.



SURFACE ANALYSIS 1100 MST APRIL 23th 1972

FROM DATA BY ENTRAL ANALYSIS OFFICE ENVIRONMENT CANADA



SURFACE ANALYSIS 1100 MST APRIL 24 th 1972

FROM DATA BY CENTRAL ANALYSIS OFFICE ENVIRONMENT CANADA

FIGURE 3 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.3 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 constructed. 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 diviations 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 Fig. 4.

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:

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

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

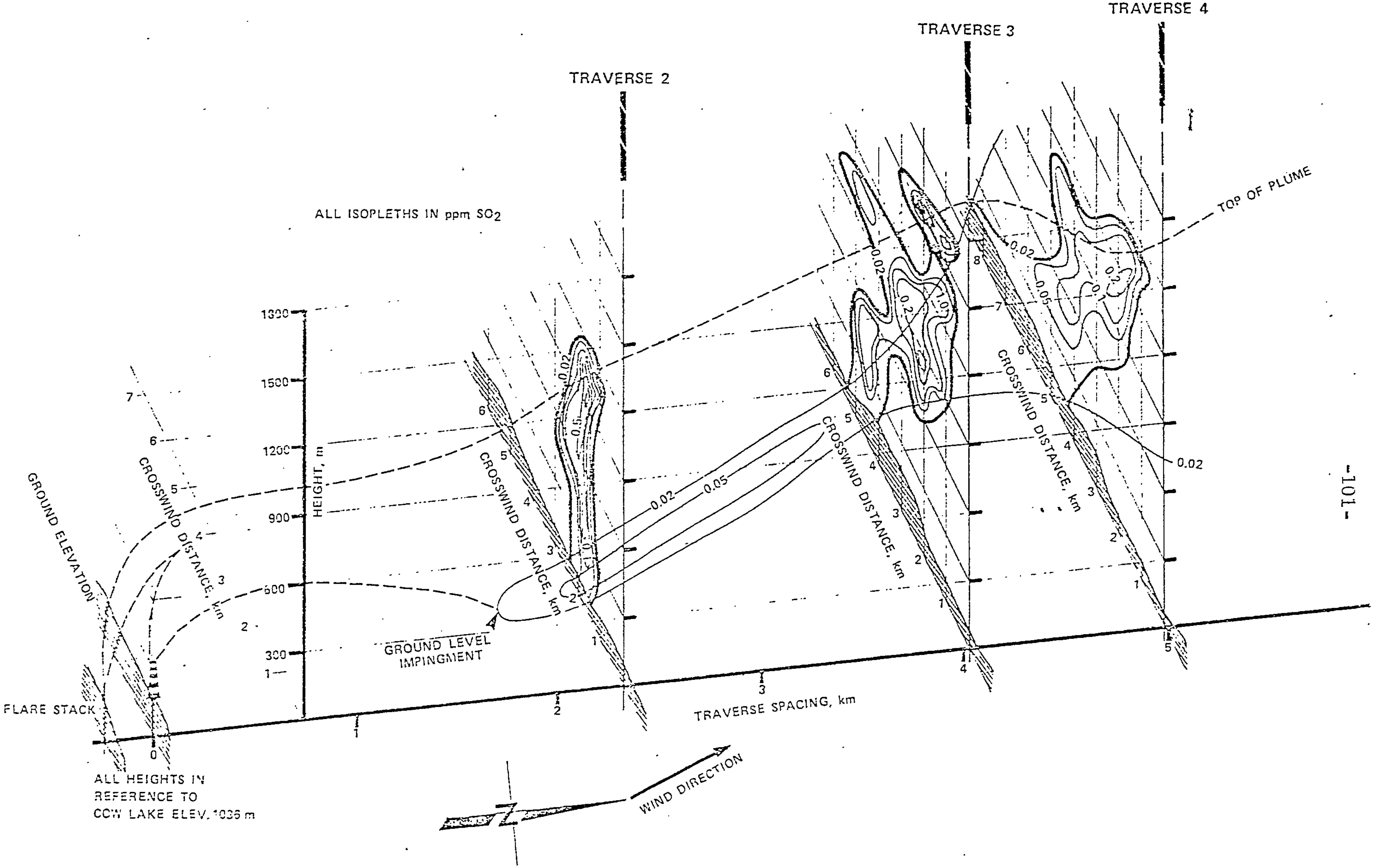


FIG. 4 PICTORIAL VIEW OF THE PLUME, AFTERNOON 23-4-72.

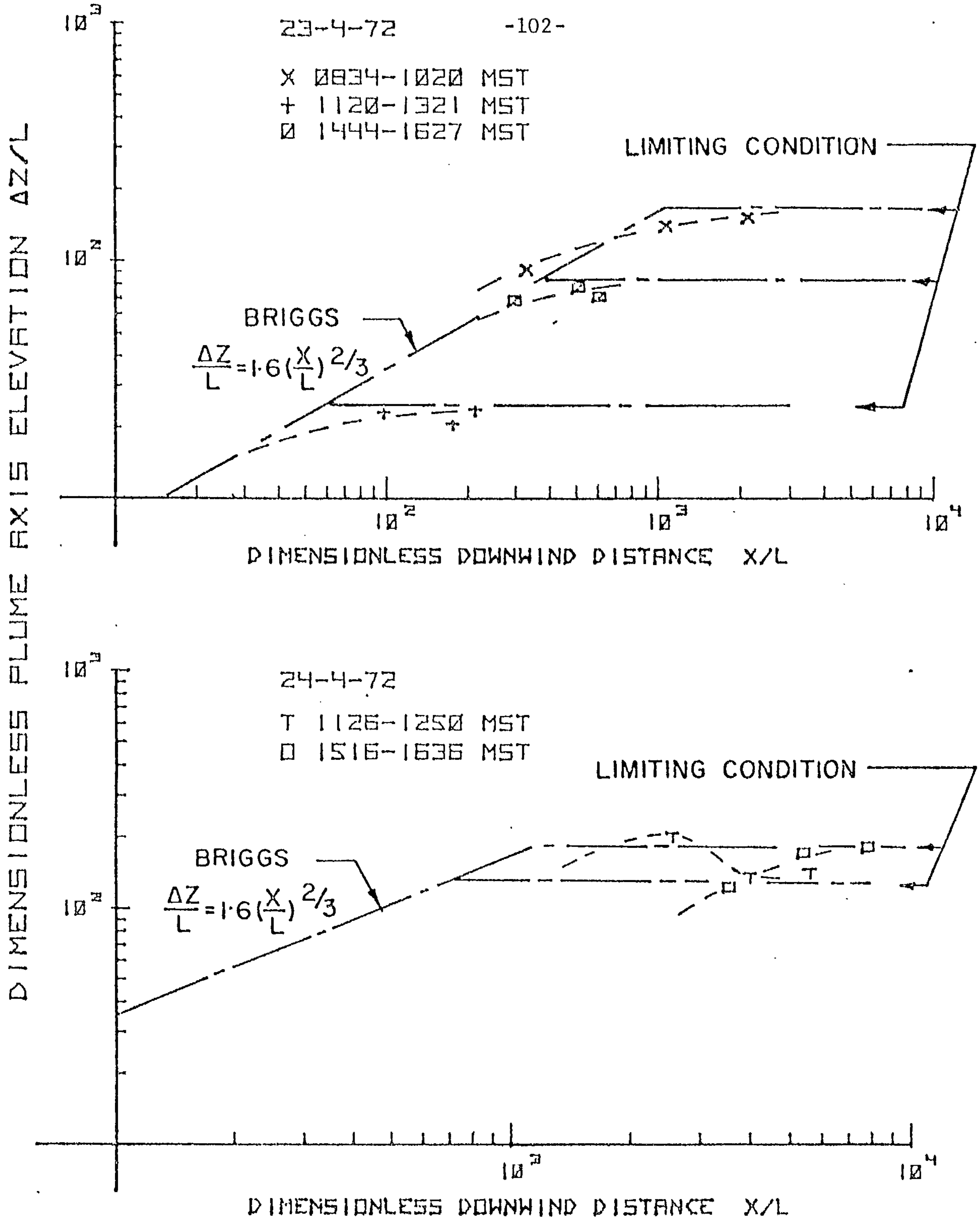


FIG. 5 DIMENSIONLESS PLUME AXIS ELEVATIONS DURING LIMITED-MIXING CONDITIONS.

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. 5. These plots show that most of the data points fall close to the estimated limit for the plume axis 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.

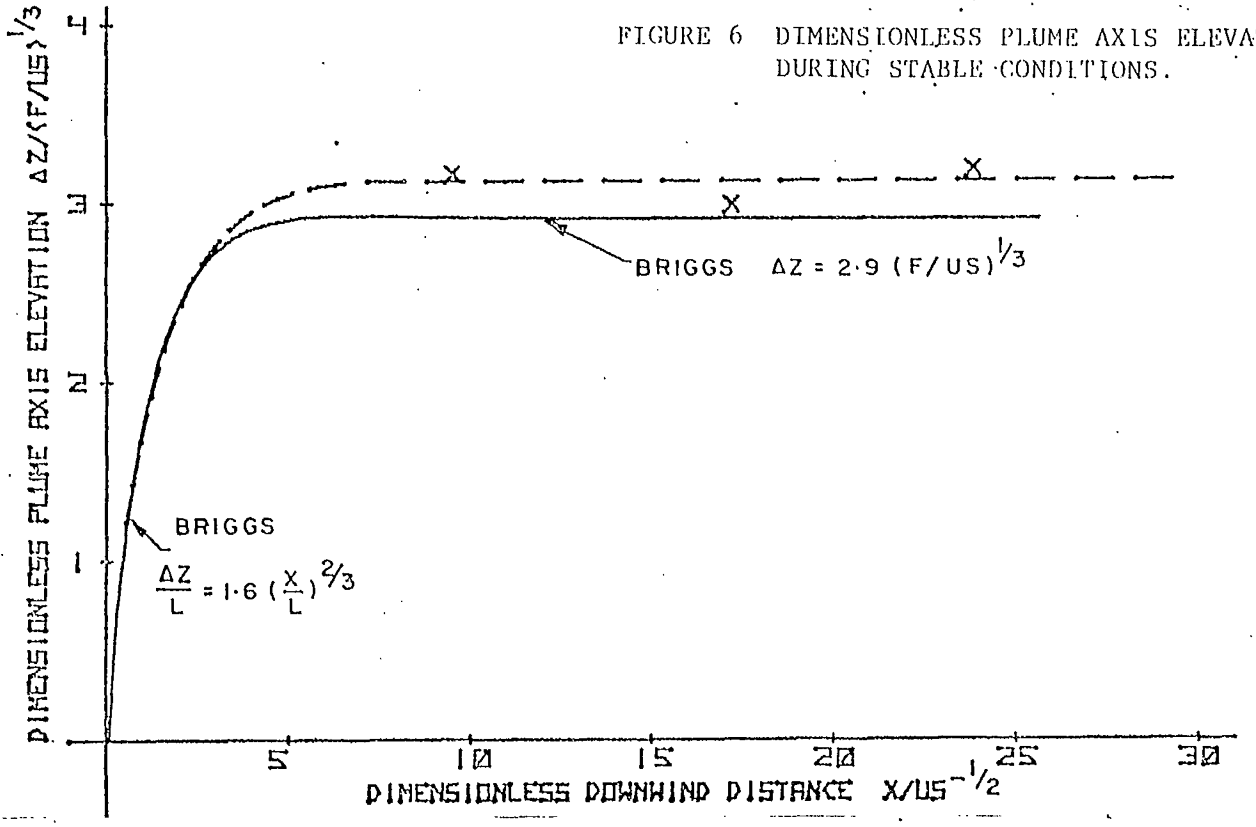


FIGURE 6 DIMENSIONLESS PLUME AXIS ELEVATIONS DURING STABLE CONDITIONS.

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 $+2^{\circ}C/100m$. As shown in Figure 6, 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.

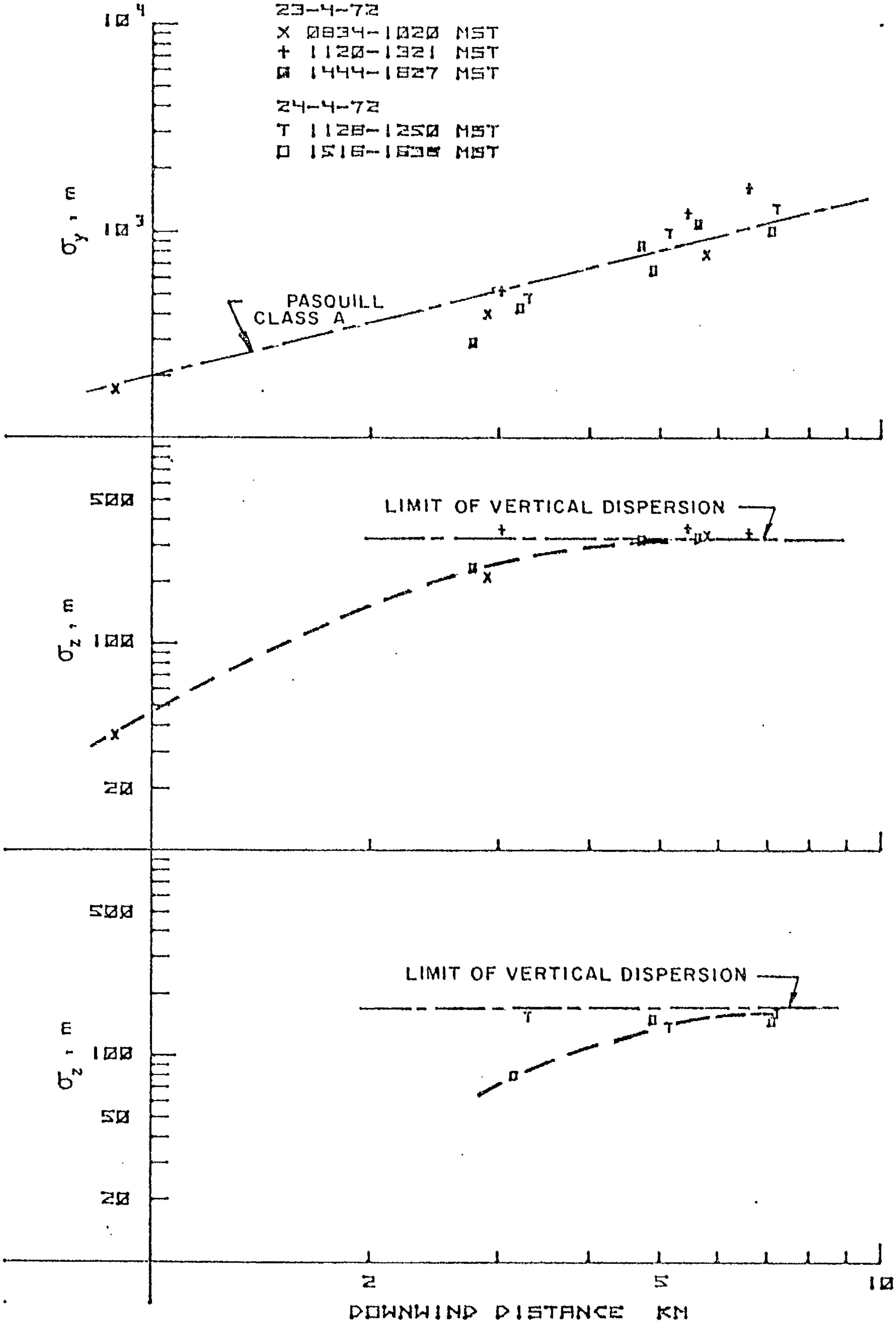


FIG. 7 STANDARD DEVIATIONS OF PLUME SPREAD DURING LIMITED-MIXING CONDITIONS.

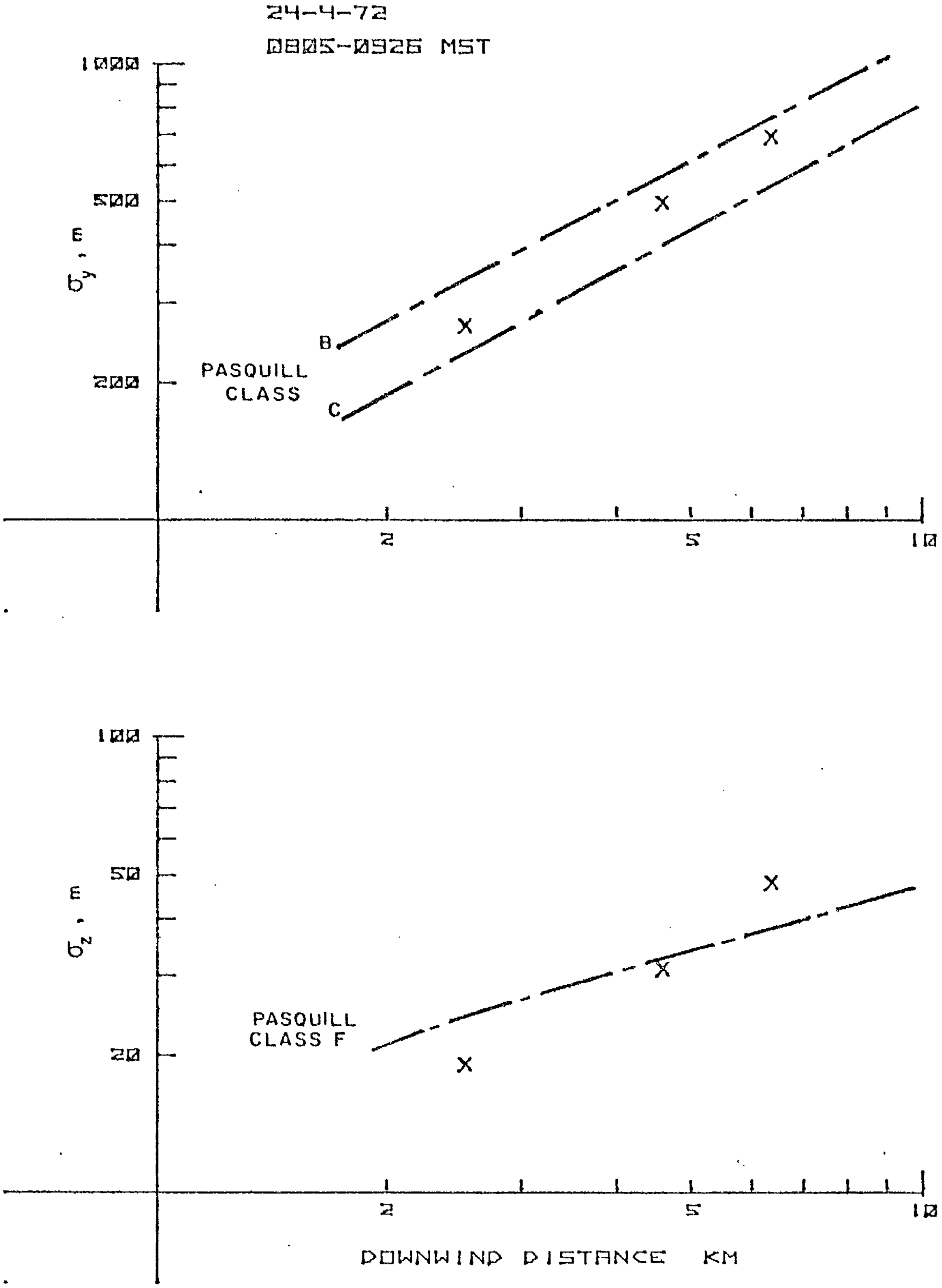


FIG. 8 STANDARD DEVIATIONS OF PLUME SPREAD UNDER STABLE CONDITIONS.

2.2 - PLUME SPREAD PARAMETERS

2.2.1 - Limited-Mixing Conditions

Fig. 7 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.

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 conditons 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. 7 , 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. 8, 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 occurred 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-^{o}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, ^{o}C
ρ	density of ambient air, kg/m
σ_y,σ_z	horizontal and vertical standard deviations of plume spread, m