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# THE BEHAVIOUR OF BUOYANT MERGING PLUMES IN THE ROCKY MOUNTAIN FOOTHILLS

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MARCH 1979

For presentation at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.



ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
ERP/ERL 79-15 (OP) (J)

# THE BEHAVIOUR OF BUOYANT MERGING PLUMES IN THE ROCKY MOUNTAIN FOOTHILLS

By

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

Abstract

Natural gas often contains high concentrations of hydrogen sulfide which must be removed before it can be transmitted by pipeline. Sour gas plants extract the sulfur, by converting it to elemental sulfur through a modified claus process. The sulfur recovery is 93% for small plants (10 - 100 tonnes of sulfur per day) to 99% for large plants (1000 - 4000 tonnes of sulfur per day). The unrecovered sulfur is incinerated giving rise to relatively small emissions of $SO_2$ characterized by high buoyancy and low momentum.

Using a unique aerial probing methodology, plume dispersion studies were conducted on two plants located in the foothills of south western Alberta, Canada. These studies were generally conducted under neutral conditions and with westerly air flows typical of chinook conditions. Notable variations of the plume dispersion parameters from accepted predictive values were found, indicating that such values cannot be used with confidence to estimate plume rise and dispersion in the mountain foothills.

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## Nomenclature

| | | |
|---|---|---|
| Cp | = | specific heat of air at constant pressure, J/kg °C |
| F | = | buoyancy flux = $gQ/\pi Cp\rho T$, $m^4/s^3$ |
| g | = | gravitation constant, $m/s^2$ |
| h | = | height of stack above ground, m |
| L | = | characteristic length for a buoyant plume = $F/U^3$, m |
| Q | = | heat emission from stack, J/s |
| T | = | absolute temperature of ambient air, K |
| U | = | mean transport wind speed, m/s |
| X | = | downwind distance along plume axis, m |
| y | = | crosswind distance, m |
| z | = | height above a reference plane, m |
| Z | = | heightof plume axis above reference plane, m |
| $\Delta Z$ | = | plume axis elevation above stack top, m |
| $\rho$ | = | density of ambient air $kg/m^3$ |
| $\Theta$ | = | potential temperature of ambient air, °C |
| $\sigma_y$ | = | horizontal plume s.d., m |
| $\sigma_z$ | = | vertical plume s.d., m |

## Introduction

A joint industry-government research project to investigate the behaviour of highly buoyant plumes from sulfur plants in the Rocky Mountain foothills was undertaken by Gulf Canada Limited and the Canada Centre for Mineral and Energy Technology (CANMET) of the Department of Energy, Mines and Resources as part of the CANMET Energy Research Program.(1) The research project was undertaken in two phases; firstly, an extensive series of sulfur incinerator plume surveys at four major gas plants operated by Gulf in Alberta and secondly, during the same season two years later, a more detailed study of one of these plants. This latter plant (Gulf, Pincher Creek) was of particular interest since it was located close to the mountains and subject to the moderating effects of chinook winds usually associated with the area in Winter and Spring. In addition the plant emissions were subject to the influence of emissions from a larger gas plant located closer to the mountains.

The first study on these two plants was carried out in mid-April and the second study was also in mid-April, two years later, during a period of reduced throughput at the larger of the two plants.

The two studies involved eight days of aerial probing with flights made during the early morning, mid-day and early afternoon of each day; seven studies were conducted during the earlier period and nine studies two years later.

## Emission Source Data

The two gas plants are located 19 km south of the town of Pincher Creek in south-western Alberta in the eastern Rocky Mountain foothills. The larger plant operated by Shell Canada Limited is located about 5 km due east of the nearest mountain range and the smaller plant operated by Gulf Canada Limited is about 14 km farther east.

At normal load the larger plant emits 200 tonnes per day of sulfur dioxide and 10.9 million mega-joules per day of heat. The smaller plant emits about 14 tonnes per day of sulfur dioxide and 1.8 million mega-joules per day of heat. Details of the actual emissions of sulfur dioxide and heat during the two study periods are given in Table I.

## Meteorological Conditions

During the first study period, which started on April 16, 1972, a minor trough along the Alberta-Montana border produced snow from the early morning until about noon the next day. Early in the afternoon of the 17th, the trough filled and allowed a Pacific ridge that had a surface extension through the Edmonton area to more southward. This resulted in increasing stability with conditions becoming clear and dry by late afternoon. On the 18th April this extension of the Pacific ridge was located along the US-Canada border and all winds aloft were from the west. Under these conditions, dry descending air on the leeward side of the Rockies produced near neutral conditions with gradual warming during the day. By the morning of the 19th April a deep low was centred north of the Alberta-North West Territories border and strong westerly winds prevailed at all levels over most of Alberta.

In the southern regions of the province, where light winds prevailed during the early morning a strong westerly flow did not develop until late in the afternoon. An overnight inversion which extended up to 1200 m, persisted, and was not dissipated by surface heating until the evening. Strong westerly winds continued on the 20th April in advance of a cold front from the north that passed through the Pincher Creek region late in the day. During the morning, the combined effect of strong winds and bright sunshine rapidly dissipated a weak overnight inversion and by noon neutral conditions had again been established. During this period surface temperatures ranged from -3.4°C to 8.6°C and mean wind speeds from 1.3 m/s to 13.3 m/s.

The second study period began on April 19, 1974. On this day a well developed surface coldfront along the continental divide was responsible for heavy cumulus cover over the dispersion zone. Winds were predominantly westerly at the ground with a pronounced wind shift at about 1200 m above ground. With passage of the cold front in the afternoon, clearing occurred and westerly flow prevailed at all levels. On 20th April a high centred off the Pacific coast of the United States resulted in weak ridging over the study area. Throughout the day the surface winds were westerly and relatively strong due to a surface low centred over south-eastern Alberta. By April 21st the surface low had moved to western Saskatchewan and a well developed ridge at surface and mid-levels was present over southern and south-eastern British Columbia. This situation favoured the development of chinook conditions which are characterized by strong low and middle-level inversions and pronounced leeward subsidence. The general wind direction was westerly but not as strong as the preceding day. Throughout April 22nd, the ridging was present at all levels over the study area, and the "Chinook Arch" was observed at Pincher Creek. Winds were again westerly at all levels, but a shift at noon resulted in southerly winds in the surface and mid-levels until late afternoon.

A cold front passed eastward through the region during the early morning of April 23rd and by noon a second cold front was lying west of Pincher Creek resulting in an upslope wind field. Ridging was noted west of the continental divide. During the late morning the winds at the Pincher Creek plant site were northerly to north easterly at the surface and southerly at levels above 100 m. Surface temperatures ranged from 2.3°C to 15.6°C during this study period with mean wind speeds varying from 2.7 m/s to 12.5 m/s. A summary of the meteorological parameters during the two study periods is given in Table II.

## Plume Dispersion Data

The procedure used for obtaining three-dimensional data on plume dispersion together with the local meteorological parameters has been described in detail previously [1]. Briefly, during each two and half hour flight, detailed $SO_2$ profiles at three or more downwind locations are obtained using simultaneously deployed and coordinated helicopter and automobile-borne probes. In this study because of the influence of inflow $SO_2$ from the Shell Waterton plant, a crosswind traverse was obtained upwind of the Gulf Pincher Creek plant. Then two or more traverses were made on the plumes from each plant, depending on the degree of plume co-mingling. On two occasions during the second study, the wind was from the south-east and no measurements on the Shell plant were taken. Each crosswind section was analyzed by a rigorous finite difference method to obtain both the plume-axis elevation downwind distance and the horizontal and vertical standard deviations of plume spread (2).

## Plume Axis Elevation

All measurements of plume axis elevation during the two study periods were obtained under neutral or nearly-neutral conditions. Infrequent or weak atmospheric stratification was not observed to be a restriction on plume axis rise. Virtually all measurements obtained were beyond the levelling-off point at X = 10 h suggested by Briggs (3). Examination of the data from both plants revealed that no levelling-off had occurred at the traverses selected, a finding which is contrary to findings elsewhere in Canada (4,5,6,7,8). All the data were therefore plotted and regression analysis showed a steeper slope with a lower constant than that of Briggs as shown in Figure 1. The steeper slope of the data points shows that neither of the plumes exhibited a tendency to level-off. The fact that almost all the data falls below the Briggs equation in Figure 1 has been observed in other studies in Canada (4-8), however, it must be emphasized that in those studies, only data obtained in the region of buoyancy-dominated plume rise (X<10h) were considered.

## Plume Standard Deviation

The data on the horizontal and vertical plume spread parameters are shown in Figures 2 and 3 respectively. To give some indication of how the data compare with accepted methods of prediction, the Pasquill-Gifford curves as modified by Bowne have been plotted. Pasquill has proposed six stability classes ranging from unstable Class A, to very stable Class F, and it is convenient to use these for comparative purposes. All data gathered in these studies were obtained under neutral or nearly-neutral conditions and would be represented by Pasquill Class D or E.

Figure 2 shows a complete separation of the Pincher Creek and the Waterton horizontal s.d. data despite the proximity of the plants; both data sets have the same but shallower slope than Pasquill, a result which reinforces earlier findings(4-8). The horizontal s.d. for Pincher Creek is wider than Pasquill Class A, indicating an extremely wide horizontal spread for neutral conditions; this also substantiates information obtained previously. However, the Waterton horizontal s.d. is narrower than Pasquill Class F indicating that horizontal plume spread was severely restricted by factors other than atmospheric stability. In general, the authors have found that neutral plumes in other regions of Canada are wider than Pasquill by about two stability classes, i.e. Class D would behave approximately as Class B.

In the case of vertical standard deviation, Figure 3 shows that the data from both plants lies between Pasquill Classes A and C indicating that the plume is much thicker than that suggested by neutral Class D. This finding again is the opposite to data obtained elsewhere in Canada, except when topographic factors prevailed (6). Over normal terrain, earlier neutral studies have shown that plumes tend to behave in the vertical as Class D at large downwind distances (>5 km) but closer to the source as Class C or B, giving a shallower slope than the Pasquill curves. In the Pincher Creek area, the vertical s.d. data, which show no flattening with distance, are greater than would be expected over the entire range of downwind distances studied.

## Discussion of Plume Dispersion Data

Chinook winds which pass over the mountains upwind of the study area bring moderating temperatures to the downwind slope. Meteorologists in southern Alberta have found that both thermal and topographic vertical turbulence induced by the mountains, persists beyond the Alberta-Saskatchewan border 290 km to the east. Conversely, horizontal turbulence induced by channelling through the mountain passes has been found to be a very local effect which persists for less than 15 km from the mountains. The Waterton plant is therefore strongly influenced by this horizontal channelling and the Pincher Creek plant only weakly, if at all. Effectively the Waterton plume is kept from spreading by a very strong channelled flow induced by mountain passes immediately upwind. This effect has dissipated by the time the airflow reaches the Pincher Creek plant, and relatively normal horizontal spread can take place. However, the vertical turbulence, being more persistent, influences both plants alike and enhances the vertical s.d.'s measured over the full dispersion zone studied. The vertical s.d. data from the plants exhibit enhanced vertical spread due to the turbulence induced by the air passage over the mountains.

## Conclusions

The behaviour of highly buoyant, low momentum plumes from two natural-gas sulfur extraction plants located in the foothills of the Canadian Rockies was strongly influenced by geographic factors including regional topography and chinook winds.

1. Plume axis elevations did not exhibit the usual levelling-off tendency in neutral conditions. Derived plume rise values were generally lower than estimated by the Briggs' neutral formula but agreement with the two-thirds power law dependence with downwind distance was observed. This conclusion reinforces findings made elsewhere in Canada in different climatic regions.

2. The derived standard deviations of plume spread showed significant differences from those indicated by Pasquill. Local channelling of air flow resulted in reduced plume width at the plant situated closest to the mountains with horizontal s.d. values, in general, less than Pasquill Class F. For the smaller plant, located farther from the mountains, the horizontal s.d. data were in excess of Pasquill Class A and agreed with studies made in flatter terrain. Vertical turbulence induced by the mountains persisted over the entire dispersion zone and resulted in enhanced vertical mixing with vertical s.d.'s corresponding to Pasquill Class B rather than Class D.

3. It is clear that application of the standard methods of predicting, to the RockyMountain foothills which are subjected to frequent chinook winds, will result in gross errors in estimated ground level impact concentrations.

Acknowledgements

The generous support of the technical staff at the Pincher Creek plant of Gulf Canada Limited during both studies are acknowledged with thanks. In addition, the authors wish to acknowledge the assistance received from Shell Canada Resources Limited. Appreciation is also expressed for the detailed meteorological data provided by the Atmospheric Environment Service, Suffield, Alberta and by Intera Weather Consultants, Calgary, Alberta, and for the active cooperation of the Alberta Department of the Environment and the Alberta Energy Resources Conservation Board.

List of Figure Captions

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TABLE I. EMISSIONS OF HEAT AND $SO_2$
FROM THE TWO PLANTS DURING THE STUDY PERIOD

| Study Period | Flight | Time Period | Pincher Creek Plant | | Waterton Plant | |
|---|---|---|---|---|---|---|
| | | | $SO_2$, $sm^3/s$ | Heat Mcal/s | $SO_2$, $sm^3/s$ | Heat Mcal/s |
| 1: 17/04 | 1 | 1600 - 1830 | 0.026 | 5.10 | 0.979 | 28.75 |
| 18/04 | 2 | 0800 - 1030 | 0.060 | 5.07 | 0.997 | 29.56 |
| 18/04 | 3 | 1500 - 1800 | 0.068 | 5.05 | 0.997 | 29.41 |
| 19/04 | 4 | 0730 - 1030 | 0.068 | 5.05 | 0.988 | 29.09 |
| 19/04 | 5 | 1300 - 1530 | 0.060 | 5.02 | 0.988 | 28.91 |
| 19/04 | 6 | 1600 - 1830 | 0.068 | 5.01 | 0.988 | 28.84 |
| 20/04 | 7 | 0900 - 1200 | 0.060 | 5.04 | 0.903 | 28.72 |
| 2: 19/04 | 1 | 1300 - 1530 | 0.083 | 1.21 | 0.803 | 26.09 |
| 20/04 | 2 | 0600 - 0900 | 0.094 | 1.22 | 0.457 | 25.87 |
| 20/04 | 3 | 1000 - 1300 | 0.085 | 1.22 | 0.457 | 25.86 |
| 20/04 | 4 | 1500 - 1830 | 0.085 | 1.21 | 0.457 | 25.67 |
| 21/04 | 5 | 0600 - 0900 | 0.089 | 1.23 | 0.421 | 25.45 |
| 21/04 | 6 | 1400 - 1730 | 0.084 | 1.21 | 0.421 | 25.05 |
| 22/04 | 7 | 0600 - 0900 | 0.088 | 1.21 | 0.472 | 25.68 |
| 22/04 | 8 | 1300 - 1500 | 0.087 | 1.20 | 0.472 | 25.34 |
| 23/04 | 9 | 0930 - 1130 | 0.087 | 1.21 | 0.374 | 25.27 |

TABLE II. ATMOSPHERIC PARAMETERS MEASURED DURING THE STUDY PERIODS

| Study Period | | Flight | Wind Speed m/s | Wind Direction | Ambient Temp °C | $\frac{\partial\Theta}{\partial Z}$ °C/100 m | Height Interval m | Atmospheric Stability |
|---|---|---|---|---|---|---|---|---|
| 1: | 17/04 | 1 | 1.3 | 135 | -3.4 | 0.39 | 0 - 1800 | Neutral |
| | 18/04 | 2 | 4.6 | 261 | -0.9 | 0.17 | 0 - 1800 | Neutral |
| | 18/04 | 3 | 7.1 | 298 | 2.2 | 0.14 | 0 - 1800 | Neutral |
| | 19/04 | 4* | 3.9 | 288 | 3.3 | 0.73 | 0 - 1000 | Isothermal |
| | | | | | | 1.00 | 1000 - 1150 | Isothermal |
| | 19/04 | 5* | 10.4 | 291 | 7.2 | 0.34 | 0 - 1050 | Neutral |
| | | | | | | 1.08 | 1050 - 1200 | Isothermal |
| | 19/04 | 6 | 13.3 | 280 | 8.6 | 0.33 | 0 - 1100 | Neutral |
| | 20/04 | 7 | 9.9 | 290 | 5.7 | 0.41 | 0 - 1800 | Neutral |
| 2: | 19/04 | 1 | 2.9 | 256 | 11.0 | 0.09 | 0 - 2000 | Neutral |
| | 20/04 | 2 | 12.5 | 257 | 4.4 | 0.23 | 0 - 2000 | Neutral |
| | 20/04 | 3 | 12.5 | 248 | 4.7 | 0.16 | 0 - 2100 | Neutral |
| | 20/04 | 4 | 11.5 | 272 | 8.6 | 0.13 | 0 - 2100 | Neutral |
| | 21/04 | 5 | 7.7 | 294 | 2.3 | 0.21 | 0 - 2000 | Neutral |
| | 21/04 | 6* | 8.5 | 263 | 10.7 | 0.10 | 0 - 1550 | Neutral |
| | | | | | | 2.54 | 1550 - 1750 | Stable |
| | 22/04 | 7 | 4.8 | 259 | 8.4 | 0.35 | 0 - 2000 | Neutral |
| | 22/04 | 8 | 6.2 | 187 | 15.6 | 0.05 | 0 - 2000 | Neutral |
| | 23/04 | 9* | 2.7 | 092 | 11.6 | 0.26 | 0 - 830 | Neutral |
| | | | | | | 1.16 | 830 - 1180 | Isothermal |

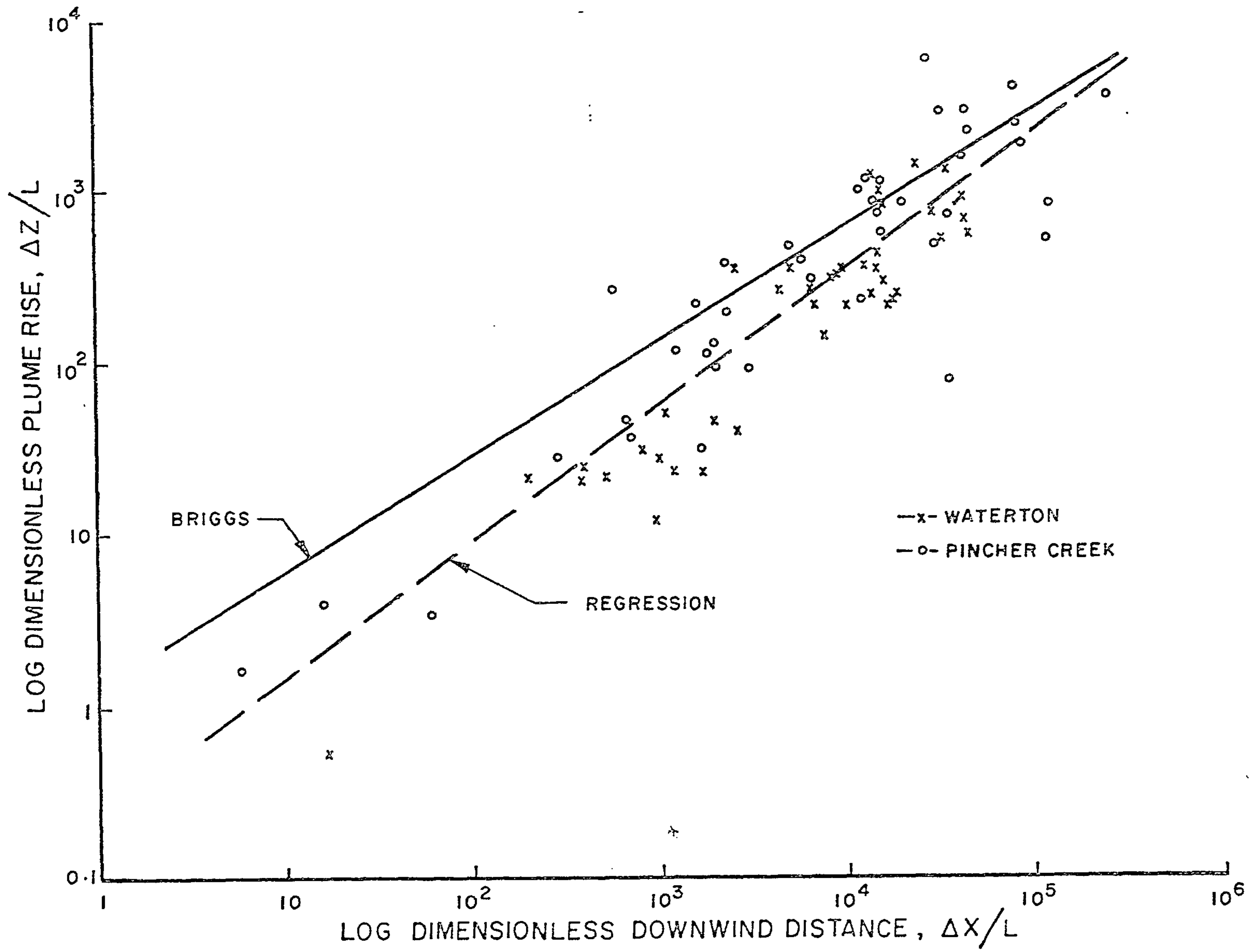


FIGURE 1. Comparison of measured plume rise data with Briggs; Pincher Creek and Waterton.

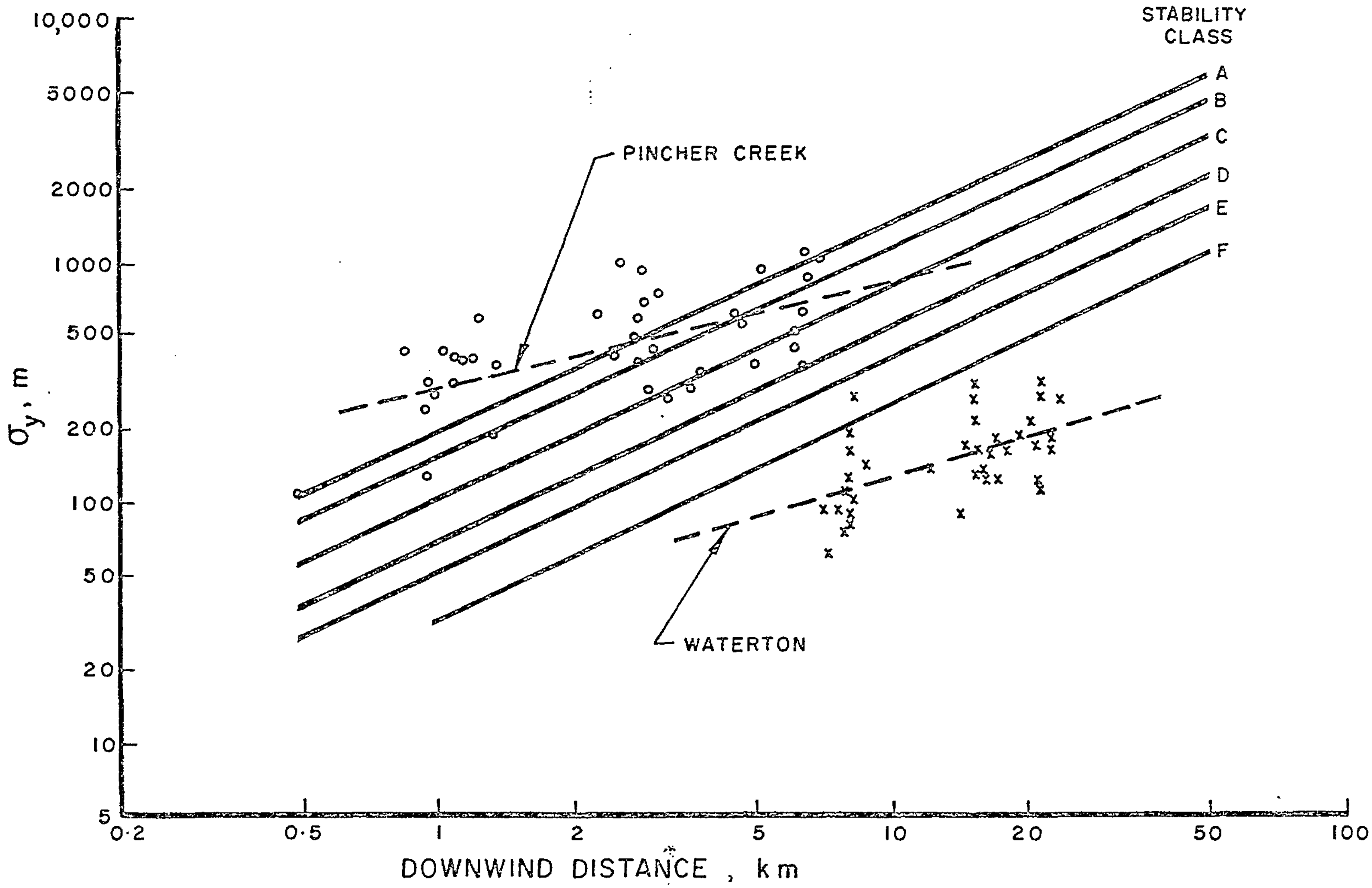


FIGURE 2. Plot of horizontal s.d.'s against downwind distance, solid lines represent P.G. curves as modified by Bowne.

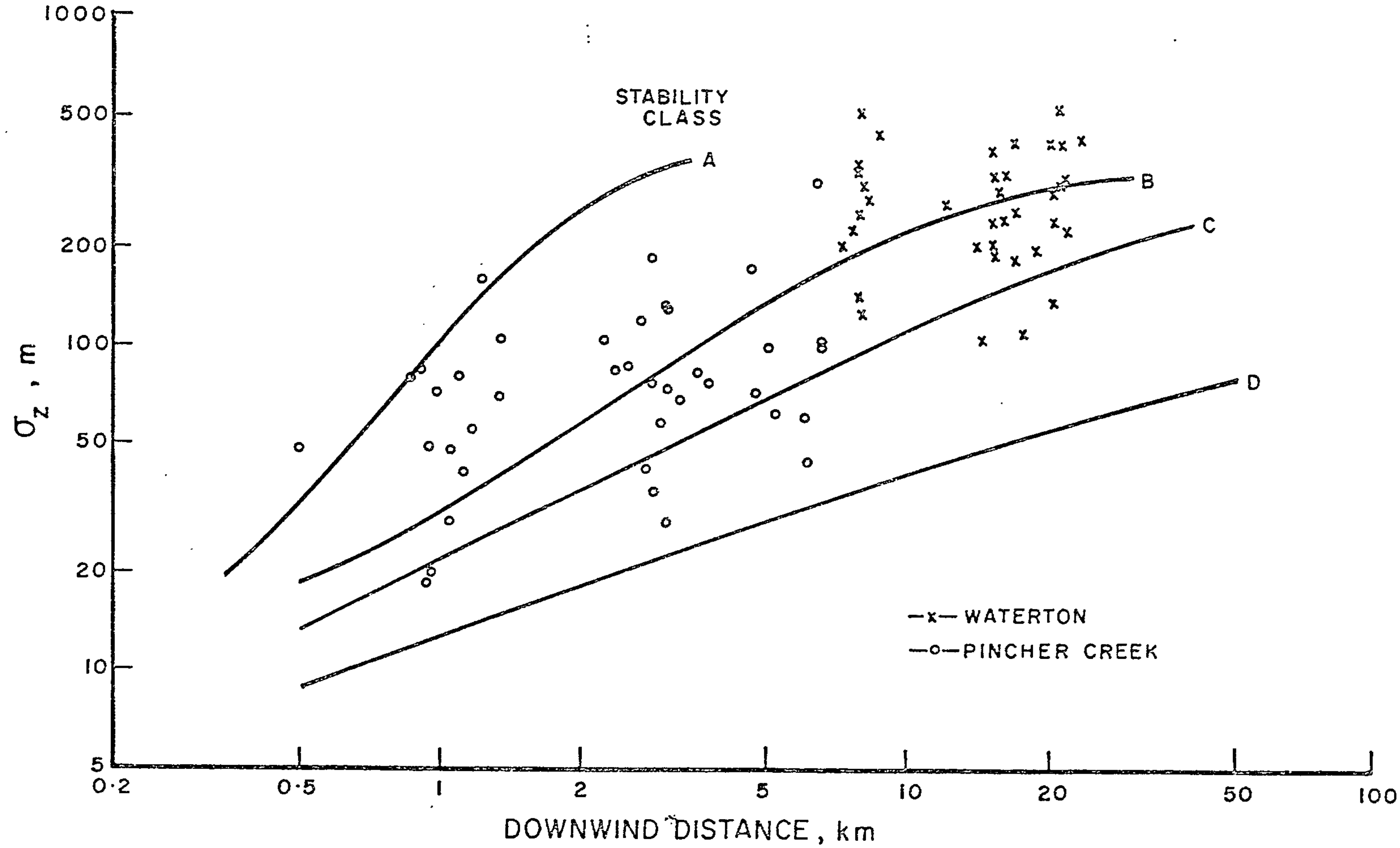


FIGURE 3. Plot of vertical s.d.'s against downwind distance, solid lines represent P.G. curves as modified by Bowne.