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EVALUATION OF THE CORRELATION SPECTROMETER AS AN AREA SO_2 MONITOR

Environmental Sciences Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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EVALUATION OF THE CORRELATION SPECTROMETER AS AN AREA SO_2 MONITOR

by

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Section 1

INTRODUCTION

Environmental Measurements, Inc. (EMI) conducted a field evaluation of the Barringer Correlation Spectrometer (COSPEC)* at a pulverized coal fired power plant in the southwestern United States. The work was funded by the Environmental Protection Agency (EPA) under Contract No. 68-02-1773. This contract was designed to contribute to the EPA's investigation of remote sensing instrumentation and methodology for stationary source emissions.

BACKGROUND

One of the active programs of the Environmental Protection Agency is the investigation of remote sensing instrumentation and methodology for electro-optical techniques in which the analyzer is physically removed (up to a thousand meters or more) from the source being investigated.

The COSPEC is a remote sensing system designed to measure sulfur dioxide and/or nitrogen dioxide by absorption phenomena using scattered sunlight as an energy source. The manufacturer's literature states that the instrument is capable of monitoring SO_2 or NO_2 from a source in three modes:

- In a helicopter or airplane, flying in the vicinity of the source plume with the COSPEC viewing downward;
- In a stationary mode at ground level by sighting the tripod-mounted instrument on the plume;
- In an upward or vertical looking mode from ground level by mounting the instrument in a vehicle and traversing the perimeter of the stationary source property.

EPA personnel have already evaluated the stationary mode at ground level. It is the third mode, the ground level moving measurements, that was investigated in this contract.

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*COSPEC is a registered name of the manufacturer, Barringer Research, Ltd., Toronto, Canada; the various models are described in Section 5.

PURPOSE

The purpose of this contract was to determine the relative accuracy of an EPA-furnished COSPEC II as a perimeter monitor for SO_2. The accuracy of the COSPEC II was compared to total pollutant burden measurements made using the compliance test methods for SO_2 concentration (Method 6, FR 23 December 1971) and for volumetric stack gas flow rate (Methods 1, 2, 3 and 4, FR 23 December 1971), and a cross-stack SO_2 continuous monitor. In addition, comparisons were made between the EPA COSPEC and two other COSPECs provided by the contractor and the manufacturer.

Section 2

SUMMARY

EQUIPMENT

Three correlation spectrometers were used to gather field data for a two week period at a pulverized coal fired power plant. A COSPEC II (Government-furnished), a COSPEC III (supplied by the contractor) and a COSPEC IV (supplied by the manufacturer) were installed in a moving laboratory to make simultaneous measurements of SO_2 in the power plant plume. The measurements were made by the upward viewing COSPECs as the moving laboratory was driven under the plume, while in-stack measurements were being conducted. Concurrent winds aloft measurements were made with a balloon theodolite.

MEASUREMENTS

The testing of the instruments involved the following activities:

- Thirty-five Method 6 SO_2 measurements and Method 2 stack gas velocity measurements were made over 20 minute periods for six days. The in-stack measurements were conducted in the single active stack by Pacific Environmental Services, Inc. (PES), a subcontractor.

- The COSPEC remote sensors made 465 individual plume measurements. There are a total of 42 hours of reported COSPEC data; 11.6 hrs. of concurrent remote/in-stack measurements resulted.

- A total of 120 pilot balloon measurements were made; they were analyzed to determine wind parameters for SO_2 mass flux calculations.

DATA PROCESSING

The COSPEC measurements were processed by computer. The moving laboratory traverse routes and the analog chart records of instrument SO_2 response were digitized. The data sets were merged into a matrix: X, Y coordinates and COSPEC SO_2. The pilot balloon (pibal) data were processed to determine wind speeds and directions within the dispersing plume. The final results, the calculation of SO2 mass flux, were computed from the geography/COSPEC data matrix and the wind speed and direction information.

COMPARISON OF RESULTS

The remote sensor and in-stack measurements were tabulated in common units of SO_2 mass flux (metric tons per day). Comparison of the COSPEC results with the EPA reference method (the cross-stack continuous monitor data were not processed) required further processing of the raw data. The COSPEC SO_2 fluxes were averaged over the 20 minute periods during which in-stack data were collected; the Method 6/ Method 2 SO_2 fluxes were augmented to account for gas not detected by the stack sampling but possibly measured by the remote sensor. Both intercomparisons between the two COSPEC instruments and comparison between the remote and in-stack methods were made using standard statistical procedures.

Section 3

CONCLUSIONS

This COSPEC evaluation shows that the instrument, when used with a single balloon theodolite to measure winds, can remotely measure SO_2 emissions with a relative accuracy of ±24%. Improvements in the accuracy of wind speed measurements would improve the relative accuracy of the remote sensing system. The methodology warrants further evaluation.

The specific conclusions drawn from the analysis of the concurrent remote sensor/in-stack measurements are:

- COSPEC Internal Consistency - The COSPEC produced consistent results, instrument to instrument; close agreement was obtained for COSPECs II, III and IV.
- COSPEC Relative Accuracy - The eight days of COSPEC SO_2 emission rates agreed within 1.5% of the six day Method 6 average; statistically, the COSPEC SO_2 mass flux could differ ±24% from the reference method using single theodolite pilot balloon wind speeds and 20-minute averages.
- COSPEC Precision - Eleven 20-minute samples of COSPEC remote sensing (four hours of plume measurements) are required to achieve a ±25% error with 95% confidence.
- Wind Measurement Errors - Increased frequency and accuracy of measuring winds aloft would improve the accuracy of COSPEC remote measurment of SO_2 emissions.

A discussion of each of these conclusions follows:

COSPEC INTERNAL CONSISTENCY

The COSPEC remote sensor, when used as an area monitor for SO_2, provides consistent results from instrument to instrument. Strong correlations were found (r = .90 - .95) between the calculated SO_2 emission rates for the three COSPECs tested. The emission rates (averaged over 20-minute periods) compared favorably even though individual (single-plume crossing) values fluctuated widely.

These fluctuations in individual readings were caused by fluctuations in wind speed and by possible variations in plant conditions indicated by varying Method 6 results. The pilot balloon data provided average, representative wind speeds for each remote sensing test period, not instantaneous wind data for each COSPEC plume crossing; also, the single theodolite system is inherently less accurate than other methods. However, the limitations of the single theodolite pibal measurements did not affect the intercomparison between instruments because the wind data were applied uniformly to all three COSPECs.

The internal consistency of the remote sensing measurements and the data processing procedures used in this study were demonstrated. Similar results were obtained with the three instruments, independent of model. However, closer agreement was found between the more recent COSPEC III and IV models.

COSPEC RELATIVE ACCURACY

Single COSPEC plume measurements of 5-to-90 seconds duration did not yield valid mass flux results because of the changing character of the plume. Averaging 20-minutes of COSPEC plume crossings improved the estimate of mass emissions; but the results were flawed by errors in determining the wind speed. Hourly and daily averages improved the results by increasing the number of both plume crossings and wind measurements. The longer the averaging time the closer agreement there was between the remote and in-stack methods.

The eight-day average SO_2 emission rates (in metric tons per day) for COSPECs II, III and IV were 52.46 MT/D, 52.99 MT/D and 51.76 MT/D, respectively. They agree within 1.5% of the in-stack six-day average (adjusted to add the estimated 15% emissions not measured in the main stack) of 52.22 MT/D. These averages, while not a direct day-for-day comparison, indicate that the two methods were providing comparable results in the long term.

The statistics derived from data obtained in this project suggest that for COSPEC remote sensor data, the true percent difference between the average COSPEC SO_2 mass flux and that of the reference method (Method 6) would fall within ±24%, using 20-minute averaged data in both cases. This "24% relative accuracy" estimate would be improved with refinements in the wind data.

COSPEC PRECISION

The use of COSPEC data in the short term must be restricted to averaging a minimum of 20-minutes of measurements--just as the in-stack data were averaged over 20-minute periods. To determine whether significant improvement in accuracy would occur for hourly- or daily-averaged data an extensive statistical analysis was performed on the paired remote/in-stack data.

The number of 20-minute samples required to achieve various percent error intervals at selected confidence levels were calculated. For example, seventeen samples are required (in the worst case) to be 95% confident that the average percent error (i.e. difference between COSPEC and Method 6) differs by no more than ±20% from the actual (i.e. long-term average) percent difference between COSPEC and Method 6 results. this precision can be achieved in a single day of measurements.

WIND MEASUREMENT ERRORS

The results suggest that the true relative accuracy and precision of the COSPEC measured SO_2 emissions is masked by other errors, principally errors in determining wind speed at the elevation of the plume. The number of plume measurements was large enough (465 over six days) to produce long-term average results comparable to the stack sampling method. A wide spread in the COSPEC data was caused by insufficient wind information. The present data base does not readily allow separation of the COSPEC SO_2 error and the pilot balloon wind speed error. However, it can be concluded that increased frequency and improved accuracy in measuring wind speed within the COSPEC-sensed plume would directly improve the accuracy of the remote sensing SO_2 mass flux calculations.

Section 4

RECOMMENDATIONS

The results of this project show the relative accuracy of the remote sensing COSPEC is better for long-term than short-term data collection periods and the true accuracy is masked by the unmeasured fluctuations in wind speed at the elevation of the measured plume. Other factors may have contributed to the cumulative error of the COSPEC results, as well. Existing information could be studied to extend the analysis and clarify the COSPEC accuracy. Examination of the following eight areas is recommended:

- Wind measurement accuracy - use existing data and new methods to improve accuracy
- COSPEC calibration - check calibration cells for accuracy
- Cross-stack monitor results - process data and compare with COSPEC
- Stationary COSPEC data - compute SO_2 mass flux and compare with moving COSPEC results
- COSPEC/SKY orientation - determine cause of instrument error and effect on accuracy
- Sampling protocols - narrow averaging times for statistical analysis
- Plume geometry - correlate plume shape to accuracy
- Archival COSPEC data - analyze other measurements for relative accuracy.

The first five areas deserve the greatest emphasis because they would yield the most useful new information. The last three are pertinent but are relatively less important. Each of the recommended areas is discussed separately in detail.

WIND MEASUREMENT ACCURACY

The use of the single balloon theodolite wind measuring system limited the accuracy of wind speed data used to calculate SO_2 mass flux from COSPEC remote sensor data. The variable wind conditions caused errors, also. The gusty winds experienced at the study site were typical of a change-in-season wind regime. The high winds threatened to cancel or shorten the in-stack monitoring. It is not surprising that the results show a significant perturbation of the flux calculations attributable to the gusty winds.

The problem of wind measurement is clarified when it is understood that this study compares the accuracy of the COSPEC and wind measurements together, with the Method 6 concentrations and the Method 2 stack gas flow measurements. The calculation of SO_2 emission rates (mass flux) by both methods involves essentially two basic measurements: the concentration of SO_2 and the flow rate of gas. For comparison the two formulas are:

$$SO_2 \text{ Mass Flux} = C_{\text{Method 6}} * Q_{\text{Method 2}} * K \qquad \text{(page A - 18)}$$

$$SO_2 \text{ Mass Flux} = C_{\text{COSPEC}} * v_{\text{PIBAL}} * K * D * A \qquad \text{(page 7 - 7)}$$

The C terms are SO_2 concentrations as measured by Method 6 and the COSPEC; the Q term is the Method 2 flow rate of gas in the stack (ft^3/hr), and v is the pibal wind speed in the plume (m/s). The constants (K) can be ignored in the present analysis; the D and A terms (distance, and wind/road angle in the COSPEC equation) contribute errors, but they are known to be on the order of ±7%. Therefore, to determine the relative accuracy of the COSPEC requires a comparison of the accuracies of the concentration and flow terms.

The three-COSPEC flux results have a high correlation; it is assumed, therefore, that the C term is more precise than the v term. Furthermore, experience with the measurement of wind speed with single and double theodolite systems support the conclusion that v is the least precise of all the measured parameters. Because the accuracy of the wind speed in the COSPEC equation is low, the COSPEC accuracy suffers.

Two types of wind speed inaccuracies occurred during this study. The single theodolite system was used which required use of a rise rate table. These assumed balloon elevations could cause significant errors (as much as 40% compared to double theodolite results). In addition, the frequency of pibal measurements (15 per five-hour day) was not sufficient to provide winds aloft data for each COSPEC plume crossing. The use of *representative* wind speeds contributed significant errors to the flux calculations.

It is recommended that:

- Other double theodolite pibal data be reviewed to quantify the error in the single theodolite data;
- Continuous tower anemometer data be used to develop a methodology for adjusting pibal wind speed data to be used in mass flux calculations;
- More frequent and more precise winds aloft measurement devices (double theodolite, acoustic or laser doppler remote sensor) be used with the COSPEC to determine possible improvement in accuracy.

COSPEC CALIBRATION

Following the field work and prior to data processing work the calibration cells in the COSPECs were checked for SO_2 content. The high concentration SO_2 cell was removed from the EPA COSPEC II (Serial Number 5922) and sent to the manufacturer for recertification. The cell was reported to have a value of 377 ppmM, as compared to the initial value of 350 ppmM SO_2 (see Table 2). This 7.7% increase in this one cell was not taken into consideration when calculating the COSPEC results.

The manufacturer was asked also to retest the cells in the COSPEC IV (the COSPEC III was being used in a field program and was unavailable for testing); the results were reported as "no change in cell values". However, the field calibrations from the COSPEC IV suggested that eigher the low cell (105 ppmM) was actually some lower value or the high cell (395 ppmM) was higher than certified. Prior to processing the COSPEC IV data the calibration curve for this instrument was adjusted using the field calibration data.

Only full retesting of all calibration cells in all three instruments would provide sufficient information to apply correction factors to the calculations contained in this report.

It is recommended that:

- All six COSPEC SO_2 calibration cells for the three instruments used in this study be recertified by the manufacturer;
- Any changes in cell SO_2 concentrations be analyzed to determine what impact they would have on mass flux calculations.

CROSS-STACK MONITOR RESULTS

The cross-stack continuous monitor SO_2 data provided by the power plant personnel were partially processed by EMI. During this procedure it was determined that there was some uncertainty about the calculation of the correction factors in the final results. The instrument manufacturer recommended going back to the original data to recalculate the final results. Then SO_2 mass flux computations could be made, using the in-stack flow rates, to compare with the COSPEC results.

It is recommended that:

- The cross-stack monitor SO_2 data be verified;
- Calculations of SO_2 mass flux be made, and compared with COSPEC mass flux using the same statistical methods applied to the Method 6 data.

STATIONARY COSPEC DATA

During four days of field measurements one of the three COSPECs was mounted on a tripod to make stationary plume measurements. Neither the field procedures nor data reduction are in this report because these experiments were not included in the scope of work. The data could be reduced to compare fixed COSPEC flux calculations with the moving COSPEC data.

This would be particularly interesting for those instances where the plume rose vertically; the COSPEC was rotated on the tripod, scanning from left to right across the top of the stack. The SO_2 emission rate could be determined from these plume profiles by using the PES stack gas velocities. Also, vertical scans were made when the plume was transported horizontally; in these cases the emission rates could be processed using the pibal wind data.

For either situation direct comparison could be made between the stationary and the moving measurements, which were being conducted simultaneously. In the first case (the use of the stack gas velocity instead of the pibal wind speeds) further insight could be obtained into the pibal wind speed errors.

It is recommended that:

- Stationary COSPEC data be processed into SO_2 mass flux;
- Comparison of stationary and moving COSPEC mass fluxes be made to help clarify errors contributed by the wind speed measurements.

COSPEC/SKY ORIENTATION

During the analysis of this large body of remote sensor data it was noted that some of the calculated SO_2 mass flux values fluctuate, from high to low numbers alternately, one traverse to the next. The pattern of alternating high and low fluxes (for example, see Table 5, 14 May 1975, Events 17-21) suggests that the COSPEC may have a sensitivity to the skyward orientation of the light-gathering telescope for certain times of day, sun angles, cloud cover, and other unknown conditions.

This COSPEC/sky orientation effect occurred about ten percent of the time. For the five events in the cited example (14 May) the six "high" fluxes for all three COSPECS average 46.2 MT/D; the nine "low" fluxes average 25.2 MT/D. Neither the high nor the low results were excluded from the statistical analysis.

A more detailed examination of the 465 flux calculations could be carried out to determine during which time periods this orientation effect occurred, whether the average of all readings is a "true" value, or whether the higher or lower calculations should be disregarded.

It is recommended that:

- An analysis of the apparent COSPEC sensitivity to sky orientation be performed to determine the extent to which it occurred during this study;
- Experimental data be gathered to measure the possible impact on COSPEC accuracy.

SAMPLING PROTOCOLS

The averaging times used for the COSPEC data *and* the in-stack data may have affected the comparison of results. Some latitude was used in grouping the COSPEC results for averaging. This included using COSPEC data gathered between the in-stack 20-minute tests when averaging over periods of one hour or longer. By narrowing the time spans used to calculate the averages for the COSPEC results the comparisons may change; similarly, by using results collected only during the 20-minute in-stack test (excluding COSPEC measurements made between) the comparisons may change.

It may be necessary to refine the statistical analysis to make certain, wherever possible, that the two methods were measuring the same flux gas parcel. Calculation of the COSPEC position and the time for transport of the parcel from the stack would insure that "simultaneous" measurements were indeed made. This could be important because there is reason to believe that the sulfur feed rate to the boiler varied over short time periods. For example, the range of daily average sulfur in the coal was 0.79 to 1.11%; the range of shift averages was 0.67 to 1.21%. It is reasonable to expect that there were short term variations in sulfur content, as well. Therefore, COSPEC plume measurements not truly concurrent with the Method 6 samples times perhaps should be excluded from the analysis.

It is recommended that:

- COSPEC plume data not concurrent with in-stack measurements be deleted from the COSPEC averages;
- The statistical analysis be made to determine the effect of narrower COSPEC averaging times.

PLUME GEOMETRY

Many of the COSPEC plume profiles measured were non-Gaussian in shape. Multiple peaks for a single plume profile occurred for three possible reasons: in-stack vortices caused plume bifurcation; gusty winds tended to break up the plumes; bumpy roads caused the COSPEC to swing in and out of plumes during some traverses.

The bifurcated (bi-modal) plume profiles occurred both at the stack exit (measured by stationary COSPEC) and frequently within one kilometer downwind (measured by moving COSPEC). This phenomenon, and the dispersion of the plume by gusty winds, probably caused most of the non-Gaussian profiles; these were fully processed. The profiles which were segmented further (by the "rotating" COSPEC traveling on rough roads) were usually excluded from the analysis.

The plume profiles could be classified into Gaussian and non-Gaussian categories; these could then be correlated with the results of the flux calculations to determine which provided more accurate results.

It is recommended that:

- Plume profiles be categorized with respect to shape and etiology;
- Correlation of profile categories with SO_2 mass flux be made to determine the effect, if any, on accuracy.

ARCHIVAL COSPEC DATA

While a large quantity of remote sensor data were gathered for this study the relative accuracy of the COSPEC could be determined more precisely if the data base were enlarged. To expand the data base for further analysis two sources of information could be used: archival data (e.g., Maryland Power Plant Siting Program) and new COSPEC measurements at other SO_2 sources. Comparable in-stack SO_2 data could be made available for either past or future COSPEC work.

For either the old or new data two important parameters could be studied. The accuracy of the wind speed measurements could be improved using double (instead of single) theodolites or remote wind sensors; the wind gustiness problem could be eliminated by selecting sites and times of measurement where wind flow is more stable. Having data from more than one site would increase the confidence in the remote sensor results.

It is recommended that:

- Archival COSPEC data be analyzed to determine relative accuracy, or
- Additional COSPEC measurements at new sites be made to broaden the data base and strengthen the analysis of relative accuracy.

Section 5

EQUIPMENT AND FACILITIES

AIR QUALITY MOVING LABORATORY

An EMI Air Quality Moving Laboratory (AQML) was used to transport the COSPEC remote sensors during the plume measurement tests. The AQML, shown in Figure 1, is designed to make moving COSPEC measurements; it was partially modified for this COSPEC evaluation. A platform was installed in the van to serve as a mounting surface for two additional correlation spectrometers. The third COSPEC was installed in the usual position behind the driver. Each instrument viewed overhead through a telescope fitted with a right-angle mirror.

To monitor ground-level SO_2 a Bendix Model 8300 flame photometric Total Sulfur Analyzer was installed in the AQML. The point sampling instrument was placed, along with the hydrogen gas needed for its operation, in the central portion of the van. Air was drawn through a teflon sampling manifold into the van by a squirrel-cage fan; a short teflon inlet tube, in turn, sampled this air stream for analysis by the point monitor.

Figure 1. The AQML carried three COSPECS; two viewed the sky out the right front window, one through the window behind the driver.

The analog signals from all four instruments were recorded on a six-pen Rikadenki strip chart recorder. A rear-mounted propane-powered generator supplied electrical power for all instrumentation.

A two-person crew operated the AQML. One person was the driver; the data logger, sat in the rear seat and observed the six-pen chart recorder, making notations of times and geographic locations on the chart records. Duties were rotated frequently with two additional persons at the fixed field site.

COSPECS

Sulfur dioxide total burdens were measured by the three vehicle-mounted COSPECS. (NO_2 channels were available from the COSPEC II and COSPEC III but they were not connected for this study.) The natural radiation of the solar electromagnetic spectrum is influenced by the absorption spectrum of the target gas, sulfur dioxide, in accordance with the Beer-Lambert law of absorption. The correlation spectrometer, an electro-optical instrument, detects portions of the molecular absorption bands specific for this molecule. The optical unit includes a Cassegrain telescope, an Ebert-Fastie quarter-meter dispersive element, a correlation disc assembly, and a photomultiplier to detect light energy levels. The electronics of the COSPEC contain signal processing circuits to provide an analog output signal for strip chart recorders.

Three different models of the correlation spectrometer were used in this study.

- The COSPEC II, (Serial No. 5922) is a dual-gas monitor intended for quantitative measurement of sulfur dioxide and nitrogen dioxide. It is designed for use in the *passive* mode only. That is, it can be operated exclusively by solar illumination.
- The COSPEC III (Serial No. 5932) is also a dual-gas monitor with the ability to function in the *passive and active* modes. This latter option allows the instrument to be operated with a remote modulated artificial light source.
- The COSPEC IV (Serial No. 6256) is designed for single-gas measurements. Improved optics allow for an increased sensitivity on the order of one magnitude above the II and III. This instrument operates in the *passive* mode.

In this study all three COSPEC's were used to detect a single gas (SO_2) in the *passive* mode of operation. The manufacturer's specifications are listed in Table 1 for a dual-gas instrument.

Table 1

BARRINGER RESEARCH COSPEC III
DUAL-GAS CORRELATION SPECTROMETER
Specifications

TARGET GASES:	SO_2 and/or NO_2
LIGHT SOURCES:	Skylight
OPTICS:	Cassegrain telescope on front turret 1° x 1°. A right-angle mirror attachment is provided for "vertical look" operation. A sighting telescope is provided for alighment on the light source or a target plume.
DYNAMIC RANGE:	1-1000 ppm-M (parts per million-meter)
SENSITIVITY:	2 ppm-M, (threshold at 8 second integration time)
RESPONSE TIME:	1,2,4,8,16, or 32 seconds
OUTPUTS:	• SO_2 Signal • NO_2 Signal • SO_2 AGC Voltage • NO_2 AGC Voltage
CALIBRATION:	Four fused-silica cells; two each for SO_2 and NO_2
CONTROLS:	• Power, ON/OFF • Signal alignment • Meter scale change • Zero offset adjust • Integration time • Entrance slit translation control • Calibration cell selectors
MECHANICAL:	• Size: 71 cm x 30 cm x 43 cm (28" x 12" x 17") • Weight: 17.2 kg (38 lbs) including isolators and mounting plate (provided with standard tripod mounting holes)
ENVIRONMENTAL:	Vibration isolators are standard Ambient temperature range: -20°C to +50°C
POWER REQUIREMENTS:	115 VAC, 60 hz, 18 watts

Calibration of the COSPEC is performed by actuating a pair of knobs to place gas-filled quartz cells into the instrument's internal light path. These cells contain fixed amounts of SO_2 in a dry nitrogen atmosphere. They provide span offsets of parts per million-meters (gram-meters/meter^3); actual values for the three instruments used in this study appear in Table 2.

When possible, calibration is done in regions of low-level SO_2 away from plumes, just prior to or following a traverse. Notations of the time and the choice of cells used during the calibration and the recorder sensitivities are made on the chart record. The voltage for the automatic gain control (AGC) circuit is also noted on the chart record to provide an indication of the changing light intensity during the day.

Table 2

COSPEC CALIBRATION AND RANGE

	SULFUR DIOXIDE (ppmM)		
	COSPEC II S/N 5922	COSPEC III S/N 5932	COSPEC IV S/N 6256
CALIBRATION CELLS:			
Low	65	75	105
High	350	180	395
Low+High	415	255	-
Linear Range*	0-650	0-600	0-800
Maximum Useful Range*	0-1600	0-2000	0-1900

*As determined by field tests; see discussion on page 5-5 and Figure 3.

On this project, calibrations were performed on each COSPEC eight to fifteen times during every measurement day. These calibrations were used to determine the sensitivity of the instrument to SO_2. Due to the varying intensity of the Rayleigh-scattered ultra-violet light, this sensitivity changes during the day. Therefore, the sensitivity values for each day were plotted and a set of sensitivity curves was determined for each instrument. A typical sensitivity curve, that for the COSPEC II for 8 May 1975, is reproduced in Figure 2. The parts per million-meters/millivolt (ppmM/mv) sensitivity for this instrument on this day varied from approximately 0.50 ppmM/mv in the morning and evening to approximately 0.28 ppmM/mv at midday, when the ultra-violet light was most intense. The sensitivity curves were used to derive the specific sensitivity value for each COSPEC measurement event.

The COSPEC has a linear range from its noise limitation, 5-25 ppmM SO_2, to approximately 700 ppmM. This is a function of the Beer-Lambert Law, and is substantiated by in-the-field experience with the instrument. The linear relationship of the three COSPECS used in this study was verified on site. High concentration SO_2 calibration cells were placed into the instrument's light path to provide calibration steps as high as 5000 ppmM. Figure 3 shows a typical COSPEC response curve. The linear portions of each COSPEC and the estimated maximum useful range (as determined from these curves of instrument response) are listed in Table 2.

These linearity data were used to process the field results. COSPEC data in the linear range were used as gathered; values in excess of the linear range were corrected using the curves generated from the field linearity tests.

In practice the non-linearity of the COSPEC was encountered only for plume measurements as close as 500 meters from the power plant stack. Measurements made 500 meters to 5 kilometers downwind were within the linear range. Approximately 19% of the data gathered were corrected for non-linearity.

PIBALS

The measurement of wind speed and direction, essential parameters in the calculation of SO_2 mass flux, was accomplished in two ways. A tower-mounted Climatronics anemometer, (8.2 meters above ground level) was located away from the immediate influence of the power plant, within about 600 meters of the source; processed data were provided by power plant personnel.

Figure 2

TYPICAL COSPEC SENSITIVITY CURVE

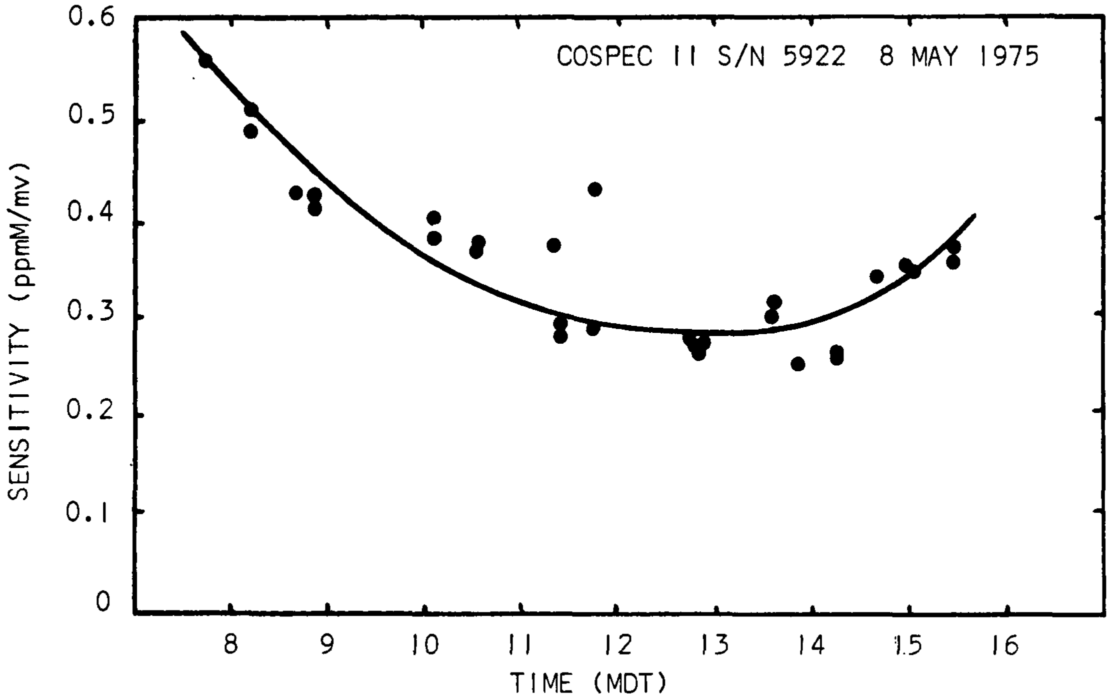
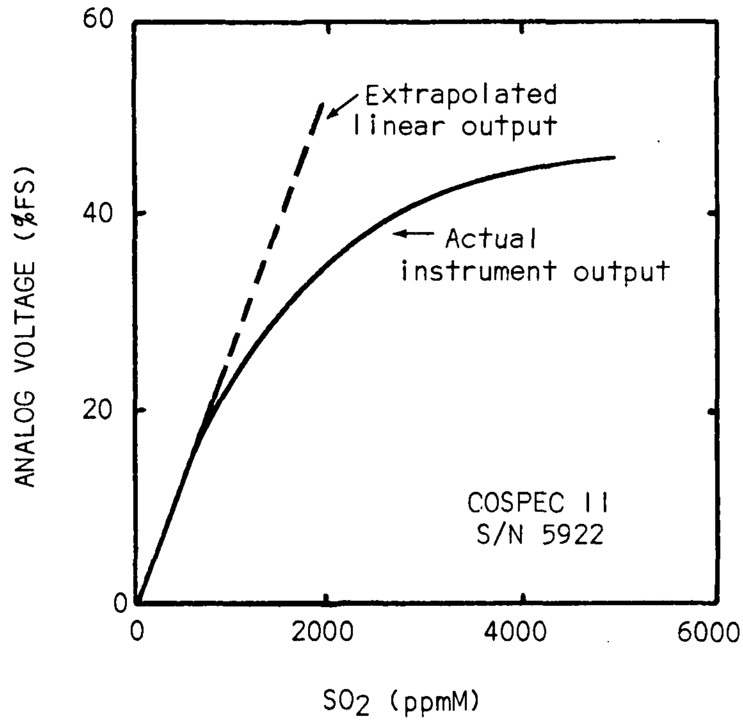


Figure 3

TYPICAL COSPEC
NONLINEARITY CURVE



Single theodolite pilot balloon (pibal) measurements were made 250 meters north of the source to measure winds aloft. The actual stack height was 122 meters; the effective stack height (stack height + plume rise) was 150-300 meters or more. The measurements were used in the field to understand the changes in wind movement at these elevations, while the moving measurements were in progress. The data were used in the calculation of SO_2 mass flux.

A WeatherMeasure Model BT 901 balloon theodolite was employed. Thirty-gram weather balloons were filled using a 139-gram filling device. The helium-filled balloons were released during Method 6 measurement periods and were tracked for five minutes or more--to an altitude of approximately 1000 meters.

STACK SAMPLING

Sulfur dioxide stack emissions were measured by Pacific Fnvironmental Services Inc. using EPA Method 6. Velocity traverses were conducted using EPA Method 2 and moisture determinations were performed using EPA Method 4. This sampling took place 82 meters above ground level in already available sampling ports. The ports were located downstream from the collection device and blowers and upstream from discharge to the atmosphere, approximately eight stack diameters downstream of any flow disturbances. The test methods are fully described in Appendix A.

All laboratory titrations were performed on site by PES personnel. Bubbler contents were titrated with barium perchlorate using Thorin as an indicator as specified by Method 6. The on site chemical analysis proved to be fortuitous. Difficulties with a vacuum pump invalidated some of the early tests; this was discovered only after analysis of the initial stack gas samples. After replacement of the faulty pump the stack sampling proceeded routinely.

Additional stack measurements were made by means of a continuous cross-stack monitor. This device measured SO_2 concentrations in the stack gases at the same platform where the manual Method 6 stack sampling was performed. Data from this instrument were telemetered to the central control room of the power plant and processed and printed on daily log sheets. These results were provided by power plant personnel.

Section 6

FIELD MEASUREMENTS

REMOTE SENSING METHODOLOGY

EMI employed procedures developed over five years to make moving measurements of power plant plumes as required by the contract.

The AQML was driven around and downwind of the power plant usually within a one kilometer radius but as far downwind as five kilometers. The objective was to cross the plume, at as many different downwind distances as possible, to measure the dispersing SO_2. This was difficult to achieve, as there were limited traverse routes; this problem was overcome, however, by making repetitive surveys on available roads.

The traversing speed varied with the distance from the source. Close to the power plant the speed was kept below 30 kilometers per hour to allow the instruments to respond fully and to provide clear definition of narrow plumes. As the AQML was moved further downwind from the source, it moved faster under the plume. Because the plume is broader at the greater distances, changes in overhead burdens and ground-level concentrations are less abrupt, and the instruments respond to them easily. Decisions were made in-the-field based on the real-time data: whether to repeat the plume-tracking measurement at the present radius or to move to a second radius of measurement.

WIND MEASUREMENTS

A single pibal theodolite was used for the entire study. The theodolite was located approximately 250 meters due north of the stack. This was far enough away to avoid influence by the superstructure of the power generating station for most wind directions and speeds encountered during the study, but close enough to maintain visual contact with the stack sampling crew. A flag system was used to indicate when stack sampling was in progress. The pibal crew would schedule equi-spaced balloon releases during these test periods.

Typically four pibals were tracked during each stack test. The moving laboratory was actively measuring before, during and after these 20-minute intervals so that supplementary pibals were released during times when the stack sampling apparatus was being purged and/or prepared for a new series of test. The measurement of winds aloft was made an average of 15 times per day.

Readings of balloon position were made by the theodolite observer and written on a data sheet by a recorder. A hand-held calculator was used to compute wind speeds and wind directions on site. This gave the field crew results with which to understand the changing meteorological conditions and to guide the moving laboratory to the proper position for plume measurement.

The real-time-data from the moving laboratory, of course, provided additional data on the wind vector. The location of the plume and visual observation of geographic position of the AQML provided continual feed back on the wind conditions. However, when winds became gusty or the wind direction would rotate rapidly, the periodic return of the moving laboratory to the pibal site was useful in validating wind conditions. This procedure optimized the data collection efficiency of the moving laboratory.

ACTIVITY SUMMARY

Measurements were made at the power plant for 12 data-days; a summary of the measurement activities is presented in Figure 4. This chart shows time periods when the moving laboratory was active and when Method 6 stack sampling occurred. No Method 6 test times are shown prior to 13 May because results from these tests were invalidated by the faulty vacuum pump.

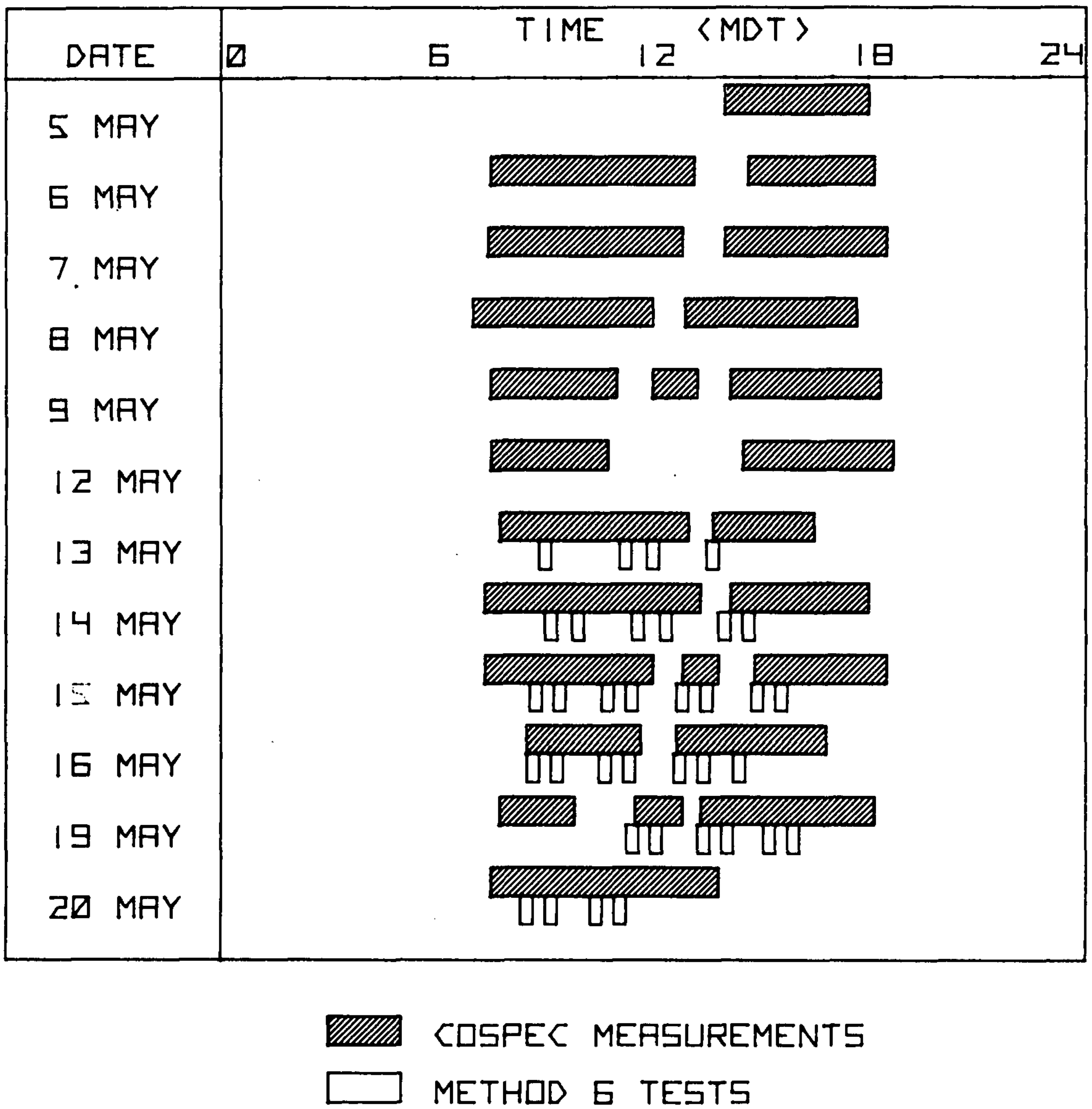
A total of 35 valid Method 6 tests were completed between 13 and 20 May 1975. This resulted in 11.6 hours of concurrent testing with the remote sensor measurements. A total of 42 hours of remote sensor measurements were actually gathered. This includes data collected between 8 and 12 May 1975, during which continuous in-stack monitor data are available. COSPEC measurements for 5 through 7 May were not treated because neither the in-stack monitor nor the Method 6 determinations were valid for these days (the in-stack monitor was undergoing calibration and adjustment).

On a typical day 60 crossings of the plume were made by driving the moving laboratory around and down wind of the power plant stack. Two or three COSPEC's were mounted in the AQML at all times: multiple COSPEC measurements resulted from most plume crossings. An average distance of 150 kilometers was covered by the moving laboratory each day.

Figure 4

ACTIVITY SUMMARY

MAY 1975



MEASUREMENT SCENARIO

The activities of the typical day can be presented in scenario form; a photographic review of EMI and PES work is shown in Figures 5 and 6.

The two measurement crews arrived at the power plant each morning in three vehicles: the AQML, the pibal station wagon and the stack-sampling van. The stack sampling train was prepared for the first series of tests while the theodolite was set up and the COSPECs were given initial calibrations. The moving laboratory immediately began surveying around the power plant, at a 250-meter radius, to determine the plume vector. The stack sampling crew reached the sampling platform by elevator and set up their equipment. When they were ready for the initial test a red flag was hung on the platform railing. Communication by radio with the pibal crew verified the starting time of the first test.

The measurement cycle was a 20-minute Method 6 sampling period followed by a 20-minute purge time and a second 20-minute test. This pair of tests was followed by an interval of 30 to 60 minutes. During the first 20-minute run, the first three or four pibals were released while the moving laboratory continued traversing.

The objective during any one 20-minute experiment was to achieve as many plume cross sections as possible at two or three downwind distances.

Coordination between the ground and stack sampling crews was maintained throughout the day. At times conditions, such as changing wind directions, would cause a few minutes delay in the start of the new run, but usually the stack sampling proceeded at its scheduled pace. The moving measurements were essentially continuous with multiple plume crossings during the 20-minute test times. Between stack sampling intervals the AQML continued traversing with an emphasis on tracing the plume as far downwind as possible.

Figure 5. EMI crew at work. Clockwise from upper right: calibrating three COSPECS prior to installation in moving laboratory; digitizing base map for computer analysis of COSPEC data; reading balloon theodolite to measure winds aloft; communicating with stack sampling crew by radio to coordinate field measurements.

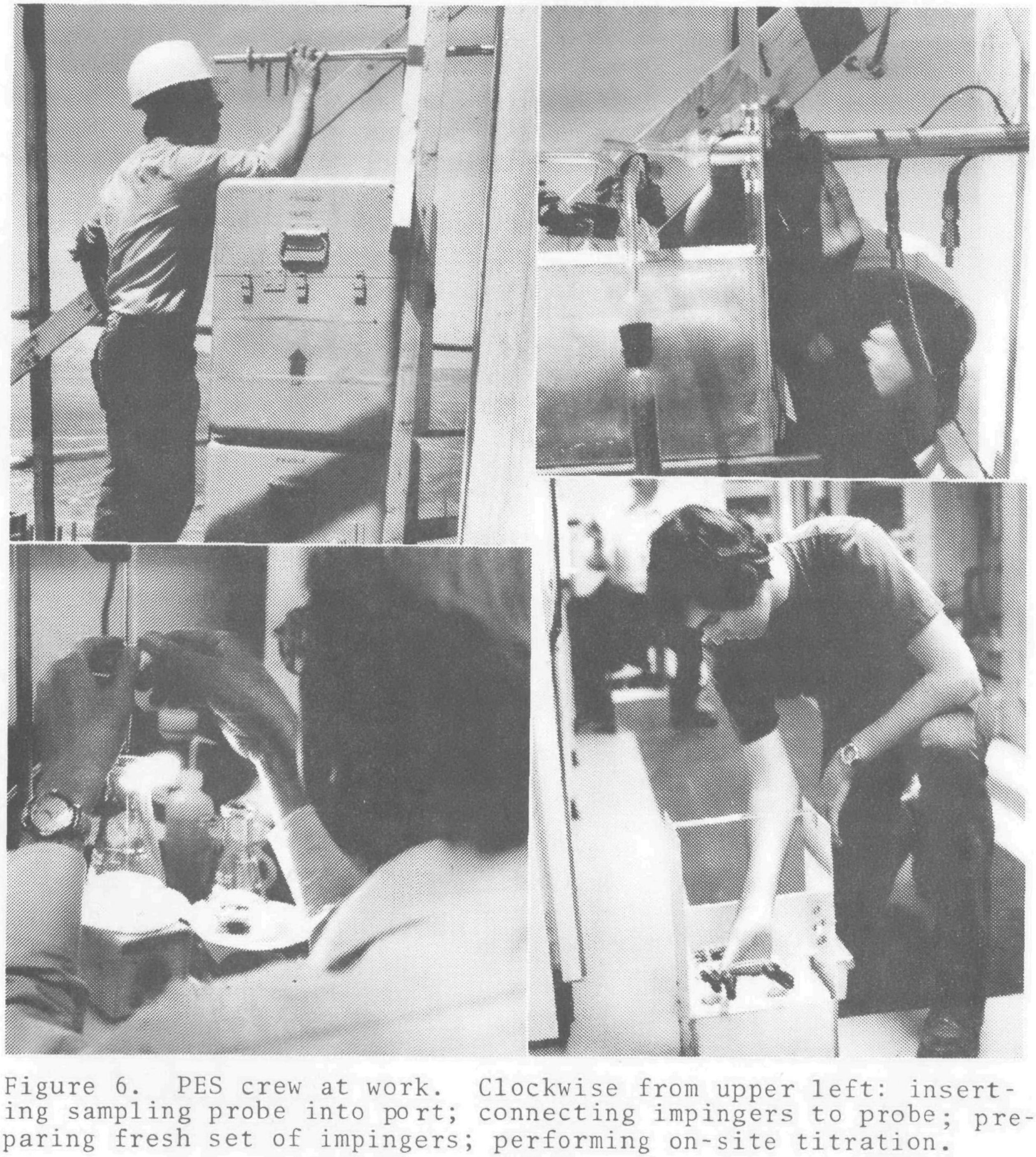


Figure 6. PES crew at work. Clockwise from upper left: inserting sampling probe into port; connecting impingers to probe; preparing fresh set of impingers; performing on-site titration.

Section 7

REMOTE SENSOR DATA PROCESSING

DIGITIZING GEOGRAPHY

The first step in processing the remote sensor moving measurement data was to generate a computer-stored map of the roads at the study site, so that air quality data could be analyzed in a Cartesian coordinate system. For the target power plant used in this COSPEC evaluation there were no complete or current detailed maps available; a map was prepared from field-gathered data.

The mapping procedure began by gathering together available engineering drawings, aerial photographs, and U.S. Geological Survey topographic maps; in addition, hand drawn sketch maps were prepared at the site. The preparation of these sketch maps was facilitated by a distance measuring device mounted in the moving laboratory, calibrated in kilometers, so that distances could be measured directly on the roads as traversed. As new routes were travelled a new map was drawn; as the route was used again additional mapping information was added to improve the accuracy of the sketch map.

Intersections and other reference points on the traversed roads were assigned identification numbers. These numbers were entered on the strip chart record as the moving laboratory passed by.

Following the field work the annotated sketch map was reviewed; the geographic reference points were transferred to an aerial photograph of the power plant site. This final photo-map was digitized in X,Y coordinates, in meters. Where after-the-field analysis found that additional geography points were necessary to properly describe the shape of a certain road they were added. Approximately ten percent of the points were added to the numbering system created in the field. A total of 190 geography points describe the traverse routes used.

Figure 7 is a computer plot of the computer-stored map showing the network of roads around the power plant stack.

DIGITIZING COSPEC DATA

To correlate the COSPEC data with the geography they, too, were digitized. The chart records were first annotated to define events. The continuous time-related data were separated into individual measurement events, (single plume crossings, calibrations) to establish an orderly, chronological list. This was done daily in the field while the events of the day were easily remembered. An average of 54 events were identified for each of the eight reported data-days. The event list formed the basis for selecting data to be processed.

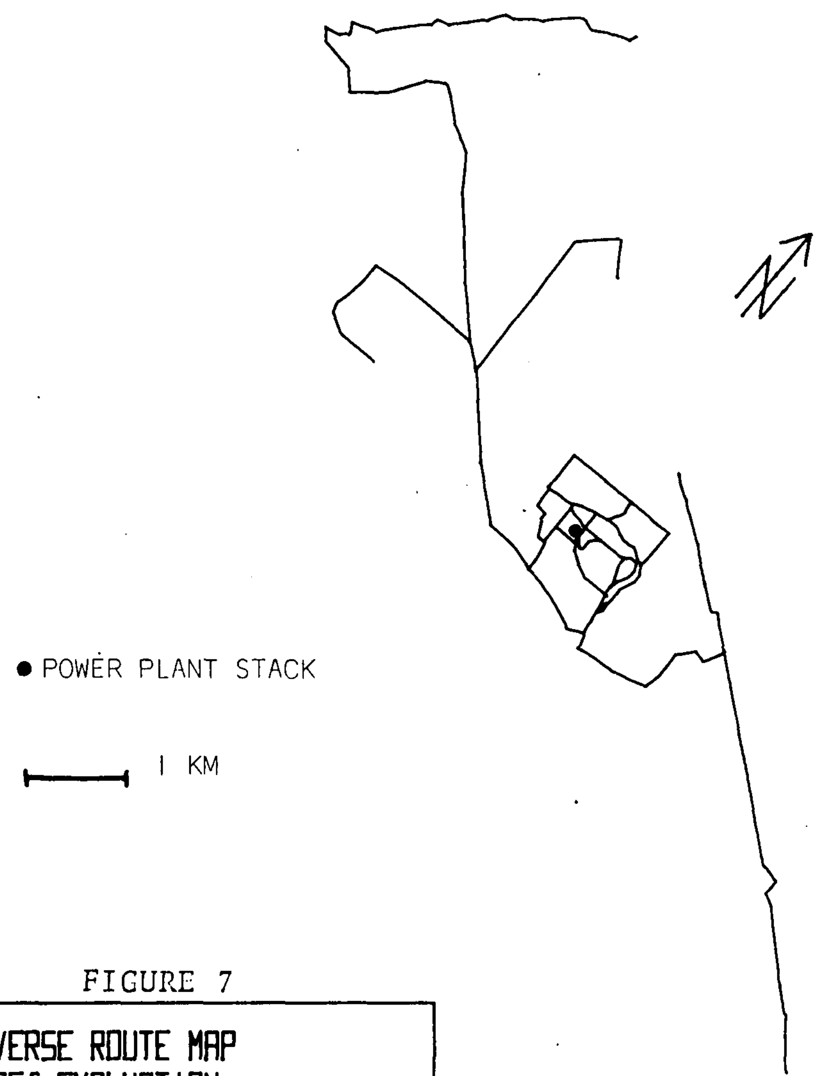


FIGURE 7

TRAVERSE ROUTE MAP
COSPEC EVALUATION
8-20 MAY 1975

ENVIRONMENTAL MEASUREMENTS, INC.
SAN FRANCISCO, CA 94111

Key events were evaluated for relevance to the project goals; events with offscale readings (because of temporarily incorrect chart recorder sensitivities) were eliminated from further consideration. Approximately 50% of the events were selected for processing.

The raw moving laboratory field data included the analog traces for SO_2 total burdens for the three COSPECS and ground-level concentrations from the point monitor on a single chart record. These records also included hand-written annotations of time and positions made by the data-logger, as well as instrument calibrations, time constants and weather conditions. Figure 8 is a sample chart record of moving measurements. The data were recorded on 12 May, 1975 in the afternoon (1514-1516) MDT. They were identified as Event 36. The digitized portion of Event 36 began at geography reference point No. 511 and ended at point 308. This route was 720 meters east of the power plant stack. The distance covered by the AQML was 310 meters.

The three COSPEC traces show that an SO_2 plume was detected which had a peak between points 512 and 513. The three analog signals tracked together (accounting for the pen offset); each instrument recorded a generally Gaussian distribution with superimposed peaks and valleys. The ground-level SO_2 monitor recorded no gas above 10 ppb during this two-minute plume crossing.

To process these data reference baselines were first drawn for the SO_2 burden records. The background was defined as the instrument output on either side of well-defined plume anomalies. For the example in Figure 8 the baselines were 12% COSPEC II, 31% COSPEC III, and 20% COSPEC IV.

Each analog trace was digitized at geographic reference points, and points inserted between to provide a sampling density sufficient to characterize the plume anomalies. Major assumptions of this procedure are a constant velocity of the vehicle between indicated landmarks, and straight line interpolation between geographic points and inflection points. Therefore, assuming straight line variations between each of the digitized points, they may be joined by straight lines to recreate the original record.

No correction was made for time delays caused by instrument response time. The COSPEC time constant was set at one or two seconds; coupled with the slow moving AQML (typically 30 km/hr) the offset in the plume anomalies with respect to the geographic reference points was assumed negligible.

MERGING THE DATA MATRIX

After the geography and the COSPEC data were separately digitized the two sets of digitized values were merged into a matrix

Figure 8
TYPICAL AQML CHART RECORD
12 May 1975, Event 36

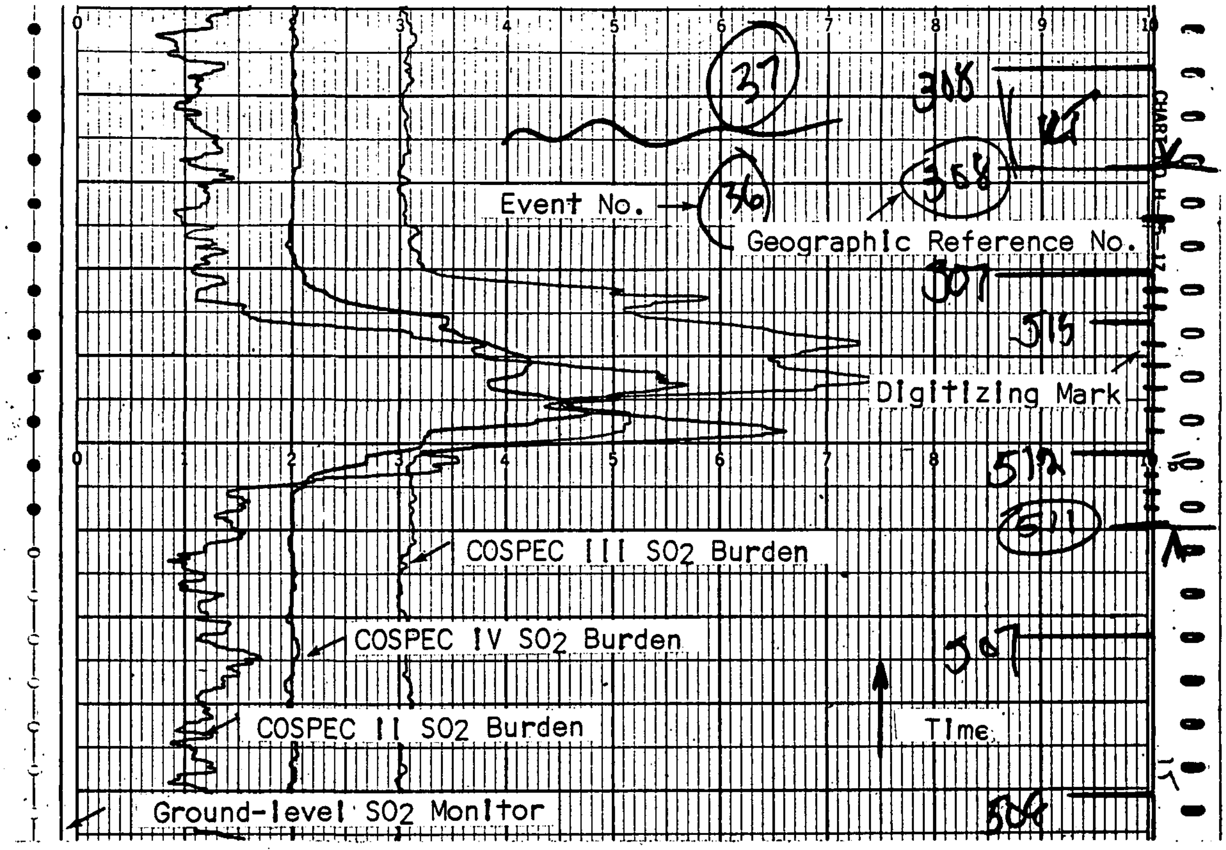


TABLE 3

ENVIRONMENTAL MEASUREMENTS INC
SAN FRANCISCO, CALIFORNIA

COSPEC EVALUATION
PROJECT 101 — 12 MAY 1975
EVENT NO. 36 — 1514 - 1516 MDT

MAP COORDS X KM	Y KM	GEOG PT	COSPEC II SO2TB PPMM	COSPEC III SO2TB PPMM	COSPEC SO2TB PPMM
729.398	75.330	511	0	0	0
729.396	75.313	0	14	0	0
729.394	75.295	0	20	0	0
729.391	75.278	0	20	13	31
729.389	75.260	512	143	79	163
729.392	75.247	0	150	158	109
729.394	75.233	0	367	356	333
729.397	75.220	0	218	317	264
729.399	75.207	0	299	251	326
729.402	75.193	0	218	290	194
729.404	75.180	513	163	198	217
729.392	75.167	0	61	150	70
729.380	75.153	0	20	53	0
729.368	75.140	307	0	13	0
729.376	75.090	0	0	0	0
729.383	75.040	308	0	0	0

to be processed by computer. An example of this matrix is presented in Table 3. These are the same data which are shown in the original chart records for 12 May 1975 Event 36 (Figure 8).

The data listing shows the X,Y coordinates of the position at which the data were recorded; geographic reference points are listed next. The zeros which appear in the geography point column correspond to the added marks which appear on the chart record. The last three columns list the COSPEC II, COSPEC III, and COSPEC IV raw data in ppmM. These results were derived from the percent full scale readings taken from the chart records, with the subtraction of the reference background and multiplication by the sensitivity of the COSPEC for that portion of the measurement day. An example of a data point processed in this way is shown below:

$$(66\%\ FS - 12\%FS)\ x\ 6.80\ \frac{ppmM}{\%\ FS} = 367\ ppmM$$

Note on Table 3 that the three sets of COSPEC readings, although not identical in value, do show a close correlation as the values rise from zero (background) to a peak and fall back to a zero. The peak values for the three instruments were 367 ppmM, 356 ppmM and 333 ppmM, respectively.

WIND DATA ANALYSIS

The wind data gathered at the study site were processed to determine wind speeds within the COSPEC-measured plumes for use in the calculation of SO_2 mass flux. The primary data used were the pibal measurements; the continuous anemometer data from the low tower were consulted for trends in wind speed. (A problem with the anemometer assembly intermittently caused wind direction readings 180^o out of phase, limiting the use of these data.)

The weather conditions observed at the site have been summarized and appear in Appendix B. A daily resume of wind and weather conditions, a copy of the anemometer wind speed and wind direction data for the daylight hours, and a summary of the pibal measurements are presented for each data-day.

The analysis of the pibal results first required the complete processing of each set of theodolite measurements for every pilot balloon released. The calculation of wind speed and direction was based on an assumed balloon rise rate. The altitude of the pibal for each thirty-second observation was taken from the tables used by the National Weather Service and the EPA. The complete listing of wind speed and wind direction at the various altitudes were tabulated and summarized.

To select a wind speed for any given event, the wind data between ground level and 600 meters were analyzed. The heights to be used in the calculation depended on the downwind distance of the traverse, plume touchdown as measured by the AQML and the overall wind speed for that period. Typical altitudes used were in the 100 to 300 meter range for in-close plumes without touchdown. Several kilometers downwind, when there was plume touchdown, the pibal heights used in determining wind speed were ground level to 500 meters.

The number of pibals varied throughout the day. The pibal nearest to the time of the plume measurements was always consulted; if additional pibals were released within the same time period, an average wind speed was used. The anemometer data were consulted for trends in wind speed. But no quantitative results were used because the instrument was measuring only low elevation winds.

The selection of wind directions for each measurement event was carried out simultaneously with the wind speed determinations. Again, where more than one pibal measurement was made, average wind directions were calculated. Additional wind direction data were inherent in the plume measurements themselves. The plume center line was plotted on a map of the power plant and surrounding area using the peak value from the COSPEC readings to locate the plume axis. These plume vectors were measured and tabulated, and agreed with the independent pibal measurements usually within 10 degrees. Frequently, due to the gusty nature of the winds, the direction of the plume measured by the moving laboratory varied considerably from that measured by the pilot balloons. In such cases the direction determined by the moving laboratory was used in the calculations.

CALCULATING SO_2 MASS FLUX

The calculation of the final results -- the SO_2 mass flux -- was done by a proprietary computer program which operates on the geography/COSPEC data matrix and the wind speed/direction information. An example of the results of the calculation is shown in Table 4. The printout lists the segment length, the wind/road angle and the mass flux for each segment and the mass flux for each segment and the cumulative sums for each of three COSPECS. The final results are expressed in metric tons per day, pounds per hour, and kilograms per hour.

Table 4

SAMPLE MASS FLUX CALCULATION

SO2 FLUX ANALYSIS 12 MAY 1975 EVENT 36

WIND = 14.1 M/S FROM 305 DEGREES

W/R ANGLE	SEG LENGTH METERS	COSPEC II SO2 PPMM	COSPEC II SO2 FLUX MT/D	COSPEC II SO2 SUM MT/D	COSPEC III SO2 PPMM	COSPEC III SO2 FLUX MT/D	COSPEC III SO2 SUM MT/D	COSPEC IV SO2 PPMM	COSPEC IV SO2 FLUX MT/D	COSPEC IV SO2 SUM MT/D
245	18	7	-0.4	-0	0	0.0	0	0	0.0	0
242	18	17	-0.9	-1	0	0.0	0	0	0.0	-0
242	18	20	-1.0	-2	7	-0.3	-0	16	-0.8	-1
242	18	82	-4.1	-6	46	-2.3	-3	97	-4.9	-5
227	14	147	-4.7	-11	119	-3.8	-6	136	-4.3	-10
222	14	259	-7.7	-19	257	-7.6	-14	221	-6.6	-17
226	13	293	-9.2	-28	337	-10.6	-25	299	-9.4	-26
222	14	259	-7.7	-36	284	-8.5	-33	295	-8.8	-35
226	13	259	-8.2	-44	271	-8.5	-42	260	-8.2	-43
222	14	191	-5.7	-49	244	-7.2	-49	206	-6.1	-49
277	18	112	-6.5	-56	178	-10.3	-59	144	-8.3	-57
277	18	41	-2.3	-58	106	-6.1	-65	39	-2.2	-60
277	18	10	-0.6	-59	33	-1.9	-67	4	-0.2	-60
227	50	0	0.0	-59	7	-0.8	-68	0	0.0	-60
226	51	0	0.0	-59	0	-0.0	-68	0	0.0	-60
TOTAL SO2 FLUX =		58.8 MT/D			68.0 MT/D			59.9 MT/D		
		2451 KG/HR			2833 KG/HR			2495 KG/HR		
		5402 LBS/HR			6244 LBS/HR			5499 LBS/HR		

TOTAL TRAVERSE LENGTH = 0.31 KILOMETERS

REFERENCE TAPE FILE NUMBER (X VALUE)= 10

The computations of SO_2 mass flux--emission rate of the target power plant--were derived from the COSPEC total burdens, the geography, and the wind speed according to the following formula:

Mass Flux = C * D * a * $\overline{v}$ * K

Where:

Mass Flux = The rate of flow of the substance, mass per unit volume in milligrams per second *(mg/s)* prior to use of constant (K).

C = The COSPEC-supplied *burden* value. Specifically it is the average value between two adjacent X & Y points as expressed in *milligrams per square meter* (mg/M^2) above background.

For SO_2, mg/M^2 is derived from parts per million-meters as follows:

ppm-M = 2.66 milligrams per square meter using:

ppm = 1 unit per 1,000,000 units

= 1 cubic cm per cubic meter

Molecular volume at STP for SO_2 =

$$\frac{64(\text{gram molecular weight})}{22.414 \text{ liters (mol volume)}}$$

Cubic meter = 999.972 liters

STP = 273^oK; 760 mm Hg

Temperature and pressure at processing of SO_2 calibration cell = 293^o, 760mm Hg. as follows, for a cubic meter,

$$\frac{64(S)}{22.414(1)} \times \frac{999.972(1)}{M^3} \times \frac{273^o(K)}{293^o(K)} = \frac{2660g}{M^3}$$

$$\frac{2660g}{M^3} \times M = \frac{2660g}{M^2}$$

and, for a cubic centimeter (ppm of a cubic meter),

$$\frac{2660g}{M^2} \times 10^{-6} = 2.66 \text{ milligrams}/M^2$$

D = distance traveled between the two X & Y points used to determine the burden, as expressed in *meters* (M)

a = The sine of the angle between the wind flow direction (from pibal results) and distance segment, D, used to adjust the segment to a position normal to the wind stream. A non-dimensional value between 1 and 0.

$\bar{v}$ = The speed of the wind estimated at the altitude of the SO_2 stream as expressed in meters per second *(M/S)*.

(1 M/S = 3.6 kilometers per hour = 2.237 miles per hour).

K = A constant to convert to a more uniform, familiar unit from the milligrams per second, as calculated:

K	Mass Flux dimensions
10^{-3}* (mg/sec)	= grams per second
3.6 * (mg/sec)	= grams per hour
$3.6*10^{-6}$ (mg/sec)	= metric tons per hour
$8.64*10^{-5}$* (mg/sec)	= metric tons per day
$7.93*10^{-3}$* (mg/sec)	= pounds per hour

Section 8

REMOTE SENSOR RESULTS

TABULATED RESULTS

A total of 465 calculations of SO_2 mass flux were made for the COSPEC/Method 6 comparison. The emission rates, as measured by each remote sensor, are presented in tabular form in Table 5. The results are listed individually for every measurement event that produced valid results. Key parameters which influenced the measurement and calculation of remote sensor mass flux are presented in the table. These include the distance downwind of the stack at which the measurement was made (meters), the wind speed (meters per second) and the wind direction (degrees *from* which the wind was blowing). In addition the date, time and event number are given, as well as indication of plume touchdown.

The SO_2 mass flux values in Table 5 show wide variation from one event to the other; conversely the results show close agreement between the two or three COSPECs. These conditions are analyzed and discussed in Section 10. It is important to note, however, that the individual values represent single plume crossings which lasted from a fraction of a minute to, at the most, several minutes in duration. Because of variations in test conditions--principally fluctuations in wind speed--great differences from one set of flux numbers to the next sometimes occur. No single measurement, therefore, is assumed to be a valid estimate of SO_2 stack emissions for comparison with Method 6 or any other measurement technique. Rather it is the average of several such measurements that is taken to be the measure of stack emissions. These individual measurements, therefore, are presented as a complete listing of the processed COSPEC data from which the comparisons of averaged results have been made.

PLOTTED RESULTS

The results for the individual COSPECs are plotted as a function of time to give a pictorial presentation of all data. Figure 9 shows SO_2 Mass Flux plotted separately for the COSPEC II, COSPEC III and COSPEC IV. Each day's data are plotted as a continuous string even though there were intervals where no measurements were made or where data were not processed. Breaks in the continuous plots do occur for days where a particular instrument was not being used for moving plume measurement.

The central tendency of the remote sensor results is expressed by the arithmetic means shown on each plot. The scatter or dispersion of the results is expressed by the standard deviation (σ), noted on the plots as a percent of the mean. The three means agree within 1.5%. The standard deviations are large (53.7%-61.4%), reflecting the fluctuations of *individual* measurements caused by variations in wind speed and other parameters.

Figure 9

COSPEC SO_2 MASS FLUX
Individual Plume Calculations
8-19 May 1975

(Data from Table 5)

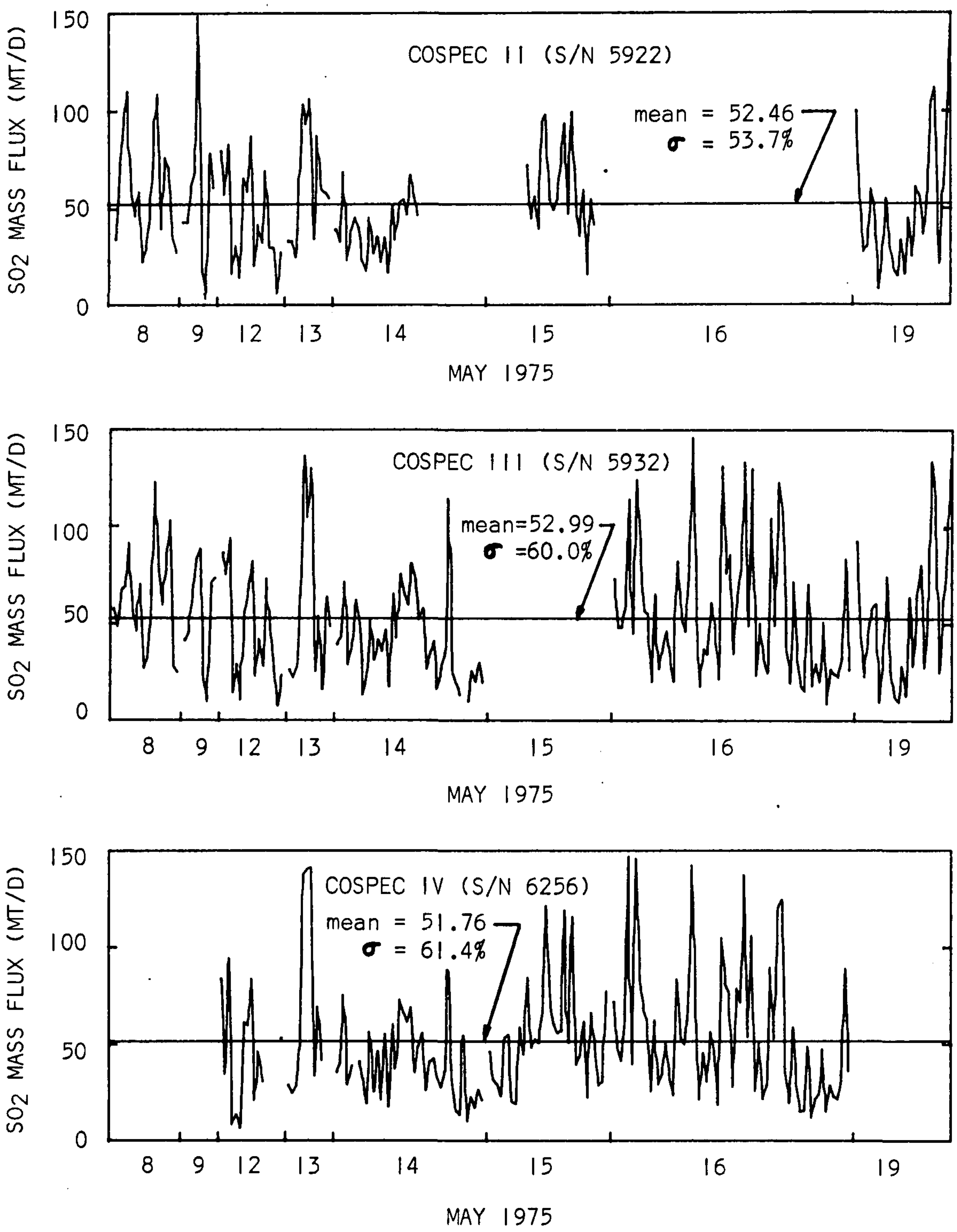


TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
8	0911-0915	5	120	-	2.1	141	-	57.7	-
	0915-0917	6	120	-	2.1	141	34.2	48.6	-
	0918-0920	8	300	-	2.1	124	73.2	67.3	-
	0920-0923	9	300	-	2.1	124	95.4	69.3	-
	0923-0926	10	300	-	2.1	124	110.2	91.6	-
	0926-0930	11	300	-	2.1	124	59.0	57.4	-
	0943-0949	14	350	-	2.3	117	46.3	46.2	-
	0949-0957	15	460	-	2.3	83	58.5	70.3	-
	0957-1001	16	350	-	2.3	117	22.7	27.3	-
	1318-1321	34	40	-	7.6	329	30.0	33.8	-
	1321-1323	35	30	-	7.6	302	46.3	57.4	-
	1323-1324	36	30	-	7.6	270	77.8	122.6	-
	1324-1325	37	30	-	7.6	260	108.8	79.2	-
	1325-1326	38	30	-	7.6	270	39.4	60.3	-
	1442-1445	53	650	-	4.9	281	76.0	80.5	-
	1445-1449	54	350	-	4.9	227	71.0	103.5	-
	1449-1453	55	660	-	4.9	275	35.9	28.4	-
	1453-1457	56	660	-	4.9	278	27.1	25.2	-

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
9	0940-0947	9	1500	No	4.4	107	42.8	41.5	-
	0947-0954	10	1500	No	4.4	107	42.7	45.7	-
	0954-1002	11	1900	No	4.4	112	60.8	65.9	-
	1002-1017	12	2100	Yes	4.4	121	69.2	83.1	-
	1017-1026	13	2100	Yes	4.4	121	148.9	88.7	-
	1427-1439	28	550	No	0.7	182	19.4	22.8	-
	1439-1443	29	800	No	0.7	233	3.5	10.2	-
	1511-1519	31	550	No	2.1	184	78.7	71.7	-
	1519-1524	32	550	Yes	2.1	181	60.9	73.6	-
12	1030-1032	5	710	No	14.1	309	79.3	86.2	83.6
	1030-1035	6	660	No	14.1	305	57.5	75.5	34.9
	1035-1041	7	610	No	14.1	300	83.2	93.9	94.5
	1500-1501	31	50	No	14.1	322	16.5	14.6	8.3
	1501-1503	32	30	No	14.1	303	30.6	29.2	13.7
	1506-1510	34	760	No	14.1	295	13.9	10.8	6.6
	1510-1514	35	680	No	14.1	298	65.8	56.1	61.3
	1514-1516	36	720	No	14.1	305	58.8	68.0	59.9
	1516-1519	37	640	No	14.1	288	87.3	82.5	83.7

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
12	1536-1542	42	5300	No	11.1	296	20.4	23.4	21.4
	1555-1601	45	1600	No	8.1	287	41.6	42.1	46.3
	1601-1610	46	1600	No	8.1	290	32.4	28.6	31.1
	1622-1624	50	740	No	10.1	307	69.4	73.2	-
	1627-1630	52	750	No	10.1	292	29.7	47.1	-
	1630-1635	53	890	No	10.1	319	29.3	22.5	-
	1635-1637	54	950	No	10.1	322	6.3	8.0	-
	1640-1644	57	330	No	11.3	325	27.4	23.6	53.1
13	0859-0904	6	740	No	2.4	310	32.7	26.2	29.0
	0904-0908	7	720	No	2.4	309	32.8	22.6	24.9
	0908-0912	8	650	No	2.4	303	24.6	27.9	28.5
	0928-0934	11	1200	No	5.8	317	61.1	65.1	48.2
	0934-0941	12	1100	No	5.8	322	103.4	136.7	137.7
	0941-0947	13	1100	No	5.8	322	93.4	104.9	140.5
	0947-0950	14	1200	No	5.8	316	106.4	130.1	141.3
	1105-1120	18	830	No	6.3	336	34.2	25.8	34.0
	1120-1125	19	720	Yes	6.3	310	87.2	54.1	69.2

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
13	1157-1200	22.5	1600	No	8.3	282	60.1	16.5	42.1
	1205-1210	24	600	No	5.3	298	58.2	63.9	-
	1210-1213	25	600	No	2.5	298	55.5	48.7	-
14	0830-0835	5	200	No	3.3	99	38.9	39.8	36.3
	0835-0838	6	240	No	3.3	127	32.7	43.1	40.7
	0838-0842	7	200	No	3.3	99	68.9	71.6	75.4
	0854-0856	9	200	No	3.3	90	23.3	29.3	29.6
	0902-0906	11	280	No	3.3	130	39.0	41.7	38.9
	0906-0908	12	220	No	3.3	122	45.3	62.4	-
	0908-0912	13	200	No	3.3	110	39.7	50.7	40.9
	0912-0915	14	220	Yes	3.3	122	23.9	13.8	32.6
	0919-0923	17	410	No	2.6	112	17.8	25.8	19.2
	0923-0926	18	320	No	2.6	122	45.1	52.2	56.5
	0926-0929	19	380	Yes	2.6	115	26.7	31.6	25.7
	0929-0934	20	380	Yes	2.6	115	35.1	41.9	46.4
	0934-0937	21	470	No	2.6	99	22.7	36.3	21.3
	0943-0950	23	1300	No	5.1	98	34.8	46.9	55.4
	0950-0954	24	1300	No	5.1	100	16.9	18.0	17.5
	0954-1002	25	1800	Yes	5.1	110	52.0	65.6	60.4
	1002-1006	26	1800	Yes	5.1	110	33.8	43.3	37.5

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
14	1006-1010	27	2100	Yes	5.1	119	52.9	75.8	73.2
	1010-1014	28	1800	No	5.1	110	54.8	65.4	65.8
	1014-1018	29	2000	No	5.1	115	47.1	60.4	61.7
	1039-1041	34	310	No	7.9	122	67.3	81.4	69.1
	1041-1042	35	200	No	4.1	110	56.5	73.0	35.8
	1042-1045	36	260	No	4.1	136	46.6	52.7	49.0
	1134-1137	40	180	No	4.1	130	-	58.1	55.7
	1137-1146	41	3100	Yes	2.3	120	-	27.2	26.5
	1146-1207	42	5200	Yes	2.3	130	-	35.2	41.2
	1215-1228	44	5100	Yes	2.3	135	-	41.3	42.9
	1230-1245	47	2500	Yes	1.4	133	-	16.8	32.3
	1252-1255	49	190	Yes	1.2	130	-	27.5	27.9
	1255-1259	50	140	Yes	1.2	141	-	37.1	36.4
	1300-1304	52	250	Yes	1.7	147	-	114.8	88.5
	1304-1307	53	250	No	1.7	147	-	24.3	29.2
	1307-1311	54	250	No	1.7	147	-	19.1	15.1

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
14	1411-1415	57	280	Yes	1.3	207	-	13.7	13.7
	1415-1420	58	240	Yes	1.3	157	-	-	54.7
	1420-1422	59	230	No	1.3	182	-	10.7	10.3
	1422-1423	60	230	No	1.3	175	-	25.9	22.6
	1423-1424	61	240	No	1.3	154	-	20.7	17.3
	1424-1426	62	250	No	1.3	147	-	30.3	26.7
	1426-1428	63	250	Yes	1.3	195	-	20.4	21.1
15	0842-0847	4	200	No	6.0	90	-	-	45.9
	0847-0849	5	200	No	6.0	98	-	-	32.2
	0849-0851	6	200	No	6.0	89	-	-	29.8
	0851-0853	7	200	No	6.0	92	-	-	23.5
	0857-0901	9	470	No	11.3	101	-	-	53.4
	0901-0903	10	460	No	11.3	83	-	-	55.0
	0910-0917	12	1500	No	5.4	109	-	-	20.7
	0917-0920	13	1700	No	5.4	109	-	-	19.2
	0920-0925	14	1700	No	5.4	109	-	-	59.2
	0925-0934	15	3300	No	5.4	103	-	-	45.3
	1030-1033	20	220	No	6.8	117	72.3	-	84.4
	1033-1037	21	240	No	6.8	123	44.8	-	48.5
	1037-1039	22	220	No	6.8	117	56.5	-	52.6

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
15	1104-1108	25	2200	No	7.3	126	39.4	-	50.9
	1127-1136	29	2200	No	7.3	126	94.5	-	66.7
	1136-1139	30	200	No	5.3	107	98.1	-	121.8
	1139-1140	31	200	No	5.3	107	54.8	-	74.7
	1140-1142	32	280	No	5.3	129	49.7	-	60.4
	1142-1145	33	200	No	5.3	96	54.3	-	56.1
	1145-1149	34	270	No	5.3	133	73.6	-	57.2
	1149-1151	35	240	No	5.3	123	93.6	-	119.3
	1151-1154	36	260	No	5.3	140	47.5	-	51.3
	1154-1156	37	210	No	5.3	112	99.5	-	116.2
	1156-1159	38	200	No	5.3	107	59.8	-	39.5
	1255-1258	41	450	No	2.3	109	35.9	-	44.3
	1258-1302	42	260	Yes	2.3	138	59.9	-	62.0
	1302-1305	43	270	No	2.3	133	15.7	-	22.6
	1305-1308	44	250	No	2.3	149	55.0	-	66.4
	1308-1311	45	280	No	2.3	129	41.4	-	51.7
	1324-1328	49	180	No	1.0	129	-	-	29.1
	1328-1331	50	130	No	1.0	140	-	-	30.7
	1333-1338	52	460	Yes	2.2	83	69.3	-	77.5

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
16	0853-0858	2	200	No	6.1	90	-	72.9	71.8
	0858-0900	3	200	No	6.1	90	-	48.4	49.2
	0900-0902	4	200	No	6.1	80	-	49.0	41.9
	0902-0904	5	200	No	6.1	94	-	59.4	61.7
	0904-0906	6	460	No	8.8	83	-	114.2	147.2
	0906-0908	7	460	No	8.8	92	-	45.7	39.7
	0908-0912	8	400	No	8.8	82	-	124.5	146.1
	0912-0914	9	480	No	8.8	83	-	94.2	95.2
	0914-0916	10	460	No	8.8	98	-	57.1	68.5
	0916-0923	11	1500	No	7.1	105	-	55.6	62.9
	0923-0932	12	1900	No	7.1	111	-	20.9	25.8
	0932-0937	13	2000	No	7.1	117	-	65.8	62.7
	0937-0945	14	1900	No	7.1	112	-	27.2	29.6
	1034-1042	17	80	No	6.0	169	-	37.5	34.7
	1042-1043	18	80	No	6.0	169	-	46.5	50.8
	1043-1045	19	80	No	6.0	169	-	35.3	33.9
	1045-1047	20	90	No	6.0	156	-	20.9	24.0

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
16	1047-1049	21	240	No	6.0	182	-	82.6	83.5
	1049-1051	22	230	No	6.0	165	-	59.7	53.6
	1051-1052	23	230	No	6.0	165	-	46.5	50.2
	1052-1053	24	240	No	6.0	156	-	80.0	70.4
	1053-1058	25	230	No	6.0	158	-	146.2	143.0
	1058-1100	26	240	No	6.0	179	-	55.5	67.4
	1100-1102	27	230	No	6.0	165	-	18.2	21.9
	1114-1118	31	630	No	5.0	153	-	37.4	45.8
	1118-1123	32	560	No	5.0	169	-	34.6	31.0
	1123-1126	33	580	No	5.0	165	-	61.4	56.5
	1126-1129	34	600	No	5.0	158	-	49.6	45.2
	1129-1132	35	560	No	5.0	173	-	21.9	18.6
	1240-1243	39	60	No	14.0	197	-	131.2	105.1
	1243-1244	40	70	No	14.0	169	-	76.5	81.3
	1244-1247	41	60	No	14.0	194	-	85.8	77.2
	1247-1250	42	120	No	10.0	185	-	35.2	28.2
	1310-1313	45	260	No	11.3	199	-	65.5	78.7
	1313-1317	46	230	No	11.3	175	-	79.5	71.8
	1317-1319	47	240	No	11.3	182	-	133.2	137.4
	1319-1322	48	240	No	11.3	190	-	49.3	54.1
	1322-1324	49	250	No	11.3	194	-	129.9	106.6

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
16	1324-1326	50	250	No	11.3	194	-	23.9	26.1
	1326-1330	51	260	No	11.3	199	-	50.5	51.6
	1330-1332	52	240	No	11.3	190	-	32.6	21.8
	1332-1335	53	270	No	11.3	203	-	25.0	28.5
	1335-1338	54	610	No	14.6	207	-	104.5	89.7
	1338-1340	55	640	No	14.6	212	-	49.4	53.1
	1340-1343	56	580	No	14.6	194	-	122.8	121.1
	1343-1346	57	580	No	14.6	194	-	106.8	124.8
	1346-1348	58	600	No	14.6	197	-	51.7	38.4
	1416-1416	63	60	No	7.6	197	-	19.8	19.7
	1416-1417	63.5	70	No	7.6	179	-	71.8	58.8
	1417-1417	64	70	No	7.6	179	-	32.3	30.1
	1417-1418	64.5	90	No	7.6	153	-	18.4	15.0
	1418-1419	65	70	No	7.6	182	-	15.9	15.5
	1419-1420	66	100	No	7.6	153	-	70.6	49.2
	1425-1426	68	240	No	5.6	182	-	18.4	11.5
	1426-1428	69	270	No	5.6	204	-	29.6	21.2
	1428-1430	70	250	No	5.6	190	-	20.7	23.9
	1430-1432	71	260	No	5.6	199	-	50.9	47.4
	1432-1433	72	250	No	5.6	190	-	9.2	15.0
	1433-1435	73	280	No	5.6	207	-	27.0	28.5
	1435-1436	74	270	No	5.6	203	-	24.3	22.9

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
16	1436-1437	75	270	No	5.6	203	-	23.3	21.8
	1437-1439	76	300	No	5.6	209	-	33.0	31.5
	1439-1441	77	380	No	5.6	236	-	83.6	89.0
	1441-1447	78	300	No	5.6	212	-	26.8	36.5
19	1132-1134	8	460	No	3.6	244	99.7	92.8	-
	1134-1137	9	400	No	3.6	225	51.5	45.5	-
	1156-1158	14.5	50	No	5.3	205	27.4	23.4	-
	1158-1208	15	30	No	5.3	228	30.7	45.5	-
	1208-1209	16	50	No	5.3	201	60.2	58.0	-
	1209-1212	16.5	30	No	5.3	269	46.1	60.9	-
	1212-1214	17	370	No	2.1	234	8.3	9.8	-
	1214-1216	18	360	No	2.1	228	27.6	34.1	-
	1216-1219	19	320	No	2.1	216	55.2	74.8	-
	1219-1221	20	280	No	2.1	205	30.9	26.9	-
	1221-1230	21	550	No	2.1	251	19.3	13.1	-
	1230-1237	22	550	No	2.1	251	14.9	10.0	-
	1237-1239	23	670	No	2.1	269	33.1	28.4	-
	1239-1242	24	670	No	2.1	273	16.0	13.5	-
	1320-1334	29	330	No	3.3	220	44.8	64.1	-

TABLE 5

REMOTE SENSING MEASUREMENT RESULTS

BARRINGER CORRELATION SPECTROMETER

Individual Plume Calculations

DATE MAY 1975	TIME (MDT)	EVENT NO.	DOWNWIND DISTANCE (Meters)	PLUME TOUCHDOWN	WIND		SO_2 MASS FLUX (MT/D)		
					SPEED (m/s)	DIRECTION (degrees)	COSPEC II	COSPEC III	COSPEC IV
19	1507-1511	38	320	No	5.6	218	25.2	28.7	-
	1511-1513	39	310	No	5.6	216	61.1	63.9	-
	1513-1516	40	420	No	5.6	242	56.4	80.6	-
	1521-1526	42	590	No	5.6	256	36.5	28.2	-
	1526-1532	43	590	No	5.6	256	58.2	62.7	-
	1534-1537	44	520	Yes	5.6	248	105.0	133.7	-
	1537-1547	45	1300	Yes	6.0	231	111.8	113.6	-
	1547-1555	46	1300	Yes	6.0	228	21.2	25.5	-
	1555-1607	47	1200	Yes	6.0	214	58.4	62.3	-
	1607-1612	48	1400	Yes	6.0	243	87.0	86.5	-
	1618-1622	49	400	No	9.7	240	143.6	135.1	-

Section 9

STACK SAMPLING RESULTS

Pertinent sections of the results of the stack sampling tests, as reported by Pacific Environmental Services Inc. to Environmental Measurements Inc. have been extracted to form Appendix A. They include the following:

- Test procedures and analytical methods
- Sulfur balance
- Equations and sample calculations

The information contained in Appendix A shows how the calculations for SO_2 stack concentrations and mass flux were made.

TABULATED RESULTS

A tabulation of all in-stack measurement results is presented in Table 6. Listed are the stack gas parameters (molecular weight, velocity and flow rate), and sulfur dioxide concentration (pounds per cubic foot, and ppm) and mass flux (in metric tons per day) for each of the 35 reported runs. The date and time for each run number are given also.

PLOTTED RESULTS

The Method 6/Method 2 results are presented in graphic form in Figure 10. This plot shows the SO_2 mass flux calculations for all 35 runs as continuous strings of data even though runs were irregularly spaced in time and a different number of stack tests were performed each day. The standard deviation of the in-stack results is 15.2 percent (of the mean).

SULFUR BALANCE

PES performed a sulfur balance on the target power plant combustion process and made other calculations to estimate the total SO_2 emissions that could be expected from the pulverized coal-fired power plant. This analysis is presented in full in Appendix A. As described, the Method 6 SO_2 determination can be expected to be as much as 15% low. This is principally thought to be due to losses between the inner and outer stacks. The samples extracted by the sampling train were withdrawn by the probe inserted into the inner refractory stack; no in-the-field measurements or estimates were made of the quantities of SO_2 flowing in the annular space between this stack and the outer mechanical supporting stack. The SO_2 mass flux values presented in Table 6, therefore, are considered raw data. The analysis performed in Section 10 adjusts the in-stack results to allow for the apparent 15% unmeasured emissions.

CROSS-STACK MONITOR

A cross-stack continuous monitor was in place and operating at the target power plant during the May 1975 measurements. Sulfur dioxide concentration data as measured by this instrument were turned over to the contractor by the power plant personnel. The data were in the form of daily computer printout logs with various power plant operation parameters and output variables. At this writing there is uncertainty about the correlation between the in-stack monitor results and the Method 6 results. Extensive checking of the raw data and verification of correction factors for moisture and percent oxygen must be performed. Therefore, neither results of the cross-stack measurements nor comparisons with the COSPEC results are presented in this report.

Figure 10

STACK SAMPLING SO_2 MASS FLUX
Individual Run Calculations
13-20 May 1975

(Data from Table 6)

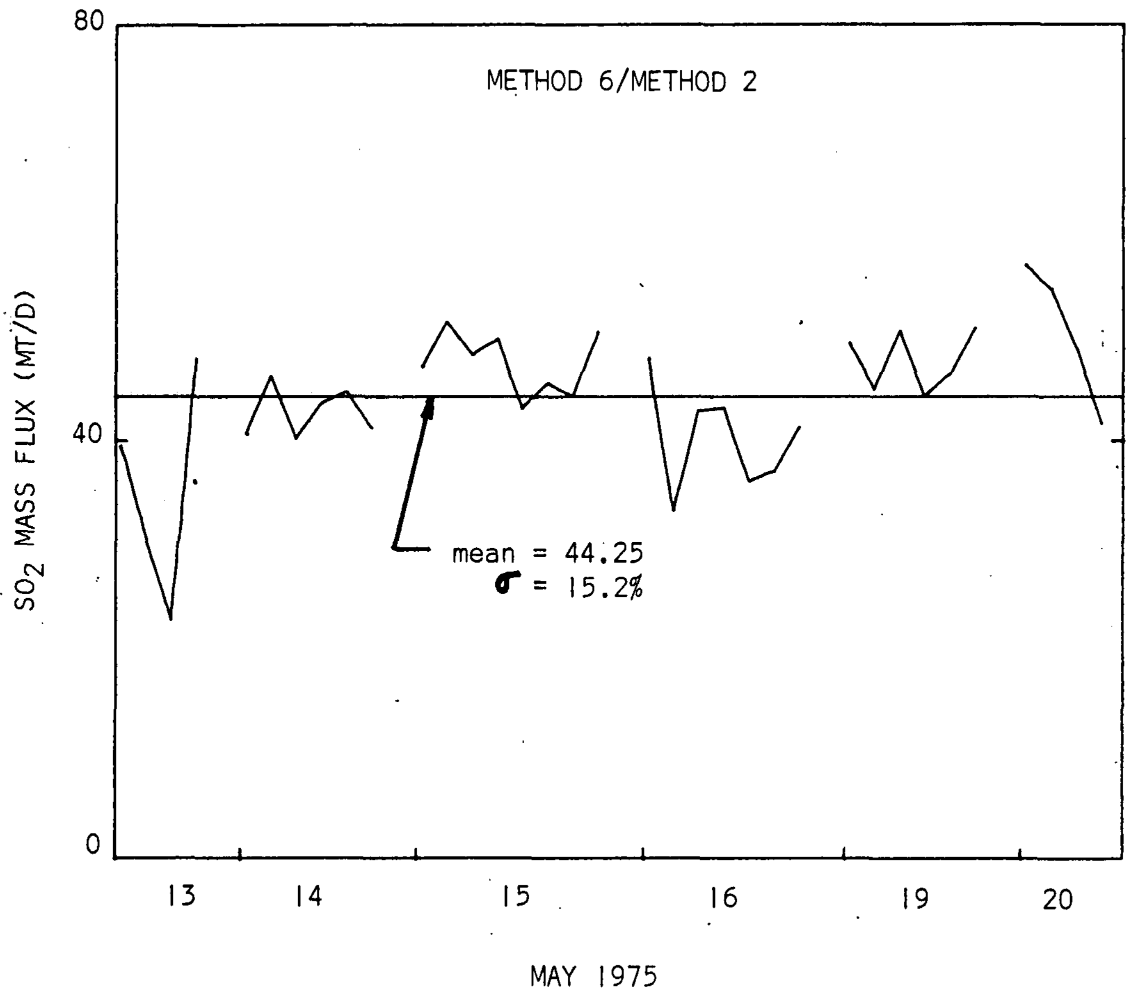


TABLE 6

IN-STACK MEASUREMENT RESULTS

EPA METHODS 2, 4 and 6

Individual Run Calculations

DATE MAY 1975	TIME (MDT)	RUN NO.	STACK GAS: MOL. WT. (lb/lb-mole) DRY	STACK GAS: MOL. WT. (lb/lb-mole) WET	STACK GAS: VELOCITY (ft/sec)	STACK GAS: FLOW RATE 10^6(ft^3/hr)	SULFUR DIOXIDE: CONCENTRATION 10^{-5}(lb/ft^3)	SULFUR DIOXIDE: CONCENTRATION (ppm)	SULFUR DIOXIDE: MASS FLUX (MT/D)
13	0850-0910	15	30.18	29.31	51.26	38.8	9.35	568	39.5
	1104-1124	17	30.18	29.31	60.14	44.9	6.30	396	30.7
	1150-1210	18	30.18	29.31	41.82	31.5	6.74	408	22.9
	1330-1350	19	30.18	29.31	44.96	33.6	13.1	792	47.9
14	0900-0920	20	30.24	29.58	36.47	27.6	13.6	822	40.8
	0945-1005	21	30.24	29.58	49.69	37.3	11.4	689	46.2
	1125-1145	22	30.24	29.58	46.43	34.6	10.7	652	40.3
	1212-1232	23	30.24	29.58	45.14	33.4	12.0	729	43.6
	1350-1410	24	30.24	29.58	43.74	31.3	13.1	785	44.7
	1430-1450	25	30.24	29.58	45.27	33.3	11.4	690	41.3
15	0835-0855	26	30.26	29.57	52.99	39.7	10.9	661	47.2
	0915-0935	27	30.26	29.57	55.98	41.8	11.3	691	51.5
	1035-1055	28	30.26	29.57	46.55	34.7	12.8	774	48.3
	1115-1135	29	30.26	29.57	47.51	35.2	13.0	790	49.8
	1240-1300	30	30.26	29.57	46.62	34.4	11.6	699	43.1
	1320-1340	31	30.26	29.57	42.65	31.5	13.3	806	45.5
	1445-1505	32	30.26	29.57	40.02	29.3	13.9	841	44.3
	1525-1545	33	30.26	29.57	47.32	34.7	13.4	812	50.5

TABLE 6

IN-STACK MEASUREMENT RESULTS

EPA METHODS 2, 4 and 6

Individual Run Calculations

DATE MAY 1975	TIME (MDT)	RUN NO.	STACK GAS MOL. WT. (lb/lb-mole) DRY	STACK GAS MOL. WT. (lb/lb-mole) WET	STACK GAS VELOCITY (ft/sec)	STACK GAS FLOW RATE 10^6(ft^3/hr)	SULFUR DIOXIDE CONCENTRATION 10^{-5}(lb/ft^3)	SULFUR DIOXIDE CONCENTRATION (ppm)	SULFUR DIOXIDE MASS FLUX (MT/D)
16	0830-0850	34	30.46	29.75	42.21	31.5	14.0	849	47.9
	0910-0930	35	30.46	29.75	33.40	24.8	12.3	746	33.3
	1030-1050	36	30.46	29.27	42.04	30.8	12.8	775	42.9
	1110-1130	37	30.46	29.75	44.71	32.7	12.1	736	43.1
	1235-1255	38	30.46	29.75	36.86	27.0	12.3	748	36.2
	1315-1335	39	30.46	29.75	36.86	27.0	12.6	762	37.1
	1415-1435	40	30.46	29.75	44.55	32.7	11.6	704	41.3
19	1116-1136	41	30.44	29.73	47.04	34.6	13.1	792	49.4
	1155-1215	42	30.44	29.73	44.03	32.4	12.7	771	45.0
	1315-1335	43	30.44	29.73	53.87	39.5	11.8	715	50.6
	1355-1415	44	30.44	29.73	50.40	37.0	11.0	666	44.3
	1505-1525	45	30.44	29.73	47.60	34.9	12.2	739	46.4
	1545-1605	46	30.44	29.73	55.55	40.7	11.5	699	50.9
20	0820-0840	47	30.42	29.72	54.30	39.9	13.1	791	56.9
	0900-0920	48	30.42	29.72	53.46	39.2	12.8	774	54.6
	1015-1035	49	30.42	29.72	47.32	34.5	13.0	786	48.9
	1055-1115	50	30.42	29.72	41.64	30.4	12.6	761	41.7

Section 10

COMPARISON OF RESULTS

MODIFICATION OF DATA

The Remote Sensor Results presented in Section 8, and the Stack Sampling Results presented in Section 9, are not directly comparable because they were gathered over different time periods and they measured different emissions. Both data sets were modified prior to making statistical comparisons.

Time-Averaged (COSPEC) Mass Flux. To make a comparison of the two measurement methods the COSPEC results were processed further to bring them into a comparable time frame with the Method 6 tests. Because the stack tests were conducted for periods of 20 minutes the COSPEC data were grouped into sets to approximate the same time span. The remote sensor data were separated into time periods averaging 23.3 minutes; these groupings were averaged.

These average COSPEC SO_2 flux measurements appear in Table 7, labelled, "20-Minute Averages". The median number of events in each COSPEC mass flux average is 5; the number of events used to calculate each average is listed in the table. The remote sensor averages are given with the concurrent Method 6 runs; twenty-five sets of simultaneous data are shown as well as additional separately-collected data.

Two further reductions in the data base were made: "60-Minute Averages" (Table 8) and "Daily Averages" (Table 9). "60-Minute Averages" for the COSPEC mass fluxes cover an average span of 59.4 minutes. The median number of averaged events is ten; the number of events in each average is tabulated. The "60-Minute" fluxes for Method 6 are the average of two 20-minute runs as shown. Twelve concurrent "60-Minute" test periods result.

"Daily Averages" include all data processed for nine measurement days; there are five days of concurrent results. The "Daily Averages" are unweighted arithmetic averages of the "20-Minute Averages". The average number of daily COSPEC events for 13-19 May is 35; the number of Method 6 runs varies from four to eight per day.

Adjusted (In-Stack) Mass Flux. The in-stack mass flux results were adjusted also to raise the calculated values to account for unmeasured SO_2 emissions--not detected by the in-stack probe--which were monitored by the remote sensor. As the sulfur balance performed by the subcontractor shows (See Appendix A) approximately 15% of the SO_2 that could theoretically be present in the stack gases was not measured by Method 6. The conclusion drawn by the subcontractor is that the SO_2 gas in the annular space between the inner refracting stack and the outer structural stack was emitted into the atmosphere undetected by the stack sampling technique. Sulfur entering the combustion process also could have left as SO_2 through other leakage paths or as sulfur in the ash.

The remote sensing method could be expected to measure both the central stack SO_2 emissions and some portion of the intra-stack and other leakage SO_2 emissions. To perform a meaningful analysis of the relative accuracy between the two methods the in-stack mass flux calculations were adjusted to add the 15%. This was done by the formula:

$$\frac{\text{Adjusted In-Stack } SO_2 \text{ Mass Flux}}{100\%} = \frac{\text{Raw In-Stack } SO_2 \text{ Mass Flux}}{85\%}$$

$$\text{ADJUSTED} = 1.18 \times \text{RAW}$$

The raw in-stack flux calculations (reported in Section 9) were multiplied by 1.18; the adjusted SO_2 mass flux values are listed in Tables 7, 8 and 9.

TABLE 7

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"20-MINUTE AVERAGES"

DATE MAY 1975	TIME (MDT)	REMOTE SENSING				STACK SAMPLING		
		NUMBER OF EVENTS	AVERAGE SO_2 MASS FLUX (MT/D)			TIME (MDT)	RUN NO.	ADJUSTED SO_2 MASS FLUX (MT/D)
			COSPEC II	COSPEC III	COSPEC IV			
8	0911-0930	6	74.4	65.3	-	-	-	-
	0943-1001	3	42.5	47.9	-	-	-	-
	1318-1326	5	60.5	70.7	-	-	-	-
	1442-1457	4	52.5	59.4	-	-	-	-
9	0940-1002	3	48.8	51.0	-	-	-	-
	1002-1026	2	109.1	85.9	-	-	-	-
	1427-1443	2	11.5	16.5	-	-	-	-
	1511-1524	2	69.8	72.7	-	-	-	-
12	1030-1041	3	73.3	85.2	71.0	-	-	-
	1500-1519	6	45.5	43.5	38.9	-	-	-
	1536-1610	3	31.5	31.4	32.9	-	-	-
	1622-1644	5	32.4	34.9	-	-	-	-
13	0859-0912	3	30.0	25.6	27.5	0850-0910	15	46.6
	0928-0950	4	91.1	109.2	116.9	-	-	-
	1105-1125	2	60.7	40.0	51.6	1104-1124	17	36.2
	1157-1213	3	57.9	43.0	*	1150-1210	18	27.0
	-	-	-	-	-	1330-1350	19	56.5

*Insufficient data for averaging.

TABLE 7

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"20-MINUTE AVERAGES"

DATE MAY 1975	TIME (MDT)	REMOTE SENSING: NUMBER OF EVENTS	REMOTE SENSING: AVERAGE SO_2 MASS FLUX (MT/D) COSPEC II	COSPEC III	COSPEC IV	STACK SAMPLING: TIME (MDT)	RUN NO.	ADJUSTED SO_2 MASS FLUX (MT/D)
14	0830-0856	4	41.0	46.0	45.5	-	-	-
	0902-0937	9	32.8	39.6	35.2	0900-0920	20	48.1
	0943-1018	7	41.8	53.6	53.1	0945-1005	21	54.5
	1039-1045	3	56.8	69.0	51.3	-	-	-
	1134-1207	3	-	40.2	41.1	1125-1145	22	47.6
	1215-1245	2	-	29.1	37.6	1212-1232	23	51.4
	1252-1311	5	-	44.6	39.4	-	-	-
	1411-1428	7	-	20.3	23.8	1350-1410	24	52.7
	-	-	-	-	-	1430-1450	25	48.7
15	0842-0903	6	-	-	40.0	0835-0855	26	55.7
	0910-0934	4	-	-	36.1	0915-0935	27	60.8
	1030-1108	4	53.3	-	59.1	1035-1055	28	57.0
	1127-1159	10	72.5	-	76.3	1115-1135	29	58.8
	1255-1311	5	41.6	-	49.4	1240-1300	30	50.9
	1324-1338	3	*	-	45.8	1320-1340	31	53.7
	-	-	-	-	-	1445-1505	32	52.3
	-	-	-	-	-	1525-1545	33	59.6
16	0853-0908	6	-	64.9	68.6	0830-0850	34	56.5
	0908-0945	7	-	63.6	70.1	0910-0930	35	39.3
	1034-1102	11	-	57.2	57.6	1030-1050	36	50.6
	1114-1132	5	-	41.0	39.4	1110-1130	37	50.9
	1240-1313	5	-	78.8	74.1	1235-1255	38	42.7

*Insufficient data for averaging.

TABLE 7

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"20-MINUTE AVERAGES"

DATE MAY 1975	TIME (MDT)	REMOTE SENSING				STACK SAMPLING		
		NUMBER OF EVENTS	AVERAGE SO_2 MASS FLUX (MT/D)			TIME (MDT)	RUN NO.	ADJUSTED SO_2 MASS FLUX (MT/D)
			COSPEC II	COSPEC III	COSPEC IV			
16	1313-1348	13	-	73.8	71.2	1315-1335	39	43.8
	1416-1447	17	-	33.9	31.6	1415-1435	40	48.7
19	1132-1137	2	75.6	69.2	-	1116-1136	41	58.3
	1156-1221	8	35.8	41.7	-	1155-1215	42	53.1
	1221-1242	4	20.8	16.3	-	-	-	-
	1320-1334	1	*	*	*	1315-1335	43	59.7
	-	-	-	-	-	1355-1415	44	52.3
	1507-1537	6	57.1	66.3	-	1505-1525	45	54.8
	1537-1612	4	69.6	72.0	-	1545-1605	46	60.1
20	-	-	-	-	-	0820-0840	47	67.1
	-	-	-	-	-	0900-0920	48	64.4
	-	-	-	-	-	1015-1035	49	57.7
	-	-	-	-	-	1055-1115	50	49.2

*Insufficient data for averaging.

TABLE 7

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"60-MINUTE AVERAGES"

DATE MAY 1975	TIME (MDT)	REMOTE SENSING: NUMBER OF EVENTS	REMOTE SENSING: AVERAGE SO_2 MASS FLUX (MT/D) COSPEC II	COSPEC III	COSPEC IV	STACK SAMPLING: TIME (MDT)	RUN NO.	ADJUSTED SO_2 AVERAGE MASS FLUX (MT/D)
8	0911-1001	9	62.4	59.5	-	-	-	-
	1318-1457	9	56.9	65.7	-	-	-	-
9	0940-1026	5	72.9	65.0	-	-	-	-
	1427-1524	4	40.7	44.6	-	-	-	-
12	1500-1542	7	41.9	40.6	36.4	-	-	-
	1555-1644	7	33.7	35.0	*			
13	0859-0950	7	64.9	73.4	78.6	0850-0910	15	*
	1105-1213	5	59.0	41.8	48.4	1104-1210	17,18	31.6
						1330-1350	19	*
14	0902-1018	16	36.7	45.7	43.6	0900-1005	20,21	51.3
	1134-1245	5	-	35.8	39.7	1125-1232	22,23	49.5
	1252-1428	12	-	31.3	30.3	1350-1450	24,25	50.7
15	0842-0934	10	-	-	38.4	0835-0935	26,27	58.3
	1030-1159	14	67.0	-	71.4	1035-1135	28,29	57.9
	1255-1338	8	*	-	48.1	1240-1340	30,31	52.3
	-	-	-	-	-	1445-1505	32,33	56.0

*Insufficient data for averaging.

TABLE 8

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"60-MINUTE AVERAGES"

DATE		REMOTE SENSING					STACK SAMPLING		
		NUMBER	AVERAGE SO_2 MASS FLUX (MT/D)						
DATE MAY 1975	TIME (MDT)	OF EVENTS	COSPEC II	COSPEC III	COSPEC IV		TIME (MDT)	RUN NO.	ADJUSTED SO_2 AVERAGE MASS FLUX (MT/D)
16	0853-0945	13	-	64.2	69.4		0830-0930	34,35	47.9
	1034-1132	16	-	52.1	51.9		1030-1130	36,37	50.8
	1240-1348	18	-	75.2	72.0		1235-1335	38,39	43.3
	1416-1447	17	-	*	*		1415-1435	40	*
19	1132-1221	10	43.8	47.2	-		1116-1215	41,42	55.7
	1320-1334	1	*	*	*		1315-1415	43,44	56.0
	1507-1612	10	62.1	68.6	-		1505-1605	45,46	57.5
20	-	-	-	-	-		0820-0920	47,48	65.8
	-	-	-	-	-		1015-1115	49,50	53.5

*Insufficient data for averaging.

TABLE 9

COMPARISON OF RESULTS

REMOTE SENSING AND STACK SAMPLING

"DAILY AVERAGES"

DATE MAY 1975	TIME (MDT)	REMOTE SENSING				STACK SAMPLING		
		NUMBER OF EVENTS	AVERAGE SO_2 MASS FLUX (MT/D)*			TIME (MDT)	RUN NO.	ADJUSTED SO_2 AVERAGE MASS FLUX (MT/D)
			COSPEC II	COSPEC III	COSPEC IV			
8	0911-1457	18	57.5	60.8	-	-	-	-
9	0940-1524	9	59.8	56.5	-	-	-	-
12	1030-1644	17	45.7	48.8	47.6	-	-	-
13	0859-1213	12	59.9	54.5	65.3	0850-1350	4	41.6
14	0830-1428	40	43.1	42.8	40.9	0900-1450	6	50.5
15	0842-1338	32	55.8	-	51.1	0835-1545	8	56.1
16	0853-1447	64	-	59.0	58.9	0830-1435	7	47.5
19	1132-1612	25	51.8	53.1	-	1116-1605	6	56.4
20	-	-	-	-	-	0820-1115	4	59.6

INSTRUMENT COMPARISONS

Comparison of SO_2 emission rates for the three COSPEC instruments is presented in graphic form. Figures 11, 12 and 13 are scatter plots of the "20-Minute Averages" covering the eight day period, 8-19 May, as tabulated in Table 7. The linear correlation coefficients (r) are shown for each plot.

The correlation coefficients indicate close agreement between instruments. The agreement is best between COSPEC III and COSPEC IV (r = + .951); COSPEC II and COSPEC IV also agree closely (r = + .933), with the least agreement showing between COSPEC II and COSPEC III (r = + .896).

These high degrees of correlation are independent of uncontrolled parameters such as variations in the wind speed. There is a wide spread in SO_2 flux results for one COSPEC from one set of calculations to the next. For example, the values range from 109.1 MT/D to 11.5 MT/D for COSPEC II (Table 7, 9 May). However, there is correlation with the other COSPEC (85.9 MT/D to 16.5 MT/D, for COSPEC III, same table, same day). These differences for one instrument from measurement to measurement are apparently due largely to wind speed variations; improvement of methods for measuring winds aloft would reduce the spread in COSPEC results.

The internal consistency of the COSPEC remote sensing measurements and the data processing procedures used to calculate the SO_2 emission rates are demonstrated by the scatter plots and correlation coefficients. Similar SO_2 mass flux results could be expected from any COSPEC, independent of which model was used, to measure a source plume when the field methodology and data processing procedures described in this report are followed.

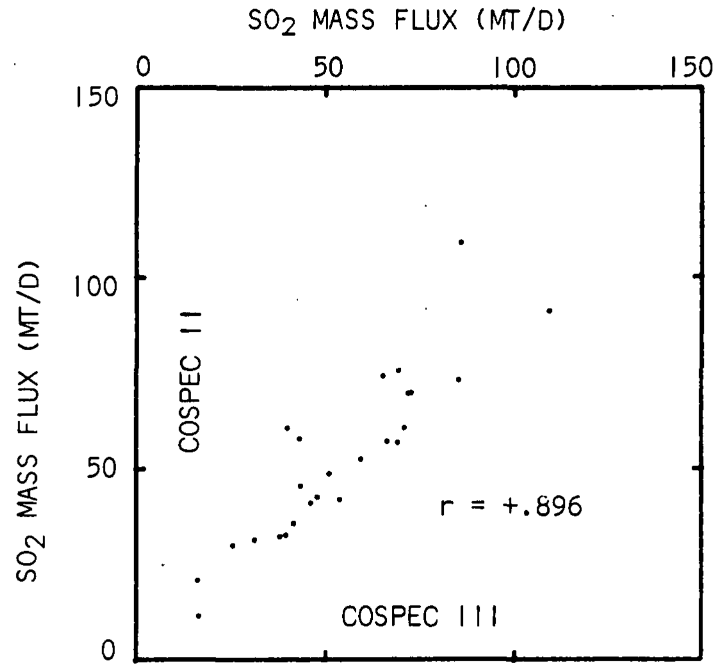


Figure 11

COSPEC II
vs
COSPEC III

"20-Minute Averages"

(Data from Table 7)

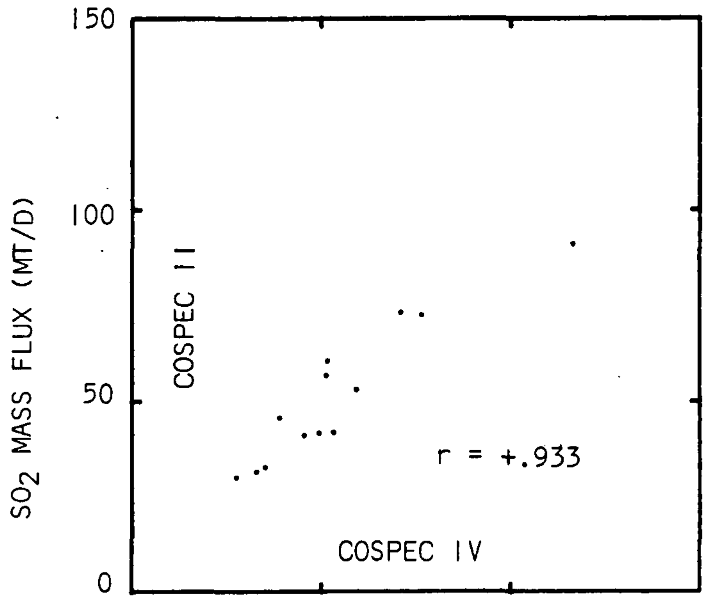


Figure 12

COSPEC II
vs
COSPEC IV

"20-Minute Averages"

(Data from Table 7)

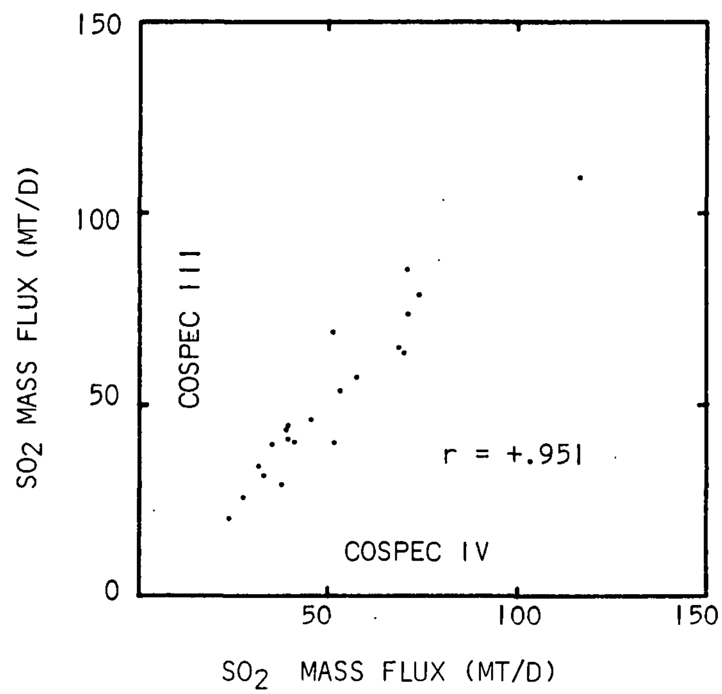


Figure 13

COSPEC III
vs
COSPEC IV

"20-Minute Averages"

(Data from Table 7)

REMOTE/IN-STACK COMPARISONS

The stack sampling mass flux values are a combination of Method 6 (concentration) and Method 2 (flow rate) data, just as the remote sensing mass flux values are a combination of COSPEC (concentration) and pibal (wind speed) data. For clarity the comparison between the remote sensing and stack sampling results is labelled "COSPEC-Pibal versus Method 6-Method 2".

Graphic Comparisons. Comparison of the remote sensor and stack sampling SO_2 emission rates are shown graphically in Figures 14, 15 and 16. These are scatter plots of the "20-Minute Averages", "60-Minute Averages" and "Daily Averages" for all COSPEC II, III and IV readings for which there are Method 6 data over the same time period (see Tables 7, 8 and 9).

Generally, as the averaging time increases from "20-Minute" to "Daily" the scatter of the data is reduced. However, for the "Daily Averages" there appears to be one set of anomalous data: that of 13 May. The three points above and to the left of the main cluster of points suggests that either there was something unusual about the power plant operation on that day or the in-stack results were erroneously low. The subcontractor has observed that the 13 May results are low (see Appendix A). Because the Method 6-Method 2 data for 13 May show significantly different results they were discarded from further analysis.

REMOTE/IN-STACK COMPARISONS

(THREE-COSPEC DATA)

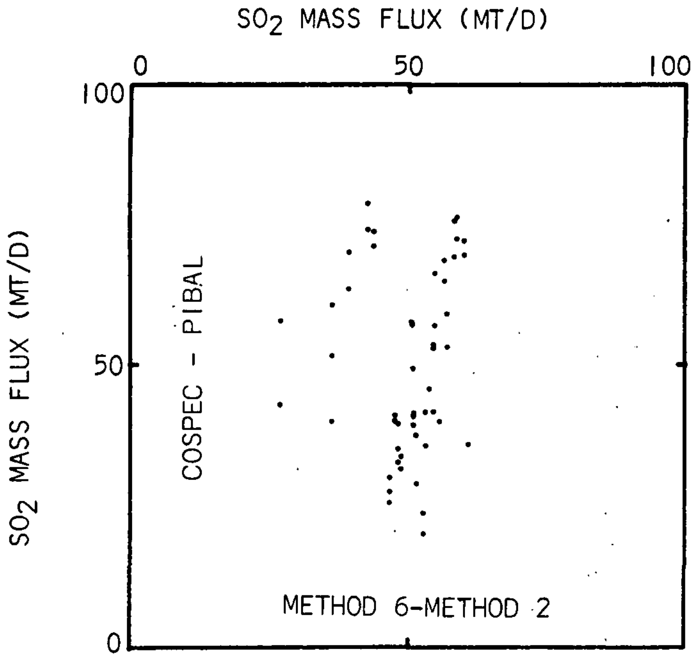


Figure 14

COSPECs II, III, IV
vs
METHOD 6-METHOD 2

"20-Minute Averages"

(Data from Table 7)

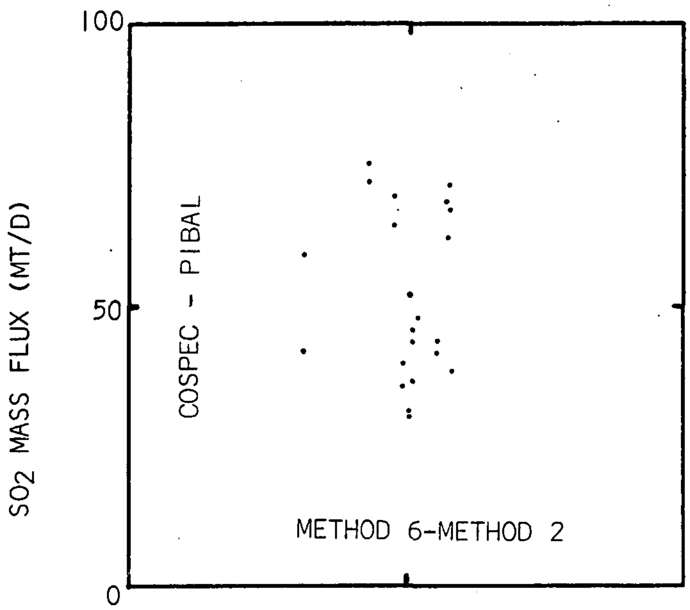


Figure 15

COSPECs II, III, IV
vs
METHOD 6-METHOD 2

"60-Minute Averages"

(Data from Table 8)

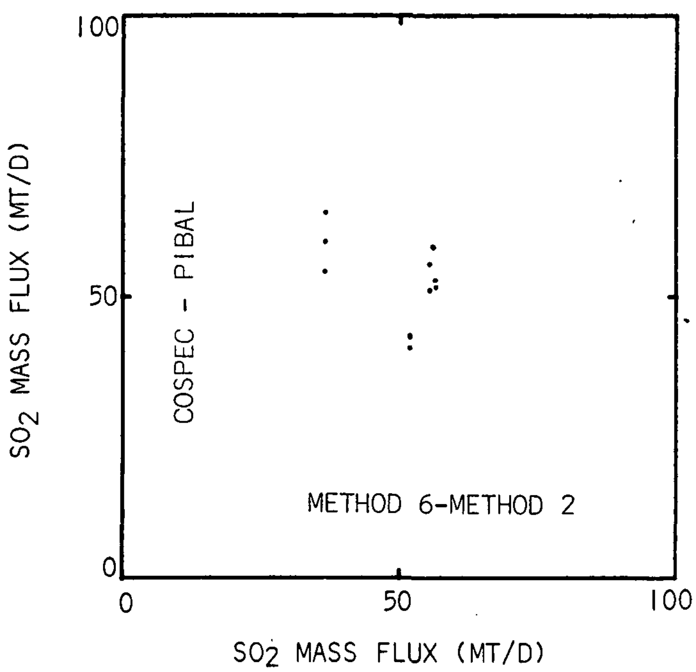


Figure 16

COSPECs II, III, IV
vs
METHOD 6-METHOD 2

"Daily Averages"

(Data from Table 9)

Comparison of Means. To determine whether the means of the COSPEC-Pibal results were the same as the means of the Method 6-Method 2 results a statistical analysis was performed on the paired data for 14, 15, 16 and 19 May 1975. The 20-minute average remote sensor data were used (Table 7) because the Method 6 runs were 20 minutes long. (The 20 minute samples are considered the fundamental measurement for both methods for this and succeeding analyses.) Confidence limits were calculated for the four days of data using the Student-t distribution.

The confidence limit analysis determined the following: how the mean of the remote SO_2 mass flux differs with respect to the mean of the in-stack SO_2 mass flux. The test was performed for each COSPEC using the 20-minute samples; three days of concurrent measurements occured for each instrument.

These confidence limits were calculated from the following formula:

$$M(L,U) = \bar{z} \pm (T_{A,v} * \sigma_{\bar{z}})$$

where:

M	=	confidence limit (at level A)
(L	=	lower limit)
(U	=	upper limit)
z	=	percent difference between remote and in-stack fluxes
$\bar{z}$	=	average percent difference between remote and in-stack, in % of Method 6-Method 2 flux value.
$T_{A,v}$	=	Student-t at level A, with v degrees of freedom (from statistical tables)
$\sigma_{\bar{z}}$	=	$\sigma_z/\sqrt{n}$
σ_z	=	Standard deviation of percent differences, z
A	=	Confidence level (90%)
v	=	Degrees of freedom (n-1)
n	=	Number of samples

The 90% confidence limits are tabulated in Table 10. The limits, expressed in percent of the EPA reference method, are given for each COSPEC. The number of samples associated with each result is shown, also.

Table 10

CONFIDENCE LIMITS

Confidence Intervals at the 90% Confidence Level

on the Percent Difference between COSPEC-Pibal Mean SO_2 Flux

and Method 6/Method 2 Mean SO_2 Flux

14-19 May 1975

	COSPEC II vs In-Stack	COSPEC III vs In-Stack	COSPEC IV vs In-Stack
Confidence Limits (%)	+10.3% -19.1%	+23.5% -12.1%	+16.8% -15.3%
Number of Samples (n)	9	16	18

Based upon the data generated in this study, the upper and lower limits of the 90% confidence interval for the percent difference between the COSPEC-Pibal SO_2 mass flux (for a given instrument) and the Method 6/Method 2 SO_2 mass flux are given by the "plus" and "minus" percentage figures in the table. Using COSPEC II as an example, the true percent difference between the remote mass flux and the in-stack mass flux lies between +10.3% and -19.1%, unless an event of probability 10% or less has occurred.

The confidence limits for all three COSPECs are similar even though the number of 20-minute samples (n) ranges from 9 to 18. They fall within inclusive limits of ±24%. Thus the conclusion is reached that at the 90% confidence level, the actual percent difference, in the very long-term average, between results obtained using the remote sensing technique utilized in this program and the "true" (i.e., as determined by Method 6) mass flux from a source is within ±24%.

Comparison of Dispersions. A further analysis of the paired 20-minute samples of remote and in-stack flux results was made to compare the dispersion or spread of the two types of data. A separate analysis was done for each of the three COSPECs tested. The instruments were used in the moving measurment mode over different periods so that unique pairings of COSPEC/Method 6 data (from 9 to 18) result. Thus, only 20-minute samples were used for which there were comparative measurements.

The means and standard deviations of the COSPEC-Pibal and Method 6/Method 2 results are given in Table 11. The means for both methods range from 50.6 to 55.1 MT/D, indicating uniformity of results. The standard deviations (σ), on the other hand, differ between methods even though they are consistent for each method. The remote sensing σ is 30.7%-33.8% compared to 7.1%-11.2% for the in-stack σ. This factor of three difference between the COSPEC-Pibal and the Method 6 - Method 2 σ gives a measure of the dispersion caused by the pibal wind measurements.

Table 11

ANALYSIS OF

20-MINUTE SAMPLES

Means and Standard Deviations of

COSPEC-Pibal versus Method 6-Method 2 Mass Flux

14-19 May 1975

	COSPEC II	IN-STACK	COSPEC III	IN-STACK	COSPEC IV	IN-STACK
Mean (MT/D)	53.3	55.1	52.8	50.8	50.6	51.3
σ (MT/D)	16.4	3.9	17.9	5.7	16.3	5.7
σ (%mean)	30.7%	7.1%	33.8%	11.2%	32.2%	11.1%
Number of Samples	9		16		18	

COSPEC II, S/N 5922; COSPEC III, S/N 5932; COSPEC IV,S/N 5256
20-minute average data taken from Table 7

It should be noted that the variability in the values of σ for the in-stack data suggests that there were variations as well in the Method 6 or Method 2 data, or variations in plant operation. Thus, while the variation in wind speed has been identified as a major source of error in the COSPEC-derived flux values, it does not account for the entire variation. Since the COSPEC estimate of flux is proportional to the true flux (assumed here to be given by Method 6) and to the estimated wind velocity it may be said that to a first order, the inherent percent variations in these COSPEC-estimated fluxes are 29.9%,* 31.9%, 30.2% respectively for COSPEC II,III and IV. That is, an approximate 30% variation in COSPEC 20-minute flux estimates can be expected if the actual flux is constant. Uncertainty in wind speed is the dominant component of this variability and can be reduced by taking more frequent wind measurements.

* Derived from σ's in Table 11; e.g., $29.9\% = \sqrt{(30.7\%)^2 - (7.1\%)^2}$

WIND SPEED VARIATIONS

The impact of wind speed variations on the COSPEC SO_2 mass flux calculations is easily illustrated. The mass flux is directly proportional to the wind speed (See Section 7); a 10% error in determining the speed of the wind at the plume elevation causes a 10% error in the calculated flux. When available, pibal results were averaged to determine a representative wind speed during a COSPEC plume measurement; often only a single pibal was tracked during as many as eight events. Thus, any fluctuations in wind speed before and after the pibal were unknown.

An example of a set of flux calculations based on a single pibal observation is presented in Table 12. The fluxes are extracted from Table 5 (Section 8); they are reproduced here to illustrate that the lack of sufficient winds-aloft data clearly affected the COSPEC results.

Table 12

COSPEC-Pibal SO_2 Mass Flux Variations

19 May 1975

COSPEC II S/N 5922

Event No.	Time (MDT)	SO_2 Mass Flux (MT/D)*
17	1212-1214	8.3
18	1214-1216	27.6
19	1216-1219	55.2
20	1219-1221	30.9
21	1221-1230	19.3
22	1230-1237	14.9
23	1237-1239	33.1
24	1238-1242	16.0

*at 2.1 M/S wind speed

There was one pibal that was tracked during these 30-minutes of COSPEC-Pibal plume measurements. Knowing that the nominal Method 6-Method 2 SO_2 mass flux was about 50 MT/D, the time of the pibal observation can be deduced from the tabulated fluxes. (The COSPEC flux(es) closest to the nominal flux would be nearest the time of upper air measurements). In fact, the pibal used to calculate these eight fluxes was released at 1219 MDT--as could be estimated from the time of Event 19; this flux was calculated at 55.2 MT/D. This means that the 2.1 m/s wind speed was "correct" for Event 19 but was low for most of the remaining events. If more pibals had been run during this period the remaining seven fluxes would probably change upward. The surface winds (see Appendix B) showed a ±60% fluctuation about a mean of 5 m/s; the pibal-measured wind speed (2.1 m/s) was *not* representative for this measurement period.

REMOTE SENSOR PRECISION

The previous analysis implys that the COSPEC remote SO_2 flux measurements differ in the long term average by no more than 24% from the Method 6 results, at the 90% confidence level. However, what is the *precision* of the remote sensing technique? The precision is essentially the accuracy with which an estimate can be made of the true mean value of the COSPEC-determined fluxes, using only a finite number (n) of actual COSPEC plume measurements.

To develop the relationship between the error interval and the required number of measurements requires the following assumption: In the long-term average the percent difference between COSPEC and Method 6 flow estimates is zero or, if not identically zero, within a few percent of zero. The preceeding analysis, while not supporting this assumption directly, gives no reason to discard it. Further, it is certainly true that adding more data to that gathered under this project would permit the narrowing of the confidence intervals given in Table 10. Even if this should ultimately show that there is some small percentage offset between the COSPEC and Method 6 results, this offset would then be accurately known and could, therefore, be accounted for in processing COSPEC flux calculations. The assumption of zero percent difference is one primarily of convenience and is not crucial to the following discussion of precision.

In general, if a statistical population has a standard deviation (σ), then the standard deviation of the sample mean is $\sigma/\sqrt{n}$ where n is the number of samples. (Thus, for example, to double the precision of an estimate it is necessary to quadruple the sample size). For the purpose of determining precision it is helpful to assume that the sample mean follows a Gaussian distribution (the Central Limit Theorem insures this as the sample size increases); then it is possible to specify the actual probability of the sample average deviating from the true population mean by more than a specified amount. This well known relationship is briefly summarized as follows:

> The probability of a Gaussian variate (where standard deviation is σ) deviating from its mean value by more than a certain amount is:

Deviation	Probability
1.64σ	.10
2.05σ	.05
$2.5\ \sigma$	.01

The above relationships were applied to the question of estimating the precision of the flux estimate obtained by averaging n - number of 20-minute samples. Following is an example of this procedure, using the case of COSPEC II.

The data in Table 7 were used to compute the standard deviation of the percent difference between corresponding COSPEC II and Method 6 20-minute flux measurements to be 22.45%. The true standard deviation of the statistical distribution of percent difference (for COSPEC II vs. Method 6) is denoted by σ. The best estimate of σ that can be made with the present data is σ= 22.45%. Considering a situation with a given number (n) of 20-minute samples the sample mean can be calculated (calling it μ_n). As stated above the standard deviation of μ_n is $\sigma/\sqrt{n}$ It has been assumed that μ_n is normally distributed. Thus, from the above probability table the possibility of μ_n deviating from its true mean value by more than 1.64 ($\sigma/\sqrt{n}$) is 0.10. Selecting n such that

$$1.64\ \sigma/\sqrt{n} = 25\%$$

than it can be said that: provided n or more samples are taken, the probability is 0.90 that the sample mean does not deviate from its true value by more than 25%. Solving this equation gives n = 2.17. Since an integer number of samples are required this is rounded up to n = 3. This is the first number in Table 13; the remainder of the numbers were derived in an idential manner.

The results of this analysis are presented in Table 13. The table gives the number of 20-minute samples required to have a mass flux estimate that has a percent error falling within a given interval, at the indicated level of confidence.

Table 13

COSPEC-PIBAL PRECISION

Number of 20-Minute Samples

Required to Achieve a Given Error Interval

Error Interval	Confidence Level	COSPEC II S/N 5922	COSPEC III S/N 5932	COSPEC IV S/N 5956
±25%	90% 95% 99%	3 4 6	7 11 16	7 10 15
±20%	90% 95% 99%	4 6 9	11 17 26	10 16 24

From the table come the following results: to achieve ±25% error in remote sensing SO_2 Mass Flux data 95% of the time, 4,11 or 10 samples, each 20-minutes long, should be gathered. Eleven 20-minute samples represents a one-half day (4-hour) measurement period or about 55 plume crossings. To raise the confidence level to 99 % the required number of samples increases to 16 maximum, or 5 hours of measurements (80 plume crossings).

A significant finding here is the fewer number of required 20-minute samples for COSPEC II contrasted to COSPEC III and IV. Given the higher noise level of the COSPEC II (and hence lower sensitivity) the opposite would be expected. However, this difference may be caused by narrower statistical spread of in-stack results on days when the COSPEC II was operational and wider spread on COSPEC III and IV days (as previously noted, see Table 11) and not by remote sensing variations.

Table 13 provides a means of determining how much COSPEC measuring is needed to achieve an accuracy comparable to other stack monitoring techniques. Using the worst case figures (COSPEC III and IV), ±20% accuracy can be obtained from a single day (6 hours, 85 plume crossings) of data gathering for the 95% confidence level. The most favorable result (COSPEC II) indicates only two hours of data are needed or about 30 plume crossings. In summary, the COSPEC-Pibal measurement system when used for two-to-six hours produces SO_2 mass flux results with ±20% accuracy. Longer measurement periods would improve the accuracy and/or improve the confidence in the remote sensing data.

APPENDIX A

AIR POLLUTION EMISSION TEST

REPORT

(FINAL)

COAL FIRED POWER PLANT

PREPARED FOR

ENVIRONMENTAL MEASUREMENTS, INC.

PES JOB NO. 088

8/12/75

PACIFIC ENVIRONMENTAL SERVICES, INC.

1930 14th Street

Santa Monica, California 90404

Robert J. Bryan, Project Manager

I. INTRODUCTION

This test was conducted on a pulverized coal fired power plant in the southwestern United States. The testing took place over the period of May 6-20, 1975. The sampling location was in the stack following the collection device and blowers.

Sampling was conducted for sulfur dioxide using EPA Method 6. Velocity traverses were conducted using both EPA Method 2 and a modified EPA Method 2. A moisture determination was also performed using EPA Method 4.

The source test team consisted of Joseph Boyd, John Stevenson and Robert Norton, all of whom are employed by Pacific Environmental Services, Inc.

The purpose of the test was to supply extractive stack test data on SO_2 for comparison with remote sensing data obtained with Barringer correlation spectrometer. The remote sensing was performed by Environmental Measurement Inc.

II. SULFUR BALANCE

An attempt has been made to perform a sulfur balance based upon information supplied by the operator of the power plant and stack sulfur emission data. In a rigorous approach it would be necessary to know the exact quantity of sulfur entering the combustion process through fuel, to identify all exit pathways, and to determine the quantity of the sulfur leaving the process. In this case information was supplied by the operator on coal firing rates and to a limited extent on coal composition. Coal firing rate data were obtained from a computer print-out showing hourly and cumulative quantities of coal fired for each day. Composition data were supplied on a shift basis for sulfur, ash and moisture content on a weight basis. Samples were obtained from the coal pulverizers. These data have some shortcomings in that (1) only total sulfur is shown whereas it may be present in organic, pyritic, or sulfate content. Thus exact combustion reactions cannot be written. Furthermore, some small amount of sulfur originally present in non-sulfate form may be converted to SO_3 which is not determined in the Method No. 6 Procecure.

Two approaches were used to examine the sulfur balance in view of the above limitations. The first approach involved the direct comparison of the average daily charge of total sulfur to the boiler (as obtained from the operator) with the quantity measured leaving through the stack. Figure 1 illustrates a possible set of in and out pathways. The only actual data available are that for sulfur entering in the coal and that leaving in the stack gases as SO_2. No specific data are available on the combustible sulfur portion of the total sulfur charged, the amount present in the ash, the amount present as non-SO_2 sulfur in the stack gases and the amount of sulfur in leaks.

Because no ultimate analysis was available on the coal, analyses of six other coals originating from the same general area were examined. From these analyses an ultimate analysis was hypothesized for the coal average determined over a three week period from May 1 to May 21, 1975. Ash and moisture content were similarly selected. The following assumed analysis was used in further calculations.

Constituent	Weight %
C	59.07
H	4
O	10
S	0.93*
N	1
Ash	20
Moisture	5
TOTAL	100

*Represents average S content from 5/1 to 5/21/75. Non combustible portion unknown, but analyses on other local coals show about 15% of the sulfur in sulfate form.

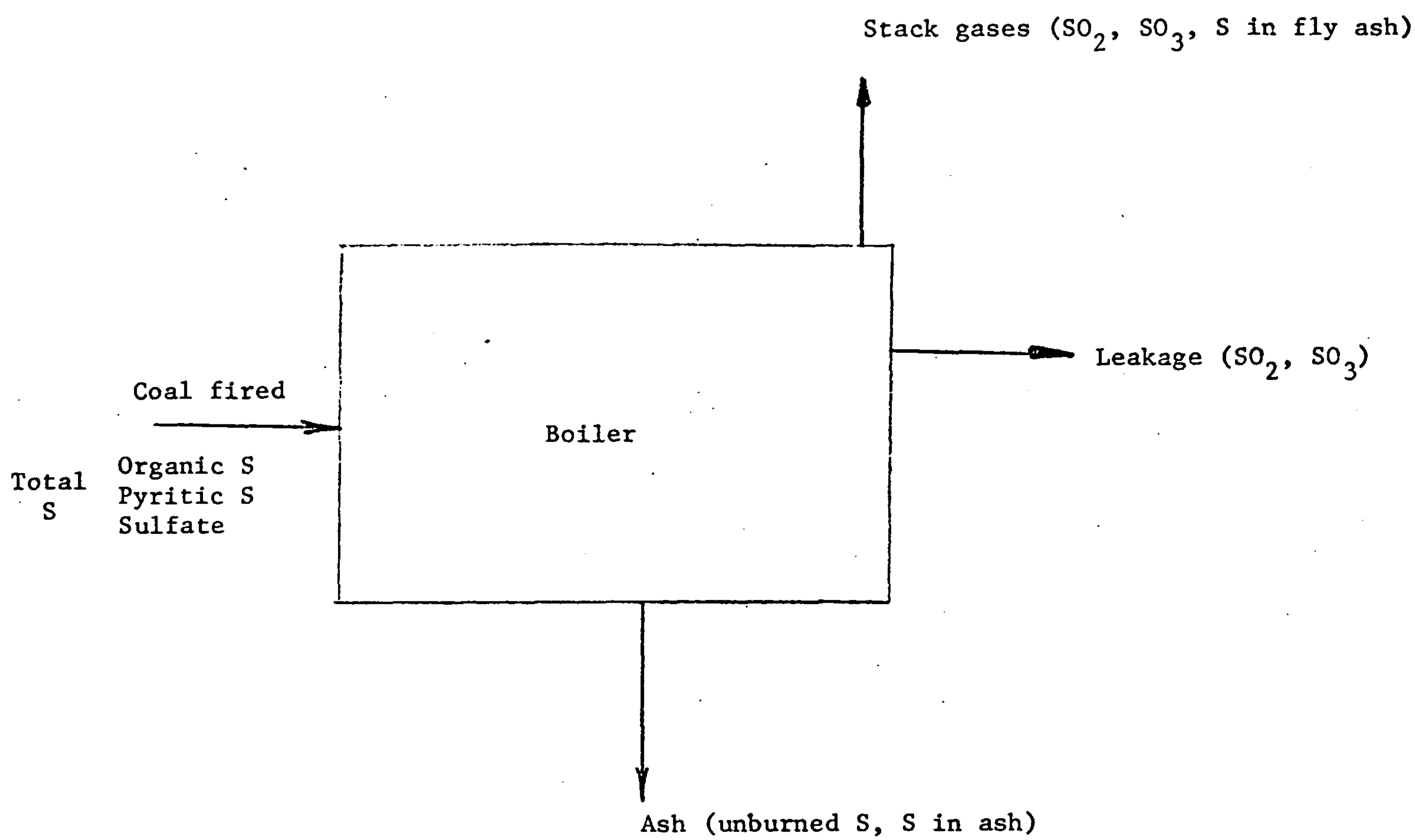


Figure 1: Schematic Flow Chart for Sulfur

Based upon the weekly fuel analysis reports from the operator an average of 31.56 metric tons per day of sulfur entered the boiler through the coal burned. If we assume that 85% is combustible, the combustible sulfur entering expressed in terms of equivalent SO_2 is:

$$31.56 \times 0.85 \times \frac{64}{32} = 53.65 \text{ metric tons } SO_2 \text{ per day.}$$

Based upon stack gas analyses and flow rates determined by PES the amount of SO_2 leaving through the stack averaged over runs 19-50 was 45.48 metric tons per day. (Note: only runs 15&17-50 are considered valid. Runs 17&18 were lower than usual. If runs 15&17-50 are included the measured average SO_2 discharge rate would be 44.25 metric tons per day.) Using this approach to a sulfur balance, approximately 15% of the entering sulfur is unaccounted for.

The second approach used was to calculate the theoretical sulfur dioxide concentration expected based upon the hypothesized coal composition. Using this approach it was necessary to assume that the measured oxygen concentration in the stack gases was correct in order to allow for the proper quantity of excess air. Both the oxygen content determined by PES and that given by the continuous analyzer installed near the test location were in good agreement. Therefore, an oxygen content of 6.5% was assumed for the stack gas.

The following calculations are used to determine the expected SO_2 concentration:

Assume 100 lb. coal as fired containing 75 lb. dry coal, 5 lb. water, and 15 lb. ash.

Constituent	Wt. (lbs.)	Lb. Mols.
C	59	4.9
H	4	2
O	10	0.32
S	1	0.031
N	1	0.036
H_2O	5	0.28

Combustion Reaction:

$$(4.9C + 2H_2 + .31O_2 + .031S + .036N_2) + (8.11O_2 + 30.51N_2) + .28H_2O =$$

$$4.9CO_2 + 2.28H_2O + .031SO_2 + 2.49O_2 + 30.55N_2$$

Number mols. combustion products (dry basis) = 37.97

Concentration SO_2 by mol = C_{SO_2} (vol.) $= \frac{.031}{37.97} \times 10^6 = 816$ ppm

If S conc. in coal is actually 0.93% and only 85% is available, then

$C_{SO_2} = 816 \times .93 \times .85 =$ 645 ppm (dry basis)

The average SO_2 concentration determined by PES by testing = 708 ppm (dry basis)

Summary and Conclusions

The calculated SO_2 concentration was approximately 9% lower than that actually determined by testing. The calculated concentration required assumptions on actual coal composition, on combustible sulfur, on excess air and on the degree to which the shift analysis for sulfur content of coal actually represented the content during firing. Measured SO_2 concentrations depend upon an efficient collection of SO_2, and accurate analysis and a correct determination of sample volume. Considering the assumptions necessary to calculate a theoretical concentration and the inherent sampling and analysis errors, this comparison seems well within the expected limits.

On the other hand, the mass emission rate determined by testing was less by about 15% than sulfur feed rate. There are several possible explantions for this:

1) Measured SO_2 concentration lower than actually exists

2) Measured stack gas volume lower than actually exists

3) Leakage of stack gases occurring so that all volume not being measured.

4) Amount of sulfur contained in ash was greater than estimated.

From earlier discussions the first reason does not seem too likely. Either one or all of the latter three explanations are possible. Even though velocity traverses were quite consistent and were similar to those measured in earlier testing at the plant, some error could be present. Also only three of the four sampling ports could be used. However, because of the distance downstream from any disturbances (over 8 pipe diameters) an uneven flow pattern would not be expected. With regard to the third point, it is known that some leakage into the annular space between the inner refractory stack and the outer concrete support stack takes place. PES personnel were required to wear gas masks to enter this space during probe position changes. The cross-sectional area is about the same as the inner stack. No way of quantifying these leaks is possible at this time.

Thus it would seem most credible to assume that the measured concentrations were quite accurate, that the volumetric stack gas flow rate might be slightly higher than determined during the tests, and that some leakage from the inner stack into the annular space surrounding the inner stack took place. Should this be true, the mass SO_2 flux leaving both the inner stack and the and the annular space at the top of the stack could be higher by as much as 15% over that reported leaving the inner stack.

III. PROCESS DESCRIPTION

The process consisted of a pulverized coal-fired boiler used to generate steam for electrical power.

TABLE OF RESULTS

RUN NO.	CONCENTRATION MT/DAY	PPM
15	39.5	568
16	Results	Discarded
17	30.7	396
18	22.9	408
19	47.9	792
20	40.8	822
21	46.2	689
22	40.3	652
23	43.6	729
24	44.7	785
25	41.3	690
26	47.2	661
27	51.5	691
28	48.3	774
29	49.8	790
30	43.1	699
31	45.5	806
32	44.3	841
33	50.5	812
34	47.9	849
35	33.3	746
36	42.9	775
37	43.1	736
38	36.2	748
39	37.1	762
40	41.3	704
41	49.4	792
42	45.0	771
43	50.6	715
44	44.3	666
45	46.4	739
46	50.9	699
47	56.9	791
48	54.6	774
49	48.9	786
50	41.7	761

IV. LOCATION OF SAMPLING PORTS

Sampling ports were located approximately 270 feet above ground level and 170-200 feet above the breeching. The stack had an inner stack of refractory material (approximately 8" thick) and an outer concrete stack (approximately one foot thick). The spacing between stacks was 5 feet. The outer diameter of the inside stack at the sampling level was 23' 4" (inside diameter 22').

Two velocity traverses were performed with six points on a diameter. These traverses could only be performed utilizing three ports. Six points were used on the N-S axis and three points on the E-W axis. The east port was inaccessible to sampling and traversing because of the angle necessary for probe entry into the port.

A third velocity traverse was performed on the three available ports. The probe was inserted into the stack to its full effective length (7 feet). Velocities were recorded at one-foot intervals.

The final traverse consisted on using two ports 90^{o} apart. A specially made 12-foot pitot tube was used. The probe was inserted into the center of the stack and velocity measurements were taken at one-foot intervals.

V. SAMPLING AND ANALYTICAL PROCEDURES

A. SUMMARY

Method No. 6, FR36, Dec. 23, 1971 was used to determine the concentration of sulfur dioxide. Method 4 was used to determine moisture content. Method 1 was used to determine the number of sampling points for the velocity traverses. Modified Method 2 was used to determine stack gas velocity. (One modification was to use the points determined by Method 2 but to only three ports, the fourth being inaccessible. The other modification was to use two ports at 90^{o} and to take velocity measurements from the center at one-foot intervals. This method was used to determine the extent of stratification across the stack.)

B. EQUIPMENT

The sampling probe for this test consisted of an eight-foot pitot tube and heated glass-lined sampling probe combination manufactured by Michrochemical Specialties Company (Misco). The pitot tube used to reach the center of the stack was a twelve-foot homemade model. Both pitot tubes were calbirated on return.

The probe was connected through glass ball joint connections to the impingers. The impingers used for the sampling train were as follows:

Impinger #1) Midget impinger modified with a fritted glass bubbler containing 15 ml of 80% iso-propyl alcohol.

Impinger #2) Midget impinger containing 15 ml of 3% hydrogen peroxide.

Impinger #3) Midget impinger containing 15 ml of 3% hydrogen peroxide.

Impinger #4) Midget impinger empty (used as splash trap). A silica gel drying tube, for pump protection, followed the last impinger.

The first pump to be used was a Gast Model 0531 rotary vane pump. This was later found to have a severe leak on the positive side. This resulted in the discarding of the first 14 test runs as invalid. For this reason only the data for runs 15-50 were reported. The rotary vane pump was replaced with a Gast Diaphragm Pump. This pump was used for runs 15-50.

The pump flow was regulated by use of a rotameter and needle valve. The sample volume was measured with Sprague Model 1755 Dry Gas Meter. Meter temperature was measured with a Weston model dial thermometer.

The stack temperature was monitored using an iron-constantan thermocouple and portable potentiometer (Thermo Electric "Minimite" Model 31101). The thermocouple parted on the second to the last day and an average stack temperature was generated from the previous day's runs.

Grab samples for CO_2 and O_2 analysis using Fyrite detectors were collected. O_2 concentration data were also available from an in-stack monitor.

C. FIELD PROCEDURES

On the first day of sampling, the test period was set at one hour. After analysis this was determined to be much more than necessary. Sampling time was then shortened to twenty minutes. This was sufficient for analytical purposes.

On Tuesday, May 13, 1975, five 20-minute runs were completed. Sampling had to be stopped early because the boiler was in an upset condition. To ease the sample handling, runs were performed in groups of two with the purge time of 20 minutes separating the runs. Each group of two runs were performed at a different port.

On Wednesday, May 14, 1975, six twenty-minute runs were performed. A problem with carry-over from one impinger to another occurred. For these runs the entire impinger contents were saved. A special analytical run was performed on the isopropyl alcohol to determine the extent of the interference. The interference was less than 1% so these samples were deemed valid.

On Thursday, May 15, 1975, eight twenty-minute runs were performed. On Friday, May 16, 1975, seven twenty-minute runs were completed and a pitot traverse was also completed.

On Monday, May 19, 1975, the boiler was in an upset condition in the morning and testing could not be started until 11 o'clock. Six twenty-minute runs were then performed.

On Tuesday, May 20, 1975 four twenty-minute samples were received. A pitot traverse was also performed.

D. LABORATORY ANALYSES

All laboratory titrations were performed on site by PES personnel. Impinger contents were titrated with barium perchlorate using Thorin as an indicator as specified by EPA Method 6.

E. SAMPLE CALCULATIONS

Shown on the following pages are the equations used and sample calculations for determining these stack gas parameters:

1. Moisture content of stack gas
2. Dry molecular weight of stack gas
3. Molecular weight of stack gas on a wet basis
4. Stack gas velocity
5. Stack gas flow rate
6. SO_2 concentration
7. SO_2 metric tons per day

DETERMINATION OF MOISTURE CONTENT OF STACK GAS

$$V_{w_{std}} = 0.0474 \frac{ft^3}{ml} V_{10}$$

where:

$V_{w_{std}}$ = Volume of water vapor in the gas sample (standard conditions), ft^3

V_{10} = Total volume of liquid collected in impingers, ml

$$V_{w_{std}} = (0.0474)(1)$$

$$= \underline{\underline{0.0474\ ft^3}}$$

$$V_{m_{std}} = 17.71 \frac{^oR}{in.Hg} \left(\frac{V_m\ P_m}{T_m}\right)$$

where:

$V_{m_{std}}$ = Volume of gas through meter at standard conditions, ft^3

V_m = Volume of gas measured at meter, ft^3

P_m = Barometric pressure at meter, in.Hg

T_m = Temperature at meter, ^oF

$$V_{m_{std}} = (17.71) \left(\frac{(0.99)\ (23.98)}{(529)}\right) = \underline{\underline{0.79\ ft^3}}$$

$$B_{wo} = \frac{V_{w_{std}}}{V_{m_{std}} + V_{w_{std}}}$$

where:

B_{wo} = Moisture content of stack gas, dimensionless

$$B_{wo} = \frac{0.0474}{0.79 + 0.0474}$$

$$= \underline{\underline{0.0566}}$$

$$= \underline{\underline{5.66\%}}$$

DETERMINATION OF DRY MOLECULAR WEIGHT OF STACK GAS

$M_d = 0.44\ (\%\ CO_2) + 0.32\ (\%\ O_2) + 0.28\ (\%\ N_2 + \%CO)$

Where:

M_d = Stack gas dry molecular weight

$\%\ CO_2$ = Percent CO_2 in stack gas from daily Fyrite test

$\%\ O_2$ = Percent oxygen in stack gas from daily Fyrite test

$\%\ N_2$ = Percent nitrogen in stack gas

% CO = Percent carbon monoxide in stack gas

TUESDAY MAY 13 RUNS 15-19

$M_d = 0.44\ (12) + 0.32\ (6.5) + 0.28\ (81.5)$

$= 5.28 + 2.08 + 22.82 = \underline{\underline{30.18\ \text{lb/lb-mole}}}$

MOLECULAR WEIGHT OF STACK GAS ON A WET BASIS

$$M_s = M_d\ (1-B_{wo}) + 18\ (B_{wo})$$

where:

M_s = Molecular weight of stack gas on a wet basis, lb/lb-mole

M_d = Molecular weight of stack gas on a dry basis, lb/lb-mole

B_{wo} = Moisture content of stack gas, dimensionless

TUESDAY MAY 13 RUNS 15-19

M_s = 30.18 (1-0.057) + 18 (0.057)

= 28.46 + 1.03 = 29.49 lb/lb-mole

DETERMINATION OF STACK GAS VELOCITY

$$V_s = K_p \; C_p \; \left(\sqrt{\Delta p}\right)avg \left(\frac{T_s}{P_s \; M_s}\right)^{\frac{1}{2}}$$

where:

V_s = Stack gas velocity, ft/sec.

K_p = 85.48 ft/sec $\left(\frac{lb}{lb\text{-mole} \; ^oR}\right)^{\frac{1}{2}}$

C_p = Pitot tube coefficient

$\sqrt{\Delta p}$ = Average velocity head of stack gas, in. H_2O

T_s = Stack gas temperature, ^oR

P_s = Absolute stack gas pressure, in.Hg

M_s = Molecular weight of stack gas (wet basis), lb/lb-mole

RUN #15

$$V_s = 85.48 \; (0.77)(0.59)^{\frac{1}{2}} \left(\frac{737.5}{24.48(29.49)}\right)^{\frac{1}{2}}$$

$$= \underline{\underline{51.10 \text{ ft/sec}}}$$

DETERMINATION OF STACK GAS FLOW RATE

$$Q_s = 3600\ (1-B_{wo})\ V_s\ A \left(\frac{T_{std}}{T_{s\ avg.}}\right)\left(\frac{P_s}{P_{std}}\right)$$

where:

Q_s = Volumetric flow rate, dry basis, standard conditions, ft^3/hr

A = Stack cross-sectional area, ft^2.

T_{std} = Temperature at standard conditions, 530 ^oF

T_{savg} = Average stack temperature, ^oR

P_s = Stack pressure, in.Hg

P_{std} = Pressure at standard conditions, 29.92 in.Hg

RUN #15

$$Q_s = 3600\ (1-0.057)(51.10)(380)\left(\frac{530}{737.5}\right)\left(\frac{24.48}{29.92}\right)$$

$$= \underline{\underline{38,800,000\ ft^3/hr}}$$

CALCULATION OF SO_2 CONC. IN LBS/CF

$$V_{m_{std}} = \left(\frac{T_{std}}{T_m}\right)\left(\frac{P_{bar}}{P_{std}}\right) = 17.71\ \frac{^oR}{in.Hg}\left(\frac{V_m\ P_{bar}}{T_m}\right)$$

$$C_{SO_2} = \frac{\left(7.05 \times 10^{-5}\ \frac{lb\text{-}l}{g\text{-}ml}\right)(V_t - V_{tb})(N)\left(\frac{V_{soln}}{Va}\right)}{V_{m_{std}}}$$

or,

$$C_{SO_2} = \frac{\left(7.05 \times 10^{-5}\ \frac{lb\text{-}l}{g\text{-}ml}\right)(V_t - V_{tb})\left((N)\ \frac{V_{soln}}{Va}\right)}{(17.71)\ (V_m)\left(\frac{P_m}{T_m}\right)}$$

where:

C_{SO_2} = Concentration of sulfur dioxide at standard conditions, lb/cf.

V_t = Volume of barium pechlorate titrant used for sample, ml

V_{tb} = Volume of barium perchlorate titrant used for blank, ml

N = Normality of barium titrant, g-eq/l

V_{soln} = Total solution volume of sulfur dioxide, 50 ml

V_a = Volume of sample aliquot titrated, ml

$V_{m_{std}}$ = Volume of gas sampled at standard conditions, ft^3

V_m = Volume of gas measured at meter, ft^3

T_m = Meter temperature, ^oR

P_m = Barometric pressure at meter, in.Hg

RUN #15

$$V_{m_{std}} = \frac{17.71\ ^oR}{in.Hg} \times 2.27CF \times 24.52\ in.Hg \times \frac{1}{516.5^oR} = 1.909\ CF$$

$$C_{SO_2} = \left(7.05 \times 10^{-5}\ \frac{lb\text{-}l}{g\text{-}ml}\right) \times 52.05\ ml \times 0.00973\ N \times 5 \times \frac{1}{1.909\ CF}$$

$$= 9.35 \times 10^{-5}\ lb/CF$$

DETERMINATION OF METRIC TONS/DAY

$$C_{mt} = \frac{\left(C_{SO_2}\right) \quad (Q_s) \quad (24)}{2204.62}$$

where:

C_{mt} = Concentration of SO_2, metric tons/day

24 = Hours/day

2204.62 = Lb/metric ton

RUN #15

$$C_{mt} = \frac{(9.35 \times 10^{-5})(388 \times 10^{5})(24)}{2204.62}$$

$$= \underline{\underline{39.5 \text{ mt/day}}}$$

APPENDIX B

METEOROLOGICAL DATA
8-19 MAY 1975

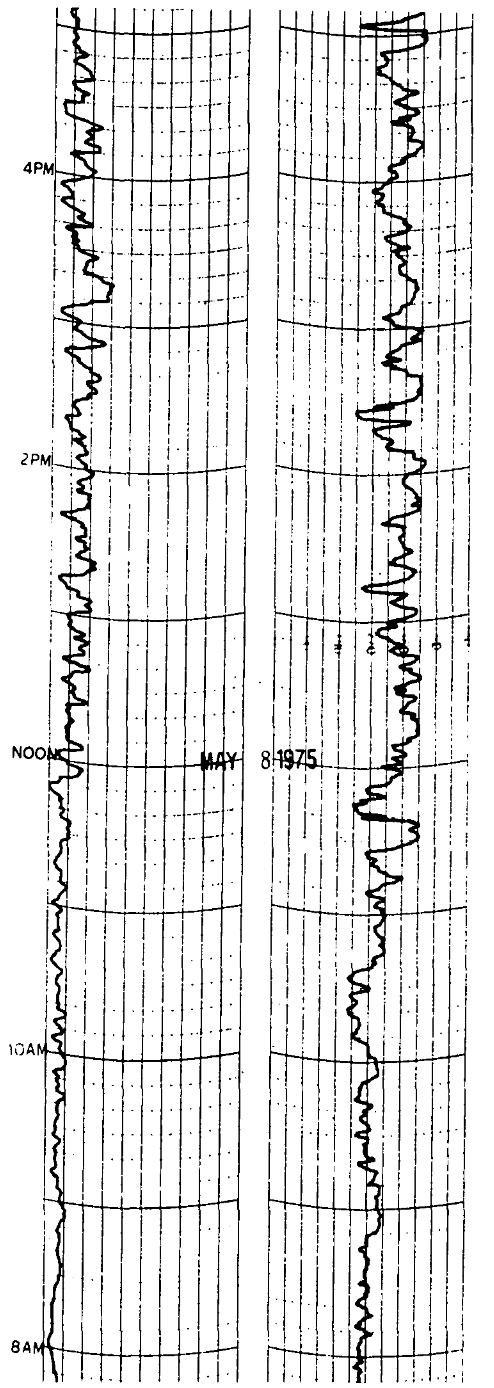
- SYNOPTIC SUMMARY
- WINDS
- PIBAL RESULTS
- ANEMOMETER RECORD

METEROLOGICAL DATA

8 MAY 1975

SYNOPTIC SUMMARY The influence of the front that had passed through the area on the 5th of May had given way to a high pressure system with fair and warm weather. The temperatures during the testing period were from 45^{o} to 64^{o} F.

WINDS In the morning the winds were 0 to 3 mps below 700 meters with increasing speed above (to 5 m/s). Winds were from 80^{o} to 115^{o} in the lower layers and 290^{o} to 310^{o} in the upper layers. Between 1100 and 1300 the winds below 700 meters were light and variable. During the 1324 pibal the lower winds had picked up to 5-10 mps, from 270^{o} to 310^{o}. This layer gradually deepened thru 700 meters by 1420.



Wind Speed (0-50 mph) Wind Direction (0-540^{o})

ANEMOMETER RECORD

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0915	83	1.9
0933	83	2.5
1100	120	0.4
1109	73	0.8
1120	197	0.8
1315	306	1.8
1324	271	8.9
1334	269	7.0
1420	310	7.7
1430	318	8.2
1445	290	2.8

METEROLOGICAL DATA

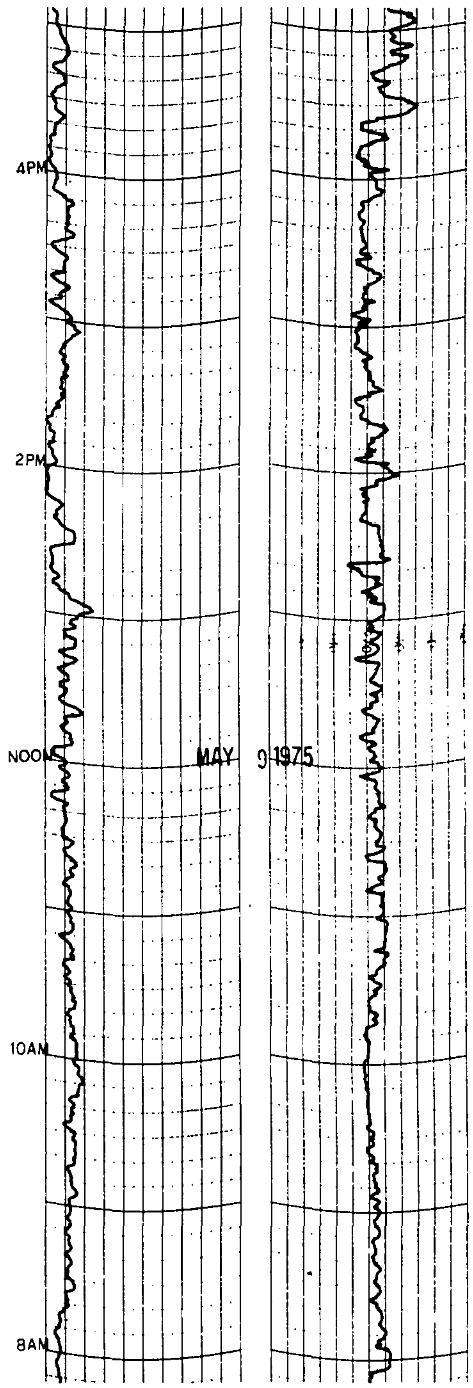
9 MAY 1975

SYNOPTIC SUMMARY Early in the day the area was still under the influence of the high pressure zone but the advance of a weak upper level trough in the afternoon caused cloudiness of 90% cirrus and cirocumulus by 1700. The maximum temperature during the day was 70°F while the minimum during the test period was 49°F early in the morning.

WINDS The winds were from 90° to 135° through 800 m at 4-8 mps until 1200. After 1200 the winds were 1 to 4 mps and the direction shifted to 135° to 180°. Later in the afternoon the winds were less than 2 mps and variable in direction.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0852	97	7.4
0916	105	8.2
0937	112	4.4
1006	104	6.1
1015	100	3.7
1025	108	4.2
1200	112	6.7
1209	102	2.3
1215	183	1.7
1236	159	3.4
1245	142	3.7
1255	143	4.5
1408	118	1.2
1416	131	1.2
1424	031	0.1
1522	152	1.2
1559	280	1.9
1612	314	1.8



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

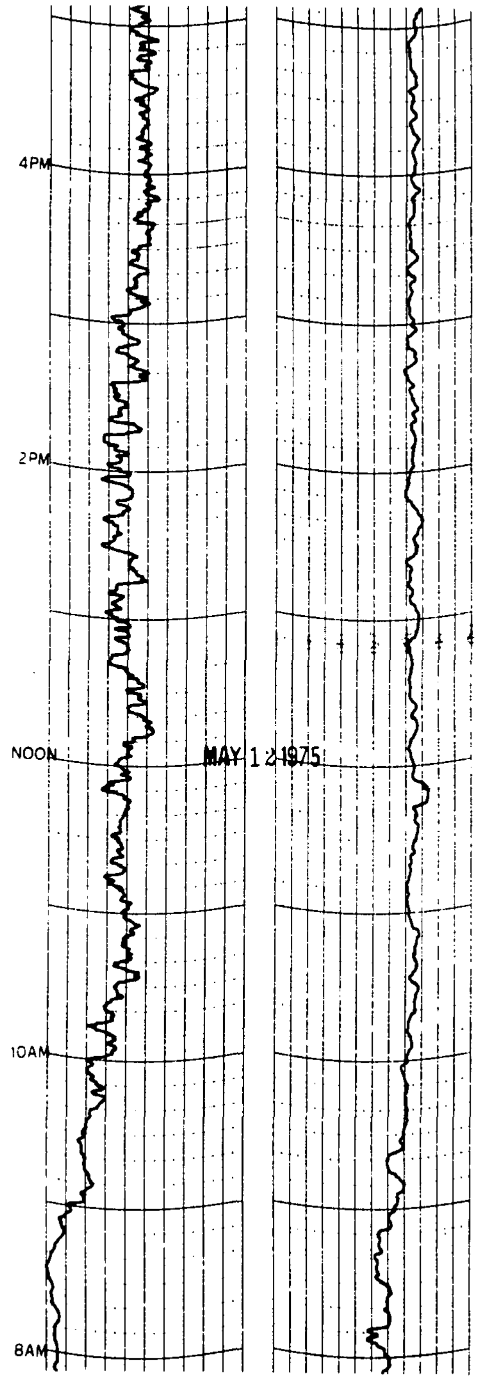
12 MAY 1975

SYNOPTIC SUMMARY A frontal passage to the north of the area brought about considerable convective activity and strong gusty winds. The temperatures ranged from 55° to 67° F.

WINDS There were very strong winds from 280° to 310° all day. The wind was gusty, with speeds varying from 7 to 20 mps.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
1140	312	18.0
1147	302	14.1
1515	302	18.4
1557	308	8.5
1652	308	16.2



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

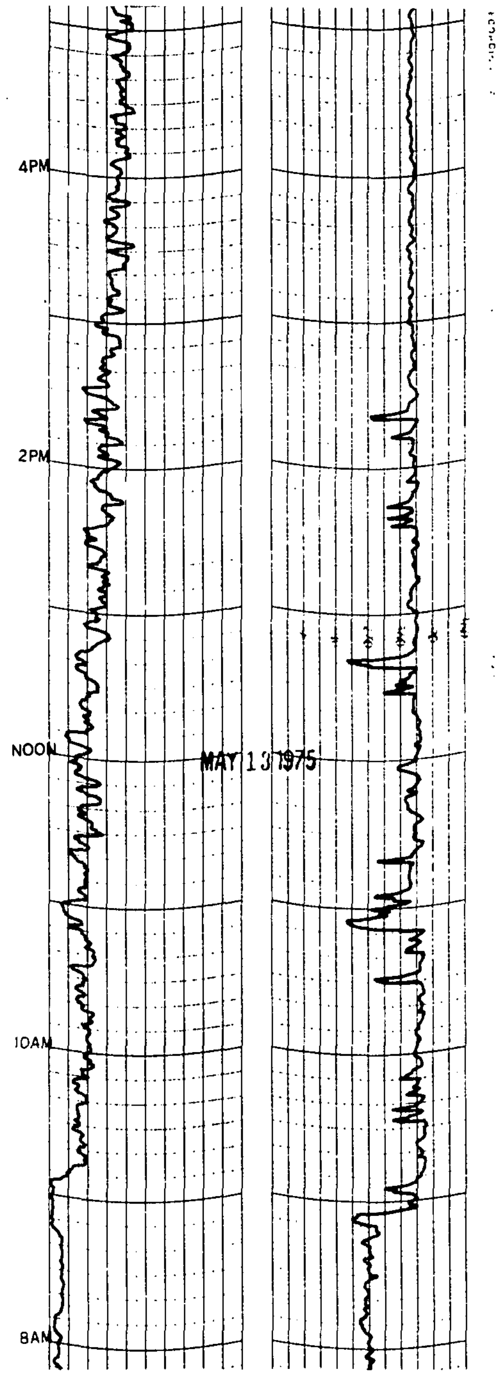
13 MAY 1975

SYNOPTIC SUMMARY The upper level trough and associated unstable air behind the front that had passed through 24 hours previously caused gusty westerly winds and scattered cumulus clouds throughout the day. During the test period the ground level temperatures were from 52° to 70° F.

WINDS The winds were from 300° to 340° at 2-7 mps up to 700 meters until 0940. The speed picked up to 8-12 mps (with gusts to 18 mps) and shifted to 270°-315° by 11:00. Winds were under 10 mps after 1300.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0904	302	3.3
0913	324	3.4
0928	323	4.6
0937	314	7.1
1100	312	10.2
1109	285	5.3
1119	297	8.2
1134	293	14.1
1155	300	8.5
1203	304	8.6
1210	270	2.3
1316	312	6.5
1329	288	4.9
1346	313	6.7
1352	325	6.9
1400	303	6.2
1435	321	8.8



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

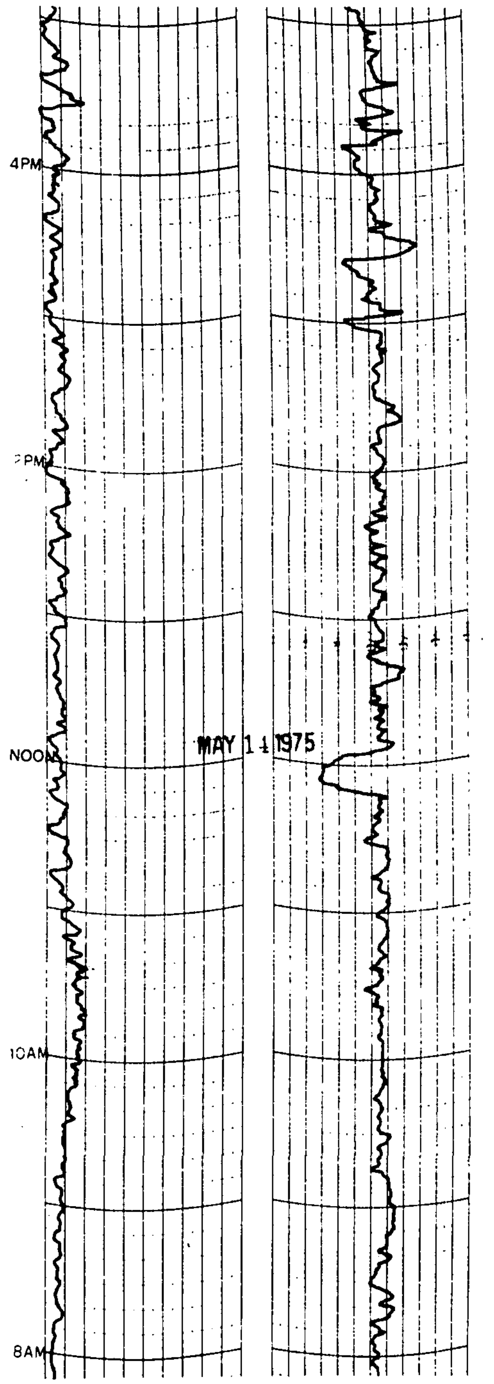
14 MAY 1975

<u>SYNOPTIC SUMMARY</u> The test area was under the influence of an upper level high pressure system on the 14th of May. There were no clouds and the temperature was as high as 77°. In the early morning hours the power plant plume was trapped beneath a low level inversion.

<u>WINDS</u> In the morning winds were from 90° to 135° and of moderate strength (as high as 10 mps). This condition continued throughout the day in the upper levels with the speed gradually diminishing to 2-4 mps. At the lower levels the winds shifted to 180° and then 215° after 1430, with speeds of 1 to 4 mps.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0908	104	6.4
0924	100	5.5
0945	100	5.5
1003	108	10.1
1129	123	2.0
1215	207	1.6
1241	141	1.5
1358	131	1.2
1417	181	2.1
1440	236	1.7



Wind Speed (0-50 mph) — Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

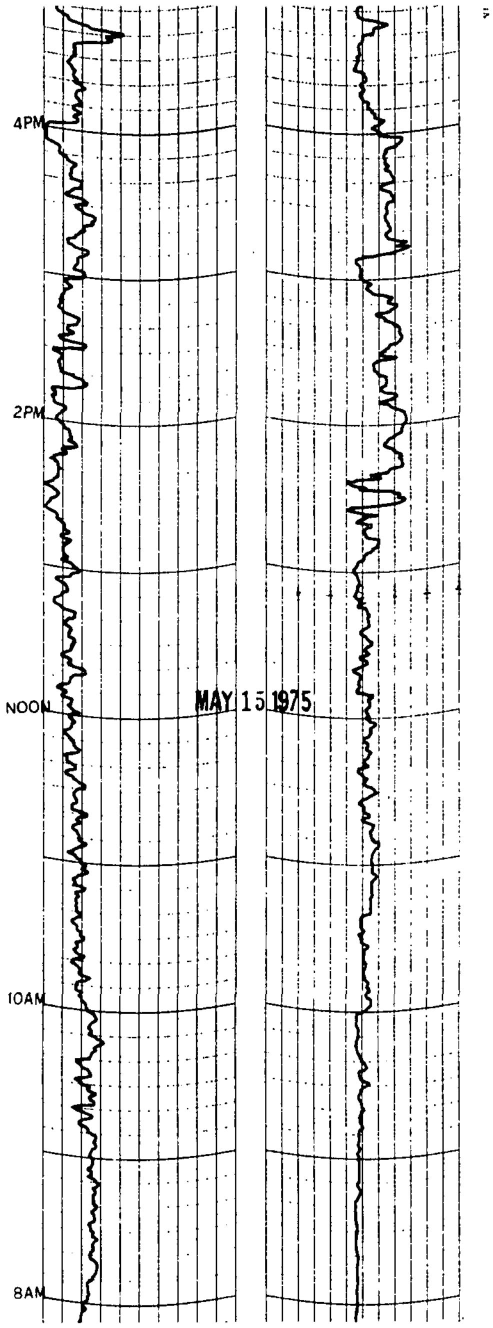
15 MAY 1975

SYNOPTIC SUMMARY The advance of a trough in the upper levels caused a few cirrus and cumulus clouds in the afternoon on this generally fair day. Temperatures ranged between 63 and 80° F during the test period.

WINDS The winds were variable, 3 to 10 mps, from 80° to 110° in the levels below 700 meters until 1300. Light and variable conditions existed until the 1345 and 1421 pibals which showed winds from 290° at speeds of 2 to 4 mps. After 1430 the winds were between 180° and 270° at speeds in the range of 2-6 mps.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0842	97	7.0
0856	99	8.9
0914	98	6.2
0927	92	7.3
0938	95	8.1
1022	102	4.9
1045	112	8.0
1054	117	8.4
1120	99	7.5
1130	110	6.1
1155	105	4.5
1248	94	4.7
1312	218	.8
1321	156	1.3
1339	354	1.0
1345	289	3.4
1421	288	5.1
1446	239	3.4
1505	200	3.7
1527	265	6.0
1542	247	6.2



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

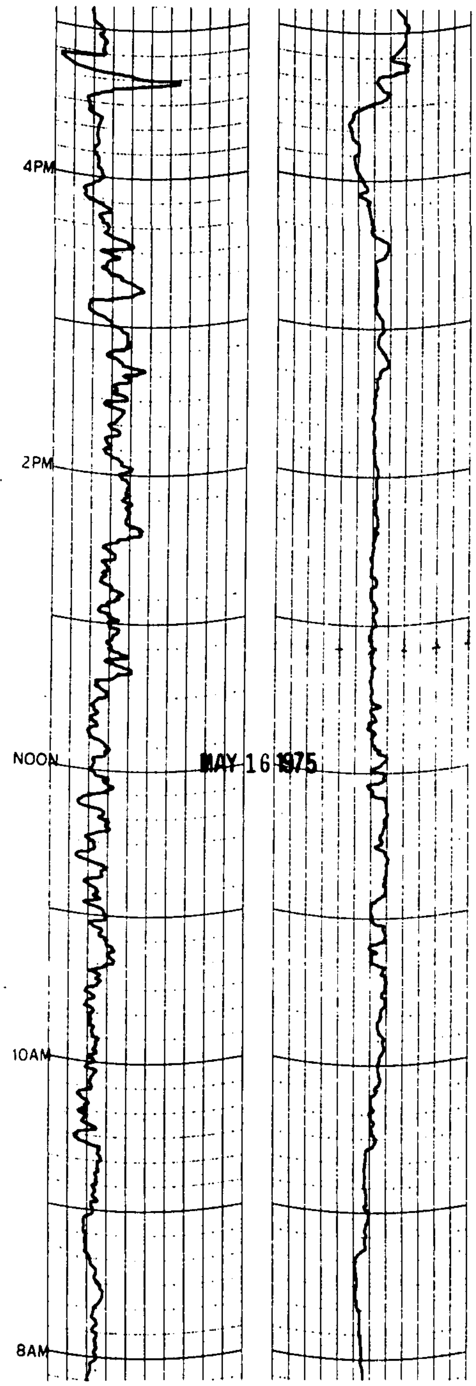
16 MAY 1975

SYNOPTIC SUMMARY The advance of a frontal system from the west caused increasing clouds throughout the day. Early morning cirrus thickened to cirrus stratus and altostratus in the afternoon.

WINDS During the first pibals the wind below 600 meters was from 80° to 100° at speeds of 4-8 mps. By 1030 the winds had shifted to 160° and by 1347 to 200°. The speeds during this time varied considerably with a range of 4 to 16 mps. During the rest of the afternoon the winds were between 170° and 200° with speeds still fluctuating between 3 and 16 mps.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
0842	91	5.0
0913	90	7.3
1032	140	5.7
1110	173	4.4
1236	176	14.2
1301	181	6.7
1320	193	13.7
1347	195	15.8
1415	168	10.2
1433	202	4.5



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

METEROLOGICAL DATA

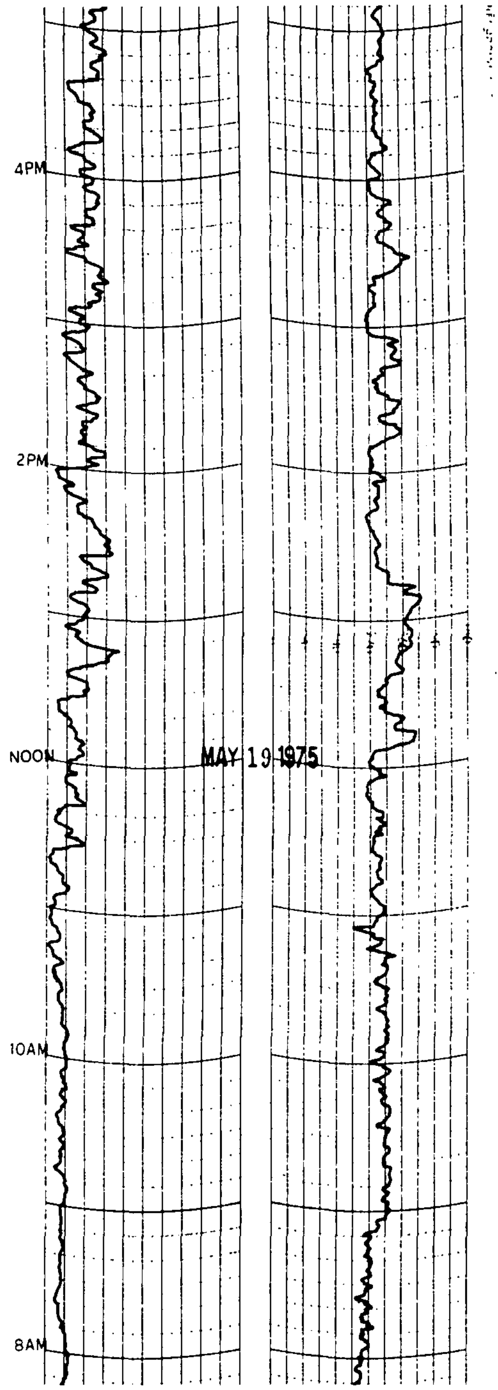
19 MAY 1975

SYNOPTIC SUMMARY During the day there were convective clouds associated with the unstable air behind the front that had been in the area on the 17th and 18th of May. Light rain showers were occasionally visible throughout the day. The temperature ranged from 53° to 71° during testing.

WINDS At the time of the first pibal the surface winds were light and variable with 3 mps winds above 500m. During the afternoon the winds were generally from 210° to 240° in the3 to 7 mps range.Additionally there were strong gusty periods with speeds as high as 18 mps.

PIBAL RESULTS
(212-316 meters)

Time (MDT)	Direction (degrees)	Speed (mps)
1118	179	3.1
1125	199	4.7
1134	233	3.9
1148	213	3.6
1158	260	3.4
1208	262	6.8
1219	207	1.3
1324	232	7.5
1334	214	8.9
1341	211	2.1
1357	228	9.1
1407	254	4.0
1422	246	3.3
1437	262	4.7
1507	218	4.5
1510	227	7.1
1513	226	7.3
1516	237	6.9
1519	231	4.4
1520	214	2.3
1523	276	5.3
1546	231	5.9
1601	227	6.9
1616	233	9.1



Wind Speed (0-50 mph) Wind Direction (0-540°)

ANEMOMETER RECORD

GLOSSARY

ACTIVE MODE - Remote sensing measurements using an artificial light source, usually with instrument aligned to axis of horizontal light path; contrasts to passive mode

AGC - Automatic Gain Control, the light sensing circuit of the correlation spectrometer

AQML - Air Quality Moving Laboratory, an array of instruments and data collection systems mounted in a moving platform designed to monitor air pollutants in a truly mobile mode

BEER-LAMBERT LAW - $I = I_s e^{-acl}$, where I is measured light intensity; I_s is source light intensity; a is coefficient of absorption; c is concentration of target gas; l is path length light has traveled

BURDEN - Vertically integrated concentration-path length measurements of pollutants as measured by the Correlation Spectrometer, (also overhead burden, total burden)

CONFIDENCE LIMITS - Upper and lower boundaries within which it is estimated a value will fall with a stated probability (e.g. 90%)

COSPEC - COrrelation SPECtrometer, manufactured by Barringer Research Ltd., an electro-optical remote sensor which monitors pollutants along light paths originating from natural or artificial radiation

CROSS-STACK - Measurement technique which continuously measures flue gases across the stack by electro-optical means

DATA-DAY -	A measurement day when personnel and equipment are mobilized to survey air quality; actual hours of measurement may range from one to twenty-four depending on conditions at the site
EVENT -	A single measurement by the moving laboratory; a plume crossing or a regional survey; may vary in length from one minute to one hour
FLUX -	See Mass Flux
GAUSSIAN -	Normal error function or normal distribution; the bell-shaped curve of statistical analyses
GROUND-LEVEL -	Ground-level concentrations of pollutants as measured by point monitors; contrasts to burden measurements by COSPEC remote sensor
IN-STACK -	Measurement technique which extracts a sample of of flue gas from the stack continuously or periodically
MASS FLUX -	Emission rate of pollutant across a traverse route calculated from remote sensing data; also mass flow rate
MEAN -	Arithmetic average; measure of central tendency of data points
MOVING LABORATORY -	See AQML
MOVING MEASUREMENTS -	Measurement of ambient air quality from a moving platform; contrasts to fixed, stationary monitoring
MT/D -	Metric tons per day, emission rate

NOISE -	Spectrometer response due to spurious, unwanted electronic signals; usually a few ppmM depending on gas measured and available light
OVERHEAD BURDEN -	See Burden
PASSIVE MODE -	Remote sensing measurements using scattered natural light, usually with instrument viewing vertically upwards; contrasts with active mode.
PIBAL -	Pilot balloon, used to measure wind speed and wind direction at the elevation of the plume
PLUME -	Dispersing stack emissions
POINT MONITOR -	Instrument capable of monitoring ambient air sample drawn into it through a sampling train from a fixed nearby point
PPB -	Parts per billion, concentration measurement
PPM-M -	Parts per million-meters, concentration-path length measurement
RAYLEIGH SCATTERED -	Light scattering process produced by spherical particles whose radii are smaller than one-tenth the wavelength of the scattered radiation
REMOTE SENSOR -	Instrument capable of monitoring a phenomenon by electro-optical means across an intervening distance; as COSPEC measures SO_2/NO_2 in ambient air
SEGMENT -	Portion of traverse route for which incremental mass flux calcuations are made
STANDARD DEVIATION -	Positive square root of mean of squares of deviation from mean of population; measure of dispersion of data points

STUDENT-t - Statistical test to compare populations independent of assumptions concerning their parameters

THEODOLITE - Optical instrument to measure horizontal and vertical angles; balloon theodolite is designed to track rising pilot balloons

TOTAL BURDEN - See Burden

TRAVERSE - A moving measurement using a moving laboratory; a traverse route is a highway, road or pathway travelled during a survey

WIND/ROAD ANGLE - Angle between wind flow and moving laboratory traverse route

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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16. ABSTRACT

The Barringer COSPEC II instrument, an SO_2 remote sensor, was compared to the manual in-stack SO_2 and velocity compliance tests for emission measurements. The correlation for short term (one hour or less) comparison was poor. Higher correlations for SO_2 emission rates on a daily basis were found. In addition to the COSPEC II, a COSPEC III and COSPEC IV were used in the study. Correlations among the three instruments were good (90-95%). Main source of error in the remote measurements was the wind velocity determinations. For a short time span of less than an hour, wind velocity may vary 100% and only averages can be obtained for the measurements.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Evaluation Comparison *Remote sensing *Ultraviolet spectrometers Air pollution *Sulfur dioxide Mobile equipment	Barringer COSPEC instruments	14G 14B 13B 07B 15B

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