EVALUATION OF PORTABLE, DIRECT-READING SULFUR DIOXIDE METERS

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ABSTRACT

A market survey was conducted to determine the availability of portable, direct-reading sulfur dioxide (SO_2) meters with a range of 1 to 50 ppm of SO_2. The market survey revealed several meters that conformed to some of these criteria, but none that conformed to all of these criteria. Manufacturers of the most suitable meters were requested to submit a meter for an evaluation of its physical and performance characteristics. Characteristics measured included stability, drifts, linearity, response times,and specificity. Physical characteristics evaluated include portability, readout, instruction manuals, and ease of zero and span adjustments. As a result of these evaluations, optimum use techniques and performance and construction standards are recommended. Quality control standards for portable SO_2 meters are also recommended based upon the evaluation results and current industry practices.

This study was conducted by the Research Triangle Institute under Contract No. HSM-99-73-1 (Task Order No. 2) for the Division of Laboratories and Criteria Development, National Institute for Occupational Safety and Health, Department of Health, Education, and Welfare. Technical monitoring was provided by Charles S. McCammon and William J. Woodfin of the Engineering Branch of the Division of Laboratories and Criteria Development.

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1.0 INTRODUCTION

The Research Triangle Institute (RTI) has conducted an investigation of portable sulfur dioxide (SO_2) meters sensitive to SO_2 concentrations in the 1 to 50 parts per million (ppm) range. These investigations were completed under a National Institute for Occupational Safety and Health (NIOSH) contract, Evaluation of Portable Sulfur Dioxide Meters, HSM-99-73-1 (Task Order No. 2).

1.1 Background and Objectives

The Occupational Safety and Health Act of 1970 authorizes the Secretary of Health, Education, and Welfare to prescribe regulations requiring employers to measure, record, and make reports on the exposure of employees to substances or physical agents which may endanger the safety or health of employees. In order to prescribe such regulations, it is necessary that the Secretary be able to provide or suggest to employers sampling and analytical methods of suitable accuracy for making measurements of employee exposure. Sulfur dioxide is high on the NIOSH priority list of toxic substances. It is a very common air contaminant, but there is still no satisfactory method available for field collection of SO_2 for subsequent laboratory analysis. Until such a method is available, industrial hygienists must continue to rely heavily on direct-reading, portable instruments such as SO_2 meters. Consequently, it is very important to learn more about the operating characteristics of these meters.

The objectives of this evaluation program were to determine the performance capabilities and limitations of available and prototype SO_2 meters, to determine the best techniques for the use of each meter in a field sampling situation, to develop a recommended set of performance standards for portable SO_2 meters, and to develop a recommended set of quality control standards for the manufacturing of portable SO_2 meters.

1.2 Procedure

This evaluation of portable SO_2 meters included a market survey to determine the availability of suitable meters, a solicitation for commercially available and prototype meters for evaluation, and an evaluation of the characteristics of the meters received. These investigations and evaluation results are discussed herein. As a result of the characteristics evaluations, use techniques are recommended for each of the meters, and construction and performance standards are recommended for portable SO_2 meters suitable for Occupational Safety and Health Act (OSHA) compliance testing. Additionally, quality control standards are recommended for portable SO_2 instruments based upon existing standards that are applicable to portable SO_2 instruments and current industrial practices as revealed by a survey of manufacturers.

1.2.1 Market Survey

The market survey was conducted by searching directories and guides to identify manufacturers and distributors of air monitoring instrumentation. Those directories and guides that listed likely sources are tabulated in Table I. Other guides and directories were searched but were not productive. In addition to these guides and directories, information was solicited from the Industrial Safety Equipment Association, the Safety Equipment Distributors Association, and from individuals at NIOSH and at the U.S. Bureau of Mines.

TABLE I

DIRECTORIES AND GUIDES SEARCHED FOR SOURCES OF INSTRUMENTATION FOR MONITORING AIR QUALITY

1. Thomas Register
2. MacRae's Bluebook
3. Guide to Scientific Instruments - 1972-73 (Science, American Association for the Advancement of Science)
4. Air Sampling Instruments, 4th Edition
5. Continuous Instrumentation for Continuous Monitoring for SO_2, Analytical Chemistry, Vol. 45, No. 1, p. 63A-72A, Jan. 1973
6. Instruments for Environmental Monitoring - AIR, Lawrence Berkeley Laboratory, LBL-1, Vol. 1 (SO_2)
7. Monitoring Instrumentation for the Measurement of Sulfur Dioxide in Stationary Source Emission, EPA-R2-73-163, Feb. 1973

A mailing list was tabulated from the above search, and a letter was mailed to each entry describing the planned evaluation program. The letter requested brochures, specifications, and other information descriptive of portable, direct-reading SO_2 meters and prototypes. A copy of this initial correspondence and a mailing list of addressees are included in Appendix A. This correspondence was supplemented by telephone contacts with known manufacturers and distributors of suitable SO_2 instruments and with those considered to be a highly probable source of such instruments. Descriptive literature resulting from this correspondence was reviewed to select suitable meters for the planned evaluation program. Guidelines provided by NIOSH were considered as basic criteria; however, these were significantly relaxed to include all available SO_2 meters and prototypes that could possibly be considered portable. (NIOSH guidelines stated in the survey correspondence suggested 10 lb. weight, one cubic foot volume, 1 to 50 ppm range, and direct reading.) Of the 6 meters received and evaluated, only 2 are reasonably portable meters and only 1 is direct-reading. The meters requested were those which most nearly conformed to the portability, range, and direct-reading guidelines. The instrument selection was reviewed with the NIOSH Project Officer.

Manufacturers of instruments for monitoring air quality, identified through responses to the original request for descriptive literature, were further requested to provide information pertaining to their quality control procedures. A copy of this correspondence and a list of addressees are also included in Appendix A. Responses to this and subsequent correspondence are reflected in the proposed quality control standards included in Section 6.0 of this report.

1.2.2 Meters Evaluated

Manufacturers of the selected instruments were requested to submit a single meter to RTI for the evaluation program. The request was in the form of a letter that included additional information about the evaluation and enclosed a paper by Roper which discussed the incentives for the evaluation and listed meter characteristics to be evaluated [Ref. 1]. A copy of this request letter and a list of addressees are included in Appendix A. Table II tabulates the SO_2 instruments evaluated, the date received, the manufacturer, and a reference name used to refer to each instrument throughout the remainder of this report.

1.3 Test Facilities

The test facility used during these evaluations is shown in the photograph of Figure 1 and is illustrated schematically in Figure 2. The facility consists of two manifolds, one to distribute SO_2 calibration gases and the second to distribute zero air. The meters were coupled to the appropriate manifold during testing by flexible Teflon tubing terminated in a ground glass ball and socket joint. The manifold pressure was monitored and controlled to 0.025 in. of water vacuum by controlling the speed of the fan in the exhaust system. The gas sources were bottled cylinders of zero air and known mixtures of SO_2 in air or in nitrogen. Certified concentrations of 28 and 49 ppm SO_2 in nitrogen were used for span and midscale calibration gases. A nominal 1 ppm SO_2 concentration in nitrogen was also used, but to a very limited extent. For low concentrations, and concentrations up to midscale values, zero air flowing through a permeation tube system was used as a calibration gas source. Figure 3 illustrates some additional detail of the calibration gas source. This arrangement provides for flowing SO_2 mixtures from certified cylinders through the SO_2 manifold or intermediate mixtures generated by mixing zero air and certified SO_2 mixtures. Also, it provides for flowing zero air through the permeation tube system and the SO_2 manifold. When the permeation system was not in use, ambient air was pumped through the permeation tube system and exhausted from the laboratory facility. Each SO_2 cylinder was certified by the supplier to be within ± 5 percent of the specified mixture, and the zero air was certified to be air with a total hydrocarbon content of less than 0.2 ppm. Gas flow in each manifold was monitored with a rotometer and was routinely maintained to a minimum of 1.5 times the aspiration rate of the meter sampling gas from the manifold. Figure 2 also shows some detail of the individual meter connections to the manifold system. All meters except the EM meter had an internal sampling system (e.g., a pump) to pull a sample

TABLE II

SO_2 METERS EVALUATED

Meter	Reference Name	Manufacturer Address	Date Requested	Date Received
Casella SO_2 Sampler T1400	Casella	C. F. Casella & Co., Ltd. Regent House, Britannia Walk, London, N. 17ND, England Dist. by: BGI Incorporated 1254 Main Street Waltham, Massachusetts 02154	9-14-73	9-27-73
SO_2 Ultra Portable Analyzer U2-DS	CEA	CEA Instruments 555 Madison Avenue New York, New York 10022	9-14-73	9-25-73
Sulfur Dioxide Analyzer S-364	EM	EnviroMetrics, Inc. 13311 Beach Avenue Marina Del Ray, California 90201	10-8-73	10-22-73
Microcoulomb Detector Mod. 724-21MS	Mast	Mast Development Company 2212 E. 12th Street Davenport, Iowa 52803	9-14-73	9-27-73
Titrilog III	PAI	Process Analyzers, Inc. 5440 Alder Houston, Texas 77036	9-21-73	11-16-73
Miran I Variable Filter Infrared Analyzer	Wilks	Wilks Scientific Corporation Box 449 South Norwalk, Connecticut 06856	9-14-73	10-3-73

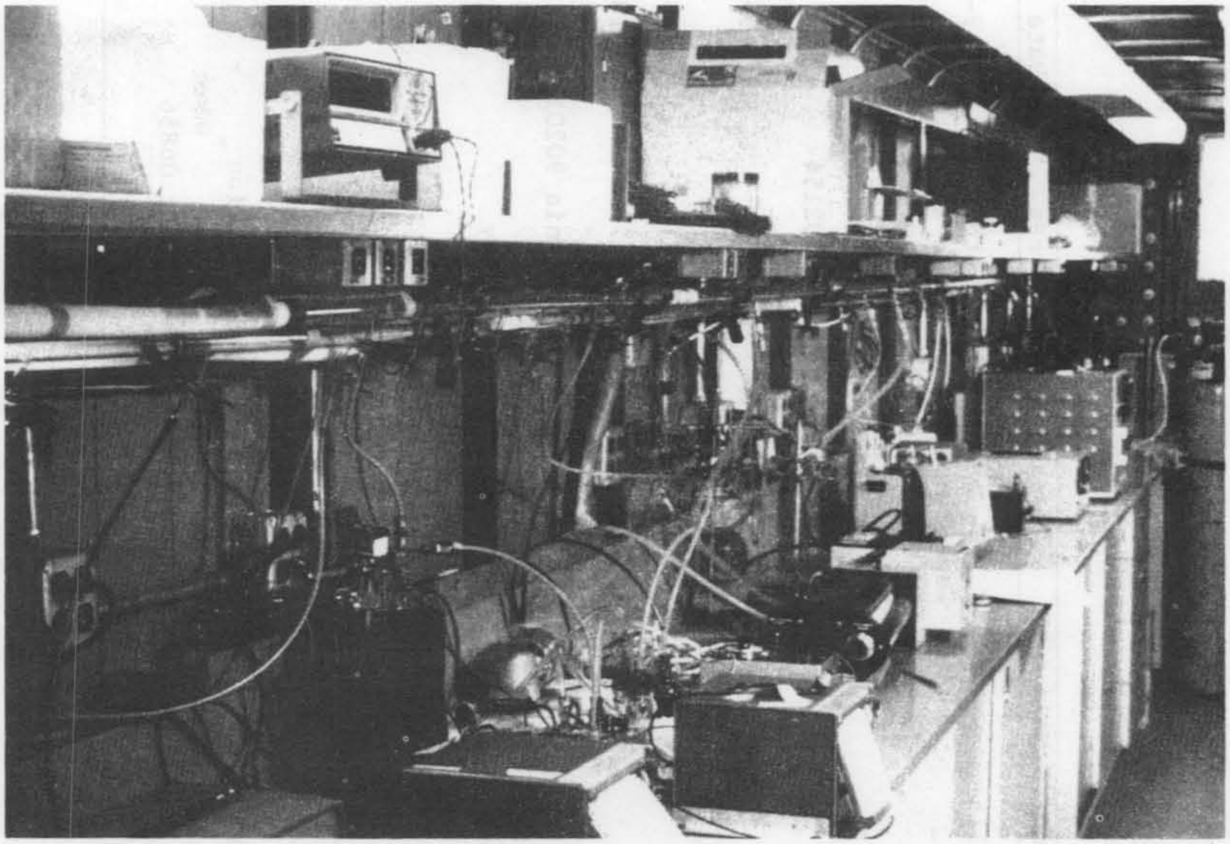

Figure 1. Photograph of the SO_2 Test Facility

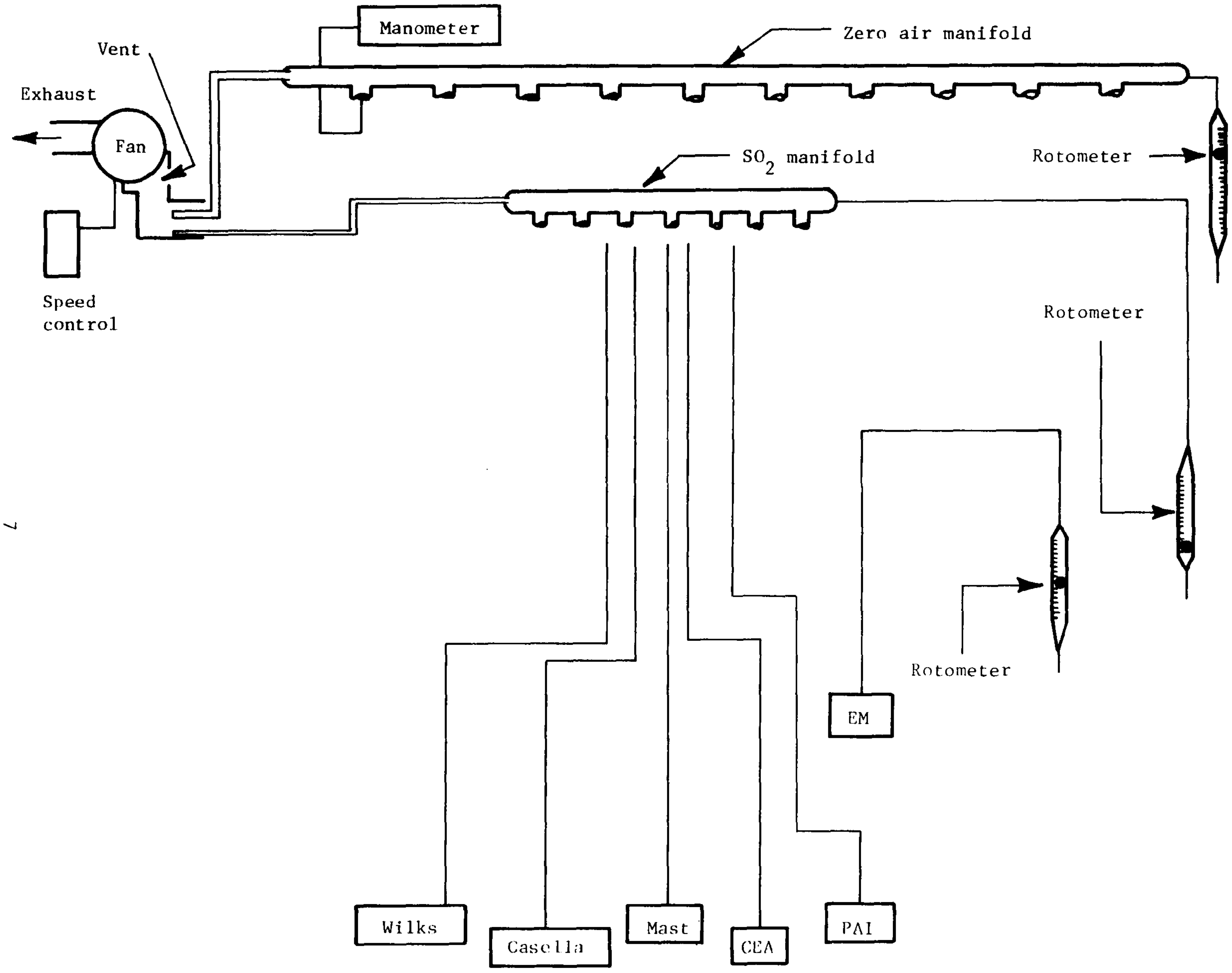

Figure 2. Test Facility for SO_2 Meters

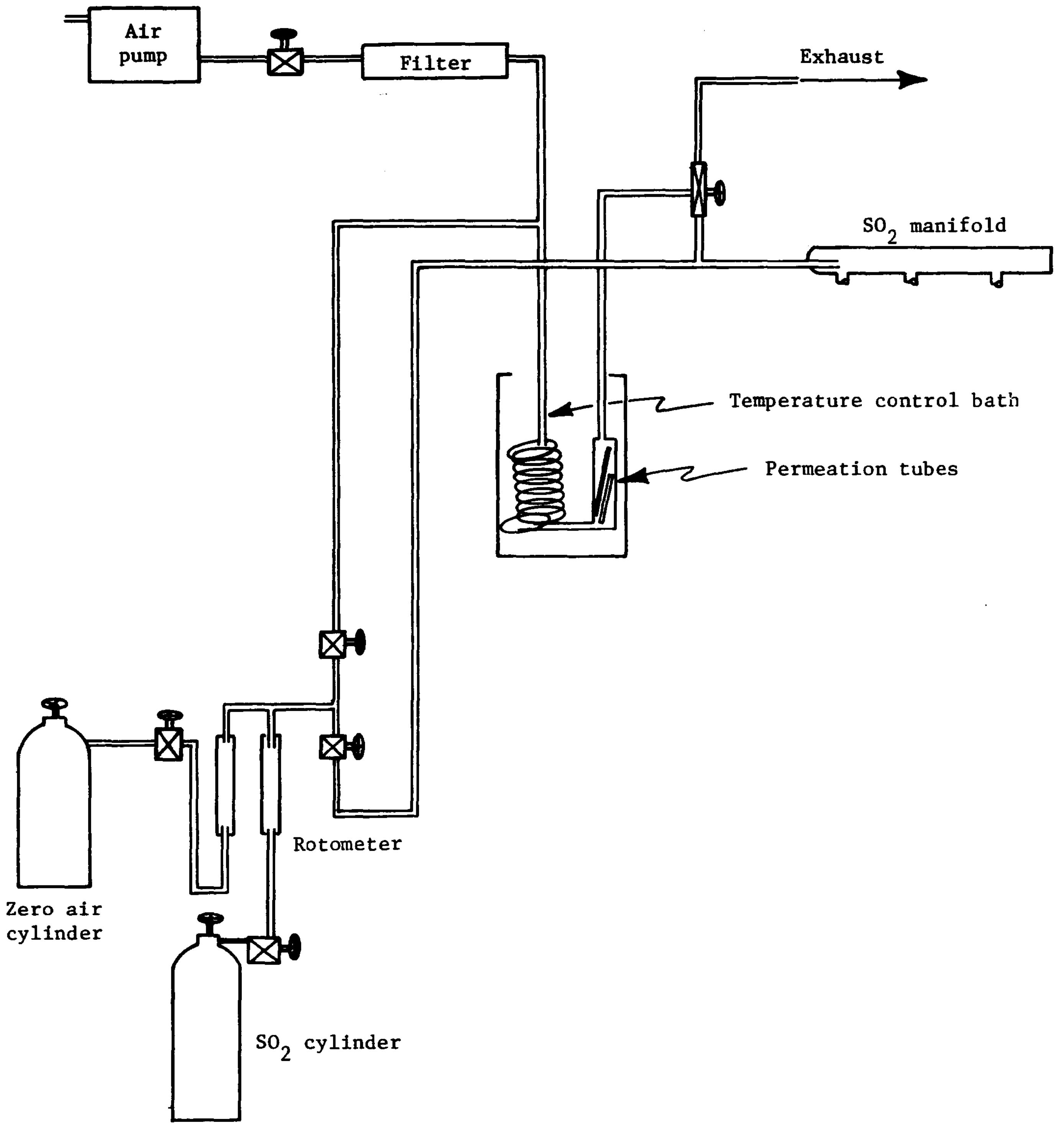

Figure 3. SO_2 Calibration Gas Source

from the manifold through the meter at the correct flow rate. In the case of the EM meter, the sampling system is a separate module and was not included in the system received for the evaluation. The correct flow to the EM meter was established and maintained by supplying the meter directly from a pressurized cylinder or from the permeation tube system.

When mixtures intermediate to the cylinder mixtures are generated by mixing gases from two cylinders with certified SO_2 mixtures or from one SO_2 cylinder and a zero air cylinder, the SO_2 concentration of the gas in the manifold is given by

$$C_3 = \frac{F_1C_1 + F_2C_2}{F_1 + F_2} \, ,$$

where

C_3 = manifold SO_2 concentration,
C_1 = SO_2 concentration of first gas,
C_2 = SO_2 concentration of second or dilution gas,
F_1 = flow of first gas, and
F_2 = flow of second or dilution gas.

Gas flows to the manifold system, as shown in Figures 2 and 3, were determined by reading rotometer settings. The rotometers were calibrated with a soap-bubble flow meter. The precision with which a given flow could be set was evaluated experimentally by repeatedly setting each flowmeter to a given flow and measuring that flow with a dry test meter that was calibrated with the soap-bubble flowmeter. Each rotometer was reset to a midscale value seven separate times and the resulting flow was measured. The maximum deviation from the average flow was 2 percent for one rotometer and 4 percent for the second. The standard deviation of the measured flow values about the mean in the second rotometer was 2 percent of the average. This suggests a probable error in setting an intermediate SO_2 concentration or a permeation tube concentration of 3 to 4 percent.

The SO_2 certified calibration gases were obtained as SO_2 in nitrogen rather than SO_2 in air because the mixture in nitrogen was concluded to be a more stable mixture over the evaluation period. Permeation tubes are impractical for concentration and flows above about 20 ppm and 1 l/min, respectively. Thus, the SO_2 in nitrogen mixtures were used for higher SO_2 concentrations and the permeation tubes were used for lower concentrations.

The SO_2 in nitrogen certified mixtures were analyzed periodically to ascertain their stability during the evaluation period. In general, these cylinders were sampled three times each week and the gas analyzed for its SO_2 concentration. The nominal 49 and 28 ppm cylinders were analyzed using the barium chloranilate method [Ref. 2]. A nominal 1 ppm SO_2 in nitrogen gas was analyzed periodically using the West-Gaeke method [Ref. 3]. The results of these analyses are summarized below and discussed in detail in Appendix B of this report.

Table III summarizes the results of the SO_2 calibration gas analyses. For the 28 and 49 ppm gases, the small ratio of the between days variance to the within days variance indicates that the within days variation explains the greatest part of the total variation and, thus, there is no trend or instability in the SO_2 concentration. In the 1 ppm data, the variation between samples is the dominant variance and, thus, moderate deviation in the SO_2 concentration would go undetected. However, the permeation tube system was used for most low concentration calibration gases. Appendix B includes the details for the SO_2 analyses.

The laboratory temperature was controlled to approximately 25° ± 2°C. Humidity in the laboratory was not controlled; however, the humidity of the gas sampled by the meters was very low unless controlled to a higher value.

1.4 Performance Characteristics

Performance characteristics measured for the SO_2 meters evaluated during this effort are defined below and the measurement procedure is discussed. Because of the diversity of the meters involved, these are general definitions and procedures. Specific details are included in subsequent sections of this report that discuss individual meters.

1.4.1 Accuracy of the Manufacturer's Calibration

The accuracy of the manufacturer's calibration is a measure of the accuracy of the meter as it is received from the manufacturer and prior to any calibration adjustments. It is an important characteristic for

TABLE III

SO_2 CALIBRATION GAS ANALYSIS

Barium Chloranilate Method
(ASTM Tentative)

28 and 49 ppm concentrations

43 samples of each
17 different days
2 to 5 samples each day

28 ppm:

Total Variance: 12.5 (ppm)^2 (σ = 3.5 ppm)
Between days : 16.3 (ppm)^2 (σ = 4 ppm)
Within days : 10.1 (ppm)^2 (σ = 3 ppm)
95% Confidence interval: 28.2 to 30.8 ppm

49 ppm:

Total Variance: 10.2 (ppm)^2 (σ = 3.2 ppm)
Between days : 10.9 (ppm)^2 (σ = 3.3 ppm)
Within days : 9.7 (ppm)^2 (σ = 3.1 ppm)
95% Confidence interval: 48.6 to 50.8 ppm

West Gaeke Method

1 ppm:

Total Variance : 0.023 (ppm)^2 (σ = 0.15 ppm)
Between Samples: 0.322 (ppm)^2 (σ = 0.57 ppm)
Between days : 0.005 (ppm)^2 (σ = 0.07 ppm)
Within days : 0.004 (ppm)^2 (σ = 0.06 ppm)

portable SO_2 instruments intended for field use because a recipient of the instrument may not have access to calibration facilities prior to using the meter. It was measured by recording each meter's responses to midrange and span calibration mixtures prior to making any calibration adjustments. For the Casella and Wilks meters, the manufacturer's calibrations are expressed as a calibration constant and a calibration curve, respectively, and these can be checked at any time. The PAI meter has provisions for setting the zero in the field environment without requiring a zero gas, and this adjustment was made. The CEA meter has an electronic calibration adjustment only that can be made in any environment and, thus, it too can be checked for the manufacturer's calibration accuracy at any time.

1.4.2 Warm-Up Time

The warm-up time for a meter is the elapsed time necessary for the meter to meet stated performance specifications after being OFF for at least 24 hours. In these evaluations, it was measured by turning each meter ON following the procedure specified in the operating instructions, and observing its responses to midrange, span, and/or zero mixtures. Any warm-up trends observed were measured and are reported as warm-up time. In general, this procedure demonstrated that the warm-up time specified by the manufacturer was sufficient. No effort was made to demonstrate a warm-up time shorter than that specified by the manufacturer or to measure or demonstrate a warm-up time starting from hot or cold temperatures other than the nominal 25°C ambient.

1.4.3 Response Times

Response times discussed in this section include the positive and negative response times, rise time, fall time, and lag time. The 90 percent response time is defined as the time interval from a step change in the input SO_2 concentration approximating the meters range and the time the meter's readout settles within ±10 percent of its final value. If the response time is due to a step increase in the concentration, it is a positive (±90%) response time and consists of the sum of the lag time and rise time. If it is due to a step decrease in the concentration, it is a negative (-90%) response time and consists of the sum of the lag time and fall time. Unless otherwise specified, response times are to be assumed to be positive. In these evaluations, both positive and negative response times were measured by causing an appropriate step change in the inlet concentration and recording the meter's response. The response times were determined from recorder outputs or by reading the meter's output concentration with time as measured with a stopwatch.

Lag time is the time interval from a step change in the input concentration to the first observable corresponding change in the meter output. It is a component of response time and was measured concurrently with response time.

The 90 percent rise time is the time interval from a meter's initial response to a step increase in the input concentration approximating the meter's range and the time the meter's output settles within ±10 percent of its final value. It was measured concurrently with the lag time and response time.

The 90 percent fall time is the time interval between a meter's initial response to a step decrease in the input concentration approximating the meter's range and the time the meter's output settles within ±10 percent of its final value. It was measured concurrently with lag time and the negative response time.

1.4.4 Zero Drift

Zero drift is the change in a meter's output over a stated period of unadjusted, continuous operation when the inlet SO_2 concentration is zero. It was measured by turning the test meter ON and allowing sufficient time for warm-up. While sampling zero air, the meter zero was off-set to a convenient up-scale value (to provide for the measurement of negative drifts). Generally, these conditions were maintained for 24 hours while the meter's output was recorded as a function of time. These tests were not continued for a full period if the drifts became excessive.

1.4.5 Span Drift

Span drift is the change in a meter's output over a stated period of unadjusted, continuous operation when the input SO_2 concentration is an up-scale value approximating the meter's range. It was measured by turning the test meter ON and allowing sufficient time for warm-up. The meter's responses to zero and span concentrations were checked and adjusted if necessary. The input SO_2 concentration was then maintained at a constant value while the meter was operated continuously and unadjusted for 24 hours or until excessive drift occurred.

1.4.6 Calibration Stability

Although span drift is one measure of the stability of a calibration setting with time, the calibration stability over a longer period of intermittent use is also an important characteristic. Calibration stability was measured by making zero and span adjustments and then recording the meter's responses to zero and span gases over long periods of unadjusted, intermittent use.

1.4.7 Minimum Detectable Change

The minimum detectable change is the smallest change in the input SO_2 concentration that can be detected in the meter's output. It was measured at various concentrations by generating small changes in the SO_2 concentration of the gas. Each meter's responses to these changes were reported herein.

1.4.8 Linearity

Linearity is the deviation between actual meter readings and the readings predicted by a specified straight line. It may be expressed as a maximum deviation or the standard deviation of the individual readings about the straight line. In the latter case, the standard deviation is usually referred to a line of best fit as determined by a linear regression analysis. If the meters are calibrated by adjusting their responses to zero and span concentrations, these end points are also convenient for specifying a straight line for evaluating linearity. In this report, linearity is expressed in the form that seems most descriptive for the specific meter under consideration.

The linearity measurements were made by measuring each meter's responses to SO_2 concentrations distributed between zero and span values. It is usually expressed as a percentage of full scale. In this report, it is also frequently expressed as a percentage of reading and the corresponding concentration is specified. Percentage of readings is a more meaningful term at high concentrations; however, it is not a meaningful term near zero concentrations.

1.4.9 Humidity Effects

The effects of humidity on each meter were measured by recording its response to a calibration gas obtained by mixing a SO_2 calibration gas with a known flow from a cylinder of zero air. The resulting mixture was very dry; i.e., the humidity was approximately zero. The dry, zero air portion of this mixture was subsequently saturated with moisture by bubbling it through water prior to mixing it with the SO_2 calibration gas. The resulting mixture then differed from the first only in moisture content, and each meter's response to the moisturized mixture was measured. The zero air portion of the mixture was usually three to four times the SO_2 portion to provide for a high humidity level after the air was saturated. In estimating the humidity, it was assumed that the air passing through the bubblers was brought to 100 percent humidity. After the high humidity response was recorded, the bubblers were again bypassed and the meter's response to the dry mixture was again recorded.

1.4.10 Temperature Effects

Temperature effects were measured by comparing each meter's responses to zero and SO_2 concentrations at normal room temperatures ($25° + 2°C$) with their responses when the laboratory temperature was elevated to 40°C. The laboratory temperature was permitted to return to normal overnight, and the procedure was repeated with the laboratory temperatures reduced to 15°C. The elevated and reduced temperatures were held constant for 4 hours prior to any measurements to enhance temperature stabilization.

1.4.11 Interferences

The effects of some interferences were measured by a procedure similar to that for humidity effects. A convenient concentration was generated by mixing known SO_2 calibration gases and zero air. Each meter's response to the resulting mixture was recorded. The mixture was then altered by substituting an identifical flow of known concentration of the selected interference for the flow of air in the mixture, and any changes in the meter's response was recorded. Finally, the zero air was again used as a diluent rather than the interference mixture, and the meter's response recorded. From these results, the interference equivalent was calculated.

In other cases, interference equivalents were evaluated by mixing a known quantity of the interference to be evaluated with a known concentration of SO_2 in air in a sample bag. The meter's response to this sample was then compared to the response to the SO_2 mixture alone.

The results of these tests are expressed in terms of an interference equivalent. An interference equivalent of 30:1 means that 30 ppm of the interference will appear as 1 ppm of SO_2 to the meter.

In some instances, high concentrations of the interference were not readily available and lower concentrations were used in these tests. Consequently, in some cases, a limit is stated for the interference considered. For example, if it is assumed that the interference being tested caused a response in the meter less than the minimum detectable change of the meter, then it can be stated that the interference equivalent is greater than:

$$\left(\begin{array}{l}\text{the interference concentration used in the}\\ \text{test divided by the minimum detectable change}\end{array}\right):1.$$

1.5 Physical Characteristics

For the purpose of these evaluations, the physical characteristics are assumed to include all characteristics which are not measureable performances. Many of these are evaluated subjectively; other are readily measured quantitatively. Each of the physical characteristics and the criteria applied to their evaluation are discussed in this section.

1.5.1 Portability

Portability is readily evaluated in terms of weight, physical dimensions (volume), and power requirements. The capability of operating from internal batteries as well as from an ac line is especially significant to portability. Portability is also enhanced if no accessories are required for the routine operation of the meter in field situations. These characteristics are readily measured and are tabulated for each of the SO_2 meters.

1.5.2 Readout

The form of the meter's readout is an important physical characteristic. It is desirable that the meter indicate the SO_2 concentration directly in ppm without reference to a calibration curve; that the meter scale provide for adequate resolution of a reading with suitable markings, multiple ranges, and a mirrored movement; and that the scaling be linear. A recorder output directly proportional to the meter deflection is also desirable. The characteristics of the readout of each SO_2 meter evaluated are described in this report.

1.5.3 Instruction Manuals

Evaluating an instruction manual is a somewhat subjective process. There are standards and specifications, pertinent to instruction manuals for equipment and systems, which specify content and style for instruction manuals (Refs. 4,5). However, none of the manuals encountered during these evaluations conform to these standards. The standards do not specify the value of the items specified for inclusion and some items are obviously more important than others (e.g., Installation and Front Matter are not as essential as General Information and Operation). Moreover, there are other subjective factors such as technical accuracy, style of writing, level of writing, and overall organization. For the purposes of this evaluation, an effort has been made to obtain a quantitative grade for each manual. A list of manual features has been tabulated and categorized as either essential information, desirable information, or useful information. Essential features are assigned a weight of six (6), desirable features a weight of four (4), and useful features a weight of two (2). Each feature is rated as either excellent, acceptable, unsatisfactory, or nonexistent according to how well it satisfies the need of the feature. An excellent rating is graded as a three (3), acceptable as two (2), unsatisfactory as one (1), and nonexistent as zero (0). Thus, for each essential feature graded as excellent, a manual accumulates eighteen (18) points (6 × 3). Following this process, each manual accumulates a total number of points which is a percentage of the total possible points.

The following manual features are considered essential for the operator of a meter. The listing under each feature further describes its content. The inclusion of Safety Precautions and Warnings in this list may be questioned on the grounds that in most instances no hazards are encountered. Safety precautions are so essential for an operator, however, that it is felt that an explicit statement relative to safety considerations is essential.

ESSENTIAL MANUAL FEATURES

1. Operational Description
    - General Description of Principle
    - Flow Diagrams
    - Schematic Diagrams
2. Operating Procedures
    - Turn-on
    - Warm-up
    - Sampling
    - Controls
3. Calibration Procedures
    - Zero Adjustment
    - Calibration (Span) Checks Adjustments
4. Safety Precautions and Warnings

The features tabulated below are not essential manual features but are extremely desirable from a user point of view.

DESIRABLE MANUAL FEATURES

1. General Organization
    - Table of Contents
    - Clearly Titled and Dated with Supersession Data
    - Bound in Single Volume
2. Table of Specifications
    - List of Interference Equivalents
    - Battery, Reagent Life

3. Theory of Operation
4. Maintenance Procedures
    - Batteries
    - Reagents
5. Performance Checks
    - Trouble Shooting Guides
6. Wiring and Plumbing Diagrams

The manual features tabulated below are considered useful information that should be made conveniently available to a meter operator.

1. Parts List
    - Adequate for Ordering and Costing
2. Warranty Information

Many of the instruction manuals for the meters evaluated are inadequate. It should be remembered that some of these meters are prototypes and manuals have not been prepared. Instead, the meters were delivered with only Operating Procedures.

1.5.4 Ease of Operation

It is essential that a portable SO_2 meter be easy to operate in the field by an operator without special knowledge or training, and that the controls provide no opportunity for operator bias in the results of a measurement. The controls should be readily accessible, clearly and unambiguously labeled, and provide no opportunity for a meter to be placed in an unacceptable mode of operation. It is also helpful if the controls provide a means of checking the condition or status of certain features of the meter, e.g., battery status checks, whenever such checks are feasible. The ease of operation is a subjective evaluation.

1.5.5 Ease of Zero and Span Adjustments

It is desirable that both zero and span adjustments be easy to accomplish in a field environment. In addition to providing easy access for these adjustments, it is desirable that provisions be made for these adjustments in uncontrolled environments. The ease of making these adjustments are discussed for each of the meters evaluated.

1.5.6 Ruggedness

The ruggedness of each of the meters evaluated is discussed subjectively in view of its principle of operation and general construction. No controlled tests of ruggedness were conducted except to observe that each meter could be picked up and carried out while in operation without any obvious degradation in performance.

1.5.7 Intrinsic Safety

The intrinsic safety of each meter is also subjectively discussed in view of its potential for harm to an operator. The use of toxic reagents and the release of byproducts are examples of these considerations.

2.0 PORTABLE SO_2 METERS

The SO_2 meters evaluated during these investigations are discussed in this section. Of the 6 meters evaluated, only 2 are reasonably portable and only 1 is direct-reading. However, as the results of the market survey indicate, these are the most portable of the SO_2 meters available and the meters most likely to be of value for use by compliance officers or industrial hygienists in the field environment. With respect to the NIOSH guidelines discussed in Section 1.2.1 of this report, no meters are available that are ideally suitable.

Test results from each of the meters evaluated are discussed in this section. Section 3.0 of this report will summarize the evaluation results in a tabular form suitable for comparison.

2.1 Casella

The Casella is one of only two truly portable SO_2 meters included in this evaluation. It is not a direct-reading meter. Some problems evolved with the electronics which limited the evaluation effort and many of the evaluation tests were not completed for the Casella. This is especially unfortunate because of the excellent performance of the Casella prior to the onset of the electronic problem, its excellent physical characteristics, and the unique design of its controls which simplify the Casella's operation.

Fig. 4 is a photograph of the Casella SO_2 meter. Controls provide for selecting a high or low range, checking and adjusting an internal voltage level, checking the status of internal electronics (amplifier), measuring the conductivity of the electrolyte cell, and placing the meter in a sampling mode. Other controls on the front panel are intended for future use, e.g., a recorder output. A rear panel includes a rotometer which registers the sample flow and a clock readout geared to the meter which registers the sampling time and, hence, the volume of the sample. Both the front and rear panels are recessed and designed for covers which completely enclose the meter controls and readouts.

The electronic failure which interrupted the Casella test program manifested itself as an incorrect reading on a meter status check included in the operating procedure; i.e., the amplifier status check incorrectly read off-scale. A description of the difficulty was communicated to Casella

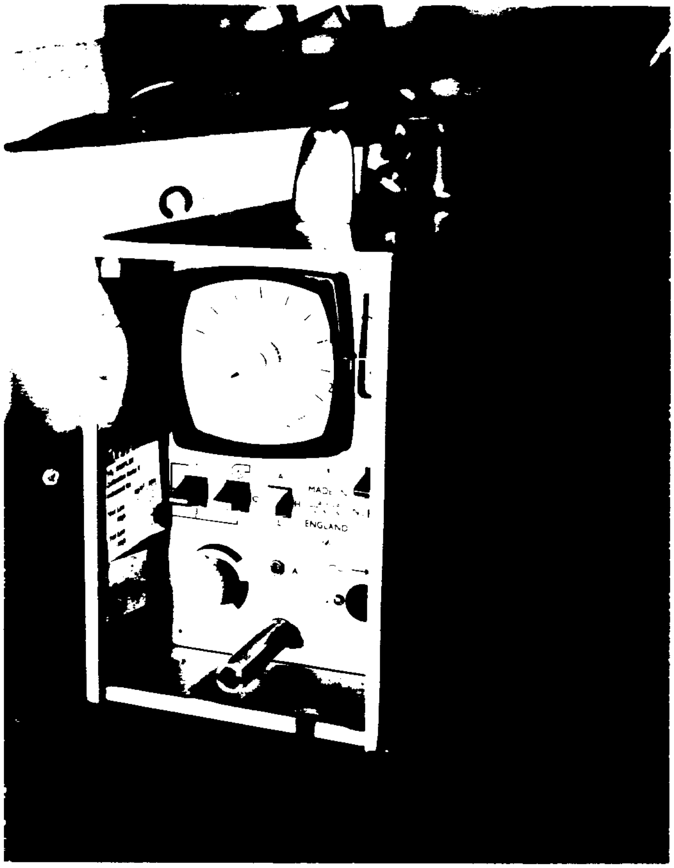

Figure 4. Photograph of the Casella SO_2 Meter

who cabled instructions for the meter repair. The recommended modifications were installed; however, the meter still performed improperly. The amplifier status reading could be brought on scale, but it was erratic and subsequent conductivity measurements were erratic.

2.1.1 Principle of Operation and Description

The Casella detects the presence of SO_2 in the sample air by trapping the SO_2 in a dilute solution of hydrogen peroxide (H_2O_2). The air sample is bubbled through the H_2O_2 electrolytic cell, and SO_2 in the air reacts with the H_2O_2 to form sulfuric acid (H_2SO_4) according to the equation

$$H_2O_2 + SO_2 \rightarrow H_2SO_4 .$$

The conductivity of the cell is proportional to the H_2SO_4 concentration. Thus, the SO_2 in the sampled air is determined by measuring the conductivity before and after sampling and the total sample volume (time since the flow rate is constant.) The meter, in effect, provides four different ranges. The electrolyte cell volume is changed by a factor of 10 to 1 by physically installing either a 70 ml cell or a 8 ml cell and, thus, provides two ranges. The electrode assembly which is immersed in the cell consists of a central electrode and two others of two different areas. A front panel high/low (H/L) switch pairs one of these electrodes with the central electrode to provide two additional ranges for a total of four.

The Casella is not a direct-reading meter. The meter indicates the conductivity of the electrolyte cell on a scale of 0 to 100, and the SO_2 in the sample is proportional to the change in the meter's conductivity reading and inversely proportional to the sample volume (or sample time since the flow is constant). Thus, the SO_2 concentration is given by

$$SO_2 \text{ concentration ppm} = k \frac{\Delta R}{\Delta t} ,$$

where ΔR is the final conductivity value minus the initial conductivity value as read from the meter's readout, Δt is the sampling time read digitally from the rear panel (or from a stopwatch), and k is a calibration constant provided by the manufacturer for each of the four ranges.

Two other design features which enhance the quality of the Casella are temperature compensation from 0° to 40°C and conductivity measurements at 1000 Hz rather than at dc.

2.1.2 Test Facilities and Procedures

The Casella has an internal sampling system which draws 1 l/min. of sample at the inlet port. For testing purposes, the Casella was physically connected to either the zero air manifold or SO_2 calibration gas manifold with flexible Teflon tubing. No special procedures were followed other than the operating procedures described in the Casella manual.

2.1.3 Performance Characteristics

The Casella is unique in that it is an integrating meter that operates on a sample that increases with the sampling period. For this and other reasons, some of the performance characteristics measured for other SO_2 meters are not appropriate to the Casella. Some performances that are appropriate were not measured because of the electronic failure described in Section 2.1.

2.1.3.1 Accuracy of the Manufacturer's Calibration: The manufacturer's calibration is expressed as a constant factor for converting the meter's readouts from conductivity and time changes to SO_2 concentrations. Thus, four constants provided by the manufacturer comprise the manufacturer's calibration. In order to estimate the accuracy of the manufacturer's calibration, the meter's responses to known concentrations of SO_2 can be used to calculate a calibration constant which can be compared with the manufacturer's calibration constant.

If the 70 ml cell and the high range are used, the SO_2 concentration is given by

$$SO_2 \text{ Concentration (ppm)} = 9.81 \frac{\Delta R}{\Delta t} .$$

Five consecutive measurements of a 28 ppm calibration gas averaged 27.4 ppm, and 5 consecutive measurements of a 49 ppm calibration gas averaged 50.4 ppm. These results are within the certification accuracy of the calibration gases.

Thus, the 9.81 calibration constant is concluded to be accurate within the limits of the certified calibration gas.

The only other calibration constant checked prior to the meter's malfunction was the 1.1 value corresponding to the 70 mℓ cell on a low range. Sampling a certified 0.92 ppm calibration mixture, the Casella registered a 0.76 ppm mixture after 8 minutes of sampling. If the calibration mixture is assumed to be exact, the calibration constant would have to be 1.3 for the meter to read accurately. This indicates a 15 percent in the 1.1 calibration constant. However, as discussed in Section 1.3 of this report, confidence in the accuracy and stability of the 0.92 certified mixture is low.

2.1.3.2 Warm-Up Time: The Casella is an integrating type meter, and acquiring a single measurement can take a time period extending from a fraction of a minute to several hours. In general, a single measurement will require several minutes of sampling. It must be assumed that any warm-up time requirements are short as compared with the sampling time because operational controls of the Casella do not provide any way to warm-up the meter. The controls only allow for a conductivity or status measurement mode. Whenever a series of measurements were made during these evaluations, each using 2 to 5 minutes of sampling time, the first measurements always compared closely with subsequent measurements and did not tend to be lower. These experiences also indicate that warm-up time is negligible.

2.1.3.3 Response Time: Response time has no significance for the Casella meter. It is an integrating type meter and requires long sample times. A conductivity measurement interrupts the sampling process and provides a stable readout within a few seconds.

2.1.3.4: Zero and Span Drifts: Zero and span drifts are not meaningful performance characteristics for the Casella. The initial conductivity measurement corresponds to a zero measurement (but is unadjustable except by changing the electrolyte in the cell) and is measured prior to sampling. It can be evaluated by sampling zero air for a long period and recording any change in the conductivity of the cell, i.e., any SO_2 readout. The meter malfunctioned before this was accomplished.

In general, the conductivity of a cell did not change significantly during periods of nonuse, e.g., a maximum of 1 percent of scale in 24 hours was observed.

2.1.3.5 Calibration Stability: An estimate of the calibration stability is made by comparing the results of a series of measurements of the 49 ppm calibration gas and a series of measurements of the 28 ppm calibration gas made 17 days later. The electrolyte in the 70 mℓ cell was changed in the interim of these measurement periods, thus introducing another potential variable in the calibration. For each series of measurements, the total conductivity change, the total sampling period and the nominal value of the calibration gases are used to calculate a calibration constant for each of the sampling periods. These results indicate that the calibration constant changed by 9.8 percent over the 17-day period. However, it is possible for the calculated values of the calibration constants to compare exactly using different values for the certified calibration gases that are within their specified tolerances.

Another approach to estimating the calibration stability is to consider the precision of a series of measurements of a certified calibration gas. For the 49 ppm gas, a series of 5 measurements averaged 50.4 ppm, the maximum deviation was 4.7 ppm and the standard deviation of the distribution about the average was 2.8 ppm. For the 28 ppm gas, a series of 5 measurements averaged 27.4 ppm, the maximum deviation was 1.4 ppm and the standard deviation about the average was 1.1 ppm.

2.1.3.6 Minimum Detectable Change (Concentration): The Casella malfunctioned before a minimum detectable concentration could be demonstrated. (It is an integrating--i.e., an averaging--meter and its readout is the average of the SO_2 concentration over the sampling period.) It was demonstrated that the Casella can detect 0.92 ppm SO_2. This concentration yielded large conductivity changes (e.g., 10 percent of scale) after several minutes of sampling. It is obvious that smaller conductivity changes can be detected and sampling can be done over a longer time period. Also, the smaller, 7 ml cell can be used to increase sensitivity. The manufacturer claims a range of from 0.005 ppm to 500 ppm over a time range of from 1 minute to 24 hours.

2.1.3.7 Linearity: Linearity measurements were also limited by the meter's malfunction. However, initial measurements on three certified calibration gases are plotted in Fig. 5 and a line-of-best-fit as determined by a linear regression analysis is drawn in. The line-of-best-fit has a y-axis intercept of -1.09 ppm and a slope of 1.04. The maximum deviation from the line-of-best-fit is 4 ppm at 49 ppm which is 8 percent of a 50 ppm range. The maximum deviation from an ideal line is 3.4 ppm at 49 ppm or approximately 7 percent of a 50 ppm range.

2.1.3.8 Others: Other performance characteristics (i.e., humidity, temperature, and interference effects) were not measured for the Casella because of the electronic malfunction. It is noted that the meter is temperature compensated electronically for a temperature range of from 0°to 40°C, and it is unlikely that the meter is sensitive to humidity changes since it bubbles the sample through a dilute solution of H_2O_2. As for interferences, it might be compared with the CEA which utilizes the same detector principle. The CEA is described in Section 2.2.

2.1.4 Physical Characteristics

2.1.4.1 Portability: The Casella was one of only two truly portable SO_2 meters evaluated. It is of a suitable size for portability, can operate for a long period from internal, rechargeable batteries, and has an internal sampling system. The chassis design provides for completely covering the meter to enhance its usefulness as a portable monitor, and its integrating principle provides for measuring on average SO_2 concentrations over the sampling period without requiring a recorder output. It is true, however, that the averaging feature would mask peak values of SO_2 concentrations.

Attributes of the Casella which principally determine its portability are tabulated below.

CASELLA PHYSICAL ATTRIBUTES

Weight: 13 lb
(5.9 kg)

Size: 10 x 11.8 x 5 in.
(25.4 x 30 x 12.7 cm)

Volume: 0.34 ft^3
($9.7 \times 10^{-3} m^3$)

Batteries: Internal, rechargeable batteries
with an external charger.

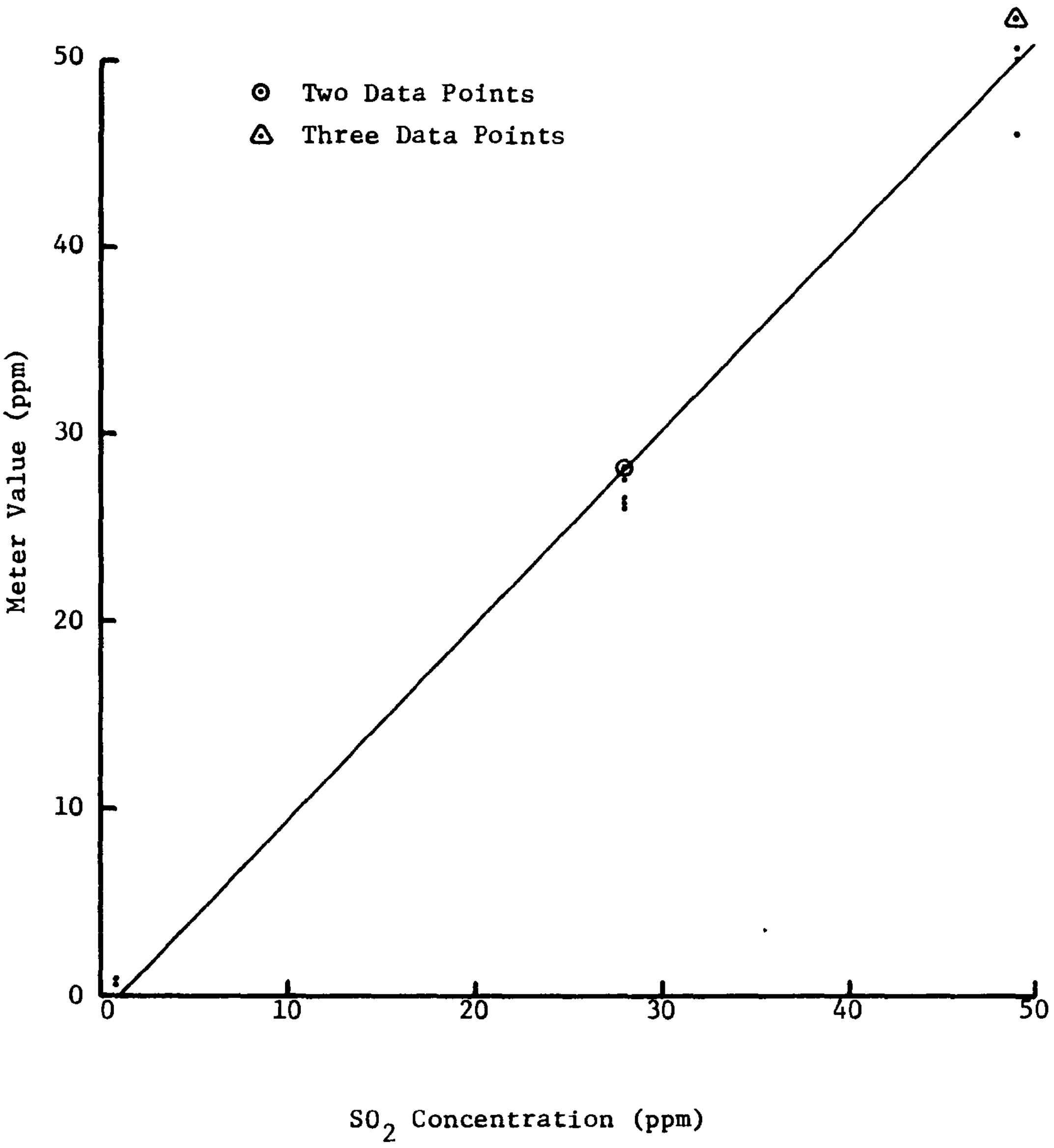

Figure 5. Casella Linearity Data

Another factor which influences the portability of the Casella is the life of the dilute H_2O_2 electrolytic cell. The life of the cell is also a measure of the Casella's ability to function as a continuous monitor. The time-SO_2 concentration product limits the life of the cell according to the equation

$$SO_2 \text{ Concentration (ppm)} = k \frac{\Delta R}{\Delta t} ,$$

where k is the Casella calibration constant for the meter and cell volume. By setting ΔR to 100 (or the remaining, unused portion of the meter readout), a cell life time can be calculated for a given SO_2 concentration. These results are illustrated in Fig. 6 for both the 7 ml and 70 ml cells, assuming a cell is completely expended and ΔR = 100.

2.1.4.2 Readout: The Casella readout is a meter movement scaled in 100 units. It is not a direct readout of SO_2 concentration, but rather a measure of the conductivity of the detector cell. The SO_2 concentration is calibrated from the change in the meter reading for a given sampling time. The sampling time is read from a digital counter geared to the meter's internal pump and visible from the rear panel. The sampling time can be read to 0.01 minutes, and the conductivity to 0.5 percent of scale. A rotometer on the rear panel reads the sample flow which remained constant throughout this evaluation period. The rotometer is exceptionally readable.

2.1.4.3 Instruction Manual: The Casella instruction manual was evaluated according to the criteria discussed in Section 1.5.3 of this report. In general, the manual was just adequate. Some specific needs are, better organization with a table of contents, clearly titled operating instructions, schematic and flow diagrams, and additional specifications, e.g., a list of interference equivalents. With regard to the features in Section 1.5.3, the manual was rated as follows:

CASELLA MANUAL RATING

Essential Features: 50%
Desirable Features: 50%
Useful Features: 33%
Overall Rating: 46%

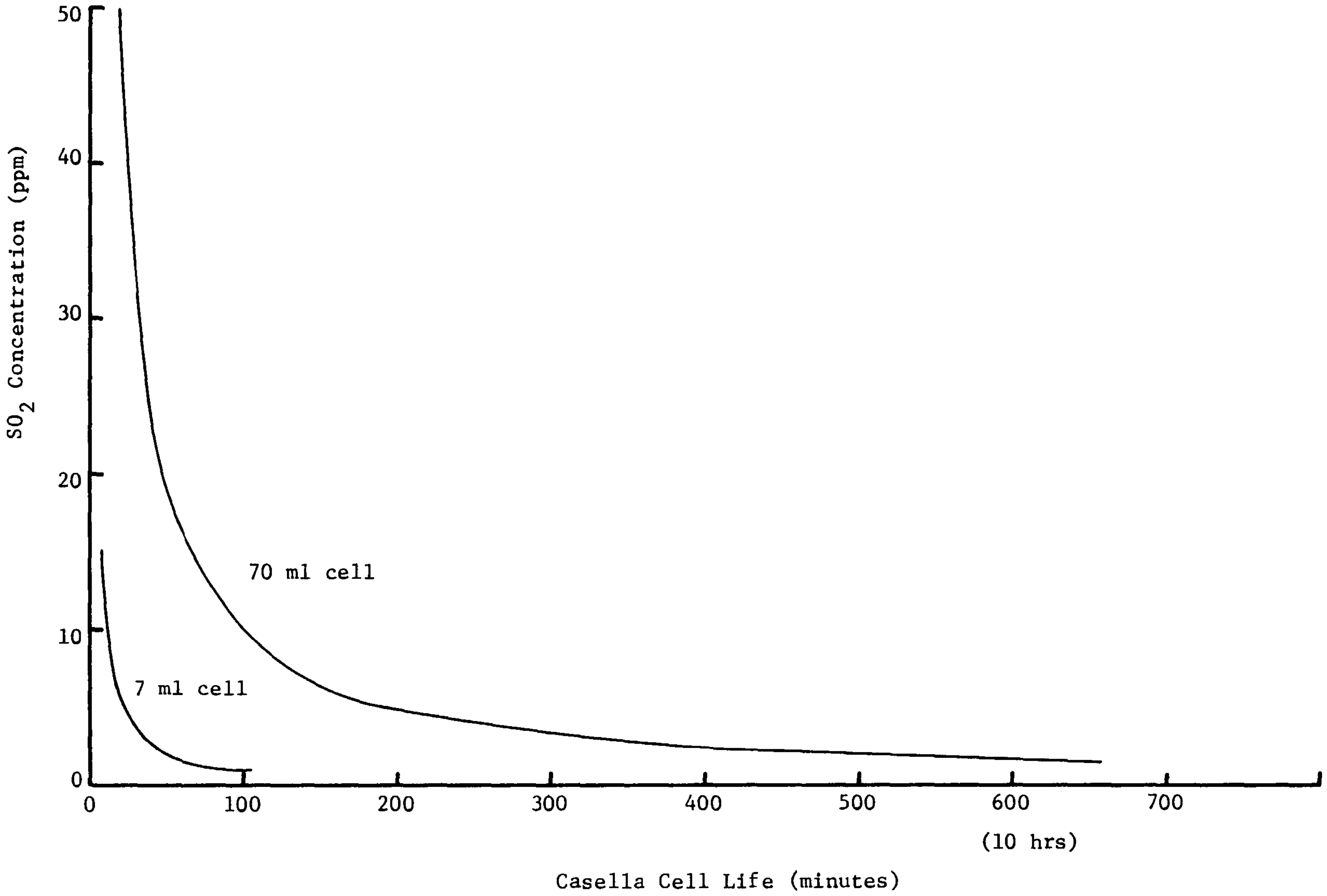

Figure 6. The Casella Cell Life as a Function of SO_2 Concentration

2.1.4.4 Ease of Operation: The Casella is very easy to operate. It features a unique arrangement of 3 front panel switches which provide complete operational control. A high or low (H/L) scale can be selected, the meter placed in an OFF, SAMPLE, or READ mode; and the battery status, conductivity, or an internal quality or status check selected for readout. The user should anticipate frequently changing the electrolyte in the cell, but this is easily accomplished from a solution that can be prepared weeks in advance.

2.1.5 Recommended Use Technique

The Casella controls are well designed and easy to operate. In addition to the manufacturer's operating instructions, the following use techniques are also recommended. In order to minimize the effects of timing errors and the volume of tubing, for example, between the meter and the atmosphere to be sampled, the sampling time should not be less than about one minute. If the conductivity changed (ΔR) observed after sampling is small, sampling should be resumed to obtain a larger ΔR or until the sampling time is sufficient to have yielded a clearly detectable ΔR for small concentrations. If only low SO_2 concentrations are to be encountered, the 7 ml cell is an obvious choice to provide increased sensitivity in a reasonable time span. If the concentrations to be encountered are unknown, the 70 ml cell is recommended. A set of graphs similar to those in Figs. 7 and 8 are recommended as helpful in making these decisions and also to enhance a quick assessment of an SO_2 concentration from the meter's ΔR and Δτ readouts. Figure 7 is a plot of the SO_2 concentration corresponding to a given ΔR reading with sampling time as a parameter for the 70 ml cell. It is a plot of the concentration equation,

$$SO_2 \text{ Concentration (ppm)} = k \frac{\Delta R}{\Delta \tau} ,$$

where k is the calibration constant for the 70 ml cell. The solid lines correspond to the high scale and the dashed lines to the low scale. Figure 8 is a similar graph for the 7 ml cell.

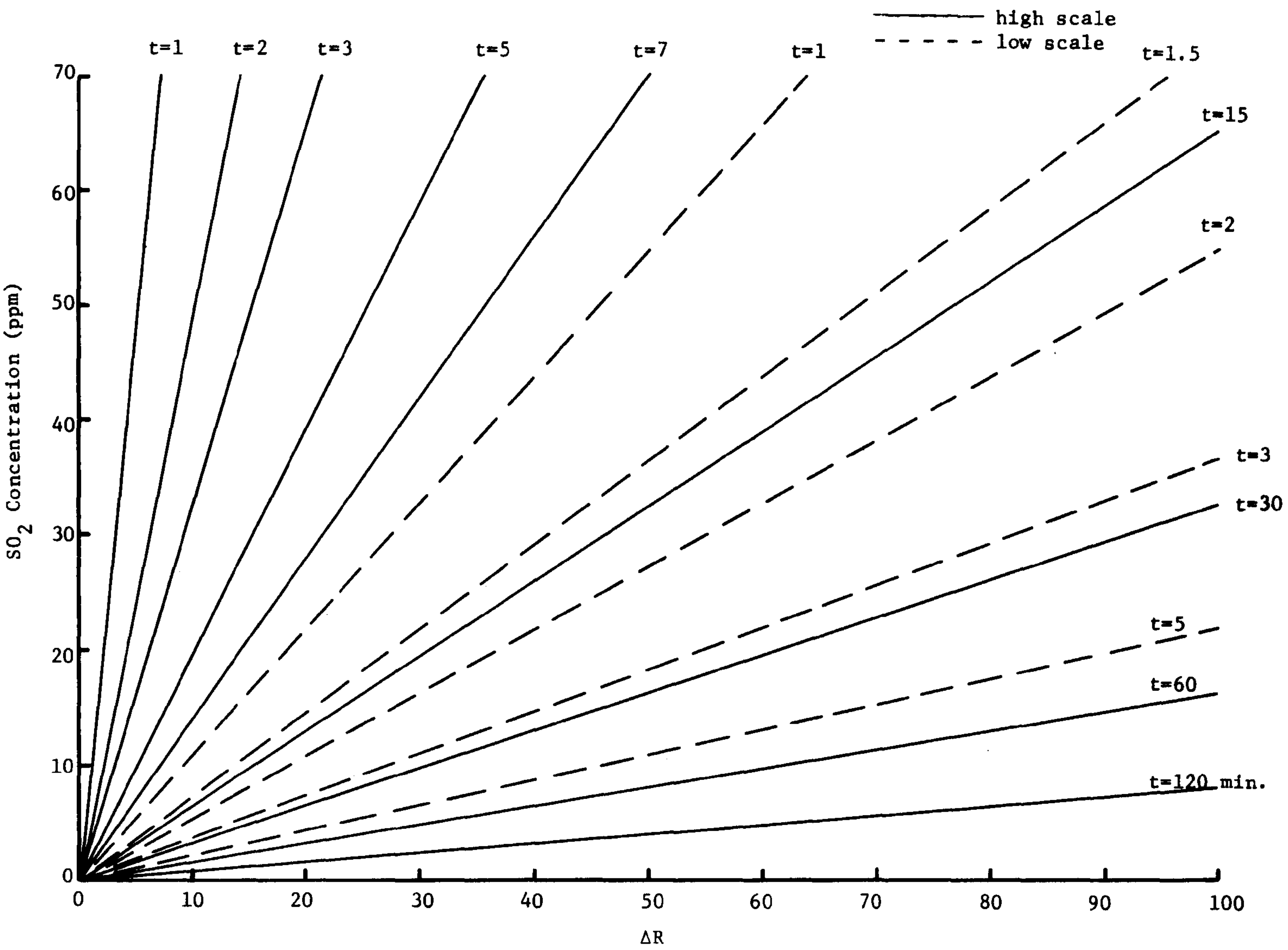

Figure 7. SO_2 Concentration as a Function of the Casella ΔR and Δt Readouts, 70 ml Cell

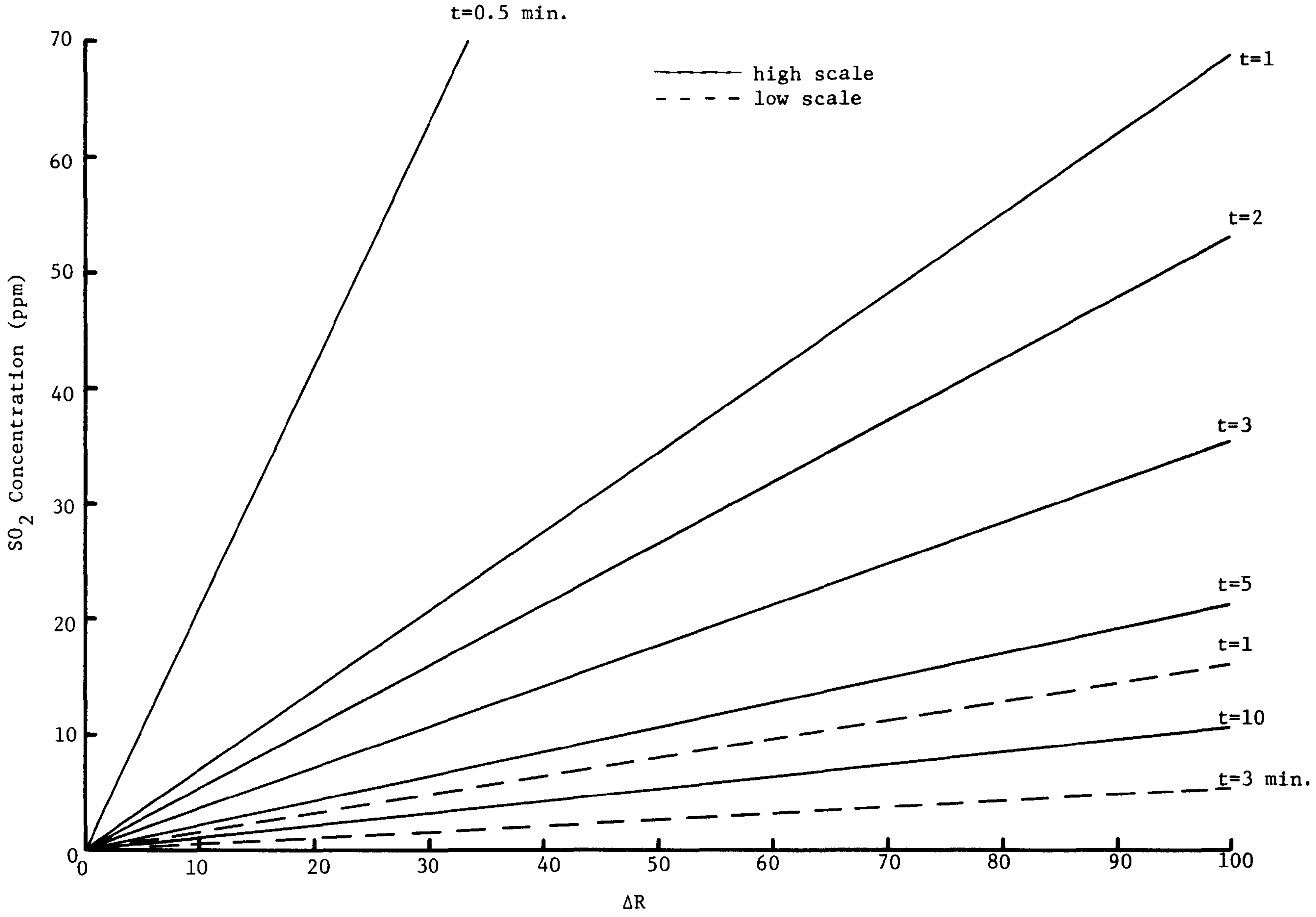

Figure 8. SO_2 Concentration as a Function of the Casella ΔR and Δt Readouts, 7 ml Cell

2.2 CEA

The CEA SO_2 meter is shown in the photograph of Fig. 9. Like the Casella, the CEA is a truly portable SO_2 meter. It does not read the SO_2 concentration of a sample directly in ppm, but the concentration is determined by multiplying the meter reading by a constant calibration factor. (The meter does read SO_2 concentration directly in ppm on one scale because the calibration factor is unity.) The CEA operates on a fixed, hand-pumped sample to determine the SO_2 concentration.

The meter readout is a dual scaled, mirrored meter movement. The meter range is adjustable, with an internal potentiometer, to 0.5, 1, and 2 ppm SO_2 full scale. An internal, Hi/Lo toggle switch increases each range by a factor of 10 such that the CEA can be ranged for 0.5, 1, 2, 5, 10, or 20 ppm SO_2 full scale. The meter scales are 0.5 and 1.0 units full scale and can be read, at best, to 1 percent of scale.

2.2.1 Principle of Operation and Description

The CEA exploits the same detection principle as the Casella, i.e., the SO_2 in the sampled air is trapped in a dilute solution of hydrogen peroxide (H_2O_2) to form sulfuric acid (H_2SO_4) according to the equation

$$H_2O_2 + SO_2 \rightarrow H_2SO_4$$

(The dilute H_2O_2 electrolyte is slightly acidified with H_2SO_4 to reduce the effects of certain interferences.)

The CEA controls are evident in the photograph of Figure 9. A mode control switch turns the meter from OFF to an ON position. In the ON mode, two BATTERY TEST positions, a CALIBRATE or a SAMPLE position can be selected. In the BATTERY TEST positions, positive and negative battery voltages are checked. In CALIBRATE, the meter's range is confirmed and adjusted if necessary. This adjustment is internal to the chassis but easily accessible since the chassis simply flips open. In the SAMPLE mode, the meter movement reads the conductivity of an aliquot of the H_2O_2 electrolyte.

The hand-operated pump is a unique design. Operation of the pump stirs the electrolyte in the 180 ml reservoir, isolates a 0.3 ml aliquot of the

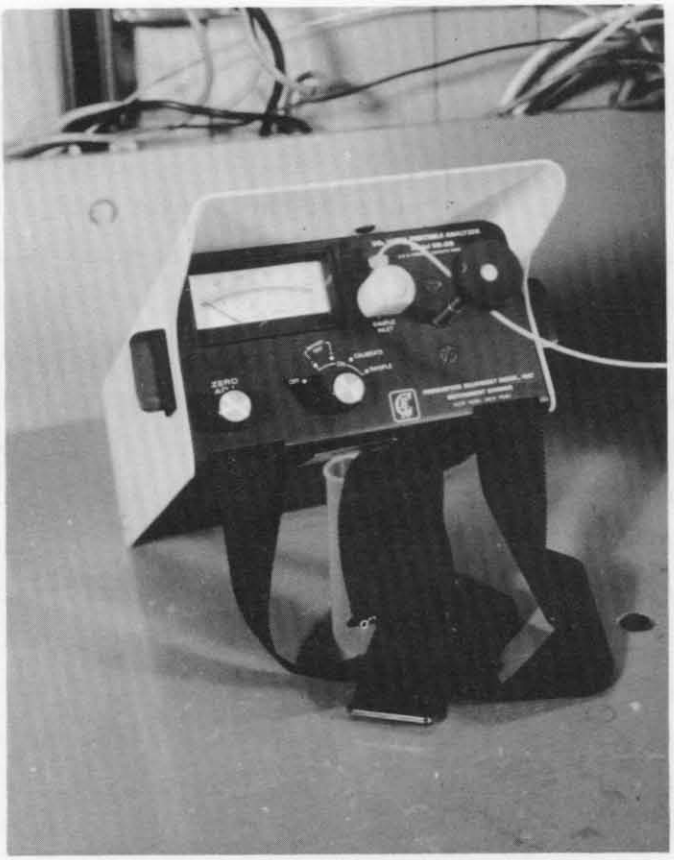

Figure 9. Photograph of the CEA Meter

electrolyte in a sample cell, and pulls a 100 ml air sample from the sample inlet to the sample cell. The ZERO ADJUST is used in conjunction with the pump to adjust the conductivity of the isolated aliquot in the sample cell to zero prior to exposing it to the 100 ml air sample. Thus, when the CEA meter is used, the electrolyte previously in the sample cell is returned to the reservoir and mixed by the operation of the pump. The pump, when returned to an intermediate position, isolates a fresh aliquot of H_2O_2 electrolyte from the reservoir in the sample cell, and the ZERO ADJUST is used to zero the meter reading. When the pump is released to return to its normal position, the 100 ml air sample is pulled to the sample cell. The SO_2 in the air sample is converted to H_2SO_4 in the sample cell increasing the conductivity of the cell. The meter readout registers the conductivity change and is proportional to the SO_2 in the air sample. Subsequent use of the hand pump begins the process anew.

Calibration of the CEA is fixed in its design and there are no provisions for altering the calibration. When the function switch on the front panel is placed in the CALIBRATE position, it is actually the range to which the meter is calibrated that is confirmed or adjusted. The CEA can be recalibrated, in effect, by applying a different multiplier to the meter reading or off-setting the range adjustment in the CALIBRATE mode, but it would be an awkward procedure.

2.2.2 Test Procedures and Facilities

The CEA meter was connected to either the zero air or the SO_2 manifold by a flexible Teflon tubing supplied with the meter, and the meter operated according to the manufacturer's instructions. (The volume of the coupling tubing was approximately 0.7 ml.) The manufacturer also recommends averaging three readings for each measurement and taking a reading only after 2 minutes from the time the pump is released. These procedures, which are examined herein, were generally followed.

2.2.3 Performance Characteristics

The CEA meter does not operate on a continuous sample but, rather, operates on a single, 100 ml grab sample whenever the pump is operated. Consequently, many of the performance characteristics measured for other SO_2 meters are inappropriate for the CEA and were not measured.

2.2.3.1 Accuracy of the Manufacturer's Calibration: There are no provisions for altering the calibration of the CEA meter. The meter reading is routinely rezeroed during each measurement, and the "calibration" procedure is actually a range adjustment. Thus, the accuracy of any measurement is a measure of the accuracy of the manufacturer's calibration.

The accuracy of the manufacturer's calibration is tabulated below in terms of averages and the percent difference between the average and the actual concentration. Each number averaged is actually an average of 3 individual measurements in keeping with the manufacturers recommendation. (When the number of measurements considered was not an integral number of 3's, the final number is either an average of 2 or 4 individual measurements.) These results show the calibration to be low by as much as 26 percent.

CEA CALIBRATION ACCURACY

SO_2 Concentration (ppm)	No. of Samples (Groups of 3)	Average Value $\bar{X}$ (ppm)	Difference (%)
0	1	0	0
0.92	6	0.88	-4.3
2.5	5	1.86	-26
3.5	4	3.2	-8.6
8.8	4	6.6	-25
17.7	8	15.3	-14

A very meaningful assessment of the accuracy of the manufacturer's calibration can be obtained by considering the linearity data discussed in Section 2.2.3.6 of this report. These data show that the line-of-best-fit to the linearity data as determined by a linear regression analysis is 15 percent lower than the ideal response curve. Thus, it is concluded that the manufacturer's calibration is 15 percent low.

2.2.3.2 Warm-Up Time: Warm-up time is not a meaningful performance characteristic for the CEA meter, and no warm-up trends were observed. In general, 3 to 4 minutes were required to complete a single measurement, and it is concluded that any warm-up requirements are negligible compared to the time required for a measurement. The first of a series of measurements did not differ significantly from subsequent measurements.

2.2.3.3 Response Time: The CEA meter operates on a fixed, 100 ml grab sample that is pulled to the sample cell by a hand-operated pump. (The pump's return to a rest position after being depressed is spring powered.) The pump returns to the rest position in approximately 50 seconds after the ZERO ADJ. is set and the pump released. The manufacturer recommends a 2-minute waiting period after the pump returns to rest before taking a reading. The procedure followed during these investigations was to take a reading between 3 and 4 minutes after the release of the pump. The meter readout was usually stable by this time, but not always. However, as the manufacturer suggested, subsequent meter movement was usually very small (but not always). Measured 90 percent response times varied from approximately 1 to 3 minutes from the release of the pump plunger.

2.2.3.4 Calibration Stability: The stability of the CEA calibration was evaluated by comparing the meter's responses to a 17.7 ppm calibration mixture on two occasions separated in time by approximately one month. The electrolyte in the cell was changed in the interim. The responses are expressed in terms of an average and the standard deviation of the individual responses about the average. In these results, tabulated below, the average response decreased by approximately 12 percent over the month's period. Also tabulated are responses to a 0.92 ppm calibration gas separated in time by one week. In this case, the meter's average response increased by approximately 12 percent. However, when these parameters are compared using a t-test with a weighted standard deviation, they do not differ significantly; i.e., the probabilities that the two 17.7 ppm samples and the two 0.92 ppm samples come from different populations are approximately 0.1. It is concluded, therefore, that changes in the calibration of the CEA are small compared to the differences attributable to the imprecision of the meter.

CEA CALIBRATION STABILITY

Responses to a 17.7 ppm Calibration Gas
(1 month)

$\bar{X}_1$ = 15.3 ppm

$\bar{X}_2$ = 13.4 ppm

σ_1 = 2.8 ppm

σ_2 = 1.6 ppm

Responses to a 0.92 ppm Calibration Gas
(1 week)

$\bar{X}_1$ = 0.8

$\bar{X}_2$ = 0.9

σ_1 = 0.1

σ_2 = 0.2

2.2.3.5 Minimum Detectable Change: To evaluate the minimum detectable change, the CEA was calibrated (ranged) to 0.5 ppm SO_2 full scale. Mixtures of certified 0.92 ppm SO_2 and zero air were used to generate small changes in the SO_2 concentration, and the meter's responses to these small changes recorded. In accordance with the manufacturer's recommendations, each recorded measurement is an average of 3 individual measurements. These results, tabulated below, show the meter responding to small changes in the SO_2 concentration. However, these changes are not representative of the meter's capability for detecting small changes in the sample SO_2 concentration. If a series of measurements of a given concentration are made, the standard deviation of the individual measurements about the average measurement is more indicative of a minimum detectable change.

CEA MINIMUM DETECTABLE CHANGE

SO_2 Concentration (ppm)	SO_2 Concentration Change (ppm)	Meter Change (ppm)
0.31 → 0.25	0.06	0.07
0.25 → 0.18	0.07	0.21
0.18 → 0.31	0.31	0.25

Standard deviations for a series of measurements of various SO_2 concentrations have been calculated, and these are tabulated below as a lower limit on the minimum detectable change. Thus, at best, the minimum detectable change is concluded to be approximately 0.6 ppm at 3 ppm, 1 ppm at 7 ppm, and 3 ppm at 15 ppm.

STANDARD DEVIATIONS OF CEA RESPONSES

$\bar{X}$ (ppm)	Deg. of Freedom (n-1)	(ppm)
0.88	15	0.14
1.9	14	0.34
3.2	10	0.59
6.6	12	0.99
15.3	23	2.8

2.2.3.6 Linearity: The linearity of the CEA meter is illustrated in the data of Fig. 10. In these data, each point is an average of three individual measurements in keeping with the manufacturer's recommendations. A line-of-best-fit as determined by a linear regression analysis is fitted to these data, and an ideal response line is also included. The line-of-best-fit has a y-axis intercept at -0.13 ppm, a slope of 0.86, and a correlation coefficient of 0.97. The maximum deviation from the line-of-best-fit is 2.6 ppm at 17.7 ppm or 13 percent of the 20 ppm scale. The maximum deviation from the true value occurs at 17.7 ppm and is 4.6 ppm or 23 percent of the 20 ppm range. It is significant that the line-of-best-fit is 15 percent lower than the ideal response line.

2.2.3.7 Humidity Effects: The effect of humidity on the CEA was measured by recording the meter's response to a mixture of 17.7 ppm SO_2 from a permeation tube at 1 l/min. and 1 l/min. of zero air and, therefore, the resultant 8.85 ppm mixture was very dry. The meter's response, established by averaging several readings, was 8.2 ppm. The zero air portion of this mixture was then diverted through bubblers to saturate it with moisture and yield a resultant 8.85 ppm mixture with a

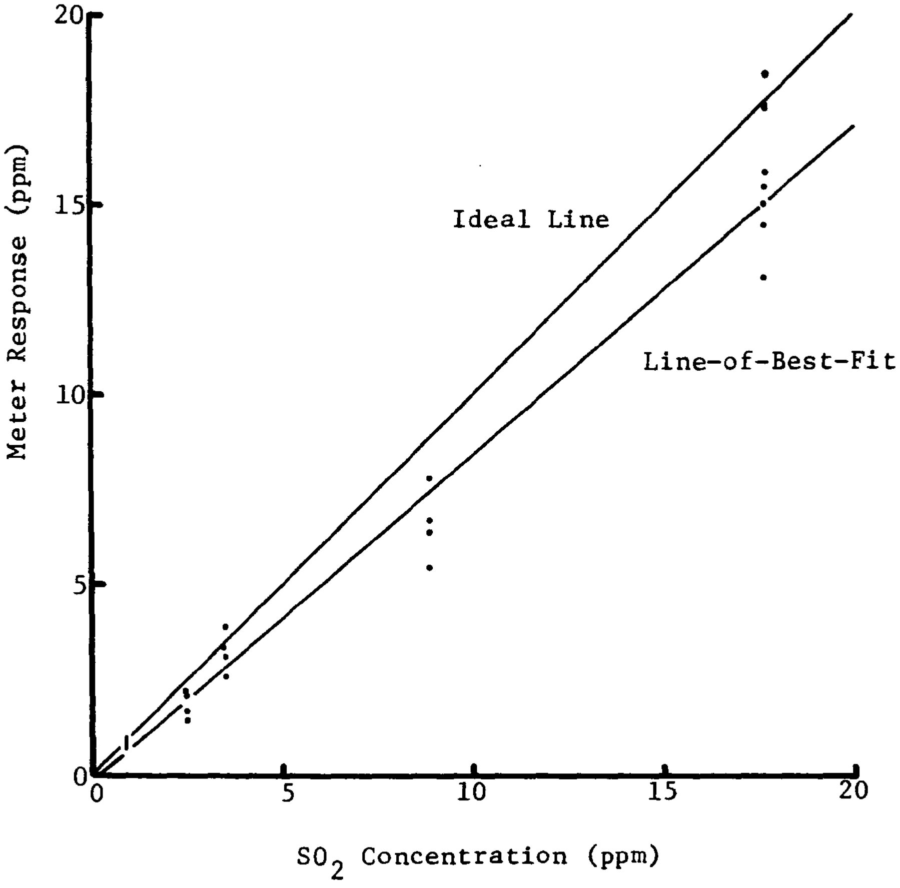

Figure 10. CEA Linearity Data

relative humidity of 50 percent. The meter's average response to the humidified mixture was 8.8 ppm. This difference is negligible when compared to the expected scatter in the data and it is concluded that the CEA is not sensitive to humidity.

2.2.3.8 Temperature Effects: The effect of temperature changes on the CEA meter was evaluated by averaging its responses to a 17.7 ppm SO_2 concentration at 25°, 40°, and 15°C. Differences between the three averages were comparable to the standard deviation of the individual measurements about the average, as shown by the data tabulated below. Thus, it is concluded that temperature effects on the CEA meter are negligible.

CEA TEMPERATURE EFFECTS

Temperature	Average $\bar{X}$	Standard Deviation σ
25°C	14.0 ppm	1.1 ppm
40°C	13.1 ppm	0.5 ppm
15°C	12.5 ppm	0.8 ppm

2.2.3.9 Interferences: The effects of several interferences were measured by one of the methods described in Section 1.4.11 of this report. Interferences investigated were water vapor, ozone (O_3), methane (CH_4), carbon monoxide (CO) and nitrogen oxide (NO). Of these, only NO caused a significant change in the response of the CEA meter. A concentration of 8.8 ppm SO_2 and 24 ppm NO decreased the CEA readout from 8.2 ppm to 7.2 ppm which corresponds to an interference equivalent of -24:1. The low concentration of NO, the small response, and the imprecision characteristic of the CEA cast considerable uncertainty on this value. Also, the low ppm concentration characteristic of the other interferences tested lead one to conclude that some of these may also be interferences but with relatively large interference equivalent ratios.

2.2.3.10 Other Performances: Zero and span drifts were not measured for the CEA. The CEA is not a continuously sampling meter. It operates on a fixed sample and provides a readout for that sample within a few minutes, and the zero setting is routinely adjusted during each measurement. Thus, span and zero drifts have no significance for the CEA. It was observed that the range adjustment, which is actually an electronics gain adjustment in the CALIBRATE mode, was very stable.

2.2.4 Physical Characteristics

The CEA is one of only two portable SO_2 meters evaluated. It is a very unique meter, as described in Sections 2.2 and 2.2.1 of this report.

2.2.4.1 Portability: Attributes of the CEA which influence its portability are tabulated below:

CEA PHYSICAL ATTRIBUTES

Weight: 7 lb
(3.2 kg)

Size: 12.5 x 4.5 x 7.5 in.
(31.8 x 11.4 x 19 cm)

Volume: 0.24 ft^3
($6.9 \times 10^{-3} m^3$)

Batteries: Internal, pen cell batteries, not rechargeable in the meter. (Battery life is enhanced by a hand-operated, spring-powered pump.)

Additionally, the electrolyte cell can be demonstrated to have a very long life. The cell consists of a 180 ml reservoir, and a 0.3 ml aliquot is isolated for each measurement. If each aliquot were 50 percent expended by a single sample, the cell would provide for more than 300 individual samples or 100 measurements of SO_2 concentration.

2.2.4.2 Readout: The CEA readout is a linear-scaled, mirrored meter movement. The meter has two scales, and the full scale range can be adjusted to either 0.5, 1, 2, 5, 10, or 20 ppm SO_2. The range adjustment is entirely an electronic adjustment. The meter scale can be read to 1 percent of full scale. It does not have a recorder output.

2.2.4.3 Instruction Manual: The instruction manual for the CEA meter was evaluated according to the criteria of Section 1.5.3 of this report, and the results are summarized in the tabulation that follows. In general, the manual was poorly organized and lacked some specific features such as schematics, a tabulation of interference equivalents, and a discussion of the electrolyte life. Most of the essential features were included and were acceptable.

CEA MANUAL RATING

Essential Features: 66%

Desirable Features: 55%

Useful Features: 50%

Overall Rating: 62%

2.2.4.4 Ease of Operation: The CEA meter is simple to operate. Initially, the mode switch provides for determining the batteries' status and the full scale range which can be adjusted if necessary. The hand pump is operated several times to return the previously used aliquot of electrolyte to the reservoir and thoroughly mix the electrolyte. The pump is allowed to return to an intermediate position which isolates an aliquot of the electrolyte in a sample cell, and the electronics is balanced until the initial conductivity of the aliquot reads zero on the meter. The pump is then released to return to a rest position. In returning, the pump pulls a 100 ml air sample to the sample cell and the meter reads the change in the conductivity of the aliquot. The meter reading and range setting determine the SO_2 concentration. The manufacturer recommends than an average of 3 readings be used rather than a single reading as a SO_2 measurement.

2.2.4.5 Ease of Zero and Span Adjustments: Zero adjustments and span checks or adjustments are a routine part of the CEA's operation. These are electronic adjustments and are readily made without requiring either zero or calibration gases.

2.2.4.6 Ruggedness: The CEA meter is well constructed and can be handled and transported with only reasonable care. The meter does have an electrolyte cell which restricts orientation somewhat, but this is not a significant handicap. It is easily the most portable of the meters evaluated.

2.2.4.7 Intrinsic Safety: The CEA is concluded to be intrinsically safe. The meter operates from dry cell batteries, and the voltage potentials are positive and negative 6 volts. The H_2O_2 electrolyte cell has a drain tube that could potentially be dislodged to drain the cell, but this would not be particularly hazardous to an operator or bystander.

2.2.5 Recommended Use Technique

The manufacturer recommends several operations of the hand-pump, that three readings be averaged for a single measurement, and that the meter be read after sufficient time for the meter to reach a reasonably stable value. These recommendations should be followed. Further, the meter should be read between 4 and 4 minutes after the pump is released.

2.3 EM

The EM meter, shown photographically in Figure 11, was the only direct-reading meter included in this evaluation program. It reads the SO_2 concentration of the inlet sample directly in ppm on one of three meter ranges, i.e., a 0 to 10, 50, or 100 ppm range. It also has a recorder output. The meter is light and readily transportable; however, it requires a 60 Hz power source and a separate pump or sample "control module" for operation. It also requires a significantly long warm-up time which detracts from its use as a portable meter.

The EM meter consists of an analyzer module into which the sensor cell, called a faristor, is inserted. A separate sample conditioning module, which is basically a pump to provide a constant gas flow to the analyzer module, is marketed by the manufacturer. Only the analyzer module with a SO_2 faristor was evaluated during this program. The calibration gases were caused to flow through the faristor sensor directly from the gas cylinder.

2.3.1 Principle of Operation and Description

The sensor in the EM SO_2 analyzer, the faristor, is basically a polarographic electrochemical cell. The cell current is generated by charge transfer of the reactant species (SO_2) at the surface of an externally biased electrode and is directly proportional to the concentration of SO_2 in the region of the electrode. The linear relationship between cell current and SO_2 concentration requires a diffusion limiting condition, i.e., a charge transfer rate limited by the concentration gradient in the thin liquid film enveloping the electrode or, more precisely, the arrival rate of the SO_2 molecule to the electrode surface. Response, sensitivity, and selectivity in this type of cell is determined to some extent by the membrane separating the sample stream and electrode.

The faristor socket in the EM analyzer module is in essence an oven to maintain the faristor sensor at a constant temperature. For continuous use, the heater power (controlled from a front panel switch) should be left continuously ON. Warm-up time for the sensor to reach thermal equilibrium is 2 to 3 hours (preferably overnight). However, the meter can be used without the heater for short-term measurements. During these evaluations, the meter was operated with the heater power ON.

Figure 11. Photograph of the EM Meter

The voltage bias on the faristor is provided by an internal mercury battery. The battery status can be determined by a momentary contact switch on the meter's front panel. A socket is also provided in the analyzer module for a spare faristor in which the spare is maintained at the proper voltage bias. This provides for a rapid null or zero condition when the spare is transferred to the faristor slot.

2.3.2 Test Facilities and Procedures

The EM meter does not provide an internal sampling system, but a separate module is marketed by the manufacturer for this purpose. To use the EM meter without a pump module, it is only necessary to provide for the correct flow of air sample through the faristor sensor. The configuration illustrated in Figure 12 was used for this purpose. The gas cylinder pressure forced the flow which was controlled with the needle control valve and measured with the rotometer. When a permeation tube source was used, the zero air cylinder pressure provided for an adequate sample flow.

2.3.3 Performance Characteristics

Performance characteristics for the EM meter are discussed in the following paragraphs.

2.3.3.1 Accuracy of the Manufacturer's Calibration: The accuracy of the manufacturer's calibration was checked by allowing the meter to warm-up with the faristor heater power ON and sampling certified SO_2 calibration gases. These results are tabulated below.

EM MANUFACTURER'S CALIBRATION ACCURACY

SO_2 Concentration (ppm)	Number of Observations	Average Reading (ppm)	Maximum Deviation (ppm)	Standard Deviation (ppm)
49	3	50	4	3
28	3	25.3	3	0.6
0.92	3	1.1	0.55	0.5

The tabulation includes the SO_2 concentration of the calibration gas, the number of measurements made, the average value of the meter's response, the maximum deviation from the certified calibration gas and the standard deviation of the individual readings about the average. The average responses differed

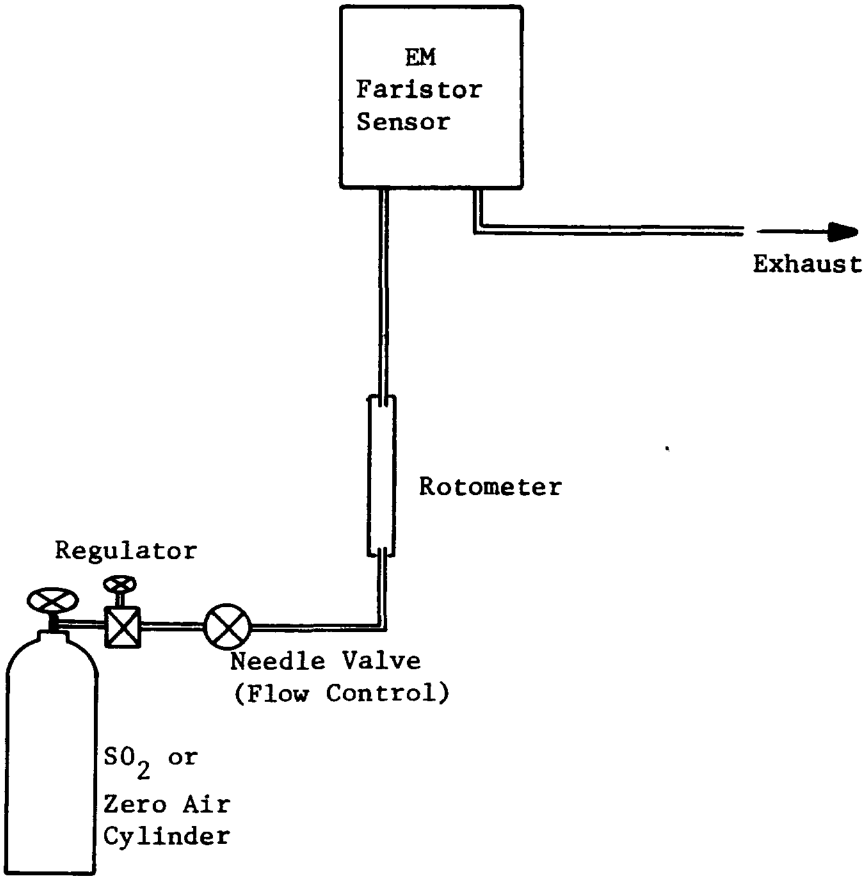

Figure 12. Gas Flow System for the EM Meter

from the calibration gases by 2, 10, and 20 percent of reading at 49, 28, and 0.92 ppm SO_2, respectively. As a percent of the 50 ppm scale, these differences were 2, 5, and 0.4 percent, respectively.

2.3.3.2 Warm-Up Time: The warm-up time specified by the manufacturer is 30 minutes. If the faristor heater is used, the recommended warm-up time is a minimum of 2 to 3 hours (preferably overnight). Without the heater, observed warm-up times varied significantly and were a maximum of about 30 minutes after long periods of OFF time. In all cases, the 30 minute period recommended was adequate. When the heater was turned ON at the same time as the analyzer power, the meter could still be used after 30 minutes. Use of the heater did not change the characteristics of the meter significantly for most use conditions. Thus, a warm-up time of 30 minutes is adequate for most purposes with or without the heater.

2.3.3.3 Response Times: The response of the EM meter to step changes in the input concentration were very rapid. Measured 90 percent responses to step increases and decreases in the input concentration were less than 7 seconds. These measurements also reflect the measurement method; i.e., the step change in the input concentration was generated by physically moving the sample inlet line from one source to a second source. Lag times were very short, i.e., less than 1 second. These responses are tabulated below.

EM RESPONSE TIMES

90% Response (+)	< 7 seconds
Lag Time	< 1 second
90% Rise	< 7 seconds
90% Response (-)	< 7 seconds
90% Fall	< 7 seconds

2.3.3.4 Zero Drift: Zero drift was measured by placing the EM meter in operation and sampling a zero gas on the 0 to 10 ppm range over a 24-hour period. The heater power was ON, and the zero was off-set up-scale to provide for the detection of negative drifts. A strip chart recorder.

was used to continuously monitor the EM meter, and the meter movement was recorded periodically. A tabulation of hourly readings is included below. Since both the strip chart recorder and the meter were off-set up-scale, the initial recorder reading is assumed to be 1.0 ppm SO_2 also. The recorder output is 100 mV full-scale or 0.1 ppm/mV on the 10 ppm scale. Using this factor for conversion, the recorder output is tabulated in both mV and ppm SO_2. From the recorder output, the maximum zero drift was 0.3 ppm or 3 percent of the 10 ppm scale. The average drift recorded in the table is 0.136 ppm (≃1 percent of scale) and the standard deviation about the average is 0.09 ppm.

2.3.3.5 Span Drift: Span drift was measured by placing the EM meter in operation and sampling a 17.7 ppm SO_2 calibration gas on the 0 to 50 ppm range over a 24-hour period. The meter's response was monitored continuously with a strip chart recorder. A tabulation of hourly readings from the strip chart record is included below. The maximum drift observed was -2.75 ppm or 5.5 percent of the 50 ppm scale. The average recorded in the table is 1.87 ppm, and the standard deviation about the average is approximately 1 ppm.

2.3.3.6 Calibration Stability: The calibration stability of the EM meter was excellent and there was seldom any need to readjust the span or calibration. The calibration stability is illustrated by the data tabulated below. These data indicate that the calibration drift over a 2-week period is not significantly different from drifts during a single day, and is a maximum of approximately 4 percent of reading or 4 percent of the 50 ppm scale.

2.3.3.7 Minimum Detectable Change: Tabulated below are several SO_2 concentration changes and corresponding meter reading changes. These results suggest that the minimum detectable change is about 20 percent of the 10 ppm scale and about 4 percent of the 50 ppm scale, i.e., about 2 ppm.

EM ZERO DRIFT

Time (hours)	Meter (ppm)	Strip Chart	
		(mV)	(ppm)
0	1.0	19.5	1.0
1	0.95	18	0.85
2	1.0	18.5	0.90
3	1.0	18.5	0.90
4	1.0	18.5	0.90
5	1.0^+	19	0.95
6		19.5	1.0
7		19.5	1.0
8		20	1.05
9		20	1.05
10		20	1.05
11		20.5	1.1
12		20.5	1.1
13		21	1.15
14		21	1.15
15		21.5	1.2
16		22	1.25
17		22	1.25
18		22	1.25
19		22.5	1.3
20		22.5	1.3
21	1.3	22	1.25
22	1.2	21	1.15
23	1.2	21	1.15
24	1.2	21	1.15

EM SPAN DRIFT

Time (hours)	Span Drift (ppm from 18 ppm)
0	0
1	-0.25
2	-0.25
3	-0.75
↓	↓
8	-0.75
9	-1.25
10	-2.5
11	-2.75
↓	↓
16	-2.75
17	-2.5
18	-2.5
19	-2.75
↓	↓
24	-2.75

EM CALIBRATION STABILITY EVALUATION

Date	SO_2 Cal. Gas (ppm)	Meter Responses (ppm)	Average Response (ppm)	Change %
11/1/73	49	48,47	48.5	
	28	27,26,27	26.7	1%(49 ppm)
11/13/73	49	48,49,50,49	49	3.6%(28 ppm)
	28	27,27,29	27.7	
1/9/74	49	49,48,47.5 48,47.5,47.5	48	
	28	27,26.5,26.5 26.5,27	26.7	3%(49 ppm)
1/23/74	49	49,50	49.5	1.6%(28 ppm)
	28	26.5,26	26.5	

EM MINIMUM DETECTABLE CHANGE

SO_2 Concentration (ppm)	Concentration Change (ppm)	Meter (ppm)	Meter Change (ppm)
0.44 → 0.51	0.07	0.4 → 0.5	0.1
0.92 → 0.46	0.46	0.95 → 0.5	0.45
9.2 → 10.1	0.9	7.85 → 8.15	0.3
10.1 → 11.1	1.0	8.15 → 8.3	0.15
12.3 → 14	1.7	14 → 13.5	0.5
25.8 → 24.5	1.3	24 → 22.5	1.5
24.5 → 23.3	1.2	22.5 → 22	0.5
23.3 → 25.8	2.5	22 → 25	3.0
28 → 24.5	3.5	27 → 23	4.0

2.3.3.8 Linearity: Linearity data for the EM meter are plotted in Figure 13 and a line-of-best-fit as determined by a linear regression analysis is fitted to these data. For each value of calibration gas, the meter reading from the most appropriate scale is plotted. The meter was not calibrated prior to taking these data, but its response to zero and 49 ppm calibration gases were checked and found to be 0 and 46.5 ppm, respectively. The line-of-best-fit has a y-axis intercept at 0.7 ppm, a slope of 0.93 and a correlation coefficient of approximately unity. The maximum deviation from the line-of-best-fit occurs at 12.3 ppm. This is 16 percent of reading or 4 percent of the 50 ppm scale. The average deviation of the 11 data points from the line-of-best-fit is 0.56 ppm.

Each of the calibration gas concentrations sampled for the preceding linearity data was read on each of the 3 meter scales that had an adequate range. For example, the 7 ppm SO_2 calibration gas was read on the 10, 50, and 100 ppm scales. These data are tabulated below to provide for comparing the agreement between the 3 meter scales. These results show excellent agreement between scales. The only significant differences are at low concentrations where the scale resolution is an obvious factor.

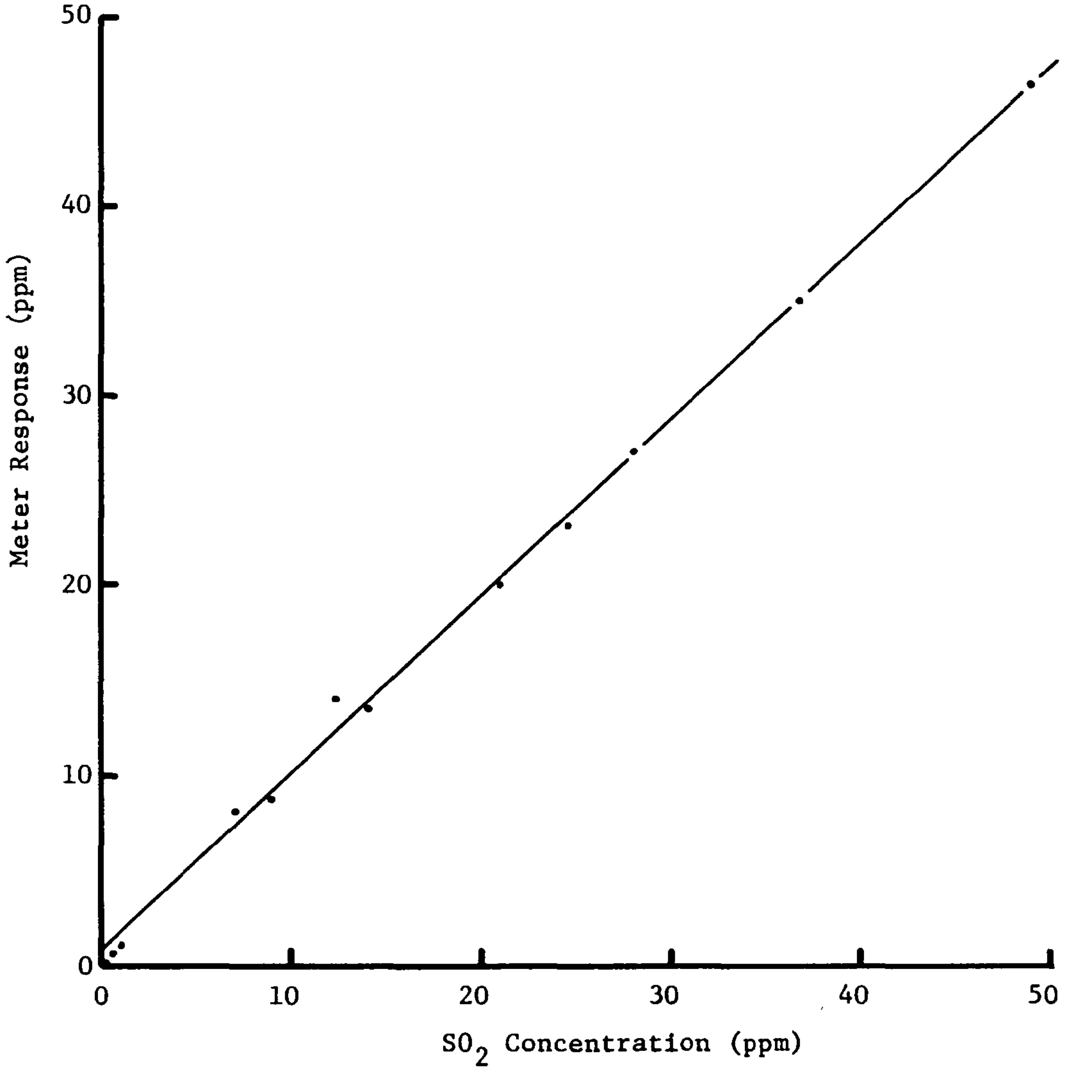

Figure 13. EM Meter Linearity Data

EM SCALE COMPARISON DATA

SO_2 Cal. Gas (ppm)	Meter Readings 10 ppm Scale (ppm)	50 ppm Scale (ppm)	100 ppm Scale (ppm)
0.46	0.5	0.75	1
0.92	0.95	1.0	1.5
7	8.1	8.0	8.5
8.85	8.7	8.5	9.0
12.3		14	14
14		13.5	13.5
21		20	20
24.5		23	23
28		27	27
36.8		35	35
49		46.5	46.5

2.3.3.9 Humidity Effects: The EM meter was evaluated for sensitivity to humidity by the method of Section 1.4.9 of this report. Changing the relative humidity of the 24.5 ppm SO_2 sample from approximately 0 to approximately 50 percent did not cause a detectable change in the meter's response. Thus, the EM meter is concluded to be insensitive to humidity changes.

2.3.3.10 Temperature Effects: The EM meter was evaluated for temperature effects by the method of Section 1.4.10 of this report. These measurements were made with the faristor heater ON. The meter's response to a 17.7 ppm mixture of SO_2 in air was sampled while the laboratory temperature was controlled and stabilized at 15°, 25°, and 40°C. The meter's response changed by 2 ppm between the temperatures of 15° and 40°C. Linearized, this is a change of 0.08 ppm/°C.

2.3.3.11 Interferences: Interference equivalents for the several interferences tabulated below were measured by one of the methods of Section 1.4.11 of this report. All of these measurements were made using the 0 to 50 ppm range, and a minimum detectable change of 2 ppm is used to estimate an upper limit on the interference equivalent.

Water Vapor: As discussed in Section 2.3.3.9, water vapor was a negligible interference.

Methane (CH_4): A 50 ppm concentration of methane did not cause a detectable change in the response of the EM meter. Thus, its interference equivalent is greater than 50:1.

Carbon Monoxide (CO): A 50 ppm concentration of CO did not cause a detectable change in the EM meter. Thus, its interference equivalent is greater than 50:1.

Nitrogen Oxide (NO): A 24 ppm concentration of NO did not cause a detectable change in the EM meter. Thus, its interference equivalent is greater than 24:1.

Hydrogen Sulfide (H_2S: A 100 ppm concentration of H_2S caused a positive 3.8 ppm response in the EM meter on the 0 to 10 ppm scale. Thus, its interference equivalent is 26:1.

Ozone (O_3): A 7.5 ppm concentration of ozone caused a 25 ppm decrease in the response of the EM meter. Thus, its interferences equivalent is -0.3:1.

2.3.4 Physical Characteristics

2.3.4.1 Portability: Although the EM meter is reasonably light, a long warm-up time (30 minutes), the requirement of a 60 Hz power source and the lack of an internal sampling system detract from its portability. Physical attributes which influence the EM portability are tabulated below:

EM PHYSICAL ATTRIBUTES

Weight:	15 lb (6.8 kg)
Size:	6.5 x 13.5 x 12.8 in. (16.5 x 34.3 x 32.5 cm)
Volume:	0.65 ft^3 ($1.8 \times 10^{-2} m^3$)
Batteries:	Operates from 60 Hz line only.
Other:	Requires external sample pump.

2.3.4.2 Readout: The EM meter is the only SO_2 meter included in this evaluation that reads the SO_2 concentration in the air sample directly. A front-panel, mirrored meter movement is linearly calibrated in 0 to 10, 50, or 100 ppm SO_2. The scale is selectable from a front-panel control. The meter is readable to 0.05 percent of full scale. A rear-panel recorder output is also available that is proportional to the meter movement. The recorder output is continuously variable with a rear-panel control between 0 and 100 mV for a full-scale meter deflection.

2.3.4.3 Instruction Manual: The EM instruction manual was evaluated according to the criteria of Section 1.5.3 of this report. Specifically, the manual lacked tabulated specifications, flow and schematic diagrams, and a parts list, for example. Its rating in the several categories of Section 1.5.3 are tabulated below:

EM MANUAL RATING

Essential Features:	62%
Desirable Features:	53%
Useful Features:	25%
Overall Rating:	55%

2.3.4.4 Ease of Operation: With the exception of handling the air sample, which must be done separately, the EM meter is very easy to operate. There are relatively few controls, and the direct readout eliminates any necessity for interpreting the data. The front-panel meter also indicates the bias battery condition at the push of a button switch, and sensor replacement (if necessary) is easily accomplished. The recorder output on the rear panel is easily adjusted to interface with a variety of recorders.

2.3.4.5 Ease of Zero and Span Adjustments: Zero and span adjustments are easily accomplished with the EM meter. Two front-panel controls are operated to set the zero and span. The two are interrelated in that a zero adjustment also changes the span. However, the inverse is not true and it is only necessary to adjust the zero first. Both zero and calibration gases are required for these adjustments and they cannot be accomplished in a contaminated atmosphere. Provisions must also be made to control the flow of zero and calibration gases externally. This problem is circumvented by the use of the control module available from the EM manufacturer.

2.3.4.6 Ruggedness: The construction features of the EM meter are such that it should be suitable for shipping, transporting, and handling without special precautions or concerns. The faristor sensor is a small, sealed unit and does not contain a significant amount of fluid to restrict orientation; the analyzer module is essentially an electronic instrument.

2.3.4.7 Intrinsic Safety: The EM meter is concluded to be intrinsically safe. The faristor sensor is a sealed unit, and there are no toxic or hazardous materials accessible from its exterior. The sensor is installed in the analyzer from the rear panel, and the analyzer chassis is completely enclosed.

2.3.5 Recommended Use Technique

It is generally recommended that the manufacturer's instructions regarding the operation of the EM meter be followed. It is also concluded that the control module marketed by the EM manufacturer would significantly enhance the usefulness of the meter. (Since all of the gases sampled by the EM meter during this evaluation came from pressurized cylinders, the lack of the control module was not a disadvantage.)

The EM meter is not suitable as a portable SO_2 meter if the NIOSH guidelines are used as criteria. However, it could be used as such provided a suitable pump--e.g., the control module marketed by the manufacturer--and 60 Hz power was available. If it is used as a portable monitor and, thus, frequently moved from site to site, the heater power for the faristor should be left OFF. If the EM meter is used as a continuous monitor or for long periods, the heater power should be left ON.

2.4 Mast

The Mast SO_2 meter is shown in the photograph of Figure 14. The meter is a prototype; however, it is a modification of the Mast ozone meter and will soon be in production. In addition to the meter readout like that in Figure 14, the Mast meter also has a recorder output.

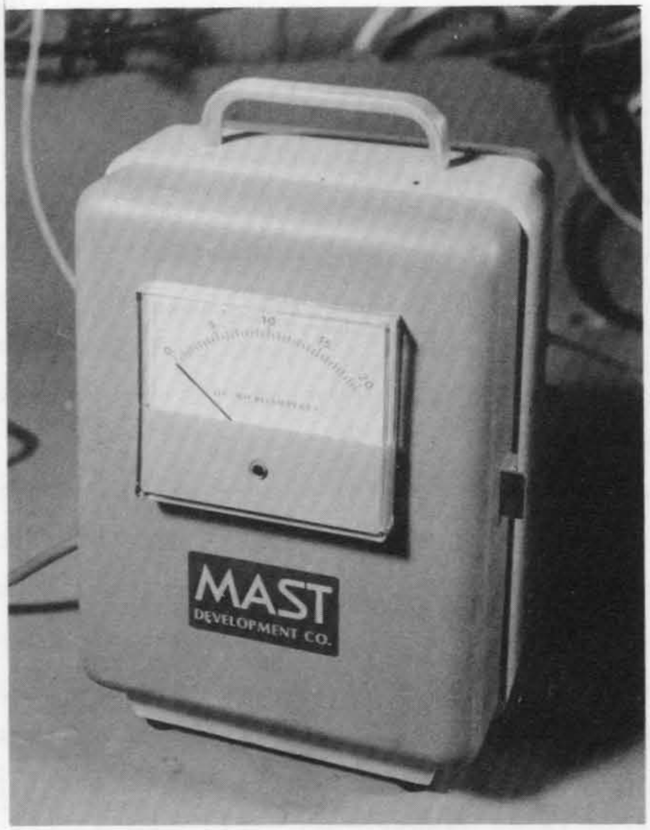

Figure 14. Photograph of the Mast SO_2 Meter

A single switch located behind the hinged front panel turns the meter ON to either the front-panel meter readout or the recorder readout. This one switch is the only control on the Mast meter.

In view of the criteria for selecting meters, the Mast is not a suitable meter for this evaluation program. It does not have a direct readout and it is not portable. The meter requires a 60 Hz source for operation and requires an extremely long warm-up time which would interfere with moving the meter from one site to another for SO_2 measurements. It is more suitable as a continuous, on-line meter.

Evaluation of this meter was complicated by several factors. A significant span drift complicated analysis of data that was acquired over a period of time. Moreover, the meter output was nonlinear with SO_2 concentrations and resolution was poor at high SO_2 concentrations. The meter's performance characteristics would be significantly improved if it were evaluated over a lower range; however, it was evaluated over the 0 to 50 ppm SO_2 range.

It has been noted that the operator has an option of either a meter readout or a recorder readout. The meter movement read approximately 5 μA dc or 25 percent of scale for a 49 ppm SO_2 concentration. In general, the recorder output was preferred and used throughout most of the evaluations. The recorder output could be ranged from approximately 5 mV to 32 mV for a 49 ppm SO_2 concentration by varying the terminal resistance from a 2 to 10 kΩ setting. This mV output for a given concentration was demonstrated to be linear with variations in the range resistor. The 2 kΩ setting was used for most of these evaluations for convenience in interfacing with a 10 mV recorder.

2.4.1 Principle of Operation and Description

The Mast meter is basically a coulometric meter. A sulfur dioxide sensor solution and the sample are brought into intimate contact at a cathode, and current flow between the cathode and an anode is an indication of the SO_2 concentration in the sample. The sample air flow rate can be adjusted by changing a gear set, and was set for approximately 170 ml/minute. The actual value is not critical since the meter has to be calibrated for each flow rate. The 250 ml reservoir of the sulfur dioxide sensor solution last for a long period and did not diminish significantly during the evaluation period.

No further description is available for the Mast meter. The meter is a prototype, and the instruction manual provides only brief introductory material and refers to a manual for the Mast ozone meter. Hardware and components in the Mast meter appear to be identical to the Mast ozone meter.

2.4.2 Test Facilities and Procedures

The Mast meter was left continuously ON as the manufacturer suggests. It was connected to either the SO_2 manifold or the zero air manifold by a flexible Teflon tube. Other than the OFF-ON (remote or meter) switch, no other adjustments or controls were accessible to the operator.

2.4.3 Performance Characteristics

Performance characteristics of the Mast meter measured during these evaluations are described in the following paragraphs.

2.4.3.1 Accuracy of the Manufacturer's Calibration: No calibration data was supplied with the Mast meter and, consequently, the accuracy of the manufacturer's calibration could not be evaluated. Efforts to generate a calibration curve were complicated by a span drift and a long recovery time after the meter was returned to a zero air sample. A representative calibration curve is given in Figure 15. This curve was generated from data taken over a period of several days and includes only data resulting from changing the sample SO_2 concentration from 0 to 28 ppm, for example, then back to zero air again. The data points at 0.92, 28, and 49 ppm concentrations are an average of approximately 11 data points at each concentration, and the vertical bar at each data point represents one standard deviation of the distribution about the mean. A more definitive curve may result if the data is taken over a shorter time period. The manufacturer suggests that the meter be recalibrated at least weekly, and

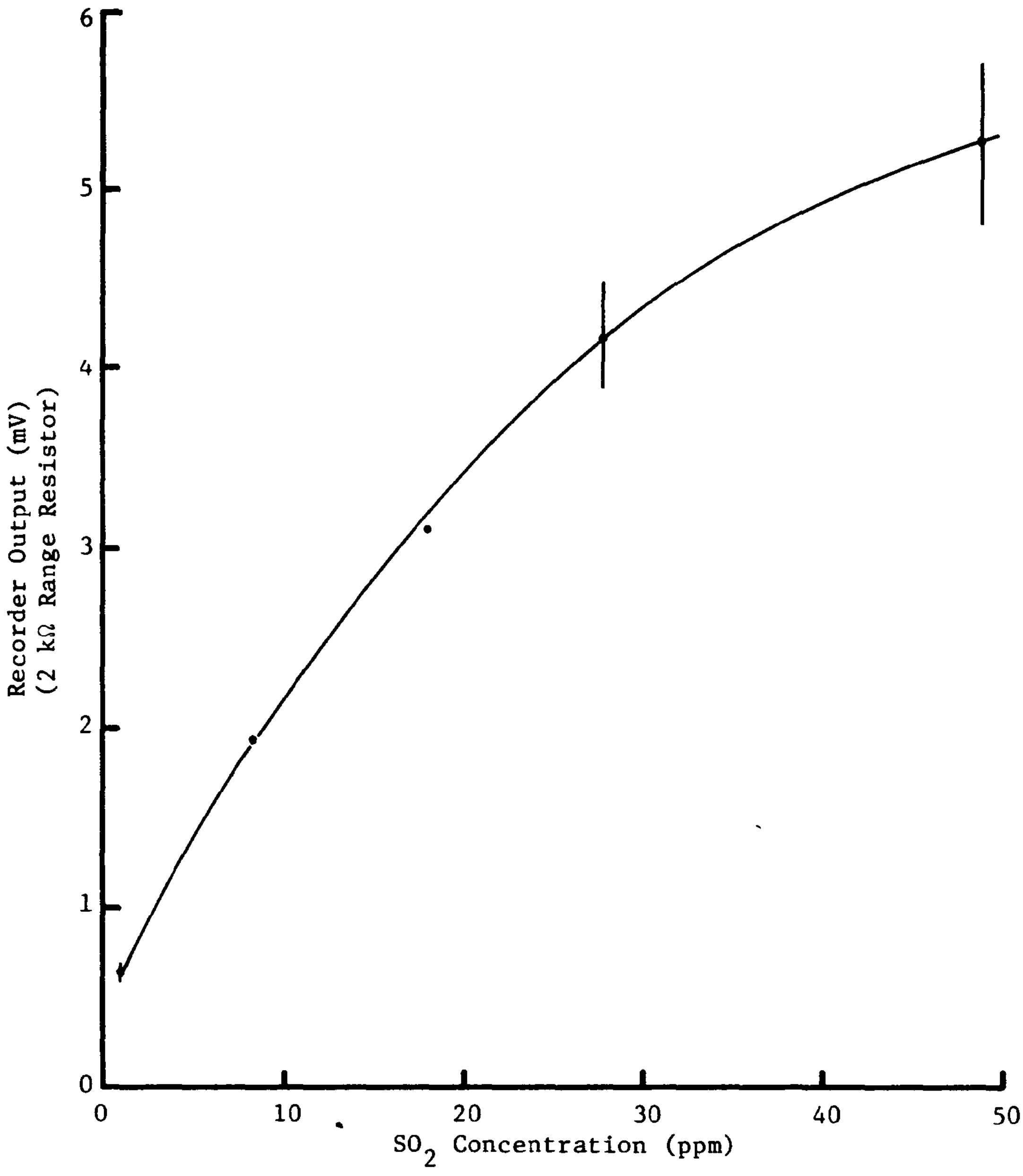

Figure 15. Mast Meter Calibration Curve

these data, taken over several days time, reflect the uncertainty that would occur between calibration. There were no obvious trends in these data.

2.4.3.2 Warm-Up Time: It is evident from the warm-up time that the Mast meter should not be considered a portable meter but, rather, a continuous monitor. The manufacturer recommends that the meter be allowed to run for a few hours on zero SO_2 gas when it is placed in operation. Observed warm-up times were approximately 120, 135, and 110 minutes.

2.4.3.3 Response Times: There are significant variations in the observed response times and, consequently, it is difficult to specify a value. In all instances, the lag times observed were small, e.g., approximately 10 seconds. The response to a step increase in SO_2 concentration depends on the magnitude of the step increase. If the step increase is small (e.g., 0.92 ppm), the 90 percent response time is 30 seconds If the step increase is large (e.g., 49 ppm), the recorder output will reach 90 percent of its final value in approximately 20 seconds; however, it will overshoot its final value and return to 110 percent of its final value in approximately 1 minute. Figures 16 and 17 illustrate the meter's responses to 0.92 ppm and 49 ppm SO_2 increases, respectively. It is concluded that the positive response time is approximately 1 minute.

Negative response times are strongly dependent on the sensor's previous exposure. If the step decrease is from 49 ppm to 0 ppm, for example, the 90 percent response time may vary from 2 to 20 minutes depending on the time period of exposure to the 49 ppm SO_2. A negative response time of approximately 20 minutes is concluded to be a somewhat worst-case value. Estimates of the Mast meter's response times are tabulated below:

MAST METER RESPONSE TIMES

90% Response (+) = 1 minute
Lag Time = 10 seconds
90% Rise = 50 seconds
90% Response (-) = 20 minutes
90% Fall = 20 minutes

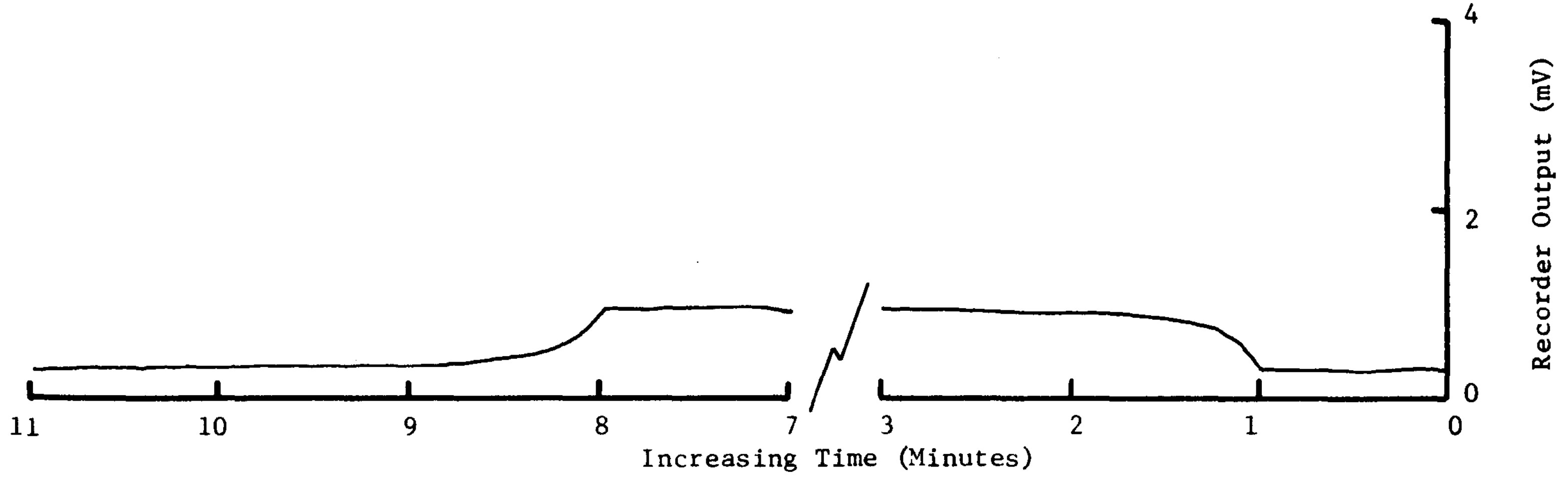

Figure 16. Mast Meter Response to a 0.92 ppm SO_2 Step Increase and Step Decrease

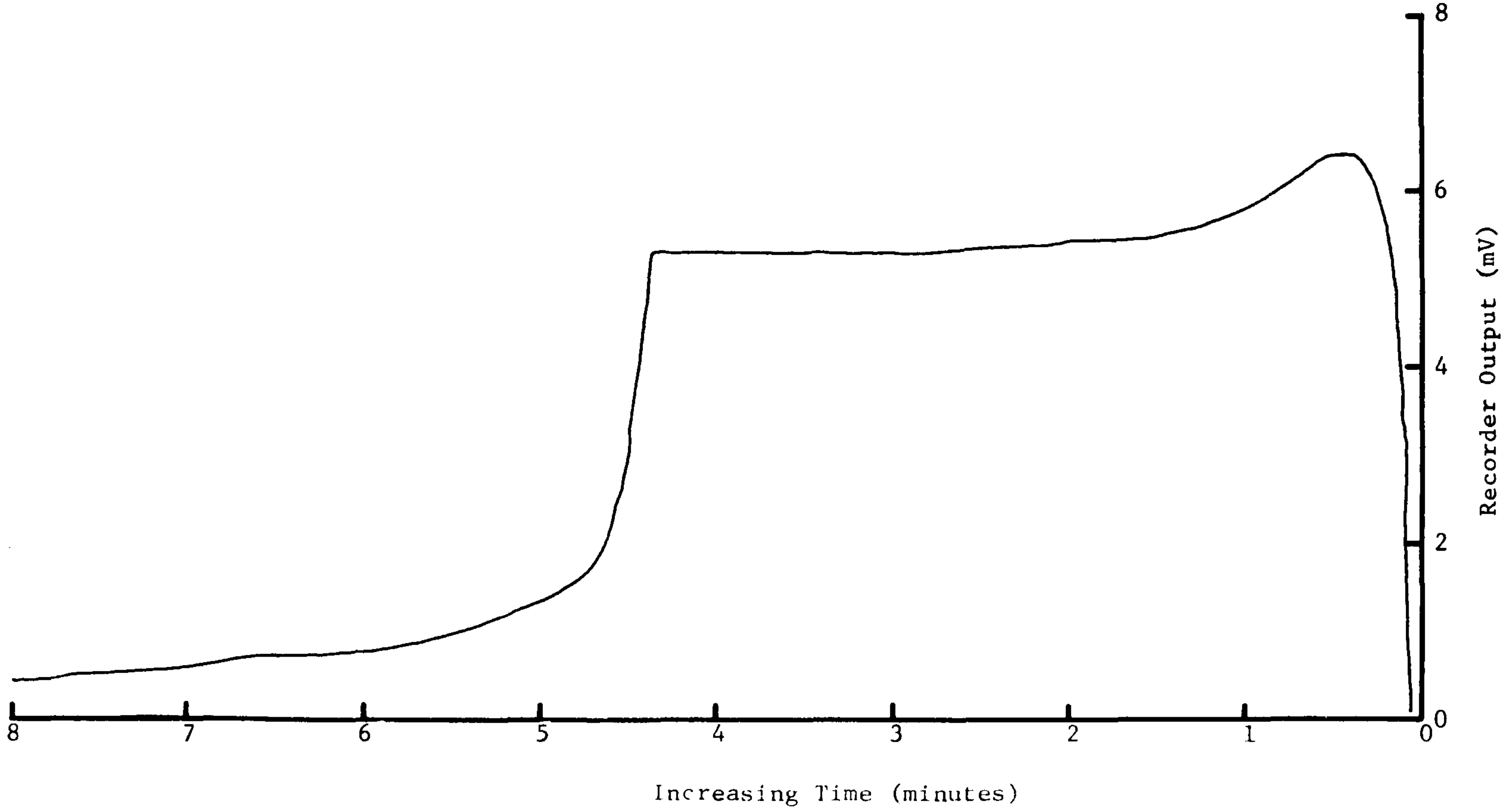

Figure 17. Mast Meter Response to 49 ppm SO_2 Step Increase and Step Decrease

2.4.3.4 Zero Drift: The zero setting of the Mast meter is very stable and does not tend to drift. Two 24-hour periods of exposure to zero air were monitored, and the maximum zero drift in both cases was less than 0.1 mV or 0.5 ppm SO_2. This zero stability is essential since no zero adjustments are made available to the operator. Under conditions of exposure to high concentrations of SO_2, however, a significant span drift occurs which is also reflected in the zero air output of the Mast meter after the exposure is terminated. (This constitutes a base-line drift that needs to be accounted for if the meter is used continuously on-line.)

2.4.3.5 Span Drift: Significant span drifts occurred in the Mast meter under conditions of constant exposure to high concentration of SO_2. Figure 18 illustrates an example of span drift during 8 hours of continuous exposure to 17.7 ppm SO_2. The drift is a 120-percent increase in the mV recorder output and corresponds to a 31 ppm SO_2 drift or 62 percent of the 50 ppm range.

2.4.3.6 Calibration Stability: The calibration stability of the Mast meter is somewhat illustrated by the standard deviation of individual data points about the average as illustrated in the calibration curve of Figure 15. However, it is explicitly evaluated by summarizing the results of measurements on certified SO_2 concentration over several days time. The recorder outputs were converted to SO_2 concentrations using the calibration curve of Figure 12. These results are tabulated below:

MAST CALIBRATION STABILITY

Calibration Gas (ppm)	Average Response over Several Days $\bar{X}$ (ppm)	Standard Deviation σ (ppm)
28	37	15
49	47	17

Much of the 28 ppm data followed exposure to 49 ppm data and, thus, was influenced by the span drift that occurred during exposure to 49 ppm SO_2. It is significant that the standard deviations about the means are approximately 38 percent of the means. If an effort is made to draw in

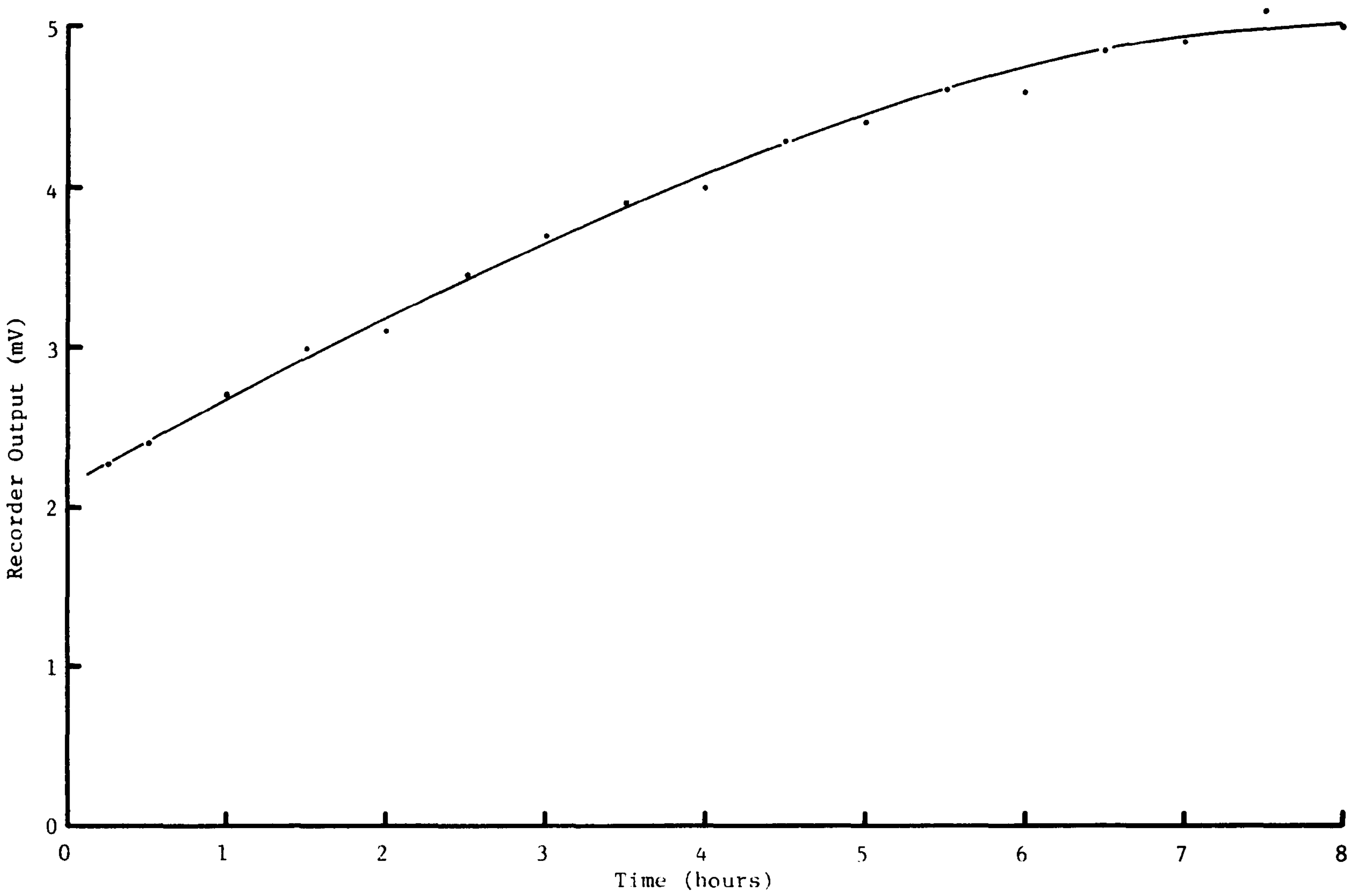

Figure 18. Mast Meter Span Drift

a base line on the strip chart and subtract out the base-line drift component in each case, the means and standard deviations become 25 ppm and 4 ppm for the 28 ppm gas, and 30 ppm and 9 ppm for the 49 ppm gas. It is probable that, over a period of several days, variations in the meter's responses to calibration gases are more attributable to other factors (e.g., span drift) than to calibration drifts. The calibration is probably reasonably stable.

2.4.3.7 Humidity Effects: Increasing the relative humidity of a SO_2 concentration of 8.85 ppm from 0 to 50 percent did not cause a significant change in the meter's output. It is concluded to be insensitive to humidity changes.

2.4.3.8 Temperature Effects: The Mast meter responses to both zero and span gases is significantly influenced by temperature changes. The zero air response changed from 1 to 2.5 to 7 ppm as the temperature was increased from 15° to 25° to 40°C. The response to a 17.7 ppm gas increased from 21 ppm to greater than 50 ppm as temperature was increased from 15° to 25°C. (The 40°C value was off the calibration curve.) Thus, the zero response is concluded to increase 0.24 ppm/°C, and the span response will increase by more than 2.9 ppm/°C.

2.4.3.8 Interferences: Interferences were measured by one of the methods described in Section 1.4.11 of this report.

<u>Nitrogen Oxide (NO)</u>: A concentration of 48 ppm of NO did not cause a significant change in the Mast output.

<u>Carbon Monoxide (CO)</u>: A 96 ppm concentration of CO did not cause a significant change in the Mast meter output.

<u>Methane (CH_4)</u>: A 100 ppm concentration of methane did not cause a change in the Mast meter output.

<u>Ozone (O_3)</u>: An ozone concentration of 7.5 ppm was a significant negative interference to the Mast meter with an interference equivalent of approximately -1:1.

<u>Hydrogen Sulfide (H_2S)</u>: Hydrogen sulfide was a relatively insignificant interference, and its interference equivalent is estimated to be 250:1.

2.4.3.9 Other Performance Characteristics: Linearity and minimum detectable change for the Mast meter were not determined.

2.4.4 Physical Characteristics

Although the Mast meter is a prototype, it utilizes much of the hardware and components of the familiar Mast ozone meter. Thus, physically, it is ready for production and will benefit significantly from the production experience with the ozone meter. It is our understanding that the meter movement readout will not be included with the production model and the output will be a recorder output. The recorder may be an integral part of the meter.

2.4.4.1 Portability: The Mast SO_2 meter is not a portable meter. Physically, it is easily transportable. However, it requires a 60 Hz power source and the warm-up time (≈2 hours) is prohibitively long for a portable meter. Other physical attributes which influence its portability are tabulated below:

MAST PHYSICAL ATTRIBUTES

Weight: 12 lb
(5.4 kg)
Size: 11.3 x 5.5 x 7.5 in.
(28.7 x 14 x 19 cm)
Volume: 0.27 ft^3
(7.6×10^{-3} m^3)
Batteries: 60 Hz source only.

2.4.4.2 Readout: The prototype Mast meter has both a meter movement readout and a recorder readout. The meter is arranged such that only one of the readouts can be used at a time. The meter movement is a 0 to 20 μA movement, and only about 25 percent of the scale (5 μA) is used for a 49 ppm concentration. It is also nonlinear with SO_2 concentrations, and resolution is very poor for high concentrations.

The recorder output is a current source and can be readily interfaced with any number of recorders by an appropriate selection of a range resistor. A convenient selection will undoubtedly be made for the production model. The recorder output is also nonlinear with SO_2 concentrations.

2.4.4.3 Instruction Manual: The Mast instruction manual consisted of several pages of introductory material and references of the Mast ozone meter manual. The ozone meter manual is a reasonably good manual; however, it is not evaluated herein as a manual for the SO_2 meter.

2.4.4.4 Ease of Operation: The Mast meter is very simple to operate. Operational controls consist of a single, 3-position switch that places the meter into operation with either a remote or meter readout. The meter is not suitable as a portable meter but, rather, should be used as a continuous, on-line monitor. If used in a continuous mode, some provisions should be made to periodically determine a base-line value corresponding to zero SO_2 concentration. This is especially true if the meter is to be exposed to high SO_2 concentrations for extended periods.

2.4.4.5 Ease of Zero and Span Adjustments: No obvious zero or span adjustments are available to the operator. (Some internal potentiometers are accessible; however, no instructions were available as to their purpose.) The zero was very stable and did not require adjustment. However, the span drift was significant under conditions of continuous exposure to high concentrations.

2.4.4.6 Ruggedness: The Mast meter was very well constructed. A reservoir of SO_2 sensor solution may limit orientation and accelerations somewhat, but would not be a significant handicap in the field environment.

2.4.4.7 Intrinsic Safety: There are no obvious safety hazards associated with the Mast meter. The content of the SO_2 sensor solution and the exhaust air sample are not known.

2.4.5 Recommended Use Technique

The Mast meter is not recommended as a portable SO_2 meter for use in the field environment. The long warm-up time is prohibitive and, if high SO_2 concentrations are to be encountered, the span drift requires some additional precautions. If it is used as a continuous monitor, provisions should be made to periodically sample a zero air (or SO_2-free gas) to determine and evaluate any span drift, i.e., baseline drift.

2.5 PAI

The PAI meter submitted for this evaluation program was calibrated for ambient air monitoring rather than for industrial atmospheres. When initially exposed to a 0.92 ppm SO_2 concentration, for example, the meter responded to read 55 percent of its full-scale output. Immediate steps were taken to extend the meter's range and it was calibrated for a 0 to 50 ppm range. Over this range, the meter's output was extremely nonlinear and span adjustments subsequent to calibrating were of questionable value. In retrospect, the meter would have been more linear and its performance characteristic significantly enhanced if it had been calibrated over a lower or intermediate range. The design of the front-panel controls and the operating instructions imply that the meter was designed for use over a reasonably linear range, and the performance characteristics of the meter would undoubtedly be significantly enhanced if its use was limited to a linear portion of its calibration curve.

The meter evaluated was not received directly from the manufacturer. It was made available for the evaluation program by a previous purchaser of the meter through the efforts of the manufacturer. It was still in its original shipping container when received by RTI. Figure 19 is a photograph of the PAI meter.

2.5.1 Principle of Operation and Description

The PAI method of SO_2 detection is based on bromine oxidation of an oxidizable sulfur compound such as SO_2 or H_2S. The bromine (Br_2) in solution is removed as a result of this oxidation-reduction and is resupplied by electrolysis of H_2SO_4 and KBr. A bromine-sensitive electrode pair (Platinum/Ag-Ag Br) develop a voltage proportional to the Br_2 level in solution. This voltage is used as a control to an amplifier which powers the two platinum electrodes of the electrolysis system used to generate the Br_2. Also generated is H_2 which is removed.

The current required by the electrolysis system is a direct measure of the Br_2 generation rate. Bromine generation is required only to supply Br_2 losses; then, if losses due to reaction with SO_2 dominate, the electrolysis current will be an effective monitor of SO_2 concentration. A bromine level less than the saturation limit is first selected. Once this level is reached, the only current required for bromine generation is that required to supply incidental bromine losses (escaping gas). Hence, the limit of detection for this system will be determined to a large extent by the rate at which bromine is lost from solution by escapement or by reaction with other compounds.

2.5.2 Test Facilities and Procedures

The PAI meter has an internal sampling pump that pulls approximately 250 ml/minute at the inlet port. Thus, for evaluation purposes, the meter was physically connected by means of a flexible Teflon tubing to either the zero air or SO_2 calibration gas manifold.

Figure 19. Photograph of the PAI Meter

2.5.3 Performance Characteristics

2.5.3.1 Accuracy of Manufacturer's Calibration: As previously discussed in Section 2.5, the PAI meter was not received directly from the manufacturer, and no calibration data was received with the meter. When it was initially placed in operation, the meter responded to read 55 percent of full scale upon exposure to a 0.92 ppm concentration of SO_2. An attempt was made to expand the range following a procedure described in the instruction manual, but the range expansion achieved was very small. The manufacturer then provided a substitute printed circuit card that enabled a significant range extension. The meter was then calibrated, and the calibration curve is included in Figure 20. The meter output is nonlinear with the SO_2 concentration, as is evident from the calibration curve.

2.5.3.2 Warm-up Time: The manufacturer recommends a warm-up time of 30 minutes. This was observed to be an adequate time.

2.5.3.3 Response Time: The PAI response times were measured by causing step changes in the input concentration and recording the PAI meter's responses as a function of time. The step changes were generated by physically moving the intake line from the zero air manifold to the SO_2 manifold or vice versa. This procedure was repeated three times for each of the response times measured. The lag times were 11, 13, and 14 seconds. The 90 percent response times of the meter movement measured in response to a step increase in SO_2 concentration were 7, 8, and 9 minutes. However, because of the nonlinear calibration curve, the corresponding 90 percent response times 18, 15, and 15 minutes. Response times measured for step decreases in the SO_2 concentration were 2.5, 2.5, and 3 minutes. Because the calibration curve is linear for low concentration, response times of the meter movement and the corresponding ppm of SO_2 readout do not differ significantly. These response times are summarized in the tabulation that follows:

PAI RESPONSE TIMES

90% Response Time (+) = 16 minutes
Lag Time = 13 seconds
90% Rise Time = 16 minutes
90% Response Time (-) = 2.7 minutes
90% Fall Time = 2.5 minutes

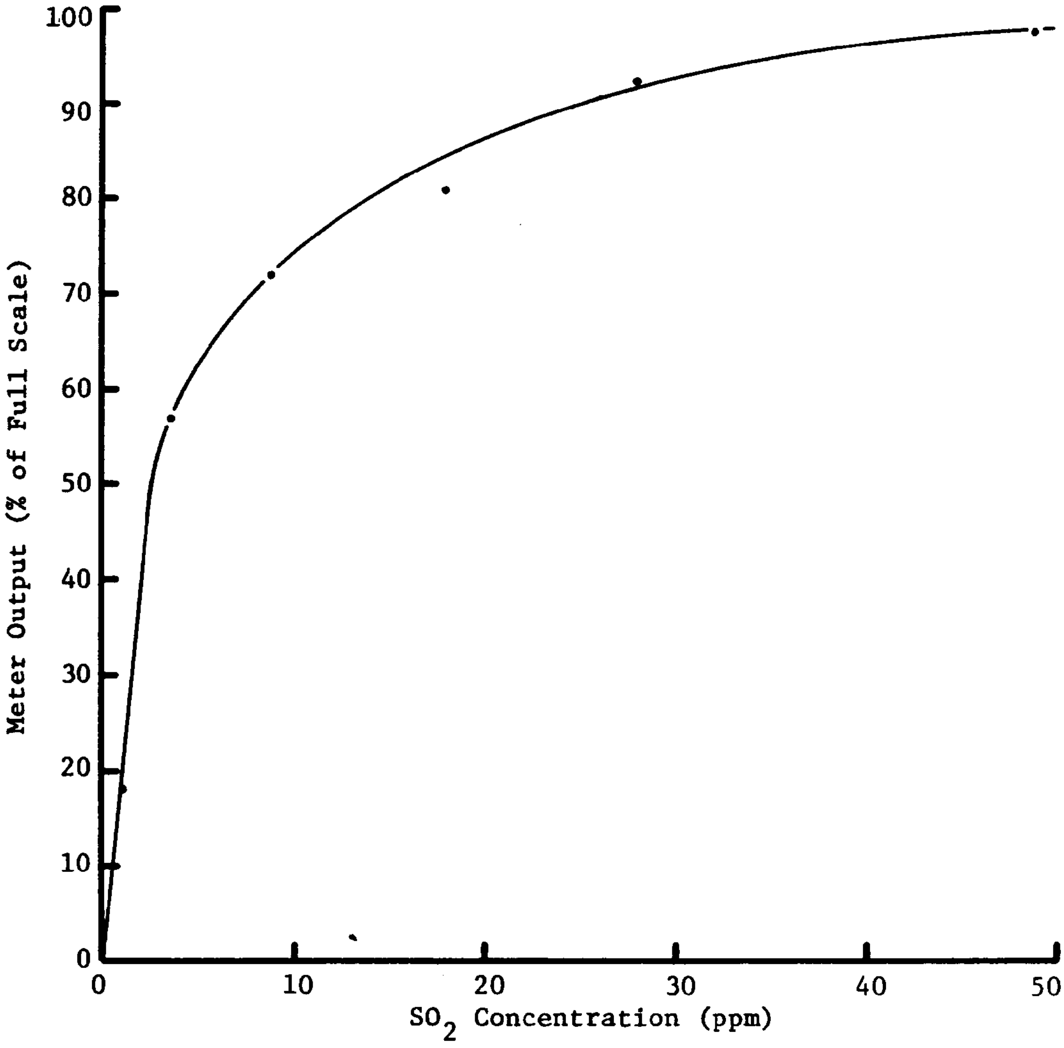

Figure 20. PAI Calibration Curve

2.5.3.4 Zero Drift: The PAI zero drift was measured by continuously sampling zero air over a period of 24 hours and monitoring the recorder output. The zero was off-set up-scale to detect any negative drifts. As a summary of these results, the recorder output was read at each hour and the following data tabulated.

PAI ZERO DRIFT DATA

Maximum Deviation from Zero Setting = 2.5% of Full Scale
< 0.14 ppm SO_2
Average Deviation from Zero Setting = 1.5% of Full Scale
< 0.08 ppm SO_2
Standard Deviation about the Average = 0.8% of Full Scale
< 0.04 ppm SO_2

Thus, the zero drift is concluded to be negligible.

2.5.3.5 Span Drift: The PAI span drift was measured by continuously sampling 17.7 ppm of SO_2 and recording the meter readout each half hour for 8 hours. These data, summarized below, show the span drift to be reasonably low.

PAI SPAN DRIFT DATA

Average Value = 13 ppm
Maximum Deviation from Average = 1 ppm
Standard Deviation about Average = 0.8 ppm

2.5.3.6 Calibration Stability: Calibration stability was evaluated by recording the meter's responses to a 17.7 ppm SO_2 concentration on five successive days without any interior adjustments. The meter's responses were 85, 84, 72, 76 and 84 percent of full scale. From the PAI calibration curve, these readings correspond to 18, 17, 9, 11, and 17 ppm. Thus, the average response in 14.4 ppm, the maximum deviation is approximately 9 ppm (17% of scale), and the standard deviation of the measured values about the mean is 4.1 ppm (8% of scale).

2.5.3.7 Minimum Detectable Change: The minimum detectable change is strongly influenced by the range to which the meter is calibrated and the concentration about which the change is measured. As the meter was originally ranged, the minimum detectable change was much less than 1 ppm SO_2; i.e., 0.92 ppm SO_2 caused a 55 percent of full scale meter deflection. When the range was modified at RTI, the resulting calibration curve was extremely nonlinear and the minimum detectable change depended upon the starting SO_2 concentration, i.e., the region of the curve the meter was on. Using the criterion that the minimum detectable change is twice the peak-to-peak noise (peak-to-peak noise on the meter is approximately 1.5 percent of full-scale), the minimum detectable change is approximately 4 ppm from 30 to 50 ppm, 1 ppm from 10 to 30 ppm, and 0.5 ppm below 10 ppm. It should be noted that the manufacturer only recommends extending the upper range to 30 ppm.

2.5.3.8 Linearity: As illustrated by the calibration curve of Figure 21, the output of the PAI meter is extremely nonlinear with SO_2 concentration if it is calibrated for a 50 ppm range. It would be more linear if calibrated over the lower range.

2.5.3.9 Humidity Effects: The effect of humidity changes on the PAI meter was measured by the method of Section 1.4.9 of this report. A change in the relative humidity from 0 to 80 percent did not cause a detectable change in the PAI response. Thus, it is concluded that the PAI meter is not sensitive to humidity changes.

2.5.3.10 Temperature Effects: The effect of temperature changes on the PAI meter were measured by recording the meter's responses to a 17.7 ppm SO_2 in air gas at 15°, 25°, and 40°C. Linearizing these results, the total meter change from 15° to 40°C was 33 percent of scale which corresponds to 30 ppm SO_2. Thus, its temperature sensitivity is approximately 1.2 ppm SO_2 per °C.

2.5.3.11 Interferences: Interferences for the PAI meter were measured by one of the methods of Section 1.4.11 of this report. Results are summarized below:

Water Vapor: As discussed in Section 2.5.3.9, water vapor was not a significant interference.

Carbon Monoxide (CO): A 230 ppm concentration of CO did not cause a detectable change in the response of the PAI meter. Thus, its interference equivalent is greater than 230:1.

Nitrogen Oxide (NO): A 48 ppm concentration of NO did not cause a detectable change in the response of the PAI meter. Thus, its interference equivalent is greater than 48:1.

Methane (CH_4): A 100 ppm concentration of methane did not cause a detectable change in the response of the PAI meter. Thus, its interference equivalent is greater than 100:1.

Ozone (O_2): A 3 ppm concentration of ozone reduced the PAI's readout from 10.5 ppm SO_2 to 5 ppm SO_2. Thus, its interference equivalent is -0.55:1.

Hydrogen Sulfide (H_2S): The interference equivalent of H_2S was 71:1.

2.5.4 Physical Characteristics

2.5.4.1 Portability: The PAI meter is not considered a portable meter because of its size, weight, and power requirements. It is concluded from an examination of the meter that it could easily be made much smaller, and the weight reduced somewhat. Physical attributes which reflect its portability are tabulated below:

PAI PHYSICAL ATTRIBUTES

Weight:	48 lb (21.8 kg)
Size:	14.5 x 15.5 x 14 in. (36.8 x 39.4 x 35.6 cm)
Volume:	1.82 ft^3 (5.2×10^{-2} m^3)
Batteries:	60 Hz power only.

2.5.4.2 Readout: The PAI meter has a meter and recorder output. The meter movement is scaled in 100 units, and can be read to approximately 1 percent of full scale. A calibration curve is required to interpret the meter reading as a SO_2 concentration. The recorder output is proportional to the meter movement and is 5 mV full scale.

2.5.4.3 Instruction Manual: The PAI instruction manual is exceptionally good and is the best of the manuals evaluated. It lacks a table of specifications and an adequate description of the electronic system. In the several categories defined in Section 1.5.3 of this report, the PAI manual was rated as follows:

PAI MANUAL RATING

Essential Features:	80%
Desirable Features:	71%
Useful Features:	30%
Overall Rating:	72%

2.5.4.4 Ease of Operation: The PAI meter is easy to operate. All controls are readily accessible from the front panel and they are adequately described in the operating instructions in the manual.

2.5.4.5 Ease of Zero and Span Adjustments: The PAI meter provides for a zero mode of operation that diverts the sampled air through a charcoal filter before it enters the cell. Thus, the meter can be zeroed in either a contaminated atmosphere or with zero air. The span or calibration gas is available. A single adjustment of the span is probably a meaningful adjustment if only the linear portion of the calibration curve is used. As a 0 to 50 ppm SO_2 monitor, the calibration curve is extremely nonlinear and a single span adjustment is inadequate. A more reasonable approach for this range of operation is to periodically determine a new calibration curve.

2.5.4.6 Ruggedness: Although the PAI meter is well constructed, it is a heavy meter with a large electrolyte cell. Its size, weight, and the volume of electrolyte in the vented cell requires thoughtful care in handling.

2.5.4.7 Intrinsic Safety: If reasonable care is exercised, the PAI meter should present no safety hazard. The large electrolyte cell (approximately 1.5 liters) contains a solution of sulfuric acid and potassium bromide, and standard precautions should be exercised when handling the cell. The meter exhausts bromine when in operation and should be vented if used in a confined environment.

2.5.5 Recommended Use Technique

The PAI meter is not recommended as a portable, direct-reading SO_2 meter for OSHA compliance inspectors. The meter is neither portable nor direct reading, and it is extremely nonlinear over the 0 to 50 ppm range. Ideally, the meter should be used over a linear range. This would significantly simplify calibration and provide for frequent calibration checks. If it is used over a range that becomes nonlinear, the meter should frequently be recalibrated.

2.6 Wilks

The Wilks MIRAN-I Gas Analyzer ("Wilks meter"), shown photographically in Figure 21, is unique among the meters evaluated in that it is not specifically a SO_2 meter. Instead, it is an infrared (IR) gas analyzer, reasonably portable when compared to other IR analyzers, that can be calibrated to measure the SO_2 concentration of a gas sample. Its use requires considerably more skill and knowledge on the part of the operator than the other meters evaluated and the casual or unskilled user will not realize the full potential of the Wilks meter. It is more suitable to a laboratory environment than to the field environment. It has the unique advantage of being useful for measuring the concentration of a large number of gases in air. It is not a portable meter and does not give a direct readout of SO_2 concentrations.

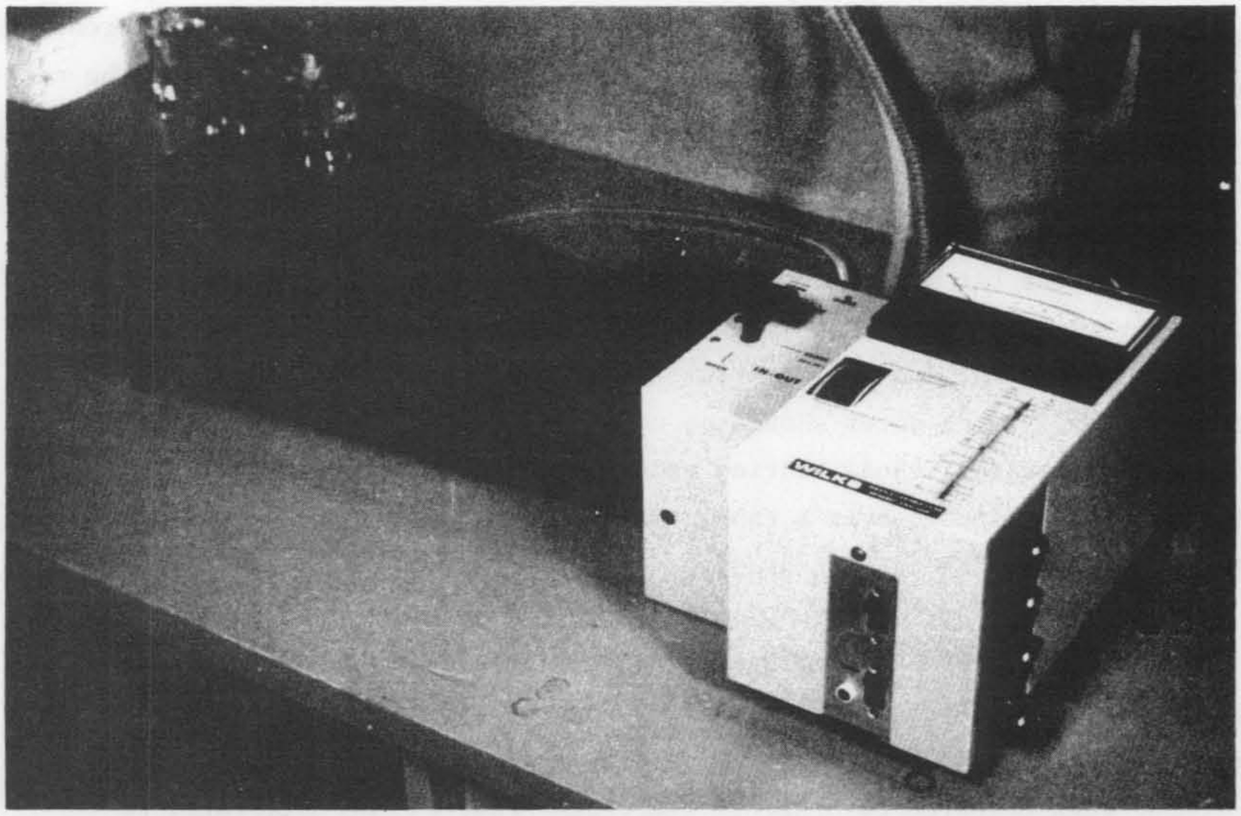

Figure 21. Photograph of the Wilks MIRAN I Gas Analyzer

The Wilks meter readout is in percent transmission (%T) rather than in ppm SO_2. The %T readout is used with a calibration curve to determine the SO_2 concentration of the sample. Figure 22 is the manufacturer's calibration curve for SO_2. The meter also has an absorbance scale; however, it is a redundant scale to the %T scale and is not of significance for the purposes of this evaluation. (Absorbance (A) is given by $A = -\log T$. It is not a linear scale as is the %T scale.) The manufacturer's calibration curve covers a range of 0 to 11 ppm; however, the meter was expanded at the expense of sensitivity and resolution. A x5 scale expansion, for example, would provide for a range exceeding 50 ppm SO_2.

The manufacturer's calibration curve of Figure 22 shows the %T to be approximately linear with the SO_2 concentration. This is not necessarily true of other gases or of higher concentrations of SO_2.

The Wilks meter differs to such an extent from other meters evaluated that many of the test procedures discussed in earlier portions of this report were inappropriate. In instances where significant differences occur, procedures used for the Wilks meter will be explained in detail.

2.6.1 Principle of Operation and Description

The Wilks meter is a single beam IR spectrometer. It exploits the property of certain gases to absorb energy at explicit wavelengths in the IR range. The meter has a wavelength (λ) range that extends from 2.5 to 14.5 microns (10^{-6} meters). Thus, if a contaminant gas such as SO_2 is known to absorb energy at a given wavelength within this range, the concentration of the gas can be measured by comparing the energy absorbed with a calibration curve generated by using known concentration of the gas. Further discussions of the principle of IR spectrometry is readily found in the literature and in the Wilks instruction manual.

The Wilks meter has a long-path cell which enhances sensitivity; and the actual pathlength is variable, in increments, from 0.75 to 26.25 meters. The instruction manual discusses the principles involved in selecting a pathlength. For the purposes of this evaluation, the manufacturer supplied a calibration curve and the pathlength specified

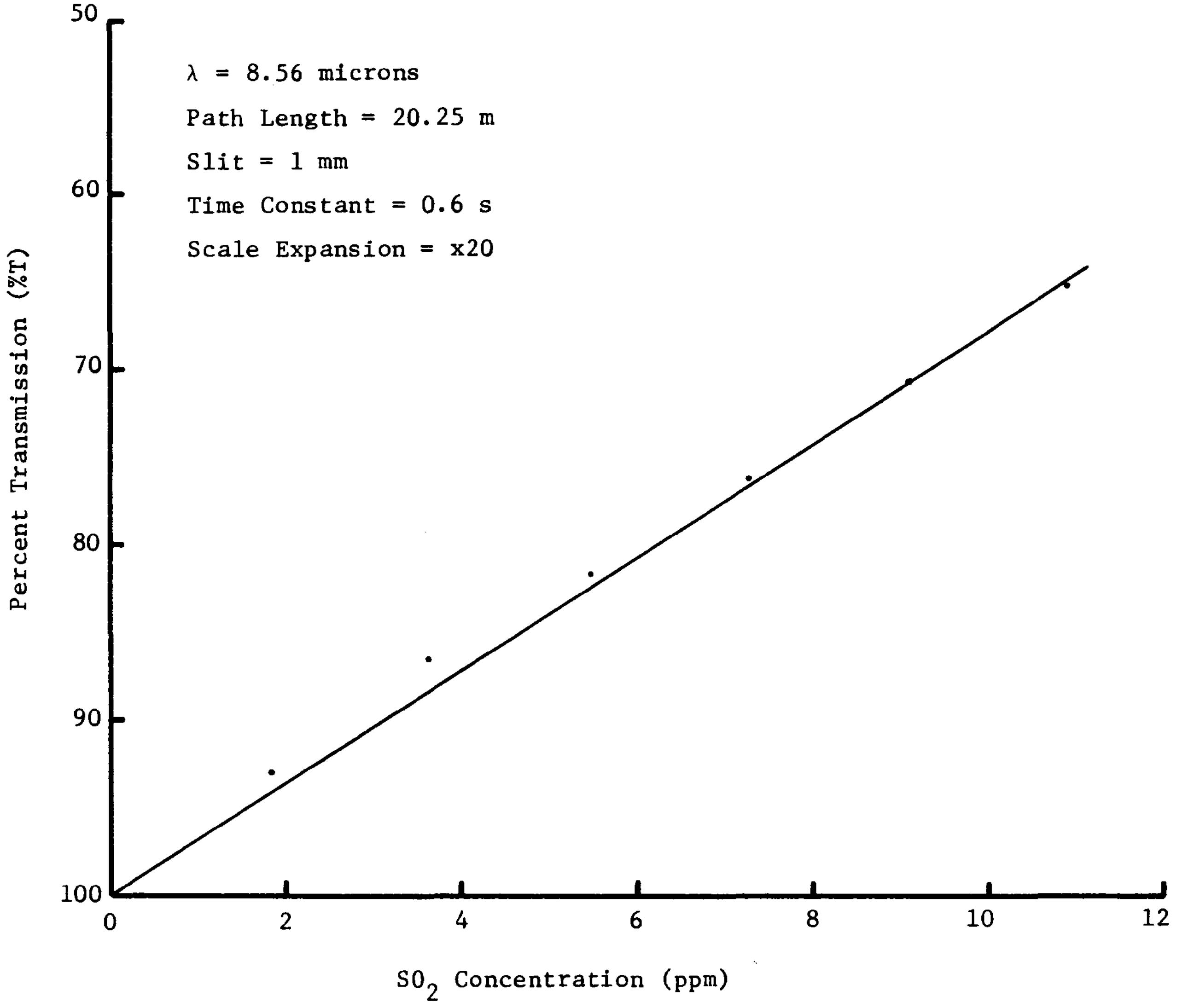

Figure 22. Wilks Meter Calibration Curve and Data

for the curve was selected. It was demonstrated that the pathlength was not critical; i.e., the pathlength was varied without significantly affecting the Wilks meter readout.

2.6.2 Test Facilities and Procedures

In order to use the Wilks meter, it is necessary to be able to fill the long-path cell (≃5.5 liters) with air and known concentrations of SO_2 (for calibration purposes). The cell has an inlet and an outlet value for filling the cell, and a small pump located on the side of the cell exhausts the cell so as to pull a fresh sample through the opened valve. Unless flow is restricted, the pump will pull approximately 8 liters/minute through the cell. This was a greater flow than could be routinely supplied from the manifold, and, consequently, a flow restriction (a stainless steel valve) was placed in the line between the manifolds and the inlet to the cell. This arrangement is illustrated in Figure 23. The valve restricted flow through the cell to approximately 2 liters/minute. The practice followed during these evaluations was to allow a minimum of 15 minutes to flush the cell and this was demonstrated to be adequate.

2.6.3 Performance Characteristics

In the performance characteristics discussed in the following sections, the Wilks meter was set up as a SO_2 monitor, i.e., $\lambda \simeq 8.6\mu$ and with a scale expansion of either x5 or x20. It is emphasized again that Wilks performance characteristics as an SO_2 meter are being evaluated. It may be better or worst as a meter for other air contaminants.

2.6.3.1 Accuracy of the Manufacturer's Calibration: The Wilks meter was received from the manufacturer with a calibration curve that covered a range of 0 to 11 ppm SO_2. The accuracy of the manufacturer's calibration was measured by duplicating the settings specified on this calibration curve and comparing the meter's percent transmission (%T) reading with the value predicted by the calibration curve for several values of SO_2. The cell was filled with a 49 ppm SO_2 in nitrogen concentration to set the wavelength (λ) control to the SO_2 absorption peak. However, a definitive absorption peak could not be detected in region of 8.6μ and this factor is probably the basic limitation of the

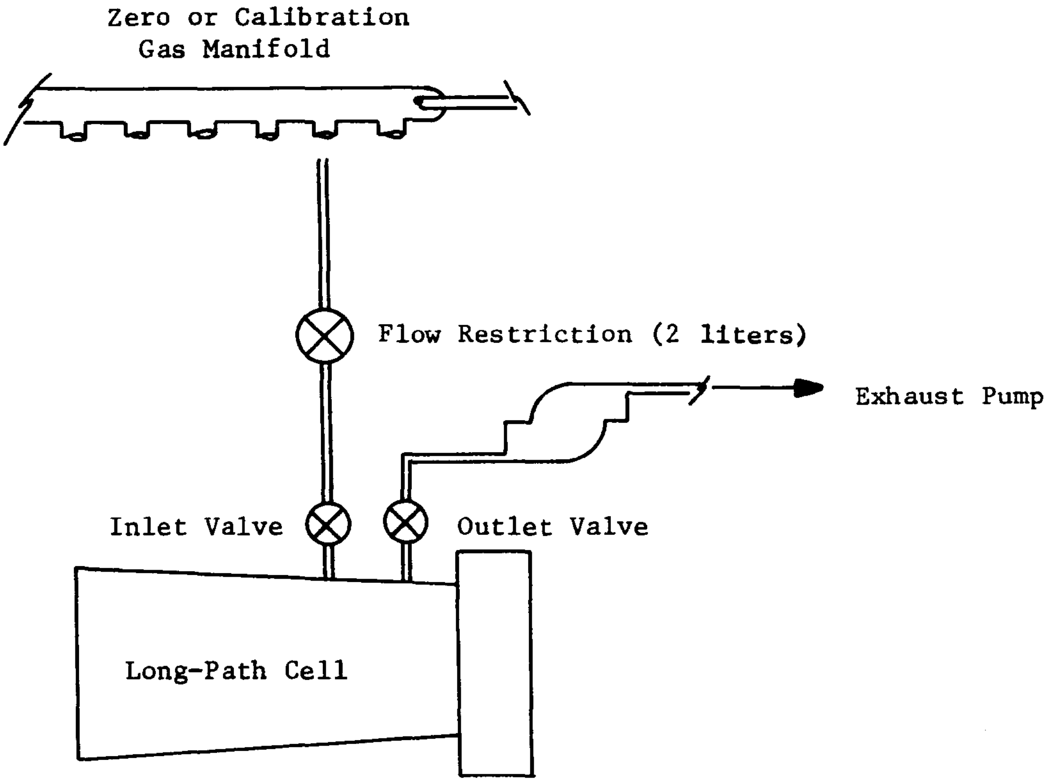

Figure 23. Wilks Meter Test Facility

Wilks meter as an SO_2 meter. Figure 24 is a reproduction of a strip chart recording of the %T as the wavelength is scanned in the region of 8.6μ. Since the SO_2 absorption peak is not easily located in the region of 8.6μ, the wavelength setting was adjusted using the calibration markings on the wavelength control. As illustrated in Figure 24, the %T was very sensitive to the λ setting and, because λ could not be set very precisely, it is unreasonable to expect the manufacturer's calibration to be very accurate. This is not necessarily true of other gases.

After setting the λ control as precisely as possible to the SO_2 absorption wavelength (as specified by the manufacturer), the recommended operating procedures were followed to duplicate the conditions corresponding to the manufacturer's calibration curve, i.e., $\lambda \simeq 8.6\mu$ (actually 8.56, but this degree precision cannot be set on the λ control), time constant (TC) = 0.6 seconds, slit opening = 1 mm, pathlength = 20.25 m, and the scale expansion factor = x20 (nominal). Several concentrations of SO_2 were sampled to determine the accuracy of the manufacturer's calibration. Results from this experiment are tabulated below as the accuracy of the manufacturer's calibration. Actually, it is more accurately a measure of how precisely the wavelength control can be set. Included in this tabulation, from left to right, are the actual SO_2 concentration of the calibration gas and the corresponding %T predicted by the calibration curve, the actual %T read from the meter and the corresponding SO_2 concentration predicted by the calibration curve, the percent difference between the actual SO_2 concentration and the concentration predicted by the manufacturer's calibration curve, and the difference as a percent of 50 ppm.

ACCURACY OF MANUFACTURER'S CALIBRATION

SO_2 Concentration and Corresponding %T ppm(%T)	%T Reading and Corresponding SO_2 (%T)ppm	Difference in ppm (%)	Difference as % of 50 ppm (%)
8.85(71.5%)	(82%)4.75	46	8
5.9(81%)	(90%)3.1	47	5.6
3.5(88.5%)	(98%)0.6	83	5.8

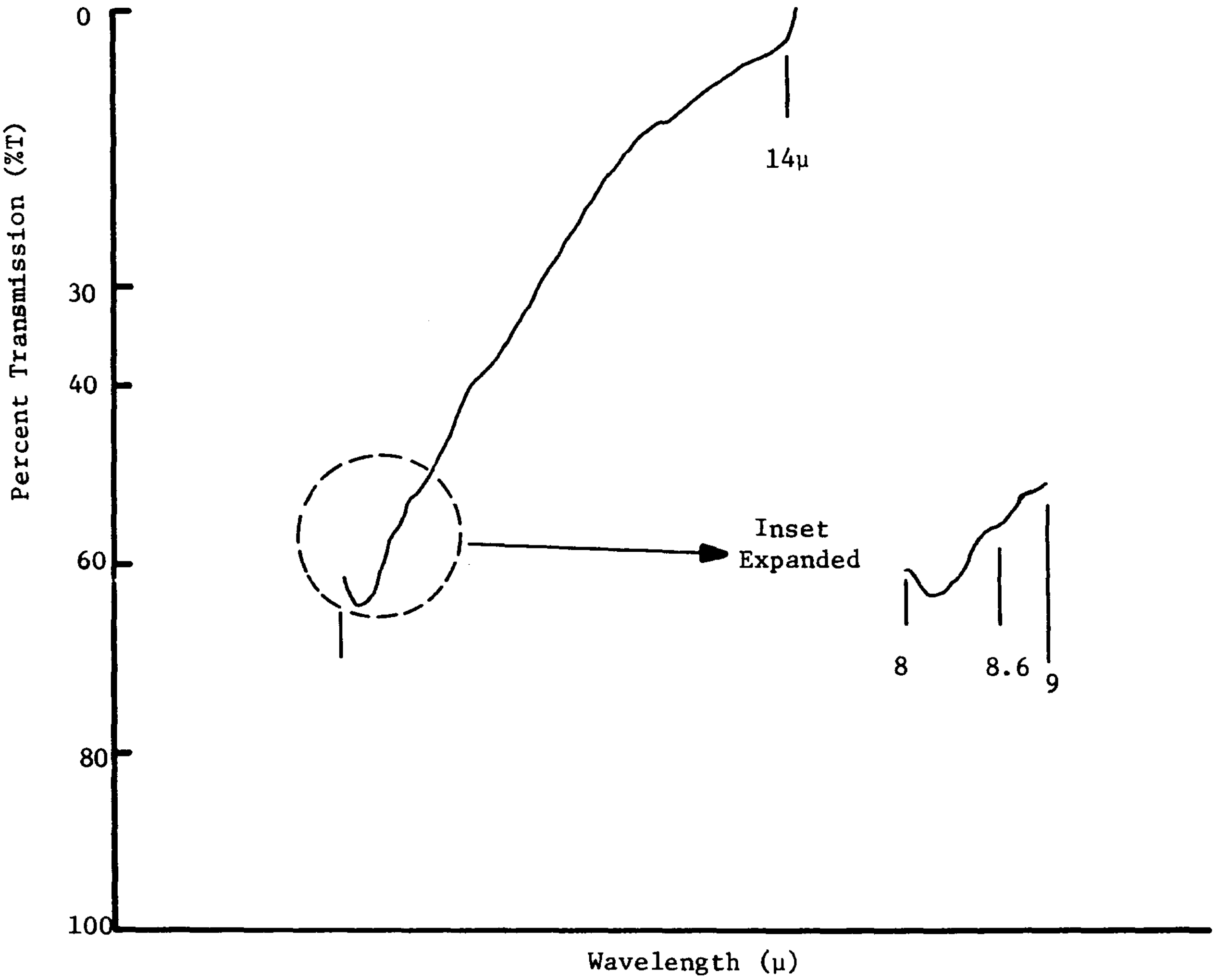

Figure 24. Percent Transmission Versus Wavelength for Cell Filled with 49 ppm SO_2 in N_2

The difficulty of duplicating conditions corresponding to the manufacturer's calibration curve in the field environment is demonstrated by the curves in Fig. 25. After recording the data in the preceding tabulation, the cell was refilled with 8.85 ppm SO_2 in air and the λ control was adjusted to 8.5, 8.6, and 8.7μ. These data and the initial 8.6μ value are plotted in Fig. 25 and used to define a linear calibration curve. The manufacturer's calibration curve, corresponding to 8.56μ, is also included for comparison. These curves demonstrate that significant errors can result from inaccuracies in setting the λ control. They also suggest that the manufacturer's calibration accuracy would be significantly improved if the 8.56μ wavelength could have been accurately set in the field environment. As an SO_2 meter for field use, the calibration curve should be established in the laboratory and not disturbed throughout the period of use in the field environment.

A calibration curve corresponding to a x5 scale expansion was generated using certified calibration mixtures of SO_2 in N_2. This curve was approximately linear, and the %T at 49 ppm SO_2 in N_2 was 61 percent. This curve is shown in Fig. 26.

2.6.3.2 Warm-Up Time: The instruction manual for the Wilks meter does not discuss warm-up requirements and no warm-up characteristics were observed during evaluation. It is concluded that warm-up requirements are negligible compared to the periods of time required to use the meter. (Several minutes are required to fill the long-path cell, for example.)

2.6.3.3 Response Times: Response times have no significance for the Wilks meter. They are negligible compared to the time required to introduce a sample into the 5.5 liter cell.

2.6.3.4 Zero Drift: For the Wilks meter, zero drift is interpreted to mean a drift in the meter requiring either a change in the zero control setting or the gain control setting. These are checked by routinely placing the meter in operation. The λ control was set to 8.6μ and the zero control was set to 0% with the light slit closed,

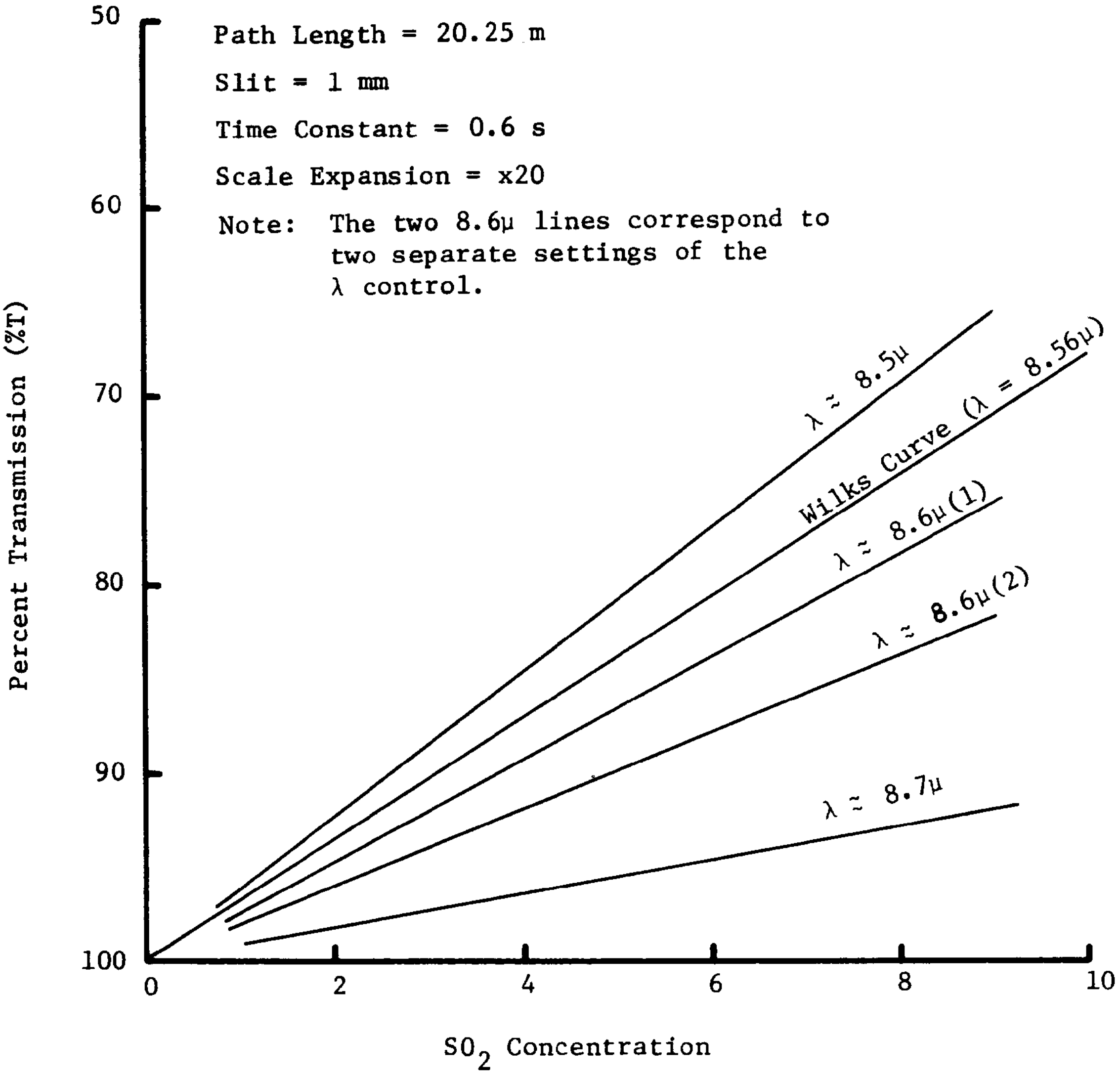

Figure 25. SO_2 Calibration Curves for Different Settings of λ

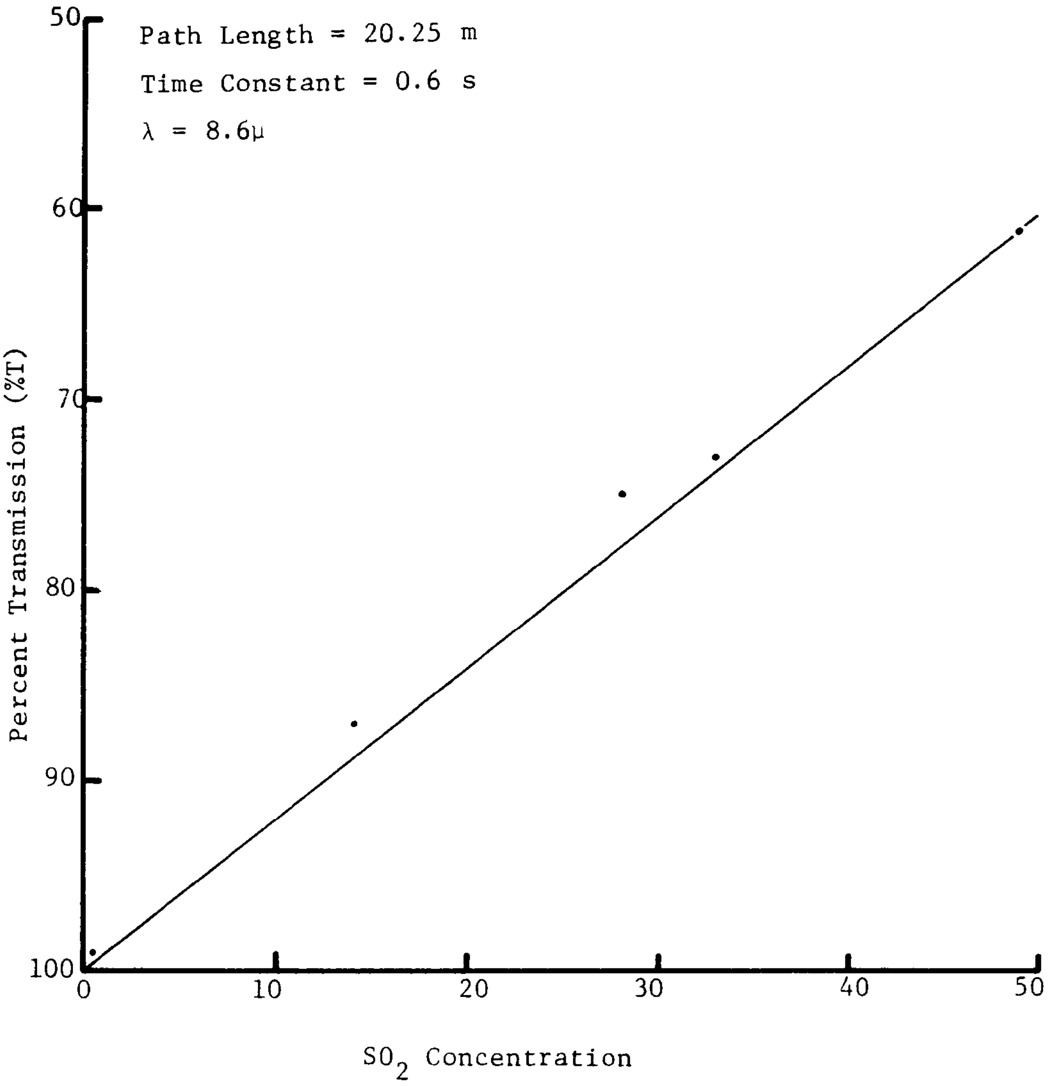

Figure 26. Wilks Meter Calibration Curve for Scale Expansion = x5

and the gain control was set by filling the cell with zero air, opening the slit to 1 mm, and adjusting the gain for 100%T. The scale expansion was set to x5 and the zero control adjusted to reset the meter to 100%T. The meter was left ON with inlet and outlet valves closed for a period of 24 hours and the drift determined by recording the %T. Hourly readings of the %T drifts and corresponding ppm SO_2 drifts are tabulated below. At the end of the 24-hour period, the cell was flushed again with zero air, but the %T reading did not change. Thus, the maximum zero drift over a 24-hour period was 13.9 ppm, and the average drift was 3 ppm. However, the average zero drift per hour was approximately 1 ppm/hr.

2.6.3.5 Span Drift: Span drift over a 24-hour period was measured similarly to the measurement of zero drift. The meter was placed in a routine mode of operation (x5 scale expansion) and the meter's response to a certified calibration mixture was monitored. For 49 ppm SO_2 calibration gas, maximum 24-hour span drifts observed were 5%T and 8%T. These drifts correspond to SO_2 concentrations of 6.3 and 10 ppm. Thus, the 24 hour span drifts observed about 49 ppm were 13 and 20 percent of a 50 ppm range.

2.6.3.6 Minimum Detectable Change: The minimum detectable change was limited by the peak-to-peak noise in the meter readout. In the x5 scale expansion mode, the peak-to-peak noise was approximately 1.5%T; and when the scale expansion was x20, the peak-to-peak noise was approximately 4%T. Using the criterion that the minimum detectable change is twice the peak-to-peak noise, the minimum detectable changes for the x5 scale expansion and the x20 scale expansion are 4 ppm and 1.6 ppm, respectively.

2.6.3.7 Linearity: The linearity of the Wilks meter is illustrated in Figure 27 by the data from a single experimental run. These data correspond to a scale expansion of x20. Both an ideal line and a line-of-best-fit as determined by a linear regression analysis is fitted to the data. The y-axis intercept for the line-of-best-fit is -1.16 ppm, the slope is 1.16, and the correlation coefficient is 0.98. The maximum deviation from the line-of-best-fit is approximately 4 ppm at 8.9 ppm or 45 percent of reading.

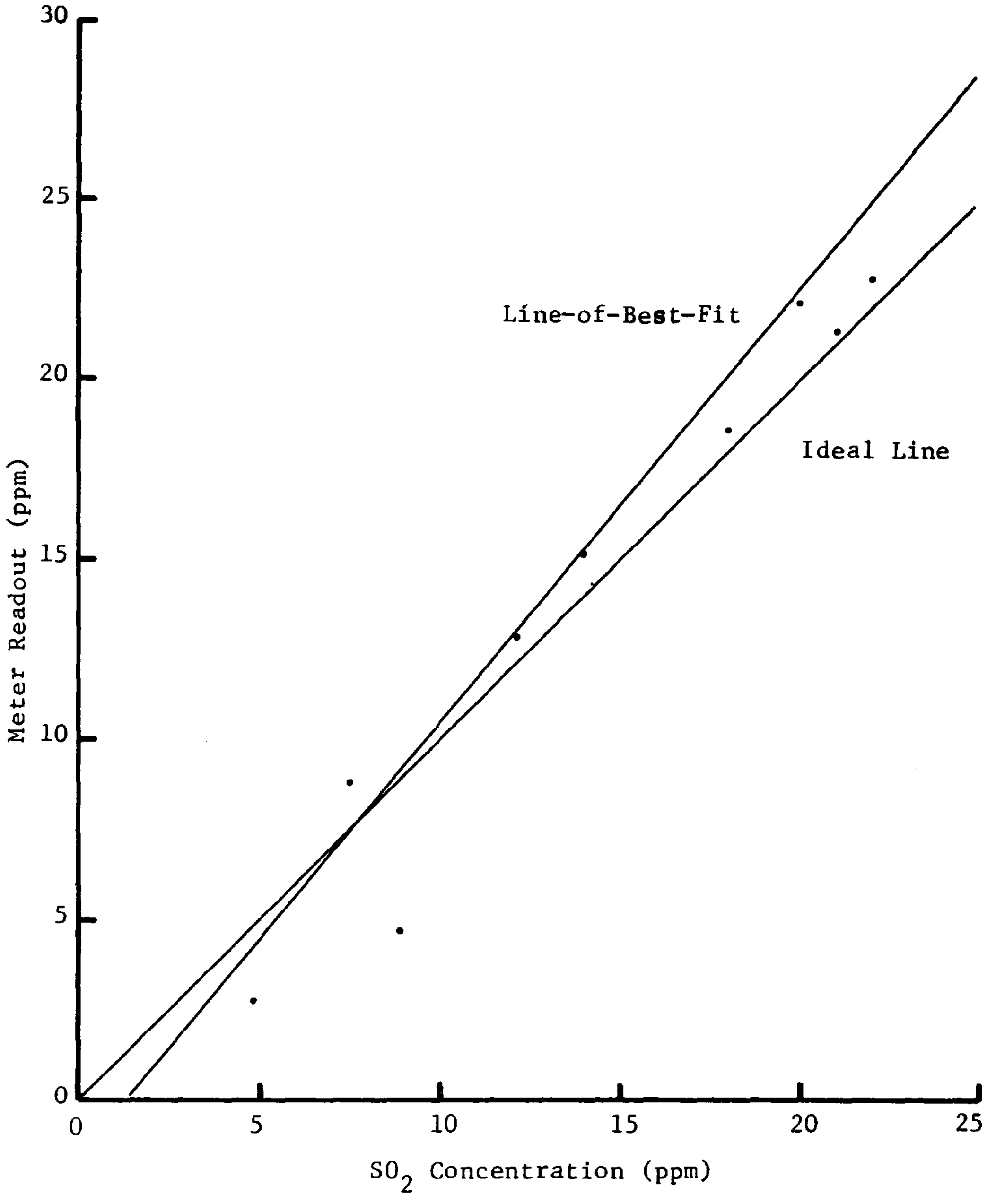

Figure 27. Wilks Linearity Data (SO_2)

WILKS ZERO DRIFT

Time (hrs)	Drift (%T)	Drift (ppm SO_2)
1	-1	-1.26
2	-2	-2.52
↓	↓	↓
10	-2	-2.52
11	0	0
12	+1	+1.26
13	+1	+1.26
14	+1	+1.26
15	+2	+2.52
16	+2	+2.52
17	+1	+1.26
18	+1	+1.26
19	0	0
20	-2	-2.52
21	-2	-2.52
22	-4	-5.04
23	-8	10.1
24	-11	13.9

2.6.3.8 Humidity Effects: The Wilks meter is sensitive to humidity at the SO_2 wavelength (8.6μ). This was demonstrated by setting the meter in operation, using a x5 scale expansion, with zero and gain settings established with dry (≃0% RH) zero air. The cell was then flushed with zero air that was passed through a bubbler (≃100% RH) and the %T changed from its original 100%T to 94%T. This corresponds to a SO_2 change of 7.5 ppm.

2.6.3.9 Temperature Effects: The Wilks meter was demonstrated to be sensitive to temperature at a wavelength of 4.6μ when it was being evaluated as a CO meter. These experiments were not repeated at 8.6μ.

2.6.3.10 Interferences: The Wilks meter was evaluated for the effects of the interferences tabulated below at 8.6μ (the SO_2 wavelength) and at a x5 scale expansion. The minimum detectable change at the x5 scale expansion is approximately 4 ppm SO_2, and this factor is used to estimate the limiting interference equivalent in cases where no detectable change was observed in the meter.

Water Vapor: As discussed in Section 2.6.3.8, water vapor was a significant interference to the Wilks meter.

Nitrogen Oxide (NO): Exposure to 48 ppm of NO did not cause a detectable change in the Wilks meter. Therefore, its interference equivalent is greater than 12:1.

Carbon Monoxide (CO): Exposure to 458 ppm of CO did not cause a detectable change in the Wilks meter. Therfore, its interference equivalent is greater than 115:1.

Methane (CH_4): Exposure to 100 ppm of CH_4 reduced the %T of the Wilks meter from 100 percent to 86 percent; i.e., it appeared as 16 ppm of SO_2. Therefore, its interference equivalent is approximately 6:1.

2.6.4 Physical Characteristics

The Wilks MIRAN-I Gas Analyzer differs significantly from the other meters analyzed in that it is a gas analyzer rather than a SO_2 meter. It is not portable, has an indirect readout, and is more of a laboratory instrument than a field-type monitor. It can be useful as a portable SO_2 monitor, however, and its usefulness is significantly enhanced if it is supported by a laboratory facility.

2.6.4.1 Portability: The Wilks meter is not a particularly portable meter although it can be readily moved about for measurements in field locations where 60 Hz power is available. The instrument does need the support of a laboratory facility for calibration and control setting assistance. Physical attributes which largely determine portability are tabulated below.

WILKS PHYSICAL ATTRIBUTES

Weight:	31 lb (14 kg)
Size:	6.5 x 9.8 x 26 in. (16.5 x 24.9 x 66 cm)
Volume:	0.96 ft^3 ($2.7 \times 10^{-2} m^3$)
Power:	Requires a 60 Hz power source.

2.6.4.2 Readout: The Wilks meter reads percent transmission (%T) between an IR energy source and a detector. (It also has an absorbance scale where absorbance (A) and %T are related by A = -logT). The meter can be calibrated at an appropriate wavelength to read ppm SO_2, for example. The readout is in %T, and a calibration curve is used to interpret the %T in terms of ppm SO_2. The readout can also be scale-expanded with the internal electronics to enhance sensitivity at the expense of range. The meter is readable to approximately 0.5 percent of scale. The Wilks unit also has a recorder output of 0 to 1 volt corresponding to 0 and and 100%T.

2.6.4.3 Instruction Manual: The Wilks is a complex meter, and a relatively extensive instruction manual is essential. The manual received was rated as one of the better manuals; however, it seemed somewhat inadequate in view of the complexity of the instrument. Careful study of the manual and some experience with the meter was required to achieve a reasonable degree of competence in the use of the meter. Some of this learning process could be circumvented with an improved manual. Specifically, the manual would benefit significantly from an improved presentation of operating procedures, improved organization, and the inclusion of a parts list. With reference to the criteria of Section 1.5.3, the Wilks instruction manual was rated as follows:

WILKS MANUAL RATING
Essential Features: 69%
Desirable Features: 83%
Useful Features: 0%
Overall Rating: 71%

2.6.4.4 Ease of Operation: The Wilks meter is not a particularly difficult meter to operate. If it is assumed that the meter is calibrated and the control setting established for a given calibration curve, it is only necessary to fill the cell, read the %T, and determine the corresponding SO_2 concentration from the calibration curve. If only the calibration curve is available, it is necessary to have zero air and SO_2 calibration gases to establish the correct wavelength (λ) and gain-control settings. Without a calibration curve, operating the Wilks meter is significantly more involved and requires access to a laboratory facility.

Use of the Wilks meter as an SO_2 monitor is somewhat complicated as compared to its use as a monitor of other gases, however. The SO_2 absorption peak at approximately 8.6 microns was very difficult to locate with reasonable precision. This difficulty may have been circumvented to some degree if high concentration of SO_2 had been used to locate the peak. (A 49 ppm SO_2 concentration was used during this evaluation.) Another complicating factor was that the range of SO_2 of interest necessitated the use of a scale expansion to obtain the best sensitivity and resolution. With scale expansion, zero and span drifts are also amplified, and more frequent meter checks with a zero gas are desirable.

2.6.4.5 Ease of Zero and Span Adjustments: A zero %T adjustment can be accomplished at any time by simply closing the opening to the IR source (slit) and setting the zero control, provided the meter is not set up in an expanded scale mode of operation. However, the SO_2 range of interest requires a scale expansion, and the zero adjustment is actually used to establish a 100%T reading for a zero gas. Adjustment of the gain control (a parallel to a span adjustment) also requires filling the cell with a zero gas. If it is also necessary to establish a calibration curve, access to various SO_2 concentrations is required.

Ideally, the meter can be set up in a laboratory and carried to a field location for SO_2 measurements referenced to a single calibration curve. If measurements are to be referenced to more than a single curve, access to a zero gas is a minimum requirement. Additional exploitation of the meter's capabilities would require additional support and compexity.

2.6.4.6 Ruggedness: A general impression of the Wilks meter is that it is well constructed. No difficulties were experienced with routine handling and operation of the meter, and control setting's seemed stable and not subject to changes during handling. The extensive use of optics in the meter suggests that it should be handled with care. It is generally concluded that the meter is a laboratory instrument rather than a field instrument and should be handled with care.

2.6.4.7 Intrinsic Safety: The Wilks meter is intrinsically safe. No toxic materials are required for its operation and none are generated. The cell is exhausted from a port on the side of the meter and an operator should be mindful of that fact.

2.6.5 Recommended Use Technique

It is recommended that an operator of the Wilks meter acquire some experience with its use in a laboratory environment prior to using it in a field situation. A general familiarity with all of the controls, option, and capabilities of the meter will significantly enhance one's ability to make accurate measurements of SO_2 concentrations, for example, in industrial environments. If the meter is to be used extensively in the field, it is recommended that reasonably clean air be used frequently (at least daily) to ascertain that the gain control is correct. If it is to be transported frequently, placing a piece of tape over the λ control is a reasonable accuracy precaution.

It is also recommended that a high concentration of SO_2 be used to establish the best wavelength control setting. The 49 ppm concentration used during these evaluations was too low.

3.0 PERFORMANCE CHARACTERISTICS - A SUMMARY

This section of the report consists of tabulations of performance characteristics measured during these evaluations. They are presented in a tabular form for convenience of comparison and only essential additional information is included in the interest of brevity. The results tabulated herein are presented in detail in Section 2 of this report and the reader is referred to that section for additional information. Values not entered in the tables of this section were not determined.

3.1 Accuracy of the Manufacturer's Calibration

In Table IV, the accuracy of the manufacturer's calibration is tabulated. Two of the meters were not calibrated by the manufacturer and, thus, this characteristic could not be determined. For a third, the Casella, it was a matter of evaluating the accuracy of a calibrated factor. For the Wilks meter, the manufacturer's calibration only extended to 11 ppm. In Table IV, this performance characteristic is presented in a form convenient for each of the meters.

TABLE IV

ACCURACY OF MANUFACTURER'S CALIBRATION

Casella:	Deviations less than 3% of reading
CEA :	Deviations approximately -15% of reading
EM :	Deviations less than 4% of reading
Mast :	Not calibrated
PAI :	Not calibrated
Wilks :	Deviations less than 8% of 50 ppm (≈ 4 ppm at 8.85 ppm)

3.2 Warm-up Time

Warm-up times evaluated for applicable meters are tabulated in Table V. These are warm-up times specified by the manufacturer in each case and each was demonstrated to be adequate. Warm-up time is not a meaningful performance characteristic for the Casella, CEA or Wilks meters and was not determined. For the others, it is a significant parameter and in each case was too long to be suitable for a portable meter.

TABLE V

WARM-UP TIME

EM: 30 minutes
Mast: 2 hours
PAI: 30 minutes

3.3 Response Times

In Table VI, the response times of the various meters are tabulated. This tabulation includes the positive 90 percent response times (+ response), lag, 90 percent rise times (rise), the negative 90 percent response times (- response) and the 90 percent fall times (fall). Response times are not meaningful characteristics for the Casella, CEA, and Wilks meters and are not tabulated for these meters.

TABLE VI

METER RESPONSE TIMES

Meter	+Response	Lag	Rise	-Response	Fall
EM	<7 s	<1 s	<7 s	<7 s	<7 s
Mast	1 min.	10 s	50 s	20 min.	20 min.
PAI	16 min.	13 s	16 min.	<3 min.	<3 min.

3.4 Zero Drift

The zero drifts measured over 24 hours of continuously monitoring zero air are tabulated in Table VII. Zero drift is not a meaningful characteristic for the Casella and CEA meters and was not measured.

TABLE VII

ZERO DRIFTS

Meter	Maximum (ppm)	Average (ppm)
EM	0.3	0.14
Mast	<0.5	
PAI	<0.14	<0.08
Wilks	13.9	3

3.5 Span Drift

Span drift data is tabulated in Table VIII for all but the Casella and CEA meters. (Span drift is not meaningful for these two.) The table includes the sample concentration, the measurement period, and the drift in absolute terms and as a percent of reading.

TABLE VIII

SPAN DRIFTS

Meter	Sample Concentration (ppm)	Sample Period (hours)	Maximum Drift (ppm)	Maximum Drift (% of Reading)
EM	17.7	24	3	16
Mast	17.7	8	31	175
PAI	17.7	8	1	6
Wilks	49	24	10	20

3.6 Calibration Stability

The calibration stability of the meters was measured by observing changes in the meter's calibration or calibration factor over a period of time. These results are tabulated in Table IX.

TABLE IX

CALIBRATION STABILITY

Meter	Time Period	Deviation (% of Reading)	Deviation (% of Scale)
Casella	1 week	10	
CEA	*		
EM	2 weeks	4	4
Mast	*		
PAI	1 week	51	17
Wilks	(not measured)		

*See Section 2.

3.7 Minimum Detectable Change

The minimum detectable change is difficult to specifiy concisely because of several factors. For the meters with nonlinear calibration curves (i.e., the Mast and PAI) it varies with the concentration or position on the curve. For the Wilks, it varies with the scale expansion factor used. In the tabulation of Table X, it is stated as a worst-case percent of reading.

TABLE X

MINIMUM DETECTABLE CHANGE

Meter	Minimum Detectable Change
Casella	(not measured)
CEA	20% of reading
EM	2 ppm
Mast	(not measured)
PAI	10% of reading
Wilks	15% of reading

3.8 Linearity

The linearity of the meters evaluated is tabulated in Table XI as a percent-of-range deviation from the line-of-best-fit and from the ideal line. Linearity was not measured for the Mast and PAI meters because their responses are nonlinear. The linearity measurement for the Wilks meter utilized the x20 scale expansion calibration curve and a range of 11 ppm is assumed. A range of 50 ppm is assumed for the Casella.

TABLE XI

LINEARITY EXPRESSED AS A DEVIATION FROM THE LINE-OF-BEST-FIT AND/OR THE IDEAL LINE

Meter (Range)	Maximum Deviation From Best-Fit Line (% of Range)	Maximum Deviation From Ideal Line (% of Range)
Casella (50 ppm)	8	7
CEA (20 ppm)	13	23
EM (50 ppm)	4	
Wilks (11 ppm)		36

3.9 Humidity Effects

None of the meters evaluated were sensitive to humidity changes except the Wilks meter. A change in humidity from 0 to 100 percent appeared as 7.5 ppm SO_2 to the Wilks meter. The Casella was not evaluated for humidity sensitivity because of the electronic malfunction; however, it is reasonable to assume that the Casella, like the CEA, is not sensitive to humidity.

3.10 Temperature Effects

The effects of temperature are tabulated in Table XII. The results tabulated have been linearized; i.e., the total meter change with temperature is divided by the total temperature change and tabulated. The temperature range was from 15° to 40°C.

TABLE XII

TEMPERATURE EFFECTS

Meter	Linearized Temperature Effect
Casella	Not measured
CEA	Negligible effect
EM	0.08 ppm/°C
Mast	2.9 ppm/°C
PAI	1.2 ppm/°C
Wilks	(See Section 2)

3.11 Interferences

Interference equivalents of interferences investigated and shown to be significant are tabulated in Table XIII. An interference equivalent of 1.4:1, for example, is interpreted to mean that 1.4 ppm of the interference will cause a 1 ppm change in the SO_2 indication of the meter. No interferences are tabulated for the Casella because of the electronic malfunction that interrupted its evaluation.

TABLE XIII

INTERFERENCE EQUIVALENTS

Meter	Interference Equivalents
CEA	NO; -24:1
EM	H_2S; 26:1
	O_3; -0.3:1
Mast	O_3; -1:1
	H_2S; 250:1
PAI	O_3; -0.55:1
	H_2S; -71:1
Wilks	CH_4; 6:1

4.0 PHYSICAL CHARACTERISTICS - A SUMMARY

A section of the report consists of a tabulation of some of the physical characteristics of the SO_2 meters evaluated. For a more detailed discussion of the physical characteristics, the reader is referred to the appropriated discussion in Section 2 of the report.

4.1 Portability

Many of the attributes that determine portability are tabulated in Table XIV. Dimensional characteristics are tabulated in both English and metric units.

TABLE XIV

PHYSICAL CHARACTERISTICS

Meter	Weight lb (kg)	Nominal Dimensions h x l x w in (cm)	Battery Requirement (volts)	Charger
Casella	13 (5.9)	10 x 11.8 x 5 (25.4 x 30 x 12.7)	DEAC, Type 2000DK Ni-Cd	External
CEA	7.0 (3.2)	12.5 x 4.5 x 7.5 (31.8 x 11.4 x 19)	AA Pen Cell (Alkaline) (8)	None
EM	15 (6.81)	6.5 x 13.5 x 12.8 (16.5 x 34.3 x 32.5)	ac Line Only	----
Mast	12 (5.4)	11.2 x 5.5 x 7.5 (28.7 x 14 x 19)	ac Line Only	----
PAI	48 (21.8)	14.5 x 15.5 x 14 (36.8 x 39.4 x 35.6)	ac Line Only	----
Wilks	31 (14)	6.5 x 9.8 x 26 (16.5 x 24.9 x 66)	ac Line Only	----

4.2 Readout

The readout characteristics of each of the meters evaluated are tabulated in Table XV.

TABLE XV

READOUT CHARACTERISTICS

Meter	Characteristics
Casella	Indirect; Reads conductivity and time; Operator computes SO_2 ppm.
CEA	Indirect; Percent of scale proportional to SO_2 ppm.
EM	Direct reading; 0 to 10, 50, or 100 ppm SO_2 scales; Mirrored meter movement readable to 0.5% of full scale.
Mast	Indirect; Meter movement or recorder output; Nonlinear over 0 to 50 ppm scale; SO_2 concentration determined from calibration curve.
PAI	Indirect; Meter movement and recorder output; Readable to 1% of full scale; Nonlinear over 0 to 50 ppm scale; SO_2 concentration determined from calibration curve.
Wilks	Indirect; Single scale meter reads percent transmission; SO_2 concentration determined from calibration curve.

4.3 Instruction Manual

Results of the instruction manual evaluations are summarized in Table XVI. Details of the evaluation criteria are discussed in Section 1.5.3 of this report.

TABLE XVI

INSTRUCTION MANUAL EVALUATIONS

Meter	Essential Features (%)	Desirable Features (%)	Useful Features (%)	Overall Rating (%)
Casella	50	50	33	46
CEA	66	55	50	62
EM	62	53	25	55
PAI	80	71	30	72
Wilks	69	83	0	71

4.4 Costs

Costs of the meters evaluated and other cost considerations are tabulated in Table XVII.

TABLE XVII

COSTS

Meter	Costs	Remarks
Casella	\$1,200	Battery Changer \$48.00 Spare Battery \$55.00
CEA	\$595	
EM	\$2,050	Replacement faristor \$100. Does not include pump.
Mast	\$1,495	Estimate includes \$495 for recorder. Operating cost ∿ \$1.00 per week.
PAI	\$2,500	
Wilks	\$4,250	

5.0 RECOMMENDED CONSTRUCTION PERFORMANCE AND STANDARDS

5.1 Introduction

The proposed construction and performance standards included in this report are based upon the results of these meter evaluations and the meter characteristics urgently needed for monitoring the industrial environment for conformance to safety and health standards. They reflect the needs of government and industry for an accurate, portable SO_2 meter, the current status of portable SO_2 meters, and the conclusions of these investigations as to achievable performance and construction characteristics for portable SO_2 meters. The proposed standards are presented in Section 5.2 of this report in a format similar to the format of other standards found in the Federal Register. Section 5.3 of this report discussed the rationale for the proposed standards.

5.2 Construction and Performance Standards Recommended by RTI

I. General

  A. The Institute will test the meters for which approval applications are submitted in accordance with this part.

  B. All meters accepted by the Institute for examination, inspection, and testing shall be designed on sound engineering and scientific principles, be constructed of suitable materials, and will evidence good workmanship. The design and construction shall permit easy access for maintenance and replacement of component parts, and to insure against the creation of any hazard to the user.

II. Physical Characteristics

  A. Portable SO_2 meters approved under this subpart shall have the following physical characteristics.

    1. Portability: Meters including all required parts and accessories shall weigh 15 lbs or less and have a volume of 1 ft^3 or less with no signle dimension in excess of 2 ft.

2. Readout: Meters shall have either a direct readout of SO_2 concentration in parts per million (ppm) or a readout that is easily interpreted in ppm without requiring additional equipment.
3. Recorder Output: Meters shall have a recorder output to indicate the SO_2 concentration in the sample. The full-scale recorder output shall be greater than 100 mV when terminated in an impedance of 2 kΩ. The recorder output shall either be referenced to the ground potential or floating such that grounding either side of the output will not affect the meter.
4. Operational Simplicity: Meters shall be simple to operate so that operators without scientific backgrounds or formal training in the use of the use of the instrument, other than reading the operator's manual, can obtain measurements that reflect the instrument's capabilities.
5. Instruction Manuals: Instruction manuals for each instrument shall include, as a minimum, complete operating instructions including procedures for turn-on, warm-up, zero and calibration checks, sample collection, maintenance, recalibration, and performance checks. The manuals shall include flow diagrams, wiring and schematic diagrams, and an estimate of the lifetime of consumable reagents. The manuals shall include a parts list suitable for identifying parts and sources of parts for replacement orders.
6. Intrinsic Safety: Meters shall conform to the intrinsic safety specifications of the U.S. Bureau of Mines or approved by Factory Mutual as intrinsically safe for use in hazardous locations, Class 1, Division 1, Group D; and non-incendive for use in Class 1, Division 2, Groups A, B, C, and D.
7. Ruggedness: Meters shall be sufficiently rugged to withstand routine transporting, handling, and use in the field environment by the operator.

8. Sample Conditioning: Any sample conditioning equipment required shall be an integral part of the meter.
9. Ease of Zero and Span Adjustments: Zero and span adjustments shall be readily accessible for field adjustment, and the meter design shall include provisions to introduce zero, and calibration gases in nonlaboratory environments. The meter shall be capable of being zeroed in a contaminated atmosphere to within 1 ppm of a true zero. If accessories are required for this capability, they shall be considered a physical part of the meter and chargeable to its weight and volume.

III. Performance Characteristics

A. Portable SO_2 meters approved under this subpart shall conform to the following performance requirements:

1. Useful Range: Meters shall have a useful range which includes values from 1/5 to 10 times the OSHA 8-hour time-weighted-average maximum allowable exposure concentration (TWA limit).
2. Accuracy: Meters shall measure the true SO_2 concentration of a sample within the greater ±10% of reading or ±20% of the TWA limit.
3. Zero Drift: A meter's zero drift shall not exceed ±20% of the TWA limit during a 24-hour period of continuous use.
4. Span Drift: A meter's response to a SO_2 concentration of approximately 80% of the maximum range shall remain within ±20% of the true value during a period of two weeks of intermittent use.
5. Minimum Detectable Change: Meters shall be able to detect changes of ±20% of reading over the useful range of the meter as defined in subsection III.A.1.
6. Warm-Up Time: The meter shall meet all performance specifications after a warm-up time of 30 minutes.

7. Response Time (90%): The time interval between a step increase or decrease in the SO_2 concentration at the meter's input of at least 70% of its maximum range and the time the meter settles within ±10% of its final readout shall not exceed 2 minutes.
8. Operating Humidity Range: The meter shall meet all performance specifications within an ambient relative humidity range of from 10 to 90% while continuously sampling for 8 hours without maintenance.
9. Operating Temperature Range: The meter shall meet all performance specifications within an ambient temperature range of from 0° to 40°C.
10. Interferences: Interference equivalents for carbon monoxide, carbon dioxide, nitrogen oxide, nitrogen dioxide, hydrogen sulfide, ozone, and other significant interferences shall be specified.

5.3 Rationale for the Recommended Standards

In this section, the rationale for the standards recommended in Section 5.2 are discussed.

5.3.1 General Considerations

In general, an obvious and essential requirement is that the design and construction be based upon sound scientific and engineering principles, and that materials and workmanship be of good quality. It is also essential that the design reflect consideration for the safety of the user of the meter and for routine maintenance.

5.3.2 Physical Characteristics

5.3.2.1 Portability: It is desirable that SO_2 meters and any required accessories be easily transportable by an average adult person over distances and obstacles routinely encountered in industry. It is also desirable that the meters be usable throughout a workday in remote locations where normal 60 Hz power sources are not routinely available; however, the current state of the art does not reflect this capability and it is not required.

5.3.2.2 Readout: A direct readout of SO_2 concentration is desirable; however, an easily interpreted indirect readout requiring a calibration curve, for example, should not exclude an otherwise good meter.

5.3.2.3 Recorder Output: A recorder output is an asset and in many situations may be essential for monitoring an environment. A recorder output compatible with most laboratory recorders is recommended.

5.3.2.4 Operational Simplicity: The meter's operational simplicity should be such that it can be readily operated by personnel without special training or a scientific background.

5.3.2.5 Instruction Manuals: Any information of value to an operator or owner of a SO_2 meter should be readily available in an instruction manual. The requirements recommended do not penalize a manufacturer who has tested his product.

5.3.2.6 Intrinsic Safety: Adherence to an established safety standard is essential for any meter marketed for general industrial use.

5.3.2.7 Ruggedness: It is essential that a portable SO_2 meter be capable of withstanding transportation between sites and normal handling by untrained personnel without undue concern for damage or resulting inaccuracies.

5.3.2.8 Sample Conditioning: If any sample conditioning is required, it should be an integral part of a portable meter.

5.3.2.9 Ease of Zero and Span Adjustments: Since frequent zero and calibration adjustments or checks are expected, they should be readily accomplished in nonlaboratory environments.

5.3.3 Performance Characteristics

5.3.3.1 Useful Range: The useful range recommended is defined in terms of the OSHA 8-hour time-weighted-average (TWA limit) for convenience and permanence. Current values of the TWA limit of toxic materials were published in the Federal Register, Volume 36, Number 157, August 13, 1971. For SO_2, this value is 5 ppm of 14 mg/m^3. It is the range of interest reflected in the NIOSH guidelines.

5.3.3.2 Accuracy: The accuracy specified seems reasonable and achievable. The recommended standard requires a minimum accuracy of ±1 ppm and increases to ±5 ppm at 50 ppm, for example.

5.3.3.3 Zero Drift: A zero drift of ±1 ppm does not seriously compromise a meter's accuracy and is achievable by the meters evaluated.

5.3.3.4 Span Drift: A maximum span drift of ±20% over a 2-week period is recommended to provide for a long period of use between calibration adjustments. Significant calibration (span) drifts are characteristic of many of the meters evaluated.

5.3.3.5 Minimum Detectable Change: The minimum detectable change of ±20% of reading over the Useful Range of the meter is recommended. This would require, for example, that a change of ±1 ppm be detectable at 5 ppm and ±5 ppm be detectable at 50 ppm.

5.3.3.6 Warm-Up Time: A 30-minute warm-up time is recommended. Longer times are considered a significant time penalty for the operator.

5.3.3.7 Response Time: A 2-minute response time is recommended as a reasonable period for obtaining a reading.

5.3.3.8 Operating Humidity Range: The operating humidity range specified is very wide but can be achieved in the laboratory for testing purposes. It is also characteristic of certain industrial environments. It does not specify a temperature range concurrently with humidity. It may be more reasonable to specify an operating humidity-temperature profile and reference a standard that limits these extremes susch as the NIOSH criteria document on heat stress.

5.3.3.9 Operating Temperature Range: The operating temperature range specified reflects extremes in industrial environments.

5.3.3.10 Interferences: It is essential to know the interference equivalents of interferences likely to be encountered in industrial environments. Interference equivalents specified include those known to influence certain types of SO_2 meters.

6.0 RECOMMENDED QUALITY CONTROL STANDARDS

6.1 Rationale

The recommended quality control standards take full advantage of standards developed previously and published in the _Federal Register_ for respiratory protective devices and gas detector tube units, for example. This approach was taken to simplify the additional steps and procedures required before these standards can be included in the _Federal Register_. Changes that have been made simply adapt previous standards to portable SO_2 meters and the AQL's selected reflect current quality control practices of manufacturers of air quality instrumentation as revealed in a survey of these manufacturers. The recommended standards are included in Section 6.2 of this report in a format similar to other quality control standards that have appeared in the _Federal Register_.

6.2 Quality Control Standards Recommended by RTI

Quality Control

I. Quality Control Plans; Filing Requirement

Applicants seeking NIOSH approval of portable sulfur dioxide meters shall file with the Institute, for approval, a proposed quality control plan (in the English language) designed to assure the quality of the meter for which approval is sought.

II. Quality Control Plans; Content

A. Each quality control plan shall contain provisions for the management of quality, including: (1) requirements for the production of quality data and the use of quality control records; (2) control of engineering drawings, documentations, and changes; (3) control and calibration of measuring and test equipment; (4) control of purchased material to include incoming inspection; (5) lot identification, control of processes, manufacturing, fabrication, and assembly work conducted in the applicant's plant; (6) audit of final inspection of the completed product; and (7) the organizational structure necessary to carry out these provisions.

B. Each provision for incoming, in-process, and final inspection in the quality control plan shall include a procedure for the selection of a sample of meters and the components thereof for inspection or testing, in accordance with procedures set forth in Military Standard MIL-STD-105D, "Sampling Procedures and Tables for Inspection by Attributes," or Military Standard MIL-STD-414, "Sampling Procedures and Tables for Inspection by Variables for Percent Defective," or an approved equivalent sampling procedure, or an approved combination of sampling procedures. Incoming bulk raw material inspection or verification of specifications, and in-process inspection shall be sufficient to insure control of product quality through the manufacturing cycle.

C. The sampling procedure shall include a list of the characteristics to be inspected or tested by the applicant or his agent.

D. The characteristics listed in accordance with paragraph (C) of this section shall be classified according to the potential effect of such defect and grouped into the following classes:

1. Critical: A defect that will cause the meter to be inaccurate so as to indicate a significantly lower-than-actual SO_2 concentration, or a defect that judgment and experience indicate is likely to result in a condition immediately hazardous to life, health, or safety for individuals either using the meter or depending upon its accuracy.
2. Major: A noncritical defect that will cause the meter to be inoperative or a defect that results in a significantly inaccurate indication of SO_2 concentration.
3. Minor: A defect that is not likely to materially reduce the usability or accuracy of the meter as a portable SO_2 monitor, or a defect that is a departure from established standards and has little bearing on the effective use or operation of the meter.

E. For each quality control inspection or test, acceptance and rejection criteria shall be described in detail.

F. Each item manufactured shall be 100 percent inspected or tested for critical defects and all items with critical defects shall be rejected. Further, during processing or assembly, each item being manufactured shall be 100 percent tested for performance as appropriate to the stage of completion, and each completed item shall be 100 percent tested for compliance with performance specifications set forth herein.

G. The AQL for each major or minor defect so classified by the applicant shall be:

(1) Major - 2.5 percent

(2) Minor - 4.0 percent

H. Except as provided in paragraph (I) of this section, inspection level II as described in MIL-STD-105D, or inspection level IV as described in MIL-STD-414, shall be used for major and minor characteristics and 100 percent inspection for critical characteristics.

I. Subject to the approval of the Institute, where the quality control plan provisions for raw material, processes manufacturing, and fabrication inspection are adequate to insure control of finished article quality, destructive testing of finished articles may be conducted at a lower level of inspection than that specified in paragraph (H) of this section.

III. Quality Control Plans; Approval by the Institute

A. Each proposed quality control plan submitted in accordance with this subpart shall be reviewed by the Institute to determine its effectiveness in insuring the quality of SO_2 meters for which approval is sought.

B. If the Institute determines that the proposed quality control plan submitted by the applicant will not insure adequate quality control, the Institute shall require the applicant to modify the procedures and testing requirements of the plan prior to approval of the plan and issuance of any certificate of approval.

C. Approved quality control plans shall constitute a part of and be incorporated into any certificate of approval issued by the Institute, and compliance with such plans by the applicant shall be a condition of approval.

IV. Quality Control Records; Review by the Institute; Revocation of Approval

A. The applicant shall keep quality control inspection records sufficient to carry out the procedures required in MIL-STD-105D or MIL-STD-414, or an approved equivalent sampling procedure. Quality control records for each batch or lot shall be kept for a minimum of four years.

B. The Institute reserves the right to have its representative inspect the applicant's quality control test methods, equipment, and records, and to interview any employee or agent of the applicant in regard to quality control test methods, equipment, and records.

C. The Institute reserves the right to revoke for cause any certificate of approval where it is found that the applicant's quality control test methods, equipment, or records do not insure effective quality control over the meter for which the approval was issued.

7.0 EVALUATION SUMMARY

The guidelines suggested for the meters evaluated during this program were portability (10 lbs, 1 ft^3 and battery operated), a direct-reading output (e.g., SO_2 in ppm), and a range of 1 to 50 ppm SO_2. None of the meters evaluated are suitable in view of these selection criteria and it is concluded from the market survey conducted that no suitable meters are currently available. The meters requested were those commercially available and prototype meters that came closest to meeting the selection criteria expressed in the guidelines.

A total of 9 meters and prototypes were requested for the evaluation program, and 6 were eventually received. Of the 6, only 2 can operate from batteries and only 1 (a third) is direct reading. In the following paragraphs, the 6 meters evaluated are discussed in view of their conformance to the selection guidelines and their performance characteristics.

The Casella is battery operated and portable. It operates from internal, rechargeable batteries and for a suitable period of time. It is not a direct-reading meter, however, and the SO_2 concentration of the sampled air must be calculated from the Casella's indirect readouts of time and conductivity. It does have a wide range and good physical characteristics, and the performance characteristics measured were also satisfactory. Unfortunately, an electronic problem evolved that prevented a complete evaluation of the Casella. However, in view of the selection guidelines, the Casella may be the most useful of the meters evaluated. If the electronic problem had not occurred and all of the performances were comparable to those actually measured, the conclusion would be that the Casella is the most suitable meter.

The CEA meter is also a portable meter. It operates from internal pen-light cells. The CEA achieves low power requirements and, thus, long battery life by utilizing a hand-operated pump to obtain an air sample. While portable, the CEA is not direct-reading and the meter readout must be interpreted in terms of the SO_2 concentration. It also has a limited range; i.e., the maximum range is 0 to 20 ppm. The performance characteristics of the CEA meter were not as good as similar performances measured on the Casella. In particular, the precision of a single measurement is not adequate and the manufacturer recommends averaging 3 separate readings for a single measurement.

The EM meter is not a portable meter. It requires a 60 Hz power source, a separate pump for sampling (it does not have an internal sampling system), and its warm-up time (30 minutes) is not conducive to portability. It was the only direct-reading meter evaluated and has ranges of 0 to 10, 50, and 100 ppm SO_2. The performance characteristics of the EM meter were excellent and the best of the meters evaluated. Aside from portability and sampling considerations, its physical characteristics were satisfactory. It does require both zero and calibration gases for zero and calibration adjustments, but its calibration stability is such that these adjustments are infrequent.

The Mast and PAI meters are neither portable nor direct-reading. Each requires a calibration curve to interpret the meter output in ppm of SO_2. Of the two, the Mast is the most portable in terms of physical size. However, it requires a 60 Hz source and its 2-hour warm-up time is not compatible with a portable meter. The meter's response is very non-linear with SO_2 concentrations. It has excellent zero stability and long-term calibration stability. However, the span does drift significantly with exposure to high concentrations of SO_2, and this drift also appears as a zero drift or base-line drift after the sample is returned to zero. The Mast meter is more suitable as a continuous SO_2 monitor and should be frequently referenced to a zero gas to detect any base-line or zero drift. The performance characteristics of the Mast would probably be much improved if it were evaluated over a lower range of SO_2 concentration.

The PAI meter is the largest and heaviest of the meters evaluated. In addition to being large and heavy, the PAI requires a 60 Hz power source and a 30-minute warm-up period. It was calibrated at RTI for a 0 to 50 ppm SO_2 range, and the calibration curve was extremely nonlinear. If it has been calibrated for a lower range (the manufacturer suggests an upper range of 30 ppm), the meter's response to SO_2 would have been more linear and its performance characteristics would undoubtedly have been improved.

The Wilks meter cannot be easily compared with the other meters evaluated. It, too, is neither portable nor direct-reading. Moreover, it is not an SO_2 meter, but an IR gas analyzer that can be calibrated to measure SO_2 concentrations. It is an excellent instrument and capable of measuring many contaminants in the hands of a skilled operator. As an SO_2 meter, the performance characteristics of the Wilks meter were compromised by the difficulty of reproducible setting the absorption wavelength for SO_2 (8.6μ). If calibrated in the laboratory and carried directly to the field without moving the wavelength control, the Wilks meter performances would undoubtedly be improved. The use of very high concentrations of SO_2 to set the wavelength control may also enhance the setting or resetting of the wavelength control.

APPENDIX A

MARKET SURVEY CORRESPONDENCE

APPENDIX A

MARKET SURVEY CORRESPONDENCE

This appendix includes copies of letters and lists of addressees for each letter mailed to determine the availability of SO_2 meters, to request meters for evaluation, and to seek information on quality control practices.

The initial correspondence was mailed to every manufacturer and distributor who could be identified as a possible source of instrumentation for air quality measurements. In some instances, correspondence was mailed to a manufacturer at multiple addresses when different guides and directories included different addresses.

The follow-up correspondence requested that specific instruments be submitted for the evaluation program. All of the instruments requested were not submitted for the evaluation program. Reasons stated included excessive inventory on consignment and inability to submit an instrument within a reasonable period of time.

Correspondence requesting quality control information and a list of addressees is also included in this appendix.

August 6, 1973

Dear

The Research Triangle Institute (RTI), under contract to the National Institute for Occupational Safety and Health (NIOSH), is conducting an evaluation of commercially available, portable sulfur dioxide (SO_2) meters. Manufacturers of suitable SO_2 meters are invited and encouraged to participate in this evaluation program. The NIOSH Contract No. is HSM 99-73-1 (Task Order No. 2), and the Project Officer is Mr. Charles McCammon, NIOSH, 1014 Broadway, Cincinnati, Ohio 45202 (513-684-2591). The Project Director at RTI is Mr. J. B. Tommerdahl, and the Project Leader is Mr. C. D. Parker.

Sulfur dioxide is a common air contaminant and is on the NIOSH priority list of toxic substances. Occupational Safety and Health Act (OSHA) inspectors would like to use direct-reading portable meters as compliance tools, but increased confidence is required in the data obtained. Consequently, an evaluation of the performance characteristics of these meters is urgently needed.

In response to the contract objectives, RTI is initially seeking to determine what portable direct-reading meters are commercially available for the measurement of SO_2 in the 1 to 50 ppm range. Manufacturers and distributors are requested to send brochures, specifications, and other information descriptive of suitable meters to RTI for consideration. As a general guideline, a suitable meter is a direct-reading SO_2 meter that weighs less than 10 pounds, occupies one cubic foot or less of volume, is sensitive in the 1-50 ppm range, and is battery operated. However, other promising meters, including prototypes, may be acceptable although they do not conform to these guidelines.

Meters will be selected for evaluation from the information received. Subsequent correspondence will include additional information relative to the program and will request specific meters for evaluation.

The duration of the evaluation program is 6 months and, consequently, it is urgent that informative descriptions of SO_2 meters suitable for the evaluation program be received as soon as possible. We would appreciate receiving this information by August 17, 1973.

Your prompt response to this request for descriptive literature and your cooperation with the evaluation program will be greatly appreciated. If additional information is desired, please call the undersigned at 919-549-8311.

Very truly yours,

C. D. Parker

CDP/jas

SULFUR DIOXIDE LIST

Combustion Equipment Instruments
ATTN: Mr. Martin Adelman
555 Madison Avenue
New York, New York 10022

Combustion Equipment Associates, Inc.
ATTN: Mr. Robert Davis
Instrument Division
1 Research Drive
Stamford, Connecticut 06906

Wilks Scientific Corporation
ATTN: Dr. Donald Lavery
P. O. Box 449
S. Norwalk, Connecticut 06856

Theta Sensors, Inc.
ATTN: Dr. Arnold Miller
1015 North Main Street
Orange, California 92667

EnviroMetrics, Inc.
ATTN: Dr. Shaw
13311 Beach Avenue
Marina Del Rey, California 90291

Pollution Monitors, Inc.
ATTN: Mr. Norman A. Lyshkov
970 Montana Street
Chicago, Illinois 60614

Mast Development Co.
ATTN: Mr. J. A. Carrig
2212 E. 12th Street
Davenport, Iowa 52803

Meloy Laboratories, Inc.
ATTN: Marketing Director
6715 Electronic Drive
Springfield, Virginia 22151

Meloy Laboratories, Inc.
ATTN: Mr. J. R. Thompson
6631 Iron Place
Springfield, Virginia 22151

The Bendix Corporation
ATTN: Marketing Director
Environmental Science Div.
1400 Taylor Avenue
Baltimore, Maryland 21204

E. I. DuPont de Nemours & Co.
ATTN: Marketing Director
Inst. Products Division
1007 Market Street
Wilmington, Delaware 19898

Dynasciences Corporation
ATTN: Marketing Director
Environmental Products Division
9100 Independence Avenue
Chatsworth, California 91311

Peerless Instrument Co., Inc.
ATTN: Mr. Simon Deutsch
512 Main Street
Westbury, New York 11590

Philips Electronics Instrument
ATTN: Mr. Frank J. Kabot
750 S. Fulton Avenue
Mt. Vernon, New York 10550

Tracor, Inc.
ATTN: Mr. Kenneth O. Mahler
Analytical Instruments
6500 Tracor Lane
Austin, Texas 78721

Lear Siegler, Inc.
ATTN: Marketing Director
Spectrometrics
30 Denver Technological Center
Englewood, Colorado 80110

Calibrated Instruments, Inc.
ATTN: Marketing Director
731 Saw Mill River Road
Ardsley, New York 10502

Metronics Associates
ATTN: Marketing Director
3201 Porter Drive
Palo Alto, California 94304

Calibrated Instruments, Inc.
ATTN: Marketing Director
17 West 60th Street
New York, New York 10023

Houston Atlas, Inc.
ATTN: Marketing Director
9441 Baythorne Drive
Houston, Texas 77041

Scientific Industries, Inc.
ATTN: Marketing Director
15 Park Street
Springfield, Massachusetts 01103

Devco Engineering, Inc.
ATTN: Marketing Director
36 Pier Lane West
Fairfield, New Jersey 07006

Intertech Corporation
ATTN: Marketing Director
19 Roszel Road
Princeton, New Jersey 08540

Leeds & Northrup Co.
ATTN: Mr. J. A. Williamson
Summytown Pike
North Wales, Pennsylvania 19454

Scott Aviation
ATTN: Mr. Robert H. Van Derveer
Division of A-T-O, Inc.
Route 29N, Box 751
Charlottesville, Virginia 22902

Atlas Electric Devices Co.
ATTN: Marketing Director
4114 North Ravenswood Avenue
Chicago, Illinois 60613

Litton Environmental Systems
ATTN: Mr. Ralph J. Sullivan
P. O. Box 745
3841 East Santa Rosa Road
Camarillo, California 93010

Barton ITT
ATTN: Marketing Director
Process Instruments and Controls
580 Monterey Pass Road
Monterey Park, California 91754

Beckman Instruments
ATTN: Marketing Director
2500 Harbor Blvd.
Fullerton, California 92634

Process Analyzers, Inc.
ATTN: Mr. Thomas C. Dennis
6400 Southwest Freeway
Suite 400
Houston, Texas 77036

Ericson Instruments
ATTN: Marketing Director
P. O. Box 226
Ossining, New York 10562

Analytical Instrument Development, Inc.
ATTN: Mr. Edward W. Cleplinski
250 S. Franklin
West Chester, Pennsylvania 19380

Varian Aerograph
ATTN: Mr. Barry Mitchell
2700 Mitchell Drive
Walnut Creek, California 94598

Barringer Research, Inc.
ATTN: Marketing Director
304 Carlingview Dr.
Rexdale, Ontario, Canada

Environmental Measurements, Inc.
ATTN: Marketing Director
215 Leidesdorff Street
San Francisco, California 94111

Aero Vac Corp.
ATTN: Marketing Director
S. Bedford St.
Burlington, Massachusetts 01803

Varian Associates
ATTN: Marketing Director
611 Hansen Way
Branch, New Jersey 08855

Aero Vac Corp.
ATTN: Marketing Director
69 Arch Street
Green Istand
Troy, New York 12183

Hewlett-Packard Co.
ATTN: Marketing Director
1501 Page Mill Road
Palo Alto, California 94304

Dynasciences Corporation
ATTN: Marketing Director
Environmental Products Division
9100 Independence Avenue
Chatsworth, California 91311

Dynasciences Corporation
ATTN: Marketing Director
9601 Canoga Avenue
Chatsworth, California 91311

Mine Safety Appliances
ATTN: Marketing Director
Instrument Division
201 North Braddock Ave.
Pittsburgh, Pennsylvania 15208

Environmental Data Corporation
ATTN: Mr. Robert J. Bombeck
608 Fig Avenue
Monrovia, California 91016

Spectrometrics of Florida, Inc.
ATTN: Mr. Forrest C. Douglas
P. O. Box 517
Pinellas Park, Florida 33565

Antek Instruments, Inc.
ATTN: Marketing Director
6005 N. Freeway
Houston, Texas 77022

Bacharach Instrument Co.
ATTN: Mr. F. T. Counsell
625 Alpha Drive
Pittsburgh, Pennsylvania 15238

Johnson-William Products
ATTN: Marketing Director
Bacharach Instrument Co.
2300 Leghorn Street
Mountain View, California 94040

Dohrmann Div.
ATTN: Marketing Director
Envirotech Corp.
1062 Linda Vista Ave.
Mountain View, California 94040

Environment/One Corp.
ATTN: Marketing Director
2773 Balltown Road
Schenectady, New York 12309

F & J Scientific
ATTN: Marketing Director
79 Far Horizons Drive
Monroe, Connecticut 06468

Lovibond of America, Inc.
ATTN: Mr. B. J. Czemba
870 Willis Ave.
Albertson, New York 11507

National Environmental Instruments, Inc.
ATTN: Marketing Director
P. O. Box 590
Pilgrim Station
Warwick, Rhode Island 02888

National Environmental Instruments, Inc.
ATTN: Marketing Director
P. O. Box 590
Fall River, Massachusetts 02722

Raytheon Co.
ATTN: Marketing Director
Submarine Signal Div.
P. O. Box 360
Portsmouth, Rhode Island 02871

Research Appliance Co.
ATTN: Marketing Director
Route 8
Allison Park, Pennsylvania 15101

Scientific Industries, Inc.
ATTN: Mr. Ralph J. Bulger
150 Herricks Road
Mineola, New York 11501

Technicon Instruments Corp.
ATTN: Marketing Director
511 Benedict Ave.
Tarrytown, New York 10591

Teledyne Analytical Instruments Div.
ATTN: Marketing Director
Teledyne, Inc.
333 W. Mission Dr.
San Gabriel, California 91776

Wilkens-Anderson Co.
ATTN: Mr. R. E. Wilkens
4525 W. Division St.
Chicago, Illinois 60651

Bendix Corporation
ATTN: Marketing Director
Process Instrument Division
P. O. Drawer 477
Ronceverte, West Virginia 24970

Central Scientific Company
ATTN: Dr. William H. Baier
Division of Cenco Instruments Corporation
2600 South Kostner Avenue
Chicago, Illinois 60623

Monitor Labs, Inc.
ATTN: Mr. Warren Steinberger
10451 Roselle Street
San Diego, California 92121

Wilks Scientific Corporation
ATTN: Mr. Paul A. Wilks, Jr.
140 Water Street
Box 449
South Norwalk, Connecticut 06856

BGI Incorporated
ATTN: Marketing Director
1254 Main Street
Waltham, Massachusetts 92154

Instrument Development Co.
ATTN: Marketing Director
1916 Newton Square, West
Reston, Virginia 22070

EnviroMetrics, Inc.
ATTN: Marketing Director
13311 Beach Avenue
Marina Del Ray, California 90291

Bell & Howell Co.
ATTN: Marketing Director
Electronic Instrument Group
300 N. Sierra Madre Villa
Pasadena, California 91109

Ranson Wallace & Baesel, Inc.
ATTN: Mr. E. F. Baesel, Jr.
Dynasciences Corporation
1815 Park Drive
Charlotte, North Carolina 28207

Bailey Meter Co.
ATTN: Marketing Director
29801 Euclid Ave.
Wickliffe, Ohio 44092

Boder Scientific Co.
ATTN: Marketing Director
810-814 Penn Ave.
Pittsburgh, Pennsylvania 15222

Combustion Engineering, Inc.
ATTN: Marketing Director
National Tank Co. Div.
Box 1710
Tulsa, Oklahoma 74101

Englehard, Inc.
ATTN: Marketing Director
Charles
East Newark, New Jersey

Gas Analysis Systems, Inc.
ATTN: Marketing Director
Box 146 R
Basking Ridge, New Jersey 07920

General Electric Co.
ATTN: Marketing Director
1 River Road
Schenectady, New York 12305

Granville-Phillips Co.
ATTN: Marketing Director
Box 1290
5675 E. Arapahoe Ave.
Boulder, Colorado 80302

The Hays Corp.
ATTN: Marketing Director
744 E. 8th Street
Department C7
Michigan City, Indiana 46360

Melpar, Inc.
ATTN: Marketing Director
Special Products Dept.
7700 Arlington Blvd.
Falls Church, Virginia 22046

The Perkin-Elmer Corp.
ATTN: Marketing Director
750 Main Ave.
Norwalk, Connecticut 06851

Seiscor, A Div. of Seismograph Service Corp.
ATTN: Marketing Director
6200 E. 41st Street
P. O. Box 1590
Tulsa, Oklahoma 74102

Standard Instrument Corp.
ATTN: Marketing Director
657 Broadway
New York, New York 10012

Thermco Instrument Corp.
ATTN: Marketing Director
U. S. 20 and 125 W.
La Porte, Indiana 46350

Veeco Instruments, Inc.
ATTN: Marketing Director
Terminal Drive
Dept. BB
Plainview, L. I., New York 11803

Ultek Division
ATTN: Marketing Director
The Perkin-Elmer Corp.
Box 10920
Dept. BB
Palo Alto, California 94303

Orion Research, Inc.
ATTN: Marketing Director
11 Blackstone Street
Cambridge, Massachusetts 02139

Canadian Research Institute
ATTN: Marketing Director
85 Curlew Dr.
Don Mills, Ontario, Canada

Intertech Corporation
ATTN: Marketing Director
262 Alexander St.
Princeton, New Jersey 08540

Kimoto Electric Corp. Ltd.
ATTN: Marketing Director
42 Funahashi-Cho
Tennoji-Ku
Osaka, Japan

Olson Horiba
ATTN: Marketing Director
1021 Duryea Ave.
Irvine Industrial Complex
Santa Ana, California 92705

Van Waters & Rogers/Will Scientific
ATTN: Marketing Director
1363 S. Bonnie Beach Place
Los Angeles, California 90054

Anacon Inc.
ATTN: Marketing Director
62 Union St.
Ashland, Massachusetts 01721

Burhans-Sharpe
ATTN: Marketing Director
P. O. Box 3906
Seattle, Washington 98124

Combustion Equipment Association
ATTN: Marketing Director
61 Taylor Reed Drive
Glenbrook, Connecticut 06906

Environmental Instruments Co.
ATTN: Marketing Director
1346 Willow Road
Menlo Park, California 94025

General Monitors, Inc.
ATTN: Marketing Director
3019 Enterprise St.
Costa Mesa, California 92626

Gow-Mac Instrument Co.
ATTN: Marketing Director
100 Kings Road
Madison, New Jersey 07940

Research & Development Products
ATTN: Marketing Director
1808A Harmon Street
Berkeley, California 94703

Rockland Instrument Corporation
ATTN: Marketing Director
P. O. Box 205
Pearle River, New York 10965

Scientific Research Instruments
ATTN: Marketing Director
6707 Whitestone Road
Baltimore, Maryland 21207

Theta Sensors
ATTN: Marketing Director
2000 Corporation
5899 So. State St.
Salt Lake City, Utah 84107

Antek Instrument Inc.
ATTN: Marketing Director
P. O. Box 7903
Houston, Texas 77007

Applied Automation Inc.
ATTN: Marketing Director
3838 S.E. State St.
Bartlesville, Oklahoma 74003

Chemical Data Systems Inc.
ATTN: Marketing Director
Oxford, Pennsylvania 19363

Unico Environmental Instruments
ATTN: Marketing Director
P. O. Box 590
Fall River, Massachusetts 02722

Carle Instruments, Inc.
ATTN: Marketing Director
1141 E. Ash Ave.
Fullerton, California 93731

RESEARCH TRIANGLE INSTITUTE
POST OFFICE BOX 12194
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27709

ENGINEERING DIVISION

We appreciate your prompt response to our recent request for information on portable sulfur dioxide (SO_2) meters. We have reviewed the information received and concluded that your Model No. is suitable for the purposes of the evaluation program we are conducting. We invite your further participation in the program by requesting that a Model No. be sent to us for evaluation. Reasonable care will be exercised in the use of this instrument and it will be promptly returned at the completion of the evaluation.

The Research Triangle Institute (RTI) is conducting this evaluation of portable SO_2 meters under contract to the National Institute for Occupational Safety and Health (NIOSH). The NIOSH Contract No. is HSM-99-73-1 (Task Order No. 2), and the Project Officer is Mr. Charles McCammon, NIOSH, 1014 Broadway, Cincinnati, Ohio 54202 (513-684-2591). The Project Director at RTI is Mr. J. B. Tommerdahl and the Project Leader is Mr. C. D. Parker.

A paper presented by Mr. Paul Roper of NIOSH at a recent seminar for industrial hygiene equipment manufacturers' representatives is enclosed which discusses the incentive for this evaluation program and lists the meter characteristics to be evaluated.

The duration of the evaluation program is six months and it is anticpated that the experimentation will be completed in early December 1973. Consequently, it is urgent that participants in the evaluation program submit meters for evaluation as soon as possible. Meters should be shipped to RTI to the attention of Mr. C. D. Parker by September , 1973.

Meters submitted for evaluation must be accompanied by a statement excluding RTI and NIOSH from responsibility for damages which might occur to the meter during the evaluation program. Each meter should be calibrated prior to shipment to RTI and should be accompanied by a calibration curve. Necessary accessories should also be included. A complete operational manual featuring operating instructions, flow diagrams and circuit diagrams, for example, are required for the evaluation program and must be included. Material routinely supplied to purchasers of the instrument should be clearly identified. The manufacturer should also submit any additional information that will enhance the evaluation of the meter characteristics to be considered.

The following points are also relevant to the SO_2 meter evaluation program and are called to your attention.

1. Based upon the results of the evaluation program, RTI will recommend to NIOSH a set of performance standards and quality control standards applicable to portable SO_2 meters.

2. Each manufacturer is entitled to see the results of the evaluation of his meter only. Results of tests on other meters will be kept confidential until Government publication of test results.

3. The results of the evaluation may be published at a later date. If so the performance of meters found not to comply with recommended standards is also subject to public disclosure. Any Government publication resulting from these evaluations will note that only one meter was tested and will state which meters, if any, are prototypes.

4. The results of the preliminary evaluation released to the participant by RTI may not be used for advertising purposes or as a claim of endorsement by NIOSH. Any publication resulting from these evaluations can, of course be referenced.

5. The loan of a meter for evaluation is made without obligation on the part of RTI or the Federal Government to reimburse you for damages to the meter.

6. Shipment of a meter to RTI may be made C.O.D. (include insurance). RTI will return the meter F.O.B. your plant (with full insurance coverage).

7. Manufacturers of SO_2 meters are not required to submit an instrument for evaluation, but are requested to do so in the interest of an improved measurement capability.

Your prompt reply to this invitation and your cooperation in this evaluation program will be greatly appreciated. If you desire additional information, please call the undersigned at 919-549-8311.

Very truly yours,

C. D. Parker

CDP:clh
Enclosure

SO_2 METERS REQUESTED

1. EnviroMetrics, Inc.
Attn: Mr. Irv A. Waterstreet
13311 Beach Avenue
Marina Del Ray, California 90291
(Model S-364 or Portable Prototype)

2. Process Analyzers, Inc.
Attn: Mr. William A. Lewis
5440 Alder
Houston, Texas 77036
(Titrilog III)

3. Scientific Industries, Inc.
Attn: Mr. Theodore M. Shlisky
150 Herricks Road
Mineola, New York 11501
(Prototype)

4. Combustion Equipment Instruments
Attn: Mr. Martin Adelman
555 Madison Avenue
New York, New York 10022
(U2-DS)

5. Mast Development Co.
Attn: Mr. J. A. Carrig
2212 E. 12th Street
Davenport, Iowa 52803
(Model 812-1)

6. Houston Atlas, Inc.
Attn: Mr. Charles L. Kimbell
9441 Baythorne Dr.
Houston, Texas 77041
(Modified Model 850)

7. BGI Inc.
Attn: Mr. Robert A. Gussman
1254 Main Street
Waltham, Massachusetts 92154
(Casella SO_2 Monitor)

8. Dynasciences Corp.
Attn: Mr. Roland V. Marcote
Environmental Products Division
9100 Independence Avenue
Chatsworth, California 91311

9. Wilks Scientific Corp.
Attn: Dr. Donald S. Lavery
140 Water Street
P. O. Box 449
South Norwalk, Connecticut 06856

RESEARCH TRIANGLE INSTITUTE
POST OFFICE BOX 12194
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27709

ENGINEERING DIVISION

August 29, 1973

Dear :

Further to our letter of August 6, 1973, we can inform you that, as a part of our NIOSH contract, previously referenced, we are preparing a draft proposed rule-making covering portable sulfur dioxide (carbon monoxide) meters. This rule-making, to be published in the Federal Register, will include performance and quality control system requirements.

In order to assist us in making rational decisions regarding quality control sampling plans and appropriate AQL's (Acceptable Quality Levels) commonly used in your industry, we are soliciting information about the following from your quality control department:

1. What sampling plans or systems do you use at incoming inspection?
2. What sampling procedures do you use in in-process inspection?
3. What sampling plans do you use in final inspection? If tests are destructive, do you use MIL-STD-414? If not, lower level sampling?
4. What AQL's do you assign to critical, major and minor attribute defects?
5. What kind of defects do you consider to be critical, major and minor?
6. What inspection procedures do you employ to determine adherence to specified values of electronic components?

Any information you can give us in these areas will be greatly appreciated and will be carefully weighed and considered in making any decisions. Please be assured that any information provided relative to your quality control procedures will be considered confidential.

Members of your industry will, of course, be given opportunity to review, comment and make recommendations for changes to the proposed rule-making prior to final publication in the Federal Register.

Thank you for your cooperation and interest.

Very truly yours,

C. D. Parker

CDP/dg

QC MAILING LIST

Combustion Equipment Instruments
ATTN: Mr. Martin Adelman
555 Madison Avenue
New York, New York 10022

EnviroMetrics, Inc.
ATTN: Mr. Irv A. Waterstreet
13311 Beach Avenue
Marina Del Rey, California 90291

Mast Development Co.
ATTN: Mr. J. A. Carrig
2212 E. 12th Street
Davenport, Iowa 52803

E. I. DuPont de Nemours & Co.
ATTN: James R. Small
Inst. Products Division
1007 Market Street
Wilmington, Delaware 19898

Dynasciences Corporation
ATTN: Roland V. Marcote
Environmental Products Division
9100 Independence Avenue
Chatsworth, California 91311

Philips Electronics Instrument
ATTN: Mr. Frank J. Kabot
750 S. Fulton Avenue
Mt. Vernon, New York 10550

Houston Atlas, Inc.
ATTN: Charles L. Kimbell
9441 Baythorne Drive
Houston, Texas 77041

Process Analyzers, Inc.
ATTN: Mr. W. A. Lewis
5440 Alder
Houston, Texas 77036

Environmental Data Corporation
ATTN: Dr. Harry C. Lord
608 Fig Avenue
Monrovia, California 91016

Dohrmann Div.
ATTN: Mr. John McCutchen
Envirotech Corp.
1062 Linda Vista Avenue
Mountain View, California 94040

Environment/One Corp.
ATTN: Mr. Robert H. Mack
2773 Balltown Road
Schenectady, New York 12309

Scientific Industries, Inc.
ATTN: Mr. Theodore M. Shlisky
150 Herricks Road
Mineola, New York 11501

BGI Incorporated
ATTN: Mr. Robert A. Gussman
1254 Main Street
Waltham, Massachusetts 92154

Thermonetics Corporation
ATTN: Mr. James J. Kacirk
P. O. Box 9112
1028-A Garnet Avenue
San Diego, California 92109

Analytical Instrument Development, Inc.
ATTN: Mr. Edward W. Cieplinski
250 S. Franklin Street
West Chester, Pennsylvania 19380

Monitor Labs, Inc.
ATTN: Mr. Edward Etess
10451 Roselle Street
San Diego, California 92121

Energetics Science, Inc.
ATTN: John D. McStravick
4461 Bronx Boulevard
New York, New York 10470

Mine Safety Appliances Company
ATTN: Tom D. McConnell
201 North Braddock Avenue
Pittsburgh, Pennsylvania 15208

Wilks Scientific Corporation
ATTN: Dr. Donald Lavery
P. O. Box 449
S. Norwalk, Connecticut 06856

Harold W. Tomlinson
1 - A Lincoln Avenue
Albany, New York 12205

E. D. Bullard Co.
ATTN: Mr. George Cisco
2680 Bridgeway
Sausalito, California 94965

Beckman Instruments, Inc.
ATTN: Mr. R. L. Chapman
2500 Harbor Blvd.
Fullerton, California 92634

Peerless Instrument Company
ATTN: Simon Deutsch
90-15 Corona Avenue
Elmhurst, New York 11373

Thermco Instrument Corp.
P. O. Box 309
La Porte, Indiana 46350

Matheson Gas Products
ATTN: Mr. Morton Gilbert
P. O. Box 85
East Rutherford, New Jersey 07037

Environmental Meteorology Corporation
ATTN: Dr. Verne R. Brown
2308 South Industrial Highway
Ann Arbor, Michigan 48104

Purad, Inc.
ATTN: Dr. W. B. Innes
724 Kilbourne Dr.
Upland, California

Olson-Horiba
ATTN: Mr. Roy W. Awalt
1021 Duryea Avenue
Irvine Industrial Complex
Santa Ana, California 92705

Universal Environmental Instruments, Ltd.
ATTN: Mr. R. Connell
31 Nuffield Estate, Poole
Dorset BH17 7RZ, England

Copy to:

Smith-Jesse, Inc.
ATTN: Marketing Director
500 Hauser Street
Los Angeles, California

APPENDIX B

ANALYSIS OF SO_2 DATA

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Barium Chloranilate Method for 28 ppm and 49 ppm SO_2

A statistical analysis of measured values of the 28 ppm and 49 ppm SO_2 concentrations was conducted for the purpose of determining the accuracy and precision of the measurements and the stability of these calibration gases over time. Data were obtained over 17 days on each of the SO_2 concentrations (28 ppm and 49 ppm). The number of measurements made each day varied from one to five, most of them being two per day. The analysis examines both the day-to-day variations and the within-day variations. Thus an analysis of variance of the data was performed to subdivide the total variation in the observed concentrations into a portion measuring the within-day variation among individual observations and that explaining the day-to-day variation in the daily mean values.

Calculations and Results

The calculations are given in Tables IA and IB for the 28 ppm and 49 ppm data, respectively. The results are given in Tables II and III. Tables IA and IB contain the number of measurements per day, n, the daily mean $\bar{X}$ and variance s^2, for each concentration level. They also contain the sum and sum of squares of the observed concentrations for use in subsequent analysis. Tables II and III contain the sources of variation in the 28 ppm and 49 ppm data, respectively, subdivided into that within and between days. The second column contains the number of degrees of freedom (D.F.) associated with the respective source. For example, there are 43 observations over 17 days, resulting in 42 D.F., i.e., 26 D.F. within days and 16 D.F. between days. (The remaining number of D.F. is obtained by subtraction, i.e., 42 - 16 = 26.) The next column in Tables II and III contains the sum of squares (S.S.) for each source. These values are obtained as follows:

TABLE IA

CALCULATIONS FOR 28 PPM SO_2

	n	$\Sigma X = D_T$	ΣX^2	$\bar{X}$	s^2
11/7/73	5	134.1	3617.55	26.82	5.247
11/10/72	2	51.9	1367.93	25.95	21.125
11/14/73	5	138.7	3863.19	27.74	3.913
11/16/73	1	32.9	1082.41	32.9	------
11/26/73	2	58.1	1690.45	29.05	2.645
11/28/73	5	145.7	4303.57	29.14	14.468
11/30/73	2	63.3	2003.49	31.65	0.045
12/3/73	2	68.5	2399.17	34.25	53.045
12/10/73	2	57.8	1670.6	28.9	0.18
12/12/73	2	54.2	1470.44	27.1	1.62
12/17/73	2	66.4	2212.48	33.2	8.00
12/19/73	2	69.4	2425.0	34.7	16.82
12/26/73	2	55.9	1564.61	27.95	2.205
1/4/74	3	88.1	2613.29	29.36	13.042
1/7/74	2	58.7	1726.49	29.35	3.645
1/9/74	2	65.1	2145.65	32.55	26.645
1/14/74	2	59.2	1758.8	29.6	6.48
Totals	43	1268.0	37,915.12		

TABLE IB

CALCULATIONS FOR 49 PPM SO_2 DATA

	n	$\Sigma X = D_T$	ΣX^2	$\bar{X}$	s^2
11/7/73	5	242.0	11765.08	48.4	13.07
11/10/73	2	97.9	4795.33	48.95	3.125
11/14/73	5	259.4	13460.82	51.88	0.787
11/16/73	2	91.6	4195.46	45.8	0.180
11/26/73	2	100.2	5020.02	50.1	0
11/28/73	5	249.8	12510.90	49.96	7.723
11/30/73	2	97.8	4788.20	48.9	5.78
12/3/73	2	98.8	4909.60	49.4	28.88
12/10/73	2	103.9	5397.73	51.95	0.125
12/12/73	2	95.7	4604.45	47.85	25.205
12/17/73	2	99.9	5000.13	49.95	10.125
12/19/73	2	104.9	5519.41	52.45	17.405
12/26/73	2	105.8	5630.44	52.9	33.62
1/4/74	1	50.6	2560.36	50.6	-----
1/7/74	2	104.7	5507.69	52.35	26.645
1/9/74	2	95.6	4575.46	47.8	5.78
1/14/74	2	91.2	4158.72	45.6	0
Totals	42	2089.8	104,399.80		

TABLE II

ANALYSIS OF VARIANCE OF SO_2 DATA

Source of Variation	D.F.	S.S.	M.S.	E(M.S.)
Total	42	523.86	12.47	
Between Days (Analyses)	16	260.81	16.30	$\sigma_W^2 + 2.49\ \sigma_B^2$
Within Days	26	263.05	10.12	σ_W^2

TABLE III

ANALYSIS OF VARIANCE OF 49 PPM SO_2 DATA

Source of Variation	D.F.	S.S.	M.S.	E(M.S.)
Total	41	417.32	10.18	
Between Days (Analyses)	16	174.13	10.88	$\sigma_W^2 + 2.43\ \sigma_B^2$
Within Days	25	243.19	9.73	σ_W^2

$$\text{S.S.(Total)} = \Sigma X^2 - \frac{(\Sigma X)^2}{N = 43} ,$$

$$\text{S.S.(Bet. Days)} = \Sigma \frac{D_T^2}{n_D} - \frac{(\Sigma X)^2}{43} ,$$

$$\text{S.S.(Within Days)} = \Sigma X^2 - \Sigma \frac{D_T^2}{n_D} .$$

In the above, D_T refers to the daily totals tabulated in Tables 1A and IB ($\Sigma X = D_T$), and n_D is the number of measurements making up the corresponding daily total. Thus,

$$\text{S.S.(Total)} = 37{,}915.12 - \frac{(1268)^2}{43} = 523.86 ,$$

$$\text{S.S.(Bet. Days)} = \frac{(134.1)^2}{5} + \frac{(51.9)^2}{2} + \ldots + \frac{(59.2)^2}{2} - \frac{(1268)^2}{43} = 260.81,$$

$$\text{S.S.(Within Days)} = 37{,}915.12 - \frac{(134.1)^2}{5} + \frac{(51.9)^2}{2} + \ldots + \frac{(59.2)^2}{2} = 263.05,$$

$$= 37{,}915.12 - \text{S.S.(Bet. Days)} .$$

Finally, the mean square (M.S.) is obtained by dividing the S.S. by the respective D.F. The last column gives the expected mean square (E(M.S.)). The calculated mean square in Tables II and III is a variance and is an estimate of a corresponding true variance. Referring to Table II, for example, $(10.12 \text{ ppm})^2$ is an estimate of the variance of observations taken within a day, σ_W^2; 16.30 is an estimate of the within day variability and that between days multiplied by a coefficient depending on the number of observations made on each day. If two were made on all days the coefficient would be 2.0. In Table II, it is 2.49 because five measurements were made on three days (Ref. 6). Estimates of σ_W^2 and σ_B^2 are denoted by $\hat{\sigma}_W^2$ and $\hat{\sigma}_B^2$, respectively, and can be obtained by equating the calculated values to the expected values and solving the resulting equations.

For Table II these values become

$$\hat{\sigma}_W^2 = 10.12, \text{ and}$$

$$\hat{\sigma}_B^2 = \frac{16.30-10.12}{2.49} = 2.48 \ .$$

The variance of a single measurement taken on each day is estimated to be

$$\hat{\sigma}^2(X) = \hat{\sigma}_W^2 + \hat{\sigma}_B^2 = 10.12 + 2.48 = (12.60 \text{ ppm})^2 \ ,$$

and the standard deviation is

$$\hat{\sigma}(X) = 3.55 \text{ ppm} \ ,$$

resulting in a coefficient of variation (ratio of standard deviation to the mean) of

$$CV(X) = \frac{3.55}{29.5} = 0.12 \text{ or } 12 \text{ percent} \ .$$

Similar analyses are performed for the 49 ppm concentration data. The values for $\hat{\sigma}_W^2$ and $\hat{\sigma}_B^2$ are 9.73 and 0.47 for a total of $\hat{\sigma}^2(X) = 10.20 \text{ ppm}^2$. Thus $\hat{\sigma}(X) = 3.2$ ppm and the CV(x) is 3.2/49.8 = 0.065 or 6.5 percent. Note that the standard deviation has not changed significantly, but that the CV has decreased. This indicates that the precision of the measurement is not dependent on the concentration level and that its precision should be reported in absolute terms, i.e., $\hat{\sigma}(X) = 3.55$ ppm or $\hat{\sigma}(X) = 3.2$ ppm. An average of these two values would be appropriate as a single reporting value.

Additional information can be obtained from Tables II and III. Note that the ratio of the between-days M.S. to the within-days M.S. is small in each case. This indicates that the within-days variation explains the greatest part of the total variation. (This is not typical of what often happens in practice. The day to day measurements often tend to fluctuate as a group due to instrumentation calibration problems, variation in technique from day to day, or change in analysts.) The small contribution between days implies that there is no trend in the data or instability in the day to day techniques.

Confidence Interval for the Mean Concentration

Using the results of the preceding analyses, a confidence interval for the mean concentration can be obtained as follows:

$$\text{Confidence Interval (CI)} = \text{Overall mean } (\bar{X}) \pm t\, s(\bar{X}), \text{ or}$$

$$(CI) = \bar{X} \pm t\, s(\bar{X}).$$

For a 95 percent confidence interval,

$$95\%(CI) = 29.5 \pm 2.12(0.616)\ .$$

Thus, $28.2 \text{ ppm} \leq 95\%(CI) \leq 30.8$ ppm, where $t = 2.12$ is obtained from a student t table (t distribution) for 16 degrees of freedom (No. of days less one). The 0.616 is the estimated standard deviation of $\bar{X}$, obtained by dividing 16.3 by 43. One notes from the above that the 95%(CI) does not include the nominal value of 28 ppm, suggesting either a slight bias in the measurements or in the reported nominal value. The bias was not apparent in the 49 ppm data as the 95 percent confidence interval is

$$95\%(CI) = 49.75 \pm 2.12(0.509), \text{ or}$$

$$48.6 \text{ ppm} \leq 95\%(CI) \leq 50.8 \text{ ppm}.$$

This interval contains 49 ppm. This fact suggests that the 28 ppm as reported was too low.

West-Gaeke Method for 0.92 ppm

The analysis of these data was conducted in the same manner as that for the 28 ppm and 49 ppm data, with the exception that an additional source of variation was introduced. These sources are tabulated in Table IV.

TABLE IV

ANALYSIS OF VARIANCE OF 0.92 PPM SO_2 DATA

Source of Variation	D.F.	S.S.	M.S.	E(M.S.)
Total	34	0.7778	.0229	
Between Samples	2	0.6442	.3221	$\sigma_W^2 + 5\sigma_B^2 + 10\sigma_S^2$
Between Days	4	0.0205	.0051	$\sigma_W^2 + 5\sigma_B^2$
Within Days	28	0.1131	.0040	σ_W^2

The estimated variance components; $\hat{\sigma}_W^2 = .0040$, $\hat{\sigma}_B^2 = .0002$ and $\hat{\sigma}_S^2 = .0317$, identify the sampling process as suspect for the large variation (as was obvious on examination of the data in this case). The degrees of freedom are small for the between samples and between days analyzed, hence not too much validity can be associated with these estimates. A check of the consistency of the observed mean concentration with the stated mean of 0.92 ppm was made using the t test,

$$t = \frac{0.967 - 0.92}{0.095} = 0.49$$

and indicated no significant difference. Because of the large sampling deviation and small number of degrees of freedom, moderate deviations in the measured concentration from the true concentration (approx. 20%) would go undetected.

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15. Supplementary Notes

16. Abstract (Limit: 200 words) The performance capabilities and limitations of available and prototype sulfur-dioxide (7446095) (SO2) meters were studied. An attempt was made to determine the best techniques for using each meter in a field testing situation and to develop a recommended set of performance standards and quality control standards for such meters. Altogether, six meters were identified and tested, including the Casella SO2 Sampler T1400, the CO2 Ultra Portable Analyzer U2-DS, the Sulfur-Dioxide Analyzer S-364, the Microcoulomb Detector Model 724-21MS, the Titrilog-III, and the Miran-I Variable Filter Infrared Analyzer. Characteristics measured for each sampler included stability, drifts, linearity, response times, and specificity. Evaluations were also made of physical characteristics including portability, readout, instruction manuals, and ease of zero and span adjustments. Recommended performance and construction standards, and quality control standards were provided.

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