BERC/RI-76/9

**QUALITY-CONTROL GAS-DETECTOR TUBE READERS:
OPTICAL VERSUS OBSERVER**

By

H. B. Carroll, Jr.

Date Published—December 1976

MASTER

Bartlesville Energy Research Center
Energy Research and Development Administration
Bartlesville, Oklahoma

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H. B. Carroll, Jr.¹

ABSTRACT

The influence of temperature and humidity upon two length-of-stain gas detector tube systems was studied. Length-of-stain tubes were exposed under carefully controlled laboratory conditions, then read by a panel of observers and a newly developed optical tube reader. Data from the study show, generally, good correlation of results between the observer panel and the optical tube reader. Also, the data indicated that temperature and humidity calibration curves or tables were needed for several of the detector tubes. The two detector tube systems were comparable in reliability; however, for detecting a particular gas, one system may be selected over the other.

INTRODUCTION

One of the portable instrument systems most widely used by the industrial hygienist and the average miner is the gas-detector tube. These detector tube systems are easy to operate, consisting only of a hand-held pump used to draw a controlled volume of the work atmosphere through a glass tube containing a reactive chemical bed. The resulting chemical reaction produces a color change in the chemical bed. Depending upon the type, the concentration of the toxic gas is proportional to the length of stain or to the color intensity. Each manufacturer has a prescribed method (or calibration scale) for use with its tube system, some even have graduated scales printed on the tube. The reliability of the results with these tubes depends upon proper calibration of the detector tubes, the degree of stability of the reacting chemical, the ambient temperature, and a means to read reliably the exposed tube.

The reliability of these devices was questioned so frequently that studies were prompted to evaluate them. Comprehensive studies of the detector systems

¹ Research physicist.

were made and results reported (7)²; however, development of new or improved devices quickly outdated these reports. More recently, Kusnetz, Saltzman, and Lanier (8) reported the calibration and evaluation of some detector tubes for gases such as arsine, carbon monoxide, nitrogen, dioxide, stibine, phosgene, chlorine, chlorine dioxide, and mercury vapor. In 1962, Saltzman (10) presented theoretical mathematical expressions for indicator-tube calibrations. He concluded that "The accuracy, limitations, and applications of indicator tubes are highly dependent upon the skill with which they were manufactured." In 1970, Morgenstern, Ash, and Lynch (9) reported results of a study on detector tubes for carbon monoxide, carbon tetrachloride, and sulfur dioxide. Ash (1) reported the accuracy of the carbon monoxide tubes to be ± 25 percent. In 1971, Ash and Lynch (2) reported that carbon tetrachloride and sulfur dioxide detector tubes have similar precision ranges. Johnson (6) published work on hydrogen sulfide detector tubes in 1972 and stated that only one set of detector tubes met performance standards. Carroll and Armstrong have published results from length-of-stain tube evaluations (3-4) attributing a large degree of the inconsistency to the observer's interpretation of the results rather than from a predominant difference in the tubes.

Because of criticism of detector tubes and the wide spread in investigators' results, a standard optical tube reader was developed by the National Institute of Occupational Safety and Health (NIOSH). This instrument has been proposed as a replacement for observer panels when establishing tube calibrations or for quality-control tests. The optical tube reader produces a permanent record of the length of stain in the form of an optical density tracer.

The objectives of this investigation were (1) to determine the influence of temperature and humidity upon detector-tube performance and (2) to establish a correlation between the two reader systems: observer and optical tube reader. In this research, length-of-stain tubes exposed under carefully controlled laboratory conditions were read by both a panel of observers and the NIOSH optical tube reader. This report describes the apparatus and techniques used for preparing gas mixtures, establishing gas concentrations, and reading the tubes, and presents an evaluation of the data.

GAS DETECTOR TUBE READERS

Observers

A panel of three observers--a physicist, a chemist, and a secretary--was chosen to read the length-of-stain tubes. These observers had normal vision based

² Underlined numbers in parentheses refer to items listed in the references at the end of this report.

on the American Optical Sight-Screening tests and normal color vision based on the Ishihara Color-Blindness tests (5).

General instructions to the panel consisted of the following:

1. Read the instructions carefully and thoroughly. Ask questions about anything of which you are not sure.
2. Do NOT observe the other reader's results. Independent readings are necessary.
3. Read the tube as accurately as possible. Interpolate between scale marks if practical. (Check to see if scale is linear when interpolating). Record all readings.
4. Rotate the tube to get the average end point and record.
5. Note any difficulties encountered or general comments.

Optical Tube Reader

The NIOSH Gas-Detector Tube Analyzer system was designed to scan length-of-stain tubes optically and provide permanent graphic records, in millimeters of length, of reagent layers, packings and stain lengths. Because of the wide range of tubes and consequently stain lengths differences, the system contains more controls than would be necessary if the system were designed to analyze only one type of detector tube. The unit shown in figure 1 is essentially made up of three subsystems:

1. A specially designed optical scanner.
2. The signal processor unit, located in the center of the mounting rack.
3. The recorder unit, located at the top of the mounting rack is a modified Hewlett Packard X-Y recorder³.

The optical tube reader has the capability of producing records of the stain lengths in one of three different modes of operations. Typical records of the three modes of analysis available from the optical tube reader are shown in figure 2. Several trial records from each mode of operation were produced with an exposed tube.

- a. Direct line scan of the detector tube length. (See figure 2-A.) Channeling in the tube is not taken into account in this mode. Even a record produced by direct scan in the integrated mode would exhibit channeling errors.
- b. Rotational direct scan of the detector tube length. (See figure 2-B.) This mode yields records with excessive noise resulting in large uncertainties in the stain length.

³ Mention of brand names does not imply endorsement by ERDA.

FIGURE 1. - Gas detector tube analyzer.

a) Direct line scan of the detector tube length. Channeling in the tube is not taken into account in this mode. A record produced by direct scan in the integrated mode would exhibit channeling errors.

b) Rotational direct scan of the detector tube length. This mode yields records with excessive noise resulting in large uncertainties in the stain length.

c) Rotational integrated scan of the detector tube length. This mode produces a record of the stain by integrating around the tube's circumference which takes into account the channeling effect in most tubes. This mode was used throughout the test program.

FIGURE 2. - Three modes of operation of the optical tube reader.

- c. Rotational integrated scan of the detector tube length. (See figure 2-C.) This mode produces a record of the stain by integrating around the tube's circumference which takes into account the channeling effect in most tubes. This mode was used throughout the test program.

EXPERIMENTAL

The scope of work in relation to the testing of detector tubes included the purchasing of two different brands of detector tubes for each of the gases listed in table 1. Five tubes of each brand of detector tubes were tested at two concentrations (TLV and 2 x TLV) under two conditions each of temperature and relative humidity.

TABLE 1. - Tube systems evaluated

Substance of interest	Detector tube number	
	Gastec/Bendix	Drager/National Mine Service
CO ₂	Carbon dioxide low-range detector tube no. 2L	Drager tube CH23501 carbon dioxide tube 0.1%/a
CO	Carbon monoxide low-range detector tube no. 1La	Drager tube CH25601 carbon monoxide 5/c
NO	Nitrogen oxides (NO and NO ₂) simultaneous detector tube no. 10	Drager tube CH31001 nitrous fumes (NO + NO ₂)a/a
NO ₂	Nitrogen dioxide low-range detector tube no. 9L	Drager tube CH 30001 nitrogen dioxide 0.5/c
SO ₂	Sulfur dioxide low-range detector tube no. 5La	Drager tube CH31701 sulfur dioxide 1/a
H ₂ S	Hydrogen sulfide extra-low-range detector tube no. 4LL	Drager tube CH29801 hydrogen sulfide no. 5/b
HCHO	Formaldehyde detector tube no. 91	Drager tube CH26401 formaldehyde 0.002

With the assistance of the NIOSH project officer, two tube systems were selected for testing. Drager tubes purchased from National Mine Service and Gastec tubes, from Bendix. Shown in table 1 are the names and numbers of the tubes used in this program.

Test Apparatus

A commercial, controlled temperature-humidity system, Model FR-256PB, manufactured by the Blue M Electric Co., contains the test chamber and controls necessary to maintain a controlled atmosphere.

The cabinet housing contains the test chamber, temperature controls, a dual recording system for wet- and dry-bulb temperatures, and a refrigeration system supplying the cooling coils. Chamber atmosphere temperature is controlled in the range of 3° to 93° C, and relative humidity, in the range from near 20 to 95 percent. Any precalibrated temperature and humidity can be reset with a precision of $\pm 1^\circ$ C temperature and ± 2 percent relative humidity.

Precise control of the simulated work atmosphere in the test chamber during instrument evaluation required continuous monitoring of the contaminants in the test atmosphere. Gas monitors for carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO), nitrogen dioxide (NO₂), hydrogen sulfide (H₂S), sulfur dioxide (SO₂), and formaldehyde (HCHO) were used to monitor the test gas concentrations in the chamber atmosphere (either as single components or simultaneously).

CO was measured with an Ecolyzer Carbon Monoxide Analyzer Model 2400 manufactured by Energetics Science Inc. A 100-ppm CO blend, checked periodically on a long-path IR Instrument, was used to calibrate the Ecolyzer.

CO₂ was measured by thermal conductivity with a Chrono-Frac gas chromatograph containing a 1-meter-long by 0.63-cm-diameter column filled with 13x molecular sieve. Samples were withdrawn periodically from the chamber and injected into the gas chromatograph. The chromatograph was calibrated after each sample injection by successive injections of a known concentration CO₂ blend.

Continuous measurement of NO and NO₂ was made with a Thermo Electron Model 14 Chemiluminescent Analyzer. The Model 14 includes a NO₂ to NO converter for the measurement of NO₂ via the chemiluminescent process. Calibration of the instrument was maintained with known concentrations of NO₂ from permeation tubes and NO from a commercial supplier.

Hydrogen sulfide was measured on a flame photometric detector manufactured by Micro Tek Instruments Corp. This instrument was calibrated with known concentrations of hydrogen sulfide from a permeation tube.

Sulfur dioxide was measured with a modified Mast ozone meter manufactured by Mast Development Co. Span gas from either a calibration blend or a permeation tube were used to calibrate the instrument at the beginning and end of a test series.

Formaldehyde was measured using the chromotropic acid method. A batch-sampling technique was used with this procedure.

Gas-Blending System

The gas-blending system, composed of gas permeation tubes and standard gas blends, was made for accurate production of atmospheres containing desired contaminants from the low parts-per-million range up to the low percent range (3-4). The permeation tube system was used for calibration purposes as well as a chamber atmosphere maintenance source. Precisely metered streams of dry nitrogen pass over permeation tubes, contained in a constant-temperature water bath, and mix with the pure component diffusing from the tube. Gas-flow restrictors and/or rotameters are used to control the flow of gases such as CO and CO₂. The gases are contained in 34-liter stainless steel blending tanks and high-pressure cylinders.

The gas stream from either the calibration blend or permeation tube was diluted with controlled amounts of air or nitrogen and flowed to the stainless steel chamber through 0.64-cm-diameter Teflon tubes. Dry nitrogen continually flows over the permeation tubes when they are not in use.

Each primary instrument was subject to periodic calibrations with known concentrations of the toxic gas obtained by dynamically blending air with effluent from either permeation tubes or flows from standard blends. The precision with which a desired concentration could be obtained during blending depended upon the reproducibility of setting and flow accuracy of the flowmeters as well as upon the permeation rate. Errors in the flow rate were evaluated by repetitive settings to a given point on the flowmeter and then measuring the resulting flow with a wet-test meter or a soap-bubble meter. Repetitive settings were periodically made at two or three points because the calibration curve was being prepared for the rotameters. The maximum deviation from the average flow was 2 percent for one rotameter and 3 percent for the other. This suggests a probable error in setting a concentration level of 3 to 4 percent.

During the course of testing, the permeation rate of each tube was determined gravimetrically. These permeation tubes maintained their rate within 3 percent until close to the end of the tube's life expectancy.

EVALUATION PROCEDURE

Preparation of the Optical Reader

The mode of operation chosen for the measurement of stain lengths was the rotational optical signal scan. The three fluorescent lamps and the recorder servo were activated and remained on for approximately 2 hours before testing began.

An exposed tube was used to adjust the balance and span of the amplifier system for optimum output to the recorder.

Preparation of the Test Atmosphere

After selecting the experimental conditions for a particular test, the chamber temperature and humidity controls were set, and the tubes to be evaluated were placed inside the chamber. The reference instruments were calibrated and connected to the chamber to monitor continuously the chamber contents. After the atmosphere had reached the preselected temperature and humidity, the chamber was quickly brought to the proper toxic gas concentration by injecting calculated volumes of pure components. Then a flow of the proper makeup blend was set such that the monitor instrument displayed a constant chamber concentration.

Exposing Gas-Detector Tubes

Testing began after the tubes had been in the chamber at constant temperature and humidity for about 2 hours. Five separate gas-detector tubes were used from each detector system at the selected fractional TLV value. The tips were broken off each end of the detector tube, and the proper end was inserted into the sample pump. The sampling cycle was started by making the required number of strokes on the pump and waiting for the time specified by the tube manufacturer after each stroke. As the work atmosphere was drawn through the tube at a controlled rate, a color change indicated the presence of the toxic gas. The exposed tube was then removed from the chamber through a 3/8-inch port for reading by observers and the optical tube reader.

RESULTS

Preparation for the tests conducted in this study involved establishing and maintaining low concentrations of reactive gases at reasonably constant concentrations during instrument evaluations. Maintaining the low concentrations at a constant value, even with a makeup air stream containing high concentrations of the contaminants, was a problem. Instrument surfaces, chamber surfaces, and glove surfaces were reactive to SO_2 , H_2S , HCHO and NO_2 , and significant losses were evident. However, the toxic gas concentration was stabilized with the makeup blend flow before testing began.

The test began after the observer panel and the optical reader were set up. Gas-detector tubes exposed in the test chamber were removed and placed in the optical tube reader. A record of the stain length was made, then a panel of three observers read the tube using the scales provided by the manufacturer. Each observer read the manufacturer's instructions before the tests began and were unaware of the gas concentration in the work atmosphere.

The NIOSH Gas Detector Tube Analyzer provided a permanent graphic record (as shown in figure 3) in millimeters of the stain length in the exposed gas-detector tubes. Each of the exposed tubes was placed in the spring-loaded collet then the balance and span were set. The scan was turned on to begin the optical examination of the material in the tube. As the pointer of the optical probe crossed the tube scale, a mark was made on the chart, as shown in the scan record in figure 3. The scan continued well into the unexposed tube and at times continued for the entire length of the tube.

FIGURE 3. - Analysis of a Gastec CO detector tube.

An analysis of each record produced by the optical tube reader yielded three points: minimum, midpoint, and maximum. An example of the analysis is shown in figure 3. First, lines corresponding to the exposed and unexposed material were drawn, A and B, then the line C corresponding to the transitional layer was drawn to intersect lines A and B. The three points consisted of each of the two intersections of the minimum and maximum lines with the transitional line C, and the midpoint between A and B along line C. The number of 0.5 mm marks was counted to each

of these points from the start of the reactive material. The position of each of these points in terms of the tube scale was calculated by a linear interpolation between the marks placed on the chart while the record was being made. Results from the analysis of the tube records and the observers are shown in tables 1 through 8 of appendix B.

DISCUSSION

Several problems encountered during the testing of the tubes were in design rather than in the performance of the reactive materials. The first rather troublesome problem was the dusty material that came from the reagent bed of some of the Drager tubes--the formaldehyde and sulfur dioxide tubes in particular. This particulate material was drawn into the pump and settled out on the face of the disk valve causing leakages to varying degrees. Another problem frequently encountered with the Gastec tubes at the temperature extremes was that their reagent material would separate when the pump handle was drawn back. This occurred randomly among the Gastec tubes.

The gas-detection tubes used in this study had calibration scales on the tubes as direct-reading scales. These marks interfered with the optical tube reader when scanning the exposed tubes. The spikes in the traces shown in figure 3 are a result of the tube scales.

The optical tube reader performed well throughout the entire test program. Rotational optical scans of a plastic tube blank with several optical densities along its major axis has shown the instrument output to be highly reproducible. This analytical instrument is a useful addition to the detector-tube testing program; however, it does not remove all observer or operator bias involved in tube readings. Ideally, the analysis of the length-of-stain tube records would be straightforward, not requiring any judgment or decision on the part of the analyst. However, many of the records produced by the optical stain tube reader for the tubes listed in table 1 were not shaped as regular as the trace shown in figure 3. Records, as shown in figures 4 and 5, were obtained which required a greater degree of judgment from the analyst as to the placement of lines A and B previously described. These uncertainties are reflected in the relatively large σ values listed in tables 1 through 8 of appendix B.

Each gas-detector-tube manufacturer recognizes that relative humidity and temperature are major variables in the chemical reactions taking place in their length-of-stain tubes, and in their operating instructions try to offset these effects with a table of corrections, if necessary. Table 2 shows the manufacturer's comments on corrections for both temperature and humidity on the tubes used in this study. Even though no correction is necessary in the 20-to-90 percent range, humidity is recognized as a potential variable in the reaction. For those that had no specification, it was assumed that no correction is deemed necessary by the manufacturer.

TABLE 2. - Manufacturer's temperature and humidity specifications

Dräger detector tubes		
Detector tube number	Temperature effect	Humidity effect
Dräger tube CH 23501 Carbon dioxide tube 0.1 percent/a	The calibrated scales printed on the tubes are valid for 1 or 5 strokes when tube and gas are within -10° and $+40^{\circ}$ C.	No specification.
Dräger tube CH25601 Carbon monoxide 5/c	The calibrated scales printed on the tubes are valid for 2 or 1C strokes when tube and gas are within -10° and $+90^{\circ}$ C.	No specification.
Dräger tube CH31001 Nitrous fumes ($\text{NO} + \text{NO}_2$)a/a	The tubes can be used in a temperature range between 10° and 40° C.	The moisture of the air sample is retained in the oxidizing layer and has no influence on the measurement.
Dräger tube CH30001 Nitrogen dioxide 0.5/c	Tubes can be used in a temperature range from 0° to 40° C.	The ambient humidity has no effect on the result of measurement.
Dräger tube CH31701 Sulfur dioxide 1/a	The calibrated scale printed on the tubes is valid when both tube and gas sample are within 10° and 30° C.	The moisture content of the gas sample does not affect the measurement.
Dräger tube CH29801 Hydrogen sulfide No. 5/b	The tubes may be used between 0° and 60° C.	No specification.
Dräger tube CH26401 Formaldehyde 0.002	The calibrated scale printed on the tube applies when both tube and gas sample are within 0° and 40° C.	No specification.
Gastec detector tubes		
Carbon dioxide low-range detector tube No. 2L	Tube calibration is based on a tube temperature of 20° C, not the gas temperature. No temperature correction required in the range 0° to 40° C.	No specification.
Carbon monoxide low-range detector tube No. 1La	Calibration based on a tube temperature of 20° C. Tube readings must be corrected with temperature correction table on each tube box. (0° to 40° C)	No humidity correction is required for relative humidity range of 20 to 90 percent.
Nitrogen oxides (NO and NO_2) Simultaneous detector tube No. 10	Nitrogen dioxide requires no correction for temperature from 0° to 40° C. Nitric oxide must be corrected according to temperature correction table on each box of tubes. (0° to 40° C).	No correction is needed for relative humidity range of 10 to 90 percent.
Nitrogen dioxide low-range detector tube No. 9L	No correction is required for tube temperatures of 0° to 40° C.	No correction required for relative humidity greater than 10 percent.

TABLE 2. - Manufacturer's temperature and humidity specifications--Continued

Gastec detector tubes--Continued		
Detector tube number	Temperature effect	Humidity effect
Sulfur dioxide low-range detector tube No. 5La	For tube temperature correction use the temperature correction table on each tube box regardless of the number of pump strokes taken. (0° to 40° C)	No correction is needed for relative humidity range of 10 to 90 percent.
Hydrogen sulfide extra-low-range detector tube No. 4LL	No tube correction is required for tube temperatures in the range of 0° to 50° C.	No relative humidity correction is required in the range of 20 to 90 percent.
Formaldehyde detector tube No. 91	No correction is required for temperatures in the range of 0° to 40° C.	No correction is required for relative humidity in the range from 20 to 90 percent.

FIGURE 4. - Gastec CO₂ tube record from a test with CO₂ at ~0.5 percent.

FIGURE 5. - Gastec CO₂ tube record from a test with CO₂ at ~1.0 percent.

Verifying the influence of temperature of the results obtained with the length-of-stain tubes requires not only detecting the effect but also determining whether recommended corrections are adequate. The effect of temperature is somewhat different for each type of tube, depending upon the chemical reaction with the gas they are used to detect. Only three systems, CO, NO, and SO₂ as shown in table 2, have temperature-correction tables included in the manufacturer's instructions. For the remainder of the tubes, the manufacturers make statements such as: "No temperature correction is required for tube temperatures in ranges from 0° to 40° C (32° to 104° F)." Notice in table 2 that the upper temperature limit on most of the tubes is 40° C (104° F). However, in this study, the upper limit on temperature is 49° C (120° F); therefore, the data must be extrapolated up to the 49° C point. (See figure 6.) The influence of both variables was considered for the tube systems according to the gas being detected.

It is evident from the data with the optical tube reader on the tube scale in tables 1 through 8 of appendix B that the midpoint shows the higher degree of accuracy when compared to the reference CO concentration. However, a test of differences showed statistically that the midpoint was closer to the accurate value than either of the end points. Furthermore, the observer's values are closer to the midpoint of the optical tube reader value showing that the observers are reading a value that is an average between the extreme cutoff point such as the maximum and the completely exposed area as the minimum.

Carbon Monoxide

The data from the Gastec-Bendix CO tubes did not indicate significant dependence upon humidity. The data plotted in figure 7 indicate a very slight increase in response as the humidity increases from 50 to 90 percent. Testing these data with the Aspin-Welch test showed no statistical difference in the means at 50 percent RH compared to 90 percent RH, and the increase has been attributed to slight scatter in the data. These results agree with the manufacturer's statement that humidity does not affect the operation of the length-of-stain tubes in the range from 20 to 90 percent.

The manufacturer stated that the temperature of the tubes will affect their performance and gave a correctional chart with instructions for their application. First, each raw data point was corrected for temperature with the curves shown in figure 6, then corrected again if more or less than one pump stroke was used. The resulting corrected data were used to calculate the mean and standard deviation. Plots shown in figure 7 of both the observer's values and the midpoint from the optical tube reader indicate the specified correction at the higher temperature, 75° to 120° F, to be adequate for the 50 ppm curve, but the 40° F point still read too high. Data for the 100 ppm curve at the temperature extremes did not

(a) Carbon monoxide tube (ILA) temperature correction

(b) Sulfur dioxide tube (8531) temperature correction

FIGURE 6. - Corrections for temperature extrapolated to 120° F for Gastec/Bendix length-of-stain gas detector tubes.

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 7. - Effects of temperature and humidity upon the Gastec/Bendix length-of-stain tubes when exposed to an atmosphere containing 50 and 100 ppm CO.

have enough of a correction range for the curve. In fact, the 40° F point was approximately 25 percent high and the 120° F point 25 percent low.

Least-square fits of the midpoint data from the optical tube reader to the reference CO level in the test atmosphere yielded an equation of

$$Y = 12.22 + 0.78X \quad (1)$$

with a correlation coefficient of 0.833. A similar exercise with the observer data yielded a least-squares equation of

$$Y = 13.64 + 0.73X \quad (2)$$

with a correlation coefficient of 0.804. The optical tube reader gave results that correlated better than observer readings of the Gastec/Bendix length-of-stain CO tubes.

The data from the Drager length-of-stain tubes, shown plotted in figure 8, indicated that the tubes were not significantly affected by temperature or humidity. These results agree with the manufacturer's statement that humidity does not affect the operation of the length-of-stain tubes in the range from 20 to 90 percent.

Least-square fit of the midpoint data from the optical tube reader to the reference CO level in the test atmosphere yielded an equation of

$$Y = 12.49 + 0.789X \quad (3)$$

with a correlation coefficient of 0.955. Similar calculations with the observer data gave a least-squares equation of

$$Y = 9.55 + 0.832X \quad (4)$$

with a correlation coefficient of 0.965. In this case, the observer's data showed a higher degree of correlation to the reference CO level.

Carbon Dioxide

Figure 9-A shows an increase in response approximately 20 percent to CO₂ for a 25° F rise in temperature at the 10⁴ ppm level. However this may only be due to the one point at 120° F. The decrease in response with a change in humidity (at the higher CO₂ concentration) is due to scatter in observer data.

Temperature and humidity had no significant effect upon the carbon dioxide length-of-stain tubes, as shown by plots in figures 9 and 10. This agreed with the manufacturer's statement that the performance of the tubes is not affected by

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 8. - Effects of temperature and humidity upon the Drager length-of-stain tubes when exposed to an atmosphere containing 50 and 100 ppm CO.

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 9. - Effects of temperature and humidity upon the Gastec/Bendix length-of-stain tubes when exposed to an atmosphere containing 5,000 and 10,000 ppm CO₂.

changes in temperature and humidity in the ranges used in this study. Examining the Gastec/Bendix system data and calculation of a least-square fit of the midpoint data from the optical tube reader to the reference CO₂ level in the test atmosphere yielded an equation of

$$Y = -683.02 + (1.004)X \quad (5)$$

with a correlation coefficient of 0.998. Similar calculation for the observer's data yielded a least-squares equation of

$$Y = -1398.7 + (0.871)X \quad (6)$$

with a correlation coefficient of 0.992. These data showed that the optical-tube-reader results gave a better correlation than the observer readings.

Data from the Drager system, plotted in figure 10, show the same trend. The results of the optical tube reader were correlated to give a least-squares fit of

$$Y = -833.7 + (1.22)X \quad (7)$$

with a correlation coefficient of 0.949. The observer's data gave a least-squares fit of

$$Y = -146.4 + (0.974)X \quad (8)$$

with a correlation coefficient of 0.941.

Nitrogen Oxide

The test data from the Gastec/Bendix tube system, plotted in figure 11, indicate no significant temperature or humidity effect. Also, in the concentration range tested, the tubes show good precision and accuracy.

Least-square fit of the midpoint data from the optical tube reader to the reference CO level in the test atmosphere yielded an equation of

$$Y = 5.27 + 0.834X \quad (9)$$

with a correlation coefficient of 0.990. The observer's data gave an equation of

$$Y = 0.757 + (1.124)X \quad (10)$$

with a correlation coefficient of 0.979.

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 10. - Effects of temperature and humidity upon the Drager length-of-stain tubes when exposed to an atmosphere containing 5,000 and 10,000 ppm CO₂.

FIGURE 11. - Effects of temperature and humidity upon the Gastec/Bendix length-of-stain tubes for NO when exposed to an atmosphere containing 25 and 50 ppm NO.

The results from the Drager tubes (figure 12) show an effect from both temperature and humidity upon the indicated NO concentration. Generally, the results show that as the temperature increases the indicated toxic gas concentration increases. The effect from an increasing humidity would be a slight decrease in tube response.

As shown in figure 12, the optical tube reader gives a higher concentration coefficient of 0.829 versus the observer's of 0.803.

Nitrogen Dioxide

The test data from the Gastec/Bendix tubes, plotted in figure 13, show a temperature effect on the response of the tubes to NO₂. Generally, the data indicate that as the temperature increases, the NO₂ response decreases. This result is shown by the data from the optical tube reader as well as from the observers. Increasing the relative humidity does not show a consistent effect.

Least-squares fit of the midpoint data from the optical tube reader to the reference CO level in the test atmosphere yielded an equation of

$$Y = 3.51 + (0.471)X \quad (11)$$

with a correlation coefficient of 0.810. The observer correlation was

$$Y = 3.13 + (0.497)X \quad (12)$$

with a correlation coefficient of 0.812. There is no significant difference in the correlation coefficients.

The test data from the Drager tubes, plotted in figure 14, indicate no significant temperature or humidity effect upon their response to NO₂. This agrees with the manufacturer's specifications for the temperature and humidity ranges tested.

Least-squares fit of the optical tube reader data and the observer data to the reference levels gave correlation coefficients of 0.994 and 0.966, respectively. The observer's results gave a higher correlation to the reference level than the optical tube reader.

Sulfur Dioxide

The data from the Gastec/Bendix tubes (figure 15) indicate no significant dependence upon temperature; however, a slight humidity effect is noted. The data plotted in figure 15 indicate a slight increase in response as the humidity

FIGURE 12. - Effects of temperature and humidity upon the Dräger length-of-stain tubes for NO when exposed to an atmosphere containing 25 and 50 ppm NO.

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 13. - Effects of temperature and humidity upon the Gastec/Bendix length-of-stain tubes for NO₂ when exposed to an atmosphere containing 5 and 10 ppm NO₂

FIGURE 14. - Effects of temperature and humidity upon the Drager length-of-stain tubes for NO_2 when exposed to an atmosphere containing 5 and 10 ppm NO_2 .

FIGURE 15. - Effects of temperature and humidity upon the Gastec/Bendix length-of-stain tubes for SO₂ when exposed to an atmosphere containing 5 and 10 ppm SO₂.

increases from 50 to 90 percent. In the plot shown, the optical-tube-reader results do not show as great a humidity effect as the observer's results.

Least-squares fit of the midpoint data from the optical tube reader to the reference SO_2 level in the test atmosphere yielded an equation of

$$Y = 2.501 + (0.629)X \quad (13)$$

with a correlation coefficient of 0.870. Similar calculation for the observers gave an equation of

$$Y = 2.931 + (0.510)X \quad (14)$$

with a correlation coefficient of 0.832. The optical-tube-reader results gave a significantly higher correlation coefficient.

The results from the Drager tubes (figure 16) were significantly influenced by both temperature and humidity. As the temperature or humidity was increased, the response of the tubes to SO_2 increased. These data suggest the need for a temperature and humidity correction chart for the tubes.

Least-squares fit of the optical-tube-reader data and the observer data gave correlation coefficients of 0.523 and 0.593, respectively. The observer's results gave a slightly higher correlation to the reference than the optical tube reader, but not significant.

Formaldehyde

The data from the Gastec/Bendix tubes in figure 17 did not indicate significant dependence upon humidity; however, the temperature slightly affected the tube response to formaldehyde. Least-squares fit of the midpoint data from the optical tube reader and the observer data to the reference level gave correlation coefficients of 0.714 and 0.841, respectively. The observer's results gave a higher correlation.

The Drager tubes gave results (figure 18) that indicate their response to formaldehyde to be slightly sensitive to changes in temperature and humidity. However, the number of data points is limited, and more work needs to be done on this system. A very low correlation coefficient was calculated for the optical-tube-reader results.

CONCLUSIONS

Generally, the agreement between the optical tube reader and the readings of the observers was good. The observer's readings of the stain length most frequently agreed with the midpoint on the curve produced by the optical tube reader when the transitional layer from stain to unstained was broad. However,

(a) Readings from optical tube reader

(b) Readings from three observers

(c) Instrument correlations

(d) Effect of humidity

FIGURE 16. - Effects of temperature and humidity upon the Drager SO₂ length-of-stain tubes when exposed to an atmosphere containing 5 and 10 ppm SO₂.

FIGURE 17. - Effects of temperature and humidity upon the Gastec/Bendix formaldehyde length-of-stain tubes when exposed to an atmosphere containing 2.5 and 5.0 ppm of formaldehyde.

FIGURE 18. - Effects of temperature and humidity upon the Drager formaldehyde length-of-stain tubes when exposed to an atmosphere containing 2.5 and 5.0 ppm of formaldehyde.

when this transitional layer was relatively short the agreement appeared to be randomly distributed between the three points: minimum, midpoint, or maximum. A statistical analysis of these data may not be sufficient to make a statement as to which point agrees for all batches from even a particular manufacturer.

The following statements generally summarize the correlation between the optical tube reader and observers.

1. The 50 percent point determined from the optical tube reader has the best correlation with the true value.
2. The observers are reading closer to the 50 percent point than to either of the end points.
3. Good agreement is found between the measured 50 percent point and the observer's readings.
4. Generally, the tube reader has less uncertainty in its readings than do the observers. (Confounded with the record analyst error.)
5. Scales on the tubes significantly interfered with the optical scan of the tube and with the interpretation of the record produced.
6. There is a need for temperature and humidity calibration curves for several of the detector tubes.

Based on the results of the tests in this study, the two detector tube systems are comparable in reliability. However, for detecting a particular gas under specific conditions, one system may be chosen over the other, depending upon the preference of the operator.

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APPENDIX A--COMPARING REFERENCE CONCENTRATIONS

As previously stated, testing length-of-stain tubes involved making blended atmospheres at approximately the same concentration level on different days because of changing other parameters in the program such as temperature and humidity. Therefore, when comparing the tube results for effects due to different temperatures and humidities there is also the possibility that some of the effects may be due to statistically different reference levels. In order to make valid comparisons and to assure there were no statistically significant differences in the prepared reference levels, the Aspin-Welch test for difference between two sample means was used. This may be thought of as a modified t-test with reduced degrees of freedom as follows:

The Aspin-Welch test (1) consists in treating

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (\text{A-1})$$

as if it had a t distribution with degrees of freedom given by

$$v = \frac{1}{\frac{c^2}{n_1 - 1} + \frac{(1 - c)^2}{n_2 - 1}} \quad (\text{A-2})$$

where

$$c = \frac{s_1^2/n_1}{s_1^2/n_1 + s_2^2/n_2},$$

$$s_1^2 = \frac{\sum (\bar{X}_1 - \bar{X}_1)^2}{n_1 - 1} \text{ and } s_2^2 = \frac{\sum (\bar{X}_2 - \bar{X}_2)^2}{n_2 - 1},$$

with

v = degrees of freedom,
 c = dimensionless variable, and
 s_1^2 and s_2^2 = variances of $\bar{X}_1$ and $\bar{X}_2$, respectively.

For example, consider the CO toxic gas concentration in appendix B, table 3 where it is given as:

$\bar{X}_1 = 51.4$ with $\sigma = 0.670$ at 50 percent relative humidity
 $n_1 = 17$

$$\bar{X}_2 = 50.8 \text{ with } \sigma = 0.852 \text{ at 90 percent relative humidity}$$

$$n_2 = 7$$

Using the Aspin-Welch test the degrees of freedom are calculated by

$$c = \frac{(0.670)^2/17}{\frac{(0.670)^2}{17} + \frac{(0.852)^2}{7}} = 0.20298, \quad (\text{A-3})$$

therefore

$$v = \frac{1}{\frac{0.04120}{16} + \frac{0.63524}{6}} = \frac{1}{0.10845} = 9.22, \quad (\text{A-4})$$

and

$$t = \frac{51.4 - 50.8}{\sqrt{\frac{(0.670)^2}{17} + \frac{(0.852)^2}{7}}} = \frac{0.6}{\sqrt{0.13011}} = 1.66 \quad (\text{A-5})$$

which is less than the $t_{.025}$ point 2.262. Therefore the hypothesis $\bar{X}_1 = \bar{X}_2$ and the two CO concentrations are statistically the same. A similar examination of the remaining pairs of means have shown them to be the same.

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APPENDIX B. - SUMMARY OF GAS DETECTOR RESPONSE

TABLE B-1. - Average length of stain and toxic gas concentration at 50 percent relative humidity and 75°F from the Gastec/Bendix tube system

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Average	σ	Average	σ	Average	σ		
CO {	51.4	0.67	3.63	0.11	5.84	0.40	8.11	0.66	29.08	0.70	57.43	2.63	88.2	4.89	55.0	5.77	58.0	5.03	63.3	4.79
	98.9	.76	6.54	.49	8.70	.73	10.87	.64	70.30	6.83	101.60	8.59	132.98	9.19	95.6	8.14	106.0	8.94	109.4	9.32
CO ₂ {	4,900	160	6.97	1.19	6.22	1.00	5.50	.76	6,440	1,330	5,540	1,080	4,660	880	5,500	930	5,660	879	5,800	834
	10,100	100	14.2	2.13	12.74	1.66	11.26	1.45	11,960	2,290	10,300	1,740	8,800	1,490	11,700	2,636	11,900	3,248	11,600	2,815
NO {	25.3	.54	5.88	1.16	8.26	.84	10.48	.84	17.55	1.44	22.98	1.37	27.40	1.25	21.40	.89	21.4	1.34	21.60	2.07
	48.8	.27	12.52	1.18	15.70	.62	37.80	.63	34.2	5.14	50.32	2.91	71.14	4.08	43.00	5.70	42.00	5.70	40.00	6.12
NO ₂ {	5.00	.11	13.00	1.47	18.80	.99	24.25	1.00	3.30	.42	5.34	.36	7.92	.55	5.30	.27	5.00	.00	5.50	.35
	9.82	.08	28.90	2.86	31.80	1.34	34.80	.74	11.08	2.67	13.74	1.78	17.14	.50	9.80	.84	9.60	.42	10.20	.45
SO ₂ {	4.80	.07	16.58	.63	12.56	.93	8.30	2.80	4.46	.30	4.02	.44	3.58	.45	4.30	.84	4.60	.65	4.52	.60
	10.00	.35	32.60	2.93	28.28	3.11	24.0	3.58	12.62	2.08	11.56	2.29	10.70	2.33	12.40	2.41	12.40	2.41	12.68	2.27
HCHO {	2.71	.29	10.72	1.84	14.61	1.62	18.41	1.55	4.06	.43	6.00	.41	8.28	.52	2.40	1.52	3.80	1.64	5.20	2.86
	3.94	.29	9.05	1.45	13.13	1.83	17.48	2.76	3.32	.33	5.35	.43	7.86	.81	5.80	1.10	6.00	1.41	6.20	1.48

TABLE B-2. - Average length of stain and toxic gas concentration at 90 percent relative humidity and 75°F from the Gastec/Bendix tube system

Toxic gas	Standard concentration, ppm		Optical tube reader										Observer panel							
			Length of stain, mm						Tube scale, ppm				Tube scale, ppm							
	Minimum Average σ	Midpoint Average σ	Maximum Average σ	Minimum Average σ	Midpoint Average σ	Maximum Average σ	Average σ	Average σ	Average σ	Average σ	Average σ	Average σ	Average σ	Average σ	Average σ					
CO {	50.8	0.85	3.17	0.95	6.46	1.43	9.73	4.08	25.7	8.5	59.3	3.3	108.6	41.2	58.4	6.7	54.2	4.3	70.4	5.5
	99.1	.94	6.75	.17	8.91	.20	10.94	.35	72.6	2.4	103.6	2.9	133.9	4.6	100.6	1.3	108.6	3.8	112.0	3.7
CO ₂ {	4,900	160	6.97	1.19	6.22	1.0	5.50	.76	7,100	800	5,500	800	4,200	900	5,600	700	5,800	700	5,900	700
	10,400	320	14.41	2.15	12.75	1.24	11.10	.14	12,300	2,400	10,300	1,400	8,600	400	11,200	1,100	11,400	1,700	11,800	1,500
NO {	25.14	.24	7.10	.22	8.85	.56	10.70	1.04	21.2	.45	24.7	1.15	28.66	3.07	21.0	1.0	20.8	.84	23.8	1.9
	47.56	.56	11.65	1.05	15.05	.54	18.35	.58	32.02	4.63	48.52	3.39	71.32	3.65	38.60	4.16	35.8	4.02	43.40	4.88
NO ₂ {	5.00	.13	14.2	1.87	19.75	1.09	25.00	.35	3.46	.36	5.78	.26	8.22	.22	5.40	.22	5.40	.42	5.70	.27
	9.83	.15	29.75	.59	32.60	.55	34.75	.35	11.74	.44	14.56	.36	17.12	.57	15.00	.71	14.60	.55	15.10	.42
SO ₂ {	4.79	.07	10.0	1.00	8.95	.94	7.75	.83	6.94	.99	5.96	1.10	5.36	.82	6.6	.89	6.5	.87	6.48	.83
	9.23	.04	19.0	.95	18.10	.68	17.15	.55	14.12	.86	13.26	.63	12.52	.65	16.00	1.00	16.20	.84	15.80	.93
HCHO {	2.30	.373	7.66	.73	11.82	.45	15.93	1.59	2.52	.30	4.58	.24	6.74	.93	4.80	1.30	4.6	.89	4.6	.89
	4.062	.526	10.78	1.22	14.52	1.67	18.49	2.52	4.06	.62	6.00	.86	8.44	1.68	6.80	1.30	6.4	1.14	6.4	1.14

TABLE B-3. - Average length of stain and toxic gas concentration at 20 percent relative humidity at 40°F from Gastec/Bendix tubes

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
			Minimum		Midpoint		Maximum		Minimum		Midpoint		Maximum		Average		Average		Average	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
CO {	51.10	0.87	4.60	0.17	7.43	0.45	10.13	0.74	37.8	1.76	73.3	6.3	107.6	9.78	68.4	7.8	79.0	6.5	77.4	4.3
	98.50	1.45	8.90	.47	11.56	1.09	14.39	1.59	93.5	7.2	127.0	13.9	162.4	20.9	127.5	16.48	127.8	13.8	142.8	15.2
CO ₂ {	5,120	110	7.24	.80	6.69	.50	5.99	.53	6,820	750	6,120	585	5,400	539	6,220	683	6,260	695	6,280	705
	10,000	340	13.39	1.61	12.16	.82	10.83	.32	11,980	2,572	10,160	1,004	8,660	479	11,300	974	11,400	824	11,500	1,000
NO {	26.20	.76	6.86	.37	8.81	.37	10.60	.81	21.23	.66	24.95	1.65	29.45	3.90	23.80	1.64	21.40	1.52	23.60	3.13
	49.30	.45	13.32	.75	16.40	.54	19.32	.74	39.62	4.36	56.80	4.09	78.10	6.39						
NO ₂ {	5.05	.05	18.25	1.68	22.20	1.19	25.40	.95	5.22	.13	6.92	.26	8.62	.10	6.80	.08	6.80	.45	7.00	.20
	9.74	.15	29.25	.20	32.00	.00	28.05	.31	9.02	.56	14.00	.17	17.45	.52	14.50	1.00	14.38	1.25	14.75	.96
SO ₂ {	5.00	.66	8.15	1.64	7.10	1.39	5.85	.86	4.66	.56	4.02	.63	3.34	.80	4.40	.65	4.60	.65	4.40	.62
	9.46	.11	13.20	.76	12.30	.67	11.30	.78	9.36	.48	8.52	.53	7.78	.54	9.50	.35	9.10	.74	9.40	.65
HCHO {	2.07	.35	3.44	1.11	7.50	.92	10.46	1.39	1.04	.34	2.22	.47	3.90	.69	2.20	.45	2.00	.0	2.60	.30
	4.95	.07	5.44	2.33	9.56	2.80	13.66	3.15	1.65	.89	3.43	1.23	5.45	1.60	4.50	1.73	4.25	1.50	4.25	1.50

TABLE B-4. - Average length of stain and toxic gas concentration at 20 percent relative humidity at 120°F from Gastec/Bendix tubes (ppm values corrected for temperature)

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
			Minimum		Midpoint		Maximum		Minimum		Midpoint		Maximum		Average		Average		Average	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
CO {	49.90	0.775	2.45	0.20	4.13	0.27	5.79	0.36	24.0	3.3	46.7	4.9	77.6	6.3	53.0	4.9	49.0	8.3	66.4	10.4
	99.00	1.28	4.22	.48	5.83	.27	7.41	.59	48.0	9.1	76.6	10.2	104.6	11.7	72.6	5.6	73.4	5.8	90.2	7.8
CO ₂ {	5,260	170	7.24	.46	6.66	.38	6.10	.41	6,850	387	6,225	411	4,480	408	6,375	427	6,375	395	6,425	340
	10,560	110	16.33	.66	14.65	.86	13.09	1.14	14,260	847	12,300	962	10,520	1,226	12,900	1,025	13,000	1,275	13,000	1,275
NO {	25.10	.50	6.88	.48	9.06	.77	11.31	1.09	20.83	.77	25.33	1.31	31.03	3.18	22.00	2.67	22.75	1.50	24.75	.50
	49.10	.89	12.80	1.51	15.50	.71	18.23	.38	33.50	4.41	51.46	3.18	69.76	1.94	43.00	5.70	45.40	4.98	46.20	2.28
NO ₂ {	5.02	.07	10.40	.14	14.30	2.70	17.80	2.71	2.62	.16	3.82	.53	5.04	.95	3.70	.57	4.26	.50	4.20	.45
	9.79	.07	17.10	.72	21.56	1.53	26.25	2.31	4.76	.07	6.78	.29	9.16	1.67	7.90	.55	7.80	.45	7.60	.42
SO ₂ {	4.84	.07	7.15	.22	6.38	.12	5.55	.11	4.90	.14	4.36	.13	3.84	.19	5.00	.0	5.00	.0	4.84	.11
	9.90	.04	14.20	2.30	12.30	1.80	10.50	1.33	10.40	1.91	8.70	1.05	7.52	.75	9.40	1.67	9.60	1.85	9.62	1.56
HCHO {	2.28	.23	7.98	1.53	10.86	1.33	13.92	1.15	2.62	.80	4.10	.73	5.62	.56	3.60	.89	4.00	.00	3.80	.45
	6.64	.10	17.00	.34	20.36	.67	23.77	1.38	7.42	.34	9.88	.56	13.22	1.06	10.20	.49	10.60	.55	10.20	.45

TABLE B-5. - Average length of stain and toxic gas concentration at 50 percent relative humidity and 75°F from the Dräger tube system

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
			Minimum		Midpoint		Maximum		Minimum		Midpoint		Maximum		Average		Average		Average	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
CO {	51.4	0.67	16.02	0.99	18.64	0.93	21.26	0.88	43.44	2.77	52.84	3.49	63.76	4.54	50.4	0.89	54.0	4.18	56.4	3.29
	98.9	.76	27.65	.45	32.43	.33	37.60	1.13	86.28	1.96	105.34	1.83	123.50	3.00	102.0	4.47	100.40	5.32	108.0	12.90
CO ₂ {	4,900	160	28.40	3.60	31.00	3.46	33.62	3.31	4,860	810	5,420	790	6,020	730	5,700	877	5,600	765	5,700	846
	10,100	100	10.13	1.64	11.82	1.43	13.31	1.28	8,300	1,620	9,760	1,160	11,640	1,410	11,160	1,670	10,480	1,590	10,740	994
NO {	25.3	.54	17.00	.81	23.4	1.21	29.85	1.50	18.00	.86	35.38	3.26	56.64	4.73	36.0	4.18	35.4	2.88	31.0	2.24
	48.8	.27	24.48	1.91	30.39	1.08	36.21	1.13	39.88	6.18	60.02	5.43	86.82	5.31	54.0	2.24	61.0	2.24	58.0	2.74
NO ₂ {	5.00	.11	21.15	1.88	30.25	2.05	39.35	2.50	1.94	.23	3.38	.30	5.62	.64	3.96	.09	3.80	.27	4.30	.27
	9.82	.08	16.70	.57	24.25	.31	31.85	.52	5.00	.25	8.36	.15	12.94	.06	12.60	1.52	11.80	1.64	12.8	1.64
SO ₂ {	4.80	.07	28.35	1.71	44.90	2.37	32.70	3.58	4.90	.22	3.76	.29	2.54	.40	3.52	.48	3.30	.45	2.82	.33
	10.00	.35	32.60	2.93	56.56	3.11	48.00	3.57	11.80	1.56	9.64	1.52	7.72	1.58	9.90	1.60	10.10	1.60	9.20	1.15
HCHO {	2.71	.29	5.21	.98	8.72	1.55	12.09	2.22	2.16	.48	5.86	2.34	12.88	4.56	3.40	1.14	2.20	.45	5.00	.00
	3.94	.29	5.18	.74	8.27	.52	11.17	.60	1.86	.30	4.18	.48	9.94	1.42	6.00	.71	6.40	.89	6.00	.71

TABLE B-6. - Average length of stain and toxic gas concentration at 90 percent relative humidity at 75°F from the Dräger tube system

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
			Minimum		Midpoint		Maximum		Minimum		Midpoint		Maximum		Average		Average		Average	
	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ	Average	σ
CO {	50.8	0.85	15.05	0.97	17.90	0.46	20.85	0.60	41.78	2.84	51.20	2.33	61.46	3.12	49.0	2.24	49.6	3.65	51.2	1.48
	98.1	1.18	28.35	.93	32.4	.58	36.6	.96	87.08	2.99	104.18	2.63	119.76	3.86	99.0	2.24	100.00	3.54	103.0	3.74
CO ₂ {	4,900	160	29.75	2.75	32.12	2.65	34.45	2.61	5,180	545	5,720	572	6,460	619	6,000	738	6,340	820	6,360	873
	10,390	320	9.66	1.24	11.32	1.27	12.89	1.35	7,280	947	8,840	1,045	10,640	1,324	10,800	1,304	11,000	1,225	12,200	1,304
NO {	25.14	.24	15.50	1.02	21.60	.55	27.80	2.01	16.12	2.13	31.44	1.79	51.00	6.67	29.00	2.24	29.00	2.24	35.4	2.07
	47.56	.56	22.80	1.65	30.20	.82	37.60	1.29	34.16	6.09	54.58	4.74	92.30	4.69	52.0	2.74	55.0	3.54	64.60	6.58
NO ₂ {	5.00	.129	22.55	1.05	32.46	1.64	42.25	2.70	2.02	.18	3.62	.33	6.44	.99	4.34	.42	3.90	.42	4.34	.42
	9.83	.150	18.35	1.46	26.75	1.62	35.15	2.22	5.86	.80	9.26	.59	15.42	1.67	10.00	1.22	11.00	1.22	11.20	1.30
SO ₂ {	4.79	.07	28.35	1.71	22.45	2.37	16.35	3.58	9.68	.61	7.16	.87	4.92	1.19	7.20	.84	7.20	1.25	6.76	1.18
	9.23	.04	47.45	.94	41.85	.65	36.80	2.04	22.34	.82	18.10	.66	14.48	1.21	19.20	.70	19.20	.84	19.56	.47
HCHO {	2.30	.373	7.25	1.03	9.26	.66	11.22	.45	3.16	1.10	5.26	1.77	9.14	1.39	4.40	2.51	3.80	1.64	5.40	2.88
	4.06	.526	9.54	3.77	12.94	2.49	16.38	1.70	9.13	7.39	15.73	7.31	28.05	8.41	26.25	16.01	21.25	19.31	23.75	17.50

TABLE B-7. - Average length of stain and toxic gas concentration at 20 percent relative humidity at 40°F from the Dräger tube system

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
	Average	σ	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Average	σ	Average	σ	Average	σ
CO {	50.8	1.09	16.0	0.64	19.0	0.80	21.8	1.32	44.2	2.37	55.3	3.91	66.2	6.38	54.0	4.18	51.8	2.95	55.2	4.09
	98.7	.58	33.2	1.32	37.9	1.43	42.7	2.06	107.1	5.83	124.6	5.29	142.4	6.98	119.6	7.30	121.0	5.87	123.0	5.61
CO ₂ {	5,120	110	4.33	.919	6.28	1.23	8.15	1.41	2,860	602	4,180	807	5,780	1,285	5,200	1,304	5,100	1,294	5,100	962
	10,000	340	8.52	1.24	10.53	1.13	12.72	1.14	6,540	1,408	8,440	1,101	10,600	1,313	11,000	1,541	9,900	742	10,500	1,275
NO {	26.20	.76	16.34	.56	19.86	.44	23.49	1.35	17.22	1.31	25.84	1.43	36.02	3.56	30.40	2.61	22.20	3.11	27.60	2.70
	49.30	.45	19.19	1.45	25.42	1.37	31.95	1.69	22.88	4.18	39.88	4.54	63.22	6.99	42.00	4.47	42.80	4.76	48.80	7.05
NO ₂ {	5.05	.05	17.55	1.40	28.40	1.56	37.90	3.09	1.48	.25	3.12	.33	5.30	.92	3.10	.22	3.20	.27	3.64	.23
	9.74	.15	15.90	.89	25.10	.96	34.20	1.74	4.78	.24	8.74	.21	15.30	1.87	9.20	1.10	9.80	1.64	11.25	1.85
SO ₂ {	5.00	.66	10.10	.89	6.75	.67	4.00	1.31	2.86	.25	1.98	.18	1.18	.13	2.08	.05	2.32	.19	1.94	.28
	9.46	.11	16.70	1.10	13.45	1.50	10.20	1.95	5.00	.29	4.04	.33	3.12	.49	4.22	.38	4.78	.19	4.56	.52
HCHO {	2.07	.35	7.22	1.35	8.70	1.19	10.06	1.21	3.42	1.22	5.04	1.61	7.34	2.56	-	-	-	-	-	-
	4.95	.07	4.96	.96	8.08	.65	11.23	.49	1.70	.35	4.00	.59	9.44	1.50	3.0	1.0	3.2	1.64	-	-

TABLE B-8. - Average length of stain and toxic gas concentration at 20 percent relative humidity at 120°F from the Dräger tube system

Toxic gas	Standard concentration, ppm		Optical tube reader												Observer panel					
			Length of stain, mm						Tube scale, ppm						Tube scale, ppm					
	Average	σ	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Minimum Average	σ	Midpoint Average	σ	Maximum Average	σ	Average	σ	Average	σ	Average	σ
CO {	49.9	0.78	12.6	0.65	15.4	0.37	18.7	0.22	32.9	1.65	45.2	0.80	57.4	1.44	48.0	2.74	48.6	2.19	49.2	0.70
	99.0	1.28	25.3	1.60	28.18	1.23	30.9	.95	81.3	6.26	92.1	4.87	102.7	3.38	95.0	5.00	93.6	4.83	96.0	4.18
CO ₂ {	5,260	170	4.45	1.04	6.30	.89	8.15	.86	3,300	851	4,680	729	6,280	867	5,400	548	5,300	837	5,400	418
	10,560	110	8.80	1.09	10.56	.89	12.43	.91	6,880	988	8,620	958	10,340	1,014	9,400	884	8,100	894	9,800	570
NO {	25.10	.50	16.25	.35	22.90	.29	29.8	.54	17.80	.51	35.08	.79	57.80	1.92	37.00	4.47	35.00	1.41	36.00	1.73
	49.10	.89	56.50	.79	64.70	1.30	73.20	1.25	51.44	1.61	68.12	2.71	89.68	6.38	78.00	4.47	80.0	7.91	87.40	6.23
NO ₂ {	5.02	.07	21.50	1.68	32.31	.75	42.44	.66	2.10	.05	3.82	.13	6.50	.12	3.30	.27	3.40	.22	3.60	.55
	9.79	.07	17.30	1.25	50.90	2.53	33.95	2.26	5.14	.55	9.02	.87	14.20	2.12	9.20	.84	10.20	1.92	9.00	1.00
SO ₂ {	4.84	.07	39.45	1.77	30.65	1.83	21.65	2.12	16.10	1.18	10.94	.98	6.94	.86	8.80	1.10	8.70	.97	9.30	1.79
	9.90	.04	46.80	3.85	38.65	2.57	29.60	3.14	22.14	2.39	15.46	1.87	10.32	1.66	16.00	2.35	14.90	2.07	15.60	2.07
HCHO {	2.28	.23	7.25	.61	9.08	.40	10.98	.70	3.80	.56	6.10	1.39	10.65	2.04	-	-	-	-	-	-
	6.64	.10	8.25	.50	10.53	.57	12.81	.83	4.20	.29	8.25	1.62	13.67	2.29	25.75	16.30	32.50	4.50	26.25	4.00