

ABSTRACT

EDWIN A. GOERING. Investigation of Direct Reading Passive Monitor Using Colorimetric Media for Various Gases. (Under the direction of Dr. DAVID A. FRASER)

The need for an inexpensive, direct reading, personal monitor to measure employee exposure to workplace atmospheric contaminants still exist. A passive monitor using variable length orifices and the principle of diffusion was designed and investigated. A colorimetric media fixed at the end of the orifices was used to indicate contaminant relative concentration. The system was tested with Hydrogen Chloride, Sulfur Dioxide, and Ammonia as atmosphere contaminants. The system showed a graduated response in relationship to the increasing orifice lengths. Parallel scale alignment charts were prepared to allow interpretation of the monitor readings by the individual employee. It is felt that the use of a system of this nature would meet the needs of industry to provide employee exposure information at an acceptable cost.

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I. INTRODUCTION

Industrial Hygiene as an applied science frequently requires the quantitative knowledge of the level of contaminant materials in the workplace atmosphere. The need for determining the quantitative levels of contaminants in the atmosphere is to insure the protection of employees' health and safety in the workplace. Impetus for workplace contaminant level investigation may be a bona fide interest in protecting the employees' health and safety, an interest in protecting the financial health of the employer from litigation by injured employee(s), or the determination of compliance with government laws or standards. (14)

To acquire this information, some form of air sampling is commonly undertaken. Methods commonly available today generally utilize one of two methods. (2)

1. Personal sampling by gathering a sample of contaminated material from as close to the breathing zone as possible on some type of adsorption or absorption device, into a container or other collection media for later laboratory analysis to determine the contaminant concentration.

2. Area sampling using a direct reading continuous

monitor for the contaminant material in some predetermined fixed location or series of fixed locations.

Both of these method have drawbacks - albeit some advantages. Method one has a significant time delay in acquiring the quantitative data. The delay ranges from several hours if the investigator has direct control of the laboratory analyzing the sample to several weeks if an outside laboratory must be contracted with to perform the analysis. Method two, although providing instantaneous results, is beyond the price many organizations are willing to pay for the information. Additionally, the direct reading instruments monitor fixed locations and may or may not accurately reflect the actual atmosphere to which the employee(s) is(are) exposed.

To get around these drawbacks and others of currently available equipment, a monitoring device is needed which will provide the required information via a direct reading device with the following features.

1. Minimum purchase and operating cost
2. Light weight
3. Small physical size to allow convenient personal use.
4. Accurate and precise for the contaminant being investigated
5. Free of interference from other contaminants
6. Have a sampling range large enough to allow for both long and short term sampling

7. Easily and accurately read by the user

A personal passive monitor could meet these criteria. Lippmann stated, "Personal sampling devices really began with the development of the first lightweight portable battery-powered pumps in about 1960. In the years since, there have been many refinements, but if anything the samplers have become bigger and heavier rather than smaller." (8)

Woebkenberg has reported that several manufacturers produce a variety of passive monitoring devices for a limited number of contaminant materials. (15) Most of the devices reported upon are not direct reading devices. That is, they require some form of laboratory analysis following contaminant collection. A few of the devices are direct reading and operate on a color change principle. Not all these devices are truly quantitative in that they show a color change when a predetermined concentration has been exceeded, but do not indicate to what level the concentration exceeded the predetermined level. Mine Safety Appliances Company is currently marketing passive, direct reading, length-of-stain dosimeters for several chemicals. (10,11) These devices meet most of the criteria listed above, but still require subjective judgment as to the actual length of the stain.

This project was undertaken to further evaluate a passive monitor using the principle of diffusion which will measure and record the exposure an employee has in the work

environment. It is felt that a passive monitor of this design can overcome the drawbacks of existing equipment and provide the required information immediately and at a reasonable cost to the employer.

II. BACKGROUND

The design of the monitor evaluated in this study was based on the principle of mass transport by diffusion. Chang defined diffusion as, "The process by which concentration gradients in a solution spontaneously decrease until a uniform, homogeneous distribution is obtained." (3) Hinds defined diffusion as: "Mass transfer of one gas through another in the absence of fluid flow". (6) Mass transport of contaminant gas in air to a collecting media in a predictable way is an application of Fick's First Law of Diffusion: (7)

$$J = -D (\Delta C / \Delta X) \quad (\text{eq. 1})$$

where:

J = mass flux of the migrating contaminant
(quantity of mass transported per unit
of area per unit time.)

D = diffusion coefficient of the
contaminant

$\frac{\Delta C}{\Delta X}$ = negative concentration gradient that
exist in space, which drives or
transports the contaminant at
concentration C through a distance X .

Hamm applied this equation to determine the volume of gas collected per unit area of indicator surface and expressed it as: (5)

$$V/A = DC't' \ 60/L \quad (\text{eq. 2})$$

where:

V/A = volume of gas or vapor collected per unit area of indicator surface at endpoint (cm^3/cm^2)

D = diffusion coefficient (cm^2/sec)

C' = ambient concentration of gas or vapor (ppm or cm^3 gas or vapor/ 10^6 cm^3 air)

t' = time to endpoint (min)

L = orifice length (cm)

From this equation, it can be seen that for each orifice length a specific exposure (parts per million-minute--ppm-min) determines spot formation for that orifice. Accordingly, each orifice length in the monitor corresponds to a specific exposure required for spot formation on the collecting media, colorimetric indicator paper, and the quantitative nature of the monitor. By counting the number of spots that have formed, the subjective judgment should be removed from the evaluation of actual contaminant exposure.

The use of this mathematical derivation is based on some assumptions which include:

1. The concentration of contaminant at the face of

the orifice is constant.

2. The concentration of the contaminant at the collection media face is zero.

The achievement of these conditions in actual practice is not always possible nor is it easily determined what is the actual condition during the period of sampling with a diffusion sampler. Figure 1 shows a diffusion tube orifice under a static air condition. Under this condition, molecules immediately at the face of the orifice will start movement into the orifice and thereby lower the concentration immediately in front of the orifice. As time continues, the space containing the lower concentration increases thereby moving the point of original contaminant concentration further away from the orifice. This effectively increases the orifice length and thus reduces the concentration gradient. Coulson states that an air velocity of ten feet per minute across the face of the orifice will reduce this problem to minimal level. (3)

If the face velocity is too great, then turbulence (convective mass transport) at the surface will cause contaminated air to reach into the orifice and thereby shorten the orifice length (figure 2). This would have the effect of increasing the concentration gradient. Lautenberger states that "cavities (orifices) with a length to diameter ratio of greater than three have been used by various manufacturers to eliminate convective mass transport". (7)

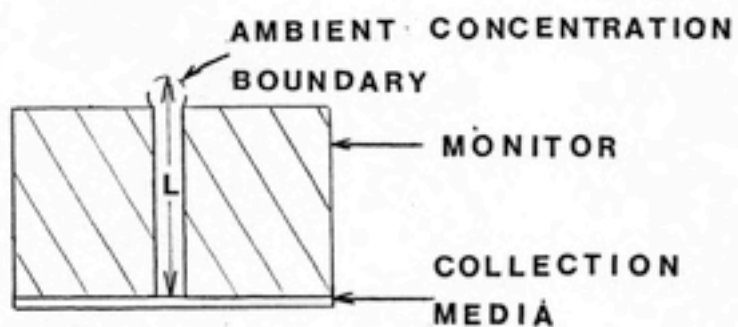


FIGURE 1 STILL AIR

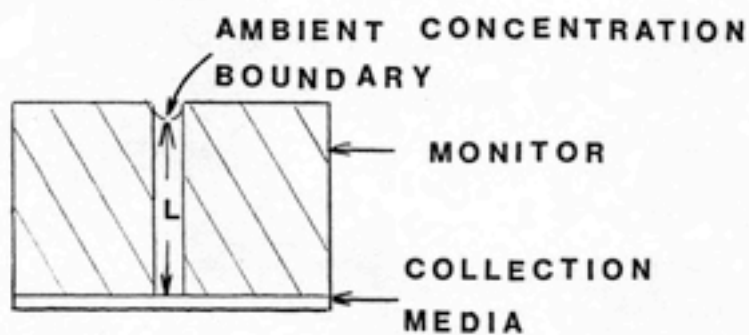


FIGURE 2 TURBULENT AIR

The second assumption made in this derivation is based on the idea that the collection surface concentration has an infinite number of active sorbent sites, thus keeping the contaminant concentration at the surface zero. In practice, the surface contains a finite number of active sorbent sites and as these sites are filled, the contaminant must diffuse further into the collection media and thereby increasing the diffusion path or orifice length (figure 3). This again would reduce the concentration gradient. Martin states "On a theoretical basis, these errors are very small, no greater than 10% if a diffusion sampler is operated within the design parameters of the sampler". (9)

The design configuration of the monitor used in this study used logarithmically increasing orifice lengths starting with the shortest orifice length meeting Lautenberger's criteria of length three times greater than diameter (figure 4a and 4b). Additionally, the depth or thickness of the collection media is less than 0.007 inches. The additional orifice length due to diffusion beyond the surface of the collection media will be well within the error range as noted by Martin.

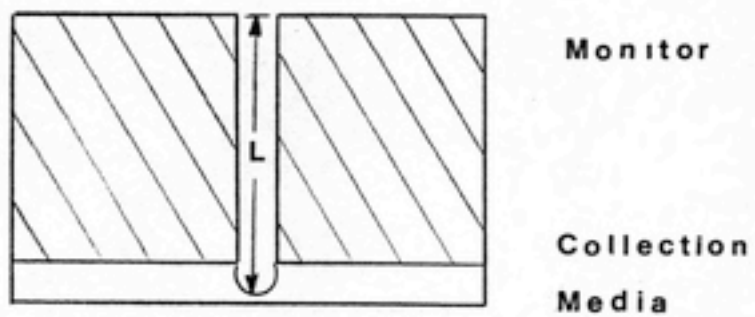


Figure 3
Finite Sorbent Sites

FIGURE 4
PASSIVE MONITOR

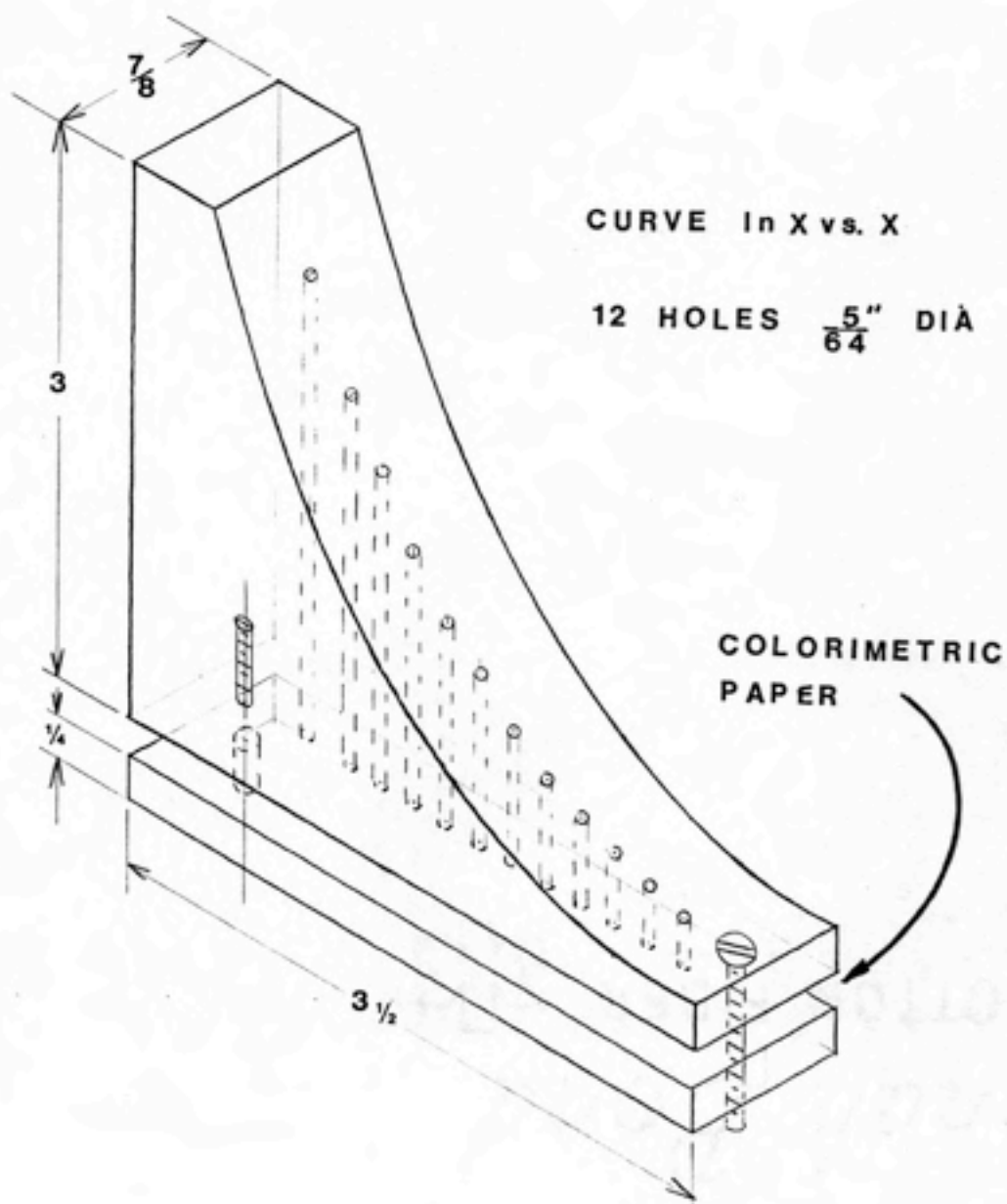
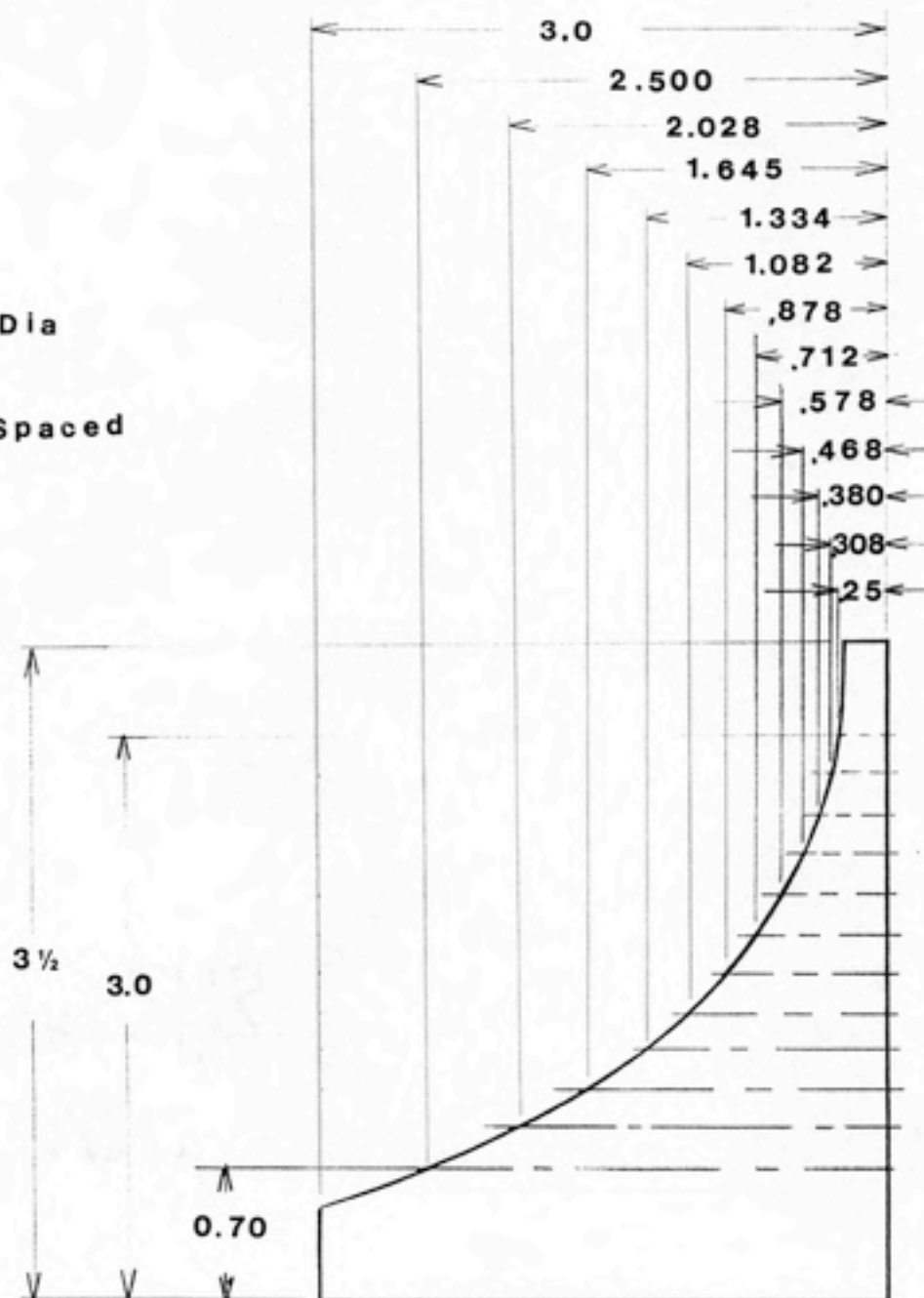


Figure 4b
Passive Monitor
Plan View

12 - 5/64" Dia
Orifices
Equally Spaced



III. EQUIPMENT AND PROCEDURE

The concept of a passive, multiple tube, diffusion operated monitor originated with Dr. David A. Fraser. The monitor evaluated in this study was a modification of the monitor investigated by Hamm in 1981. (5) The design of the monitor in this study used exponentially increasing tube lengths instead of linearly increasing tube lengths as studied by Hamm.

The objectives of this project were to:

1. Prepare calibration graphs
2. Prepare Time Weighted Average exposure chart for use by the monitor wearer
3. Demonstrate the feasibility of a bench model test system.

The gases chosen for this project were Sulfur Dioxide, Hydrogen Chloride and Ammonia. These gases were chosen because of the availability of the gas, the availability of the collection media, colorimetric paper, to detect the specific gas, and availability of proper safety equipment to handle the gases during the project. The colorimetric papers were obtained from MDA Scientific Inc. of Glenview, Illinois. MDA Scientific Inc. manufactures the paper as a proprietary product for use in their machines for measuring

specific chemicals in industrial environments. The use of the colorimetric paper for this project was an extrapolation of the intent of the paper. That is, the papers are intended to measure low concentrations of contaminant gas, low ppm range. This is accomplished by drawing a metered flow of contaminated air through the paper and then reading the color change which is proportional to the concentration of the contaminant gas using a spectrophotometric technique. (13) In this project, the monitor with colorimetric paper was exposed to high concentrations of contaminant gas for sufficient duration to allow diffusion of the gas to the paper through tubes until spot formation occurred. The occurrence of spot formation was determined by visual reference.

The colorimetric paper has an operating temperature range of 0 - 40 degrees C and a relative humidity range of 10% - 90%. (13) The paper has a recommended shelf life of 2 1/2 to 3 1/2 months and requires refrigerated storage until used. MDA does not provide any information, because of its proprietary nature, which would allow the user to test the paper prior to use. The user has to depend on MDA's quality control for paper reliability. Each roll of paper is assigned a serial number. The papers used in this study were:

Ammonia	SN. 144340
Sulfur Dioxide	SN. 151012
Hydrogen Chloride	SN. 137871

All tests conducted during this study were conducted at ambient conditions which ranged as follows:

Temperature	22.6 - 26.0 degrees C
Pressure	747.1 - 761.0 mm HG
Relative Humidity	31 - 72%

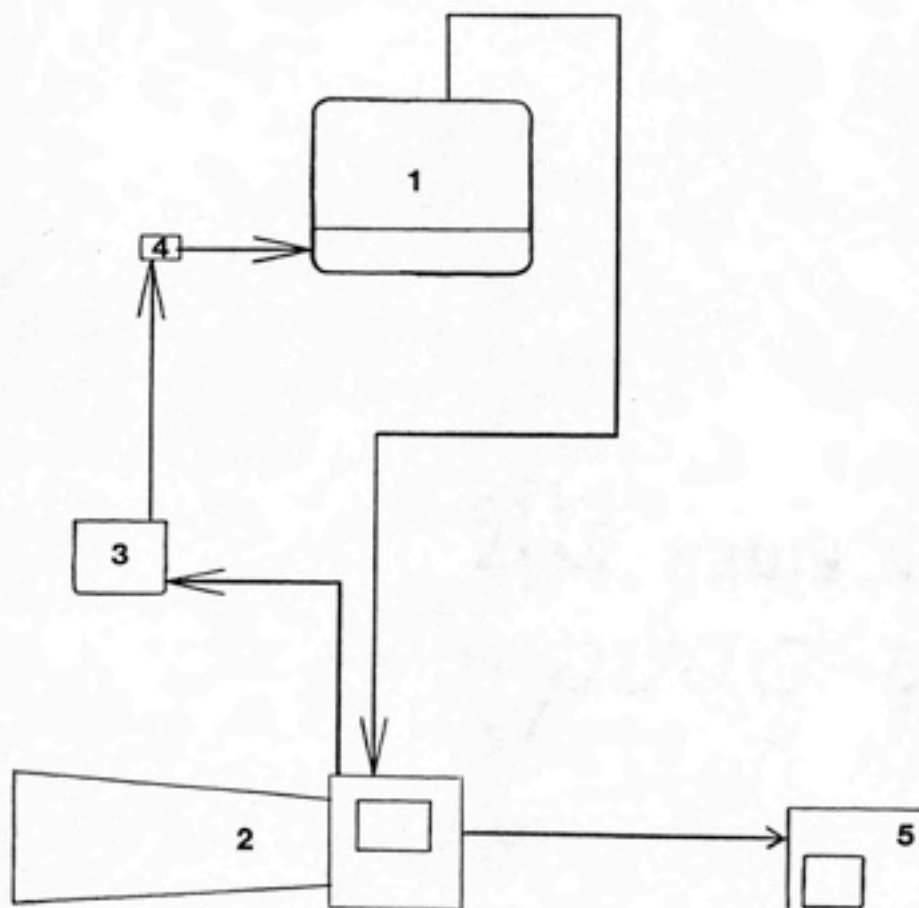
The test system consisted of an eight liter test chamber, Miran 1A CVF (SN 1A-3401) infrared gas analyzer, Metal Bellows Corp pump (SN16097), and interconnecting tubing in a closed loop system as shown in figure 5. A Cole-Palmer Linear strip chart recorder was connected to Miran 1A.

The Miran 1A was used to determine the concentration of contaminant gas in the system throughout the duration of each trial and the chart recorder was used to record that data for later interpretation. A calibration curve for each of the contaminant gases was initially prepared using the method recommended by Foxboro Inc., manufacturer of the Miran 1A. The data and calibration curves are shown in Appendix 2.

Test concentrations were determined by using the Threshold Limit Value (TLV) for each contaminant gas and calculating the ppm-minutes exposure for eight hours. (1) That is, the TLV value in ppm multiplied by 60 minutes per hour times eight hours. The 40%, 90%, and 150% equivalents were then determined. Arbitrary test times were then set at 10 minutes for 40%, 20 minutes for 90%, and 30 minutes for 150%. Using these parameters, the test chamber

FIGURE 5
EQUIPMENT SCHEMATIC

- 1 TEST CHAMBER
- 2 MIRAN IR GAS ANALYZER
- 3 PUMP
- 4 INJECTION PORT
- 5 CHART RECORDER



concentration was then calculated and the quantity of contaminant gas needed to achieve the test chamber concentration calculated.

Each trial was conducted by loading the monitors with the colorimetric paper and placing them on test stands in the test chamber. The lid was placed on the chamber, sealed and the pump started. The calculated quantity of contaminant gas was introduced into the closed loop system through the injection port and timing was begun. The strip chart recorder recorded the Miran readings and the time of spot formation was recorded manually. Spot formation was determined by observing a uniform color intensity throughout an area equal to the orifice area on the side of the colorimetric media opposite the orifice side of the colorimetric media. After all the data was collected, the mean contaminant gas concentration for the duration of each spot formation was calculated using the strip chart. Trials were repeated so as to get six data points for each spot with sulfur dioxide and ammonia and four data points for each spot for hydrogen chloride. From this data, the mean exposure in ppm-minutes was calculated for each spot.

To improve upon the ability to delineate spot formation time, several steps were tried. The background in the laboratory hood was changed from dark to light to change the contrast. Colored lights were employed to aid in the visual interpretation of spot formation. And

varying the room lighting was also tried. The extent of these steps tried, did not produce noticeable improvement in ability to delineate spot formation time.

IV. RESULTS

The concept of the multiple tube passive monitor clearly is viable as seen the the photo (figure 6) of the exposed colorimetric media. Although this is a qualitative picture, the photo clearly shows a gradation in spot size and color intensity from the long tube to the short tube.

The data presented in appendix 1 shows the exposure for the experimental gases and for each spot at the three experimental concentrations and the mean of the exposure for each spot in parts per million - minutes. The data is presented in graphical form in figure 7. The exposure in ppm-minutes versus spot number is shown for each of the concentrations tested. The plot shows a linear response as predicted by equation 2. However, Figure 7 does show a variability in response to concentration, but does not show a clear relationship between changing concentration and required exposure for spot generation. This is probably due to the subjectivity in determining the time of actual spot formation.

Figure 8 shows the summary of the data by plotting the mean exposure for each spot versus spot number. The lines are nearly parallel indicating a consistent response by the monitor for the different gases. Figure 9 is a plot of

Figure 6
Exposed Colorimetric Media

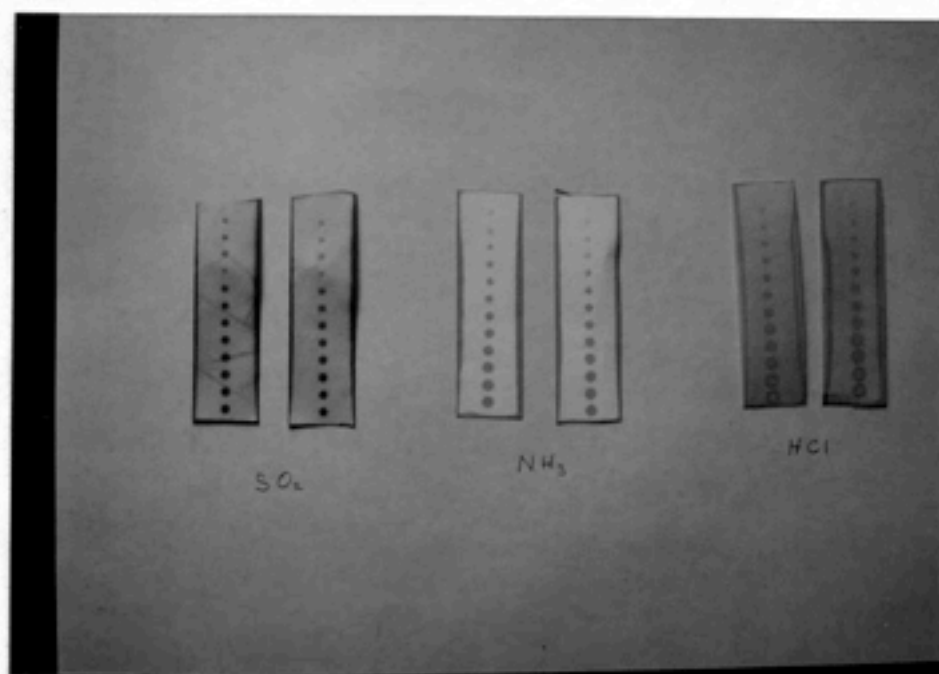


Figure 7
Exposure at Tested Concentration

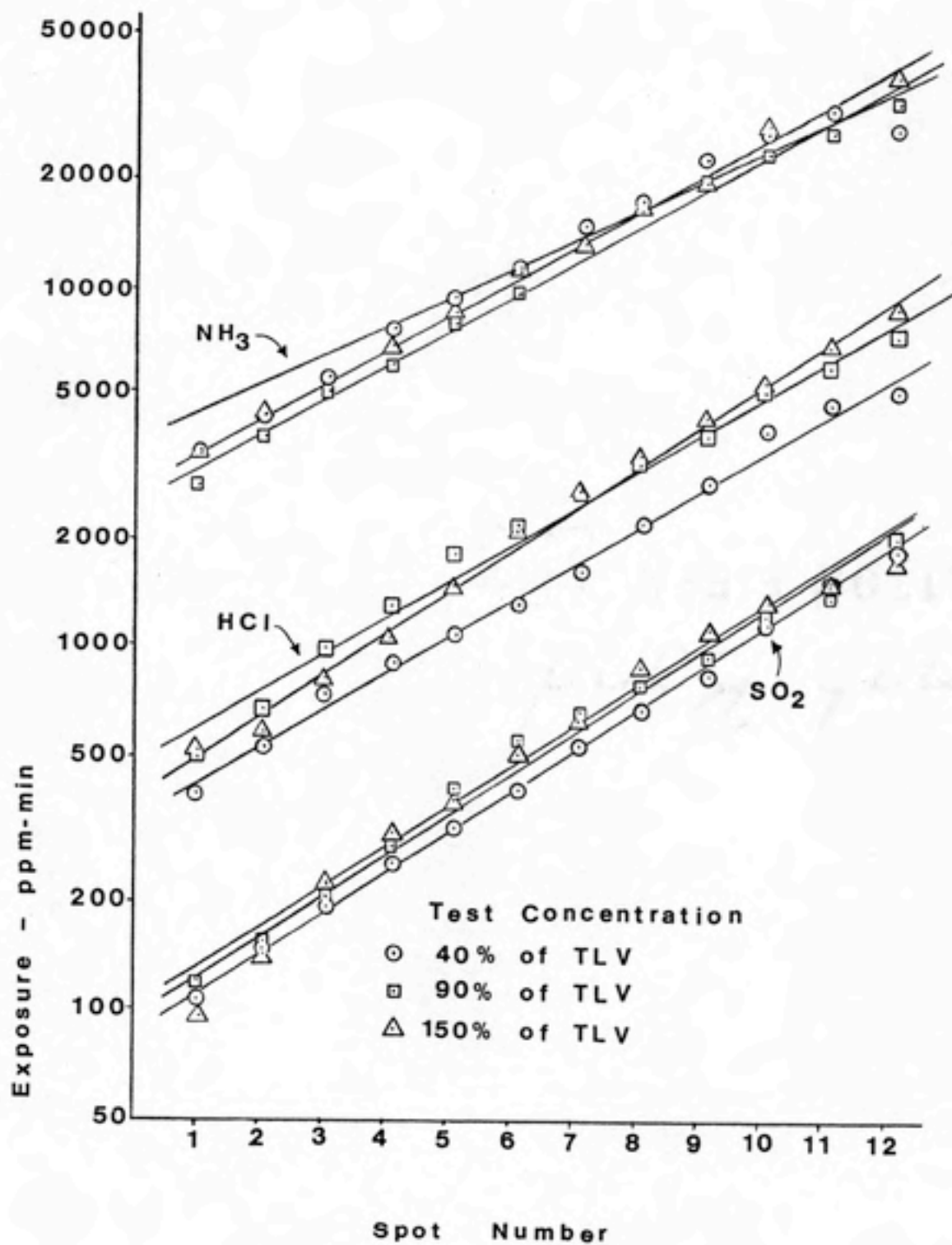


Figure 8
Exposure vs Spot Number

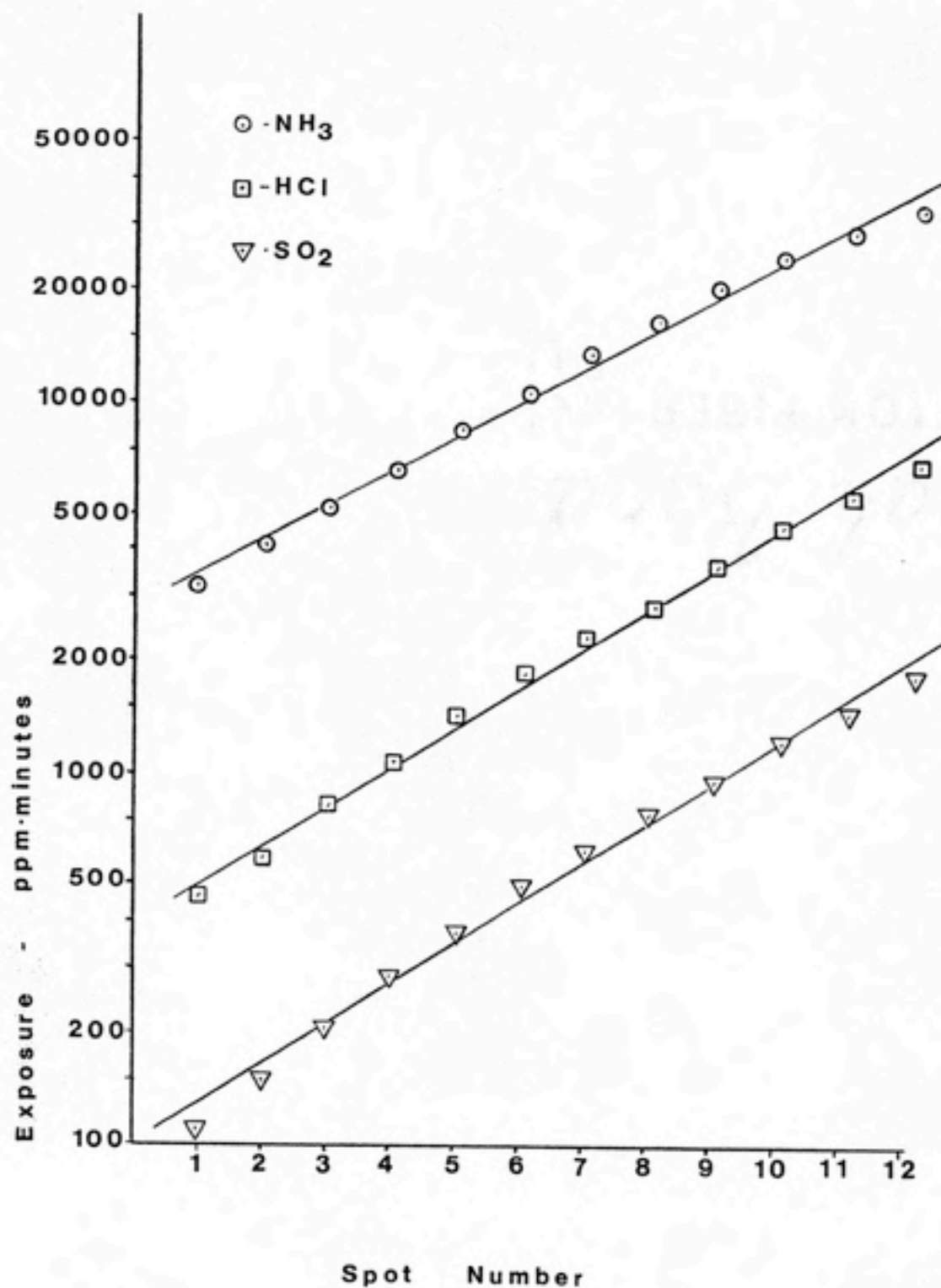
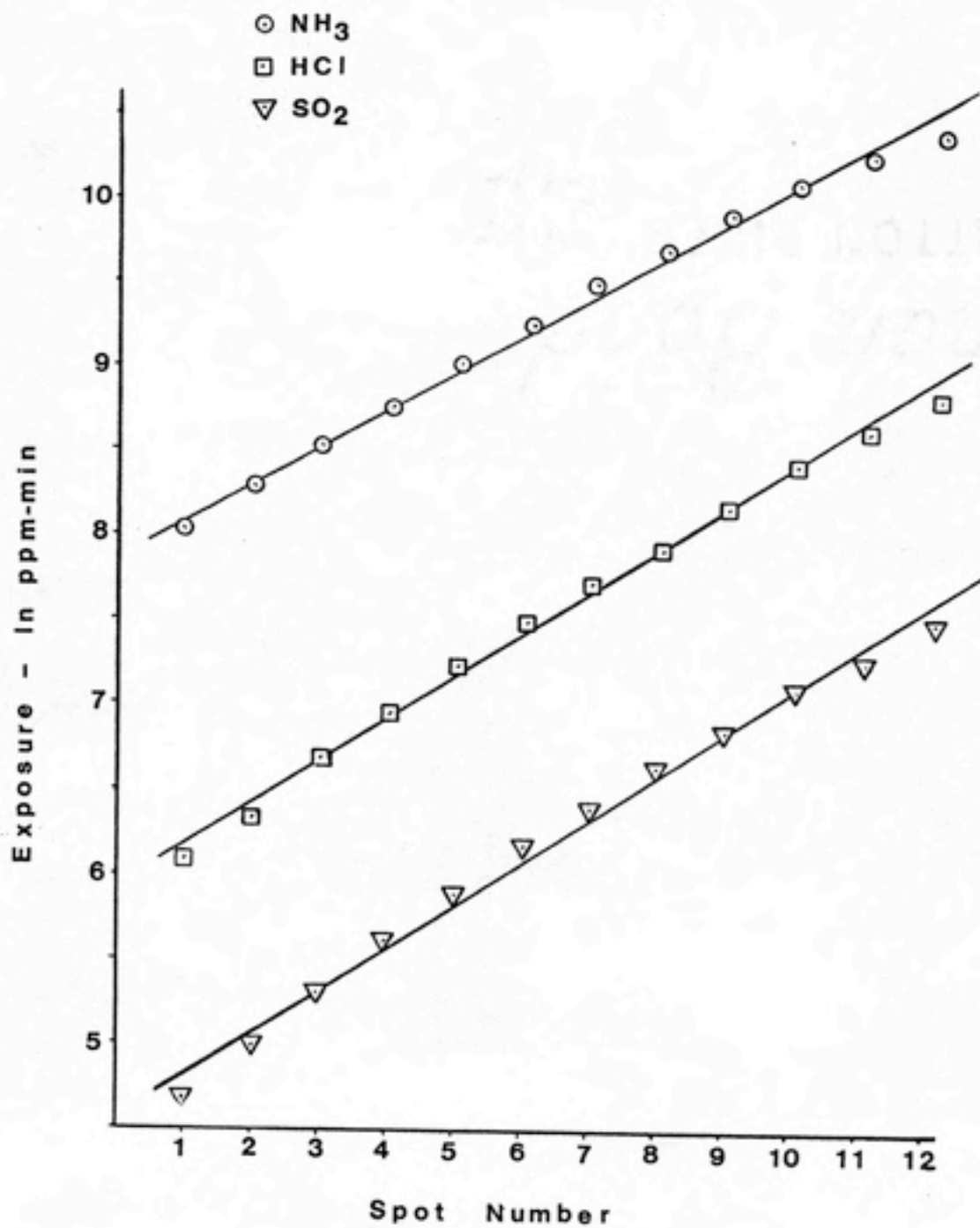


Figure 9

Exposure vs Spot Number



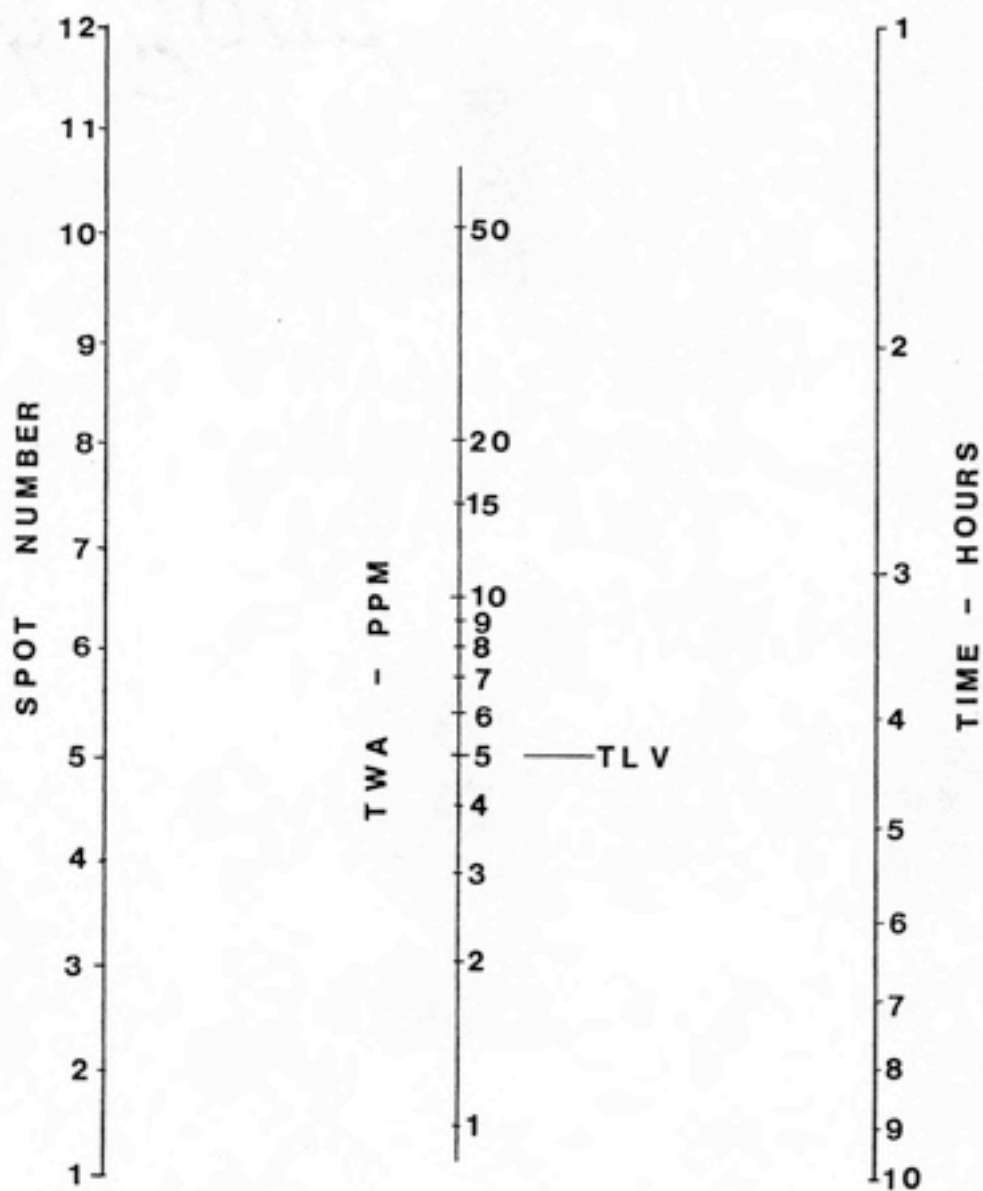
the same information except using the natural log of the exposure versus spot number. The slopes of the lines for all chemicals are nearly equal ranging from 0.21 for ammonia to 0.25 for sulfur dioxide. The difference in slope may be due to the differences in the coefficients of diffusion. Additionally, the difference in the vertical spacing between the lines is not in same proportion as the difference in spacing of the TLV's. This may be due to the difference in sensitivities of the specific colorimetric media used for each contaminant.

The summary data is consistent with previous experiments conducted on passive monitors using other forms of experimental chambers. This would indicate that the use of the bench model test chamber does provide for adequate test conditions. Gas velocity past the monitor sufficient to overcome the problems of turbulent or still air at the monitor's orifice entrance was achieved in the experimental chamber.

Figure 10 is a calibration chart which can be used to determine the exposure to hydrogen chloride for the time period the individual was exposed. The chart is read by placing a straight edge on the appropriate spot number and the time the individual was exposed giving the time weighted average as the reading on the center line. This parallel alignment chart would allow the wearer of the monitor to easily determine the exposure for the time period. This chart would require a minimum of training to

FIGURE 10

TIME WEIGHTED AVERAGE (TWA) EXPOSURE
HYDROGEN CHLORIDE



allow the monitor wearer to read the results.

Additionally, this form of information presentation meets the intent of the "Right to Know" or Hazards Communications requirement for informing the employee of his/her exposure. Additional training would be required for the specific hazards of the particular chemicals to which the employee is exposed to allow interpretation of the results of the monitor reading.

Figures 11 and 12 are parallel alignment charts for ammonia and sulfur dioxide respectively. These charts would be used in a similar fashion to allow the wearer of the monitor to read the time weighted average exposure for the period of monitor use. These charts clearly show the TLV for an eight hour exposure. They could further delineate the TLV by the use of color. For example, the section of the middle scale above the TLV could be shown in red. This would easily allow the employee with minimal qualifications to understand the monitors reading. Additionally, the middle scale could be colored yellow in the action level range and green below the action level.

Different styles of charts were reviewed for use as a method to easily allow the monitor wearer to determine exposure. Trilinear charts were considered, but were determined to be too confusing for quick and easy interpretation. Leaving the chart in the form of figure 8 was considered, but this chart would require division of exposure by time to determine the Time Weighted Average

FIGURE 11

TIME WEIGHTED AVERAGE (TWA) EXPOSURE
AMMONIA

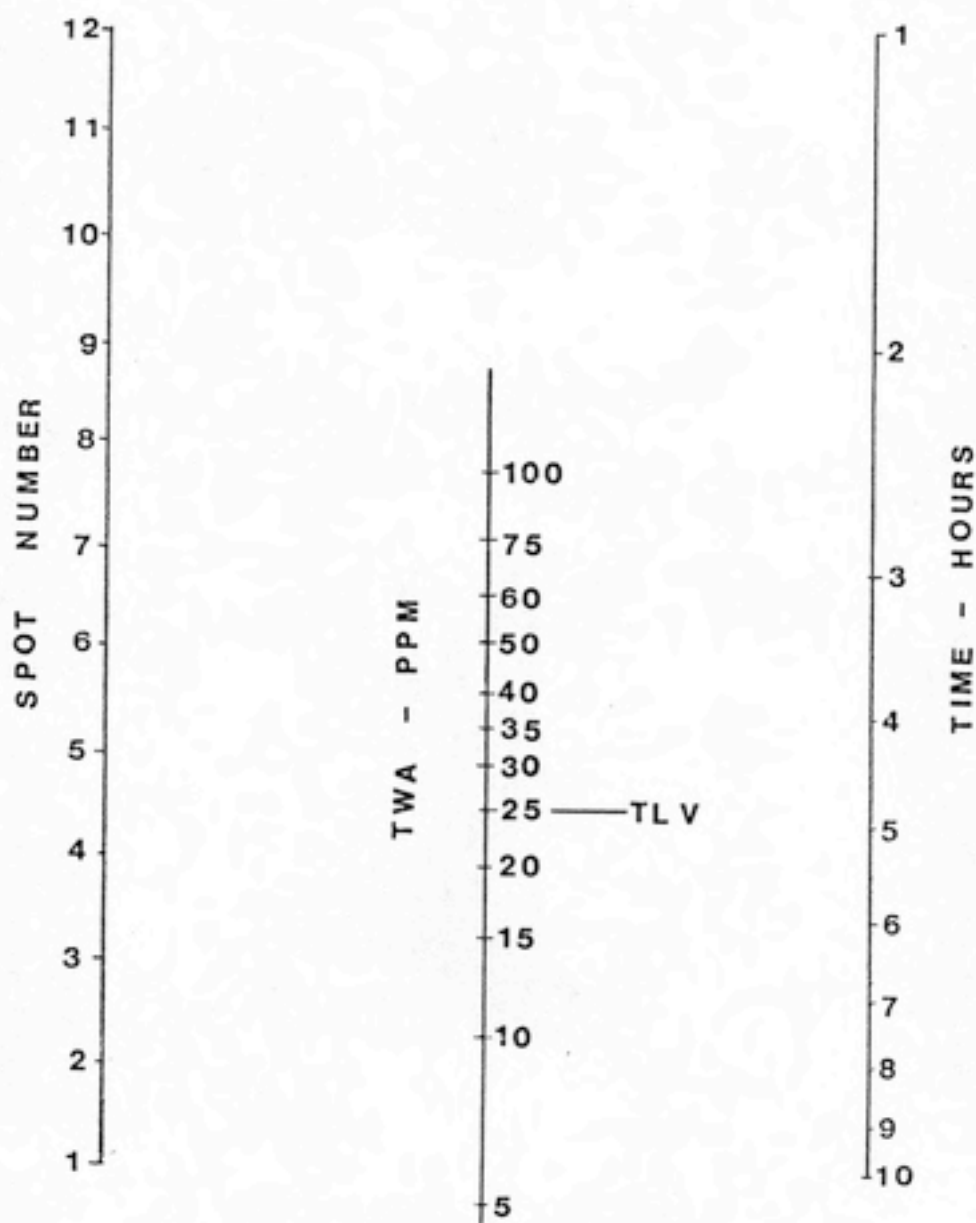
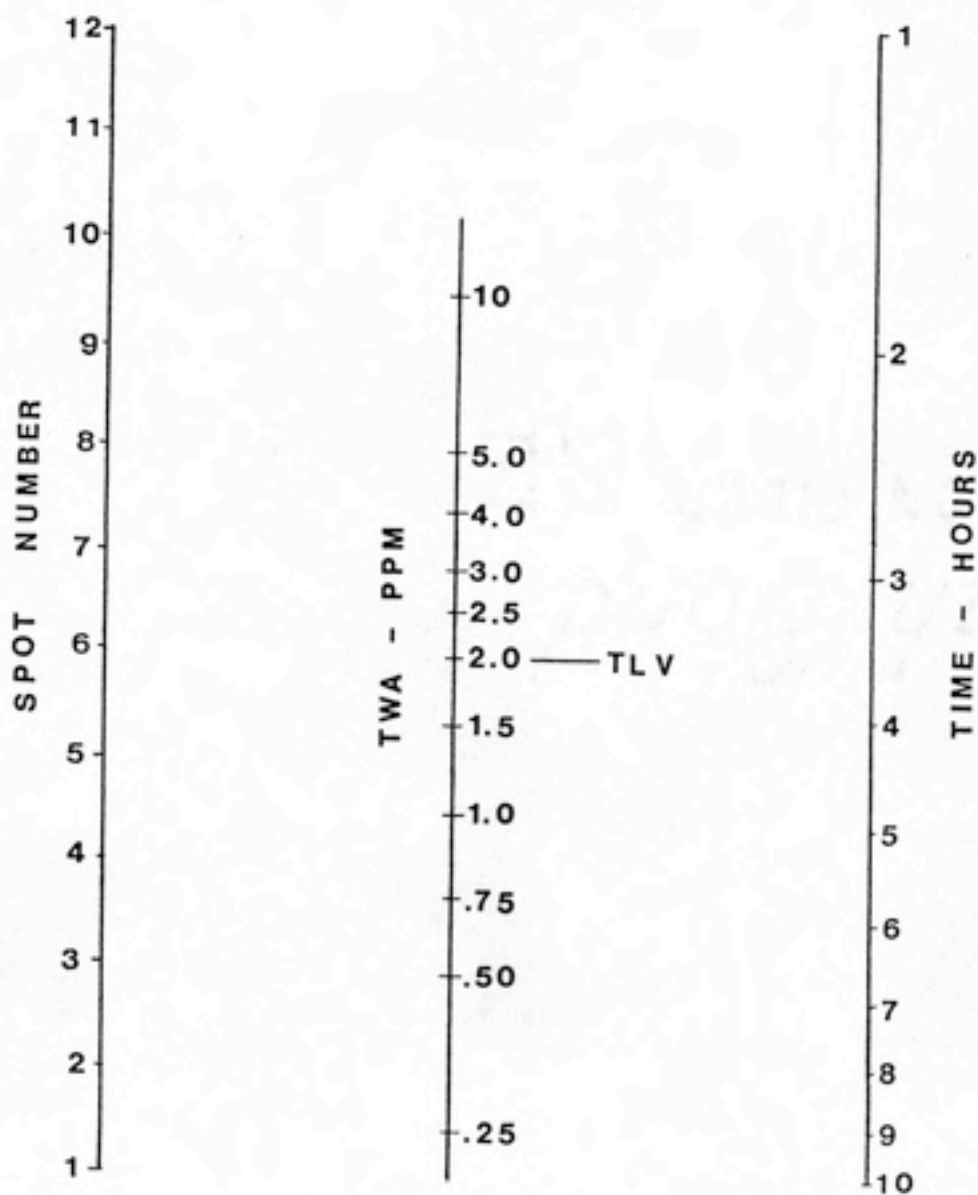


FIGURE 12

TIME WEIGHTED AVERAGE (TWA) EXPOSURE

SULFUR DIOXIDE



(TWA) concentration and would lead to many errors.

Therefore, the parallel scale alignment chart was chosen as the best form of information presentation considering that it would be used by relatively untrained employees.

Other types of devices such as circular slide rule type could also be used.

V. CONCLUSIONS AND RECOMMENDATIONS

The monitor as tested demonstrated consistent results over the three chemicals. The linearity of the response shows that the monitor performs as predicted. With calibration charts prepared for a given chemical and these charts converted to easily interpreted TWA diagrams the monitor can be used to give satisfactory results for use by the typical employee.

However, for the monitor to gain a wide acceptance in the field of Industrial Hygiene, several improvements should be made to the system:

1. The colorimetric media must be designed specifically for this application with the idea in mind that the monitor will be read by the human eye under varying conditions of light.
2. The change in color due to contaminant reaching the collection media should be made more pronounced.
3. A wider range of collection medias must be developed for the more commonly used chemicals in the workplace.

It is clear to this researcher that the diffusion operated, passive monitor has good commercial potential. It is simple to use, can be made of very light weight

material and small in size. The use of injection molded or even thermoformed plastic monitors would make the monitor a low initial cost item. Each device would probably be low enough cost that each monitor would be a one time use device. The one time use cost would have to be balanced against the cost of labor and handling to refill a multiple use monitor before each use with the collection media. The cost of the collection media for this experiment was \$36.25 (retail) for 240 strips. These cost factors along with the ease of use and rapidity of results should make the system acceptable in the market place.

Further research is needed to determine the TWA charts for other commonly used chemicals and the appropriateness of the passive monitor device for these chemicals.

To further test the monitor, it should be used experimentally in a lifelike situation with movement through the contaminated environment similar to movement by a working employee.

A modification of the monitor which might provide for easier determination of which spot to consider the endpoint would be to create a monitor with fewer holes spaced further apart.

VI. REFERENCES

1. American Conference of Governmental Industrial Hygienists, Threshold Limit Values for Chemical Substances in the Work Environment Adopted by ACGIH for 1984-85, ACGIH, Cincinnati, OH, 1984.
2. Brief, R. S., "Sampling for Gases & Vapors", Basic Industrial Hygiene A Training Manual, Winter 1975 Supplement to the Medical Bulletin, Exxon, New York, 1975, pp. 47-55.
3. Chang, R., "The Liquid State", Physical Chemistry with Applications to the Biological System, 2nd ed., Macmillan, NY, 1981, p83.
4. Coulson, D. M., "Method Validation", Annals of American Conference of Governmental Industrial Hygienists, Vol. 1, pp. 83-89, 1981.
5. Hamm, M. E., Design and Evaluation of A Direct-Reading Passive Monitor for Gases and Vapors, Master's Technical Report, Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, 1981
6. Hinds, W. C., "Properties of Gases", Aerosol Technology - Properties, Behavior, & Measurements of Airborne Particles, 1 ed., Wiley, New York, 1982, p. 23.
7. Lautenberger, W. J., Kring, E. V., and Morello, J. A., "Theory of Passive Monitors", Annals of American Conference of Governmental Industrial Hygienists, Vol. 1, pp.91-99, 1981.
8. Lippmann, M., "Dosimetry for Chemical Agents: An Overview", Annals of American Conference of Governmental Industrial Hygienists, Vol. 1, pp. 11-21, 1981.
9. Martin, J. E., "An Intuitive Approach to Passive Monitors", Annals of American Conference of Governmental Industrial Hygienists, Vol. 1, pp. 101-106, 1981.

10. McConnaughey, R. W., McKee, E. S., Pritts, I. M., "Passive Colorimetric Dosimeter Tubes For Ammonia, Carbon Monoxide, Carbon Dioxide, Hydrogen Sulfide, Nitrogen Dioxide and Sulfur Dioxide", American Industrial Hygiene Association Journal, Vol. 46, No. 7, pp. 353-362, July 1985.
11. McKee, E. S., McConnaughey, P. W., "Passive, Direct Reading, Length-of-Stain Dosimeter for Ammonia", American Industrial Hygiene Association Journal, Vol. 46, No. 8, pp. 407-410, Aug, 1985.
12. McMahon, R., Personal Communications, Oct. 10, 1985.
13. MDA Scientific, Inc., "Series 7100 Continuous Toxic Gas Monitor", Data Sheet No. 970372, Jun 1985.
14. Occupational Safety and Health Administration, General Industry Safety and Health Standards (29 CFR 1910), U. S. Department of Labor, Washington, D. C., 1976, p 504-510.
15. Wuebkenberg, M. L., "Personal Passive Monitors for Chemical Agents", Annals of American Conference of Governmental Industrial Hygienists, Vol. 1, pp. 107-115, 1981.

APPENDIX 1

D A T A

Ammonia

Exposure for spot formation (ppm-minute)

Spot # Spot	Percent of TLV Concentration				Mean
	Trial #	40%	90%	150%	
1	1a	3539	3296	3216	
	1b	3494	3296	3216	
	2a	3613	2224	3581	
	2b	3654	2224	3267	
	3a	2961	2668	3475	
	3b	2961	2792	3678	
	Mean	<u>3370</u>	<u>2750</u>	<u>3405</u>	3175
2	1a	4615	4060	4750	
	1b	4696	4060	4768	
	2a	4375	3581	4187	
	2b	4389	3581	4187	
	3a	3847	3602	4080	
	3b	3847	3692	4118	
	Mean	<u>4295</u>	<u>3763</u>	<u>4348</u>	4135
3	1a	6466	5212	5225	
	1b	5852	5212	5225	
	2a	5576	4749	4862	
	2b	5643	4565	4862	
	3a	4615	4677	4742	
	3b	4615	4959	4999	
	Mean	<u>5461</u>	<u>4896</u>	<u>4986</u>	5114
4	1a	8559	6530	7248	
	1b	8386	6472	7248	
	2a	8742	5431	6242	
	2b	8368	5258	6496	
	3a	5723	6428	6613	
	3b	5723	6428	6656	
	Mean	<u>7583</u>	<u>6091</u>	<u>6750</u>	6808

5	1a	10697	8223	9810	
	1b	10415	8060	9810	
	2a	10655	7227	7425	
	2b	10655	6843	7216	
	3a	7366	8036	8916	
	3b	7060	8145	9386	
	Mean	<u>9475</u>	<u>7756</u>	<u>8310</u>	8514
6	1a	13145	10310	11931	
	1b	13278	10263	11931	
	2a	11693	9578	9977	
	2b	11424	8621	9064	
	3a	9636	9810	11178	
	3b	8970	9810	11241	
	Mean	<u>11358</u>	<u>9632</u>	<u>10887</u>	10659
7	1a	17303	15847	13758	
	1b	17820	13417	13758	
	2a	12843	12797	12933	
	2b	13656	11016	12001	
	3a	12388	12378	13511	
	3b	11573	12378	13549	
	Mean	<u>14264</u>	<u>12972</u>	<u>13252</u>	13496
8	1a	19855	19045	16942	
	1b	20002	19099	16890	
	2a	17417	15384	16693	
	2b	17826	14761	15399	
	3a	14342	16174	15686	
	3b	13195	16174	17182	
	Mean	<u>17106</u>	<u>16773</u>	<u>16465</u>	16781
9	1a	26104	22557	19748	
	1b	26344	19911	19748	
	2a	23379	18052	20977	
	2b	23379	17434	18357	
	3a	17896	18864	17567	
	3b	17009	18969	20769	
	Mean	<u>22352</u>	<u>19298</u>	<u>19528</u>	20392

10	1a	31810	24933	26349	
	1b	30937	21874	26349	
	2a	*	20281	26099	
	2b	*	20253	24228	
	3a	21063	24602	21828	
	3b	21063	25833	27270	
	Mean	<u>26218</u>	<u>22963</u>	<u>25354</u>	24673
11	1a	37809	28213	30621	
	1b	38648	25485	34732	
	2a	*	23744	28684	
	2b	*	23583	28511	
	3a	22904	27958	28978	
	3b	22904	28958	27748	
	Mean	<u>30566</u>	<u>26323</u>	<u>29879</u>	28717
12	1a	*	34816	*	
	1b	*	33076	*	
	2a	*	29190	36290	
	2b	*	28518	37059	
	3a	26676	31840	36713	
	3b	26676	33741	37260	
	Mean	<u>26676</u>	<u>31863</u>	<u>36830</u>	32655

Hydrogen Chloride

Exposure for spot formation (ppm-minute)

Spot # Spot	Percent of TLV Concentration				Mean
	Trial #	40%	90%	150%	
1	1a	360.4	657.0	357.0	463.0
	1b	360.4	680.5	357.0	
	2a	412.5	347.8	625.0	
	2b	412.5	361.0	625.0	
	Mean	386.5	511.6	491.0	
2	1a	456.5	820.1	431.4	585.8
	1b	456.5	834.1	431.4	
	2a	600.4	468.0	699.2	
	2b	600.4	532.7	699.2	
	Mean	528.5	663.7	565.3	
3	1a	589.3	1022.1	497.2	829.6
	1b	589.3	1096.3	497.2	
	2a	856.3	839.0	1090.3	
	2b	856.3	931.9	1090.3	
	Mean	722.8	972.3	793.7	
4	1a	798.5	1196.9	808.5	1065.1
	1b	798.5	1386.8	1000.7	
	2a	983.1	1231.6	1181.1	
	2b	983.1	1231.6	1181.1	
	Mean	890.8	1261.7	1042.8	
5	1a	1001.9	2152.7	1358.0	1422.4
	1b	1001.9	1663.2	1459.9	
	2a	1117.6	1605.1	1285.9	
	2b	1117.6	1605.1	1699.9	
	Mean	1059.8	1756.5	1450.9	

6	1a	1346.9	2330.6	1907.3	
	1b	1346.9	2152.7	2315.9	
	2a	1245.3	2131.2	2089.8	
	2b	1245.3	1879.8	2041.6	
	Mean	<u>1296.1</u>	<u>2123.6</u>	<u>2088.6</u>	1836.1
7	1a	1725.0	2906.1	2676.7	
	1b	1725.0	2804.0	2928.2	
	2a	1493.5	2633.4	2392.9	
	2b	1493.5	2442.8	2705.8	
	Mean	<u>1609.2</u>	<u>2696.6</u>	<u>2675.9</u>	2327.2
8	1a	2363.8	3158.1	3389.6	
	1b	2363.8	3009.6	3576.0	
	2a	1972.7	3521.5	3248.7	
	2b	1972.7	2861.7	3080.4	
	Mean	<u>2168.2</u>	<u>3137.7</u>	<u>3323.7</u>	2876.6
9	1a	2830.7	3766.0	4570.3	
	1b	2830.7	3366.5	4324.6	
	2a	3019.1	4294.7	4056.8	
	2b	2457.1	3594.5	4268.9	
	Mean	<u>2784.4</u>	<u>3755.5</u>	<u>4305.2</u>	3615.0
10	1a	3436.4	4519.8	5383.5	
	1b	3436.4	4565.5	5820.1	
	2a	4130.8	5670.3	4676.3	
	2b	4410.0	5362.7	5085.6	
	Mean	<u>3853.4</u>	<u>5029.6</u>	<u>5241.4</u>	4708.1
11	1a	3699.5	5474.2	7007.2	
	1b	3699.5	5951.1	7711.0	
	2a	5189.1	6348.4	5293.4	
	2b	5189.1	5757.2	6707.0	
	Mean	<u>4444.3</u>	<u>5882.8</u>	<u>6679.7</u>	5668.9
12	1a	4195.3	6758.9	8888.9	
	1b	4195.3	7724.2	9662.0	
	2a	5730.8	6869.5	5931.4	
	2b	5730.8	6891.9	9400.1	
	Mean	<u>4963.1</u>	<u>7061.1</u>	<u>8470.6</u>	6831.6

Sulfur Dioxide

Exposure for spot formation (ppm-minute)

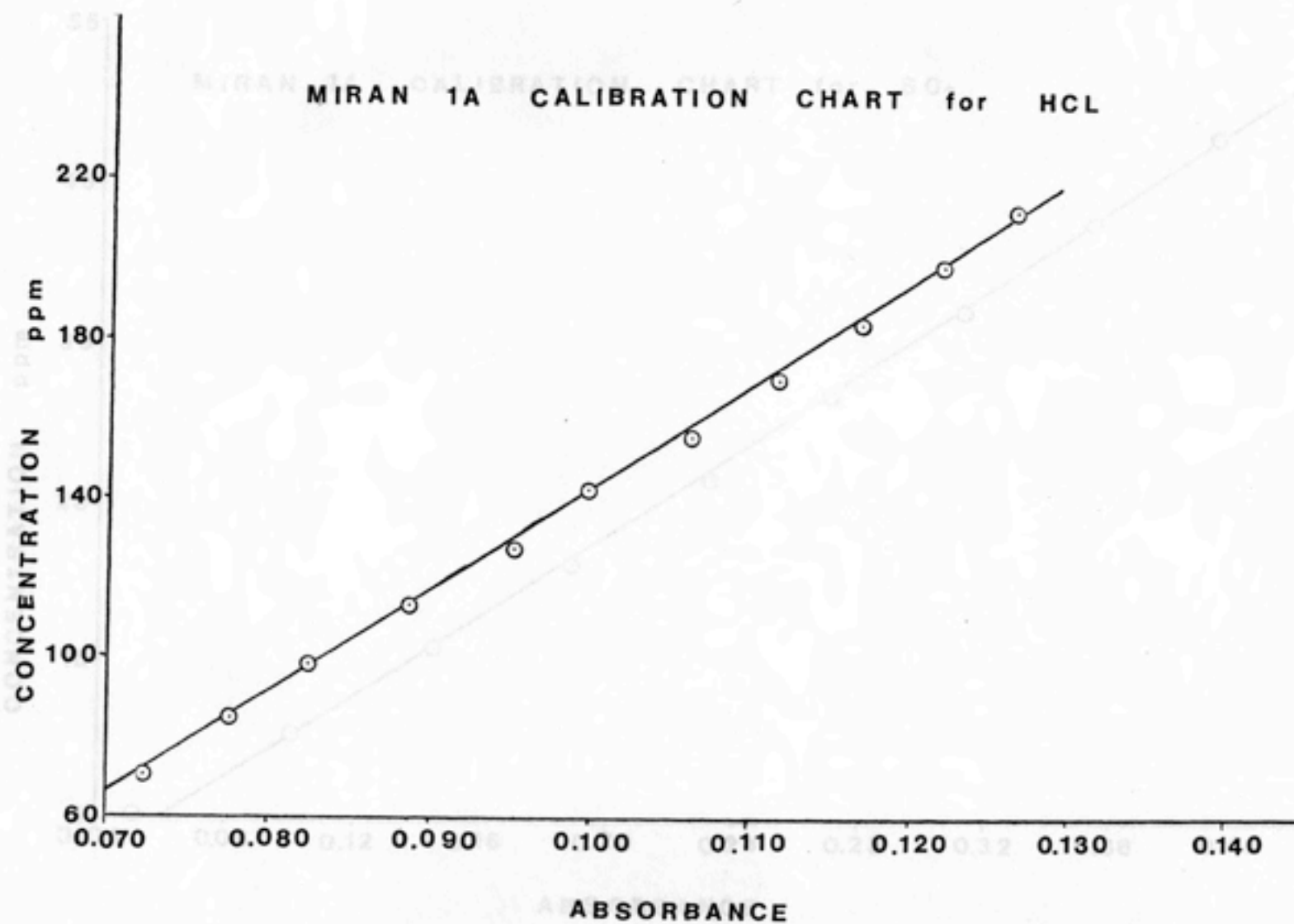
Spot #	Trial #	Percent of TLV Concentration 40%	90%	150%	Mean
1	1a	96.8	100.6	79.0	
	1b	99.5	102.7	80.5	
	2a	112.1	170.6	105.4	
	2b	110.8	122.6	105.4	
	3a	115.6	123.0	113.5	
	3b	106.9	123.0	101.3	
	Mean	106.9	123.7	97.5	109.4
2	1a	125.2	129.1	98.0	
	1b	130.6	132.3	106.7	
	2a	158.0	185.5	136.7	
	2b	158.0	190.8	140.0	
	3a	154.8	138.2	186.3	
	3b	159.2	138.2	187.1	
	Mean	147.6	152.3	142.5	147.5
3	1a	166.3	175.9	151.6	
	1b	190.2	173.6	158.7	
	2a	186.1	235.6	270.8	
	2b	180.7	238.7	282.0	
	3a	228.8	183.5	234.9	
	3b	222.9	204.6	237.1	
	Mean	195.8	202.0	222.5	206.8
4	1a	250.2	278.3	194.1	
	1b	298.8	266.9	198.8	
	2a	255.8	297.6	349.1	
	2b	223.7	293.7	354.4	
	3a	256.7	247.3	360.2	
	3b	267.7	288.4	360.2	
	Mean	258.1	278.7	302.8	280.1

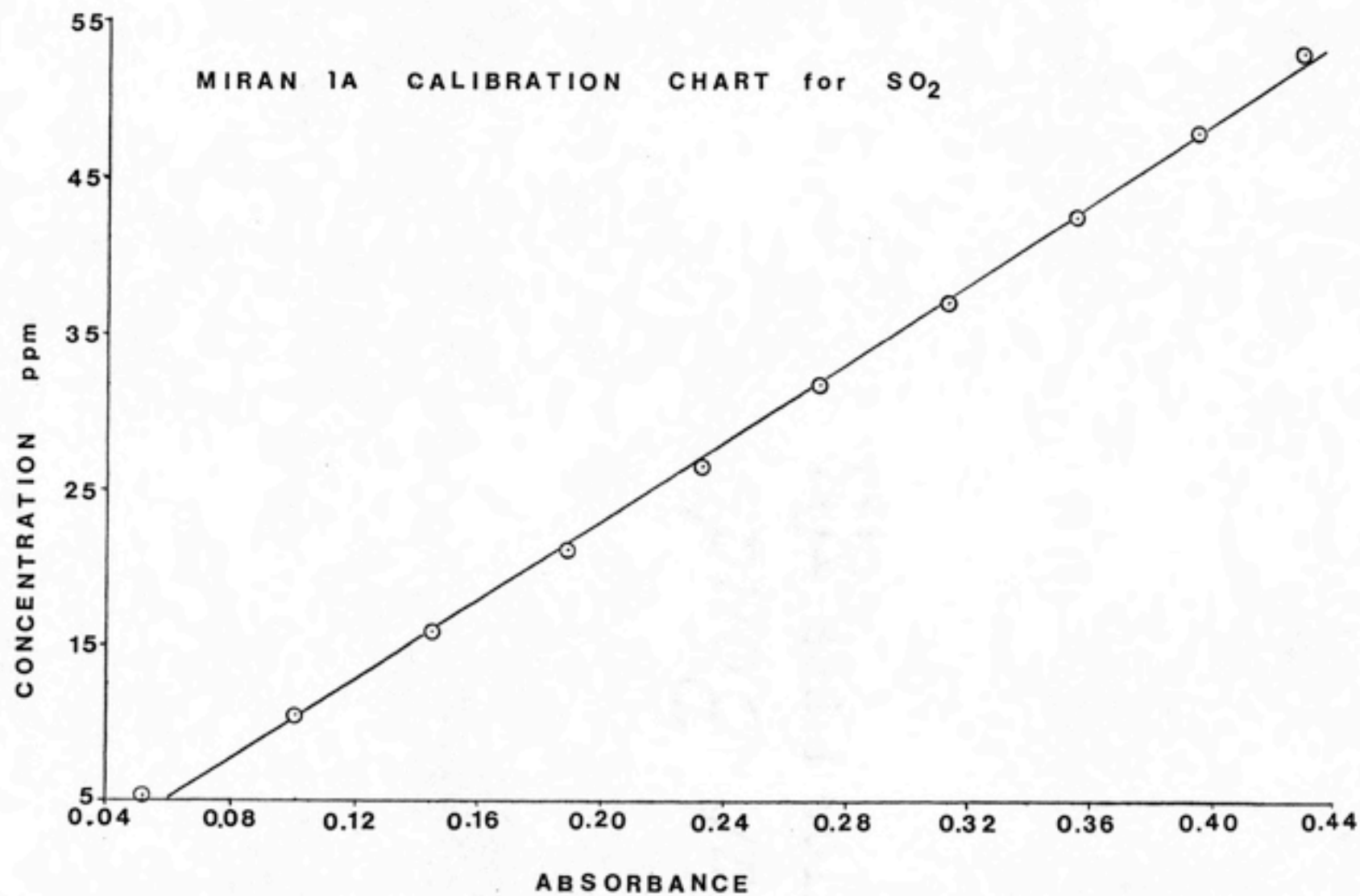
5	1a	325.7	407.2	273.5	
	1b	330.4	389.8	269.0	
	2a	303.1	434.4	449.4	
	2b	260.6	438.1	456.5	
	3a	332.2	336.1	414.2	
	3b	337.4	411.9	413.3	
	Mean	<u>314.9</u>	<u>402.9</u>	<u>379.3</u>	365.7
6	1a	402.5	547.6	358.9	
	1b	394.1	555.0	378.4	
	2a	424.5	532.8	556.4	
	2b	371.4	532.8	572.5	
	3a	458.2	540.9	570.2	
	3b	465.6	552.6	575.5	
	Mean	<u>419.4</u>	<u>543.6</u>	<u>502.0</u>	488.3
7	1a	446.1	658.5	518.7	
	1b	476.4	640.9	521.4	
	2a	501.5	630.0	706.2	
	2b	552.2	630.0	690.4	
	3a	599.5	643.7	686.9	
	3b	605.3	749.8	653.8	
	Mean	<u>530.2</u>	<u>658.1</u>	<u>629.6</u>	606.2
8	1a	525.2	810.8	748.7	
	1b	530.6	700.7	755.7	
	2a	604.1	743.4	988.0	
	2b	640.9	743.4	988.0	
	3a	809.6	807.4	870.5	
	3b	866.2	837.1	873.2	
	Mean	<u>662.8</u>	<u>773.8</u>	<u>870.7</u>	769.1
9	1a	712.0	844.0	945.1	
	1b	*	*	*	
	2a	748.6	895.0	1150.3	
	2b	*	*	*	
	3a	1057.9	1055.4	1159.1	
	3b	*	*	*	
	Mean	<u>839.5</u>	<u>931.5</u>	<u>1084.8</u>	951.9

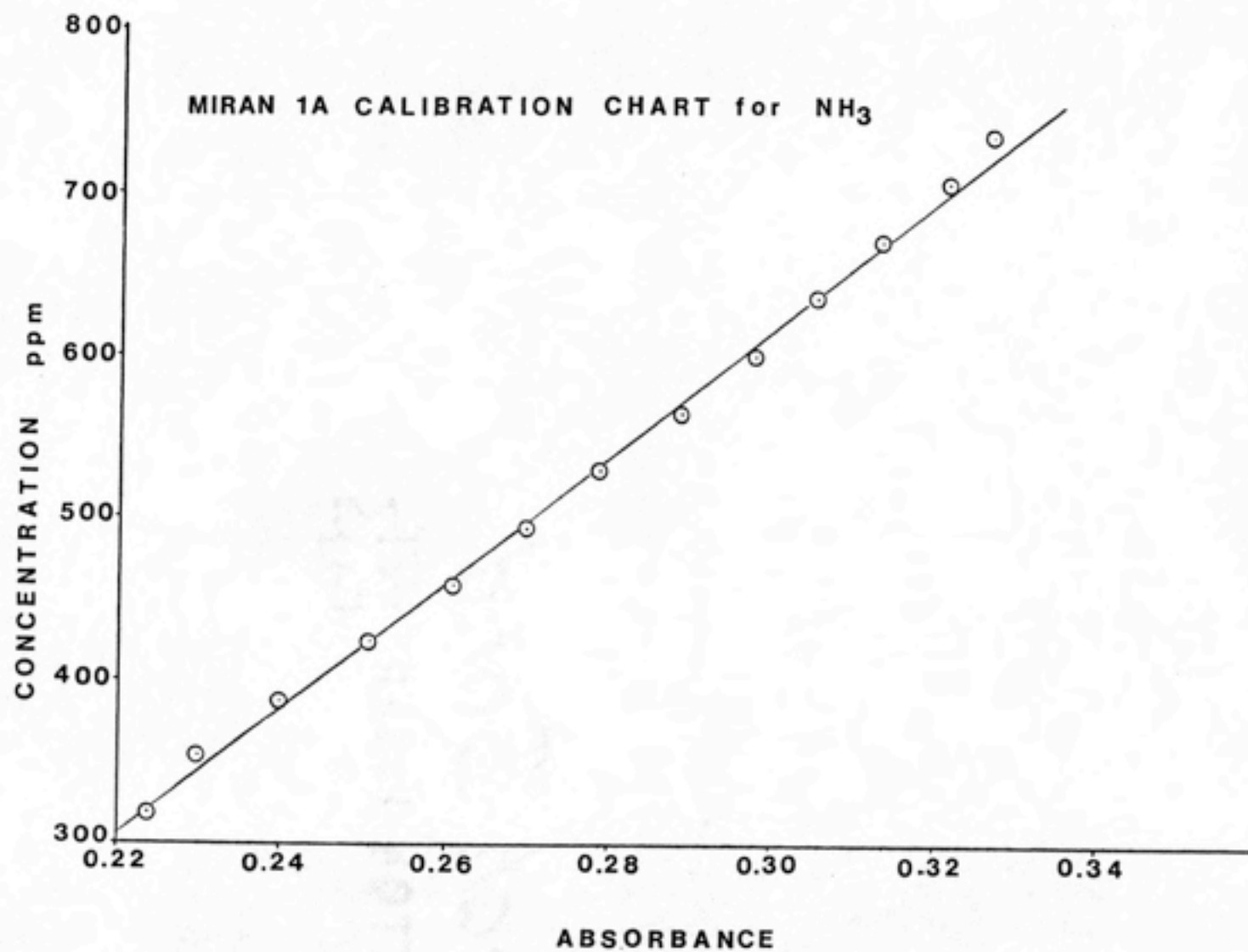
10	1a	937.9	1166.9	1206.1	
	1b	1075.4	920.1	1212.2	
	2a	920.7	1065.3	1297.9	
	2b	1227.8	1095.4	1320.6	
	3a	1347.1	1233.8	1386.0	
	3b	1413.2	1444.9	1398.0	
	Mean	<u>1153.9</u>	<u>1154.4</u>	<u>1303.5</u>	1203.8
11	1a	1314.0	1316.7	1468.4	
	1b	1375.2	1135.7	1460.2	
	2a	1415.8	1254.7	1441.2	
	2b	1570.2	1250.3	1443.6	
	3a	1639.5	1491.8	1474.9	
	3b	1656.9	1581.7	1477.4	
	Mean	<u>1495.3</u>	<u>1338.5</u>	<u>1460.9</u>	1431.6
12	1a	1592.0	1927.1	1648.5	
	1b	1598.5	1820.9	1653.2	
	2a	1727.2	1904.0	1756.9	
	2b	1863.7	2035.7	1793.9	
	3a	1992.2	1765.2	1621.2	
	3b	2000.0	2159.7	1783.6	
	Mean	<u>1795.6</u>	<u>1935.4</u>	<u>1709.5</u>	1813.5

APPENDIX 2

MIRAN CALIBRATION CHARTS







Miran 1A Calibration Chart for HCl

Ambient Conditions

Temperature: 23.3 C

Barometric pressure: 747.1 mm Hg

Relative Humidity: 50%

Equipment Settings

Wavelength: 3.40 um

Pathlength: 20.25 m

Slit width: 1 mm

Gain: X1

Meter Response: 1

Injected Volume ul	System Conc. ppm	Absorbance		Trial # 3	Trial # 4	Mean
		Trial # 1	Trial # 2			
400	70.9	0.069	0.072	0.074	0.075	0.072
480	85.1	0.069	0.077	0.082	0.077	0.076
560	99.3	0.075	0.085	0.086	0.084	0.083
640	113.5	0.082	0.091	0.092	0.090	0.089
720	127.6	0.089	0.098	0.098	0.096	0.095
800	141.8	0.095	0.103	0.104	0.101	0.101
880	156.0	0.100	0.109	0.109	0.107	0.106
960	170.2	0.105	0.115	0.115	0.112	0.112
1040	184.4	0.111	0.120	0.121	0.117	0.117
1120	198.6	0.116	0.125	0.125	0.122	0.122
1200	212.8	0.121	0.130	0.130	0.127	0.127

Miran 1A Calibration Chart for SO₂

Ambient Conditions

Temperature: 23 C

Barometric pressure: 757.6 mm Hg

Relative Humidity: 31%

Equipment Settings

Wavelength: 7.42 μ m

Pathlength: 20.25 m

Slit width: 1 mm

Gain: X1

Meter Response: 1

Injected Volume ul	System Conc. ppm	Absorbance			Mean
		Trial # 1	Trial # 2	Trial # 3	
30	5.3	0.049	0.051	0.055	0.052
60	10.6	0.099	0.100	0.104	0.101
90	16.0	0.145	0.146	0.144	0.145
120	21.3	0.192	0.189	0.186	0.189
150	26.6	0.237	0.230	0.232	0.233
180	31.9	0.270	0.270	0.272	0.271
210	37.2	0.312	0.312	0.318	0.314
240	42.6	0.353	0.351	0.360	0.355
270	47.9	0.395	0.389	0.399	0.394
300	53.2	0.432	0.420	0.430	0.427

Miran 1A Calibration Chart for NH3

Ambient Conditions

Temperature: 26 C
 Barometric pressure: 752.4 mm Hg
 Relative Humidity: 66%

Equipment Settings

Wavelength: 10.5 um
 Pathlength: 20.25 m
 Slit width: 1 mm
 Gain: X1
 Meter Response: 1

Injected Volume ul	System Conc. ppm	Absorbance		Trial # 3	Trial # 4	Mean
		Trial # 1	Trial # 2			
1800	319	0.241	0.200	0.209	0.248	0.224
2000	355	0.241	0.218	0.211	0.250	0.230
2200	390	0.249	0.229	0.223	0.260	0.240
2400	426	0.258	0.240	0.237	0.270	0.251
2600	461	0.264	0.251	0.249	0.280	0.261
2800	496	0.272	0.257	0.260	0.290	0.270
3000	532	0.281	0.265	0.270	0.300	0.279
3200	567	0.291	0.274	0.280	0.309	0.289
3400	603	0.300	0.286	0.289	0.318	0.298
3600	638	0.308	0.293	0.298	0.326	0.306
3800	674	0.317	0.302	0.307	0.332	0.314
4000	709	0.324	0.311	0.313	0.340	0.322

APPENDIX 3
PHYSICAL PROPERTIES

Physical Properties

	Ammonia	Hydrogen Chloride	Sulfur Dioxide
Formula	NH ₃	HCl	SO ₂
Formula weight	17.03	36.47	64.06
Diffusion (12) coefficient cm ² /sec	0.2204	0.1684	0.1386
Solubility grams in water 0° C	89.9	82.3	22.8
TLV ppm(1)	25	5	2