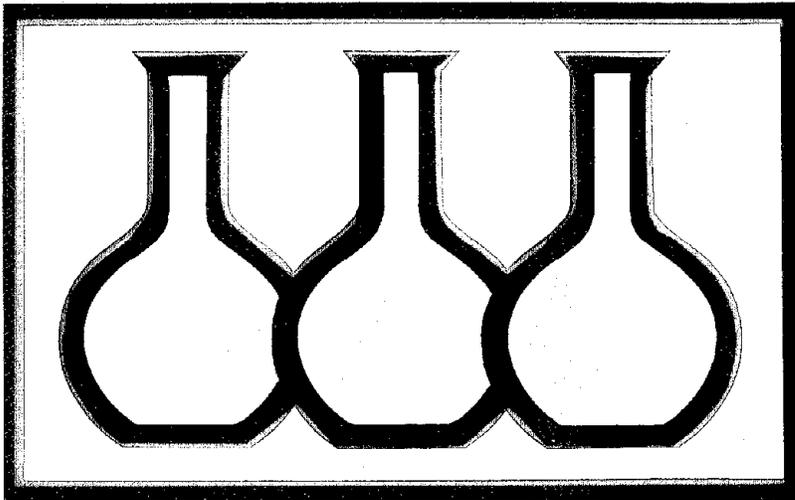


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**DESIGN SPECIFICATIONS FOR  
RESPIRATORY BREATHING DEVICES  
FOR FIREFIGHTERS**

**NIOSH** Research Report

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DESIGN SPECIFICATIONS FOR RESPIRATORY BREATHING  
DEVICES FOR FIREFIGHTERS

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## FOREWORD

This final report summarizes all work performed by the Harvard School of Public Health during the period June 1, 1972, to October, 1973. The project upon which this publication is based was performed under Contract No. HSM 99-72-21 with the National Institute for Occupational Safety and Health, Health Service and Mental Health Administration,\* Department of Health, Education, and Welfare. This program was administered technically by Mr. A. Gudeman of the Engineering Branch, Division of Laboratories and Criteria Development at the National Institute for Occupational Safety and Health.

\* The National Institute for Occupational Safety and Health is now a part of the Center for Disease Control, U.S. Department of Health, Education, and Welfare.

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## ABSTRACT

The desired protection factor for self-contained breathing apparatus used in the fire service is proposed at 100 based on a series of tests with a personal air sampler which revealed maximum air concentrations of carbon monoxide of approximately 20,000 ppm. The sampler continuously monitors the concentration of carbon monoxide and oxygen during the fire fighting episode.

A combustible gas detector was modified to be specific for carbon monoxide in the range of 0.02 to 10.0%, and a membrane sensor is used to measure oxygen in the range of 0-21%. The data is recorded on a small cassette tape recorder using a voltage to frequency converter. A series of seventy-four incidents were studied in cooperation with the Boston Fire Department.

A study of the respiratory minute volume during active work, while wearing open-circuit, self-contained breathing apparatus indicated a median value of 60 liters per minute and 70 liters for the eighty percentile group. If the self-contained device is to have a service life of thirty minutes, the stored air capacity must be 1800 liters and 2100 for the median and eighty percentile values respectively.



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## I. INTRODUCTION

In 1969 the Boston Fire Department reviewed its respiratory protection program and decided to eliminate the use of air-purifying respirators and rely totally on the use of self-contained, open circuit, compressed air breathing apparatus. Early experience with this equipment prompted complaints by the firefighters of weight, bulk, limited use time, and questionable efficiency. At that time the Department requested assistance from the Harvard School of Public Health in evaluating the respiratory protection needs of the fire service. We responded to this request by indicating the need for general application information which could be used in developing design specifications for the engineer. The program outlined in this report is a joint study by the Harvard School of Public Health and the Boston Fire Department, designed to provide these specification elements. The minimum protection factor required for residential and commercial structural fires and volume of stored air necessary for a given work period were to be defined by the study. Protection factor is a measure of the degree of protection afforded by the respirator, defined as the ratio of the concentration of the contaminant in the ambient atmosphere to that inside the respirator facepiece under conditions of use.

The firefighter has a unique respiratory protection problem, quite unlike the emergency use of respirators by the industrial worker. Industry requires emergency respiratory protection when large amounts of toxic materials are accidentally released, as occurs in refineries, steel mills, and chemical plants. In the industrial setting, one can usually identify the contaminant and its approximate concentration range and specify the correct breathing apparatus. This approach has not been utilized in the fire service. We know neither the specific air contaminants in the fire environment, nor their concentration.

Extensive literature does exist on the nature of the products of pyrolysis and combustion of many common and esoteric materials in laboratory studies<sup>(1,2)</sup>. Certain fires produce unique combustion products that pose immediate danger to life - nitrogen dioxide from fur or silk fires, sulfur dioxide from rubber fires, and hydrogen cyanide from wool fires<sup>(3,4)</sup>. In most fire situations, however, the primary respiratory hazard is probably exposure to carbon monoxide and low oxygen levels. Autopsies consistently demonstrate that the cause of civilian fire deaths is usually carbon monoxide poisoning. Such data are not generally available on fire fighters<sup>(5)</sup>.

In deliberate burns of dwellings and other structures, combinations of high carbon monoxide concentrations and oxygen deficiency have been found where only a few breaths would be fatal<sup>(2,6,7,8,9)</sup>. A study of members of the Denver Fire Department pointed out the risk of carbon monoxide to fire fighters by demonstrating blood carboxyhemoglobin (COHb) levels

of up to 43% after fighting a fire (10). Breyse and others have also found elevated COHb levels in firefighters (11-13).

Although the danger from high carbon monoxide levels and oxygen deficiency is clear, it is difficult to estimate this risk to the firefighters since no systematic attempt has been made to evaluate his exposure patterns under actual firefighting conditions. This approach appeared to be the first step in defining the requirements of respiratory protective devices for the fire service. The data from real fire conditions would permit assigning a minimum acceptable protection factor for respirators to be used by the fire services.

One of the restrictions of self-contained breathing apparatus as described by operating fire departments is the limited use time available under work conditions. The designer of the device must have a firm specification on air storage needs based on actual fire fighting data. The total air volume required in compressed air devices is simply the product of the respiratory minute volume of the firefighter and the desired work time. The desired work time can be obtained by asking the firefighter. The minute volume requires spirometry during actual work conditions. Measurement of respiratory minute volume of the firefighter will also permit one to estimate the peak inspiratory flow which is another requirement to be met by the equipment.

Statements by Boston firefighters on the duration of the present self-contained compressed air apparatus indicates that respiratory minute volumes during active fire fighting using demand apparatus may be in the range of 50-60 liters per minute. If this is the case, the peak inspiratory flows are as high as 180 liters per minute. It would be helpful in the design of equipment if firm figures were available.

This present study was designed to provide specification data on these two major areas. The required protection factor can be based on the exposure concentration to carbon monoxide and oxygen. In generating these data firefighters at selected fires were asked to wear a sling mounted personal air sampler designed for this study to continuously measure the concentration of carbon monoxide and oxygen in the fire environment. This information was continuously recorded on a miniature recorder.

The second desired specification input, the minute volume of the firefighter during work, was evaluated by adapting the respirator facepiece to accept a miniature spirometer which provided an average minute volume during the work period. With this information and the desired work time, one can assign the minimum air storage capacity for the open circuit compressed air apparatus.

As an adjunct project, an attempt was made to monitor heat stress by rectal temperatures on firefighters during active work in fire situations; however, this proved completely impractical.

## II. EXPOSURE TO CARBON MONOXIDE AND OXYGEN

### A. Personal Sampler

#### 1. Design Requirements

Firefighters said that the samplers should be light-weight, of minimum bulk, self-contained and have a mechanism for data storage. The sampler must be rugged and insensitive to the extreme environmental conditions to which it would be exposed. The construction and design had to be simple enough to allow servicing by firefighters selected and trained for this task. The required operating time of one hour was based on the maximum probable time at a single fire.

The primary danger to the firefighter could well be exposure to high concentrations of carbon monoxide for a few minutes or less, rather than long term exposure to lower concentrations; therefore, the carbon monoxide sensor must be able to measure concentrations from 0.05% to 10%. This lower limit was chosen because there are few acute physiologic dangers associated with exposure to this concentration for one hour or less<sup>(14)</sup>. Concurrent with variation in the carbon monoxide concentrations, oxygen levels may vary from zero to 21%.

Since the concentrations of carbon monoxide to be measured cover two-and-a-half orders of magnitude, only physical measurement techniques seemed feasible. The thermistor/Hopcalite method is the most common of these, however, its weight and power requirements are excessive. Spectroscopy and chromatography cannot be suitably miniaturized for this type of field instrumentation. The hot wire, combustible gas detector (CGD) was chosen for detailed study since it met our general requirements. Although the CGD is not specific in its response, it can be made so by scrubbing the sample stream with suitable reactants.

The polarographic membrane sensor was the obvious choice for oxygen measurement since it is suited for portable operation, specific for oxygen, and responsive to the desired range<sup>(15-19)</sup>.

A miniaturized commercially available cassette tape recorder was chosen as the recording system for the final package. Output signals of the carbon monoxide and oxygen circuits are alternately fed, by means of a timing motor micro-switch assembly, into a voltage-to-frequency converting circuit. The frequency signal is recorded on the cassette tape.

## 2. Carbon Monoxide Detector

### Principles of Operation

The operation of CGD depends upon the catalytic oxidation of combustible gases on a heated platinum filament. The heat of combustion released on the surface of the filament raises the temperature of the wire and increases its electrical resistance. The filament is one arm of a Wheatstone bridge circuit which indicates the change in resistance. The resistance is directly proportional to the concentration of combustible material on the surface of the filament.

The theory and design of combustible gas detectors has been discussed by Monicard, Poole, and Coleman<sup>(20-22)</sup>. Coleman has also reviewed the performance of commercially available instruments<sup>(23)</sup>.

Initial investigation of the sensitivity of the combustible gas detector to carbon monoxide was made with a J & W Aromatic Hydrocarbon Indicator, Model SS. The calibration curve of this instrument to carbon monoxide, shown in Figure 1, demonstrates that the method is sensitive over the range required for this study. The lower detection limit is a function of read-out sensitivity; the upper limit is the lower explosive limit for carbon monoxide (12.5%).

### Operation in Oxygen Deficient Atmospheres

The detecting principle of the CGD depends upon the combustion of carbon monoxide with oxygen on the platinum wire. Since the fire environment may be oxygen-deficient, the response of the CGD had to be studied under these conditions. The reaction of carbon monoxide on the surface of the filament is given in Equation 1.



The stoichiometry of the reaction requires that there be at least half as much oxygen present in a molar ratio, as carbon monoxide, for the CGD to respond properly. The influence of the stoichiometry on the CGD was investigated by sampling an oxygen-nitrogen mixture containing 0.55% carbon monoxide with the oxygen concentration varying from zero to 21%. The response of the instrument under these conditions is shown in Figure 2. The uncorrected response to 0.55% carbon monoxide increased linearly with decreasing oxygen levels until insufficient oxygen was present for complete oxidation of the carbon monoxide on the filament surface. The baseline increased in a similar manner. However,

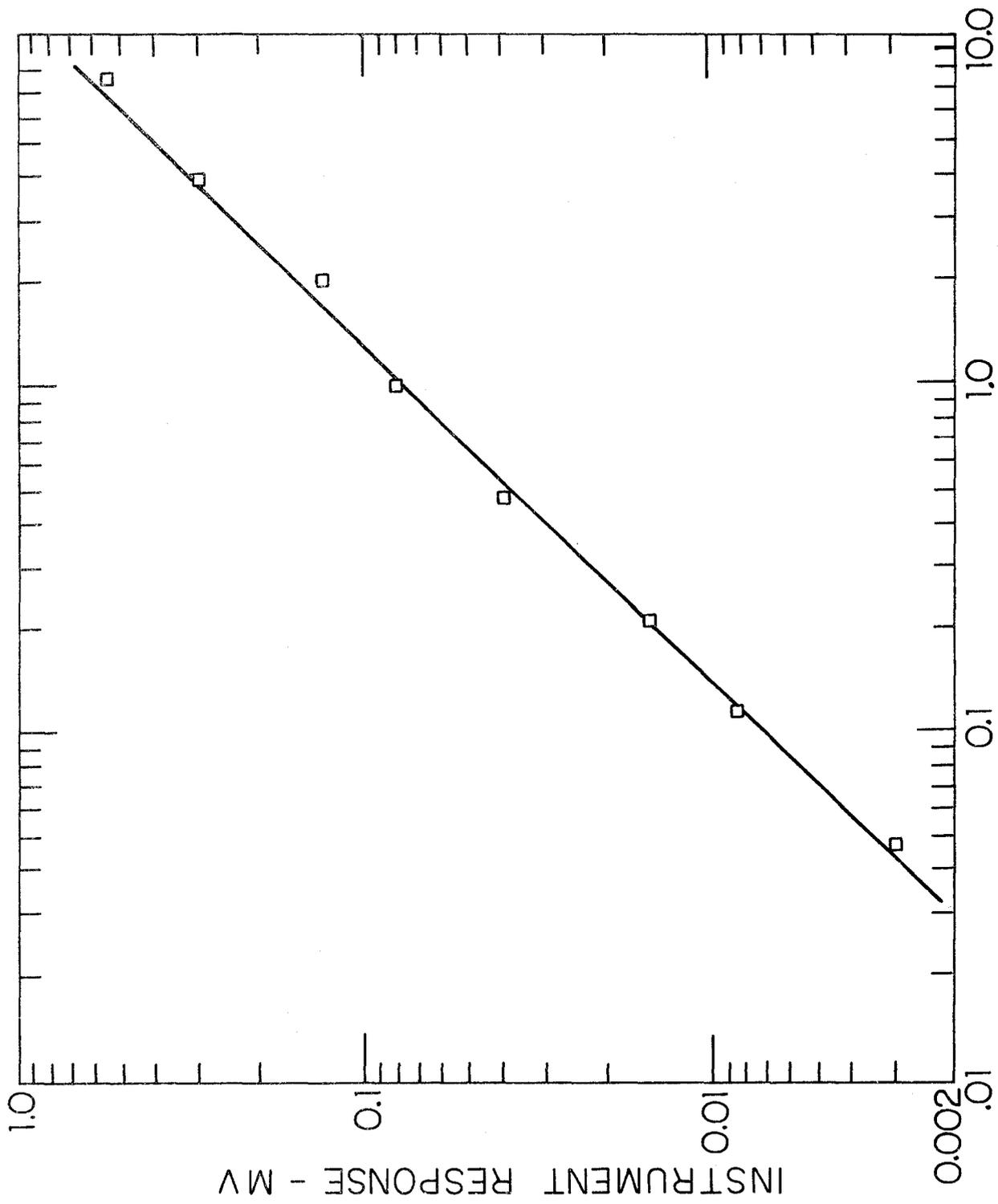


FIGURE 1  
% CARBON MONOXIDE IN AIR

Response of J & W Model SS Combustible Gas Detector to Carbon Monoxide

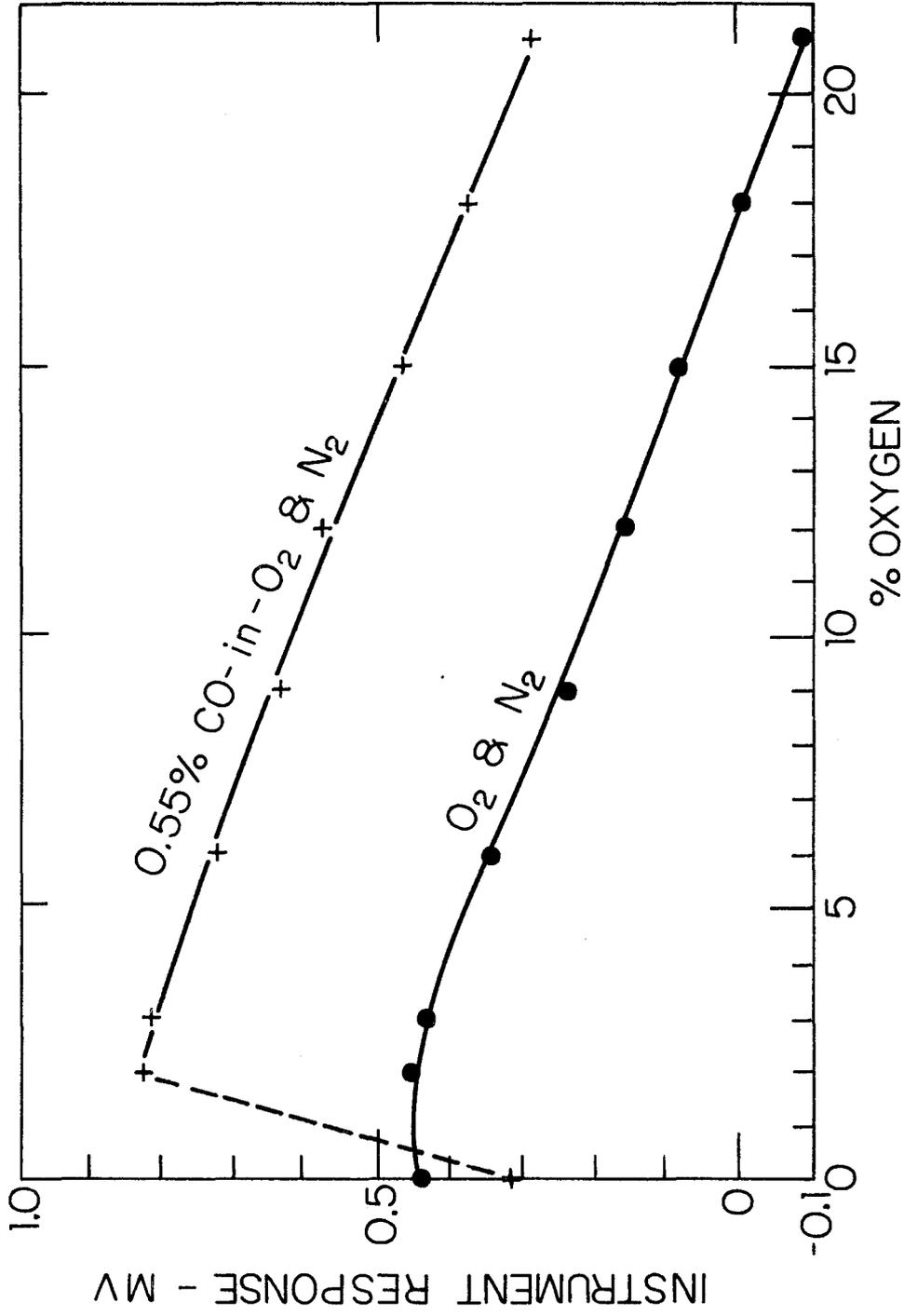


FIGURE 2

Response of J and W Model SS Combustible Gas Detector to 0.55% CO in

Atmospheres Containing Less Than 21% Oxygen

the difference between the response to carbon monoxide and the baseline was constant until there was less than the stoichiometrically required amount of oxygen. This investigation proved that the CGD can be used in an oxygen-deficient atmosphere if sufficient oxygen is present for combustion.

The baseline shift noted above is due to a difference in the heat capacities of the gas in the sample stream and the air in the closed reference cell. This difference is most pronounced at low oxygen concentrations. The baseline shift could introduce appreciable errors in carbon monoxide readings when low carbon monoxide and oxygen levels are simultaneously encountered, but since independent oxygen measurements are available this error is correctable. It can also be minimized by making the reference gas approximately the same composition as the sample gas. This was achieved by changing the filament cell so that the reference gas stream passed directly over the reference filament. The reference gas now consists of gas identical to that in the active cell except that the carbon monoxide has been removed using a Hopcalite catalyst bed. Instrument response was checked using this modified filament cell configuration with an oxygen-nitrogen mixture of 0.78% CO, oxygen varying from zero to 24% as shown in Figure 3. The baseline shift was minimized with this sampling configuration and the response of the CGD to carbon monoxide remained constant until oxygen concentrations dropped below 0.5%.

Hopcalite is a mixture of metal oxides including those of copper, cobalt, manganese, and silver and is widely used in gas mask canisters for removing carbon monoxide<sup>(24)</sup>. The heat rise generated by carbon monoxide oxidation in a Hopcalite bed is the basis of many commercial carbon monoxide monitors<sup>(25)</sup>. A bed of 5cc of Hopcalite at 25°C packed in a 2 cm diameter glass tube quantitatively removes carbon monoxide from a flow of up to 5 lpm at the concentrations considered here. The filaments and circuitry used in the Mine Safety Appliance Co. (MSA) Model 40 Portable Gas Indicator could most easily be modified as described above and subsequent investigation was done with components of this instrument.

#### Interference from Condensable Combustible Vapors

Since the CGD is non-specific, gases and vapors of all combustible components in the sample stream, except carbon monoxide, must be removed. A suitable gas scrubbing system was investigated by Adams and Summons in their study of the iodine pentoxide technique for measuring carbon monoxide<sup>(26)</sup>. The authors were able to remove interfering gases in carbon monoxide measurements of mine air, diesel exhaust, and coal gas by using chromic acid and acid mercuric sulfate impregnated silica gels. Hydrogen and the light aliphatic gases such as methane and ethane were not removed by this scrubbing system. The suitability of this method for our carbon monoxide detector was evaluated in a simple but conclusive manner. Approximately

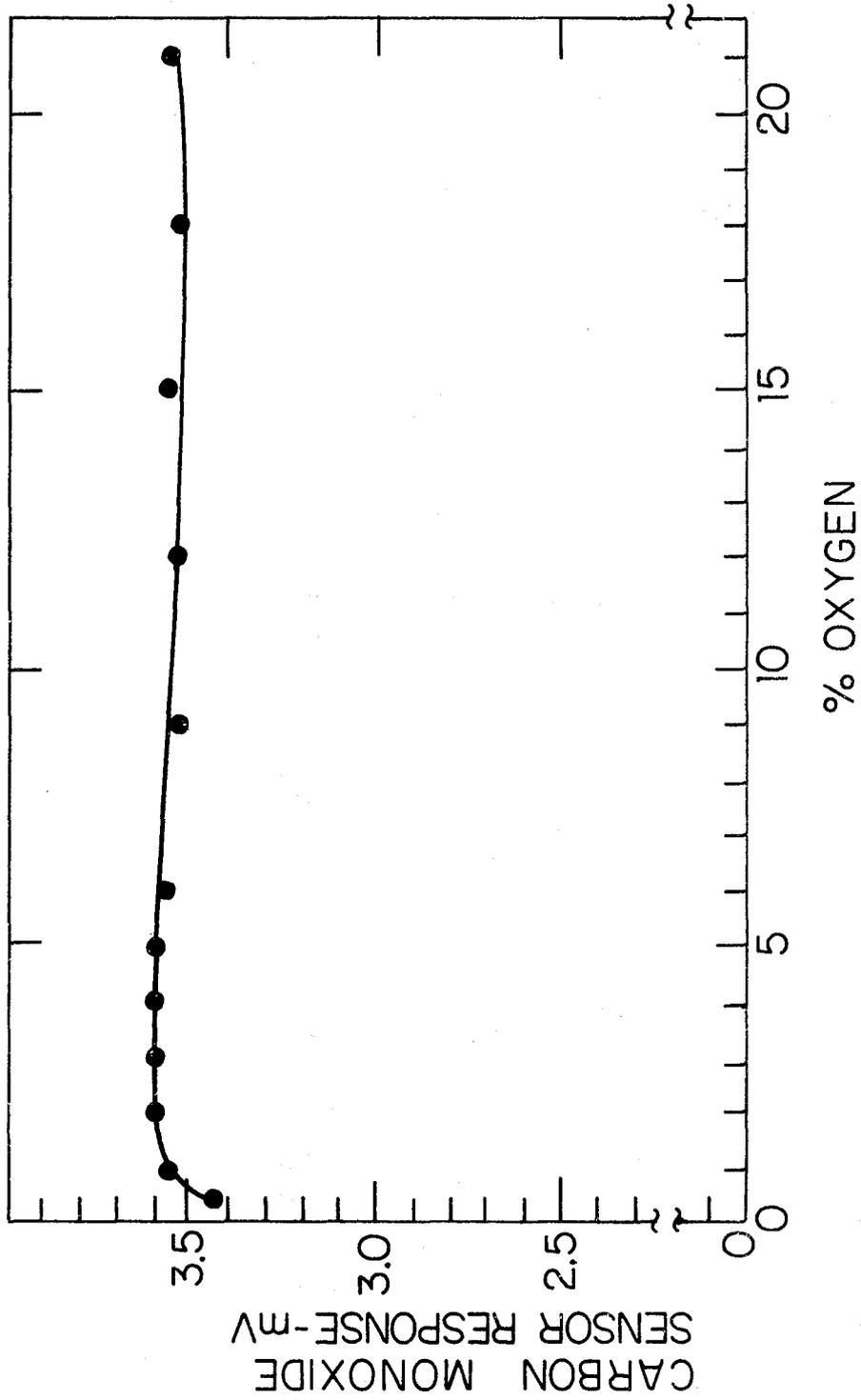


FIGURE 3

Response to CGD with Modified Reference Cell to 0.78% Carbon Monoxide in Atmospheres  
Containing Less than 21% Oxygen

twenty cc each of benzene, toluene, iso-octane, and acetone were introduced into a 500 ml suction flask; the vapor concentration in the flask headspace for this mixture was above the lower explosive limit. A series of three calibrations for carbon monoxide in air were run. In the first, the sample was pulled directly into the instrument. In the second, the sample was pulled through a scrubber consisting of silica gel, and chromic acid impregnated silica gel. In the third and final calibration, the sample was pulled through the headspace of the solvent-containing flask, through the scrubbing system and into the instrument. There were no significant changes in calibration between the three sampling modes; the scrubber was effective for the organic vapors tested, and therefore for most fire gases, and did not modify the carbon monoxide calibration.

#### Interference from Non-Combustible Gases

We reviewed interference from hydrogen and light aliphatic gases present in fire situations where there is an oxygen deficiency. Under extremely low oxygen conditions the concentration of hydrogen and methane can equal that of carbon monoxide. Ethane and the heavier aliphatic gases are generally only 10% or less of the carbon monoxide level (2,27,28).

In the modified filament cell configuration, combustible gases not scrubbed from the sample stream pass over both the sample and reference filament. Under optimum conditions with matched legs this should balance out the signal so that no instrument response will occur. But if the individual filaments do not have the same resistance the Wheatstone bridge circuit will not balance since their change in resistance will be unequal. In this case the instrument will give a response even when combustible gases are present at the same concentration on both filaments. This is what occurred in our instrument.

The problem of methane interference was resolved by considering the effects of varying the temperature of the platinum filament. The MSA Model 40 is normally operated with a potential of 0.88 volts D.C. across the filaments which heats the filament to a bright red. At lower voltages the temperatures of the filament decreases. Measurements of the relative response to carbon monoxide, hydrogen, methane and propane were made at lower applied filament voltages and compared to that at the normal operating voltage as shown in Figure 4. The response to all gases except methane increased slightly with decreasing voltages and upon reaching a maximum, dropped to zero. For methane the relative response immediately decreased with decreasing voltage. Below an applied filament voltage of 0.45 volts, the CGD still responded to carbon monoxide, hydrogen, and propane, but not to methane. Poole and Coleman have discussed this filament temperature phenomena (21-22).

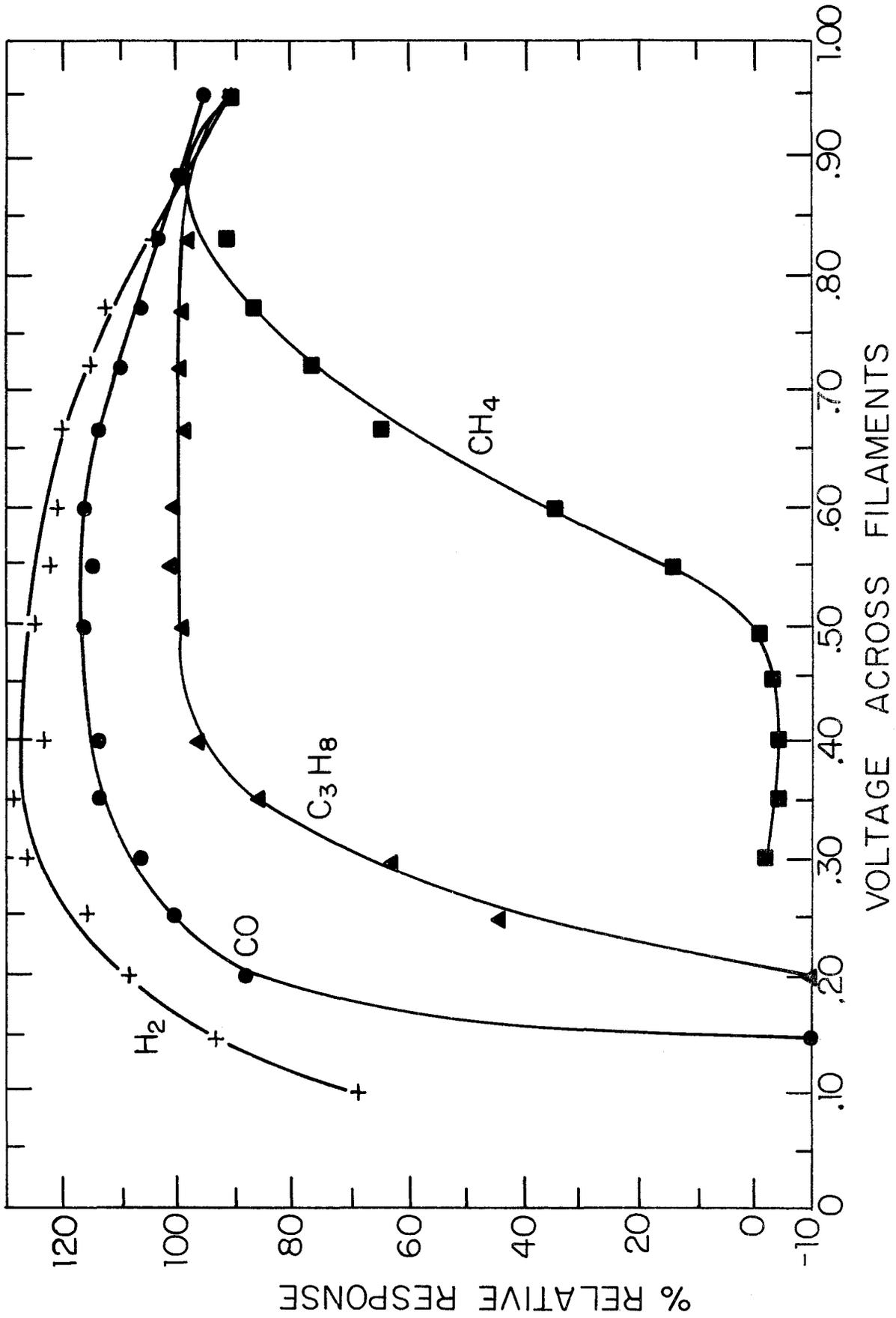


FIGURE 4

Relative Response of CGD to Combustible Gases at Various Applied Voltages

These data suggested that methane would not interfere if the instrument was operated with an applied filament voltage of less than 0.45 volts. This tactic was justified with a calibration run on 0.1 to 5% carbon monoxide in air with and without 1% methane. At an applied filament voltage of 0.35 volts, no additional response from methane was noted on the carbon monoxide measurement. Reduction in operating voltage also reduced the drift in the CGD output from 8.6 mv/hr at normal operation voltage to 0.0 mv/hr at 0.35 applied volts.

The interference from hydrogen was then considered. A plot of the error in the CGD's response to carbon monoxide in the presence of hydrogen is shown in Figure 5. When the carbon monoxide concentration is less than one percent, the negative error due to filament mismatch is less than 10% until the hydrogen/carbon monoxide ratio reaches 0.5. The error is still only about 20% when the hydrogen to carbon monoxide ratio is one to one. When the carbon monoxide concentration is greater than one percent the Hopcalite bed reaches sufficient temperature for the oxidation of hydrogen: this reduces the hydrogen concentration over the reference filament so that a positive error will eventually result. If carbon monoxide concentrations are greater than two percent and high hydrogen concentrations are also present, instrument readings become very unstable. Since the error is only 20% when the concentration of hydrogen and carbon monoxide is a ratio of one to one and such situations are rarely encountered, the problem of hydrogen interference is negligible.

#### Stability of the Carbon Monoxide Signal

The hot wire filament circuit is quite stable when operated at a potential of 0.35 volts. Maximum baseline drift over an hour corresponds to a concentration change of about 500 ppm of carbon monoxide. The maximum drift in the signal (4.6%) was noted when sampling 2.9% carbon monoxide air for over one hour. This represents the worst possible operating condition, since extended sampling periods of high carbon monoxide concentrations are not expected. The drift of the instrument is not excessive considering the demands placed on the carbon monoxide sensing system.

### 3. Oxygen Sensor

The sensor and circuit of Instrumentation Laboratory's Model 406 Oxygen Monitor was adapted to the fire environment sampler. The unit is specific for oxygen and has an automatic temperature compensation circuit; its response to varying oxygen concentrations at 24.4°C is given in Figure 6. A similar response curve was obtained when the gas was cooled to 0°C and no further investigation of this sensor seemed necessary.

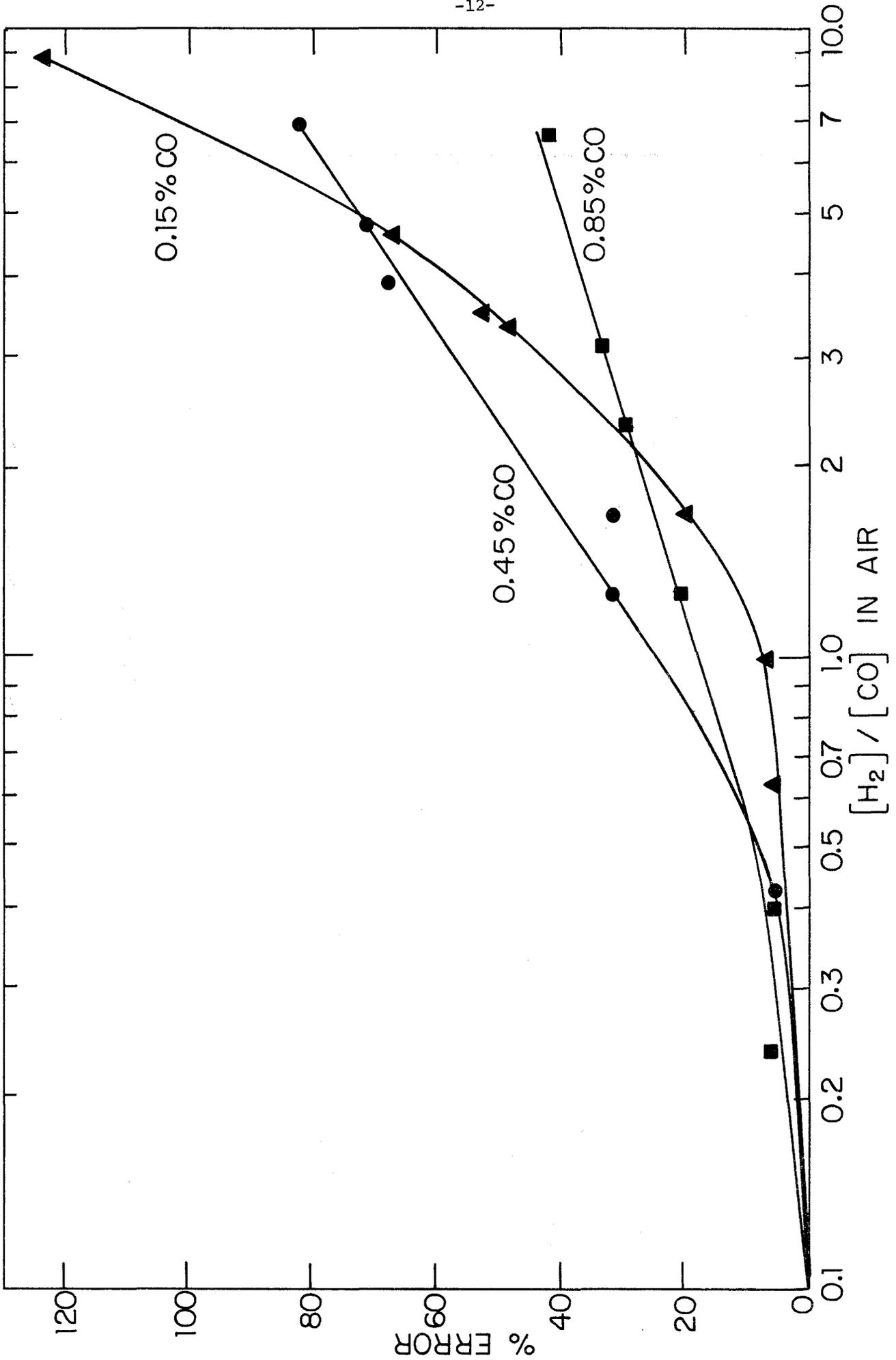


FIGURE 5

Error Introduced in CGD Response to Carbon Monoxide due to the Presence of Hydrogen

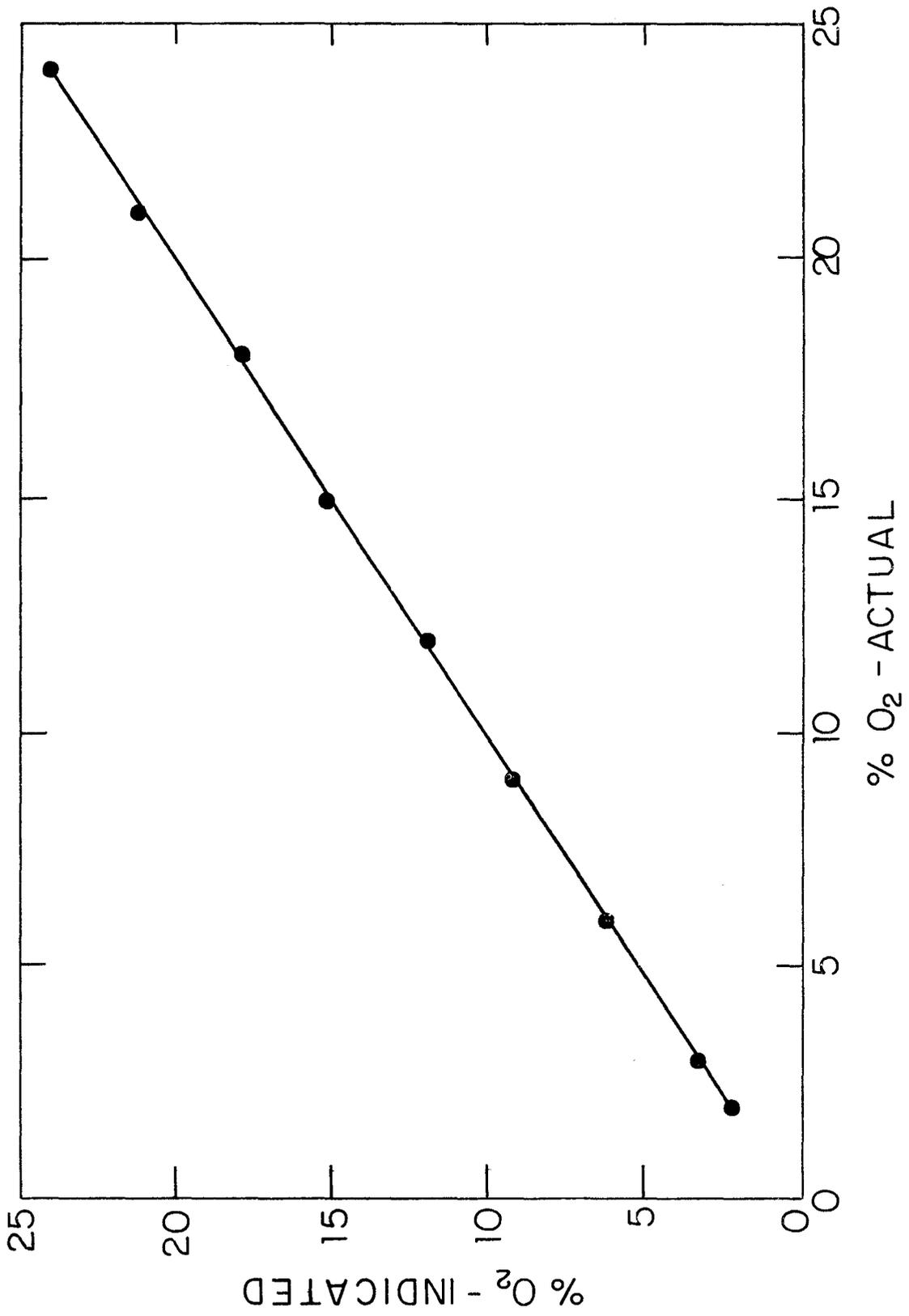


FIGURE 6

Response of Instrumentation Laboratory Oxygen Monitor, Model 406 H

#### 4. Sampler Assembly

##### Sample Gas Flow

A diagrammatic presentation of the personal sampler is shown in Figure 7. Air from the fire environment is drawn into the sampler with a diaphragm pump assembly. A roughing filter positioned in the oxygen sensor manifold removes coarse particulates. The sample stream then passes over the oxygen sensor and into the gas scrubbing system, where condensable organic gases are removed. The first scrubber component is Drierite which protects the silica gel and Hopcalite from poisoning by water vapor. The next layer is pure silica gel, used because its capacity for vapor combustion products is higher than impregnated materials. The acid mercuric sulfate impregnated silica gel removes olefins. The chromic acid impregnated silica gel acts as a backup to the scrubbing system. When the latter gel turns from orange to black the scrubber is depleted.

The gas sample is then split with one half passing through active Hopcalite and the other through inactive Hopcalite. These two streams are drawn over the reference and sample filaments respectively, are recombined, pass through the sampling pump, and are dumped from the sampler case. The filament cell is protected by flame arrestors to prevent propagation of a flame in the sample stream.

##### Data Signal

Signals from the oxygen (0-21mv) and carbon monoxide sensors (0-60mv) generated by their respective sensing circuits go to a microswitch/cam assembly drive by a 5 rpm timing motor. The signals are then fed alternately into a voltage-to-frequency converting circuit. The cycle is five seconds for oxygen, a 1/2 second pause, six seconds for carbon monoxide, and a final 1/2 second pause before repetition of the entire cycle. The voltage-to-frequency circuit generates a frequency signal (10-6000 cps) which is recorded on a Sony TC 40 cassette tape recorder.

The signal is retrieved by playing the tape back through a frequency-to-voltage converting circuit. In order to retain resolution of the carbon monoxide data, the signal is fed to a chopper-stabilized, logarithmic amplifier and finally to a chart recorder.

##### Operating Characteristics

Operating time of the sampler is limited by the sixty minute tape in the recorder. The next limiting factor is the four-hour operating time of the battery-driven pump. With a fully charged battery, the pump pulls air through the sampler

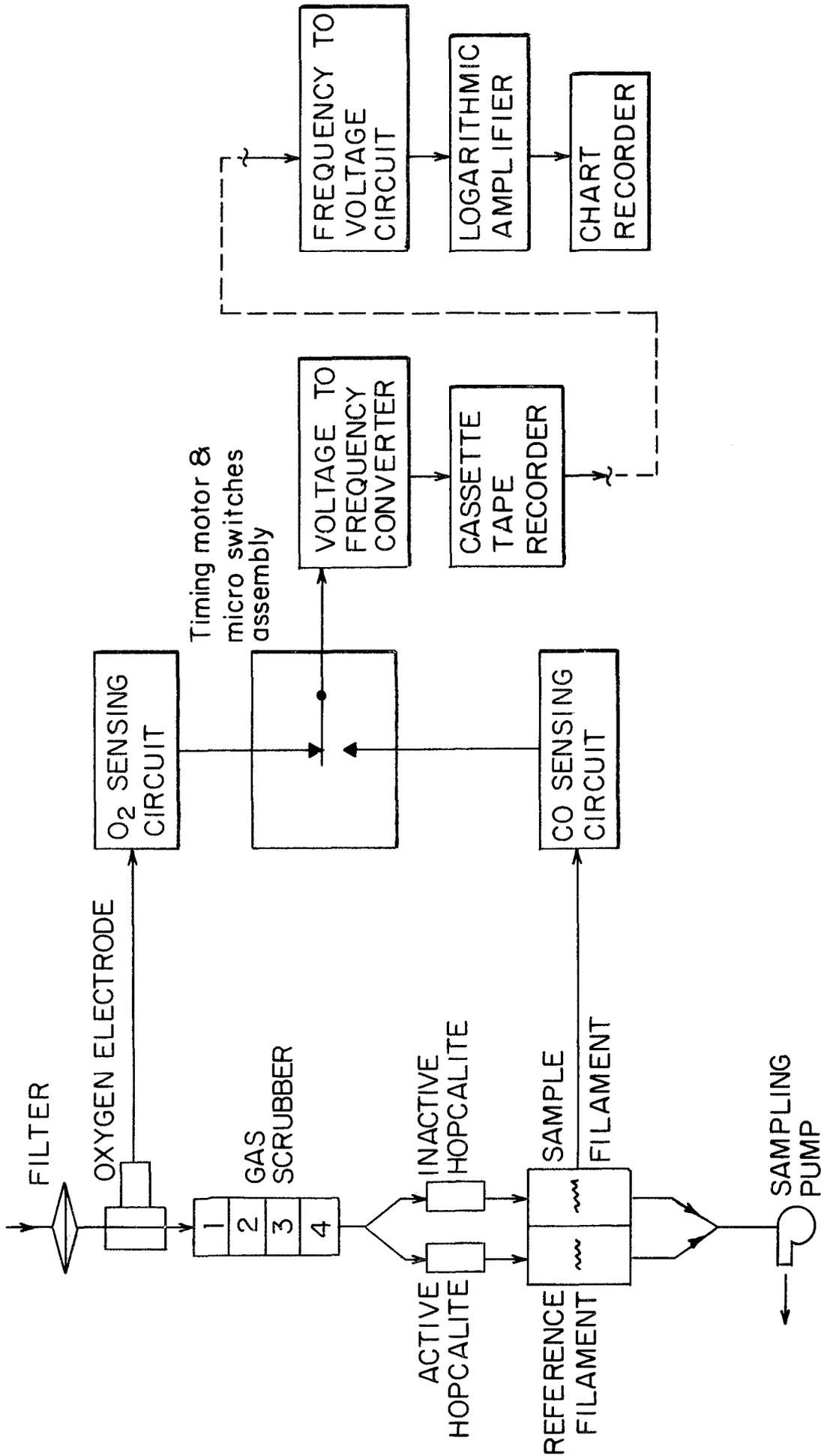


FIGURE 7

Diagrammatic Layout of the Personal Sampler System

at 1.75 lpm with a resistance to flow of 8.0" H<sub>2</sub>O. After 2-1/2 hours of running time the flow rate drops to 1.45 lpm at 6.5" H<sub>2</sub>O.

The carbon monoxide signal takes four seconds to appear and rises to 90% of peak signal in about 5 seconds. Since carbon monoxide from the sample stream diffuses to the sensing filament, the CGD response is relatively insensitive to sample flow.

Signal stability of the assembled unit was tested by strapping it on the back of an investigator who undertook a violent exercise routine. The unit was sampling a dynamically generated 0.75% carbon monoxide in air mixture. Data were recorded on the cassette tape recorder and played back to a Hewlett - Packard Model 5231B Frequency Counter. Both carbon monoxide and oxygen signals were stable during the most violent exercise routines.

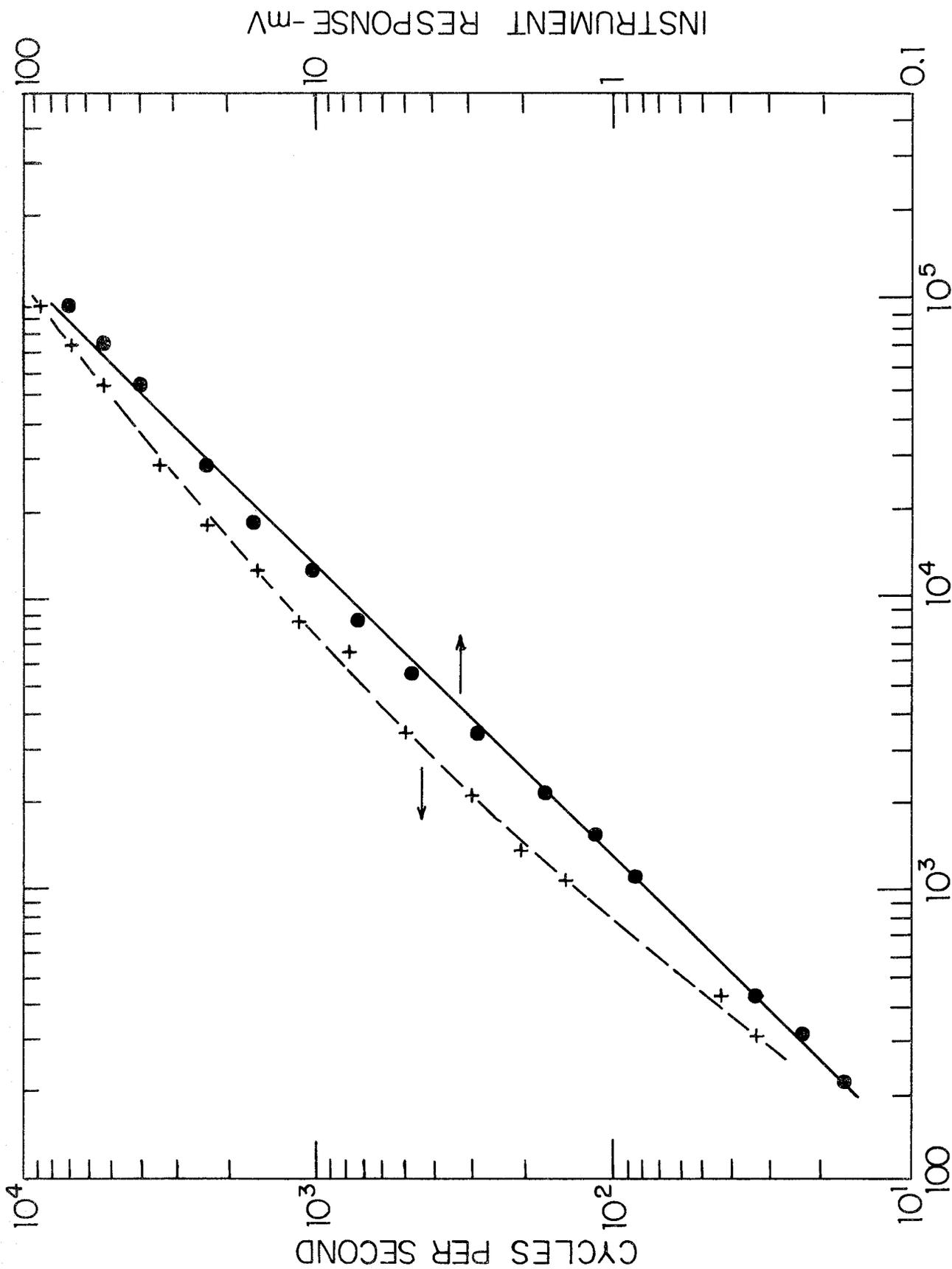
In the final field version of the sampler all electrical circuit switches are coupled to a multiple-pole single-throw switch. This allows the wearer to activate the sampler with only one manipulation.

The final carbon monoxide sensor configuration has a relatively linear response as shown in Figure 8 over a range of .02 to 10% carbon monoxide. Nonlinearity in the output of the voltage -to-frequency converter above 4000 cps results in a slightly curvilinear output for the total sensor system. While curvilinearity adds a troublesome factor in interpreting the final readout of the data, it is a small problem considering the extensive range of the sensor.

#### Field Use and Service

The sampler is housed in a 1/4" vacuum-formed molded acrylic butadiene-styrene case. This material was preferred over metal for its resistance to impact and better heat insulation characteristics. The housing dimensions are 24.4 cm X 19.7 cm X 12.7 cm and the assembled sampler weight is 4.6 Kg (10 lbs. 2 oz.). The unit is equipped with shoulder straps and a belt and is worn on the fire fighter's hip.

Before use in a fire, the sampler is serviced and the calibration is checked dynamically by sampling a gas containing 15% oxygen and 0.2% carbon monoxide. These data are recorded on the tape as a calibration check for the fire exposure data to be gathered later. An immediate read-out of the calibration signal is obtained using a small plug-in meter console.



CARBON MONOXIDE - ppm

FIGURE 8

Response of Sampler to Carbon Monoxide (1) as Millivolt Output of Wheatstone Bridge  
Circuit and (2) as Output in Cycles Per Second of Voltage to Frequency

## 5. Prototype Evaluation

### Analysis of Actual Fire Gases

The accuracy of the carbon monoxide and oxygen sensors was evaluated on fire gases from wood, upholstery, and rubber fires in the smoke house at the Boston Fire Fighting Academy. Air samples were taken from the room through a 3/8" diameter metal tubing. A filter removed particulates before the sample stream was drawn through the gas scrubbing bed described previously. Each sample was stored in a Saran bag for analysis in the laboratory by the personal sampler and for independent verification of oxygen level by a paramagnetic instrument and carbon monoxide levels by gas chromatography. Results from the personal sampler are compared with the independent analytical methods in Figures 9 and 10.

The personal sampler had a mean error of 25.6% in analysis of the carbon monoxide content of the five sampled fire gases as shown in Figure 9. If one considers only those concentrations above 0.05%, the mean error was 14.0%. This higher error range at lower concentrations was probably due to the presence of non-condensable fire gases. We anticipated an error of this magnitude and consider it acceptable.

A significant calibration shift was discovered in the carbon monoxide sensing circuitry due to filament aging and loss of catalytic activity. To avoid this shift, each instrument must be checked prior to use with a calibrating gas mixture as previously described.

The mean error in oxygen measurements from Figure 10 was 3.2%, which is acceptable for this study. This is a negative error and will result in conservative oxygen readings.

The ability of the personal sampler to withstand the rigors of a fire environment was tested by placing it in wood and upholstery fires in a non-ventilated room of the smoke house. As shown in Figure 11 these were extreme tests and the conditions encountered were potentially fatal. The oxygen level in the wood fire (Figure 11-a) dropped to 17.5%, not a dangerous level in itself except that the carbon monoxide rose to 0.2 - 0.3% which could be lethal for exposures of 30 minutes.

The upholstery fire was monitored in two stages. The first phase involved vigorous burning of a sofa ignited with fuel oil and the second phase a decay of the fire to a smoulder. Fire-fighters especially dislike this latter type of fire. During the vigorous burning phase (Figure 11-b), the oxygen level

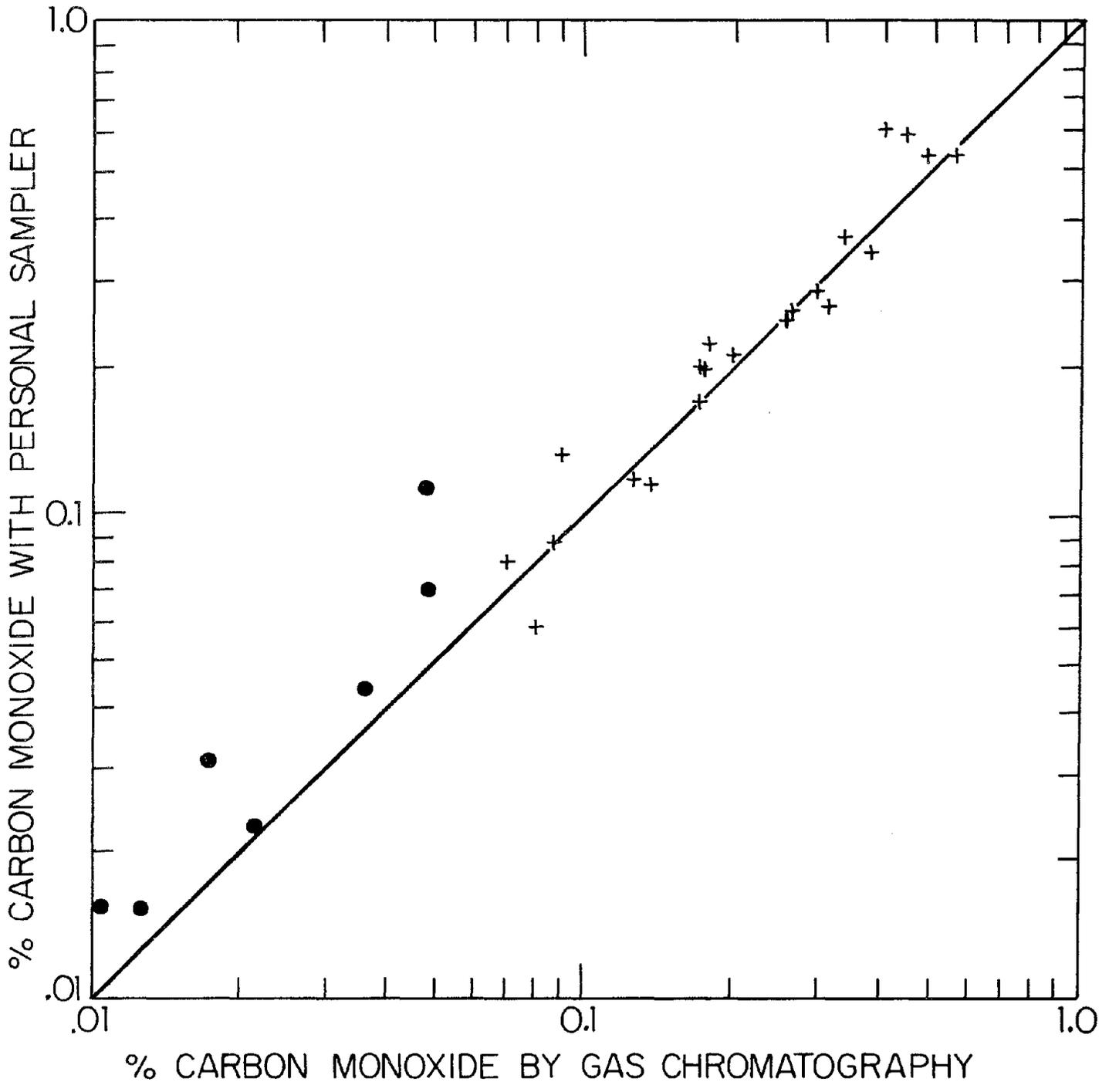


FIGURE 9

Comparison of Fire Gas Analysis for Carbon Monoxide by  
Personal Samplers and Gas Chromatography

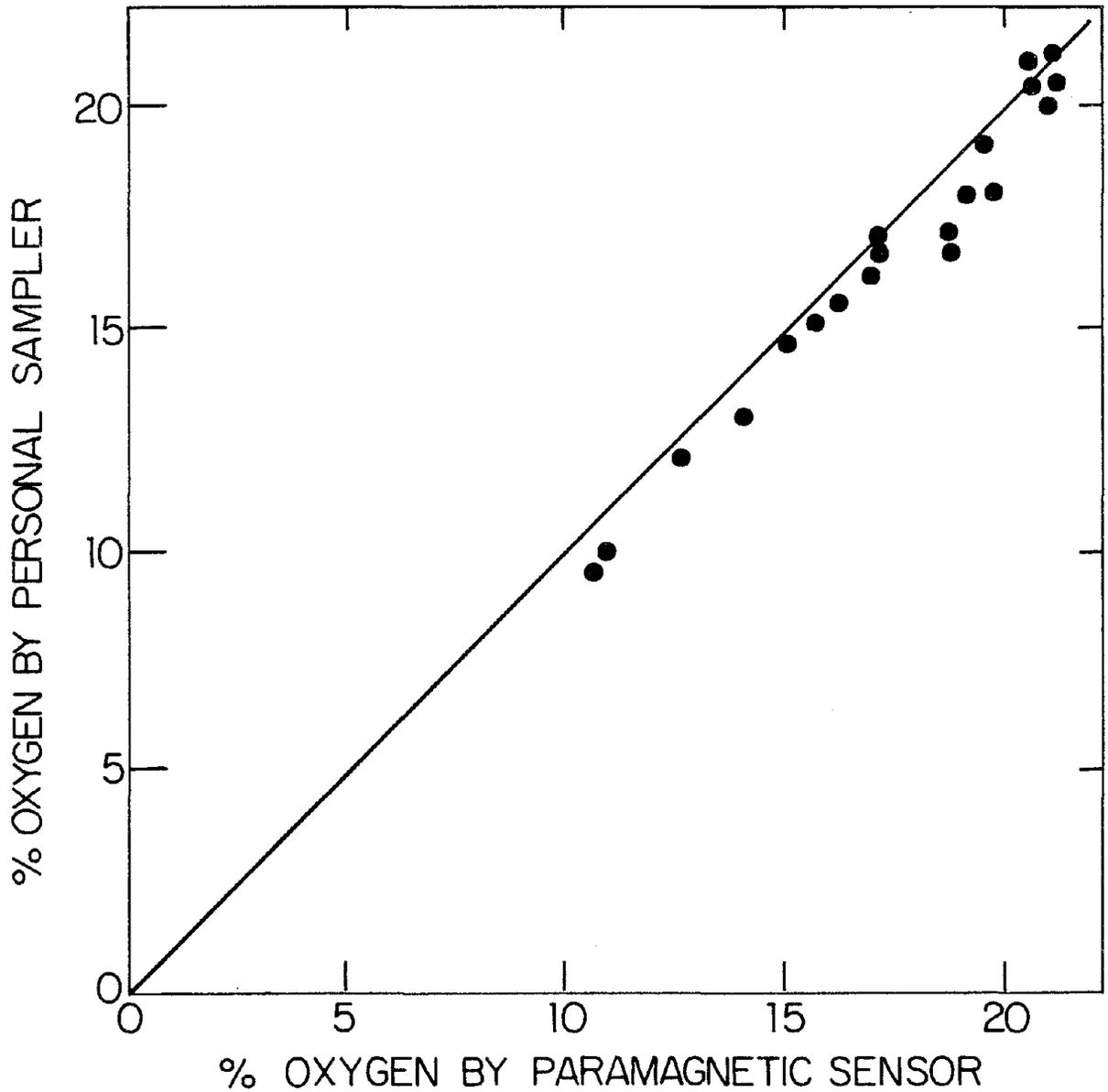


FIGURE 10

Comparison of Fire Gas Analysis for Oxygen by Personal Sampler  
and Paramagnetic Oxygen Sensor

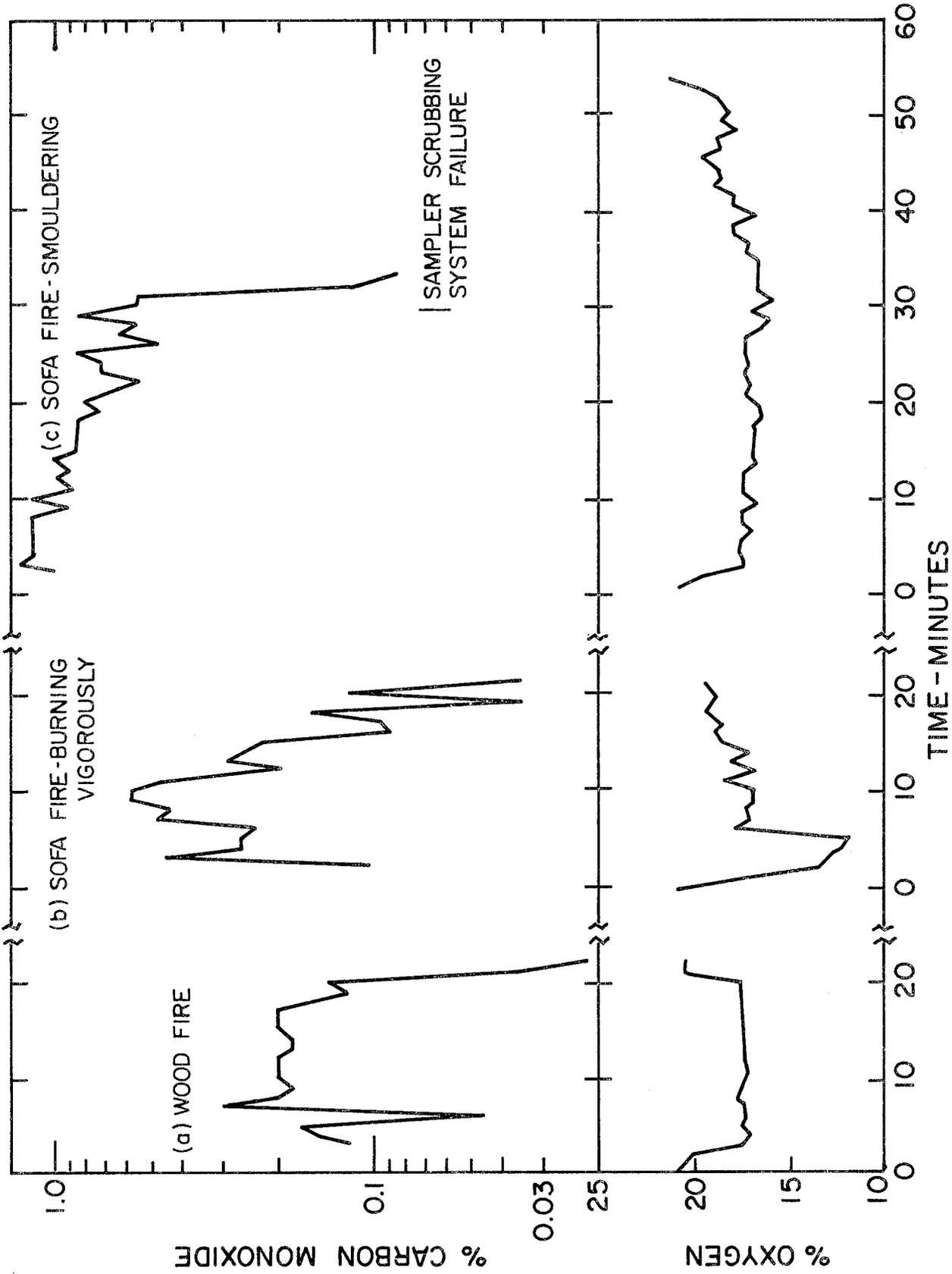


FIGURE 11

Fire Gas Analysis by Personal Sampler in Controlled Fires

dropped to a minimum of 12% which could be lethal in a short period for a hard-working firefighter. The carbon monoxide concentration rose to almost 0.6%, which can be lethal in ten minutes.

The most severe carbon monoxide exposure occurred during the initial phase of the smouldering fire (Figure 11-c), when carbon monoxide concentrations of 1.2% were measured. Such an exposure could be lethal in 1 to 3 minutes. These high carbon monoxide concentrations may explain why firefighters suffer severe stress when fighting upholstery fires.

After monitoring the smouldering sofa fire for thirty minutes the gas scrubbing system became saturated and the carbon monoxide signal was lost. Such saturation would not be expected under normal fire situations because the firefighter is not expected to stay in such a hostile environment for very long.

Although the metal fittings of the sampler case were too hot to touch after these fires, the case retained its integrity and all components continued to function without loss of calibration.

## B. Test Results

### History

In August, 1972, the personal samplers were first placed with the busiest companies of the Boston Fire Department. Initially samplers were placed with Engine Companies 12 and 21 and in September, 1972, samplers were also placed with the two Rescue Companies. Sampling was continued to June, 1973. At the fire, the samplers were worn by firefighters judged to have a significant exposure. Random placement of samplers did not seem feasible since maximum exposure conditions were required for our purposes. At the conclusion of the test, the sampler was returned to the Harvard School of Public Health with a completed data sheet shown in Appendix A. After retrieving the tape cassette and servicing the batteries and chemicals, the units were returned to the Department.

The samplers withstood the physical rigors of use in the fire environment. In several cases, the samplers were saturated with water and required minor repairs. A sampler was thrown out of a second story window, and except for a jarred electrical contact, it was functional afterwards.

Some of the samplers malfunctioned and data from a number of runs were lost due to battery failure in the signal recording

circuit. An additional battery added to the unit eliminated this problem.

Acceptable records of carbon monoxide and oxygen were obtained on 72 fires. A tabulation of incident numbers, time parameters, carbon monoxide and oxygen concentrations and carbon monoxide dosage for each incident is shown in Table 1. Breathing apparatus was used in 18 of the 72 fire incidents as indicated by the letter suffix "R" after the tape number in Table I. All calculations described below presume that the firefighter was not wearing a respirator. Selected records are shown in Appendix B.

### Carbon Monoxide

The 72 incidents evaluated represent a total sampling time of 1,329 minutes or over 20 hours for an average sampling period of 18.5 minutes. As shown in Figure 12 the median sampling time for an incident is 14.5 minutes with a geometric standard deviation of 2.1. If one reviews the time distribution of incidents in which respirators were worn, the median value is 18 minutes.

In evaluating exposure time to toxic contaminants, the length of time in an incident when the carbon monoxide concentration is greater than 0.05% (500 ppm) is a significant parameter and is presented in Table I. Out of the 1,329 minutes of sampling time, the carbon monoxide concentration exceeds 0.05% for 328 minutes or approximately 29% of the time. These data, shown in Figure 13, demonstrate that the median value is less than 2 minutes and that the data spread is large.

The highest carbon monoxide concentration encountered in the 72 sampling incidents was 2.7% (27,000 ppm) in Tape No. 17R. The distribution of maximum carbon monoxide concentrations of all incidents listed in Table I are shown in Figure 14. In approximately one-half the incidents, the maximum concentration encountered was greater than 0.11% (1100 ppm) and in 10% of the incidents the maximum concentration exceeded 0.55% (5500 ppm). One would expect that these data would demonstrate that respirators were used in conditions of higher carbon monoxide concentrations, that is the distribution line would be shifted to the left. This is not the case.

In addition to evaluating the maximum carbon monoxide concentrations in the fire environment, one can express the dose (%-mins) the firefighter may receive in a fire as shown in Table I. These values are calculated by integrating the

Table I

## SUMMARY OF CARBON MONOXIDE AND OXYGEN MEASUREMENTS

Incident No.	Tape No.	Total Time (min.)	Maximum % CO	Time % CO >0.05%(min.)	CO - Dose		Minimum % O <sub>2</sub>	Time % O <sub>2</sub> <20% (min.)
					Min.	Max.		
22396	001	19	0.07	0.3	0.03-0.41	>20	-	
22766	002	3.6	0.13	0.9	0.06-0.132	>20	-	
24128	007	12	0.15	9.7	0.85-1.09	>20	-	
24645	010	10.5	0.58	3.9	0.87-1.08	17.5	3.6	
25601	011	9	0.06	0.1	0.09-0.27	>20	-	
25862	012	30	0.14	2.1	0.20-0.80	>20	-	
26000	013	14	0.05	-	<0.28	>20	-	
26093	014	52	2.40	13.8	10.3-11.3	18.0	5.4	
26360	015R	12	0.14	2.7	0.35-0.59	19.5	0.2	
26360	017R	14	2.70	3.3	3.94-3.77	18.0	2.9	
27056	018	11	0.07	0.4	0.11-0.33	-	-	
27258	019R	13	<0.05	-	0.00-0.26	>20	-	
27726	020A	10	0.06	1.4	0.05-0.25	>20	-	
27726	020BR	25	0.27	3.8	0.58-1.08	>20	-	
30307	028	9	<0.05	-	0.00-0.18	>20	-	
30414	029	5	<0.05	-	0.00-0.10	>20	-	
31263	036B	23	0.31	1.1	0.44-0.90	>20	-	
32017	045R	16	0.20	4.1	0.62-0.94	19.5	0.2	
32175	046	29	1.13	2.3	2.23-2.81	19.0	0.4	
35462	062	10	0.22	2.3	0.26-0.46	>20	-	
35504	063R	27	0.57	10.6	2.24-2.78	19.0	0.4	
35661	064	9	0.12	6.9	0.62-0.80	18	8.8	
36905	067	13	<0.05	-	0.00-0.26	>20	-	
37330	070	11	<0.05	-	0.00-0.22	19.5	1.3	
37959	071	11.5	<0.05	-	0.00-0.23	>20	-	
38173	072R	16	<0.05	-	0.00-0.32	19.5	4.3	
275	073	14	0.12	11.3	0.80-1.08	>20	-	
402	074	57	<0.05	-	0.08-1.22	>20	-	
870	075	21	0.12	0.7	0.09-0.51	15.5	0.3	
1091	077	55	0.72	12.5	2.44-3.54	>20	-	
1635	079R	15	<0.05	-	0.00-0.3	>20	-	

Incident No.	Tape No.	Total Time (min.)	Maximum % CO	Time % CO >0.05%(min.)	CO Dose (%-min.)	Minimum % O <sub>2</sub>	Time % O <sub>2</sub> <20% (min.)
1640	080R	17	<0.05	-	0.00-0.34	>20	-
2805	082B	49	0.38	10	1.76-2.74	17.5	1.3
2998	083R	16	<0.05	-	0.00-0.32	>20	-
3413	084	15	<0.05	-	0.00-0.30	19.5	3.7
3612	085	11	0.12	10.4	0.86-1.08	19.5	0.5
3784	086AR	16	0.39	5.8	1.18-1.50	17.5	4.2
3804	087	8.5	0.10	6.5	0.16-0.33	19.5	0.3
4087	088R	58	0.10	32.3	2.47-3.63	17.0	6.2
4145	089A	30	<0.05	-	0.00-0.60	>20	-
4145	089BR	22	0.11	13.2	0.51-0.95	18.5	0.6
4216	090	16.3	0.08	0.4	0.24-0.56	19.0	15.8
7178	093B	22	0.11	21	1.85-2.29	18.0	0.7
7604	094	4	<0.05	-	0.00-0.08	>20	-
8955	097	41	0.95	41	1.94-2.76	20	-
10731	098R	13	0.13	4.0	0.34-0.60	19.5	1.7
10973	100B	16.5	<0.05	-	0.05-0.38	-	-
11415	102R	13	0.09	1.0	0.16-0.42	>20	-
11344	103A	24.5	0.86	4.1	1.10-1.59	19.0	6.4
11344	103B	31	0.12	30.5	1.85-2.47	>20	-
11940	106	46	0.15	30.1	2.75-3.67	20.0	-
12331	108	9	<0.05	-	0.00-0.18	>20	-
12743	109R	2.5	<0.05	-	0.03-0.08	>20	-
13085	110	17.5	0.1	0.4	0.07-0.42	>20	-
13186	111	13	0.40	12.1	1.65-1.91	16.5	5.3
13708	112	13	<0.05	-	0.00-0.26	>20	-
13438	113	13	<0.05	-	0.00-0.26	19.0	0.8
13297	114	4	0.29	2.8	0.45-0.53	19.5	0.2
13357	115	12	0.05	-	0.01-0.25	>20	-
14576	117	18	0.35	1.1	0.25-0.61	>20	-
14944	119	13	<0.05	-	0.08-0.34	>20	-
15642	121	4	0.17	2	0.20-0.28	19.0	1.2
16707	123	8	0.06	0.2	0.04-0.20	>20	-
17037	124R	44	0.05	-	0.00-0.88	>20	-
17709	125	8	0.07	0.5	0.06-0.22	>20	-
18051	126R	23	0.20	22	1.67-2.13	>20	-

Incident No.	Tape No.	Total Time (min.)	Maximum % CO	Time % CO >0.05%(min.)	CO Dose (%-min.)	Minimum % O2	Time % O2 <20% (min.)
20321	128	2	0.19	1.2	0.15-0.19	18.5	2
19996	129	5	<0.05	-	0.00-0.1	>20	-
24825	132A	16	0.50	14	2.73-3.05	19.5	5
24825	132B	30	0.09	0.4	0.04-0.64	>20	-
25464	133	9	0.22	8	0.77-0.95	19.0	2.7
26059	134	10	0.10	2.6	0.25-0.45	20.0	-

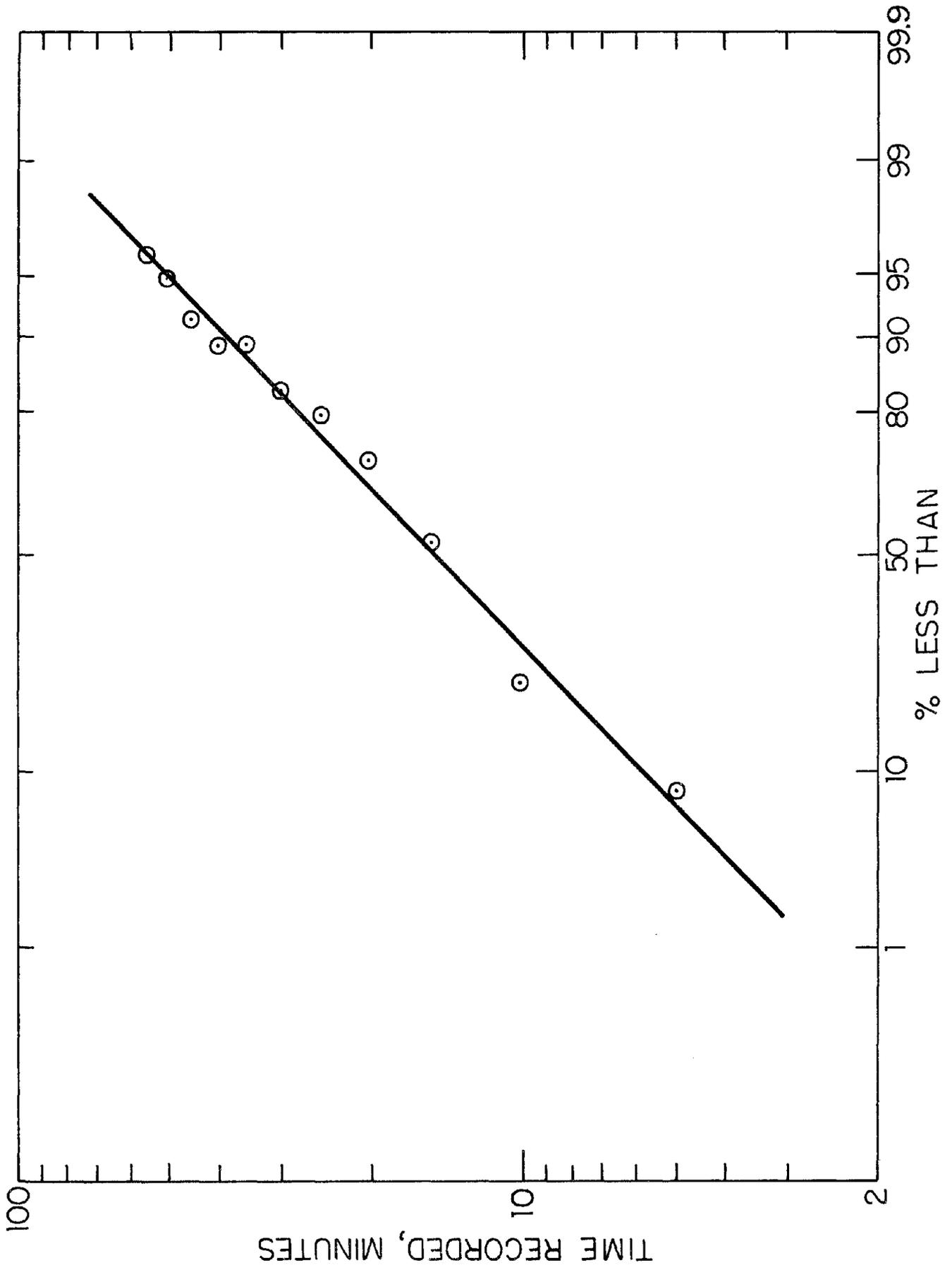


FIGURE 12

Time of Sampling Records

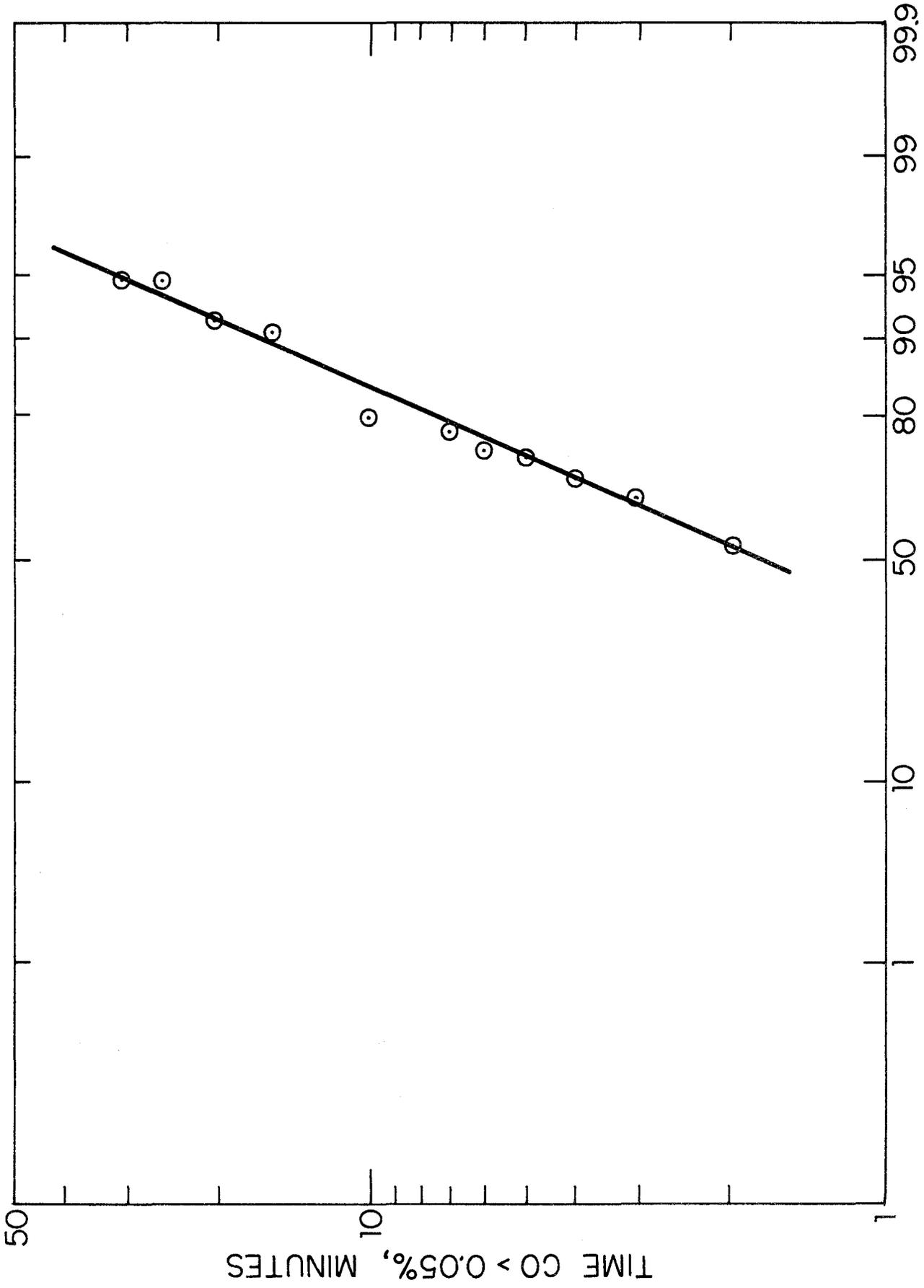


FIGURE 13

Time When Concentrations of Carbon Monoxide Were Greater Than 0.05%

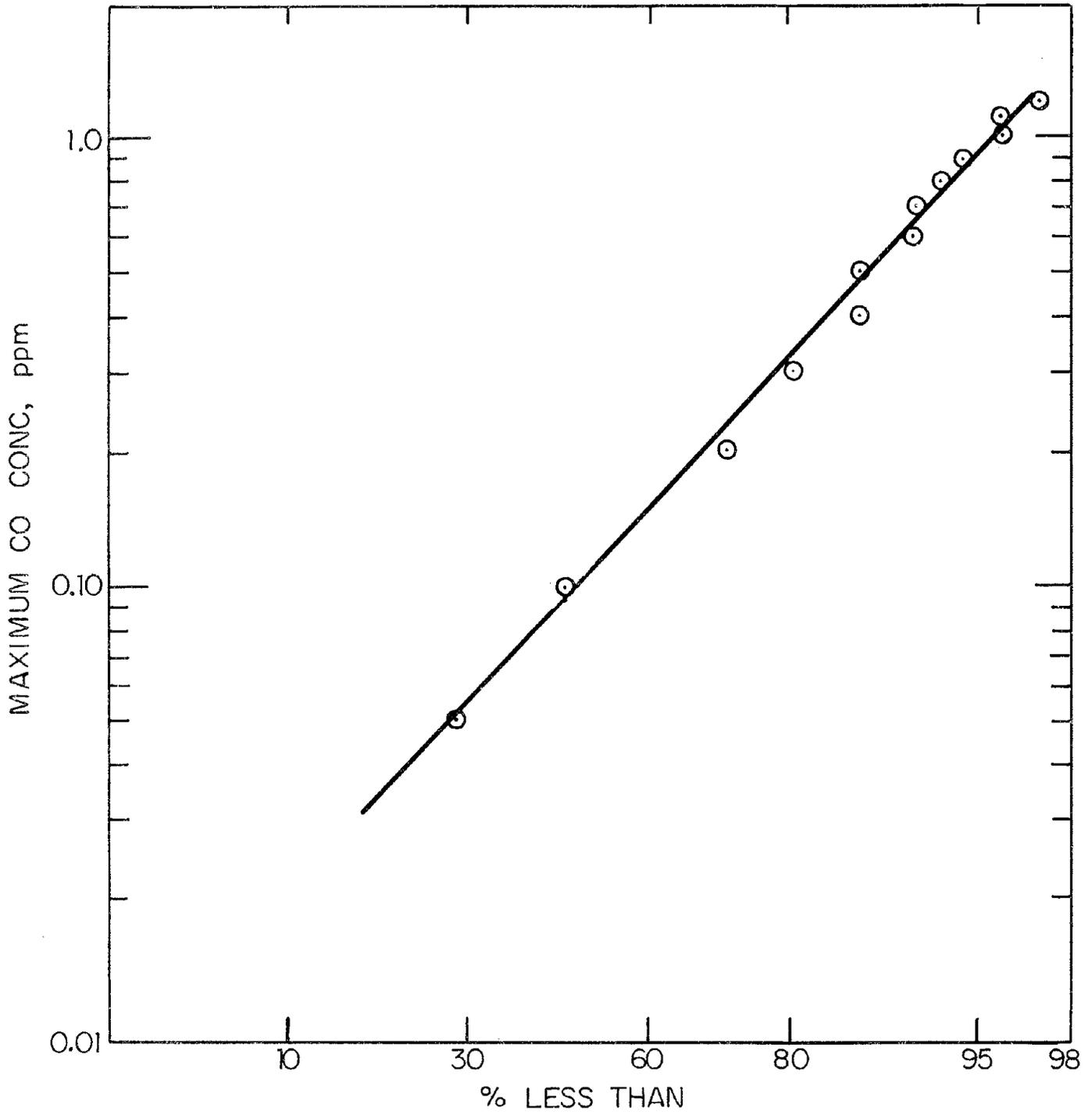


FIGURE 14

Distribution of Maximum Carbon Monoxide Concentrations

concentration-time curve of each incident. Since the sampler cannot discriminate between 0% and 0.02% carbon monoxide in air, there is some uncertainty in proposing a carbon monoxide dose for each fire. We have chosen to identify that uncertainty by presenting both a minimum dose which is obtained by integrating the area under the concentration versus time curve using 0.02% as the baseline (Area A) and a maximum dose obtained by integrating the area under the curve using zero concentration as the baseline (Area B) as shown in Figure 15. For a 10-minute record this would mean a range differential between minimum and maximum dose of 0-0.2% minutes and for a 30 minute record a differential of 0-0.6% minutes.

The minimum and maximum carbon monoxide dose distributions shown in Figure 16 display bimodal distributions. In 22 to 30% of the incidents, the firefighter could receive a carbon monoxide dose greater than 1.0%-minutes, that is, 1,000 ppm for 10 minutes or 333 ppm for 30 minutes. In 12 to 16 percent of the incidents, the dose could exceed 2.0%-minutes.

From this dose description, it is possible to calculate the % carboxyhemoglobin that could result assuming a heavy work rate (30).

$$\% \text{ COHb} = (a) (\% \text{ CO}) (t)$$

%CO = percentage of CO in inspired air.

t = duration of exposure, minutes.

a = constant which varies with work rate: , 11 for heavy work

### Oxygen

The minimum oxygen concentrations noted during the test series are shown in Table II, and the distribution in Figure 17. In only six incidents was the concentration less than 18% and the lowest concentration was seen in Tape No. 075 when the concentration dropped to 15.5% for a fraction of a minute.

### C. Carboxyhemoglobin Estimation from Exhaled Breath Samples

In the original protocol, it was planned to obtain a sample of exhaled breath from the firefighters wearing the sampler after they left the fire. This was impossible due to the limitations on Fire Department manpower available to take the samples. It is unfortunate that the samples could not be taken since the carboxyhemoglobin levels estimated from the dose calculated from the samples could have been compared to the carboxyhemoglobin levels obtained from the exhaled breath samples.

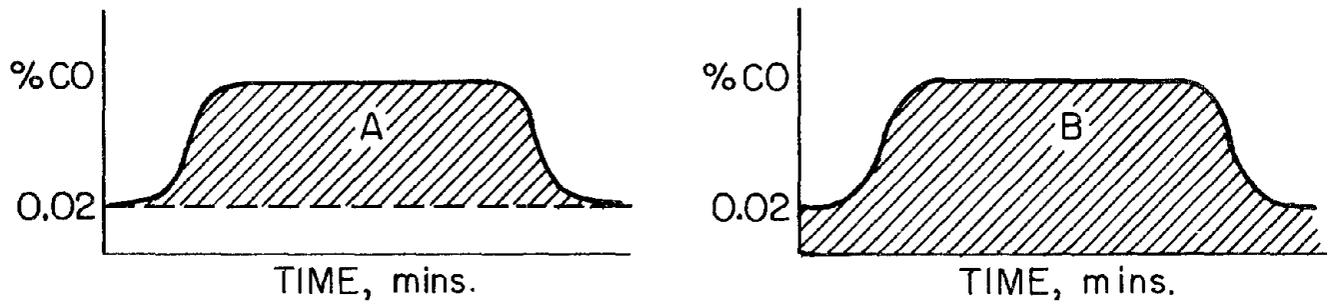


FIGURE 15

Method of Identifying Carbon Monoxide Dose

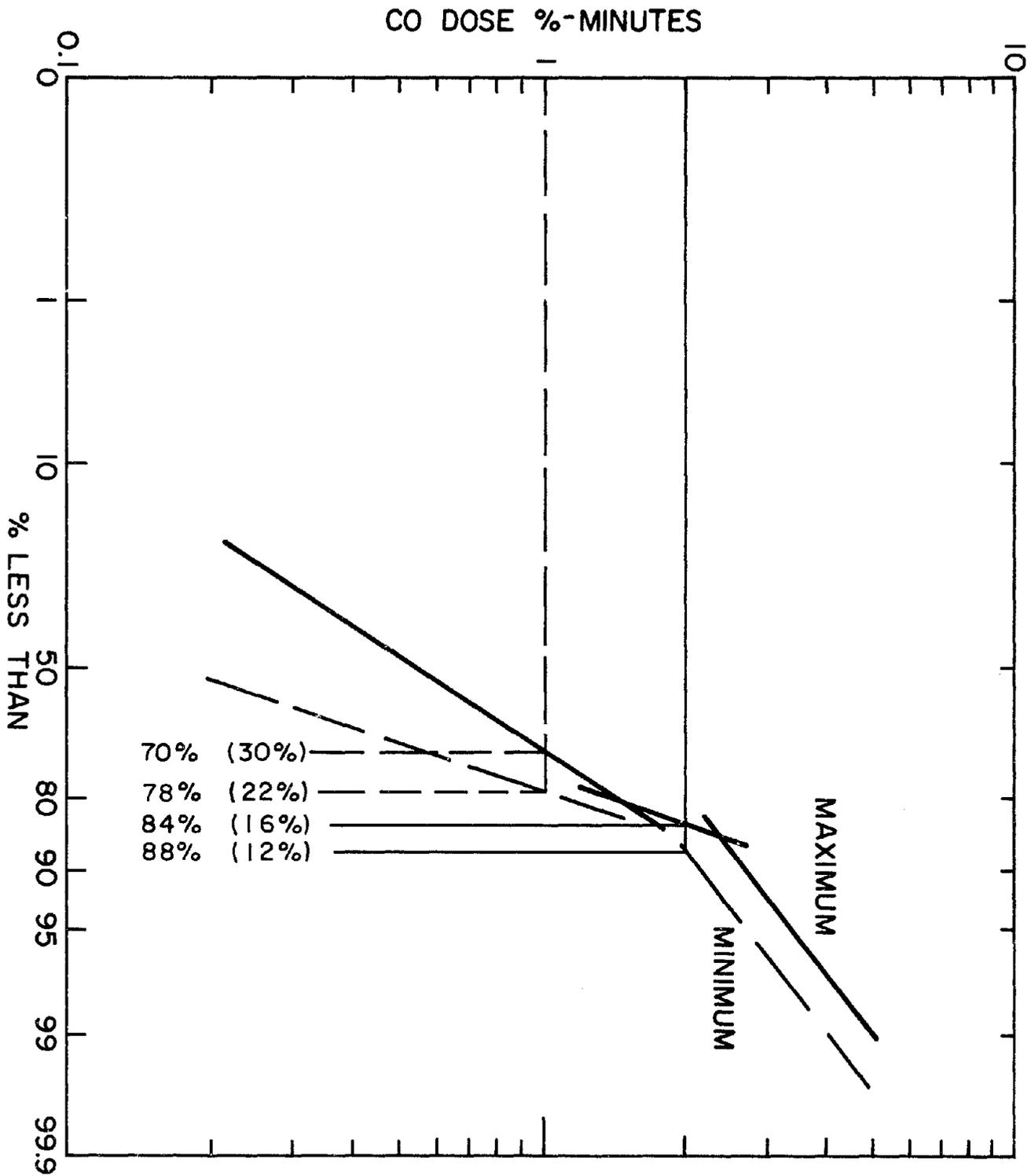


FIGURE 16

Maximum and Minimum CO Dose

TABLE II  
Summary of Oxygen Measurements  
(Abstract From Table I)

Incident No.	Minimum, % O <sub>2</sub>	Incident No.	Minimum, % O <sub>2</sub>
22396	>20	3612	19.5
22766	>20	3784	17.5
24128	>20	3804	19.5
24645	17.5	4087	17.0
25601	>20	4145	>20
25862	>20	4145	18.5
26000	>20	4216	19.0
26093	18.0	7178	18.0
26360	19.5	7604	>20
26360	18.0	8955	20
27056	--	10731	19.5
27258	>20	10973	--
27726	>20	11415	>20
27726	>20	11344	19.0
30307	>20	11344	>20
30414	>20	11940	20
31263	>20	12331	>20
32017	19.5	12743	>20
32175	19.0	13085	>20
35462	>20	13186	16.5
35504	19.0	13708	>20
35661	18	13438	19.0
36905	>20	13297	19.5
37330	19.5	13357	>20
37959	>20	14576	>20
38173	19.5	14944	>20
275	>20	15642	19.0
402	>20	16707	>20
870	15.5	17037	>20
1091	>20	17709	>20
1635	>20	18051	>20
1640	>20	20321	18.5
2805	17.5	19996	>20
2998	>20	24825	19.5
3413	19.5	24825	>20
		25464	19.0
		26059	20.0

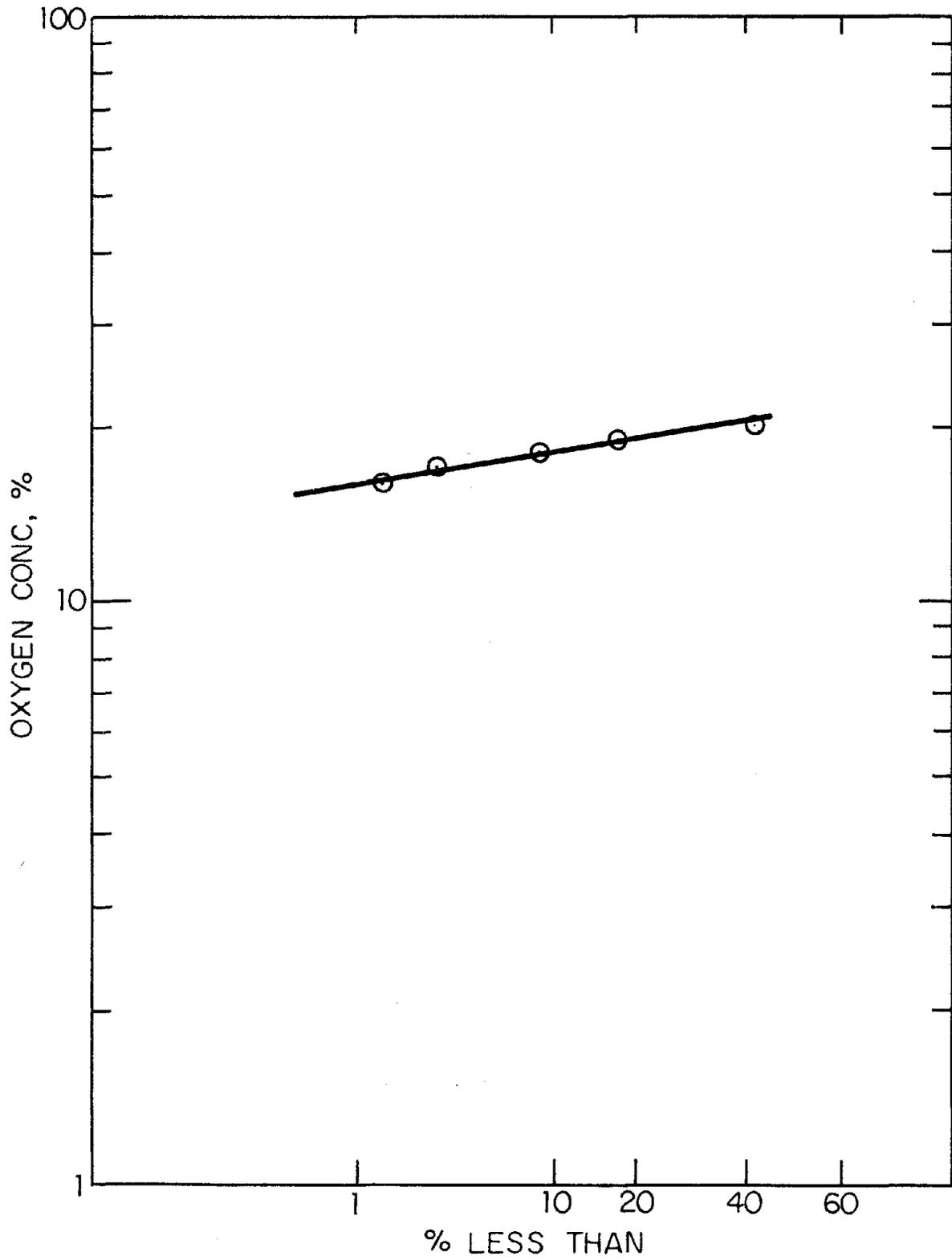


FIGURE 17

Oxygen Concentrations

A limited number of samples were taken at fires during the study and the distribution of carboxyhemoglobin levels is shown in Figure 18. The distribution is bimodal with a median of 6.6%. The sampling protocol and the calculation method are shown in Appendix C.

#### D. Discussion

The concentration data presented in this report represent selected structural fires chosen to document the most severe applications of respiratory protective devices. The samplers were not being worn into every fire to which the companies responded. Also, the firefighters made individual judgements on turning the samplers on and off. These factors probably resulted in measurement of the most severe situations in which the firefighters worked.

The early results from this monitoring program clearly demonstrate that the firefighter is exposed to concentrations of carbon monoxide requiring a high level of protection. The serious oxygen deficiencies seen in model fires were not observed. High carbon monoxide levels rather than oxygen deficiency would appear to be the more significant risk factor to the safety of the firefighters. The highest carbon monoxide level noted in the study series (2.4%) exceeds the operating criteria of the air-purifying masks previously used by the Department.

The firefighter is exposed to significant carbon monoxide concentrations under fire conditions where he does not use a respirator. Of the 271 minutes of monitored exposure when respirators were not worn, 23 minutes (8.5%) involved exposure to carbon monoxide in excess of 0.05% (500 ppm). The highest concentration encountered was 1.7%, with a mean exposure of 0.40% during the 23 minutes.

Comparable carbon monoxide levels were encountered when the firefighters wore respirators. Of a total of 124 minutes of monitored exposure, 29 minutes were to concentrations in excess of 0.05%. The highest level encountered was 2.40%; the median exposure during those 29 minutes was 0.28%.

The highest carbon monoxide concentrations and lowest oxygen levels were generally encountered in the first few minutes of the exposure record. This pattern is probably due to the firefighter entering unventilated spaces in the early part of the fire.

The firefighter is trained to make judgements as to when he is exposed to a toxic atmosphere. However, our experience in this sampler program and from other episodes indicate that unrecognized hazard situations do occur. Anecdotally, one of

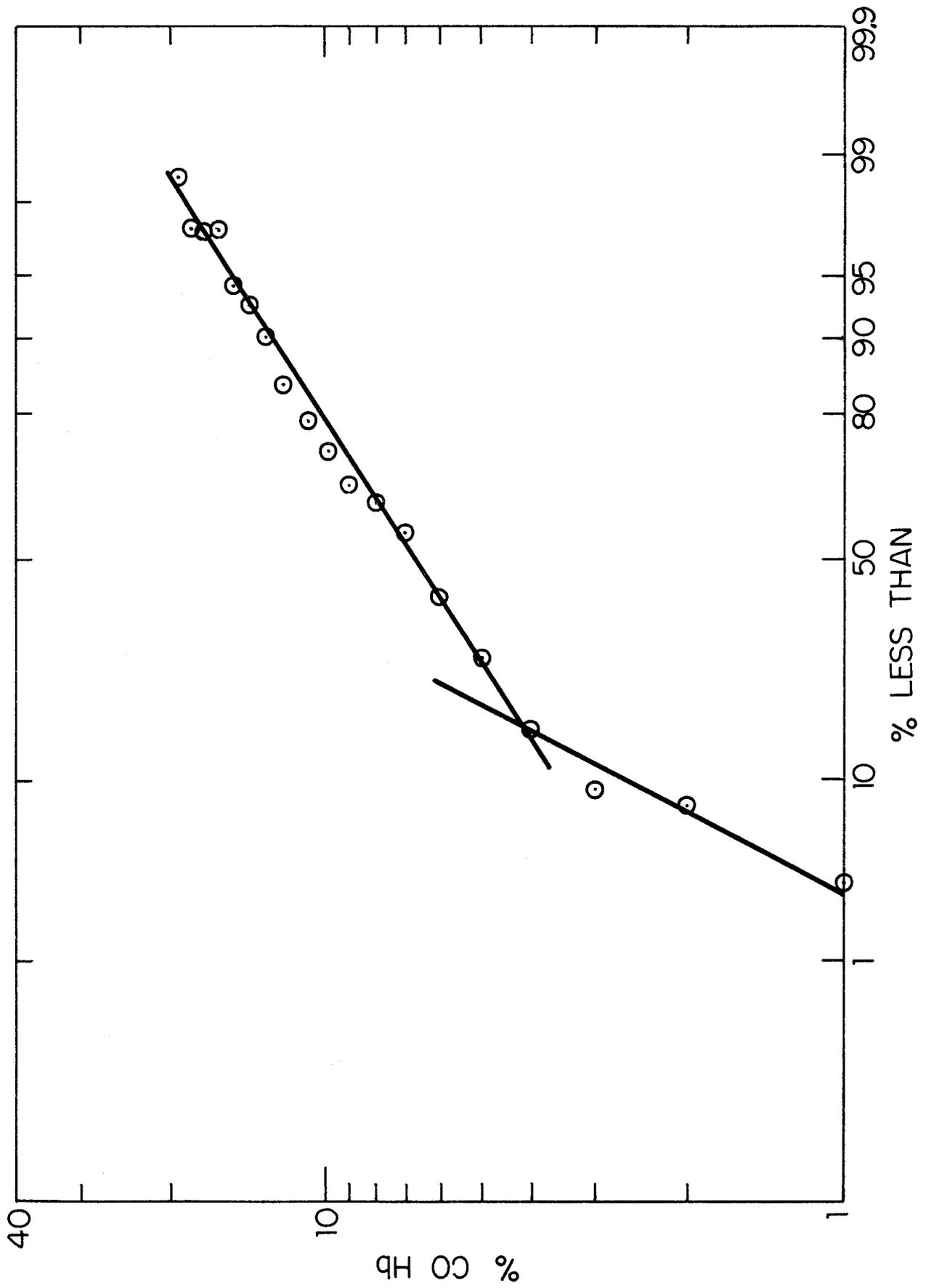


FIGURE 18

Carboxyhemoglobin from Exhaled Breath Samples

the highest carbon monoxide exposures was experienced by a firefighter who was working without a respirator. This man turned the sampler off, thinking his exposure was insignificant. When he turned the sampler off, he was exposed to a carbon monoxide concentration of 1.7%.

### III. RESPIRATORY REQUIREMENTS FOR FIREFIGHTERS

#### A. Mask Spirometer

A major criticism of the present open circuit compressed air breathing apparatus operated in either the demand or pressure-demand mode is that the equipment does not provide the rated 30 minute duration in fire service. The information on duration obtained from the firefighters in Boston suggests that the respiratory minute volume is in excess of 50 liters per minute. Firm application requirements on the minute volume is necessary to provide the designer with specification data. In this portion of the study, methods of retrieving spirometry data on current apparatus during work conditions was explored.

##### 1. Motor Spirometer

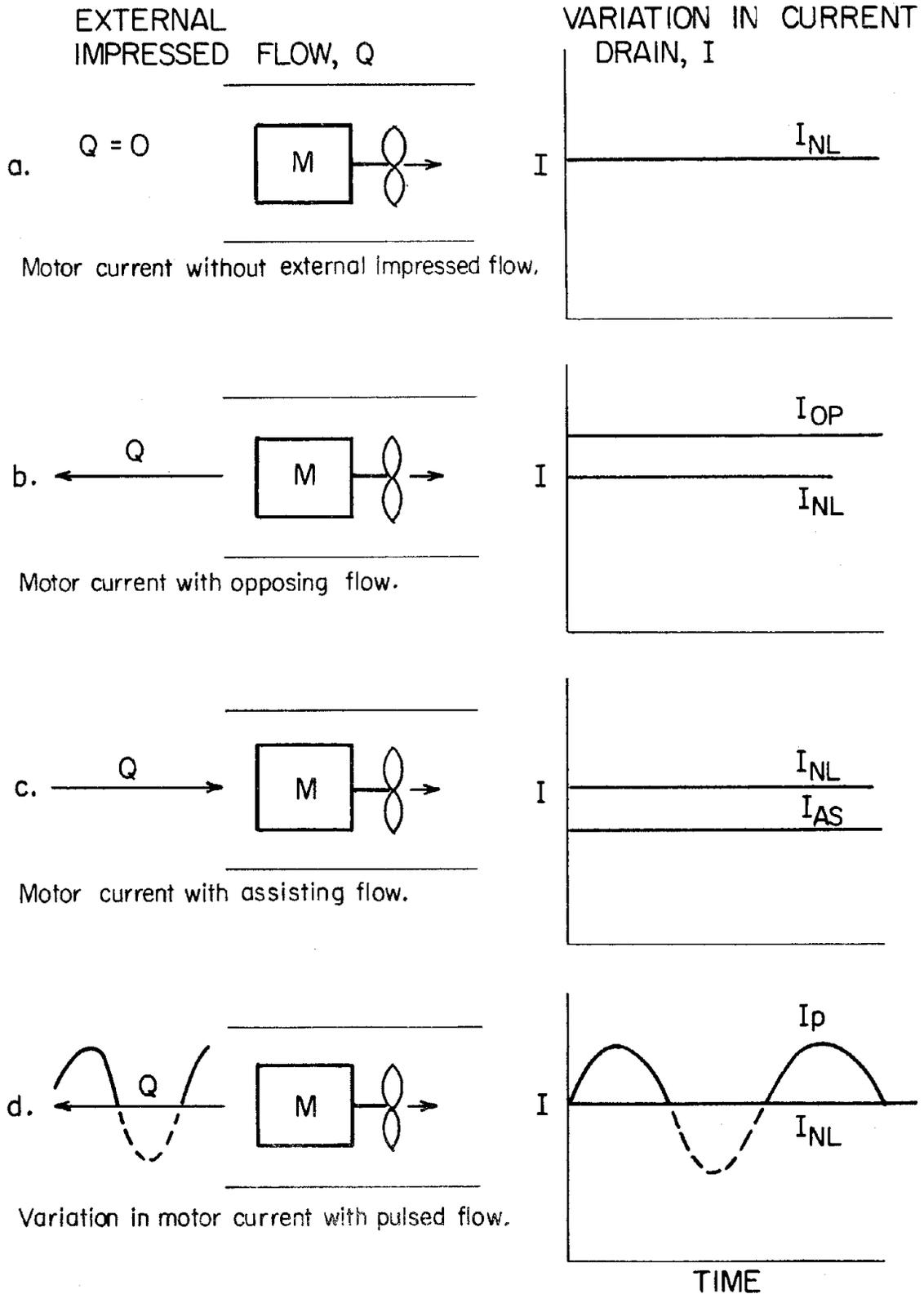
In a previous study at this laboratory, we devised a fan spirometer which, in preliminary studies, appeared suitable for field application(31). The active sensor was a miniature motor-fan sensor placed in either the exhalation or inhalation air flow path in a counter-flow position. If the current drain is monitored during the cyclic respiratory air flow one notes variations in current coupled to the respiratory pattern of the test subject. In the previous study, these current variations were found to be proportional to the minute volume of the wearer.

The concept could be implemented as shown schematically in Figure 19a. The axially mounted fan-motor is positioned in a ductway with check valves to provide unidirectional flow. Without flow in the ductway, the motor-blower has a current drain  $I_{n1}$  shown in Figure 19b. This current drain,  $I_{n1}$ , represents the current at a minimum operating torque condition. If an opposing air flow were directed down the ductway against the normal delivery direction of the blower,  $I_{n1}$  increases to a value of  $I_{op}$  due to the increased torque on the fan element.

If one pulses this flow, one sees a variation in current drain to  $I_p$  as shown in Figure 19c. If this device is placed in either the inhalation or exhalation air flow path of a protective mask, variations in current drain occur which have a relationship to the wearers minute volume. The excursions of  $I_p$  from the base line current drain can be integrated and calibrated to identify minute volume.

FIGURE 19

Fan Spirometer Operation



Such a device had been calibrated in our laboratory with pulsating flow with a subject working at 4 different work rates on a bicycle ergometer to provide minute volumes from five lpm to 48 lpm. The subject's actual minute volume was measured with a conventional spirometer. A zero suppression circuit was used to measure the motor current changes from a no-load condition and this difference was integrated with an Acromag Radial Type Integrator 921 Series using a voltage read-out. The results of this calibration revealed an excellent calibration. With the feasibility of this device identified, it was decided to apply the concept to the firefighter study.

A test program was initiated with an experimental spirometer consisting of an axial mounted fan driven by a "Micro-Mo" permanent magnet DC motor Model 05/015 mounted in a 1" diameter duct in a counter flow position. The duct size was chosen to allow the unit to be placed in the exhalation path of the standard face mask facepiece used by the Boston Fire Department. The motor was powered by a 1.35 volt mercury battery or a regulated supply adjusted to this voltage, and measurements were taken of the voltage drop across a 4.7 ohm resistor in series with the motor. A second variable resistor in the power lead reduced the motor voltage to 1.0 volt with no opposing air. This value was found to give the most linear response.

The position sensitivity of the device was evaluated since it would be attached to the mask and operated in varying positions. The variations in voltage across the resistor were noted, as shown below.

Position: Vertical, fan up - 0.286 V  
Vertical-Horizontal, fan down - 0.293 V  
Vertical, fan up, input blocked - 0.298 V  
Vertical, fan up, exhaust blocked - 0.288 V

The voltage change with orientation increased somewhat as running time accumulated due presumably to the bearing "run-in". The bearings in these miniature motors seemed to be a major weakness when used for our application.

The temperature dependence of the motor-sensor was then evaluated. The results shown in Figure 20 reveal significant variations in voltage over a moderate temperature range. The spirometer was then connected to an amplifier as shown in Figure 21 and tests were conducted to ascertain the linearity of the complete system including the motor spirometer and the Acromag Radial Type Integrator, 921 Series. The results obtained with the amplifier and motor assembly using the

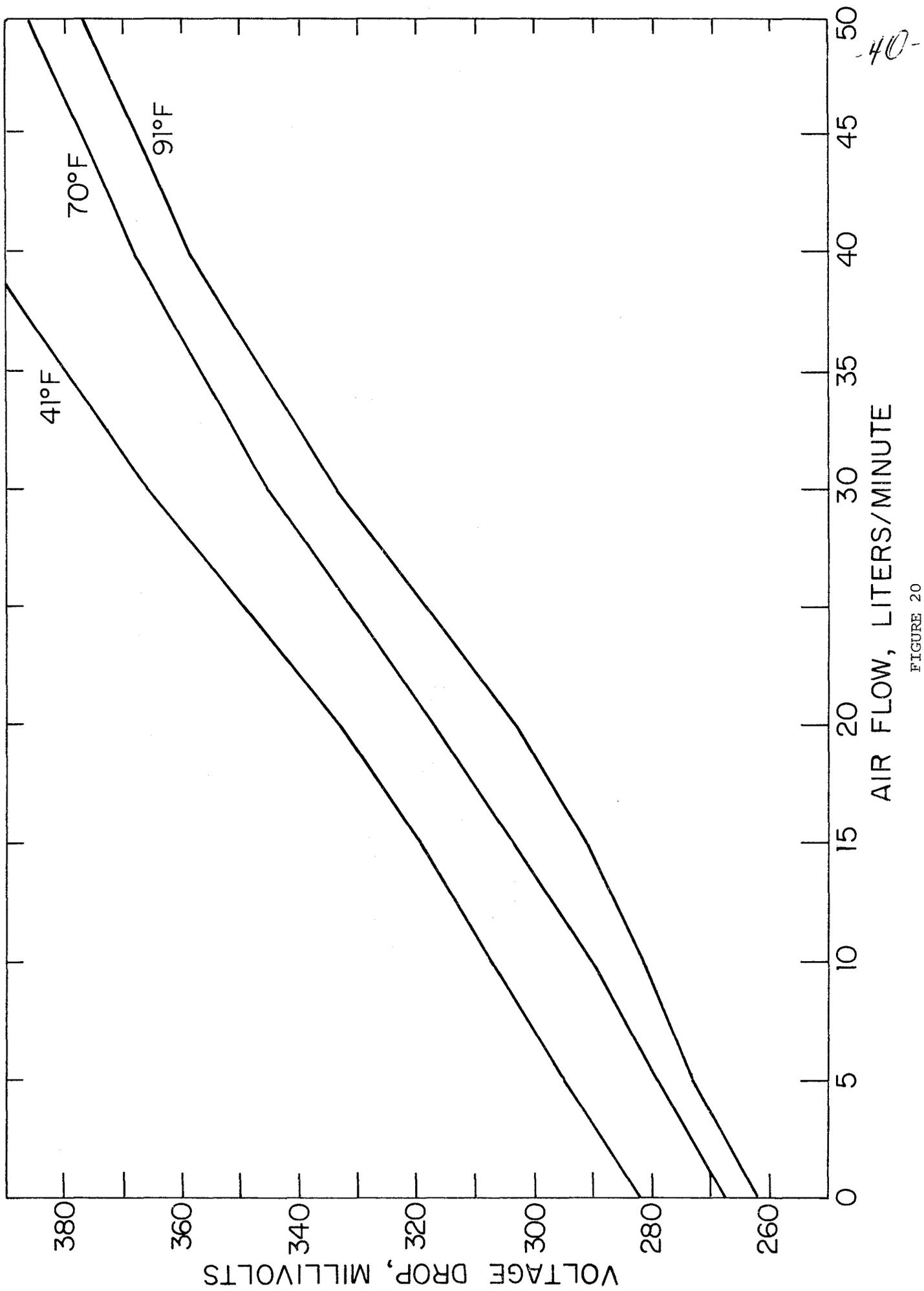


FIGURE 20

Dependence of Fan-Spirometer with Temperature

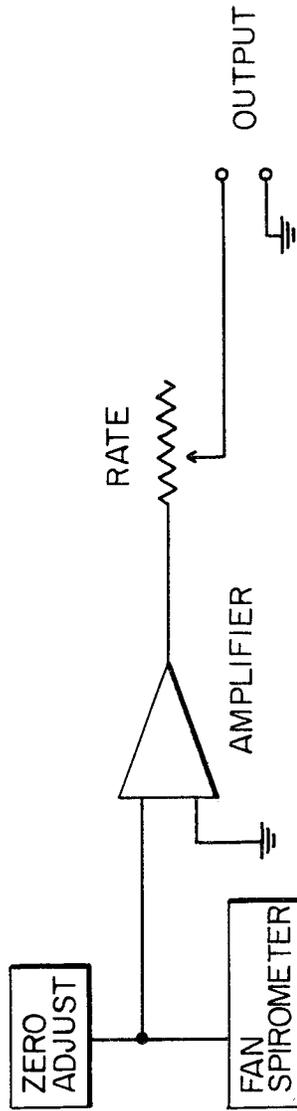


FIGURE 21

Linearity Test Configuration for Fan Spirometer

Acromag Integrator as a readout device when compared to a standard spirometer were very good. Based on this success, the large Acromag unit was replaced with a Curtis Model 420CP3E coulometric meter. A similar meter was utilized for the measurement of the time of the test and the electronics were packaged into a 3" X 4" X 1 5/8" container suitable for field testing. This unit contained the amplifier, its power supply, the Curtis meters, motor battery and control switches as shown in Figure 22.

The Curtis meter used to measure time showed very good linearity. The duct assembly was installed in the exhaust line of a face mask and the instrumentation shown in Figure 22 was used to measure the respiratory minute volume of several subjects while at rest and at several work rates. In addition to the Curtis instrument, the Acromag Model 921 integrator and a Hewlett Packard recording system were used as "read outs" and all showed very good agreement.

Although the specification for the coulometric meters supported its choice as the readout device on the spirometer, many shortcomings of these devices became evident as additional tests were conducted. The units are inherently fragile and a minor shock such as dropping a few inches to a padded surface destroyed the mercury discontinuity. If the units are permitted to run over, irreparable damage is done and the device must be replaced. To reset the instruments to zero for the next sampling period requires about the same period of time as for sampling, and careful monitoring of the process is required to insure that the discontinuity is not driven off scale. Each unit requires a calibration to convert the scale units to units of volume. Due to the cyclic character of the instrument output, the linearity varies by 5 to 10 percent from one end of the scale to the other. The scale length is only 1/2 inch so reading errors must also be taken into consideration. If these units were to be used in a sampling package worn by firefighters in the field, extraordinary shock mounting would be required. The present read-out system was, therefore, found unsatisfactory for this application.

Variations in output due to sensor position is not a serious problem but one that cannot be ignored. The maximum changes in motor current caused by position changes is the equivalent to a change in current caused by a change in flow rate of 5 lpm. With minimum attention paid to mounting on the mask, the error introduced by sensor orientation this could be kept small.

The variation in output due to temperature extremes seemed to be a serious drawback. A change of temperature of 50°F



(41° to 91°F) caused a change in motor current equivalent to a flow of 22 lpm, and a change of 10°F (67° to 77°F) caused a motor current change equivalent to 3 lpm.

It appeared that major changes in design would be required if this approach were to be utilized. Another readout system could be considered. One could amplify the motor current through a LP filter to minimize any changes caused by zero drift and possibly temperature compensation could be added. This signal could then be fed through a full wave rectifier to a high quality, long term integrator. The accumulated voltage or volume could then be read out with a simple voltmeter after the test had been concluded. A second method would be similar to the first except the integrator would be replaced by a voltage to trap converter and its output fed through a scaler to LED's used as counters.

The alternate design approaches described above represent rather sophisticated, expensive equipment for a demanding work environment and their continued development was not possible within the scope of work of the contract. An alternate method of measuring respiratory minute volume using an existing device was therefore used in the study, as described below.

## 2. Wright Respirometer

A miniature, rotating vane, volume meter which has been routinely used in medical applications was evaluated for field spirometry on firefighters (32). The unit can be adapted to mounting in the exhalation port of the facepiece worn by firefighters as shown in Figure 23 and provides minimal exhalation resistance. It measures the total volume of air passing through the device so it must be used with a stopwatch to evaluate minute volume. The unit is calibrated against a standard spirometer to insure the mounting procedure does not modify its calibration. Laboratory testing validated this spirometer technique and the device was used directly in the field.

### B. Field Results

The results of field testing on firefighters under work conditions at a training facility is presented in Figure 24. The median value for minute volume is 58 liters per minute and in 20 percent of the cases, the minute volume exceeded 70 liters per minute.

The desired operating time for compressed air breathing apparatus for the Boston firefighter is thirty minutes. With the present cylinder capacity of 1274 liters, the use time is approximately 20 minutes based on the median minute volumes noted above. If a full thirty minutes is to be obtained, the storage capacity must be increased to 1800 liters for the median

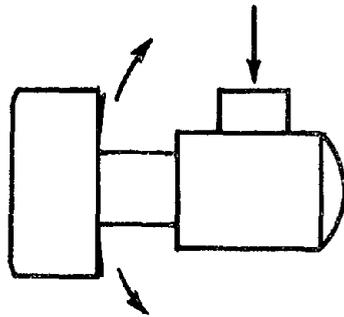


FIGURE 23

Mounting of BOC Spirometer in Exhalation

Port of MSA Clearvue Facepiece

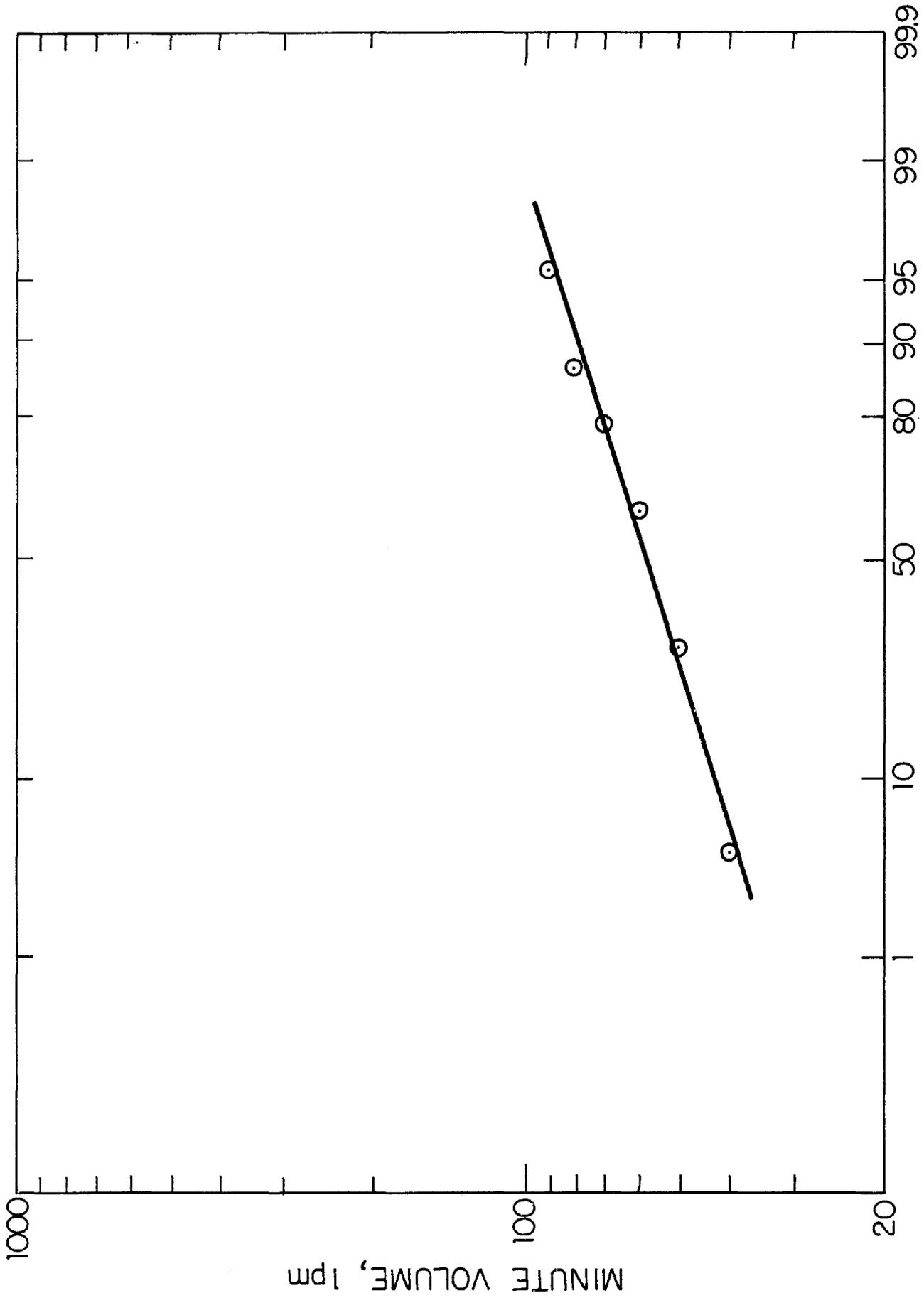


FIGURE 24

Minute Volume of Fire Fighters at Work

value (58 lpm) and 2100 liters for the eighty percentile groups (70 lpm).

#### IV. SPECIFICATIONS FOR RESPIRATORY PROTECTIVE DEVICES FOR FIREFIGHTERS - CONCLUSIONS AND RECOMMENDATIONS

This study has developed application data which can be used to prepare specifications for breathing apparatus for firefighters. The specific conditions under which this information was obtained must be defined to insure that the results are correctly interpreted by the reader. All studies were conducted with one municipal fire department and therefore the data reflects the operating practices of that department. This point is important in considering the startling data on oxygen deficiency in the fire environment. The Boston Fire Department provides early ventilation in structural fires and this practice is reflected in the oxygen levels noted in the study. Poor ventilation practice will, of course, result in the low oxygen concentrations seen in some model fires.

Industrial fires were not included in the study. Obviously such fires can produce unique toxic air contaminants at exceedingly high concentrations. Required protection factors for such firefighting situations may be higher than those required for structural firefighting.

It is with these reservations that the present specification inputs for breathing apparatus for firefighters are proposed. It is the first comprehensive study of the levels of carbon monoxide and oxygen levels encountered during actual firefighting and the authors believe it provides a reasonable design base for equipment. Due to the wide range of operating conditions noted in firefighting, additional studies should be undertaken in other departments to provide a broad data base. Obviously this study is concerned with only the required protection factor and air storage capacity. Data are also needed to permit development of other specification elements for breathing apparatus for firefighters.

The personal air sampling conducted for carbon monoxide and oxygen during this study revealed maximum air concentrations of carbon monoxide (duration greater than one minute) of approximately 2% (20,000 ppm) and minimum oxygen levels as low as 15.5%. The governing value for protection appears to be the carbon monoxide concentration. If we are to observe a ceiling value of .02% (200 ppm) for carbon monoxide (33), a protection factor of 100 must be assured for all firefighters for protection at the 20,000 ppm level. If one achieves this level of protection, the occasional low oxygen level will be guarded against. It is possible that future studies may reveal that carbon monoxide is not the governing contaminant, and this statement of required protection must be revised.

The levels of carbon monoxide and oxygen noted in this study of the real fire environment are not comparable to those concentrations noted in scale or model fires(34). This observation suggests the importance of active fire tests to provide design criteria for equipment for the fire service. The sampling program also suggests it is impossible for the firefighters to anticipate the conditions under which breathing apparatus must be used. Until a suitable instrument is available to monitor the exposure, breathing apparatus should be used continuously in fires.

Spirometry on working firefighters indicates a median minute volume of 60 liters per minute. If thirty minute open-circuit, self-contained breathing apparatus is required, storage capacity of 1800 liters must be provided for the median requirement and 2100 liters for the eighty percentile group. It is our recommendation that a minimum supply of 2100 liters be provided.

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-53-

APPENDIX A

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CARBON MONOXIDE-OXYGEN-SAMPLER DATA FORM

55

The wearer of the sampler should fill out this form each time after the sampler has been used. This information is needed for the proper interpretation of the data.

Date \_\_\_\_\_ Company \_\_\_\_\_  
 BFD Incident No. \_\_\_\_\_

Estimated time of sampler use: \_\_\_\_\_ minutes  
 Estimated time of fire gas exposure during sampler use: \_\_\_\_\_ minutes  
 How soon after the sampler was turned on did the exposure start: \_\_\_\_\_ min.

Was the sampler taken off, placed in the fire? Yes \_\_\_ No \_\_\_  
 If yes, how soon after it was turned on, \_\_\_\_\_, for how long \_\_\_\_\_

When wearing the sampler, did you use breathing apparatus? Yes \_\_\_ No \_\_\_

Briefly describe the type of fire, what was burning, where was sampler worn \_\_\_\_\_

The general smoke condition was (check one)

- None \_\_\_\_\_
- Light \_\_\_\_\_
- Medium \_\_\_\_\_
- Heavy \_\_\_\_\_

I judge the exposure to have been

- |                                      |                             |
|--------------------------------------|-----------------------------|
| a) while wearing sampler (check one) | b) while sampler was placed |
| No exposure _____                    | No exposure _____           |
| Light _____                          | Light _____                 |
| Moderate _____                       | Moderate _____              |
| Severe _____                         | Severe _____                |

During or after the fire did you

	Yes	No		Yes	No
Have a headache	___	___	Have burning eyes	___	___
Feel dizzy or light headed	___	___	Loose consciousness	___	___
Feel nauseous	___	___	Choke from the smoke	___	___
Take a pasting	___	___	Cough from the smoke	___	___
Cough up lungers	___	___	Other _____	___	___

The sampler wearer should blow up the balloon using the special valve attachment. This will be used to estimate the amount of carbon monoxide in his blood. The incidence number should be marked on the balloon's tag.

Estimate the time between the last exposure to smoke and gases at the fire and blowing up the balloon. \_\_\_\_\_ minutes.

Do you smoke cigarettes? Yes \_\_\_ No \_\_\_

If yes, how many packs/day? \_\_\_\_\_

How long since your last cigarette \_\_\_\_\_ minutes.

\_\_\_\_\_  
signature



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APPENDIX B

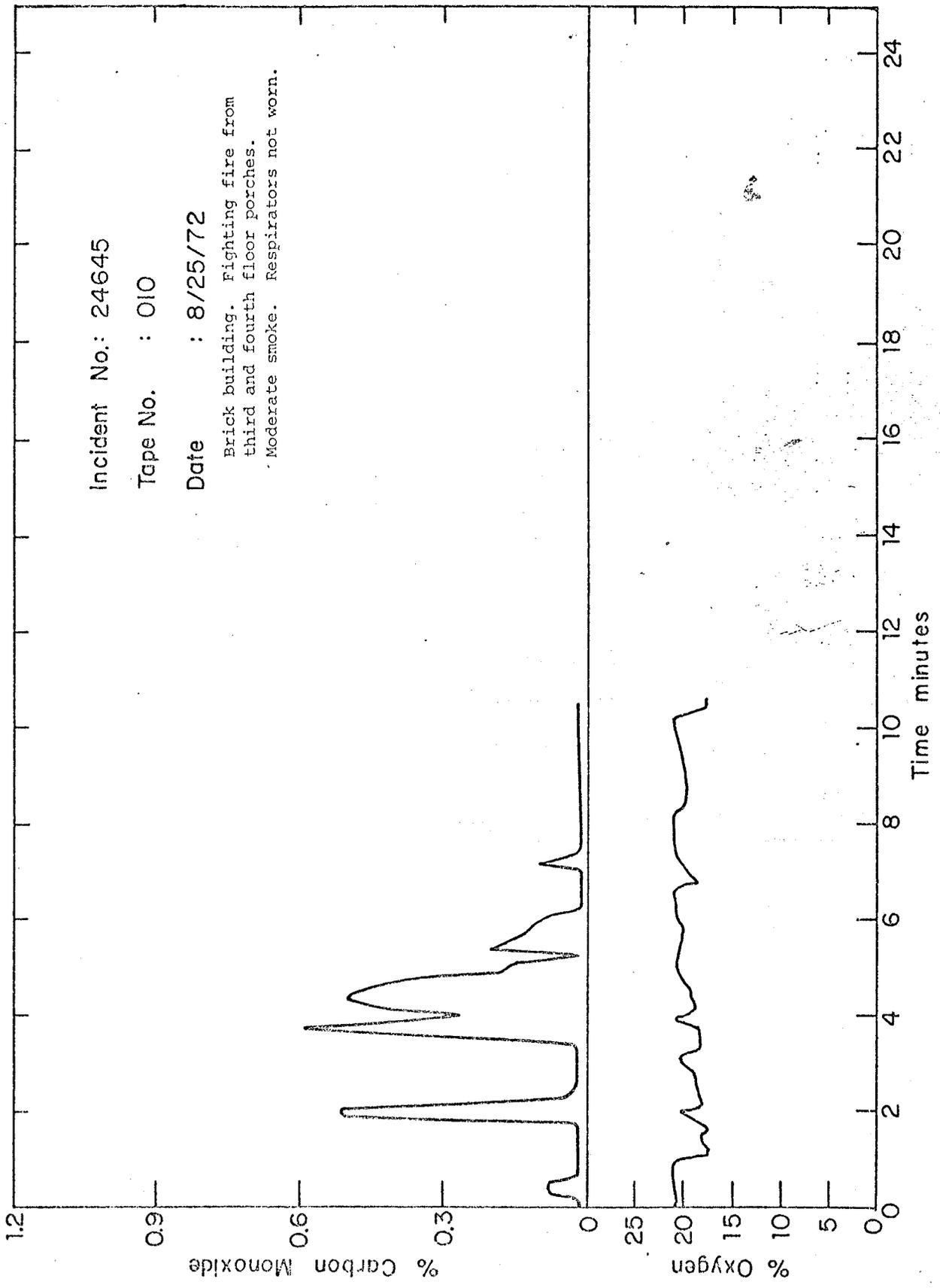


Incident No.: 24645

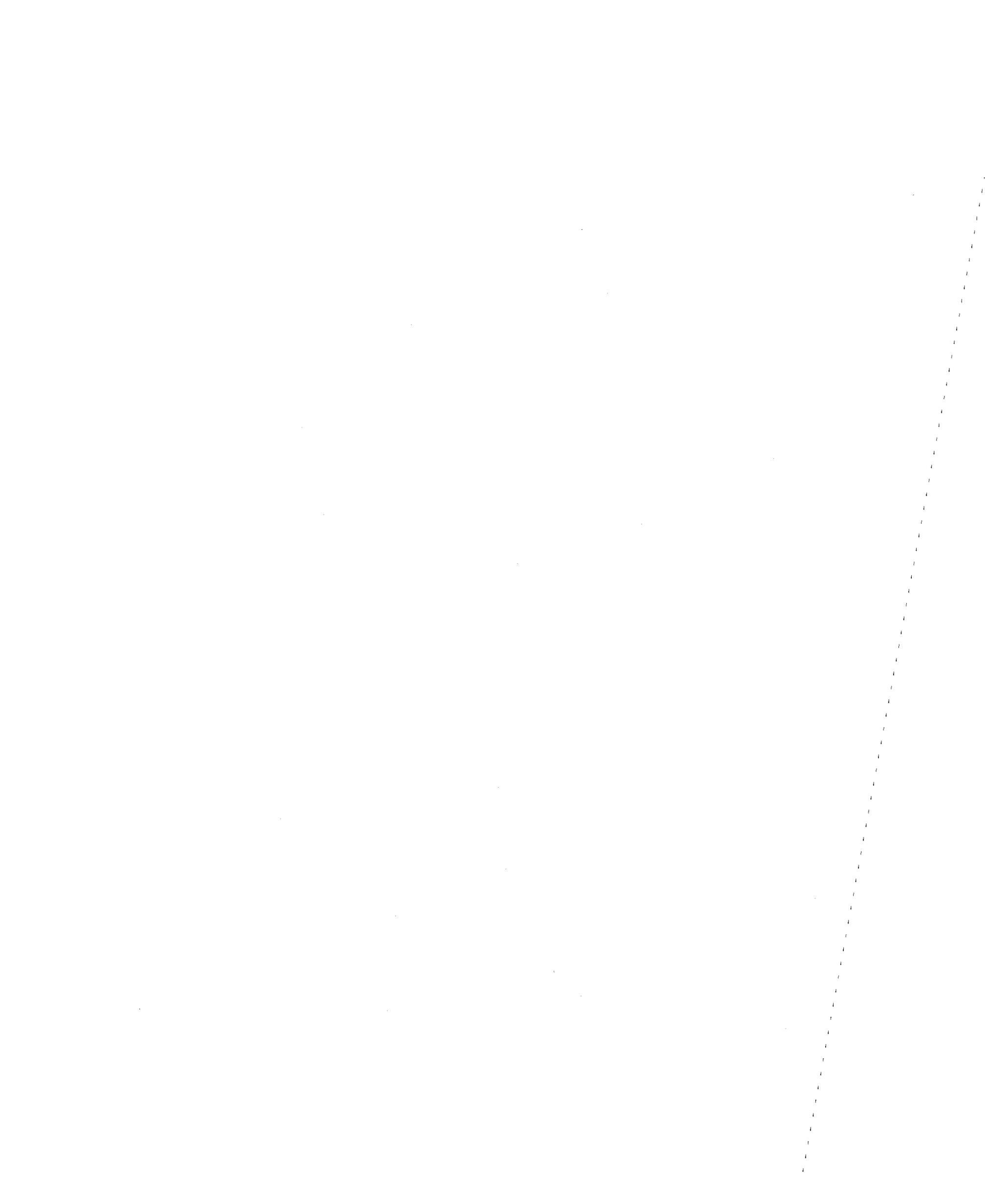
Tape No. : 010

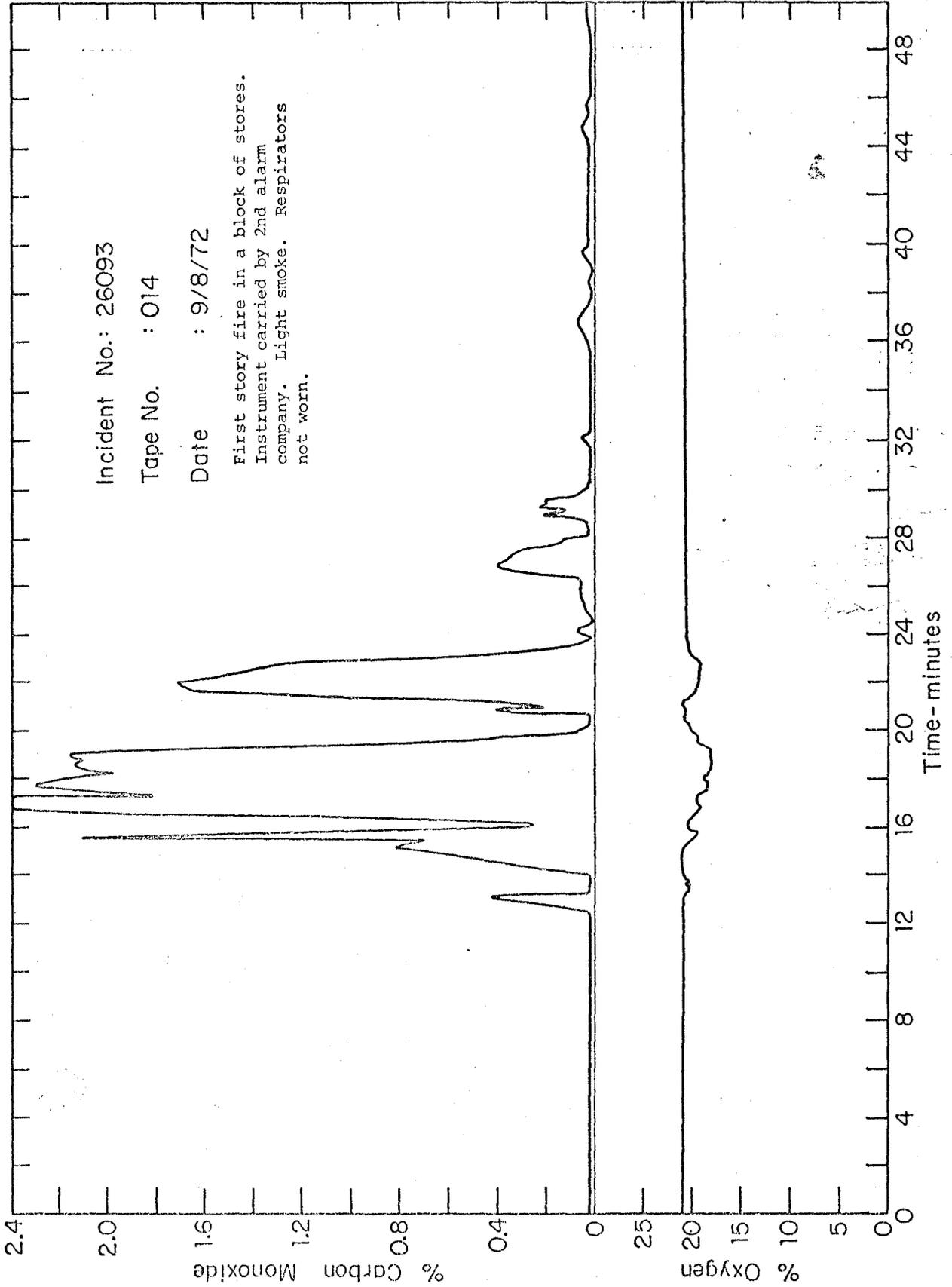
Date : 8/25/72

Brick building. Fighting fire from  
third and fourth floor porches.  
Moderate smoke. Respirators not worn.



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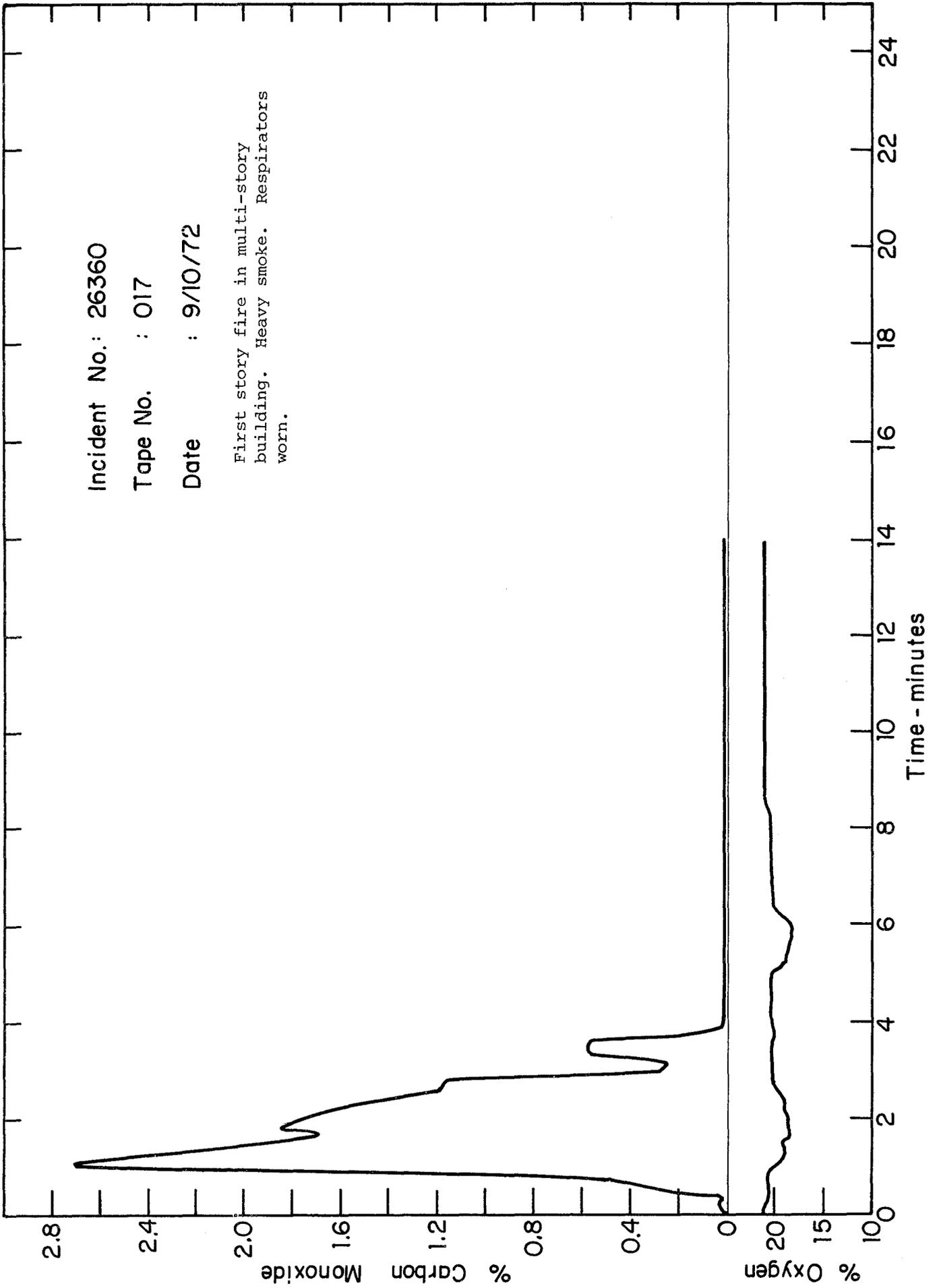


Incident No.: 26360

Tape No. : 017

Date : 9/10/72

First story fire in multi-story building. Heavy smoke. Respirators worn.

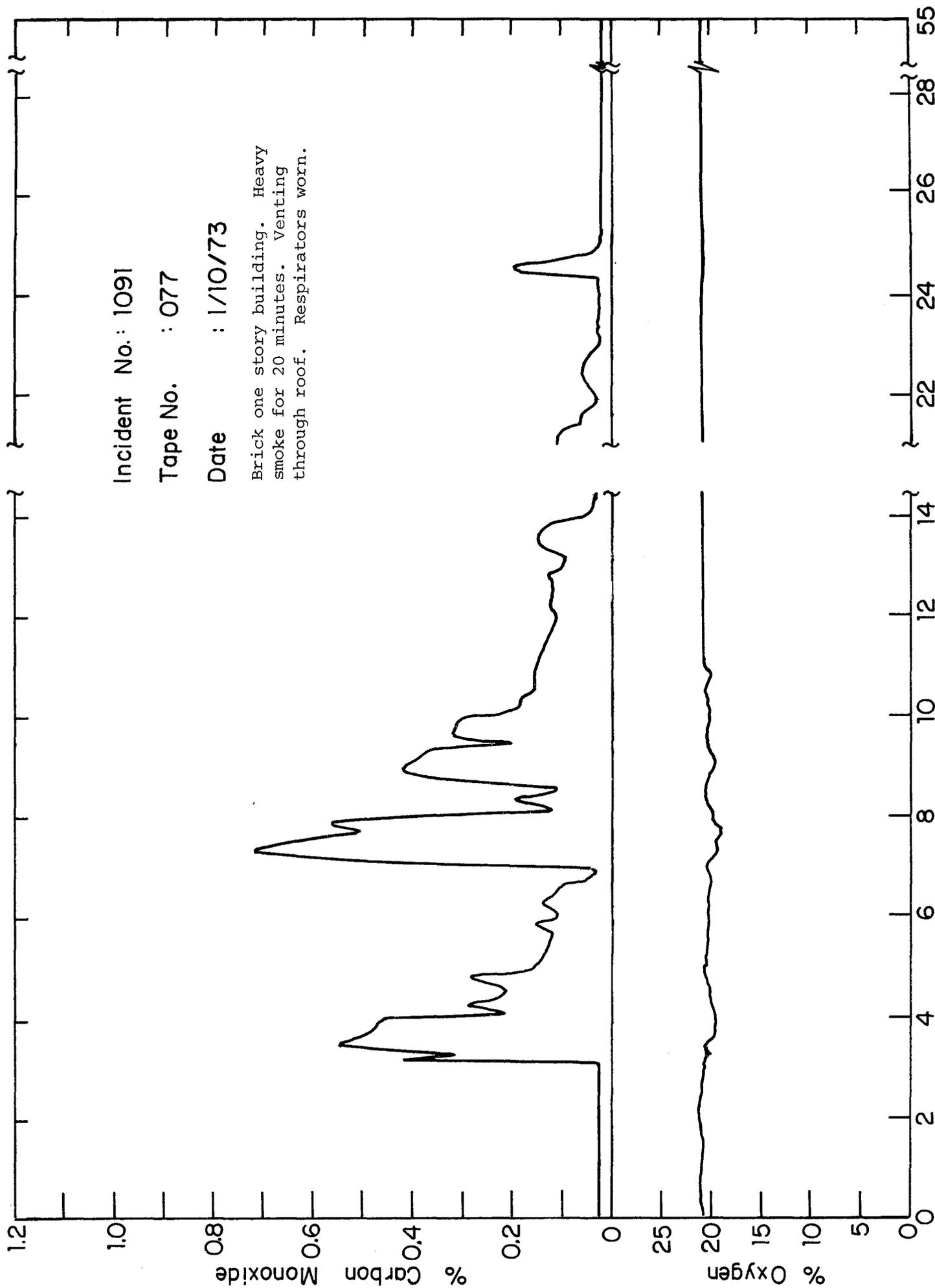


Incident No.: 1091

Tape No. : 077

Date : 1/10/73

Brick one story building. Heavy smoke for 20 minutes. Venting through roof. Respirators worn.



Time - minutes

62

APPENDIX C



## INSTRUCTIONS FOR THE BREATH CARBON MONOXIDE SAMPLES

### Introduction:

The carbon monoxide level in the blood can be estimated by measuring the carbon monoxide level in the exhalation air. The exhaled breath sample for this analysis should be taken as soon as possible after the fire, preferably within one hour. To account for the carbon monoxide due to cigarette smoking, it is important that we know the time since the last cigarette and the daily cigarette consumption.

### Procedure:

Attach the aqua colored vinyl bags to the special valve attachment. Insert a new mouthpiece into the valve. The red nipple of the vinyl bag should be pulled out. Take a deep breath and hold it for 20 seconds. Time this period with a watch, then blow that breath into the mouthpiece. It is not necessary to blow hard. When the vinyl bag is filled, push in the red nipple and slip the bag off the rubber tubing. Write the incident number and your name on the tag attached to the bag.

### Who Should Blow Up the Balloon:

The bag should be blown up by the person who wore the fire gas sampler into the fire. The sampler wearer should also fill out the Sampler Data Form. Exhaled breath samples can also be given by firefighters who think they were exposed to high carbon monoxide levels. That person should write the incident number, his name, and note that he did not wear the sampler on the tag. He should also fill out a Data Form, ignoring the parts regarding the sampler.

If the sampler was not used in a fire, but the firefighters think they took a good pasting, several members of the company can blow up the bags. The firefighters should fill out the Sampler Data Form, ignoring the parts that have to do with the sampler. Please put the incident number, firefighter's name, and "no sampler used" on the tag that is attached to each balloon.

### Results:

The results from the exhaled air tests will be tabulated each week and given to District Fire Chief, "Mike" Buchanan. The firefighter can call him to obtain the results from his test.

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## Estimating Carboxy-Hemoglobin Levels in Blood From Measurements Taken After the Exposure

### Introduction:

Exhaled breath samples from the firefighters are obtained some minutes to a few hours after the cessation of exposure to carbon monoxide. Since the carboxyhemoglobin (COHb) levels follow exponential decay, one can calculate to estimate the probable blood level when the exposure to CO was terminated. The calculations are based on the following assumptions.

- (1) The firefighter probably has a light-to-moderate work rate after his exposure, one can, therefore, (1) assume a carboxyhemoglobin half-life of 2 ½ hours.
- (2) Other than from smoking, there was no other exposure to CO since the first exposure.
- (3) The carboxyhemoglobin levels of cigarette smokers is relatively constant during the day (2). Therefore, one can subtract the COHb level due to smoking from the measured level, to arrive at a level resulting from occupational exposure. The following COHb levels are assumed for cigarette smokers (pipe and cigar smoking is ignored).

<u>Smoking Habit</u>	<u>Mean COHb Level</u>
Light (< ½ pack/day)	3%
Moderate (½ - < 2 packs/day)	5%
Heavy (>2 packs/day)	6%

### Procedure:

The CO concentration is measured by NDIR or the Ecolyser CO monitor. Convert the data from ppm to % COHb by interpolation of Forbes' data (Table 1). Subtract the COHb resulting from smoking from the measured COHb level. Enter the enclosed Figure 1 with (1) the COHb level due to occupational exposure and (2) the time the exhaled breath sample was taken after the exposure. Now follow the parallel lines left to zero minutes and read the COHb level. This is the COHb level of the firefighter due to his exposure in the fire when he was last exposed to CO. Add back the COHb level normally found due to smoking. The resultant is the total COHb in the firefighters when last exposed to CO at the fire.

Example:

An exhaled breath sample taken 80 minutes after the exposure contained 155 ppm CO. The firefighter smokes 1 1/4 packs of cigarettes per day.

- (1) 155 ppm in exhaled breath = 21.5% COHb (from Table 1)
  - (2) COHb level in moderate smoker = 5%
  - (3) 21.5% COHb - 5% COHb = 16.5% COHb due to occupational exposure
  - (4) 16.5% COHb @ 80 min after exposure = 24% COHb at time of exposure (from Figure 1)
  - (5) 24% COHb from fire + 5% COHb from smoking = 29% COHb due to smoking and occupational exposure at the time of cessation of the occupational exposure.
- 
- (1) Personal Communication: W. H. Forbes, Harvard School of Public Health, April 25, 1973.
  - (2) Goldsmith & Landow, Science 162:1352 (1968).

TABLE I

Relationship of Carbon Monoxide in Exhaled  
Breath to Carboxyhemoglobin\*

PPM CO in Exhaled Breath	% Carboxyhemoglobin
11.44	2%
23.36	4%
35.78	6%
48.74	8%
62.29	10%
73.44	12%
91.25	14%
106.77	16%
123.04	18%
140.14	20%
158.10	22%
177.62	24%
196.95	26%
218.00	28%
240.24	30%
301.84	35%
373.70	40%
458.64	45%
560.56	50%

\*Assuming:

$$\frac{(\text{COHb})}{(\text{O}_2\text{Hb})} = 230, \text{ arterial } p\text{O}_2 = 98 \text{ mm Hg, total saturation of blood} = 100\%.$$

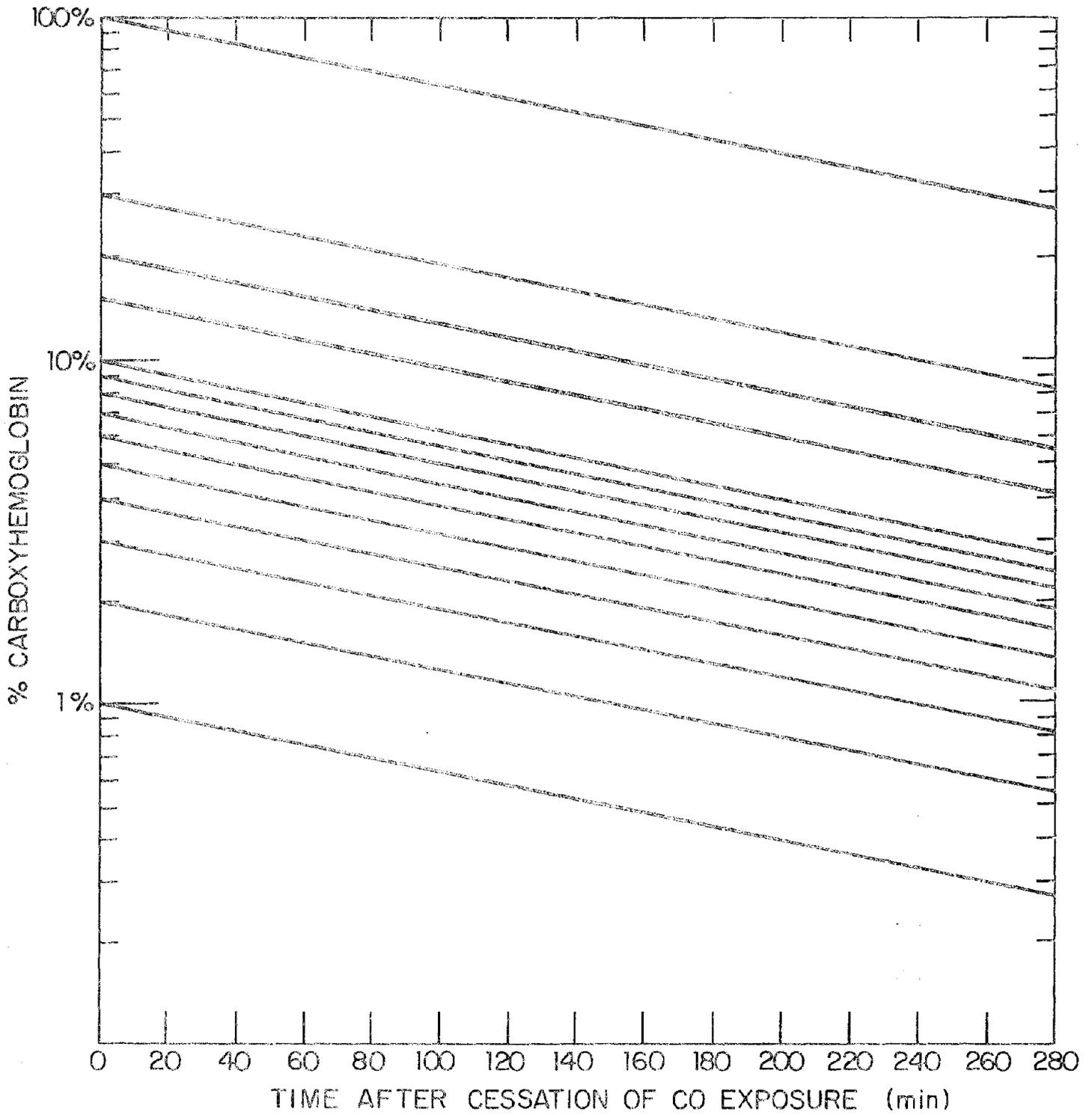


FIGURE 1

Graph for Estimating Carboxyhemoglobin Level at Times of Cessation  
of CO Exposure

(Assumption: light to moderate work rate resulting in a CO-Hb  
half-life of 2.5 hours)

half-life of 2.5 hours)

