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GENERAL AMERICAN TRANSPORTATION CORPORATION

SHELTER ATMOSPHERE

MONITORING INSTRUMENTS

A. L. Kapil

R. J. Baschiere

GARD Report 1277

January 1966

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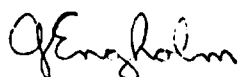
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FOREWORD

This report was prepared by the General American Research Division of the General American Transportation Corporation for the Stanford Research Institute under Subcontract B-70921(4949A-26)-US, OCD Work Unit 1233C, with Mr. C. A. Grubb of SRI as the project technical monitor.

The report covers the work performed on the subcontract during the period of February 1965 to January 1966. Reported data of preference polls conducted on three effective temperature meters developed under this subcontract, and on a commercial gas detector, were obtained under the scope of Contract OCD-PS-66-9, OCD Work Unit 1522A.

ABSTRACT

The environmental factors within fallout shelters were reviewed to identify those factors that can reach dangerous levels during occupancy and hence must be controlled to protect the lives of the shelterees. These factors were determined to be:

1. The effective temperature.
2. The concentration of carbon dioxide, carbon monoxide, oxygen and the hydrocarbon gases within the shelter.

A survey was then made to locate suitable commercial instruments for monitoring these factors. This survey showed that:

1. Instruments for directly indicating the effective temperature are not available.
2. Reliable instruments for measuring carbon dioxide, carbon monoxide, oxygen, and the hydrocarbon gases are available, but are generally too expensive for shelter use and are only intermittent in operation.

As a consequence of this survey, effort was directed towards developing inexpensive instruments that could indicate the effective temperature and measure the concentration of the various gases in the shelter. This work resulted in the following:

1. Development of three different meters for indicating effective temperature.
2. Development of an inexpensive method for continuously monitoring the combined level of carbon dioxide and oxygen in a shelter.
3. Recommendations for research to determine methods for controlling the environment and a system approach to the further development of detection instruments.

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SECTION 1

INTRODUCTION

Civil Defense fallout shelters for most of the population are of the dual-purpose type, i.e. they are spaces in existing buildings having a normal use which will not interfere appreciably with their use as shelters in an emergency. Many of the environmental factors within these shelters have the potential of becoming critical during occupancy and some means for monitoring them is necessary to safeguard the occupants and to let them know when to initiate corrective measures.

Studies have shown that during hot weather the temperature and the humidity, and hence the effective temperature*, within these shelters can reach a dangerously high value¹. To overcome this high effective temperature some ventilation or air conditioning equipment is generally necessary. In addition, the chemical composition of the air can become altered under certain conditions to such an extent that it becomes a hazard. For instance, if the ventilation rate per person is reduced below about 3 cfm, the carbon dioxide concentration in the air will rise and reach a harmful level. Also externally generated toxic gases may enter the shelter through the ventilation system making the environment hazardous.

To monitor these changes in the shelter environment a survey of suitable detection instruments was made³. This survey showed that cheap, simple and

*The effective temperature (ET) is defined as that combination of dry-bulb temperature, humidity and air velocity that produces the same subjective sense of comfort or discomfort as the given dry-bulb temperature in a saturated atmosphere at air speeds of about 20 feet per minute.²

¹ Superscripts refer to References, p. 53.

reliable instruments for environmental monitoring are not generally available.

The present study was therefore initiated with the specific objectives of:

1. Identifying those environmental factors for which a clear need for monitoring exists.
2. Investigating low-cost and reliable methods for monitoring them.
3. Making recommendations for further engineering development of promising instruments.

As a consequence of this study three inexpensive effective temperature meters were developed. Two of these were modifications of existing meters while the third was of an entirely new design. An inexpensive method for continually monitoring the combined level of carbon dioxide and oxygen was also established. This method makes use of the length of a candle flame as a measure of the amount of carbon dioxide present in a shelter.

Suitable commercial instruments for detecting carbon monoxide and the hydrocarbons gases were located since there is a possibility that these toxic gases may find their way into shelters. No attempt was made to develop new instruments for these gases.

SECTION 2

ENVIRONMENTAL FACTORS

Both the thermal level and the chemical content of the environment must be controlled so as to maintain the environment within a shelter safe for habitation. The relative importance of the different environmental factors will depend on the type of shelter involved. The two main classes of shelters are:

1. Ventilated shelters (either natural or forced ventilated).
2. Sealed shelters (shelters capable of being sealed from the external environment).

2.1 Ventilated Shelters

Effective Temperature

The effective temperature that will develop within a ventilated shelter will depend on the thermal and moisture balance between the incoming air and the sensible and latent heat lost by the people within the shelter. Certain other factors such as the heat loss through the walls of the shelter, solar radiation, soil temperatures in the case of basement shelters, etc., will also influence this balance. However, the single most important variable is the ventilation rate. Studies have shown that if proper ventilation is not provided, shelter temperatures greater than 90°F effective temperature (ET) can be reached during the summer months in many areas of the U.S.¹ A shelter ET of 90°F is considered a severe environment for people.⁴ Thus ventilation of the shelter, and hence control of the effective temperature, is of extreme importance.

The problem of monitoring the ET of an environment can be approached in two ways. The first approach is to measure the ET directly. The second is to measure the ventilation rate and from this to compute the ET.

The first approach is quite feasible since simple and relatively inexpensive ET meters can be constructed. With such a meter, the ET could be monitored easily and continuously and would indicate when corrective action should be taken to maintain the ET at a reasonable value. Such a meter would also be useful as a psychological tool by helping to eliminate controversy between shelter occupants regarding their level of comfort or discomfort.

The indirect approach of measuring the the ventilation rate and computing the ET, though theoretically possible, is not practical for shelter use. This method requires information relating the ventilation rate to the ET for that shelter under different ambient conditions, and simple and inexpensive instruments for accurately measuring the ventilation rate. Such instruments are neither available nor is their innovation considered possible. In addition, information relating the ventilation rate to the ET will not be generally available.

Carbon Dioxide

Carbon dioxide (CO_2) is a product of human metabolism and its level in a shelter will depend on the rate of ventilation through the shelter. As the ventilation is reduced the carbon dioxide level will rise and the oxygen level will fall (Fig. 1)⁵. The changes in the concentrations with time are shown in the chart that was developed by F. C. Allen at the Office of Civil Defense (Fig. 2)⁶.

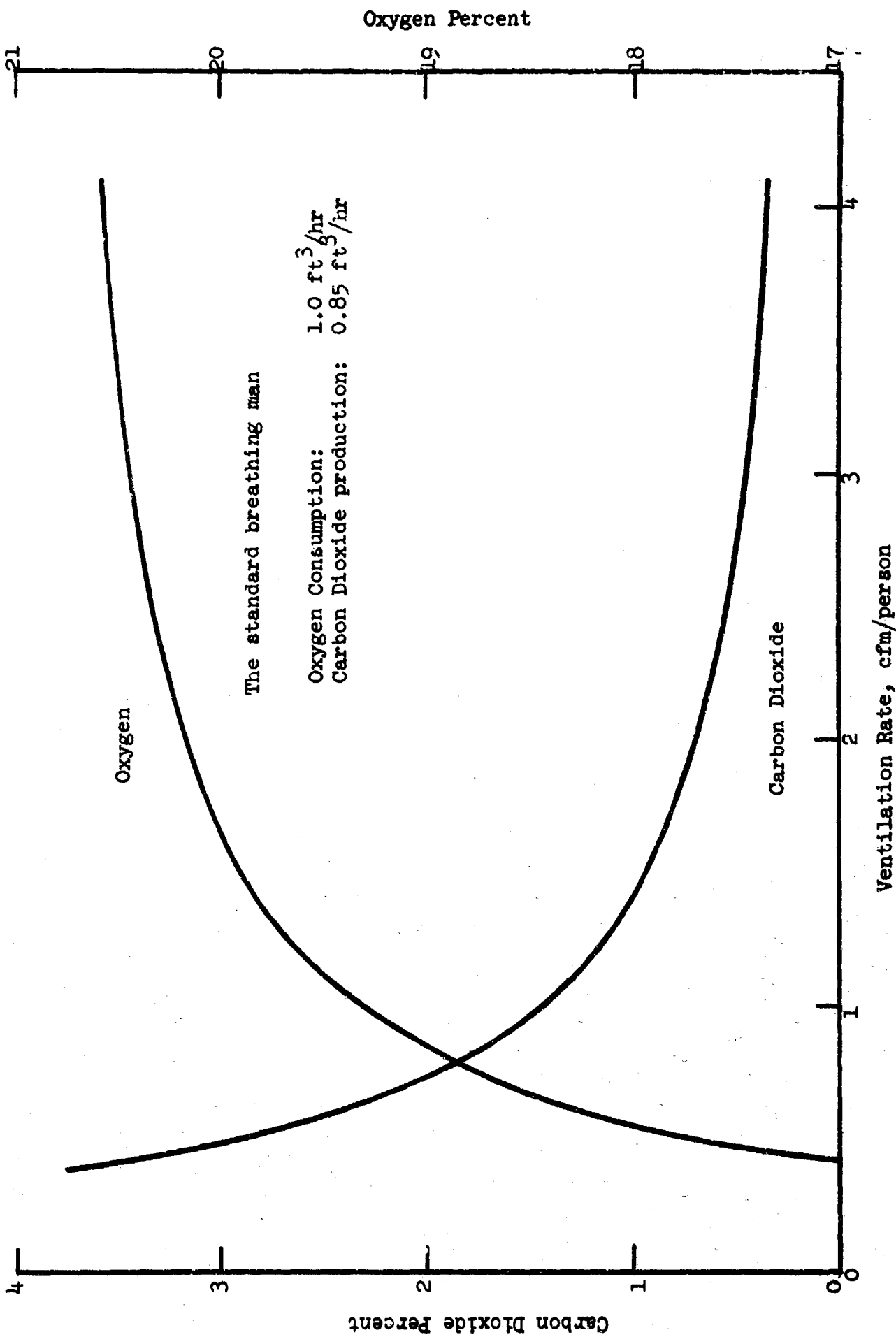
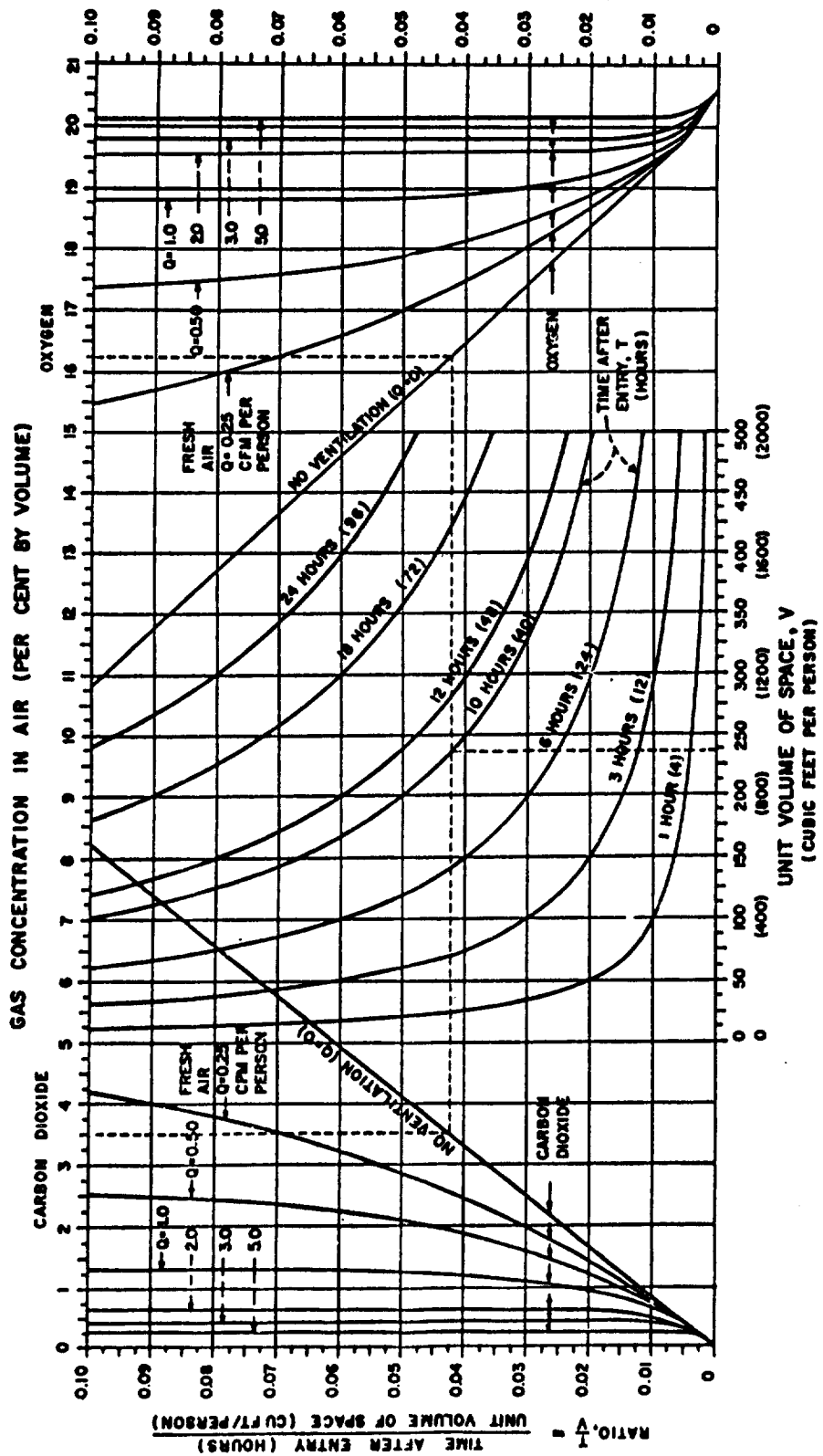


Fig. 1 STEADY STATE CONCENTRATIONS OF CARBON DIOXIDE AND OXYGEN IN THE ATMOSPHERE OF SHELTERS VS. VENTILATION RATE



TERMINAL VALUES OF GAS CONCENTRATION

VENTILATION RATE (CFM/PERSON)	CARBON DIOXIDE (PERCENT BY VOLUME)	OXYGEN (PERCENT BY VOLUME)
0.25	5.35	14.15
0.50	2.67	17.25
1.00	1.35	18.77
2.00	0.69	19.83
3.00	0.47	19.79
5.00	0.29	20.11

FRESH AIR QUANTITIES CORRECTED TO STANDARD DENSITY OF 0.075 LB/CU FT.

PHYSICAL DATA
 OXYGEN CONSUMED = 0.90 CU FT/HR/PERSON *
 CARBON DIOXIDE PRODUCED = 0.75 CU FT/HR/PERSON *
 MOISTURE LOSS FROM BODY = 0.144 LB/HR/PERSON *
 OXYGEN IN FRESH AIR = 20.62% BY VOLUME
 CARBON DIOXIDE IN FRESH AIR = 0.03% BY VOLUME
 DRY-BULB TEMPERATURE = 77°F = 25°C
 RELATIVE HUMIDITY OF FRESH AIR = 50%
 BAROMETRIC PRESSURE = 760 MM OF HG
 * REFERRED TO DENSITY AT 0°C, 760 MM OF HG

Fig. 2 PREDICTED CONCENTRATIONS OF CARBON DIOXIDE AND OXYGEN IN THE ATMOSPHERE OF SHELTERS WITH TIME DUE TO HUMAN METABOLISM

During cold weather the ventilation rate will in general be reduced to maintain a comfortable temperature within the shelter. In extremely cold weather it is therefore possible for the ventilation rate to be so low that a dangerous level of carbon dioxide is formed. A ventilation rate lower than 3 cfm/person will cause carbon dioxide to exceed 0.5%, the accepted industrial limit value.⁷ At this value of carbon dioxide it can be shown that if the carbon dioxide is produced by human metabolism only, the oxygen level is about 20.3% which is well above the 16.25% necessary to support life.⁸ Hence of the two factors, the carbon dioxide content of the air is the more critical one, and the one which should be monitored.

Carbon Monoxide

Carbon monoxide (CO) is an extremely toxic gas with an established industrial limit value of 50 ppm.⁷ It could appear in a shelter from the following three sources:

1. Mass fires adjacent to the shelter. (Measurement near burning buildings have shown that CO as high as 70,000 ppm may be produced.⁹)
2. Tobacco smoking.
3. Operation of faulty combustion equipment.

Because the gas is toxic, odorless, and colorless, a means for detecting the presence of this gas in a shelter is desirable.

Hydrocarbons

The hydrocarbons which could appear as contaminants in shelters are methane (CH₄), ethane (C₂H₆), and the vapors of gasoline. The major sources of these contaminants are the exhaust of internal combustion engines and other

fuel burning devices. They may also appear as a result of direct evaporation of fuels or the bursting of city gas mains. Methane and ethane are simple asphyxiants while gasoline vapor is toxic. The accepted industrial limit value for gasoline vapor is 500 ppm.⁷ Most of these hydrocarbons, in addition to being health hazards, are also explosive hazards when present in concentrations greater than about 3000 ppm. To ensure that their presence is quickly detected, a hydrocarbon detector would be needed in a shelter.

Relative Importance of the Environmental Factors

Of the different environmental factors which need to be monitored and controlled in ventilated shelters, the effective temperature is the most important one during the summer months. During this period high effective temperatures will develop in most shelters if they are used to their capacity and adequate ventilation rates will be necessary to keep the ET down. The concurrent problem of excessive accumulation of metabolically produced carbon dioxide will not be present, since the ventilation rates required to keep the ET down will be greater than the 3 cfm/person necessary to maintain a low concentration of carbon dioxide (i.e., <0.5%).

On the other hand during the winter months, the ET problem will become unimportant but accumulation of a high concentration of metabolically produced carbon dioxide will have to be prevented. This will be especially true if the ventilation is reduced below 3 cfm/person. Hence means for monitoring and controlling carbon dioxide will be required. It should be emphasized that in ventilated shelters there is no need to measure the concentration of oxygen if the carbon dioxide is monitored, since in such shelters a safe level of carbon dioxide will assure a safe level of oxygen.

The presence of toxic gases such as carbon monoxide or the hydrocarbons in a shelter cannot be predicted with any certainty. Their presence will be independent of the other environmental factors and could reach hazardous concentrations because of fires adjacent to the shelters, the presence of fuel vapors, or the exhaust of fuel burning devices. Hence means for separately monitoring these toxic gases should be available in the shelter.

The relative importance of the different environmental factors in ventilated shelters could therefore be stated to be as follows:

1. The effective temperature.
2. The carbon dioxide concentration.
3. The concentration of toxic contaminants such as carbon monoxide and the hydrocarbons.

2.2 Sealed Shelters

These are shelters capable of being sealed from the external environment either temporarily or permanently. The purpose in temporary sealing is to allow continued occupancy during periods when the ventilation system cannot be operated because of fires or atmospheric contamination. Many shelters designed to provide protection for emergency operations of military, governmental, or essential industrial installations would fall in this category. During normal operation these shelters would be similar to ventilated ones and the order of importance of the different environmental factors would be as pointed out earlier. During sealed operation, however, the chemical content of the atmosphere would assume a greater importance than the thermal level for two reasons. The first is that air conditioning equipment would generally be

present in these relatively sophisticated shelters. The second is that toxic gases and vapors from stored fuel or fuel burning equipment, which will be present in these shelters, may leak into the shelter and accumulate to hazardous levels.

It is possible also to have the concentration of carbon dioxide which is produced metabolically exceed the established industrial limit of 0.5% under crowded conditions (Fig. 2). If life support equipment is provided to remove CO_2 and replace oxygen (as may be the case with most of the permanently sealed shelters and many of the temporary sealed shelters) instruments to measure these two gases would be essential in order that such life support equipment may be operated properly.

In summary, it can be said that in sealed shelters the monitoring of the toxic gases such as carbon monoxide and the hydrocarbons is of primary and equal importance with the monitoring of the metabolic gases CO_2 and O_2 . The control of effective temperature is next in importance.

SECTION 3

EFFECTIVE TEMPERATURE METER

Three effective temperature meters suitable for shelter use were developed. Two of these were modifications of existing instruments while the third was entirely new in design. A fourth ET meter, developed by the McGraw-Edison Company of West Orange, New Jersey, and a fifth one contrived by the Stanford Research Institute of Menlo Park, California, were also evaluated.

The requirements for a shelter ET meter are considered to be the following:

1. Low cost.
2. Accuracy within $\pm 1^\circ$ ET, since daily variations in ET are of the order of $\pm 2^\circ$ ET¹¹.
3. Strong construction so that it can be used over a two-week period by shelterees without breakage or loss of accuracy.
4. Simple to use so that persons not familiar with the instruments can quickly learn to read it and interpret the readings in terms of ET.
5. Shelf-life of at least five years¹².

3.1 ET Meter No. 1 (Modified THI Meter)

This ET meter consists of a liquid-in-glass thermometer and a paper-metal humidity sensing element mounted on a common panel (Figs. 3 and 4). The ET is read at the point where the temperature line meets the movable ET scale mounted on the needle.

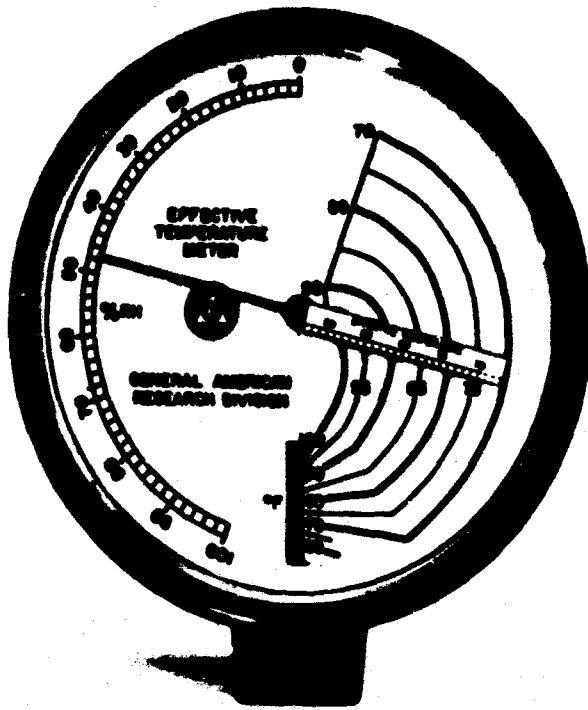


Fig. 3 ET METER NO. 1 (MODIFIED THI METER)

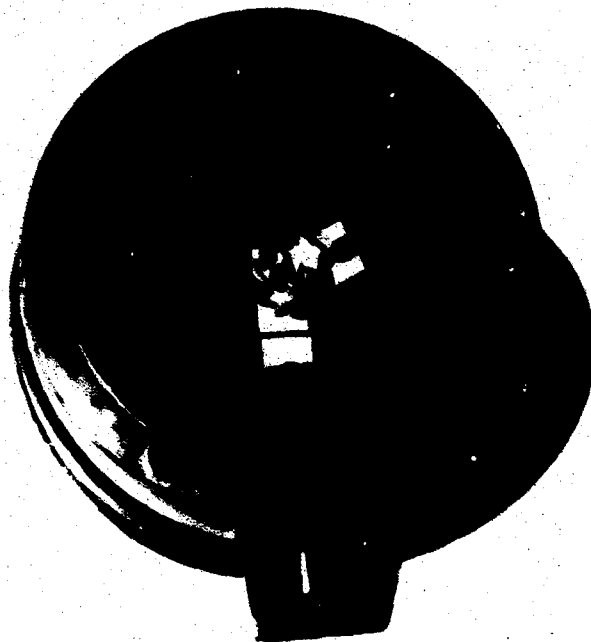


Fig. 4 ET METER NO. 1 (MODIFIED THI METER) - BACK VIEW

The meter was obtained by modifying the dial of a commercial temperature-humidity-index (THI) meter. It is ruggedly constructed and was determined by tests to be accurate to within $\pm 1^\circ$ ET. In large quantities (10,000 pcs.) the meter would cost about \$1.60 each. It appears suitable for shelter use.

Several tests were conducted on the unmodified meter to determine the effects of extreme humidities and extreme temperatures on performance. This was done to find out how well the meters would be able to withstand the wide variations in temperature and humidity likely to develop during storage.

The tests were performed on twenty meters. Ten meters were used as controls, five were subjected to humidity changes and the remaining five to temperature changes. The values selected for the tests were 0% RH and 100% RH at 75°F, and -10°F and +125°F at constant RH. Tests were run in each case for 100 hours. After exposing the meters to a given test condition they were brought back to room condition and their readings compared with those of the control meters. The results of these tests were as follows:

1. After exposure to 0% RH at 75°F for 100 hrs: the meters read higher than the controls by about 3% to 4% RH.
2. After exposure to 100% RH at 75°F for 100 hrs: the meters read lower than the controls by about 12% to 14% RH.
3. After exposure to -10°F (at 62% RH) for 100 hrs: the meters were in agreement with the controls, i.e. the low temperature exposure had no effect on subsequent performance.
4. After exposure to +125°F (at 18% RH) for 100 hrs: the meters read higher than the controls by about 6% to 7% RH.

(The RH readings of the respective control meters differed at the most by $\pm 1.5\%$).

Thus, exposure to low temperature had no effect on subsequent performance; very low and very high humidities and high temperature all affected the calibration. This points out the need for packaging the meters in hermetically sealed containers and storage at relatively cool temperature if the initial as-manufactured accuracy of the meters are to be preserved.

The dynamic response characteristics of these meters to humidity changes was also evaluated. The time-response curve for a step change in humidity from 0% RH to 44% RH is given in Fig. 5. As can be seen, the time constant, i.e. the time to read 63.2% of the final value was found to be 27.5 minutes. This is not excessive for an instrument which is to be used in shelters since temperature and humidity changes usually take place at a slow rate, the general variation in ET over a 24 hour period being about 4°ET^8 .

3.2 ET Meter No. 2 (Two-needles)

An instrument known as a "moisture content meter" is commercially available for measuring the moisture content of air. The dial of this meter was modified to read effective temperatures directly (Fig. 6). This instrument uses two sensors, a bimetallic thermometer and a nylon fiber hygrometer (Fig. 7). These two sensors are so mounted on a dial that the needles attached to them cross each other and in the modified meter the point at which they intersect represents the ET for the temperature and the humidity indicated by the two sensors.

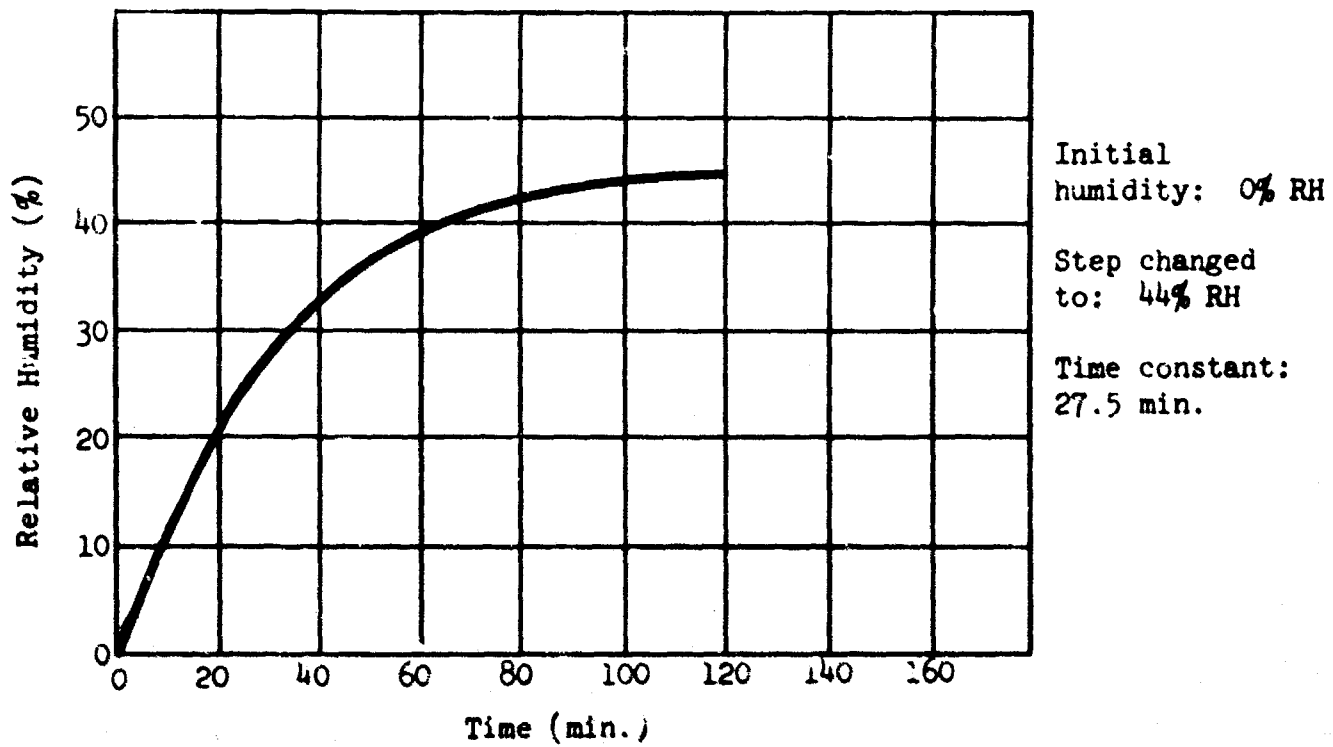


FIG. RESPONSE TO A STEP CHANGE IN HUMIDITY OF ET METER NO. 1 (MODIFIED THI METER)

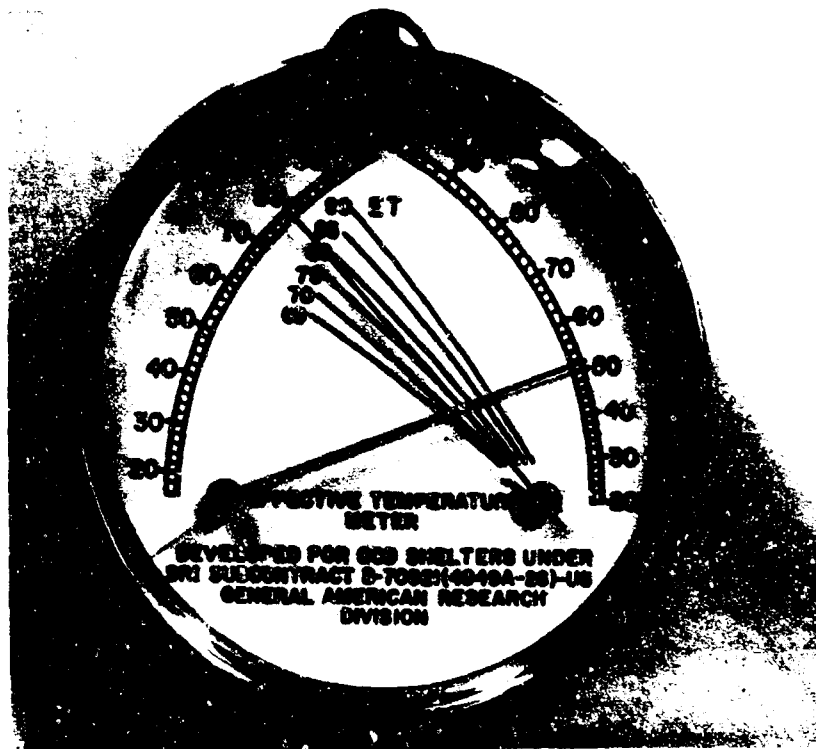


Fig. 6 ET METER NO. 2 (TWO-NEEDLES)

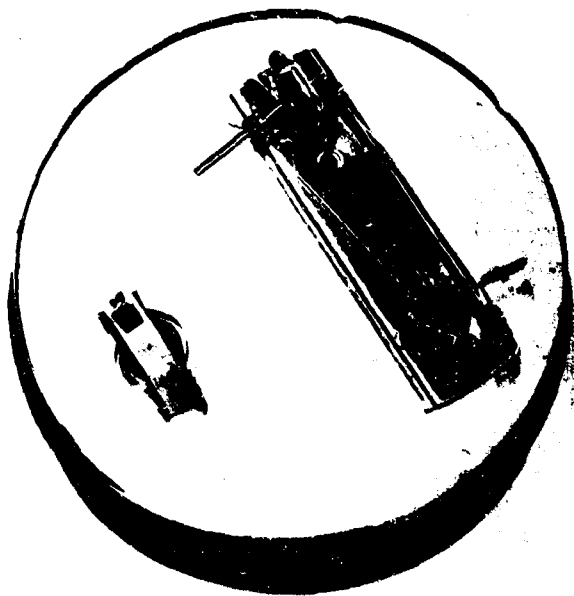


Fig. 7 ET METER NO. 2 (TWO-NEEDLES) - BACK VIEW

The meter is ruggedly constructed, easy to read, and was found by tests to be accurate to $\pm 1^\circ\text{ET}$. It is therefore quite suitable for shelter use.

The cost of this meter is \$16.50 but in large quantities would be about \$10.00. However, this cost is still high for an instrument for shelter use.

A new cheaper model can be developed if cheaper sensors are substituted for the ones used. A metal-plastic temperature sensor could be substituted for the bimetallic thermometer and a biplastic humidity sensor for the nylon fiber hydrometer^{13,14}. The advantages of these changes would be that needles, bearings, etc., would be eliminated since these sensors act as their own indicators. During use, one end of these sensors is fixed, the other free to move. As the temperature or humidity changes, the free end moves over a circular arc indicating the change. It is estimated that by these substitutions the cost could be reduced to about \$1.60 and the meter made competitive with ET meter No. 1.

3.3 ET Meter No. 3 (Colorimetric)

This meter consists of a liquid-in-glass thermometer and a color change humidity sensor (Fig. 8). The sensor itself consists of seven sub-elements the first one of which changes from blue to pink at 15% RH, the second at 25% RH, and so on up to 75% RH. With a little practice the relative humidity can be easily estimated to within 5% RH and extrapolated to cover the range of 10 to 80% RH.

The thermometer and the humidity sensors form the co-ordinates of a graph on which ET lines are drawn and the ET is read at the point where the temperature and the humidity lines intersect.

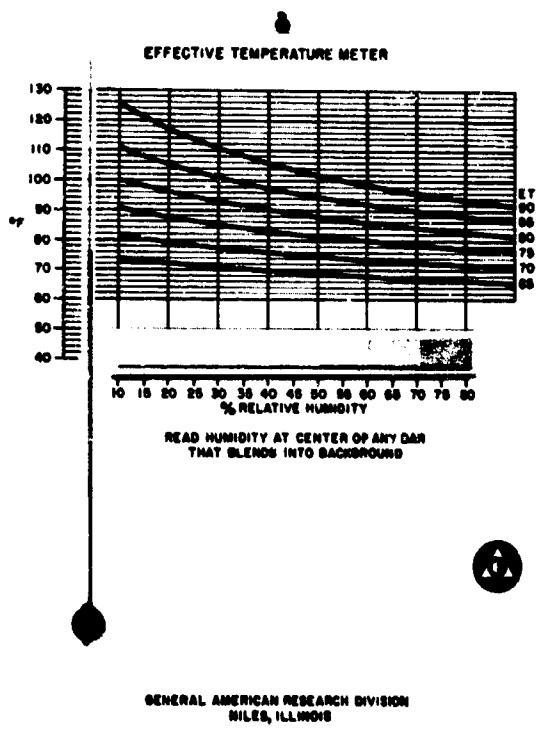


Fig. 8 ET METER NO. 3 (COLORIMETRIC)

The accuracy of this meter is within $\pm 1^\circ$ ET and the cost in large quantities (10,000 pcs.) is expected to be lower than \$1.00 each. This meter is quite suitable for shelter use.

The humidity sensor is not affected by low or high environmental temperatures or by low humidities. Humidities over 95% RH for several days however will ruin it, since under these conditions excessive moisture will be absorbed by the sensor, resulting in a transfer of chemicals from one sub-element to another and loss of calibration¹⁵. Storage of the meter in hermetically sealed containers would therefore be necessary.

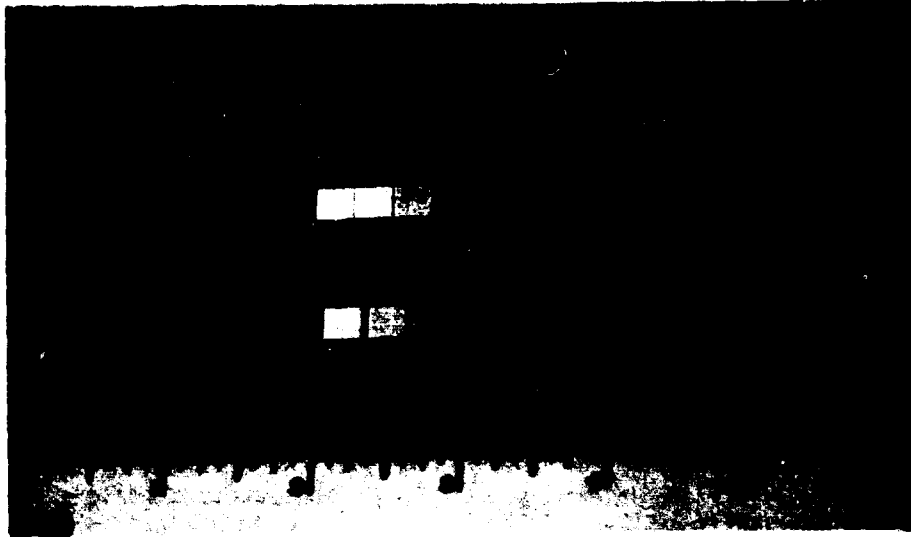
These deleterious effects of high humidities can be reduced by:

1. Providing air gaps between the sub-elements to form barriers to the transfer of chemicals (Fig. 9).
2. Supplying spare sensors in sealed envelopes so that field repairs could be made in case of damage. This is quite feasible since these sensors are very inexpensive (approximately 3¢/meter).

3.4 McGraw-Edison ET Meter

A prototype ET meter invented by the McGraw-Edison Company of West Orange, New Jersey, was obtained from them for evaluation³. This meter consists of a bimetallic thermometer and an animal-membrane humidity sensor mechanically coupled to a needle so that the movement of the needle is proportional to the ET of the environment (Figs. 10 and 11).

This meter is easy to read but is very delicate because of the fragile coupling between the elements. A slight jar knocks the needle off calibration. A commercial humidity indicator using a similar humidity sensor retails for



A Original element

B Modified element with air-gaps between
subelements

Fig. 9 MODIFICATION OF COLORIMETRIC HUMIDITY ELEMENT

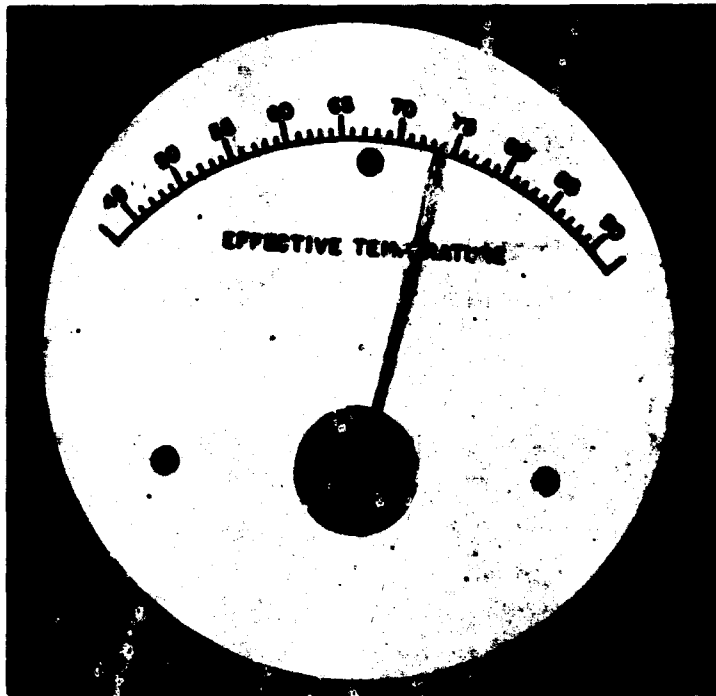


Fig. 10 MCGRAW-EDISON ET METER

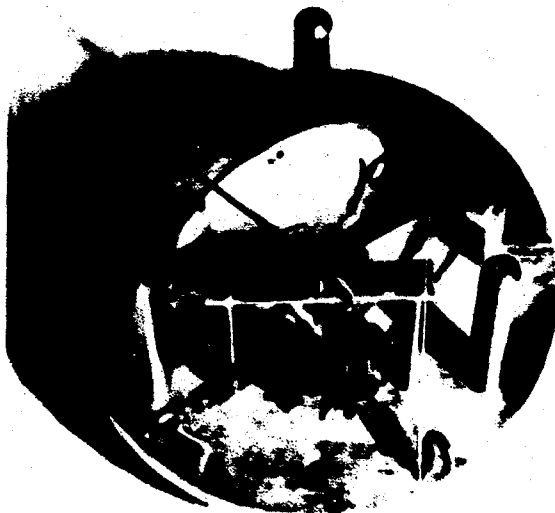


Fig. 11 MCGRAW-EDISON ET METER - DIAL REMOVED

\$75.00. Hence the cost of this ET meter, which is much more complicated, would in all probability be greater than \$50.00 even if mass produced. This meter in its present form is therefore considered unsuitable for shelter use.

3.5 Stanford Research Institute ET Meter

An ET meter has been recently contrived at SRI which is based on the sling psychrometer (Fig. 12)*. It consists of a wet-bulb and a dry-bulb thermometer mounted on a thin aluminum frame which has a freely rotating handle. Between the two thermometers a nomogram is provided on which ET's can be read.

In operation, the wick of the wet-bulb is saturated with distilled water and the thermometers whirled rapidly until two consecutive temperature readings are the same. This usually takes about a minute or so. A transparent lucite strip is then placed under the thermometers and the straight line scribed on it is made to coincide with the thermometer readings. The ET is then read on the nomogram at the point where the scribed line intersects it.

The meter is accurate and suitable for use in shelters but is susceptible to breakage. Although the incorporation of protective guards could eliminate this problem, the meter requires space to whirl in and some difficulty may be encountered in using it in very crowded shelters. It is estimated that in large numbers the cost would be around \$7.50 each.

*Klein, E. J., "Effective Temperature Meter", Stanford Research Institute, Calif., October 1965, (Private communication).

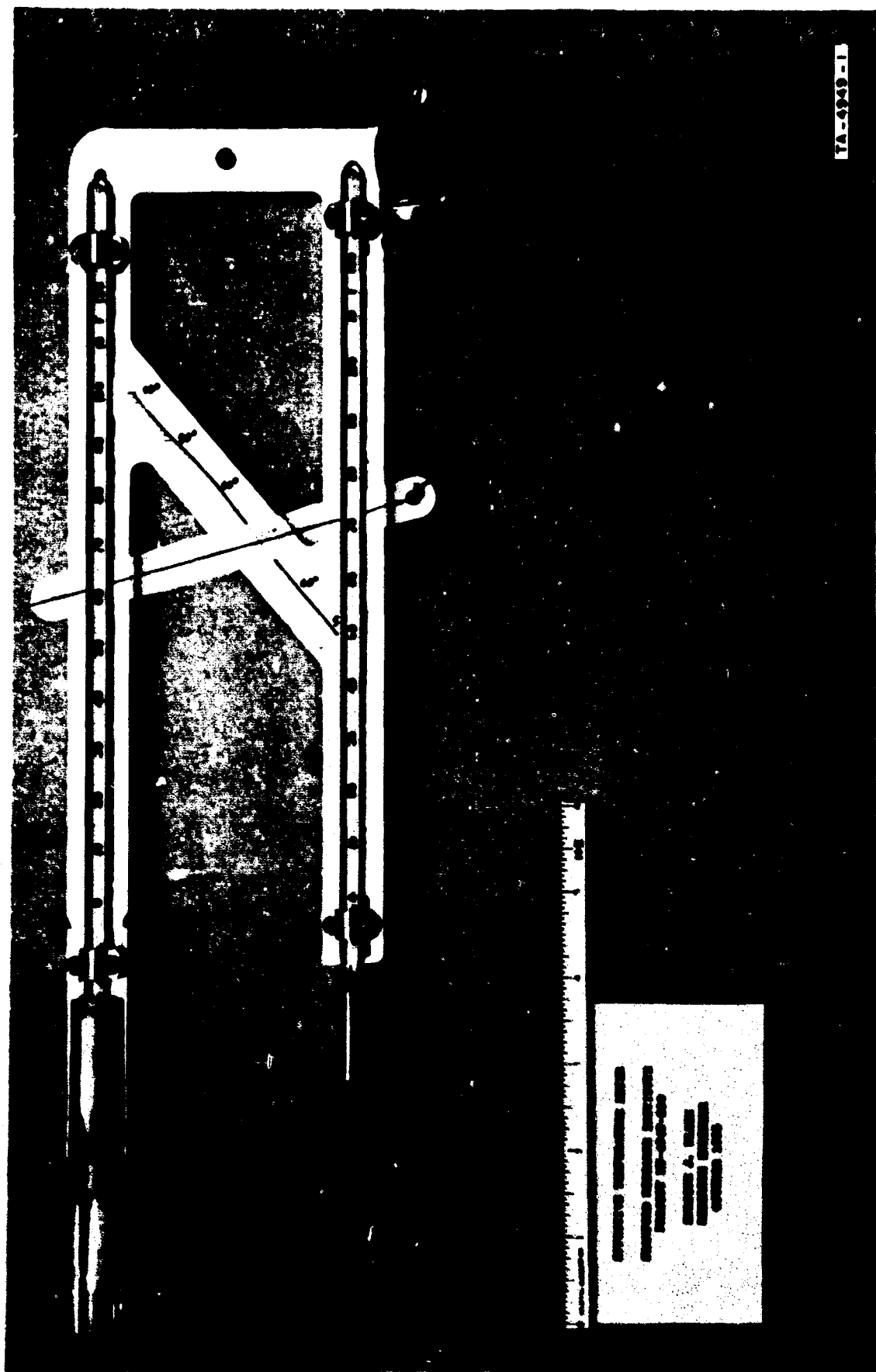


Fig. 12 STANFORD RESEARCH INSTITUTE ET METER

3.6 Readability of ET Meters

The American Institutes For Research of Pittsburgh, Pennsylvania, was requested (under contract OCD-PS-66-9) to evaluate ET Meters Nos. 1, 2 and 3 using subjects selected at random. The specific objectives of this evaluation were to:

1. Determine which of the three meters was the easiest to read.
2. Determine what changes could be made to improve their readability.

The results of 97 tests (Table 1) showed that each meter was read incorrectly at one time or the other. The percentage of the readings which were in error was as follows:

Meter No. 1 (modified THI meter):	40%
Meter No. 2 (two-needles):	28%
Meter No. 3 (colorimetric):	84%

Thus No. 2 was the best and No. 3 the poorest.

Meter No. 3 was therefore modified to improve its readability (Fig. 13).

These modifications involved:

1. Elimination of the °F and percent humidity markings.
2. Expansion of the scale on the graph.
3. Elimination of some unnecessary ordinate and abscissa lines from the graph.

The modified meter was read incorrectly only 56% of the time, which is an improvement of 28% (Table 2). Although the reading errors are still high it may be possible with additional alterations to reduce it to a level

Table 1

Evaluation of ET Meters by 97 People

Test Sessions 1 through 5

ET Meter	% People who Read the Meter Incorrectly	% People who Judged the Meter to be the Easiest to Read of the Three Meters	% People who Could not Read the Meter
No. 1 (Modified THI Meter)	40	16	5
No. 2 (Two-needles)	28	61	2
No. 3 (Colorimetric)	84	21	6

1. Readings not within $\pm 2^\circ$ ET of the indicated meter value were considered incorrect.
2. Two percent of the people expressed no opinion.

Table 2

Evaluation of ET Meters by 62 People

Test Sessions 6 through 8 Using Modified ET Meter No. 3 (Colorimetric) instead of the Original

ET Meter	% People who Read the Meter Incorrectly	% People who Judged the Meter to be the Easiest to Read of the Three Meters	% People who Could not Read the Meter
No. 1 (Modified THI Meter)	44	21	2
No. 2 (Two-needles)	39	64	0
No. 3 (Colorimetric) modified	56	15	3

1. Readings not within $\pm 2^\circ$ ET of the indicated meter value were considered incorrect.

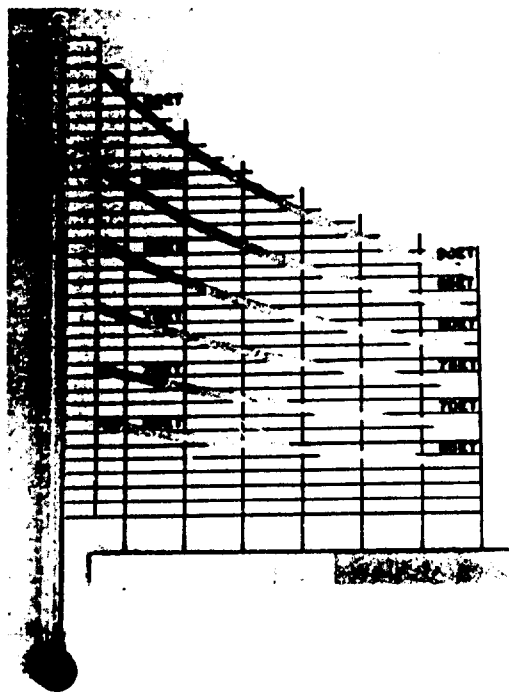


Fig. 13 MODIFIED VERSION OF ET METER NO. 3 (COLORIMETRIC)

comparable with the others. Effort to achieve this can be justified since this meter is the cheapest one and hence very desirable for shelter use.

The characteristics of the five meters are compared in Table 3.

3.7 Interpretation of ET Readings

The ET values read on a meter will have no meaning unless information is supplied relating ET's to the condition of the environment and suggesting possible remedial actions to counteract high ET's. A suggested format and set of instructions which might be included with each meter or printed on the face of each meter is shown in Fig. 14. The exact instructions to be included must await a detailed study of the overall environmental control problem.

Table 3

Comparison of ET Meters

Meter Characteristics	ET Meter No. 1 (Modified THI Meter)	ET Meter No. 2 (Two-needles)	ET Meter No. 3 (Colorimetric)	McGraw-Edison ET Meter	Stanford Research Institute ET Meter
Accuracy*	Good	Good	Good	Good	Good
Construction	Good	Fair	Good	Poor	Fair
Readability**	Fair	Good	Fair	Very Good	Good
Shelf-life (5 yrs)	Good ⁺	Good ⁺	Good ⁺	Good ⁺	Very Good
Cost (approximate)	\$1.60	\$10.00	\$1.00	>\$50.00	\$7.50

*Accuracy is considered good if meters can read within $\pm 1^\circ\text{ET}$.

**Only meters nos. 1, 2 and 3 were evaluated by people for readability.

+Provided they are stored in hermetically sealed package.

EFFECTIVE TEMPERATURE	EFFECT ON BODY	RECOMMENDED PROCEDURES TO FOLLOW
Below 70	Cool	Decrease ventilation
70-76	Comfortable	
76-80	Muggy	Increase ventilation
80-82	Hot and humid	Restrict unnecessary activity increase ventilation further
82-85	} To be developed by the Office of Civil Defense	
85-90		
Above 90		

Fig. 14 SUGGESTED FORMAT FOR REMEDIAL PROCEDURES TO ACCOMPANY EFFECTIVE TEMPERATURE METERS (Caution: recommended procedures for illustrative purposes only.)

SECTION 4

GAS DETECTORS

A survey was made to locate commercial detectors for measuring the concentrations of carbon dioxide, carbon monoxide, oxygen and the hydrocarbons in shelters. This survey showed that:

1. Instruments for continuously monitoring the above gases are expensive ($> \$100.00$).
2. Of the intermittent detectors available, the ones which are most suitable are of the colorimetric type. In these detectors a known volume of air is aspirated through a tube containing a chemical sensitive to a particular gas and the change in color or the length of stain produced due to chemical reaction is used as a measure of that gas. Detectors of this type are available for CO_2 , CO and O_2 .
3. Colorimetric detectors for all hydrocarbons are not available. Combustion type instruments are however available but are expensive ($\$100.00$ to $\$150.00$) and require regular renewal of batteries at the end of their shelf-life of about 1 year. Such instruments can be used in shelters.

4.1 Commercial Detectors for Carbon Dioxide and Carbon Monoxide

Several detectors are commercially available for carbon dioxide and carbon monoxide (Table 4). The one which is relatively inexpensive and appears suitable for shelter use is detector No. 4 (Fig. 15).

Commercial Instruments for Detecting Carbon Dioxide and Carbon Monoxide

S/N	Item	Gas	Type ¹	Range ²	Type	Price ³ \$	Remarks
1	Gas Analyzer Kit	CO ₂	I	.05-4.0%	Length of stain	43.10	Refill liquid:\$1.00/ bottle
2	CO ₂ Indicator	CO ₂	I	0 -7.6%	Absorption	72.00	Refill liquid:\$2.00/ bottle
3	CO ₂ Indicator Kit	CO ₂	I	0 -5.0%	Absorption	43.50	Suitable for 51 gases
4	Toxic Gas Detector	CO ₂ ,CO	I	0 to TLV+	Colorimetric	9.95	Suitable for 51 gases
5	Toxic Gas Detector Kit	CO ₂ ,CO	I	0 to TLV+	Colorimetric	45.00	Suitable for 51 gases
6	Universal Tester Kit	CO ₂ ,CO	I	0 to TLV+	Colorimetric	75.00	Suitable for 79 gases
7	Multigas Detector	CO ₂ ,CO	I	0 to TLV+	Colorimetric	85.00	Suitable for 70 gases
8	Gas Detector	CO ₂ ,CO	I	0 to TLV+	Colorimetric	80.00	Suitable for 36 gases
9	Detector Ampoules	CO	I	0 to TLV+	Color change	1.25/ pkg.	10 ampoules per package
10	Detector Ampoules	CO	I	0 to TLV+	Color change		Suitable for 34 gases
11	CO Meter Kit	CO	I	0 to TLV+	Color change	30.00	
12	CO Tester	CO	I	.001-.1%	Color change	45.00	
13	Gas Detector Kit	CO	I	0 to TLV+	Color change	-	
14	CO Indicator Kit	CO	I	0 -.2%	Length of stain	42.50	
15	CO Detector Kit	CO	I	0 to TLV+	Length of stain	25.20	
16	CO Indicator	CO	C	0 -.15%	Heat of reaction	300.00	Hand operated
17	CO Detector Alarm	CO	C	0 - .01%	Color change	190.00	Photo-electric color detector

¹ I: Intermittent in operation; C: Continuous in operation

² TLV: Threshold Limit Value

³ For basic instrument. Detector tubes are extra.

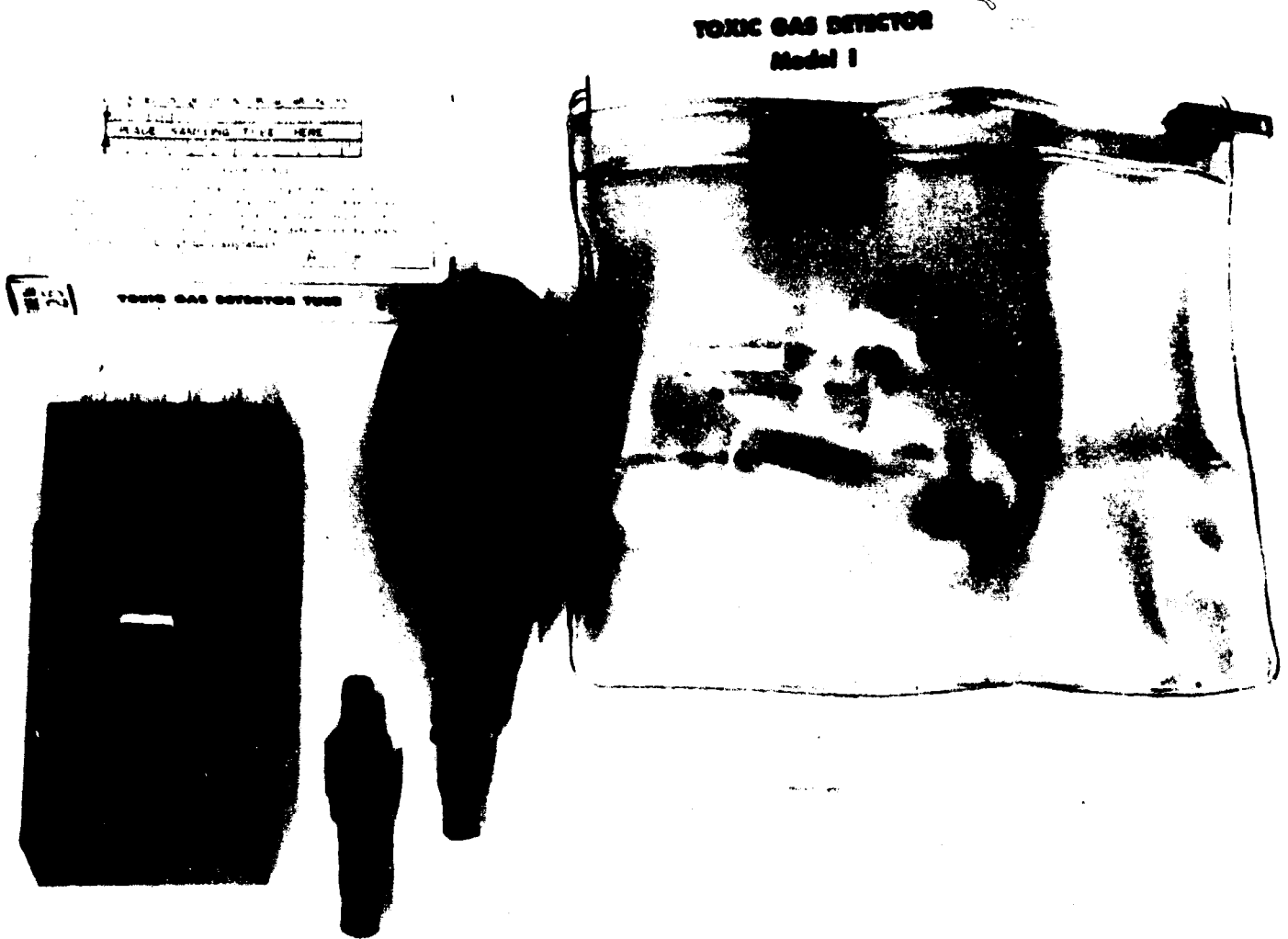


Fig. 15 TOXIC GAS DETECTOR (NO. 4) FOR CARBON DIOXIDE AND CARBON MONOXIDE

This detector is of the colorimetric type and uses a rubber bulb of fixed volume to aspirate air through the tubes. The bulb is provided with check valves at both ends to allow the air to be aspirated in one direction only. The carbon dioxide tubes are of the length-of-stain type, the carbon monoxide ones of the color-change type. The shelf-lives of the tubes are 2 and 3 years respectively.

To operate this detector, the correct tube for the gas to be detected is selected and both ends broken off in a slot provided for this purpose in one of the check valves. The tube is then connected to the rubber bulb and the bulb aspirated the specified number of times to draw the required volume of air through the tube. The length-of-stain or the color-change that is produced in the chemical in the tube is then compared with a standard length or color chart supplied with the detector and an estimate of the concentration of the gas made.

Recently a novel method for detecting different concentrations of CO₂ in a closed environment was developed by NASA¹⁶. With some modifications this method could be adopted for shelter use. It is capable of giving unambiguous colorimetric indication of carbon dioxide at concentrations of 0.25%, 0.5%, 0.75% and 1.0%. It consists of chemically treated paper which changes in color at a particular CO₂ concentration depending on the chemical used. The change in color is irreversible. Four different chemical solutions are used in the preparation of the paper for the four concentrations. This idea has potential for shelter use and further investigation of the technique is recommended.

4.1.1 Evaluation of Detector

Detector No. 4 (Table 4) for carbon dioxide and carbon monoxide was evaluated by the American Institute for Research of Pittsburgh, Pennsylvania, under contract OCD-PS-66-9. The object was to find out what problems, if any, would be encountered in using it. People selected at random were used in this evaluation.

Two weaknesses were uncovered which need correction before the detector can be recommended for shelter use. The first defect was found in the construction of the tubes, the second in the labeling.

The ends of some of the tubes were found to be too large and some too small. As a result difficulty was encountered in breaking off the ends in the groove provided for this purpose. Improved quality control during manufacture is necessary to ensure that the ends are properly constructed.

The labeling of the boxes containing the colorimetric tubes was judged to be inadequate. Also, the tubes were not marked to indicate the gas they could detect. These defects must be corrected to prevent any mix up and errors in readings.

4.2 Commercial Detectors for Oxygen

Most of the oxygen detectors which are commercially available are expensive (Table 5). The detector which appears to be quite suitable for sealed shelters is No. 1 (Fig. 16). This is the only one which is of the colorimetric type and is also the cheapest.

Table 5

Commercial Instruments for Detecting Oxygen

S/N	Item	Type ¹	Range	Type	Price \$	Remarks
1	Oxygen Analyzer Kit	I	2-30%	Length of stain	22.75	Shelf-life of tubes: 3 years
2	Multi-gas Detector	I	0-25%	Length of stain	85.00	Suitable for 70 gases
3	Oxygen Indicator	I	0-21%	Absorption	39.70	Refill liquid: \$2.40/ bottle
4	Oxygen Indicator	C	0-25%	Electrode depolarization	225.00	Battery operated, shelf- life 1 year
5	Oxygen Analyzer	C	0-25%	Paramagnetic	295.00	Battery operated, shelf- life 1 year
6	Portable Oxygen Analyzer	C	0-25%	Galvanic cell	150.00	Replacement detector cell: \$40.00

¹ I: Intermittent in operation
C: Continuous in operation

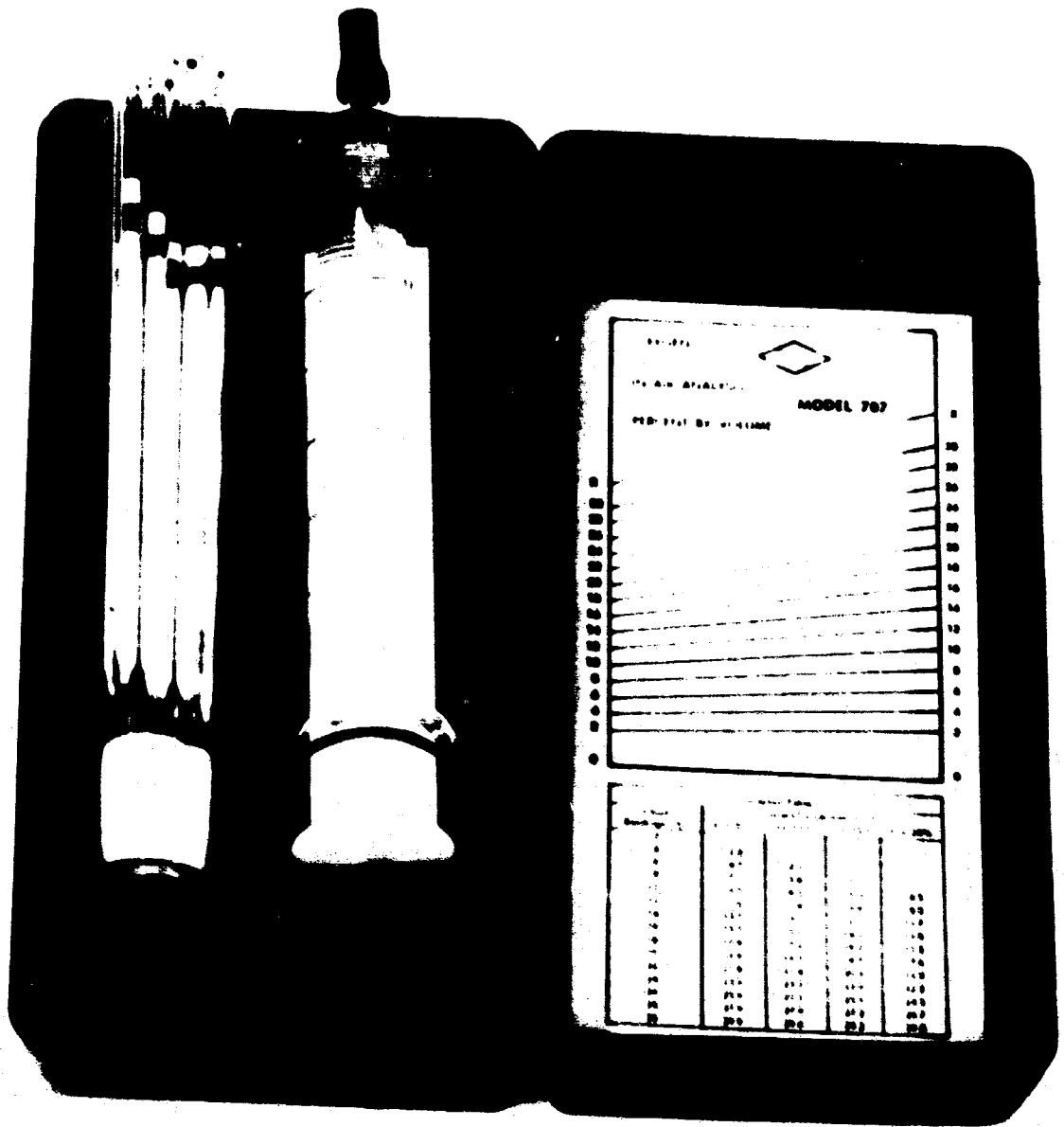


Fig. 16 OXYGEN ANALYZER (NO. 1)

With this detector oxygen in the range of 2% to 30% by volume can be accurately determined. The colorimetric tubes contain an oxygen sensitive reagent which is initially red in color but turns dark brown on contact with oxygen. The length-of-stain that is produced is proportional to the oxygen concentration. The shelf-life of these tubes is 3 years. A plastic syringe having a capacity of 50 ml is used to aspirate the air through the tubes.

To operate this detector, a 50 ml sample of the air is aspirated into the syringe. The ends of a colorimetric tube are broken off and one end quickly connected to the syringe. The air from the syringe is then expelled through the tube at a uniform rate of about 0.5 ml/sec so that the entire sample passes through in about 100 seconds. The tube is then disconnected and placed in a vertical position on the concentration chart which is supplied. The concentration of oxygen corresponding to the stain length is then read off.

If the ambient temperature is lower than 60°F or higher than 95°F the observed concentration has to be corrected to get the true concentration. A temperature correction table is provided.

4.3 Commercial Detectors for Hydrocarbons

Most of the hydrocarbon detectors are of the combustion type and indicate the presence of a hydrocarbon on a meter in terms of the lower explosion limit (L.E.L.), i.e., the lowest concentration of the gas that will burn in air. The readings are expressed as a percentage of the L.E.L. for the gas, the L.E.L. being 100%. The detectors are calibrated for one particular gas such as Pentane or Hexane and will give correct readings only for that gas. For other combustible gases the true reading is found from a graph which

gives the correct percentage of L.E.L. versus the observed meter readings. If the gas being measured is not known, the only information such a detector will give is that some combustible gas or gases are present. Since the toxic threshold limit value for most hydrocarbons is of the order of about 10% of L.E.L., any significant meter reading would immediately warn the shelterees of potential danger. Hence such a detector would be useful in a shelter. Instruments Nos. 1, 3 and 7 (Table 6) appear to be equally good and any one of these would be suitable for shelter use.

4.4 Shelter Air Composition (SAC) Sensor

A definite need exists for an inexpensive method for continuously monitoring carbon dioxide in both ventilated and sealed shelters. If the recommended colorimetric detectors are used to detect CO_2 , the monitoring will be only intermittent and the cost will be high (although still less than any of the other available detectors). For example, if it is assumed that conditions within a shelter would require checking for CO_2 during only 10% of the occupancy period of two weeks, i.e., 33.6 hours, and a test is run every half hour during this time, a total of 68 tests would have to be run. This would consume 68 detection tubes and at a price of 50¢ each would cost a total of \$34.00.

The Shelter Air Composition (SAC) sensor was contrived to reduce this cost. This sensor is an inexpensive method for continuously monitoring the CO_2 level by means of the length of a candle flame. With the help of this sensor, a continuous check on the environment can be maintained and the colorimetric gas detector used only when hazardous levels of CO_2 are

Table 6

Commercial Instruments for Detecting Hydrocarbons¹
(methane, ethane, benzene, gasoline vapors)

S/N	Item	Gas	Range ²	Type	Price \$	Remarks
1	Vaportester	all	0-100% L.E.L.	Combustion	105.00	Calibrated for natural gas
2	Ethane Detector	Ethane	0-100% L.E.L.	Combustion	395.00	
3	Explosimeter	all	0-100% L.E.L.	Combustion	100.00	
4	Combustible Gas Indicator	all	0-100% L.E.L.	Combustion	152.00	Provided with individual calibration for 5 gases
5	Gascope Indicator	all	0-100% L.E.L.	Combustion	157.00	Provided with dual scale.
6	Aromatic Hydrocarbon Detector	Benzene	0-100 ppm	Length of stain	45.00	Price of detector tubes: \$0.42/each
7	J-W Sniffor	all	0-100% L.E.L.	Combustion	100.00	
8	J-W Gas-Pointer	all	0-100% L.E.L.	Combustion	150.00	

¹ All instruments are intermittent in operation.

² L.E.L.: Lower Explosion Limit

approached. After appropriate remedial action has been taken and the CO_2 reduced to a safe level, the environment monitoring could be transferred back to the SAC sensor.

4.4.1 Description of Prototype SAC Sensor

The SAC sensor is based on the fact that the level of CO_2 and O_2 in an environment (Figs. 1 and 2) affects the length of a candle flame placed in that environment. As the level of CO_2 increases and the level of O_2 decreases the candle flame becomes shorter. Similarly as the level of CO_2 decreases and the level of O_2 increases the candle flame becomes longer. Thus the changing length of the candle flame is an indication of the combined level of CO_2 and O_2 in the shelter. This relationship is further simplified because the concentration of CO_2 is uniquely determined by the O_2 level in those shelters where CO_2 is produced only by human metabolism (Appendix). As a result it is possible to correlate the length of the candle flame with the CO_2 level. Thus, a CO_2 detector can be established by providing a scale that measures a candle's flame length in units of CO_2 concentration.

A prototype sensor using this concept is shown in Figs. 17 and 18. It consists of a candle, a base, a follower, a wire gauze chimney, and a scale.

The candle used in this sensor is a "standard candle" having a uniform burning rate. It is made of beeswax and is intended for photometric applications in instruments like the Jackson Water Turbidimeter and meets the American Public Health Association burning rate tolerance of 114 to 126 grains per hour. It is $13/16$ " dia. x $5-1/4$ " long and costs approximately 17¢ each.

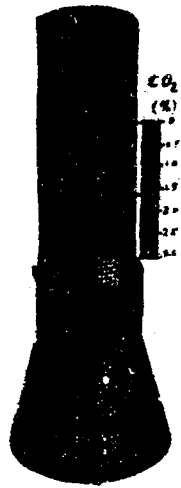


Fig. 17 PROTOTYPE MODEL OF SHELTER AIR COMPOSITION (SAC) SENSOR

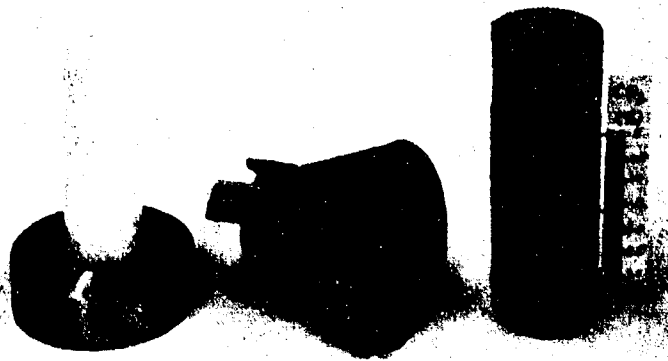


Fig. 18 COMPONENTS OF SAC SENSOR

Tests with other candles indicate that any homogeneous candle with a constant burning rate can be used in this sensor although a new CO_2 scale will have to be established for that particular candle.

The base is provided to support the candle vertically during operation and the follower is designed to ensure uniform burning of the candle. The follower is necessary because the wax surface just below the flame undergoes cyclic changes as the candle burns which produces cyclic changes of flame height. During burning without a follower, the wax surface melts forming a shallow crater which is followed by a deepening of the crater and finally by the collapse of the side walls that causes dripping of some wax down the candle length. This cycle is continuously repeated throughout the burning of the candle. The use of a follower eliminates this cycling and maintains a molten wax pool of constant depth and hence a constant flame length. To function properly, the follower must have the proper weight and angle, α , at which it rests on the candle (Fig. 19). This angle was established as 50° although commercially available followers are designed with angles of about 45° .¹⁷ When the 45° angle was used initially the follower was found to tip as it moved down the candle. Changing it to 50° stabilized the follower. The optimum angle must be empirically determined for a given candle diameter and follower weight. If the angle is too large, melted wax will accumulate at the top of the follower and drip down the side and produce non-uniform burning. On the other hand if the angle is too low, melted wax will accumulate inside the follower and solidify and prevent uniform motion of the follower down the candle. A ring collar is inserted at the base of the follower which clears the candle diameter by 0.010 inch to further insure

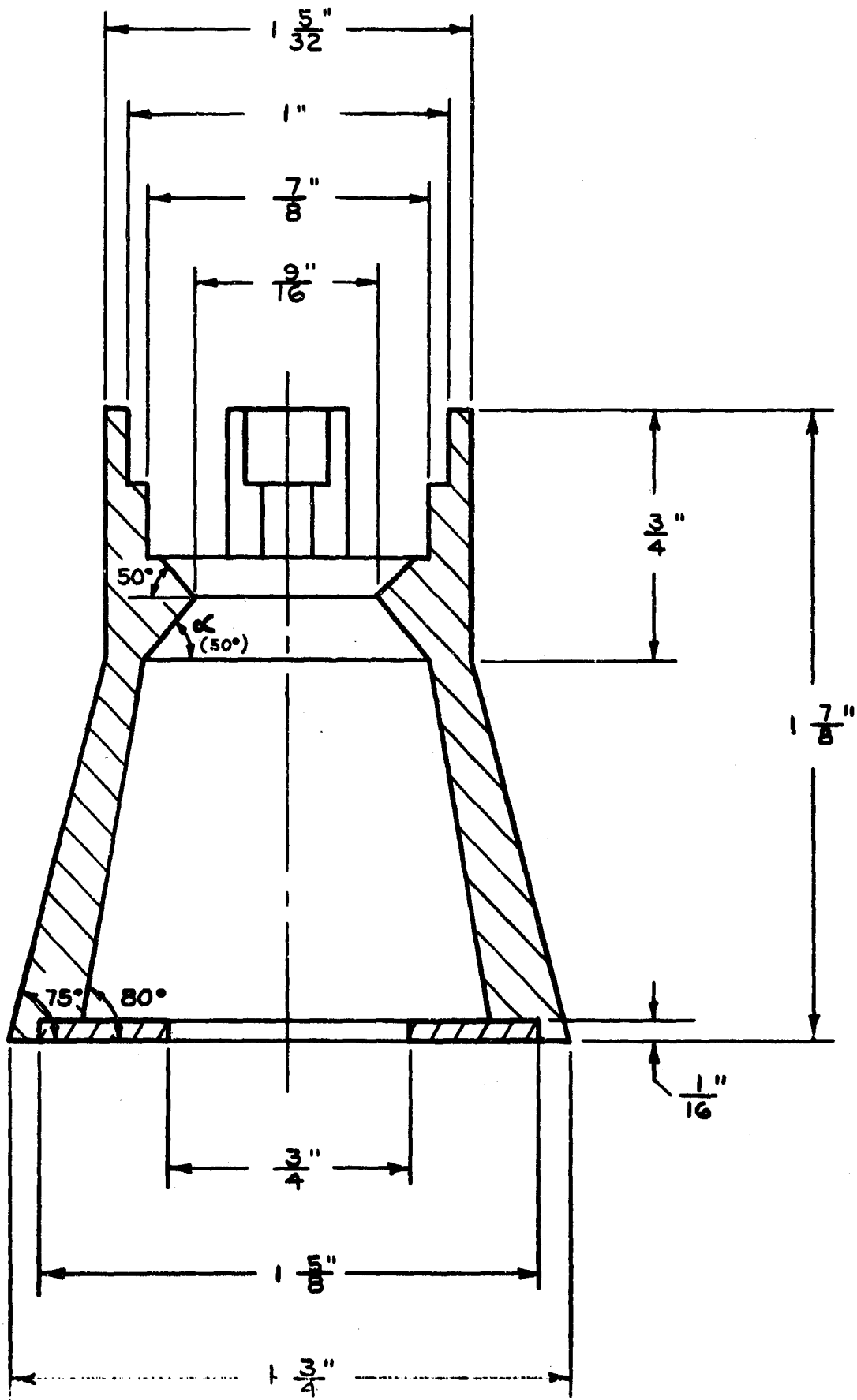


Fig. 19 CROSS-SECTIONAL VIEW OF FOLLOWER OF PROTOTYPE MODEL OF SAC SENSOR

that the longitudinal axis of the follower will coincide with the longitudinal axis of the candle.

The wire gauze chimney is provided to reduce the flame glare and make the flame length easier to observe. The CO₂ scale is calibrated to read flame length in terms of CO₂ level and is mounted on the wire gauze chimney. The follower provides the base for mounting the wire gauze chimney and the CO₂ scale.

4.4.2 Tests of the SAC Sensor

The SAC sensor was tested at one level of increased CO₂ and decreased O₂ to evaluate the flame length changes that can occur.* The check was made using air with 1.5% CO₂ and the corresponding 18.5% O₂ which are the terminal steady-state values of CO₂ and O₂ for a ventilation rate of 0.65 cfm/standard man. The concentration of 1.5% CO₂ was used in order that flame length changes between the altered air composition and normal air could be maximized. If the flame length at 1.5% CO₂ was found to be not sufficiently different from the flame length in normal air (0.03% CO₂), the SAC sensor could not be considered feasible as a CO₂ sensor. This concentration though three times the accepted industrial limit value of 0.5%, can be withstood by people for two weeks without changes in basic performance or physiological function and hence was not unreasonably high.¹⁸ Further tests with other concentrations of CO₂ will be required to completely evaluate the capabilities of the sensor.

*The test was restricted to only one level of increased CO₂ and decreased O₂ for lack of time and funds.

The test set-up consisted of the SAC sensor located in an open-topped plastic cylinder into which either normal air or the air with 1.5% CO₂ could be introduced from the cylinder base, passing around the candle and coming out at the top (Fig. 20). The plastic cylinder isolated the air about the SAC sensor from the rest of the air in the laboratory and thus established a controlled environment about the sensor. Preliminary tests showed that when normal air was passed through the cylinder, the flame length was identical to the flame length of the sensor when it was outside of the apparatus in the laboratory. Also it was found that the particular rate at which air flowed through the cylinder did not influence the flame length to any discernable amount for flow rates between 10 and 50 standard cubic foot per hour (scfh).

The possibility that variations in air humidity could effect the flame length was checked by bubbling air through water before it was introduced into the plastic cylinder. The saturated air produced the same flame length as dry air directly from the compressed gas cylinder in the case of both normal air and air with 1.5% CO₂.

The test itself was conducted in the following manner. First normal air from a compressed air cylinder was introduced at a flow rate of 35 scfh. After a few minutes when steady-state conditions had been reached, the flame length was measured and found to be 1-15/16" long. Next the air with 1.5% CO₂ was introduced at the previous flow rate and after steady-state condition had been reached the flame length was again measured. This time the length was found to be 1-3/16", a reduction of 3/4" in the flame length. The test was repeated several times to verify the reproducibility of the result. Four different

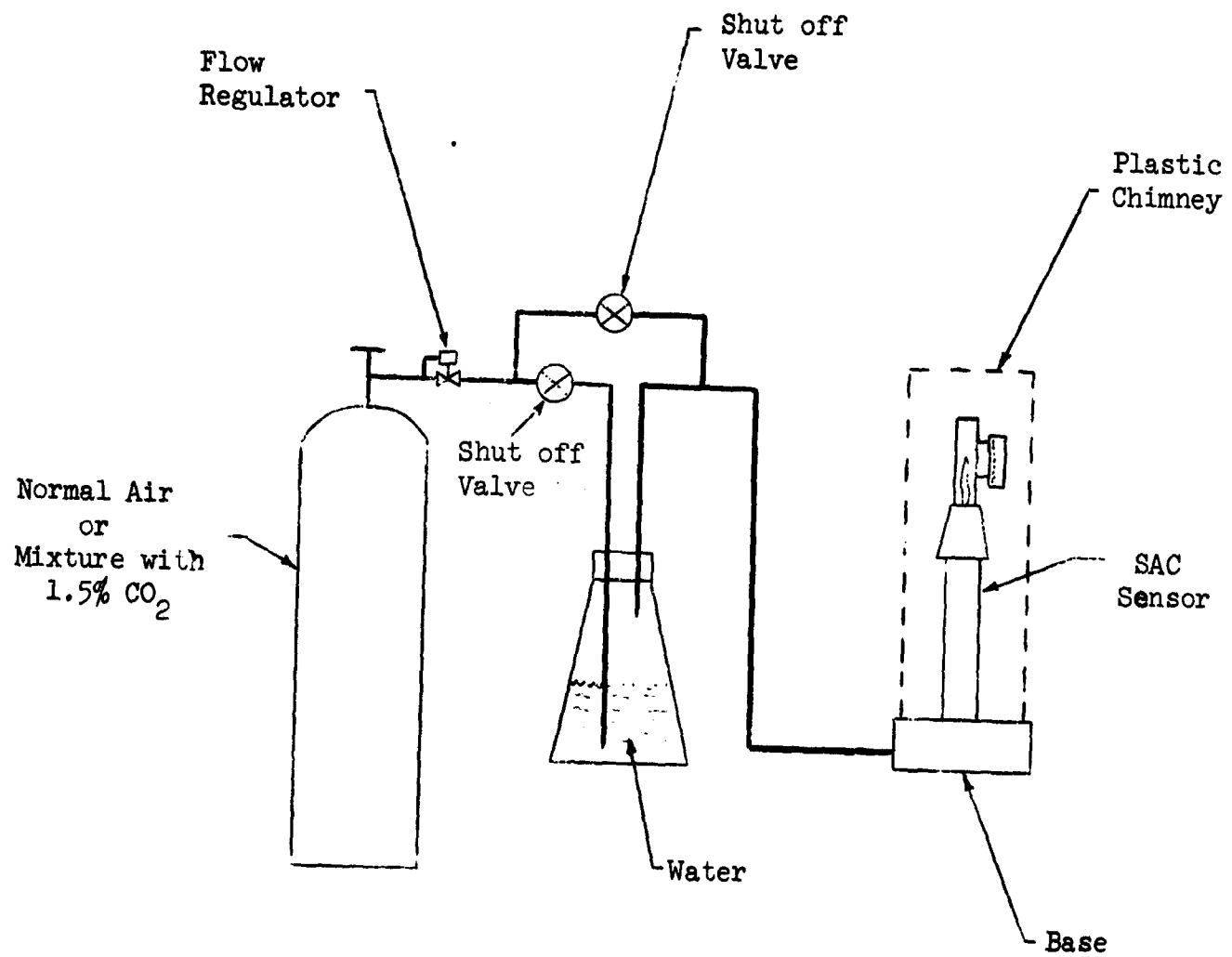


Fig. 20 SCHEMATIC OF SAC SENSOR TEST APPARATUS

observers repeated the entire test procedure to insure that the observations were not dependent upon the observer. The results agreed to within $\pm 1/16$ ".

It is felt that these test results confirm the technical feasibility of using a candle flame's length as a measure of the CO_2 level in a shelter. Further tests will have to be run to determine whether or not other values of CO_2 will produce flame lengths that are sufficiently different to allow the various CO_2 levels to be distinguished, i.e., to establish the sensitivity of the SAC sensor to CO_2 changes.

A candle $7/8$ " dia. x 12" long was found to be adequate for 10 hours. Assuming as before that conditions within a shelter would require the use of this sensor for 10% of the time a total of four such candles would be required. The cost of these candles together with the base, follower, wire gauze chimney and scale, if ordered in large quantities should not be more than \$2.00.

A device like this is recommended for use in shelters to indicate that the CO_2-O_2 levels are approaching dangerous levels.

SECTION 5

DISCUSSION OF SHELTER INSTRUMENTS

In the foregoing analysis emphasis was placed on the development or location of instruments for monitoring changes in the shelter environment. From this study it can be concluded that an instrument kit intended for stocking in shelters must contain instruments of the following type:

1. An effective temperature meter.
2. A carbon dioxide detector.
3. A carbon monoxide detector.
4. A detector for toxic hydrocarbons.

Detailed recommendations regarding these detection instruments cannot be made until the problem of controlling the environment in the shelter is also considered. This is because the choice of the control method that will be used in a particular shelter will determine the detection method which is best suited. A system approach to the environmental control problem is therefore necessary to establish the specifications and make proper selection of these instruments.

The adopted control method could be simple as in the case of small fallout shelters. Here the effective temperature and the internally generated carbon dioxide level can be controlled by merely altering the ventilation. Increasing the ventilation will reduce the ET and decrease the carbon dioxide concentration and vice versa. On the other hand in the larger sophisticated shelters the control system may be complex. Air conditioning may be necessary to maintain a reasonable thermal level and oxygen may have to be provided during periods of closed operation. Chemical systems may be required to control the level of carbon dioxide and toxic contaminants.

In shelters using simple control systems, relatively inexpensive detection devices may suffice. Shelters with complex control systems may require relatively accurate, reliable and hence expensive detectors. Thus the problem has to be looked at from a system standpoint before definite recommendations can be made regarding the detection instruments which should be stocked.

In addition to these instruments, other instruments may be required in shelters which are closely allied with the control system. For example, the Packaged Ventilation Kit (PVK) has a ventilation fan that is driven by a pedal crank which should be rotated between 45 and 60 rpm. Shelter tests conducted under contract OCD-PS-66-9 have shown that most people do not consistently maintain the rpm within this range.* This problem was corrected by installing an rpm indicator which costs less than \$3.00 per unit (Fig. 21). When the needle is maintained within a designated green area on the indicator face, the pedal crank is between 45 and 60 rpm. Tests of a PVK with this rpm indicator showed a marked improvement in PVK performance¹⁹. An instrument such as this should form part of an overall shelter instrument package. Only a system approach will uncover the need for all the instruments that are required in shelters.

*Unpublished results, Eight-day Shelter Test, Contract OCD-PS-66-9, OCD Work Unit 1522A.



Fig. 21 RPM INDICATOR MOUNTED ON PVK

SECTION 6

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Instruments for detecting hazardous conditions within shelters are only a partial answer to the overall problem of maintaining a safe environment within shelters. The other aspect of the problem is what can and should be done once the environment becomes hazardous or approaches hazardous levels. Among the problems which will have to be resolved are:

1. Methods for keeping the build-up of heat and humidity within a shelter due to the metabolic functioning of its occupants within reasonable limits.
2. Methods of supplying oxygen when closed shelter operation becomes necessary.
3. Methods for absorbing or eliminating toxic contaminants once they have entered the shelter.

At present some solutions are available for these problems but application of these solutions in detail to actual shelters remains to be done. Also the precise detection instruments to be used in a given shelter will be dictated by the control methods used; and hence a system approach must be applied to the environmental control problem before initiating any further investigation or development of detection instruments. This will ensure compatibility between the detection devices and the control method employed and will maximize the effectiveness of the environmental control.

The present study however indicates that the colorimetric ET meter and the SAC sensor are promising instruments and their further development should

be continued. The ET should be made easier to read, cheaper and stronger. The SAC sensor should be investigated thoroughly to determine its characteristics under different values of CO₂ and O₂, and evaluated for use in shelters during a live-occupancy shelter test. This work, nevertheless, should be preceded by the integrated environmental control study. After completion of such a study, detailed recommendations could be made regarding the instruments which should be stocked in each type of shelter to insure that minimum survival conditions are maintained during the entire period of occupancy.

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APPENDIX

CONCENTRATION OF CARBON DIOXIDE AND OXYGEN IN SHELTERS

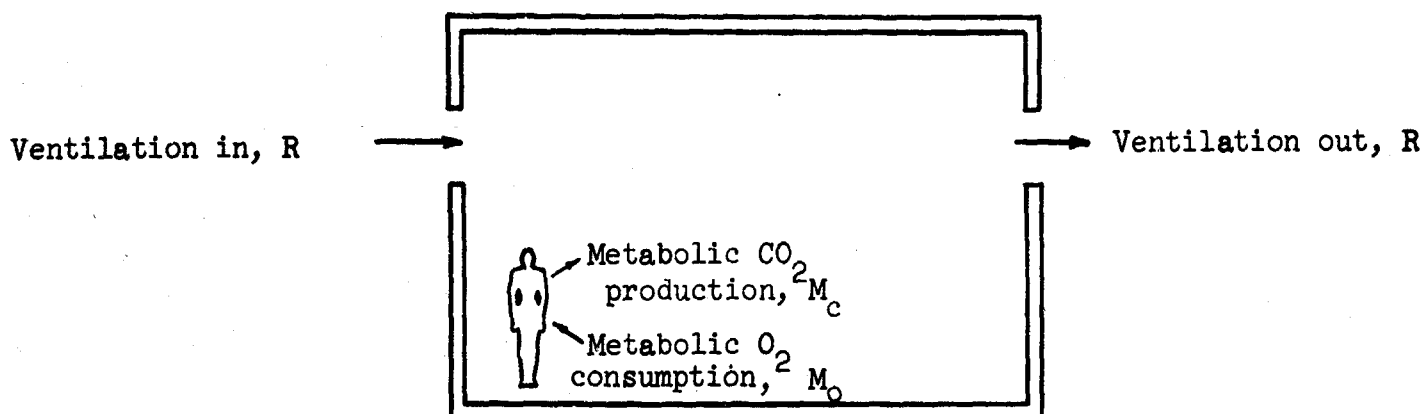


Fig. A-1 Shelter Model used in Analysis

Nomenclature:

- V = total shelter volume, ft^3
- N = total number of people in shelter
- $\bar{V} = \frac{V}{N}$
- R = ventilation rate, $\text{ft}^3/\text{hr}/\text{person}$
- M_c = metabolic production rate of CO_2 , $\text{ft}^3/\text{hr}/\text{person}$
- M_o = metabolic consumption rate of O_2 , $\text{ft}^3/\text{hr}/\text{person}$
- x = volume of CO_2 in shelter at time t , $\text{ft}^3/\text{CO}_2/\text{ft}^3$ air
- x_1 = initial volume of CO_2 in shelter, $\text{ft}^3 \text{CO}_2/\text{ft}^3$ air
- \bar{x} = volume of CO_2 in ventilation air, $\text{ft}^3 \text{CO}_2/\text{ft}^3$ air
- y = volume of O_2 in shelter at time t , $\text{ft}^3 \text{O}_2/\text{ft}^3/\text{air}$
- y_1 = initial volume of O_2 in shelter, $\text{ft}^3 \text{O}_2/\text{ft}^3$ air
- \bar{y} = volume of O_2 in ventilation air, $\text{ft}^3 \text{O}_2/\text{ft}^3$ air

It is required to show that for any ventilation rate, the concentrations of carbon dioxide and oxygen within a shelter are related to each other and for a given value of CO_2 one and only one value of O_2 exists.

In the analysis the following assumptions are made:

1. The incoming ventilation air is thoroughly mixed with the shelter air prior to exhaust.
2. Air leaves the shelter at the same rate as it enters the shelter.
3. Carbon dioxide is produced and oxygen consumed only metabolically.

If the concentration of CO_2 in the shelter changes by Δx in time Δt , we have the following:

$$(x + \Delta x)V = xV + \bar{x}R \Delta t + M_c N \Delta t - (x + \Delta x) R \Delta t$$

$$\frac{\Delta x}{\Delta t} = \frac{\bar{x}R + M_c}{\bar{V}} - (x + \Delta x) \frac{R}{\bar{V}}$$

$$\lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \lim_{\Delta t \rightarrow 0} \frac{\bar{x}R + M_c}{\bar{V}} - \lim_{\Delta t \rightarrow 0} (x + \Delta x) \frac{R}{\bar{V}}$$

$$\text{thus } \frac{dx}{dt} + x \frac{R}{\bar{V}} = \frac{\bar{x}R + M_c}{\bar{V}}$$

$$\text{Now with } x = A e^{\lambda t} + \frac{\bar{x}R + M_c}{R}$$

$$\lambda = - \frac{R}{\bar{V}}$$

$$\text{and } x = A e^{-\frac{R}{\bar{V}}t} + \left(\bar{x} + \frac{M_c}{R}\right) \tag{1}$$

But when $t = 0$, $x = x_1 = \bar{x}$, thus

$$A = - \frac{M_c}{R} \tag{2}$$

Substituting (2) in (1)

$$x = \bar{x} + \frac{M_c}{R} - \frac{M_c}{R} e^{-\frac{R}{\bar{V}}t} \quad (3)$$

which is the equation for the concentration of CO_2 at time t .

It can similarly be shown that for oxygen:

$$y = \bar{y} - \frac{M_o}{R} + \frac{M_o}{R} e^{-\frac{R}{\bar{V}}t} \quad (4)$$

Now from equation (3)

$$e^{-\frac{R}{\bar{V}}t} = \frac{R}{M_c} \left(\bar{x} + \frac{M_c}{R} - x \right) \quad (5)$$

Substituting (5) in (4)

$$y = \bar{y} + \frac{M_o}{M_c} (\bar{x} - x) \quad (6)$$

Thus, in a shelter with metabolic consumption and production of O_2 and CO_2 respectively, the values of O_2 and CO_2 are uniquely related and independent of the ventilation rate.

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