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AIRCREW AND PASSENGER PROTECTIVE BREATHING EQUIPMENT STUDIES

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16. Abstract

This document represents a collection of various reports concerning the protective capability of passenger and crew oxygen breathing equipment and specialized devices and concepts against smoke and toxic gases produced by aircraft fires.

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AIRCREW AND PASSENGER PROTECTIVE BREATHING EQUIPMENT STUDIES

INTRODUCTION

This is a collection of reports of various studies and evaluations of the protective capability against smoke and toxic gases produced during an aircraft fire of current crew and passenger oxygen systems primarily designed for high-altitude and decompression emergencies. These studies were in general designed and oriented toward (i) obtaining answers to particular questions or problems posed by Governmental approval authorities or the aviation industry with respect to the life-support capability of a given device or procedure and/or (ii) advancing the state-of-the-art in protection of crew and passengers from the toxic byproducts of combustion produced in aircraft fires. Certain of these reports were presented at scientific meetings and/or published in preprints of proceedings with limited distribution while others consist of preliminary memorandum reports for internal use and may contain theoretical material requiring additional testing and evaluation for validation of concepts and/or procedures. Information contained in these reports is subject to additional evaluation or change on review of the data, conduct of additional testing, or receipt of additional facts.

SYNOPSES OF REPORTS

The Use of n-Pentane as a Tracer Gas for the Quantitative Evaluation of Aircrew Protective Breathing Equipment, presented at the Survival and Flight Equipment Association Symposium, 1976.

> This report describes a technique developed by the authors for quantitatively determining the performance of protective breathing equipment. Subjective evaluation previously used to evaluate aviation protective breathing equipment employing substances such as tear gas or isoamyl acetate are questionable because of variations among individuals in motivation, ability to detect stimuli, ability to repeatedly detect the same level of stimuli, and ability to describe stimuli. Employing a nonirritating nontoxic substance as a tracer or challenge gas, quantitatively analyzed by gas chromatography, and utilizing multiple discrete sampling, we developed a sensitive and accurate technique. This method yields numerical information that may be readily plotted as a function of time by minicomputer.

The Objective Evaluation of Aircrew Protective Breathing Equipment: I. Oxygen Mask/Goggles Combination.

> Operational rules require flight deck crews of large pressurized turbine-powered transport aircraft operating above 25,000 ft be provided specific types of oxygen equipment in the event of decompression. The equipment must be connected to the aircraft oxygen supply and be readily available to the crew. Although several alternatives are allowed, the general mode of compliance is to equip the aircraft with a quick-donning mask that is connected to a demand or pressure-demand regulator and

capable of being donned in less than 5 s. Because of the possibility that smoke and products of combustion from in-flight fires, toxic fumes from leaking cargo containers, or carbon dioxide from fire-extinguishing systems (including dry ice utilized in frozen food shipments) might enter the flight deck, protective breathing equipment must also be provided. Because respiratory protection is required in both of the above conditions, the use of the oxygen mask as a protective breathing device would appear logical, provided provisions are made to protect the visual processes. The general approach has been to utilize the flight deck crew oxygen mask for respiratory protection and add vented or nonvented goggles to protect the visual processes. This report describes the testing and evaluations of 118 mask/goggles combinations utilized or proposed to protect the wearer against the introduction of contaminants into the respiratory and visual compartments.

The Objective Evaluation of Aircrew Protective Breathing Equipment: II. Fullface Masks and Hoods.

Fullface masks are employed for specific functions aboard large transports. These include fullface masks connected to portable oxygen cylinders located on the flight deck for use by crewmembers to investigate and/or fight fires in aircraft compartments remote from the flight deck. These masks may also be located in isolated separate compartments, such as upper or lower lobe galleys, in which crewmember occupancy is allowed during flight. Their effectiveness in the event of a rapid decompression is limited because of the relatively large dead space that must be washed out by oxygen before effective protection is achieved. This report describes the testing and evaluation of 17 fullface masks and two hoods for their capability to protect the wearer against the introduction of contaminants into the combined respiratory-visual compartment.

An Assessment of Protective Breathing Devices for Use by Flight Attendants.

Federal Aviation Regulations Part 25 (Airworthiness Standards: Transport Category Airplanes 25.1439 Protective Breathing Equipment, Amendment 25-38, effective February 1, 1977) requires that protective breathing equipment be installed in each isolated separate compartment in the airplane, including upper and lower lobe galleys in which crewmember occupancy is allowed during flight. In addition, sufficient protective breathing equipment must be provided during flight for the maximum number of crewmembers expected to be in the area during any operation. These areas are primarily the duty stations of the flight attendants, both male and female, with the female flight attendants numerically predominating. Since the Paris-Varig accident, many European airlines have provided protective breathing devices for all flight attendants, regardless of their assigned duty stations. Fullface oxygen masks connected to a portable oxygen cylinder are most frequently utilized to comply with this requirement. More recently, however, hood-type devices supplied by portable oxygen cylinders or chemical oxygen generators have been developed. This study was directed to evaluating the contaminant protective capability of 10 fullface masks and two hoods which are being used or are proposed for use by flight attendants.

Use of Passenger Oxygen Masks on Air Carrier Aircraft During Smoke/Fire Conditions in the Cabin, Memorandum Report AAC-119-74-2(S).

This memorandum report was prepared in response to a proposal to utilize the passenger oxygen system for smoke protection. The passenger oxygen system of a modern jet transport, the basic breathing requirements of the user, and the characteristics of the oxygen system design in meeting these requirements for high-altitude life support are generally not well understood. This report points out the inadequacies of the current passenger system, which was originally designed solely for high-altitude protection, to provide the passenger protection from smoke and toxic gases. It does, however, point out several theoretical modifications of the passenger oxygen system to possibly render it capable of providing smoke as well as high-altitude protection. Although several preliminary exploratory experiments indicate that these modifications are feasible, considerable additional research and testing into the many facets of the problem are required before these theoretical modifications can be shown to be practical and worthy of implementation.

THE USE OF n-PENTANE AS A TRACER GAS FOR THE QUANTITATIVE EVALUATION OF AIRCREW PROTECTIVE BREATHING EQUIPMENT

D. deSteiguer,* E. B. McFadden,* M. S. Pinski,* and J. R. Bannister**

INTRODUCTION

Various types of oxygen masks and regulators have been carried aboard transport category aircraft to provide breathing oxygen to flightcrews in the event of cabin pressurization loss. The oxygen masks must be connected to the aircraft oxygen supply, be readily available to the crew, and be capable of being donned in less than 5 s (1). Technical Standard Order (TSO) C78, Part 37 of the Federal Aviation Regulations (2), defines the minimum performance standards for crew oxygen masks and certain testing requirements to demonstrate acceptable performance by these masks.

Because of the possibility that smoke and other combustion products from in-flight fires or toxic fumes from leaking cargo containers might enter the flight deck, the flight deck crew must also be provided protective breathing equipment (1). This equipment must include a mask covering the eyes, nose, and mouth (fullface mask or hood) or a mask covering the nose and mouth together with accessory equipment that covers the eyes (mask/goggles combination). Since specific performance standards and testing requirements for protective breathing equipment have never been defined, subjective evaluations have been used in granting approvals for this equipment. Two

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recent cases, Pan American World Airways, Inc., Boston, Massachusetts, November 3, 1973 (3), and Federal Express, Atlanta, Georgia, October 10, 1975 (4), have demonstrated problems with the effectiveness of the protective breathing equipment that was carried aboard the respective aircraft.

Several procedures have been used in recent years for the subjective evaluation of protective breathing equipment. Of these procedures, the most widely used have depended on the ability of a subject to detect tear gas or isoamyl acetate while wearing protective equipment in the respective environments. Subjective evaluations of this type are questionable because of variations among individuals in their motivation, ability to detect stimuli, ability to repeatedly detect the same level of stimuli, and ability to describe stimuli.

If quantitative methods are used, nonirritating substances may be used as the tracer or challenge gas. This approach allows for repeated use of a subject pool and is particularly useful if several different shapes and sizes of masks are to be tested on similar faces. Instrumental methods give numerical values and, in combination with continuous sampling or with multiple discrete samples, allow plotting of concentration change as a function of time. Consequently, additional test parameters such as communications may be included in a program to gain additional information.

To avoid the pitfalls of subjective testing, methods have recently been developed for the quantitative evaluation of industrial respirators, self-contained devices, and other types of protective breathing equipment. One method was developed by using Freon gas as the tracer (5); however, exposures to high concentrations of Freon could produce adverse effects. Methods using dioctyl phthalate (DOP) for the challenge atmosphere have been developed (6); however, continuous sample rates as high as 8 L/min have been used. Sample rates of this magnitude are excessive when goggles (with a volume of approximately 200 to 800 ml) are to be tested as a component of a mask/goggles combination. A sodium chloride solid aerosol method has been used by some workers (7); however, the high solubility of sodium chloride in water could cause erroneous results. Two methods using mass spectrometers have been developed, one using argon as a tracer (8) and the other using helium (9). While these methods are useful for testing devices that have a large internal volume or a high flow rate (as in self-contained breathing devices or fullface masks), the sample rates are excessive when the volumes of various types of goggles are considered. n-Pentane has been used as a tracer for testing hoods (10). This method appeared to be useful for testing protective breathing devices because the problems of high concentrations and large samples could be readily overcome.

METHOD

Tracer Gas Selection. n-Pentane (C_5H_{12}) was selected as a tracer or challenge gas for the objective evaluation of protective breathing equipment after consideration of the following: (i) Pentane is a gas and not a solid or an aerosol; (ii) pentane has a molecular weight of 72 and is in the range of many known products of aircraft fires (Table 1); (iii) pentane, with a

threshold limit value of 500 ppm, is not considered toxic at low concentrations (11); (iv) pentane is not irritating to the subject; (v) pentane does not require the specific handling procedures or work areas that could be required by irritating products; and (vi) very small amounts of pentane can readily be analyzed with a gas chromatograph.

TABLE 1. Comparison of Molecular Weights of a Number of Common Combustion Products Produced in Aircraft Fires

Combustion Product	Molecular Weight
Hydrogen fluoride	20.0
Hydrogen cyanide	27.0
Acetonitrile	41.0
Sulfur dioxide	64.1
Phosgene	98.9

General Approach: The general analytical method developed for the use of pentane in testing protective breathing equipment is diagrammed in Figure 1. A simple exposure chamber of sufficient size to accommodate a subject and the equipment to be tested was used to contain the challenge atmosphere. Small needles were inserted into the protective breathing device to provide for the collection of gas samples from specific locations within the device. Small-bore flexible tubing, passed through the chamber wall, connected the sample needles to a selector valve located outside the chamber. The sample gas was drawn through a twin-loop collector valve, where a known aliquot was collected and delivered to a gas chromatograph equipped with a hydrogen flame ionization detector.

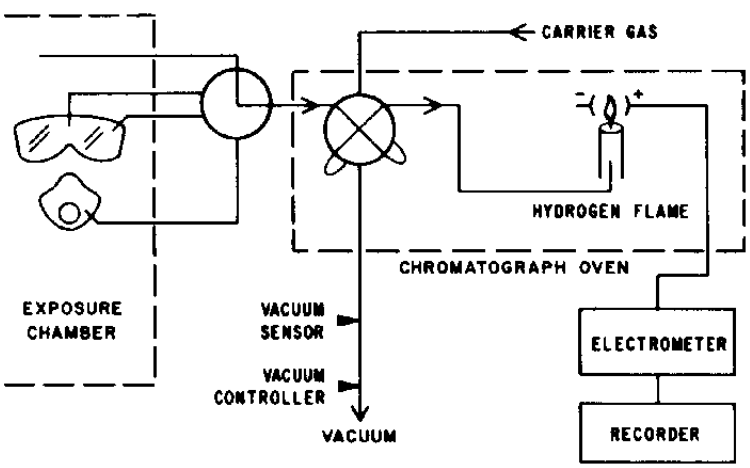


FIGURE 1. Analytical flow diagram for testing protective breathing equipment.

Detailed Test Procedure: An exposure chamber of 85 ft^3 was fabricated from plywood and plexiglass. To provide for observation of the subject, large plexiglass panels were incorporated into three walls of the chamber. A large, quick-opening door provided access to the subject. A small vent prevented the development of any pressure differentials between the chamber and ambient air.

The chamber interior was equipped with a 6-in blower to maintain a uniform mixture of pentane and air and with an "explosion proof" speaker for the transmittal of instructions to the subject.

Two thermistor-type temperature detectors designed for use in air environments were mounted at two levels within the chamber. A multichannel digital voltmeter/printer recorded the temperatures each minute. The barometric pressure was recorded from a mercury barometer.

A variable-speed, syringe-type infusion pump was used to control the infusion of pentane into the chamber. An initial rapid infusion rate (1.36 ml/min) was used to establish the desired concentration of 120 ppm of pentane, and then a slow infusion rate (0.068 ml/min) was used intermittently to maintain the desired pentane concentration.

"Aviator's breathing oxygen" (or air of comparable purity) was supplied to aircraft oxygen regulators located inside the chamber, where they were accessible to the subject. The supply cylinder was positioned on a sensitive high-capacity balance. Weight difference was used to compute the oxygen requirements (cylinder drainage) for each test.

A Bendix MD-1 aircraft regulator was used to control the delivery of oxygen to those test items that were designed to mate with panel-mounted regulators. For those test items equipped with mask-mounted regulators, a Robertshaw accessory control panel was used.

When "aviator's breathing oxygen" was supplied to the test equipment, safety precautions were taken to control the increase of oxygen within the chamber. The nitrogen concentration within the chamber was monitored continuously with a Med-Science Model 505 Nitralyzer. Since carbon dioxide buildup was nil, the oxygen concentration was considered as 100 minus the percentage of nitrogen. Cylinders of compressed air were connected, through flowmeters, to the chamber to provide vent air. The rate of venting was adjusted to compensate for increases in the oxygen concentration. Testing was immediately terminated if the oxygen concentration within the chamber reached 40 percent.

Small stainless steel needles (21 gauge x 25-mm long) were inserted through the facepiece of each test item for collecting gas samples. The needles were retained in place by the use of sleeves made from 0.02-in inner diameter (I.D.) plastic tubing. Each set of goggles was prepared with two needles, each oxygen mask was prepared with one, and fullface masks and hoods were prepared with three (corresponding to the mask/goggles combination of three sample ports).

Flexible plastic tubing (0.02 in I.D.) was passed through ports in the chamber wall, and it connected the needles to inlet tubes of a selector valve. The flexible tubes were of sufficient length to allow for head movement by the subject.

A microvolume rotary selector valve (Carle Instruments) having four inlet positions and one delivery position was used to select the location from which a gas sample was drawn at any given time. During testing the selector valve was

rotated every 15 s, thus providing a sample sequence of chamber, side of goggles, top of goggles, and mask cup (or equivalent positions for fullface masks and hoods). This provided for one discrete pentane measurement from each sample location once each minute during each 15-min test (Figure 2).

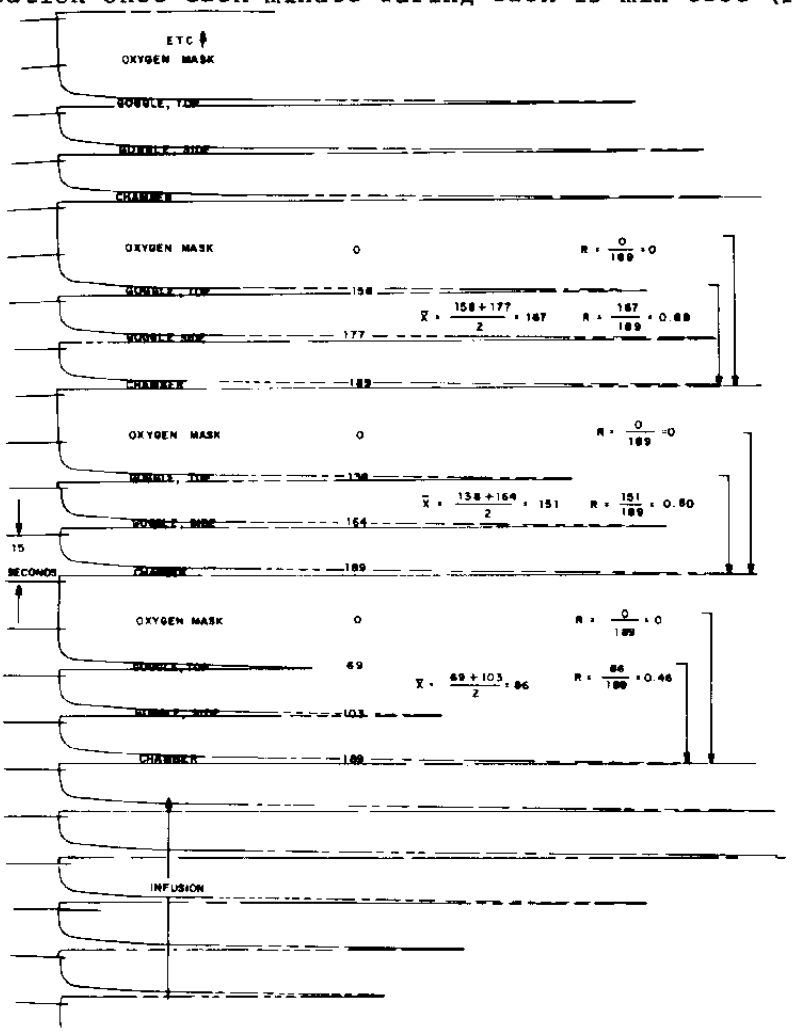
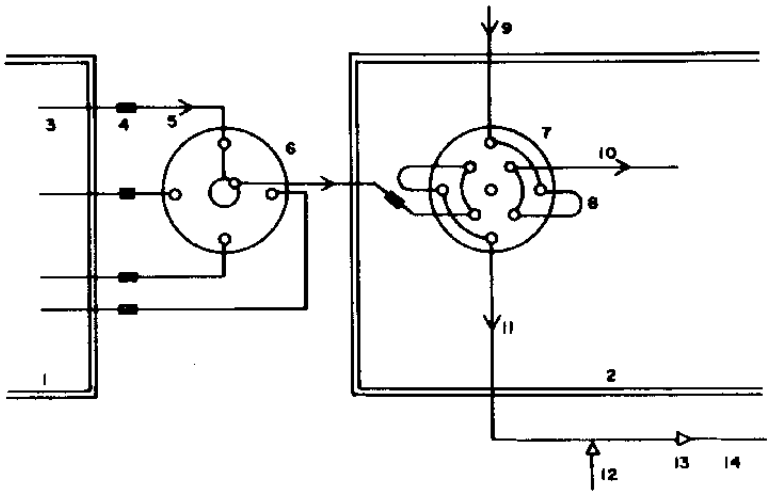


FIGURE 2. Typical data recording.

The selector valve was connected to a microvolume collector valve (Carle Instruments) having two matched sample loops of 50 microliters each. Every 15 s the collector valve was pneumatically actuated and cycled simultaneously with the rotation of the selector valve. The collector valve was designed to have one sample loop connected to the column inlet of the gas chromatograph to deliver the 50-microliter sample for analysis, while the opposite sample loop was being charged with a new sample from the device being tested (Figure 3).

A slight, negative differential pressure was used to transfer a gas sample from the device being tested, through the connecting tubing and selector valve, to the collector valve. The pressure differential was maintained at 12 mmHg with a double-pattern micrometering valve (Nupro). The pressure differential was monitored with a differential pressure transducer coupled to a numerical display. This display also indicated that all sample tubes were unobstructed and that the selector and collector valves were properly seated after each rotation (Figure 3).



LEGEND

1--exposure chamber	8--sample loop
2--gas chromatograph	9--carrier gas
3--flexible tubing	10--chromatograph column
4--junction fitting	11--vacuum line
5--stainless steel tubing	12--vacuum sensor
6--selector valve	13--vacuum control valve
7--collector valve	14--vacuum source

FIGURE 3. Sample collection diagram for testing protective breathing equipment.

A gas chromatograph equipped with a hydrogen flame ionization detector (Perkin-Elmer Model 800 or, alternately, a Hewlett-Packard Model 4730A) was used to quantitate the pentane concentration in each sample. Because of detector design and configuration, the Perkin-Elmer chromatograph was operated in the dual-column mode but the Hewlett-Packard chromatograph was operated in the single-column/detector mode. The chromatograph columns were stainless steel, 0.023 in I.D. x 10 in long, and were maintained at 110°C within the chromatograph oven. Hydrogen and airflow rates to the detectors were adjusted to give maximum sensitivity for pentane. Dry nitrogen, at a flow rate of 14 ml/min, was used as the carrier gas. Detector response vs. pentane concentration was linear for both instruments (Figure 4). As retention time was constant, peak height was used as the quantitative measure.

Contaminant ratios for the test items equipped with one sample port (mask) were calculated by dividing the peak height for that sample by the peak height of the immediately preceding chamber sample. For the test items with multiple sample ports (goggles, fullface masks, and hoods), contaminant ratios were calculated by dividing the mean peak height for that item by the immediately preceding chamber sample (Figure 2). The ratios for a given item (or component) were then plotted vs. sample number (time) (Figures 5 and 6). The mean contaminant ratio for a given item (or component) was then calculated.

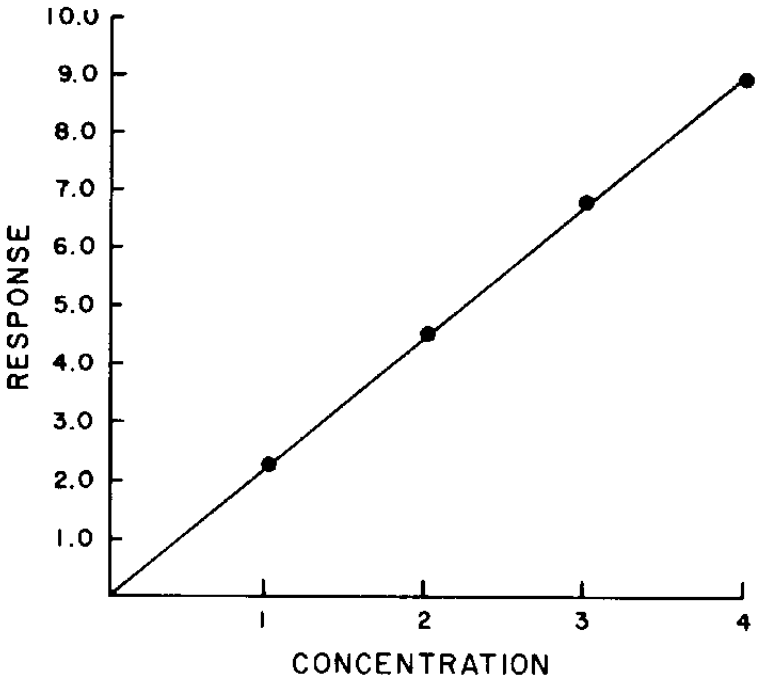


FIGURE 4. Analytical response vs. pentane concentration.

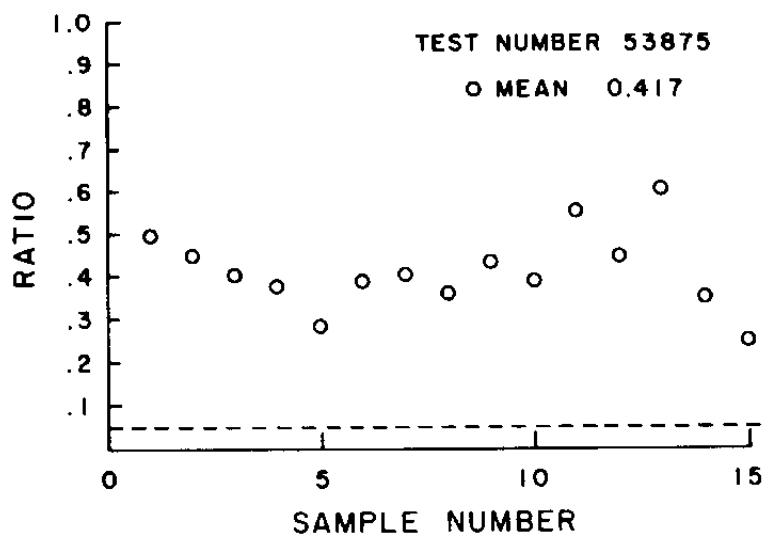


FIGURE 5. Typical data plot for a fullface mask.

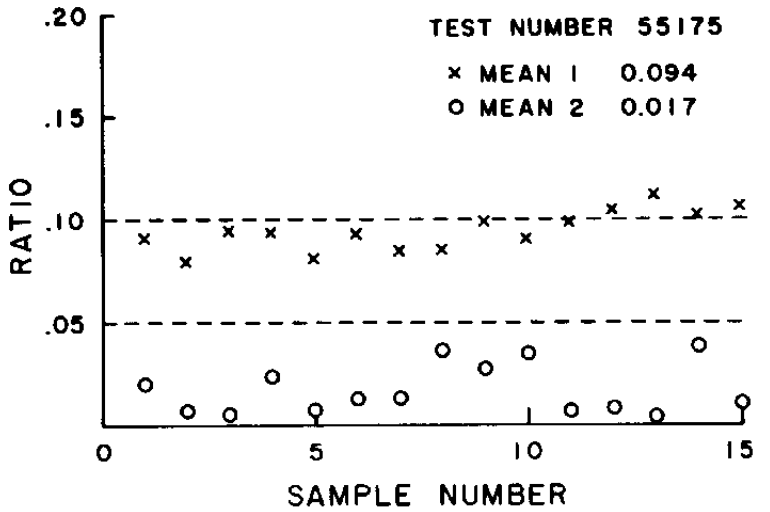


FIGURE 6. Typical data plot for a mask/goggles combination (mask--o; goggles--x).

Data reduction was accomplished by using a Hewlett-Packard Model 9820 programmable calculator connected to a digitizer (Model 9864A), a cassette memory, and an XY plotter. The chromatograph recording was positioned on the digitizer where the peak heights were quantitated and transferred to the calculator. The calculator was used to control the accessories, complete the required computations, and store and transfer data. All data were transferred to the cassette memory for storage while data summaries were plotted on the XY plotter.

Operational Procedures: A restricted randomization design was used to select the test item and subject for any given test. Each subject was fitted with a pair of noncorrective eyeglasses having plastic frames (American Optical Corporation No. F9848SM). The test item was donned by the subject and initial equipment adjustments were made. Considerable assistance was given the subject during the donning procedure to insure optimal fit. The controlling regulator was then set to the emergency pressure setting for leak testing and final adjustments and then was returned to the normal setting. The oxygen cylinder was then weighed, the subject was given final instructions, and the chamber was closed.

Immediately prior to the infusion of pentane into the chamber, the subject was instructed to set the controlling regulator to the emergency pressure setting (for those items designed to accept positive pressure) and a timer was actuated. A rapid infusion of pentane was used to establish the desired concentration of approximately 120 ppm. The concentration of pentane was monitored with the chromatograph and the 15-min test was started after a uniform air/pentane mixture had been obtained. Head movements simulating those of a flight deck crewmember were included throughout the entire test interval. A 5-min period of communication by the subject was included to test for possible

effects of facial movements on the performance of the item. On completion of the 15-min test, the subject was instructed to set the controlling regulator to the normal position and the time was noted. The oxygen cylinder was weighed and the cylinder drainage computed and normalized to 15 min.

SUMMARY

A method is presented for the objective evaluation of protective breathing equipment that used n-pentane as a tracer gas and a gas chromatograph, equipped with hydrogen flame ionization detectors, as the analytical instrument. This method provided a nontoxic, nonirritating test environment for the subject. Contaminant ratios as low as 0.01 were detected without changes in instrument attenuation. The use of electronic integration would allow for increases in sensitivity.

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THE OBJECTIVE EVALUATION OF AIRCREW PROTECTIVE BREATHING EQUIPMENT: I. OXYGEN MASK/GOGGLES COMBINATIONS

D. deSteiguer,* M. S. Pinski,* J. R. Bannister,** and E. B. McFadden*

INTRODUCTION

Various types of oxygen masks have been carried aboard aircraft to provide breathing oxygen to flightcrews. With the increase in routine flight altitudes to 40,000 ft and the concurrent improvement in cabin pressurization systems, flightcrews have relied on oxygen equipment for protection required in the event of decompression rather than for routine flight use. However, the oxygen equipment must be connected to the aircraft oxygen supply, be readily available to the crew, and be capable of being donned in less than 5 s (1). Because of the possibility that smoke and products of combustion from in-flight fires or toxic fumes from leaking cargo containers might enter the flight deck, the flight deck crew must also be provided with protective breathing equipment (1).

Because respiratory protection is required in both of the above conditions, the use of the oxygen mask as a protective breathing device would appear logical, providing provisions are made to protect the visual processes. The air carriers have taken the approach of utilizing the crew oxygen mask for protecting breathing processes and adding goggles to provide visual protection. This approach reduces the number of emergency items present on the flight deck and the inherent problems of maintenance, inventory, training, cost, and added weight to each aircraft.

Problems encountered with the combination (oxygen mask/goggles) are: (i) the fit of the goggles to the outside surfaces of the oxygen mask; (ii) mating the goggles with the suspension system of the oxygen mask; (iii) the possibility of incompatible mask/goggles combinations because of the large variety of both items; (iv) fitting a wide variety of facial contours with a standard size and shape of mask and goggles; (v) the requirement that the protective equipment function for an individual wearing corrective eyeglasses (1); (vi) the possibility of having to provide the goggles with internal positive pressure or venting as a means to purge and control inbound leakage around eyeglass

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frames, mask/goggles and goggles/face interfaces; and (vii) the possibility that, once donned by a crewmember, the protective equipment will cause displacement of corrective eyeglasses.

The manufacturers and users of oxygen and protective breathing equipment submitted 18 types of oxygen masks and 16 types of goggles for testing. Because of the large variety of items submitted and the required level of effort to test every possible mask/goggles combination, systematic criteria were used to select the test items. For a combination to be included in the testing, a specific request from industry was necessary. A particular mask equipped with a mask-mounted regulator was considered to be a different test item from the same mask connected to a panel-mounted regulator. Goggles submitted with different attachment locations for the suspension system were considered to be separate test items. Variations such as hose length and microphone fittings were disregarded.

After these selection criteria were applied, 118 mask/goggles combinations were identified for testing. Of these combinations, 54 were masks in combination with unvented goggles and 64 were masks in combination with vented goggles (goggles equipped with venting tubes or in combination with masks that were equipped with venting valves). Nine mask/goggles combinations were designed to operate in the 100-percent oxygen mode while the remaining 109 were designed to accept 100-percent oxygen with positive pressure.

For this test series, a combination was acceptable if a mean contaminant ratio of less than 0.1 (10%) for the goggles and, simultaneously, 0.05 (5%) for the mask was maintained in 10 of 12 individual tests. If a combination failed any 3 of the 12 tests, it was eliminated from further testing.

METHOD

Each set of goggles was prepared by inserting two small stainless steel needles (21 gauge x 25-mm long) through the goggle facepiece and as close to the lens as possible. The location of the two needles (Figure 1) was selected to provide sampling from the lowest anticipated level of contaminant (the center location) and the highest level of contaminant (the outer edge). The needles were retained in place by the use of sleeves made from 0.02-in I.D. plastic tubing. Each oxygen mask was prepared by inserting one needle through the facepiece (Figure 2).

Of the 12 trained male subjects (35 to 55 yr old) that participated in the test program, 8 were pilots. Selected anthropometric measurements were taken for each subject (Table 1) and were generally compatible with corresponding data from military personnel (2).

A restricted randomization experimental design was chosen to distribute the testing of each manufacturer's product throughout the test program. In addition, this design was selected to reduce the effects of a subject's first exposure to a test item and to minimize long-term effects, such as seasonal changes and subject weight changes.

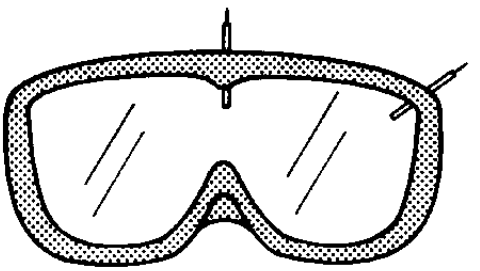

FIGURE 1. Location of the sample needles in goggles.

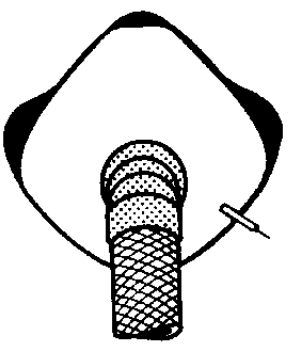

FIGURE 2. Location of the sample needle in oxygen masks.

Nonexaggerated eyeglasses were worn by all subjects during the leak testing. American Optical Corporation frames F9848SM, ranging in size from 46 x 20 mm to 48 x 22 mm, with plano lens were used.

The mask/goggles combination to be tested was connected to the appropriate regulator, and the regulator inlet pressure was adjusted to 100 psig. Immediately prior to a given test, the subject was fitted with the test item; then, for those items designed to accept positive pressure, the test item was leak tested with the controlling regulator set to the emergency-mode position. The regulator was then returned to the normal setting and the oxygen cylinder was weighed. The gas sample tubes were then connected to the appropriate needles previously fitted into each test item. The exposure chamber was then closed and a 15-min test was conducted (3).

TABLE 1. Selected Anthropometric Measurements, in Millimeters, of Subject Population Compared to U.S. Army Aviators (1970)

Subject No.	Head Length	Head Breadth	Face Length	Face Breadth
1	195	154	133	142
2	200	156	122	144
3	198	150	112	145
4	198	152	120	139
5	202	156	126	146
6	202	153	121	137
7	198	159	120	142
8	202	149	131	132
9	201	154	111	139
10	194	147	117	136
11	188	154	117	140
12	202	155	114	144
U.S. Army Flight Personnel (1970)				
5%	188	147	102	130
95%	208	162	125	147

RESULTS

Fourteen mask/goggles combinations passed the acceptance criteria of maintaining a contaminant ratio (in 10 of 12 tests) of less than 0.1 for the goggles, and simultaneously, 0.05 for the mask (Table 2). Every test item that passed consisted of an oxygen mask supplied with emergency pressure in combination with vented goggles. Every test item that consisted of an oxygen mask supplied with emergency pressure in combination with unvented goggles failed to pass the acceptance criteria. These failures were due to the contaminant ratios within the goggles exceeding 0.1, while the contaminant ratios within the masks were well below the 0.05 level. In all cases in which the mask was supplied with positive pressure, the respiratory system was acceptably protected. A failure to provide acceptable protection to the visual processes was the basic cause for these failures.

TABLE 2. Number and Type of Mask/Goggles Combinations Tested and a Summary of the Results

Mask (100% O_2)		Goggles: Vented	Goggles: Unvented
With Pressure:	No. Tested	61	48
	No. Failed	47	48
	No. Passed	14	0
Without Pressure:	No. Tested	3	6
	No. Failed	3	6
	No. Passed	0	0

Of those mask/goggles combinations that were not designed to accept positive pressure, none met the acceptance criteria. These failures occurred in both the mask and the goggles; i.e., neither the respiratory system nor the visual process was provided acceptable protection.

When a mask/goggles combination failed to pass an individual test, it was generally due to a very rapid failure within the goggles; i.e., the contaminant ratio exceeding 0.1 within 2 or 3 min of testing (Figures 3 and 4).

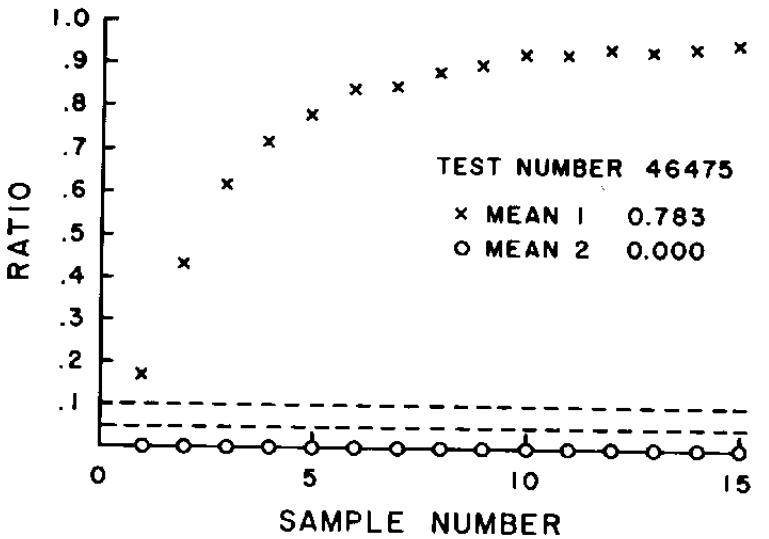

FIGURE 3. Typical data plot for an oxygen mask with emergency pressure applied in combination with unvented goggles (mask--O; goggles--X). Communication from sample 5 to sample 10.

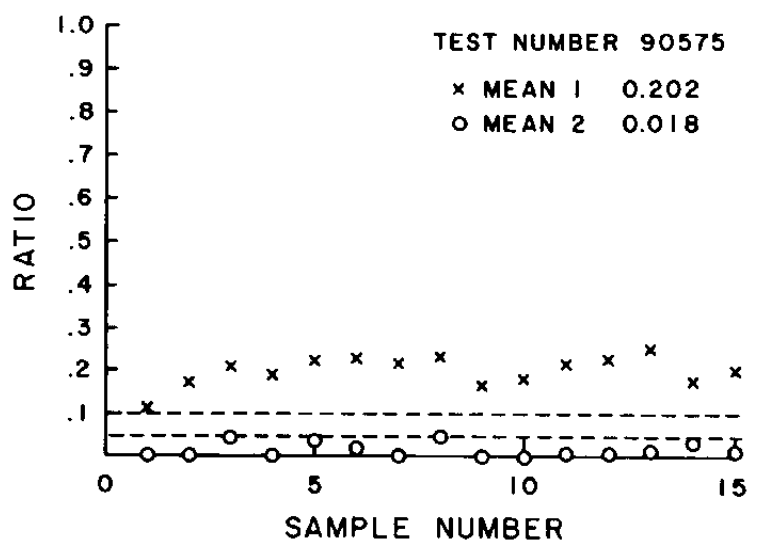

FIGURE 4. Typical data plot for an oxygen mask with emergency pressure applied in combination with vented goggles (mask--O; goggles--X). Communication from sample 5 to sample 10.

The protective capability of both vented and unvented goggles was influenced by the degree of mask fit around the bridge of the nose. In the case of many unvented goggles, mask leakage around the nose into the goggles was sufficient to effectively vent the goggles and thus cause these goggles to pass some of the individual tests (Figure 5).

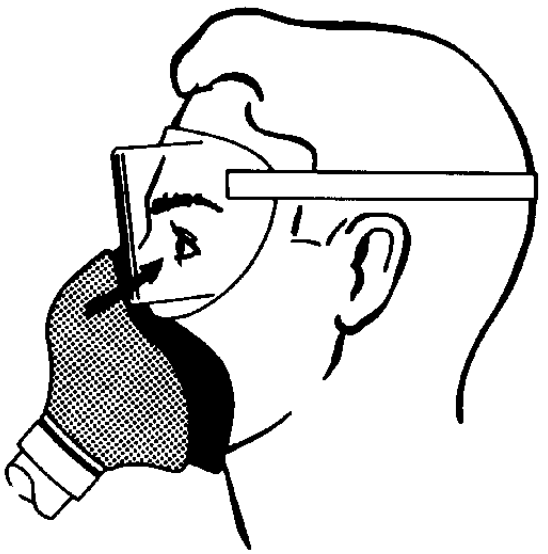

FIGURE 5. Mask leakage along nasal bridge.

A number of the vented goggles received insufficient flow through the venting tubes or valves and failed those individual tests in which a good mask fit was achieved around the nose. When a poor mask fit occurred at the bridge of the nose, outbound leakage was frequently directed under the goggles and produced supplemental venting. These items passed many of the individual tests. Comments by the subjects confirmed these observations.

In some cases the flow across or into the eyes was sufficient to cause visual problems. Comments by the subjects indicated that severe eye irritation was associated with the direction and velocity of oxygen flow within the goggles.

Other factors were observed to influence the protective capability of the goggles. Some models of goggles were too small to be worn over the eyeglasses used in this study. In such a case, large gaps were present between the goggles and the subject's head. Several goggles did not mate with the surface contours of the oxygen masks. The penetration of the goggles/temple interface by the eyeglass frames caused small to moderate gaps. The location of the

suspension strap for the goggles tested was fore or aft on the temple piece (Figures 6 and 7). Those goggles suspended near the front of the temple piece were less affected by a wide mask suspension system.

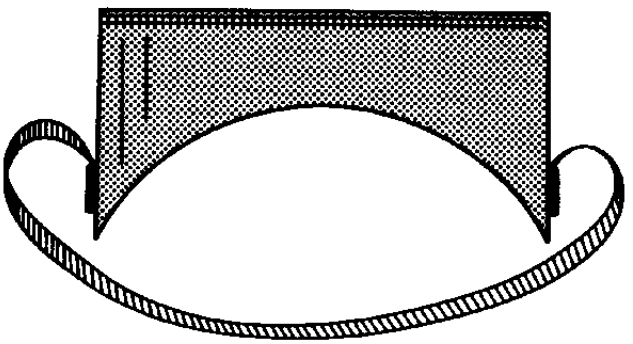

FIGURE 6. Goggles with aft attachment of suspension strap.

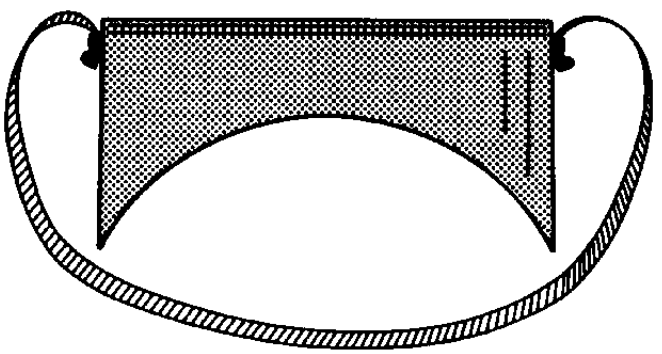

FIGURE 7. Goggles with forward attachment of suspension strap.

Many of the vented goggles were equipped with vent tubes that were too short and, when donned, did not position into the cavity of the oxygen mask (Figure 8). In these cases the ends of the vent tubes frequently were pressed against the face of the subject, partially or completely sealing the tubes. Markings on the subject's face following such tests confirmed these findings.

Considerable attention to the donning procedure was required for goggles equipped with vent tubes because of the tendency of these tubes to lie under the mask/face sealing surface (Figure 9) or for a vent tube to work itself into the mask lip (Figure 10). Special concern was directed to the donning and fitting of the test items during this study; however, outside assistance of this type would not be possible during an emergency. One pair of goggles, vented by means of a valve incorporated into the mask, was relatively easy and quick to don; however, the position of the goggles against the valve influenced the flow and reduced the venting into the goggles.

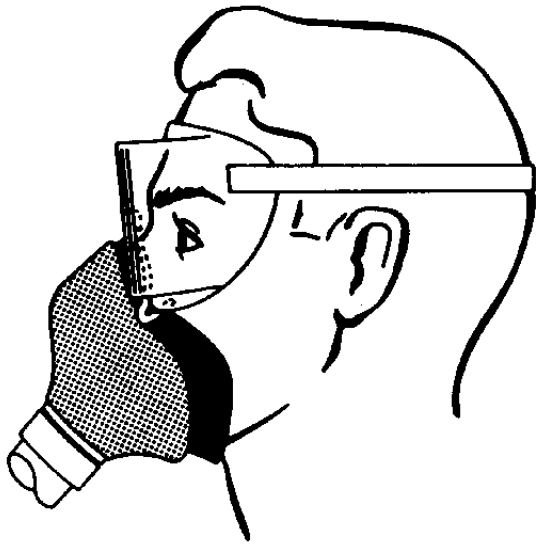

FIGURE 8. Goggles with short venting tubes.

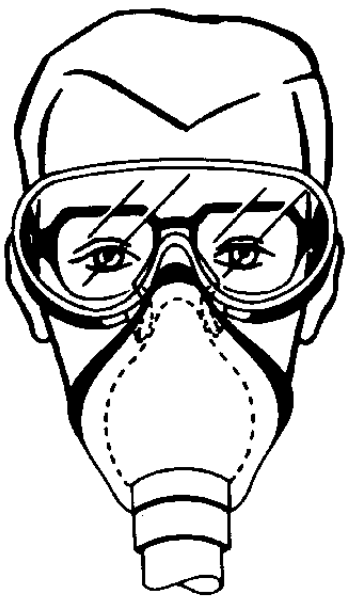

FIGURE 9. Goggles with venting tubes positioned under mask lip.

Fogging was noted in numerous tests. The fogging was not as serious a problem as had been expected, possibly because all equipment was tested at room temperature. Had the goggles been cold soaked, as often occurs when these items are stored in the aircraft, the fogging would have been more severe. Fogging frequently occurred during the donning of the equipment but generally cleared once the regulator was set to the emergency pressure mode of operation. Goggles not equipped with vent tubes often cleared as a result of mask outbound leakage along the bridge of the nose into the goggles.

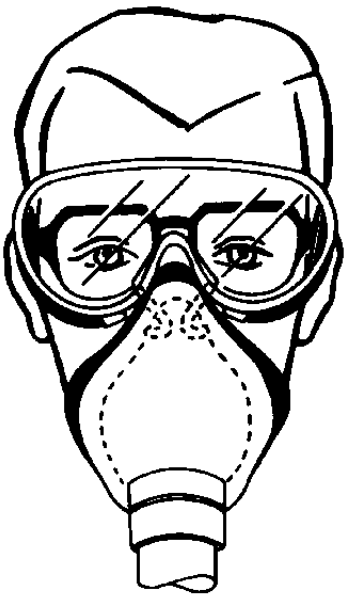

FIGURE 10. Goggles with venting tubes sealed against mask lip.

Many of the mask/goggles combinations caused an upward displacement of the subject's eyeglasses. The implications of eyeglasses displacement have been discussed in another publication (4). Several of the goggles that were equipped with vent tubes caused intense pressure against the eyeglasses. The results of this pressure ranged from considerable discomfort to intense pain for the subjects.

The effects of communication on the performance of the protective devices were inconsistent and a general trend was not identified. Occasionally, facial movements caused the mask to unseat around the nose; as a result, there was increased oxygen leakage into the goggles and thus the contaminant ratio was reduced (Figure 11). Conversely, on occasion, facial movements caused a mask to seat around the nose and thus reduced oxygen leakage into the goggles and increased the contaminant ratio (Figure 12).

The positive pressure provided by the emergency pressure setting of the regulator was necessary to obtain reliable contaminant protection, regardless of the type of equipment being tested. Those items not designed for use with emergency pressure did not pass the leakage criteria. Goggles equipped with vent tubes, when used with a mask that does not have emergency pressure applied, will allow serious contaminant leakage into the mask. The use of pressure increases outbound oxygen leakage from the mask for any given mask/face interface problem.

The oxygen usage for various mask/goggles combinations is presented in Table 3. The variability in oxygen usage by vented goggles vs. unvented goggles ranged from 1 L/min to 15 L/min, depending on the particular combination and the controlling regulator. A large variation in the oxygen

usage for various mask/goggles combinations was observed (Table 3) and was influenced by the degree of mask fit, goggles effects, and the controlling regulator.

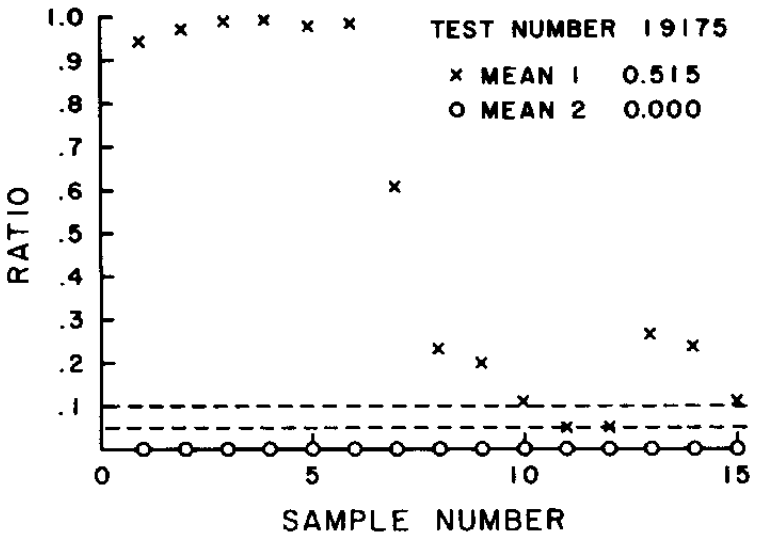

FIGURE 11. Typical data plot for oxygen mask/goggles combination (mask--0; goggles--x). Communication, from sample 5 to sample 10, caused the mask to unseat around the nose.

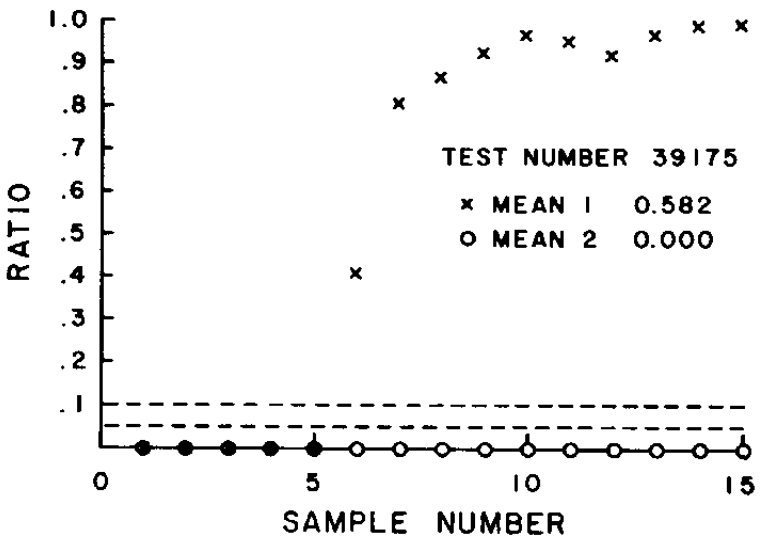

FIGURE 12. Typical data plot for oxygen mask/goggles combination (mask--0; goggles--x). Communication, from sample 5 to sample 10, caused the mask to seat around the nose.

Different oxygen usage was noted for the same mask/goggles combinations when tested with different controlling regulators; i.e., panel-mounted vs. mask-mounted regulators (Table 4). These differences can be the result of different delivery pressures by the regulators and the effects that the different items (mask-mounted regulator vs. large-bore delivery hose) might have on the mask/goggles fit.

TABLE 3. Oxygen Usage for Mask/Goggles Combinations. Values are means and standard deviations of oxygen usage for masks with emergency pressure in combination with vented and unvented goggles.

Mask	Vented Goggles (L/min) $\bar{x}$	S.D.	Unvented Goggles (L/min) $\bar{x}$	S.D.
A	48	17	44	19
B	37	16	22	13
C	31	8	25	9
D	27	9	21	10
E	25	9	22	14
F	30	16	19	12
G	23	15	11	4
H	20	11	14	4
I	18	11	13	6
J	18	11	14	6
K	15	6	13	3
L	12	2	11	1
M	13	4	11	2

TABLE 4. Oxygen Usage for Eight Mask/Goggles Combinations. (Four Masks With Panel-Mounted Vs. Mask-Mounted Regulators). Values are the means and standard deviations of oxygen usage for all goggles tested in combination with each mask.

Mask	Regulator	Vented Goggles (L/min) $\bar{x}$	S.D.	Unvented Goggles (L/min) $\bar{x}$	S.D.
1	Panel-Mounted	31	8	25	9
	Mask-Mounted	18	11	13	6
2	Panel-Mounted	25	9	22	14
	Mask-Mounted	23	15	11	4
3	Panel-Mounted	20	11	14	4
	Mask-Mounted	18	11	14	6
4	Panel-Mounted	15	6	13	3
	Mask-Mounted	12	2	11	1

The wide range of oxygen usage among subjects within a given test item demonstrates the problem of fitting different facial features with a given mask size or design (Table 5). Those subjects using the larger amounts of oxygen generally passed more of the individual tests, an indication of a poor mask fit around the nose that allowed supplemental venting into the goggles. Those subjects using lesser amounts of oxygen generally failed more of the individual tests, an indication of a good mask fit around the nose that prevented supplemental venting into the goggles. Comments by the subjects confirm these observations.

TABLE 5. Oxygen Usage by Subject. Values are means and standard deviations of oxygen usage for each subject for all mask/goggles combinations tested.

Subject No.	O_2 Usage (L/min) $\bar{x}$	S.D.
1	31	15
2	16	10
3	23	14
4	18	9
5	24	17
6	28	16
7	22	13
8	18	10
9	18	10
10	16	10
11	29	19
12	20	12

SUMMARY

One hundred and eighteen mask/goggles combinations of protective breathing equipment were tested for contaminant leakage. Fourteen of these combinations passed the acceptance criteria of simultaneously maintaining contaminant ratios of less than 0.1 for visual protection and 0.05 for respiratory protection. Emergency pressure from the controlling regulator was necessary to obtain acceptable protection, regardless of the type of equipment tested.

The fit of the oxygen mask around an individual's nasal bridge was a significant factor in the number of individual tests a given item passed and was also a major factor in the amount of oxygen used by that item. The use of goggles equipped with vent tubes did not guarantee acceptable protection and, in addition, complicated the donning procedure.

The difficulty of trying to fit several different faces with one facial size and configuration of equipment was demonstrated by the twofold variation in oxygen usage among subjects. The fourfold variation in oxygen usage among types of equipment demonstrated significant problems when this equipment was supplied with positive pressure.

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THE OBJECTIVE EVALUATION OF AIRCREW PROTECTIVE BREATHING EQUIPMENT: II. FULLFACE MASKS AND HOODS

D. deSteiguer,* M. S. Pinski,* J. R. Bannister,** and E. B. McFadden*

INTRODUCTION

Because of the possibility that smoke and other products of combustion from in-flight fires or toxic fumes from leaking cargo containers might enter the flight deck, the flight deck crew must be provided protective breathing equipment (1). Two types of protective breathing equipment are identified in the Federal Aviation Regulations; these are masks that cover the nose and mouth and are equipped with accessory equipment to cover the eyes (mask/goggles combinations) and masks that cover the eyes, nose, and mouth (fullface masks and hoods). Both types of equipment are required to function for an individual wearing corrective eyeglasses.

The use of fullface masks and hoods in smoke environments has been the approach generally taken by most (municipal and industrial) firefighting organizations. The U.S. Navy has recently equipped several ships with hoods incorporating a supply of compressed breathing gas to provide a means of escape for personnel trapped below deck during ship fires. The U.S. Air Force has proposed to equip several missile silos with hoods incorporating a system of chemically recycled breathing gas for fire evacuation purposes.

The air carriers have used the fullface mask, generally with portable oxygen supplies, to provide the means for a crewmember to investigate and/or fight fires in compartments other than the flight deck. The principal advantages of fullface masks are: (i) a single unit may be donned to obtain both respiratory and visual protection, and (ii) the problems of insuring compatibility of a mask/goggles combination are avoided. The disadvantages of fullface masks are: (i) increased mask dead space that limits protection in the event of loss of cabin pressure, (ii) donning and leaking problems associated with eyeglasses, and (iii) contaminant leakage that affects the eyes and respiratory system simultaneously. The principal advantages of hoods

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are: (i) a single unit that may be donned to obtain both visual and respiratory protection, (ii) easy donning over corrective eyeglasses, (iii) less weight per unit, and (iv) elimination of the problems encountered in providing an effective mask seal to a wide variety of facial configurations. The disadvantages of hoods are: (i) a large dead space that limits protection in the event of a loss of cabin pressure, (ii) a large dead space that limits the effectiveness of purging the system, and (iii) the unsatisfactory optical properties of many pliable plastics.

The manufacturers and users of oxygen and protective breathing equipment submitted 17 fullface masks and two hoods for contaminant leakage testing. Of the fullface masks, 6 were designed to accept positive pressure and 11 were designed to provide 100-percent oxygen without positive pressure. Eight were designed to operate with panel-mounted regulators and nine were equipped with mask-mounted regulators. Both hoods were equipped with hood-mounted regulators that provided a slight positive pressure within the hood. Any item designed to operate in both the 100-percent and positive pressure modes was tested only with emergency pressure applied.

METHOD

Each fullface mask was prepared by inserting three small stainless steel needles (21 gauge x 25-mm long) through the facepiece--one at the top center of the mask, one at the side, and one at the bottom of the mask near the oxygen inlets (Figure 1). These locations corresponded to the equivalent needle locations for the mask/goggles combinations that were a part of the overall test (2). The needles were retained in place with the use of sleeves made from 0.02-in I.D. plastic tubing. The hoods were prepared by inserting three needles in equivalent locations.

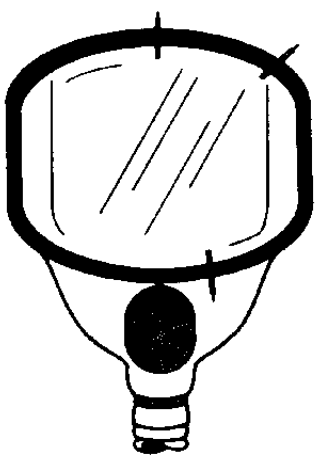

FIGURE 1. Location of the sample needles in fullface masks.

The same subject population, experimental design, and test preparation as described in "The Objective Evaluation of Aircrew Protective Breathing Equipment: I. Oxygen Mask/Goggles Combinations" (2) were used for this test.

The procedures described in "The Use of n-Pentane as a Tracer Gas for the Quantitative Evaluation of Aircrew Protective Breathing Equipment" (3) were used to complete the testing of the fullface masks and hoods.

RESULTS

Six fullface masks and two hoods passed the acceptance criteria of maintaining a contaminant ratio of less than 0.05 (5%) in 10 of 12 tests. Every fullface mask and hood that passed the acceptance criteria was designed to accept some amount of positive pressure (Table 1). Of those fullface masks that were not designed to accept positive pressure, none passed the acceptance criteria.

TABLE 1. Number and Type of Fullface Masks and Hoods Tested and a Summary of the Results

Type		100% O_2 With Pressure	100% O_2 Without Pressure
Fullface:	No. Tested	6	11
	No. Failed	0	11
	No. Passed	6	0
Hoods:	No. Tested	2	0
	No. Failed	0	0
	No. Passed	2	0

A tight seal at the mask/face interface was difficult to obtain while the subject was wearing the eyeglasses used in these tests. Considerable contaminant leakage occurred where the temple bars of the eyeglasses penetrated the mask/face seal. Some amount of positive pressure within the fullface mask was required to counter the resulting inbound leakage (Figures 2 and 3). However, when positive pressure was applied within the mask, considerable outbound oxygen leakage occurred (Table 2). A large variation in the oxygen usage (cylinder drainage) for various fullface masks occurred and was influenced by the degree of mask fit and the pressure output of the controlling regulator. The wide variation in oxygen usage among subjects demonstrates the problem of fitting different facial features with a given mask size or design (Table 3).

The effects of communication did not produce a consistent trend in contaminant leakage; however, an increase in fogging did occur during communication. Fogging of consequence was noted but was not as serious as had been expected, possibly because all equipment was tested at room temperature.

Donning the fullface mask over eyeglasses was a continual problem that required considerable attention. Once donned, the mask generally forced the eyeglasses down on the nose as opposed to the upward displacement that occurred with the mask/goggles combinations (2). The implications of eyeglass displacement are discussed in another publication (4).

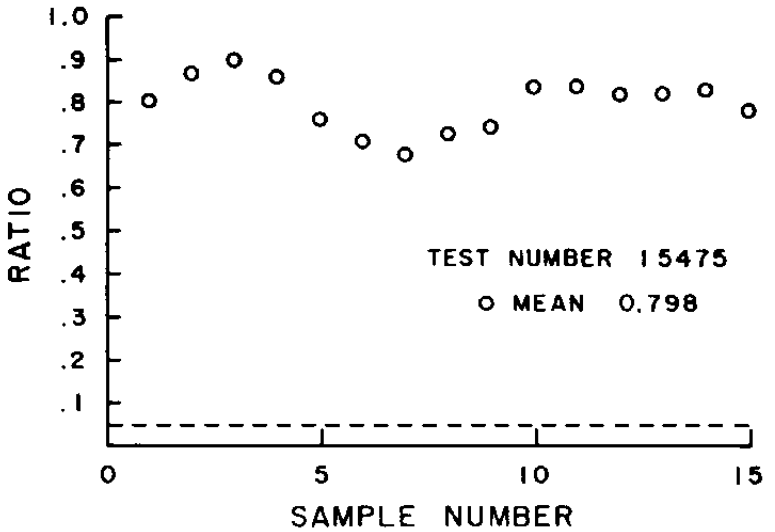

FIGURE 2. Typical data plot for a fullface mask without positive pressure. Communications from sample 5 to sample 10.

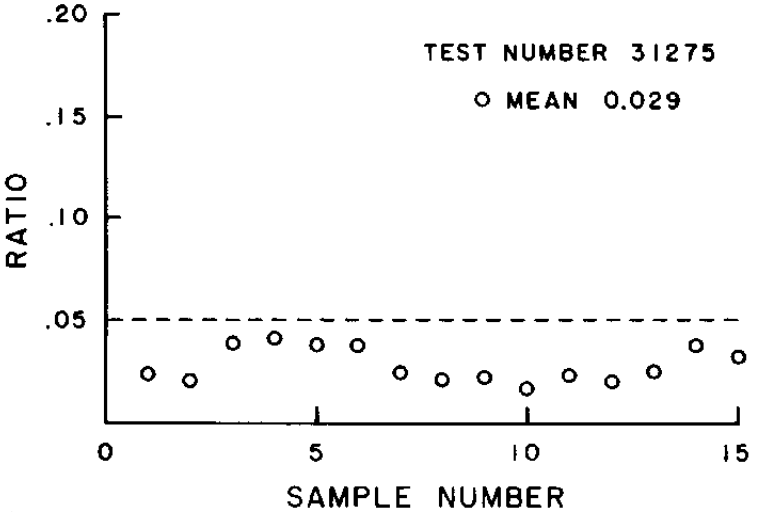

FIGURE 3. Typical data plot for a fullface mask with positive pressure. Communications from sample 5 to sample 10.

The hoods were quickly and easily donned by pulling the device over the head and letting the neck seal contract. The eyeglasses were generally displaced during donning but were easy to reposition. One of the hoods, manufactured from a clear plastic, caused a considerable decrement in visual acuity. Both hoods had a high noise level associated with the introduction of oxygen from the regulator. Fogging of consequence, noted throughout these tests, was more severe during communication. The oxygen usage for these devices, as compared to that for fullface masks, indicates fewer problems with neck seals than with mask/face seals (Table 2).

TABLE 2. Oxygen Usage for Fullface Masks and Hoods. Values are means and standard deviations of oxygen usage for each item.

100% O_2 With Pressure (L/min)		
Mask No.	$\bar{x}$	S.D.
1	69	27
2	62	13
3	52	13
4	31	22
5	17	6
6	14	3

Hood No.	$\bar{x}$	S.D.
1	15	2
2	10	1

100% O_2 Without Pressure (L/min)		
Mask No.	$\bar{x}$	S.D.
7	8	3
8	6	5
9	7	1
10	5	5
11	3	3
12	6	4
13	1	1
14	6	4
15	6	4
16	7	3
17*	--0--	

*Mask could not be donned over eyeglasses worn by subjects during this test.

TABLE 3. Oxygen Usage by Subjects Wearing Fullface Masks. Values are means and standard deviations of oxygen usage by subjects for all fullface masks designed to accept positive pressure.

Subject No.	O_2 Usage (L/min) $\bar{x}$	S.D.
1	61	30
2	27	19
3	38	22
4	32	22
5	37	27
6	53	30
7	44	31
8	51	33
9	32	27
10	42	28
11	37	21
12	38	27

SUMMARY

Seventeen fullface masks and two hoods were tested for contaminant leakage. Six fullface masks and the two hoods passed the acceptance criteria of maintaining contaminant ratios of less than 0.05. Some amount of positive pressure from the controlling regulator was necessary to obtain acceptable protection, regardless of the type of equipment tested.

The penetration of the mask/face seal by eyeglass temple bars was a significant factor in a mask's failing the acceptance criteria. The degree of mask/face seal interruption caused by the eyeglasses and the output pressure of the controlling regulator were major factors in the amount of oxygen used by any given item.

The difficulty of trying to fit several different faces with one piece of equipment was demonstrated by the twofold variation in oxygen usage among subjects. The fourfold variation in oxygen usage among types of masks demonstrated significant fitting problems when this equipment was worn with eyeglasses and was provided positive pressure.

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AN ASSESSMENT OF PROTECTIVE BREATHING DEVICES FOR USE BY FLIGHT ATTENDANTS

D. deSteiguer, M. S. Pinski, and E. B. McFadden

INTRODUCTION

Because of the possibility that smoke and other products of combustion from in-flight fires or toxic fumes from leaking cargo containers might enter the flight deck, the flight deck crew must be provided protective breathing equipment (1). Federal Aviation Regulations now require protective breathing devices for flight attendants assigned to duty stations within isolated compartments, such as lower deck galleys. Since the Paris-Varig accident, most European airlines have provided protective breathing devices for all flight attendants, regardless of their assigned duty stations. These protective breathing devices may be classified into two basic types: fullface masks that enclose the eyes, nose, and mouth and hoods that enclose the entire head.

Testing of protective breathing devices intended for use by flight deck crewmembers has been conducted (2,3,4). These tests indicated that many of

these devices did not provide acceptable protection from contaminant gases when worn over eyeglasses. These tests also indicated that eyeglasses were generally displaced from the normal wear position (5) by the masks, that some amount of internal positive pressure was required within the protective breathing device to provide acceptable contaminant leak protection, and that high rates of oxygen cylinder drainage frequently occurred when positive pressure was applied. After reviewing these data, we expanded the test program to include those items suitable for flight attendant use.

Subjective vs. Objective Testing. Several procedures have been used in recent years for the subjective evaluation of protective breathing equipment. Of these procedures, the most widely used have depended on the ability of a subject to detect tear gas or isoamyl acetate while wearing protective equipment in the respective environments. Subjective evaluation of this type is questionable because of the variations among individuals in their motivation, ability to detect stimuli, and ability to describe stimuli.

If quantitative methods are used, nonirritating substances may be used as the tracer or challenge gas. This approach allows for repeated use of a subject pool and is particularly useful if several different shapes and sizes of masks are to be tested on similar faces. Instrumental methods give numerical values and, in combination with continuous sampling or with multiple discrete samples, allow plotting of concentration change as a function of time.

Tracer Gas Selection. n-Pentane (C_5H_{12}) was selected as a tracer or challenge gas for the objective evaluation of protective breathing equipment after consideration of the following: (i) pentane is a gas and not a solid or aerosol; (ii) pentane has a molecular weight of 72 and is in the range of many known products of aircraft fires (see Table 1 below); (iii) pentane is not considered toxic at low concentrations; (iv) pentane is not irritating to the subject; (v) pentane does not require specific handling procedures or work areas as would be required by irritating products; and (vi) very small amounts of pentane can be readily analyzed with a gas chromatograph.

TABLE 1. Comparison of Molecular Weights of a Number of Common Combustion Products Produced in Aircraft Fires

Combustion Product	Molecular Weight
Hydrogen fluoride	20.0
Hydrogen cyanide	27.0
Acetonitrile	41.0
Sulfur dioxide	64.1
Phosgene	98.9

Analytical Approach. The general analytical method developed for the use of pentane in testing protective breathing equipment is shown in Figure 1. A simple exposure chamber of sufficient size to accommodate a subject and the equipment to be tested was used to contain the challenge atmosphere. Small needles were inserted into the protective breathing device to provide for the collection of gas samples from specific locations within the device. Small-bore flexible tubing was passed through the chamber wall to connect the sample

needles to a selector valve located outside the chamber. The sample gas was drawn through a twin-loop collector valve, where a known aliquot was collected and delivered to a gas chromatograph equipped with a hydrogen flame ionization detector.

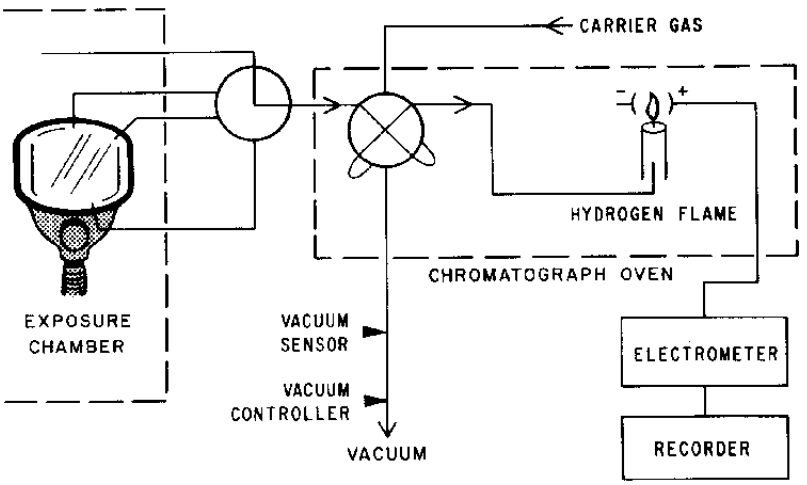

FIGURE 1. Analytical flow diagram for testing protective breathing equipment.

Subject Population. The subject population consisted of eight females (20 to 45 yr old) trained in the test procedures and equipment donning. Selected anthropometric measurements were taken for each subject and compared to corresponding data for military personnel.

Test Items. Ten fullface masks and two hoods were tested for contaminant leak protection. Of these, six fullface masks and two hoods were designed to accept some amount of internal positive pressure. Of the fullface masks, six were coupled to panel-mounted regulators having settings for 100-percent oxygen and emergency pressure. The remaining four fullface masks were equipped with mask-mounted regulators that provided 100-percent oxygen automatically and with a setting for emergency pressure. The two hoods were equipped with regulators that provided a continuous flow positive pressure to the hood.

Test Procedure. Each subject was seated in a small ambient pressure chamber and instructed to don and adjust the protective breathing device to obtain what she felt to be an optimal fit. Assistance in adjusting the device was given to the subject if an obvious misfit was encountered. The chamber was closed and a concentration of 120 ppm of pentane was established and maintained through each 15-min test. Freestyle head movements were continued throughout each test by the subject. In addition, a 5-min period of communication was required of the subject from the 5th to the 10th min, silence being maintained otherwise. The cylinder drainage for each test was calculated from weight change data and normalized to 15 min.

Discrete gas samples (50μl) were drawn sequentially every 15 s from the chamber and three specific locations from within the protective breathing

device for analysis in a gas chromatograph. The contaminant ratio was calculated for each minute by dividing the mean pentane level for the three mask samples by the immediately preceding chamber pentane level. The 15 ratios obtained were then plotted on a time base and a mean contaminant ratio for that test was calculated. A mean contaminant ratio of 0.05 was defined to be the pass-fail criterion for this study.

Test Configuration. Each fullface mask was tested in four configurations: (i) with the subject not wearing eyeglasses and the controlling regulator set to deliver 100-percent oxygen; (ii) with the subject not wearing eyeglasses and the controlling regulator set to deliver 100-percent oxygen at approximately 1 to 1½ in of water pressure (0.2 to 0.3 kN/M^2); (iii) with the subject wearing eyeglasses (American Optical Corporation frames F9846SM) and the controlling regulator set to deliver 100-percent oxygen; and (iv) with the subject wearing eyeglasses and the controlling regulator set to deliver 100-percent oxygen at approximately 1 to 1½ in of water pressure (0.2 to 0.3 kN/M^2).

Test Results. The fullface masks generally did not provide acceptable contaminant protection (a contaminant ratio of less than 0.05) when worn in configurations (i) and (iii). The fullface masks did provide acceptable contaminant protection when worn in configurations (ii) and (iv). Because of design constraints, the hoods were tested only in configurations (ii) and (iv). The hoods did provide acceptable contaminant protection when worn in these configurations (Table 2).

TABLE 2. Results of Contaminant Leak Testing of 10 Fullface Masks and Two Hoods. Values presented are number of subject tests with mean contaminant ratios of less than 0.05 and more than 0.05 (<0.05 - >0.05).

Configuration		i	ii	iii	iv
Eyeglasses		No	No	Yes	Yes
Pressure		No	Yes	No	Yes
	Fullface Masks With Panel-Mounted Regulators				
Device:	1	4-4	8-0	0-8	8-0
	2	4-4	8-0	0-8	8-0
	3	5-3	8-0	0-8	8-0
	4	6-2	8-0	0-8	8-0
	5	8-0	8-0	1-7	8-0
	6	6-2	8-0	0-8	8-0
	Fullface Masks With Mask-Mounted Regulators				
	7	7-1	8-0	0-8	8-0
	8	8-0	8-0	2-6	8-0
	9	7-1	8-0	0-8	8-0
	10	5-3	8-0	0-8	8-0
	Hoods With Hood-Mounted Regulators				
	11		8-0		8-0
	12		8-0		8-0

Cylinder Drainage. Excessive cylinder drainage occurred with all fullface masks not designed to accept internal positive pressure when operated in that mode (Table 3). The noncompensating exhalation valves of these masks remained open and allowed a free flow of air (or oxygen) through the mask. For those masks designed to accept internal positive pressure, high cylinder drainage frequently occurred because of the presence of eyeglass frames through the mask-to-face seal. Both hoods, designed to operate with a slight internal positive pressure, had acceptable cylinder drainge.

TABLE 3. Cylinder Drainage During Contaminant Leak Testing of 10 Fullface Masks and Two Hoods. Values presented are L/min--average for eight subjects.

Configuration		i	ii	iii	iv
Eyeglasses		No	No	Yes	Yes
Pressure		No	Yes	No	Yes
	Fullface Masks With Panel-Mounted Regulators				
Device:	1*	5.9	59.2	2.5	61.7
	2*	7.1	59.7	3.5	60.1
	3	5.8	17.4	3.0	30.0
	4	7.6	8.8	5.0	23.6
	5*	6.8	59.2	5.0	59.9
	6*	6.9	63.5	2.1	61.2
	Fullface Masks With Mask-Mounted Regulators				
	7	6.6	8.8	4.3	15.5
	8	7.4	7.5	6.2	10.4
	9	6.7	10.3	4.2	32.5
	10	8.1	14.6	4.7	42.1
	Hoods With Hood-Mounted Regulators				
	11		16.1		15.5
	12		13.0		11.4

*Exhalation valves not designed for pressure breathing.

Problems Identified. Problems identified in these tests included: (i) difficulty in fitting a variety of facial contours with a given-size mask, (ii) penetration of the mask-to-face seal by eyeglass frames, (iii) downward displacement of eyeglasses from the normal wear position by the masks, (iv) increased cylinder drainage associated with pressure settings and mask fit, (v) the requirement that the wearer manually set the controlling regulator to the emergency pressure setting, and (vi) donning problems associated with the number of adjustment straps and the difficulty encountered by most female subjects in adjusting these straps.

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USE OF PASSENGER OXYGEN MASKS ON AIR CARRIER AIRCRAFT DURING SMOKE/FIRE CONDITIONS IN THE CABIN

E. B. McFadden

Several preliminary experiments relative to the use of the passenger oxygen masks for in-flight smoke protection have been carried out. Of first importance is a thorough understanding of the design and functional characteristics of the passenger system and mask.

The passenger oxygen systems of turbine-powered air carrier aircraft are of a continuous-flow design. Aircraft such as the B-707, B-720, B-727, B-737, DC-8, and DC-9, which utilize high pressure gaseous oxygen, employ a distribution system with the general characteristics as shown in Figure 1.

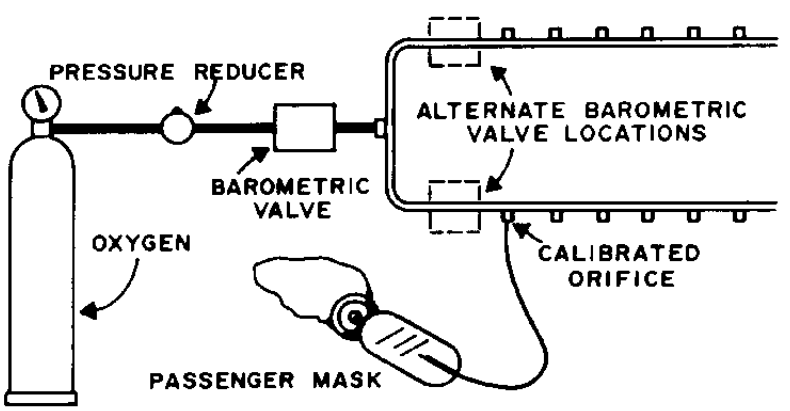

FIGURE 1. Simplified passenger oxygen system schematic.

Although there are some variations from the above schematic, the basic system consists of manifolded oxygen cylinders charged to an initial pressure of 1,800 psi delivering oxygen to a pressure reducer and variable pressure regulator controlled by an aneroid sensitive to altitude. The pressure reducer and regulator may be separate or combined in one instrument. In large transports the system may be split; i.e., a separate system servicing 60 to 100 or more outlets on the left side of the aircraft and a similar system on the right.

The barometric controller incorporates an aneroid and triggering mechanism that, in the event of cabin pressure loss to a predetermined value (for example, cabin pressure equivalent to 14,000 ft), automatically drops the mask. At the same time, pressure is distributed into the distribution lines and through calibrated flow orifices (drilled or fiberglass packed). As the altitude increases, the aneroid mechanism in the pressure controller increases pressure in the lines and thus produces a flow increase through individual flow orifices to the passenger masks. Line pressures as delivered by the pressure controller may, for example, vary from 0 at 8,000 ft to 70 to 100 psi at 40,000 ft and produce flows of from 0 to 4.2 L/min {Normal Temperature, Pressure Dry (NTPD)}. The resultant altitude-flow curve must be in excess of the minimum curve calculated from the requirements set forth in Part 25.1443(c) of the Federal Aviation Regulations (FAR) and take into consideration the performance efficiency (coding) of the mask as described in FAR Part 37.169(a)(2)(iii)1.4.

Values for minimum flow as calculated from the requirements of 25.1443(c) are shown in Table 1. The last three columns are of particular interest; i.e., percent total oxygen, fraction of minute volume derived from the supply, and the required minimum oxygen flow of oxygen to the mask. Minimum flow requirements to FAR 25.1443(c) are plotted in Figure 2 (Curve A).

As no oxygen is required at normal pressurized altitudes (below 10,000 ft), a passenger wearing a mask would, in a smoke-filled cabin, be breathing 100-percent ambient contaminated air through the dilution valve of the mask. In the case of an in-flight smoke problem, inhalation of smoke and toxic byproducts of combustion would be the same with or without the mask. At 12,000 ft, only 0.2 L/min of oxygen is required and the fraction of added oxygen constitutes only about 2.5 percent (0.0248) of the inspired gas. Even at a cabin altitude of 33,000 to 34,000 ft, the added oxygen constitutes only one-half of the 30 L/min minute volume. The remaining 50-percent of the minute volume must therefore be derived from the smoke-filled cabin interior.

To meet the requirements of FAR 25.1443(c), airframe manufacturers employ a flow curve slightly above the required minimum. These curves vary from aircraft to aircraft and manufacturer to manufacturer. A hypothetical but representative curve is shown as Curve B in Figure 2. Curves for various types of aircraft are available from the manufacturers. Table 1 illustrates that only when a cabin altitude of 40,000 ft is approached does the fraction of the minute volume obtained from the oxygen supply equal the inspired minute volume (30 L/min) and constitute the total inspired gas to the extent that cabin air is not drawn into the mask through the dilution valve. A flow of 3.6 L/min NTPD (70°F, 760 mmHg, dry) equals 30.6 L/min BTPS (body temperature, 141 mmHg, saturated).

TABLE 1. Calculated Minimum Passenger Oxygen Flow Required by the Federal Aviation Regulations

Altitude (Thousands of ft)	Volume Ratio NTPD / BTPS	L/min NTPD	% Total O_2 Required	F/MV	Required Min. Flow to Mask in L/min-NTPD
		AT 15 (L/min BTPS)			
10.0	0.5939	8.909	21.02	0.0020	0.0178
11.0	0.5690	8.535	21.94	0.0133	0.1135
12.0	0.5449	8.174	22.91	0.0248	0.2027
13.0	0.5215	7.823	23.94	0.0370	0.2895
14.0	0.4989	7.484	25.02	0.0500	0.3742
15.0	0.4770	7.155	26.17	0.0640	0.4600
16.0	0.4558	6.837	27.39	0.0785	0.5367
17.0	0.4353	6.530	28.68	0.0940	0.6138
18.0	0.4154	6.231	30.05	0.1106	0.6891
18.5	0.4057	6.086	30.77	0.1200	0.7303
		AT 30 (L/min BTPS)			
18.5	0.4057	12.171	25.78	0.0592	0.7205
19.0	0.3962	11.886	26.40	0.0664	0.7892
20.0	0.3777	11.331	27.70	0.0824	0.9337
21.0	0.3597	10.791	29.08	0.0990	1.068
22.0	0.3424	10.272	30.55	0.1176	1.208
23.0	0.3257	9.771	32.12	0.1374	1.343
24.0	0.3095	9.285	33.81	0.1594	1.480
25.0	0.2939	8.817	35.60	0.1828	1.612
26.0	0.2788	8.364	37.52	0.2078	1.738
27.0	0.2642	7.926	39.59	0.2347	1.860
28.0	0.2502	7.506	41.81	0.2653	1.991
29.0	0.2367	7.101	44.20	0.2988	2.122
30.0	0.2236	6.708	46.78	0.3350	2.247
31.0	0.2111	6.333	49.57	0.3740	2.369
32.0	0.1989	5.967	52.59	0.4189	2.500
33.0	0.1873	5.619	55.87	0.4680	2.630
34.0	0.1760	5.280	59.43	0.5215	2.754
35.0	0.1652	4.956	63.33	0.5833	2.891
36.0	0.1548	4.644	67.59	0.6514	3.025
37.0	0.1448	4.344	72.25	0.7283	3.164
38.0	0.1353	4.059	77.33	0.8146	3.307
39.0	0.1262	3.786	82.88	0.9118	3.452
40.0	0.1176	3.528	88.98	1.0216	3.604

In practice the minute volume of a passenger may be less or even more than 30 L/min. In addition, an individual breath (tidal volume) may approach 2,000 cc or more and exceed the 1,100-cc volume of the mask reservoir bag (plus the volume entering the bag during inspiration) to the extent that cabin air may be drawn into the mask through the dilution valve.

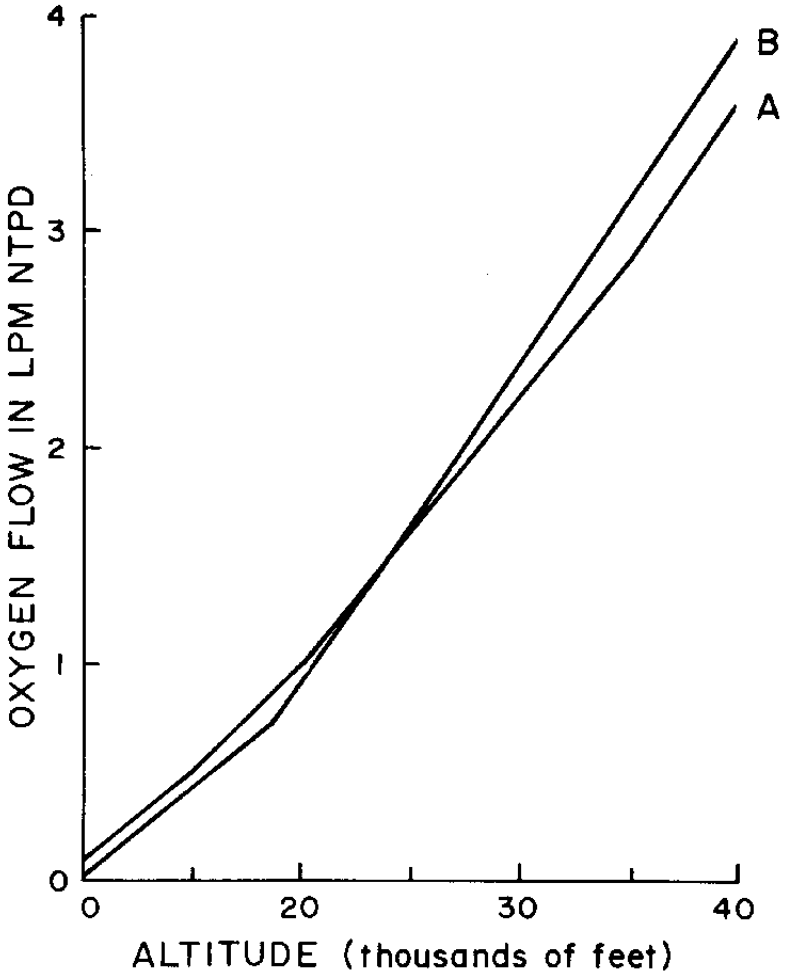

FIGURE 2. (A) Minimum passenger oxygen flow as required by the Federal Aviation Regulations, (B) hypothetical curve provided by manufacturer to meet the requirements.

A thorough understanding of the functional characteristics of the phase dilution passenger mask as employed on air carrier aircraft is necessary in evaluating its potential use as a passenger smoke protective device. The functional characteristics of the phase dilution mask are shown in Figure 3.

Starting with a reservoir bag filled with oxygen (just prior to inspiration), the passenger next inhales the contents from the reservoir bag until the bag collapses. When the bag collapses, negative pressure within the mask opens the dilution valve and thus admits cabin air to fulfill the remainder of his inspiratory requirement. In this type of mask, 100-percent oxygen is introduced at the most advantageous point in the respiratory cycle (at the beginning of inspiration) and is delivered deep into the lungs, where oxygen absorption takes place in the alveoli of the lungs. Ambient air delivered by the dilution valve at the end of inspiration may only penetrate into the bronchi, trachea, and oral cavity--the so-called anatomical dead

spaces. These physiologically inactive areas are not engaged in absorption of oxygen. Upon expiration, ambient air from the dead spaces is the first to be expelled. In this manner, some ambient air may be used to fulfill inspiratory requirements and thus afford high oxygen concentrations in the lungs and economical utilization of the available oxygen supply.

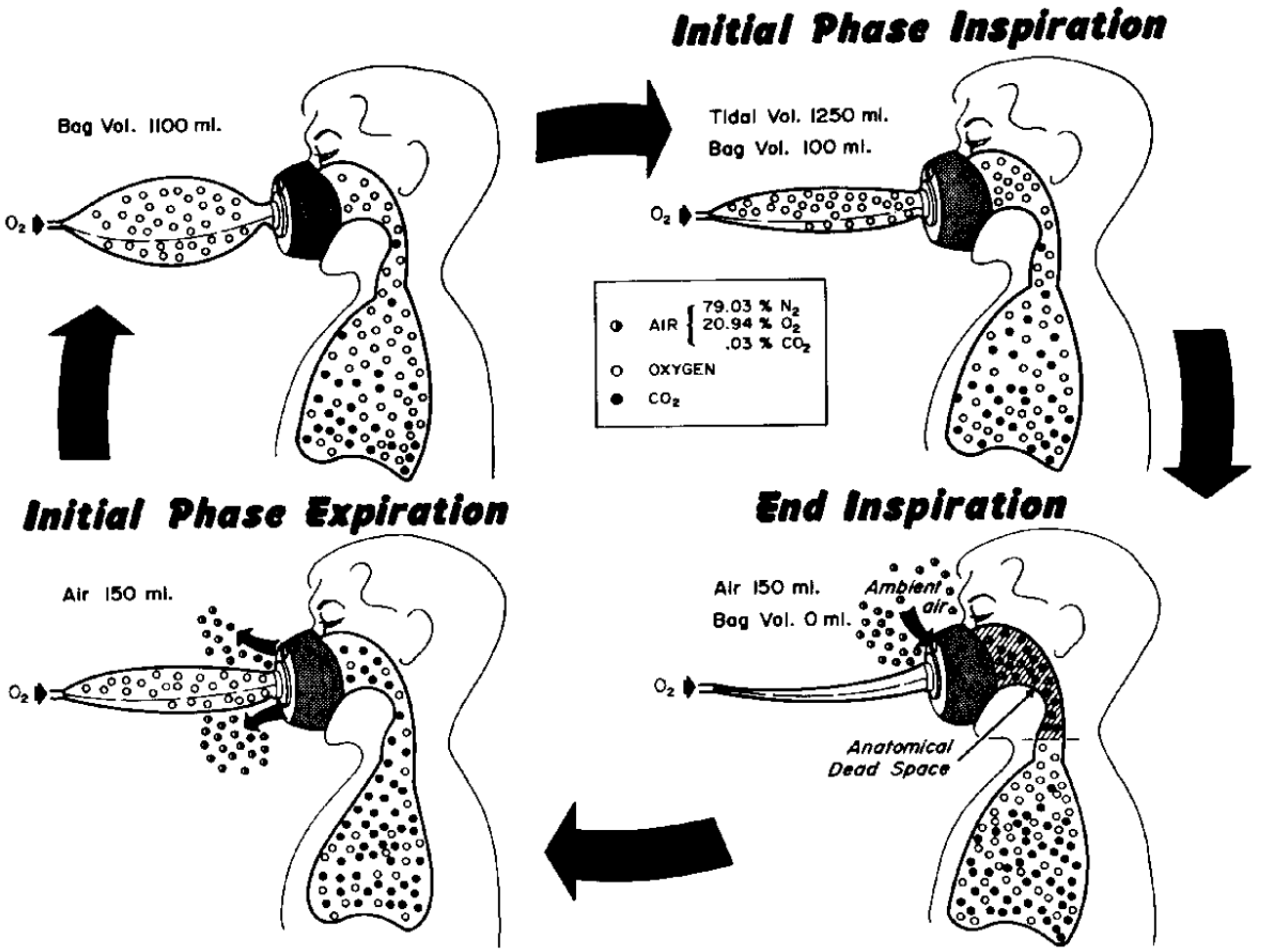

FIGURE 3. Diagrammatic representation of the sequential performance of a phase dilution passenger oxygen mask.

The proposed use of the passenger oxygen mask to protect occupants of air carrier aircraft during smoke/fire conditions in the cabin would require modification of the system and/or accessory equipment and operational procedures. Based on the current design and operational characteristics of the passenger oxygen system, a number of possibilities exist as follows:

Flood the Mask With Oxygen. As described in the previous discussion, the maximum flows provided by current passenger oxygen systems range from 3.6 to 4.2 L/min NTPD at an altitude of 40,000 ft. Even if these flows were provided at sea level (by a crew-operated manual bypass of the altitude-sensitive regulator), they would only furnish about 14 percent of the volume of gas

required by a passenger breathing at 30 L/min; the remaining 86 percent would consist of smoke-contaminated cabin air. To meet the requirements of a passenger breathing 30 L/min (BTPS) at sea level would require a flow of 27 L/min (NTPD). At a pressurized cabin altitude of 8,000 ft, 20 L/min (NTPD) would provide a flow of 30 L/min (BTPS). At these flows the aircraft passenger oxygen supply would be depleted in only a few minutes. For example, a CV-880 is normally equipped with one 115 ft^3 oxygen cylinder for the crew system and two 115 ft^3 cylinders for the passenger system. Each 115 ft^3 cylinder provides 3,255 liters of oxygen or, in this case, the two cylinders provide 6,510 liters. With a load of 100 passengers and an average flow of 25 L/min (NTPD) per passenger, the total passenger oxygen supply would be depleted in 2.6 min. In addition, aircraft with cylinder pressures as low as 1,400 psi may be dispatched because at this pressure the quantity is still sufficient to meet the appropriate FAR's. Some typical oxygen quantities as provided by a major airline are shown in Table 2. Variations are encountered, depending on aircraft model and seating density.

TABLE 2. Typical Oxygen Supply Quantities

Aircraft	No. Cylinders (115 ft^3)	
	Passenger	Crew
CV-880	2	1
B-707	3	1
Stretched B-727	2	1
L-1011	Chemical	1
B-747	5	2

Isolate the Passenger and Mask From the External Cabin Environment. If a pliable bag with an adequate neck seal is placed over the head of the individual wearing a passenger mask, protection may be afforded at much lower oxygen flow rates. If fire protection is not a consideration, a hood manufactured of a variety of transparent, pliable materials may be used. Under these conditions, oxygen from the reservoir bag is inspired until the reservoir bag collapses, at which time ambient gas from the hood is inspired through the dilution valve. Only 4 to 6 percent of the 100-percent oxygen introduced into the lungs is absorbed. Upon exhalation the remaining 94 percent, along with 3- to 5-percent carbon dioxide, is expelled into the hood. The next inhalation of 100-percent oxygen from the mask reservoir bag continues until the bag collapses, at which time inspiration is topped off by uncontaminated air high in oxygen concentration from the hood and through the dilution valve. Change in volume within the hood as a result of gas exchange is negligible; that is, the small portion of the oxygen breathed which is absorbed is converted to carbon dioxide and exhaled. The so-called respiratory quotient; i.e.:

$$\text{R.Q.} = \frac{\text{carbon dioxide produced}}{\text{oxygen absorbed}}$$

in a resting individual approximates 0.83 (some O_2 is used in metabolic processes such as production of H_2O) but may be greater than 1.0 or less than 0.83, depending on diet, respiratory activity, etc.

When a hood is worn over the mask, the flow vented from the hood is, for all practical purposes, approximately equal to the flow delivered to the mask. This continuing oxygen flow into the mask and hood produces in the hood a source of uncontaminated gas high in oxygen concentration and available for meeting breathing requirements by way of the dilution valve. Oxygen flowing through the system ventilates the hood and sweeps carbon dioxide out through the neck seal. With a continuous outward flow at the neck seal, smoke and toxic contamination are prevented from entering the hood.

A series of experiments using the hood-passenger mask combination as shown in Figure 4 have been carried out in this laboratory at altitudes of 1,200 ft (ground level at Oklahoma City), 8,000 ft, and 14,000 ft at flow rates of 4.2 L/min and 5.5 L/min. Carbon dioxide accumulation in the hood and end expiratory carbon dioxide were measured and several thousand feet of recordings were obtained. End expiratory carbon dioxide recordings are more significant than hood carbon dioxide levels but are tedious and time-consuming to read. Although there was some elevation of the end expiratory carbon dioxide partial pressure, the subject wore the mask-hood combination for a period of 35 min at each of the altitudes tested. Preliminary scanning of recordings indicates a rise in carbon dioxide in the hood until the hood is fully inflated by the oxygen flowing into the mask and hood. The hood then starts venting at the neck seal and the carbon dioxide level decreases to, and equilibrates at, a lower level that is dependent on the flow into the mask. This equilibrium level may continue as long as the oxygen flow rate is maintained. Inflation of the hood improves visibility and comfort. To attain flows of from 4 to 5 L/min would require modification of the current oxygen systems by placing a pressure regulator upstream from the altitude sensitive oxygen regulator and bypassing the altitude-controlled regulator with a manual valve activated by the crew. It might be technically feasible for this bypass system to be automatically activated by smoke detectors. However, reliability and maintenance would, in all probability, constitute a major problem. Based on the figures in Table 2, the duration of the supply of a CV-880 with 100 passengers at a flow rate of 4 L/min would approximate 16 min and for a B-707 carrying a similar number of passengers would approximate 24 min.

Additional Approaches. The principal requirement for increased flow into the mask and hood is to ventilate and remove carbon dioxide. Most of the oxygen is wasted. It would be exceedingly unusual for a passenger to use (absorb) more than 0.5 to 0.8 L/min of oxygen. The limiting factor is the accumulation of carbon dioxide. If carbon dioxide could be effectively removed, very low oxygen flows would be required and the duration of the aircraft's supply extended. Removal of carbon dioxide by using absorbents, such as soda lime, lithium hydroxide, etc., is theoretically feasible. Most absorbents require a flow through a bed of the chemical, plus moisture as provided in the exhaled gas.

The quantity of chemical required should be minimal, depending on duration. Quantities, configuration, and flow characteristics would have to be determined experimentally. Using a pliable hood over the mask presents a situation wherein the chemical absorbent could be located at several locations in the respiratory circuit; these include attachment to the exhalation valve,

removing carbon dioxide during exhalation, or attachment to the dilution valve, removing carbon dioxide during inhalation. Removing carbon dioxide on exhalation would appear to be the more effective method. Installation of such a device should not affect mask performance for use as a protective device at high altitude. The chemical bed would require a seal that could be removed automatically by the same lanyard that initiates flow when the mask is pulled down from the dropout container.

An alternative method would include the use of an aspirator device designed by the author of this report. A simple prototype made of laboratory plastic tubing has been made and found to be functional. An improved prototype has been made, but instrumentation required to determine its flow characteristics and efficiency are being used in another project.

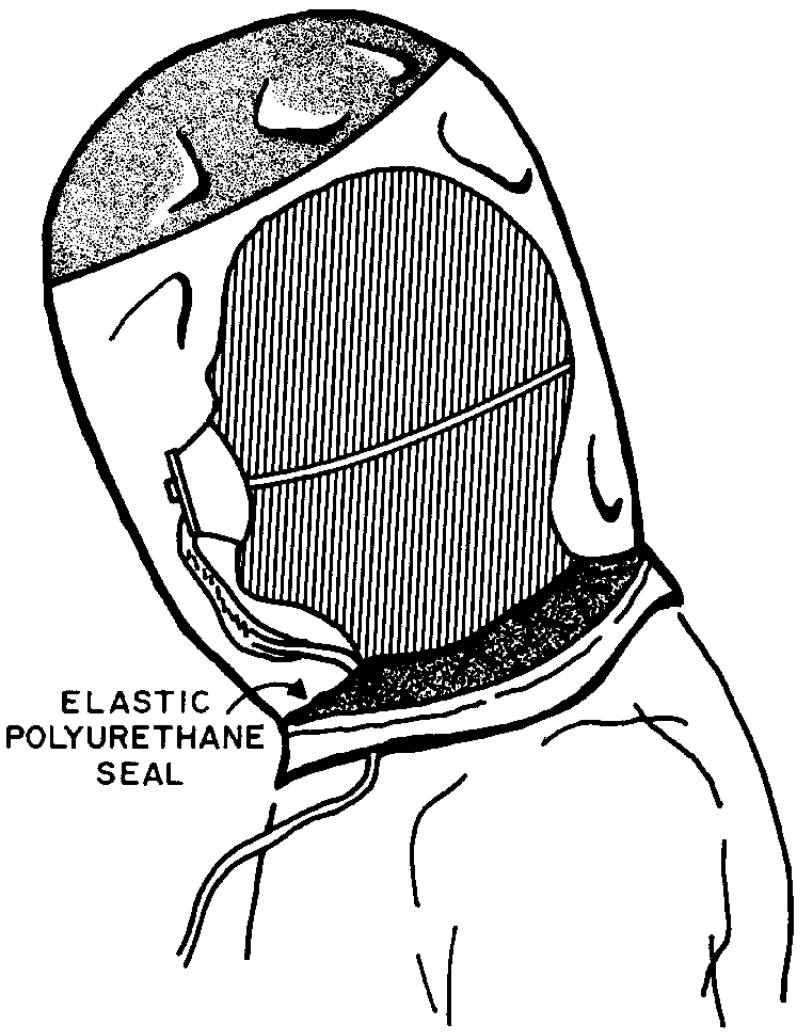

FIGURE 4. Phase dilution passenger oxygen mask in combination with the septal smoke hood.

In its most simple form the device consists of an aspirator that utilizes flow from any pressure source to draw expired air over a bed of carbon dioxide absorbent and thereby remove the carbon dioxide from the system. The potential use of a carbon dioxide absorbent attached to the exhalation valve, or by use of an aspirator, is shown in Figure 5. The aspirator system might need to be closed off for use at high altitudes.

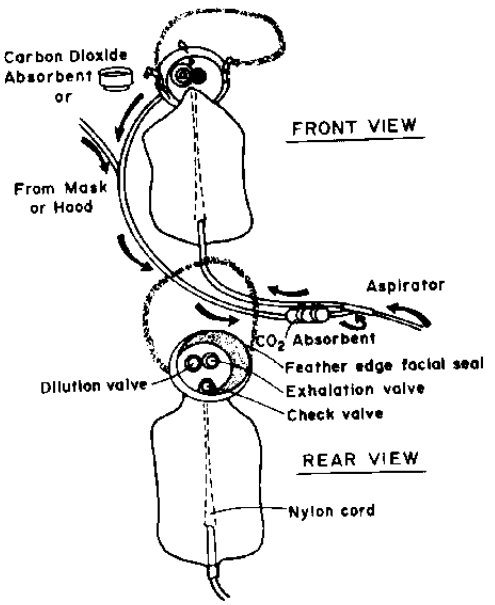

FIGURE 5. Two alternative concepts in modifying a passenger oxygen mask to provide respiratory protection from smoke and toxic gas. A third improved variation has been constructed that uses a carbon dioxide absorbent bed superimposed between the exhalation and dilution valves and an additional reservoir, thereby producing a double pass of the exhaled gases through the absorbent bed.

In aircraft such as the L-1011 and DC-10, which utilize chemical oxygen generators to supply passenger oxygen, a different problem exists relative to oxygen flow. Chemical oxygen generators for these systems utilize a shaped core designed to provide high flows on decompression and decreased flows during emergency descent but must equal or exceed the requirements of FAR Part 25.1443(c) (Curve A, Figure 2).

In practice, the chemical generator manufacturers are required by the airframe manufacturers to meet their specifications, such as the hypothetical curve represented by Curve B in Figure 2.

Chemical oxygen generators such as used in the L-1011 and DC-10 on initiation produce an initial flow of from 4 to 6 L/min, which decays to 1.5 L/min in the last 2 to 3 min of their 15-min duration. Use of this system would require some sort of recycling and carbon dioxide absorption to be effective as a smoke protective device for any extended duration.

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