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AN ANALYSIS OF POTENTIAL PROTECTIVE BREATHING DEVICES INTENDED FOR USE BY AIRCRAFT PASSENGERS

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16. Abstract

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INTRODUCTION

Various types of oxygen masks and supporting regulators 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 continuous in-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 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 also be provided with protective breathing equipment (1).

Because respiratory protection is required in either of the above conditions, the use of the quick-don crew oxygen mask as a protective breathing device is logical, providing provisions are made to protect the visual processes. The air carriers have taken this approach and provide supplementary goggles for use with crew oxygen masks, thereby satisfying the requirements for respiratory and visual protection.

Various types of oxygen masks with supporting oxygen supplies and controls have been used aboard air carrier aircraft to provide breathing oxygen to passengers in the event of a loss of cabin pressure. Passenger masks must cover the nose and mouth and provide a tracheal oxygen partial pressure of at least 100 mm for altitudes to 18,500 ft and 83.8 mm for altitudes from 18,500 ft to 40,000 ft (2,3). Most passenger oxygen masks are of the continuous-flow, phase-dilution type that provide a high concentration of oxygen during the initial portion of each inhalation, thereby providing a high concentration of oxygen to the alveoli of the lungs. As inhalation continues and the oxygen reservoir bag is drained, ambient air is introduced through the ambient-dilution valve, providing air to the respiratory "dead spaces" where little gas exchange occurs. A system of this type provides sufficient oxygen to maintain useful consciousness, yet is very conservative in the amount of oxygen required from the aircraft system.

Continuous-flow, phase-dilution masks are generally provided with a flow of oxygen that increases from about 0.5 L/min at 15,000 ft to 3.1 or 3.2 L/min at 40,000 ft. A design of this type utilizes the expansion of the oxygen as it is released from the aircraft system to provide an increased volume flow to the mask. At 40,000 ft, with a flow of 3.1 L/min and an expansion ratio of approximately 8.5/1 {Body Temperature, Pressure, Saturated/Normal Temperature, Pressure, Dry (BTPS/NTPD)}, the system becomes very efficient and little, if any, ambient air is inhaled. At 15,000 ft, where

*40,000 ft (12,192 m). In order to be consistent with the units commonly used in the aircraft industry, in aircraft instrument displays, and in air traffic control flight levels, all altitudes in this report will be expressed in feet.

very little supplemental oxygen is required (a flow of 0.5 L/min and an expansion ratio of approximately 2.1/1 BTPS/NTPD) most of the inspired gas will be ambient air inhaled through the dilution valve. Consequently, the masks function as intended by providing protection during decompressions, but are of limited value in a smoke/fume environment unless a decompression to a high altitude also occurs.

In November 1979, an American Airlines B-727 developed a smoke/fume atmosphere following an in-flight explosion of a low-yield bomb. Because of the intense increase in the smoke/fumes concentration in the cabin, the flight-deck crew manually deployed the passenger oxygen masks. Passengers donned the masks and, in the ensuing investigation, indicated that this action by the crew had saved their lives. In January 1980, a Hughes Airwest DC-9 developed fumes in the cabin while in flight. The flight-deck crew manually deployed the passenger oxygen masks. Passenger reactions were similar to those in the B-727 incident. Subsequently, Boeing and McDonnell Douglas issued bulletins indicating that manual deployment of the passenger masks, without a decompression, would not provide protection from smoke/fumes because there is no oxygen flow to the masks at normal cabin altitudes (4,5). Passengers in the incidents cited probably derived some psychological benefit from the masks, feeling that "something" was being done. This probably reduced the tendency to hyperventilate which often accompanies anxiety. However, partial protection could be provided by deploying passenger oxygen masks in aircraft equipped with oxygen generator systems (e.g., the DC-10, L-1011, and A-300). The oxygen generators are designed to provide flows of 3.3 to 3.5 L/min NTPD per attached mask during the early period of generation, with decreasing flow during the later period of generation. This partial protection would be limited in value but would be better than no protection.

Fume protection for evacuation purposes during a postcrash fire can be provided with a simple hood device provided the hood is donned prior to an increase in the smoke/fume concentrations within the aircraft cabin (6,7,8). It was proposed to locate these devices where they would be readily available to passengers for use in an emergency evacuation where smoke/fume concentrations constituted a hazard (9). This proposal was never adopted due to the resulting criticism concerning excessive cost, pilferage, liability, questions concerning passenger acceptability, and the hazards caused by delay in donning the device or its improper use (8). Though the use of evacuation hoods was not approved, the Federal Aviation Administration (FAA) made a commitment to continue its research and study of any potentially beneficial approach to providing passengers protection from smoke/fume environments (10).

A cooperative project with the FAA Technical Center (ACT-350) was initiated to examine concepts that might lead to the development of passenger-type protective breathing devices. The desirable features of such a device include decompression protection, protection from toxic smoke/fumes produced during in-flight fires, and some protection during emergency evacuations. It was intended that these capabilities would be included in a single device that would not require decision-making by the passenger other than to don the device. Additional considerations included the oxygen requirements for the device vs. those in current use, variations in user populations, and potential economic factors.

METHODS

A respiratory mass spectrometer (Perkin-Elmer MGA-1100) that provided on-line analyses for oxygen, nitrogen, and carbon dioxide of each breath was used as the primary analytical instrument (Figure 1). A sample volume totaling 15 mL each minute was continuously drawn from the breathing device for gas analyses. Digital readouts for carbon dioxide, nitrogen, and oxygen provided instantaneous monitoring of gas concentrations. A Honeywell Model 1858 fiber-optic oscillograph was used to produce fast-response, analog recordings of the gas analyses from the mass spectrometer. The mass

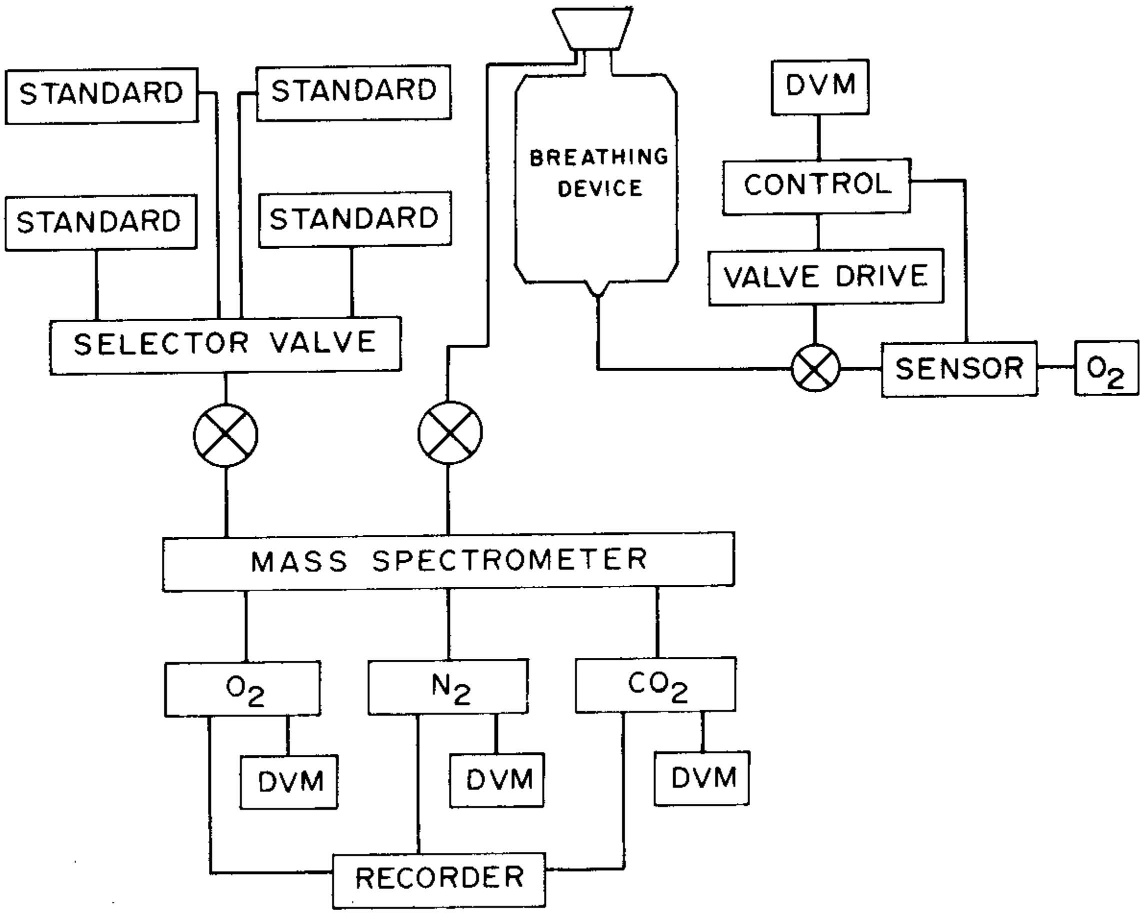

Figure 1. Diagram of the system used for testing protective breathing devices.

spectrometer was calibrated in the static mode by continuous sampling of calibration gas mixtures and in the dynamic mode by alternating gases every 3 to 5 seconds with a multiple selector gas chromatography valve (Figures 1 and 2). Calibration gases were Matheson Primary Standard grade mixtures, and oxygen used for testing was Aviator's Breathing Oxygen. A Matheson Model 8240 mass flow controller was used to regulate gas flow to those test devices that required a constant flow of oxygen (Figure 1). An Eros Intertechnique Model 10-04 oxygen mask-regulator assembly with emergency pressure capabilities was used to obtain respiratory control data for each test. A Hewlett-Packard Model 78203A heart rate module was used to monitor subjects' heart rates. Data reduction was accomplished using a Hewlett-Packard Model 9820 computer equipped with digitizer and X-Y plotter accessories.

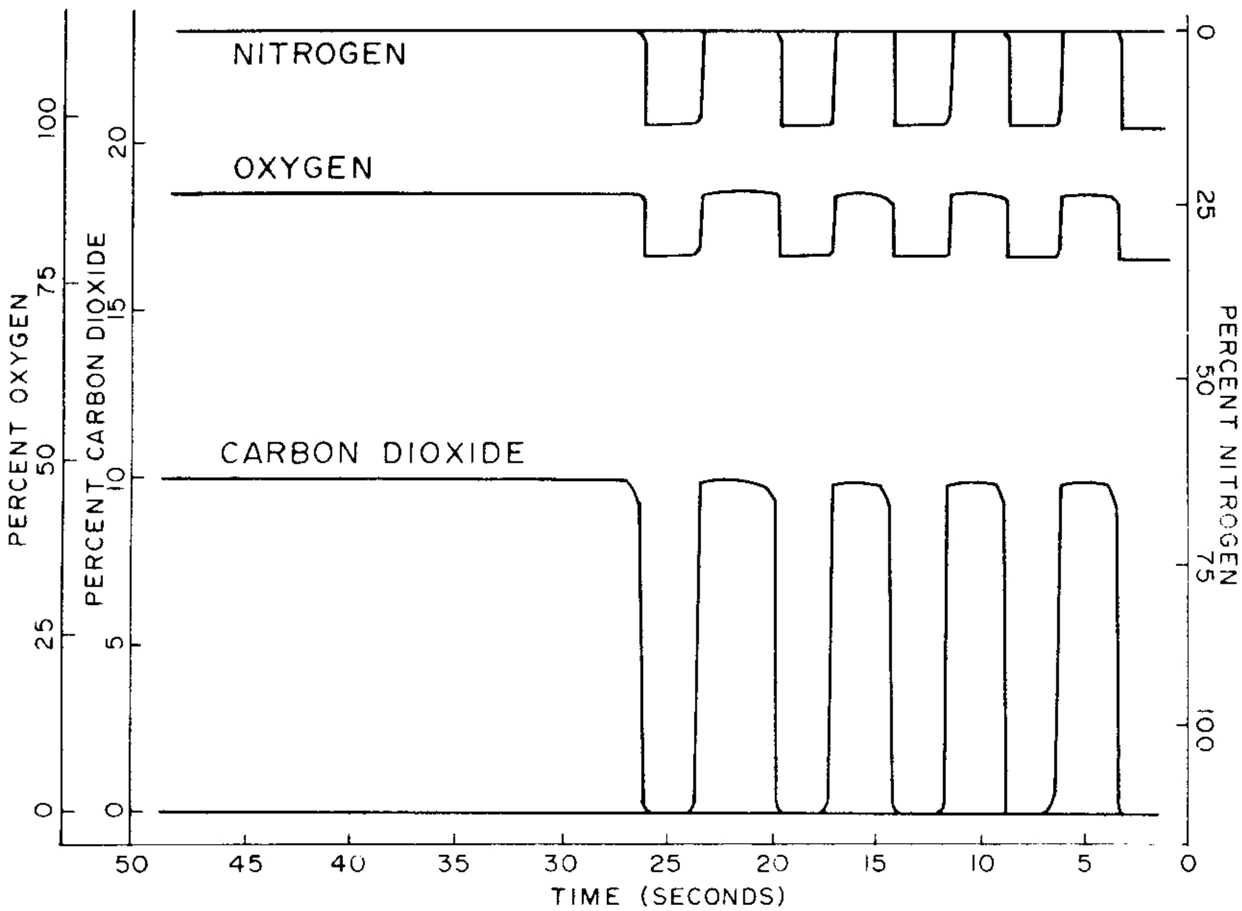

Figure 2. Static and dynamic calibration recording from the mass spectrometer.

TEST DEVICES

I. Robertshaw part number (P/N) 900-700-062-01, equipped with a hood-mounted demand regulator, P/N 900-002-143, that maintained a slight positive pressure inside the hood. The hood had an elastic band-type neck seal with an internal volume slightly in excess of an adult's head.

II. Sheldahl P/N 1009729, modified to include a continuous-flow gas inlet to provide a breathing and venting flow of oxygen. The hood had a septum-type latex neck seal and an internal volume of approximately 20 L (Figure 3).

III. Sheldahl hood as described in II, modified to have an internal volume of approximately 10 L (Figure 4).

IV. Sheldahl hood as described in II, modified to include a dual compartment system having approximately 10 L in each compartment (Figure 5). Oxygen was delivered to the lower compartment. The two compartments were interconnected through four 10 mm open ports to provide restricted venting between the compartments. The upper compartment had one 10 mm open vent to ambient air.

V. Scott-Sierra mask P/N 289-601-5, a continuous-flow, phase dilution type passenger oxygen mask equipped with a heavy duty head strap, P/N 289-607 (Figures 6 and 7). This mask has been FAA approved under technical standard order (TSO) -C64, oxygen mask assembly, continuous flow, passenger (for air carrier aircraft), and was used for comparison testing.

VI. Scott-Sierra oxygen mask as described in V, modified to include a flat rebreather bag 10 in wide X 14 in long fabricated from a soft, lightweight plastic. The rebreather bag was connected to the mask exhalation and ambient dilution valves (Figures 8 and 9). Two 6 mm open ports were located in the distal end of the rebreather bag to provide ambient venting.

VII. Scott-Sierra oxygen mask as described in VI. The rebreather bag was modified to contain two one-way valves located in the distal end in lieu of the open port vents. Of these, one was a dump or exhalation valve from the rebreather bag and was spring-compensated to maintain a slight internal positive pressure in the bag. The other was an ambient dilute (or antisuffocation) valve into the rebreather bag and was nonpressure compensating.

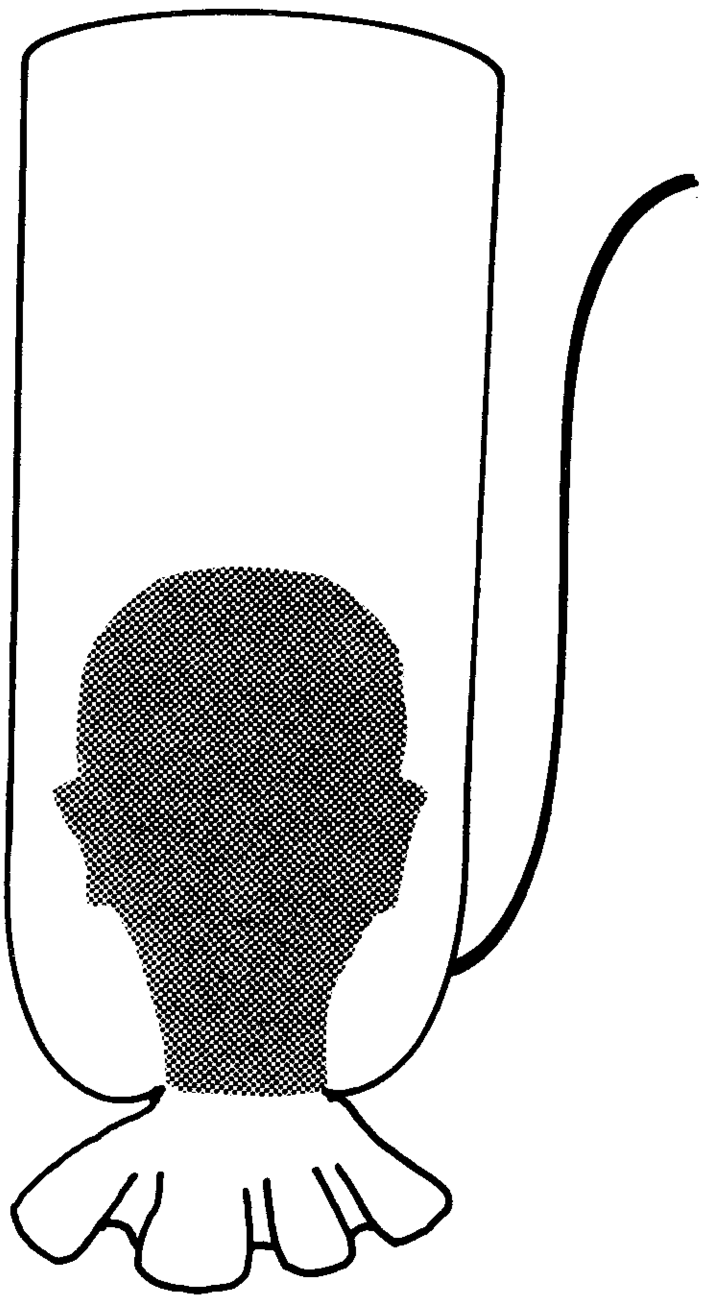

Figure 3. Sheldahl hood modified to include a continuous-flow gas inlet.

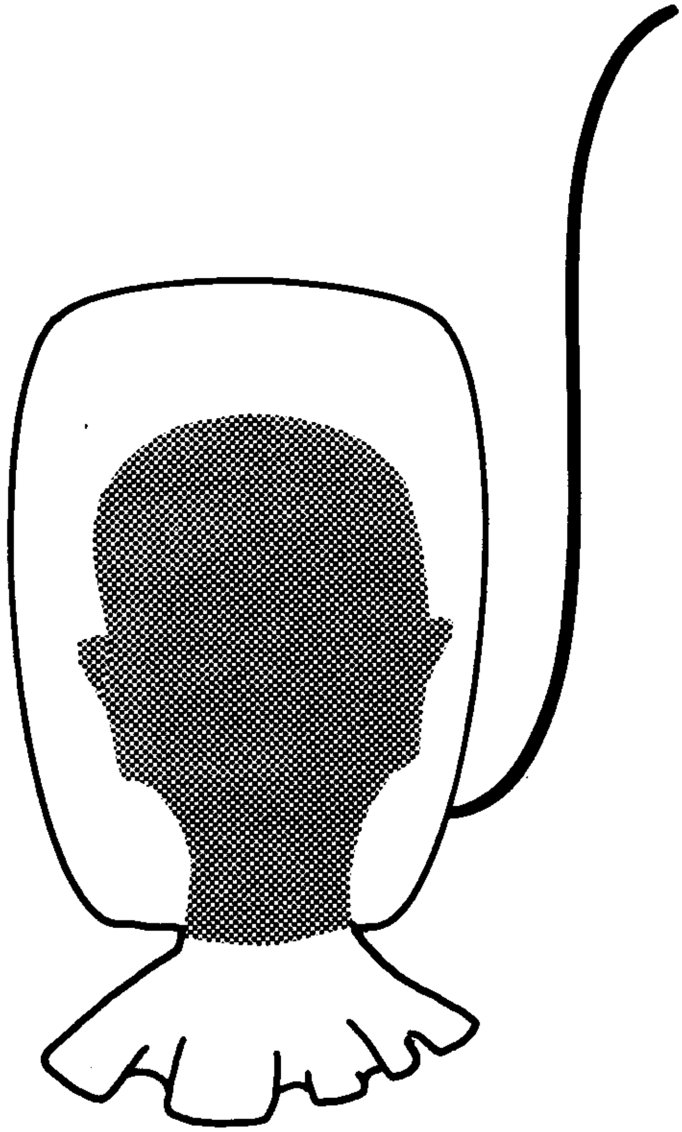

Figure 4. Sheldahl hood modified by reduction of the internal volume.

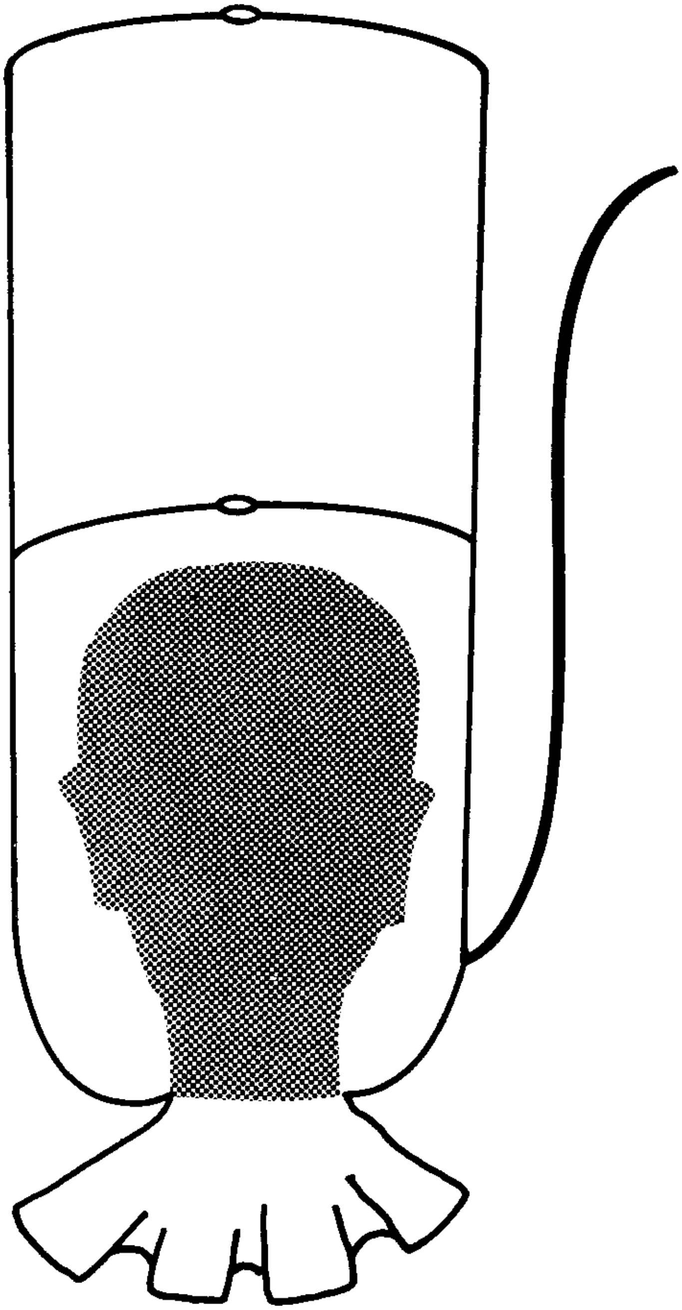

Figure 5. Sheldahl hood modified to include a dual compartment system.

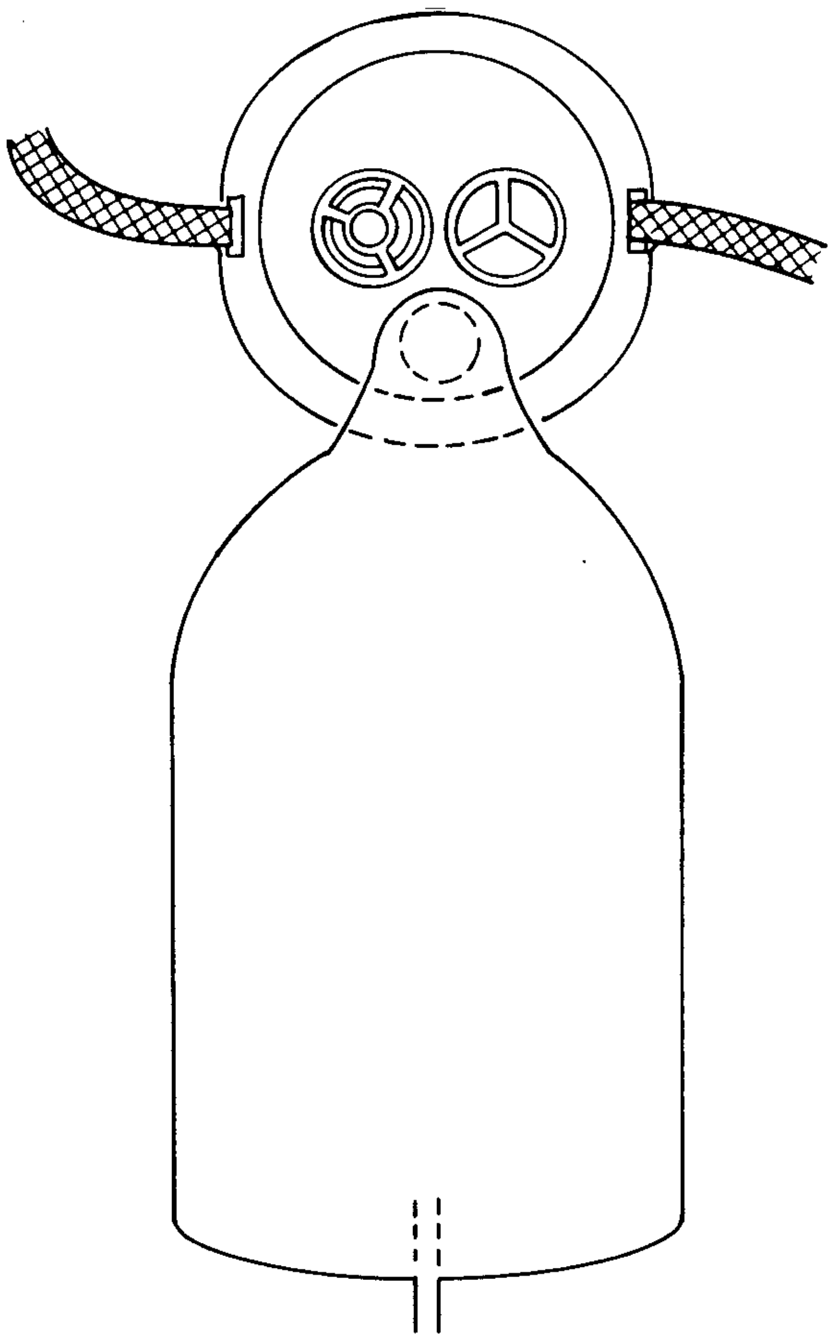

Figure 6. Front view of unmodified Scott-Sierra passenger mask.

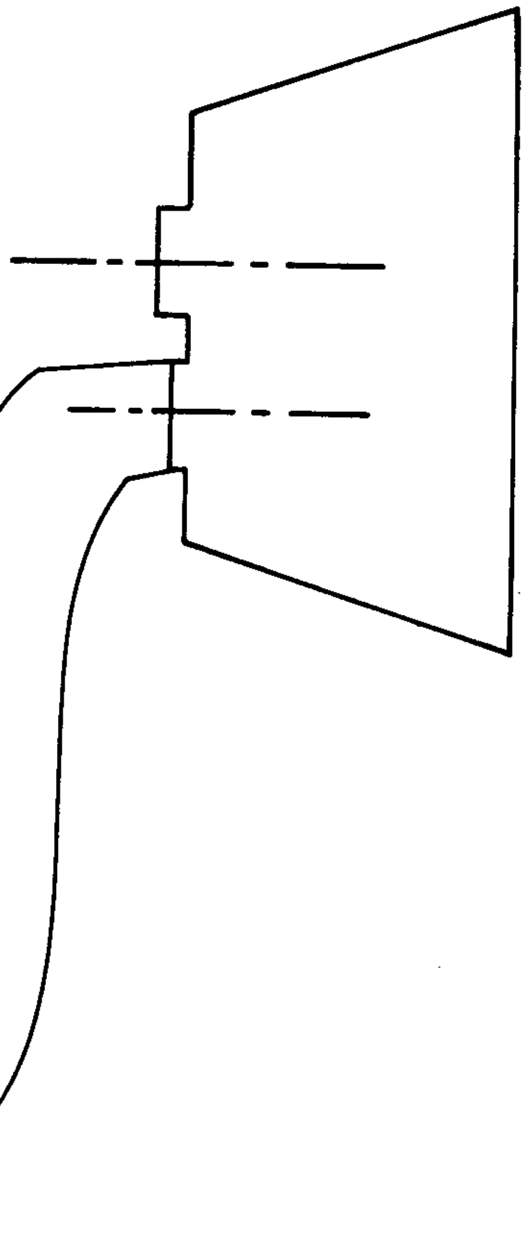

Figure 7. Side view of unmodified Scott-Sierra passenger mask.

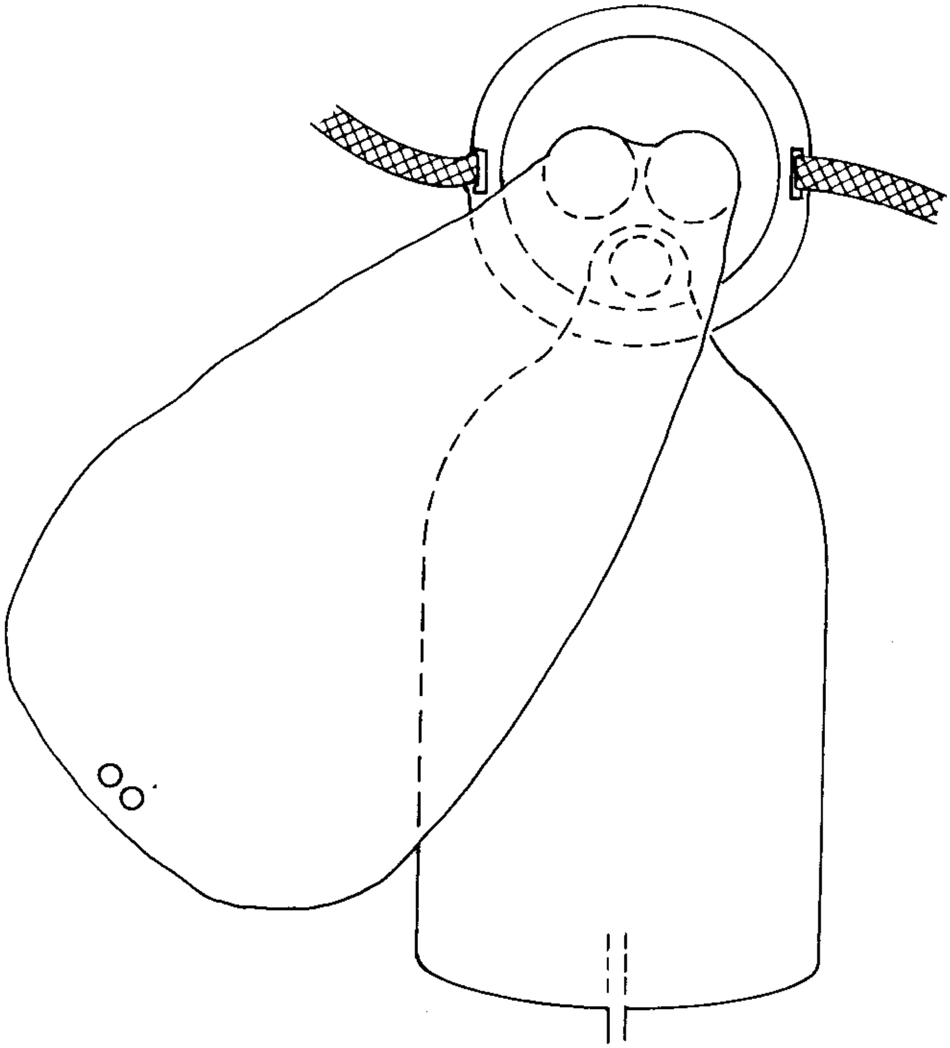

Figure 8. Front view of modified
Scott-Sierra passenger mask.

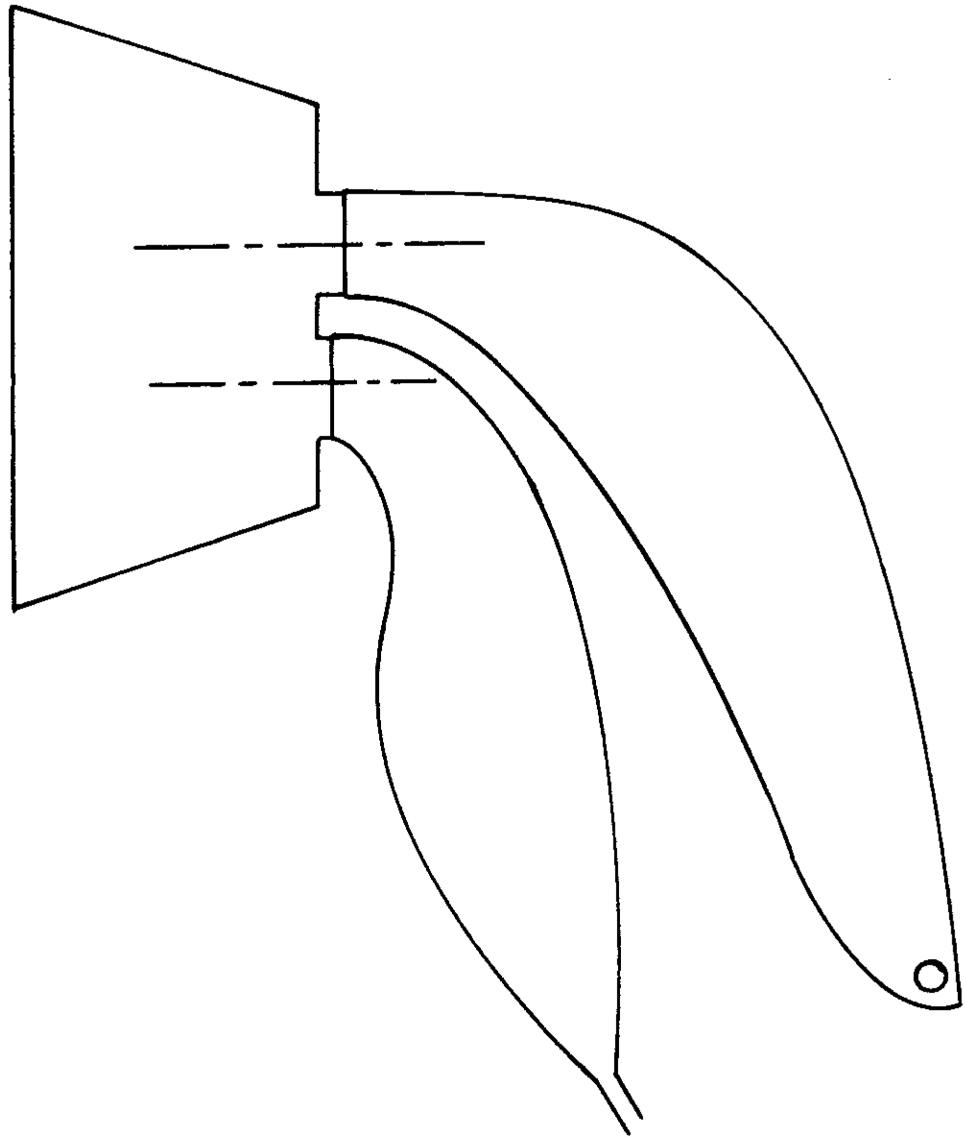

Figure 9. Side view of modified
Scott-Sierra passenger mask.

TEST PROCEDURES

Baseline (control) tests

Each subject was provided a brief period to relax. Then the overall project objectives and specific testing procedures were explained. To establish baseline data from which to evaluate the passenger-type protective breathing devices, subjects were tested while using a crew mask-regulator assembly. An Eros assembly was donned by the subject, and the regulator set to the nondilution and emergency pressure modes. The subject remained quietly seated and read items of interest during testing to minimize any conscious influence on the breathing pattern. Breathing air was delivered through a manifold assembly to the mask-regulator combination for 4 min. By adjusting the manifold assembly, Aviator's Breathing Oxygen was delivered to the mask-regulator for another 4 min. These data provided a baseline concerning each subject's breathing rate and pattern, end expiratory P_{O_2}, P_{N_2}, and P_{CO_2}, while breathing air and oxygen. They also provided a measure of the maximum rate of increase in end respiratory P_{O_2} that could be expected for each subject after being provided with 100 percent oxygen. These data allow a more reliable basis for making comparisons to the various test devices.

Protective breathing (experimental) tests

Sheldahl hoods

A passenger oxygen mask with the reservoir bag and delivery hose removed was positioned over the subject's nose and mouth to provide a means for sampling respiratory gases as they were exhaled from the lungs. A mass spectrometer gas sampling capillary was positioned through the mask wall into the mask cavity. The hood was then inflated with air, donned by the subject, and the specified flow of oxygen to the hood initiated. The hood was then worn for the 15-minute test period or until the subject indicated a desire to remove the hood. For each succeeding test in the series, the flow of oxygen to the hood was regulated as follows: 10, 8, 6, 5, or 4 L/min. The test series was continued at decreasing flow rates until the subject requested that testing be terminated. Early testing indicated that the hood, when used in this manner, would not provide adequate protection during a decompression. The testing procedure was then changed to include an initial 2-minute purge with oxygen provided at the rate of 20 L/min. The flow was then reduced to the scheduled rate for the remaining 13 minutes of each test. End expiratory P_{O_2}, P_{CO_2}, and P_{N_2} were recorded for each breath. End inspiratory P_{CO_2} was recorded as a measure of carbon dioxide buildup within the hood. Though a record was made of the entire test, only those data from minutes 1 to 10, 12, and 15 were processed, thereby saving considerable time and effort in data reduction.

Robertshaw hood

The same gas sampling and data recording techniques used for the Sheldahl hoods were used in testing the Robertshaw hood. Adjustments in the flow of oxygen were not possible since this hood is equipped with a demand regulator. The flow of oxygen during each breath was determined by means of an electronic flowmeter.

Modified passenger masks

A mass spectrometer gas sampling capillary was inserted through the mask wall into the mask cavity. The subject donned a mask equipped with a rebreather bag and oxygen flow was initiated. The oxygen flow of 10 L/min for the first test of each series was reduced for each following test in the series to 8, 6, 5, 4, or 3 L/min, or until the subject requested that the test be terminated. Each test condition was repeated with the same subject wearing a standard oxygen mask (of the same design) without the rebreather bag in order to estimate any improvement in mask efficiency due to the modification.

RESULTS

Robertshaw hood: test device I

It has been previously demonstrated that the Robertshaw hood, P/N 900-700-062-01, provides adequate respiratory protection for 15 minutes from the contaminants expected to be present in an otherwise survivable in-flight fire (8). When compared to the crew mask (100 percent oxygen with emergency pressure applied) the end expiratory P_{O_2} obtained while wearing the hood was approximately 101 mm Hg less for the first minute, 48 mm less for the second minute, and 15 mm less for the third minute (Table 1). The increased time required to achieve a high P_{O_2}, or conversely, a low P_{N_2}, is due to the additional volume within the hood and the time required to flush nitrogen from the hood and respiratory system. By the end of the sixth minute, the P_{N_2} was less than 3 mm--an indication that acceptable respiratory protection from contaminants produced during in-flight fires can be provided with this hood.

The increase in end expiratory PO_2 for subjects wearing this hood compares favorably with corresponding values obtained with passenger oxygen masks that have been TSO-C64 approved. However, the oxygen requirements for this hood ranged from 3.5 to 4.0 times the amounts required for TSO approved masks (Tables 11-18) when tested under similar ambient environments. These data indicate that acceptable decompression protection might be provided with the Robertshaw hood; however, the oxygen requirements to support this type of system would be expensive for aircraft use. Therefore the use of this hood with current aircraft oxygen systems and supplies is not feasible.

Results showed that the end expiratory PC_{O_2} levels in the hood were slightly higher than the corresponding values obtained when the crew mask was worn (Table 1). The end inspiratory P_{CO_2} levels (an indication of CO_2 concentrations in the hood) were approximately 8 mm for the hood as compared to less than 1 mm for the crew mask. Inspiratory carbon dioxide pressures of 8 mm are tolerable for the time intervals involved and would not be expected to cause the user to prematurely remove the device when used with an appropriate oxygen system.

This hood would not provide acceptable protection for evacuations requiring more than a few seconds due to the elevated carbon dioxide concentration that could develop once the hood was disconnected from the aircraft oxygen system.

TABLE 1. Respiratory Rates in Breaths per Minute, Respiratory Volumes in Liters per Minute, and End Expiratory and Inspiratory Gases in mmHg for the Robertshaw Hood.

	Control: Crew Mask				Test: Robertshaw Hood					
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory	
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate	Volume
1	412	240	37	13	311	336	40	8	16	25.4
2	612	43	37	14	564	84	40	8	16	23.7
3	641	14	37	14	626	25	39	7	16	23.3
4	648	7	37	14	643	8	39	8	16	23.0
5	*				646	4	38	7	15	22.5
6					648	3	39	7	16	22.6
7					650	3	38	7	17	22.3
8					649	2	38	8	16	22.3
9					650	1	38	8	16	22.1
10					651	1	38	8	16	22.3
12**					650	1	38	8	16	22.0
15					651	2	38	7	16	22.1

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

Sheldahl hood: test device II

Due to the large internal volume of the Sheldahl hood, P/N 1009729, the purge flow of 20 L/min of oxygen for 2 minutes did not produce a rapid increase in end expiratory P_{O_2} or, conversely, a rapid decrease in P_{N_2} (Tables 2, 3, 4, and 5). When compared to the crew mask, the end expiratory P_{O_2} obtained while wearing the hood was approximately 200 mm less for the first minute and 210 mm less for the second minute. When compared to a TSO-C64-approved passenger oxygen mask provided with a flow of 6 L/min (approximately equivalent to the volume flow provided these masks at 26,500 ft) (Tables 11 and 15), end expiratory P_{O_2} values obtained while wearing the hood were approximately 170 mm less for the first minute and 150 mm less for the second minute, the most probable critical times during a decompression. These data indicate that this hood, even when provided with a purge flow of 20 L/min of oxygen for 2 minutes, would not provide acceptable protection should a severe decompression occur.

It has been previously demonstrated (6,8) that this hood, when worn for emergency evacuations (1-3 min) did provide protection from a contaminant atmosphere. End expiratory P_{N_2} values obtained while wearing this hood indicate that an acceptable neck seal had been achieved. The higher P_{N_2} values occurred during those tests having lower sustaining flows of oxygen, a reflection of the time required to flush residual nitrogen from the large internal volume of this hood.

End expiratory and inspiratory P_{CO_2} values obtained while wearing the hood were stable during the first 2 minutes. After the purge flow was discontinued and the sustaining flow was established, P_{CO_2} levels increased inversely to the flow rate (Tables 2, 3, 4, and 5). At a sustaining flow of 10 L/min, end expiratory P_{CO_2} increased from 37 to 43 mm and end inspiratory levels increased to 28 mm. Of the five subjects tested at a sustaining flow of 5 L/min, two removed the hood prior to completion of the 15-minute test. These data indicate that a sustaining flow of about 8 L/min would be required if the hood is to be used for in-flight fume protection. If this hood is to be worn for evacuation purposes following in-flight use, a sufficient sustaining flow would be required to keep P_{CO_2} levels within tolerable limits following disconnection from the aircraft system.

Sheldahl hood, reduced volume: test device III

The internal volume of the Sheldahl hood, P/N 1009729, was reduced to determine to what extent the oxygen and carbon dioxide levels could be controlled as compared to the corresponding times and flow rates for the unaltered hood. As expected, an increase in end expiratory P_{O_2} did occur due to the decreased hood volume (Tables 6, 7, 8, 9, and 10). However, oxygen levels were not adequate to provide acceptable protection should a decompression occur.

TABLE 2. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood. Purge Flow of 20 L/min for 2 min then 10 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	388	258	34	12	211	434	37	7	13
2	598	50	33	12	419	222	38	8	12
3	633	16	34	11	501	139	39	11	12
4	642	7	34	11	532	110	38	13	13
5	*				549	92	38	14	13
6					565	76	38	14	13
7					576	66	38	15	14
8					587	56	37	15	14
9					598	46	37	15	14
10					609	35	37	15	14
12**					626	19	37	15	15
15					637	8	37	15	14

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 3. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood. Purge Flow of 20 L/min for 2 min then 8 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	392	252	35	11	200	442	36	6	13
2	594	52	34	11	370	271	37	7	12
3	631	17	34	12	478	164	37	9	13
4	641	8	34	11	526	116	36	11	14
5	*				556	87	37	12	14
6					576	66	38	13	13
7					593	50	37	14	14
8					605	38	38	15	13
9					614	29	37	16	13
10					621	23	38	16	14
12**					631	14	38	16	13
15					637	6	38	17	14

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 4. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood. Purge Flow of 20 L/min for 2 min then 6 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	391	252	35	10	203	439	36	7	14
2	599	48	35	11	393	249	37	7	12
3	634	14	35	11	494	147	38	10	13
4	642	7	34	12	526	115	38	12	13
5	*				547	94	38	15	13
6					564	77	39	17	14
7					578	64	39	19	13
8					590	52	39	20	14
9					599	44	39	21	14
10					606	35	40	22	13
12**					618	24	40	23	14
15					627	14	40	23	14

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 5. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood. Purge Flow of 20 L/min for 2 min then 5 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	408	236	35	11	188	452	37	7	14
2	597	50	35	11	387	252	39	8	12
3	631	17	35	12	486	152	39	10	12
4	640	8	34	12	516	123	39	13	13
5	*				532	107	39	16	13
6					547	91	40	19	14
7					561	78	40	20	14
8					573	66	41	22	14
9					583	56	41	23	14
10					590	48	42	25	14
12**					600	34	42	26	14
15					613	22	43	28	14

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 6. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood with Reduced Volume. Purge Flow of 20 L/min for 2 min then 10 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	PO_2	PN_2	PCO_2	Rate	PO_2	PN_2	PCO_2	PCO_2	Rate
1	437	210	37	14	247	401	39	10	18
2	621	29	36	15	449	196	40	10	18
3	642	8	37	15	531	114	40	13	17
4	647	4	36	14	574	71	40	16	18
5	*				599	46	41	17	18
6					617	30	41	19	17
7					627	19	41	20	17
8					634	13	41	20	17
9					638	8	41	20	17
10					641	6	40	21	18
12**					644	3	40	20	17
15					645	1	40	19	18

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 7. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood with Reduced Volume. Purge Flow of 20 L/min for 2 min then 8 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	PO_2	PN_2	PCO_2	Rate	PO_2	PN_2	PCO_2	PCO_2	Rate
1	420	220	37	13	229	409	39	8	17
2	603	41	37	14	446	192	39	9	16
3	632	12	36	14	530	108	39	12	16
4	639	7	36	13	566	73	40	16	16
5	*				589	51	40	18	16
6					604	35	41	19	16
7					615	24	41	20	15
8					623	18	41	20	16
9					627	13	41	22	15
10					631	9	41	22	16
12**					635	5	41	22	15
15					637	2	41	22	15

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 8. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood with Reduced Volume. Purge Flow of 20 L/min for 2 min then 6 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	PO_2	PN_2	PCO_2	Rate	PO_2	PN_2	PCO_2	PCO_2	Rate
1	420	227	36	13	232	412	39	8	15
2	606	46	36	13	466	178	39	8	16
3	636	15	36	13	554	91	39	12	15
4	643	8	36	12	583	62	39	16	17
5	*				599	46	40	19	15
6					611	35	41	21	15
7					618	27	42	22	15
8					624	23	44	23	15
9					629	19	44	25	14
10					632	15	44	25	14
12**					638	9	44	26	15
15					641	5	44	26	15

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 9. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood with Reduced Volume. Purge Flow of 20 L/min for 2 min then 5 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	374	266	37	12	218	422	40	7	16
2	583	59	38	12	438	200	40	9	14
3	623	21	38	12	513	126	41	14	15
4	634	11	37	12	540	98	42	18	14
5	*				562	76	42	22	15
6					579	58	42	24	15
7					591	46	43	26	15
8					601	36	44	27	14
9					609	28	44	28	16
10					615	22	45	29	15
12**					623	14	45	30	15
15					629	7	45	31	16

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

TABLE 10. Respiratory Rates in Breaths per Minute and End Expiratory and Inspiratory Gases in mmHg for the Sheldahl Hood with Reduced Volume. Purge Flow of 20 L/min for 2 min then 4 L/min.

	Control: Crew Mask				Test: Sheldahl Hood				
	Expiratory			Respiratory	Expiratory			Inspiratory	Respiratory
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	Rate	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	Rate
1	395	245	37	14	249	387	40	5	12
2	596	47	36	13	472	165	39	6	12
3	624	19	36	13	544	93	39	12	15
4	629	15	36	14	567	69	40	17	13
5	*				580	55	41	21	14
6					590	45	42	25	14
7					598	36	43	26	15
8					604	29	44	28	14
9					610	23	45	29	15
10					614	20	45	30	15
12					620	14	45	31	15
15					625	9	45	32	15

*Control test was for 4 minutes only.
**Data for minutes 11, 13, and 14 were not processed.

As expected, end expiratory and inspiratory P_{CO_2} levels increased as the sustaining flow rates decreased. Respiratory rates did not increase as a function of the carbon dioxide levels; however, ventilatory volume increased (direct observation of the subjects). Subjects began to remove the hoods during those trials in which a sustaining flow of 6 L/min was provided (Table 6). These data indicate that, if protection from contaminants produced by in-flight fires is to be provided with these hoods, a sustaining flow of approximately 8 L/min would be required. If these devices are to be worn for evacuations following in-flight use, a sustaining flow of 10 L/min or greater would be required to insure that carbon dioxide levels in the hood would be sufficiently low to allow time for an evacuation.

Sheldahl hood, dual compartment: test device IV

The Sheldahl hood, P/N 1009727, was modified to a dual compartment configuration to increase the effectiveness of the sustaining oxygen flow in controlling oxygen and carbon dioxide levels in the compartment around the head (Figure 5). The gases vented through this compartment via the sustaining flow are accumulated in the upper compartment before being vented to the atmosphere. The second compartment provided a residual volume of breathable gas (via the open ports between the compartments) that might extend the time this hood could be used for evacuation purposes. Since data from the initial tests indicated that the dual compartment system did not produce any improvement in oxygen or carbon dioxide levels when compared to test device III, testing was discontinued.

Scott-Sierra mask: test device VI

The continuous-flow, phase-dilution passenger oxygen mask accumulates oxygen in a reservoir bag during the exhalation phase of the respiratory cycle. When inhalation starts, a valve between the mask and reservoir opens and oxygen is drawn from the reservoir until it is emptied. At this time a dilution valve is opened and ambient air is drawn into the mask, providing the volume necessary to complete the inhalation process. All expired gases are passed through an exhalation valve to the ambient atmosphere. If the aircraft is supplied with stored oxygen, the flow delivered to the mask is controlled by a pressure valve that increases the flow as cabin pressure drops. If the aircraft is equipped with a chemical generator system, the flow of oxygen to the mask is controlled via core design of the generator. As oxygen is released, both systems utilize gas expansion as a means to provide the mask with a sufficient volume of oxygen for the particular cabin pressure. Consequently, a minimum volume of oxygen is provided during mild decompressions. Under these conditions, most of the respiratory volume is composed of ambient air drawn through the dilution valve and the mask is of limited value in a smoke/fume environment. An additional gas reservoir bag, coupled to the exhalation and dilution valves, was added to the mask (Figures 8 and 9). A rebreather reservoir of this type prevents inhalation of ambient air and requires an oxygen flow sufficient to maintain oxygen and carbon dioxide levels within acceptable limits. Two open ports of 6 mm diameter were provided at the distal end of the rebreather reservoir to vent carbon dioxide from the system and to prevent the development of back pressure in the mask. These ports must be properly sized if the rebreather reservoir is to function properly.

Results from tests in which the mask was provided sustaining flows of 10 L/min and 8 L/min are not included in this report since the data indicated that these flow rates were excessive. At flow rates of 5 or 6 L/min (Tables 11, 12, 13, and 14), the PO_2 values obtained with the modified passenger mask were 20-35 mm less than those obtained with the crew mask (100 percent oxygen with positive pressure). Considering the types of masks being compared, these data are remarkable since they indicate the critical sustaining flow for the modified passenger mask to be between 5 and 4 L/min.

Carbon dioxide levels were tolerated by the subjects through those tests that had a sustaining flow of 4 L/min oxygen. However, a sustaining flow of 3 L/min did not sufficiently flush carbon dioxide from the rebreather reservoir. The data indicate that a sustaining flow of about 5 L/min would be required to control oxygen and carbon dioxide levels within acceptable limits.

Scott-Sierra mask: test device VII

This modification of the passenger oxygen mask differed from test item VI in that valves were incorporated in the distal end of the rebreather reservoir in lieu of open ports. Based on data relating to the open port design, it was assumed that further improvements might be achieved by replacing the open ports with flapper valves. The data obtained from testing this device does not support that assumption (Tables 15, 16, 17, and 18). In consideration of the limited number of subjects, it would be difficult to identify any true differences between the two masks that could be attributed to the use of valves in the rebreather reservoir rather than the ports. However, the use of open ports instead of valves in the rebreather reservoir is worthy of consideration from an economic standpoint.

CONCLUSIONS

The use of hood devices for decompression protection would be of limited value due to their internal volume and the time and oxygen flow required to raise oxygen concentrations to acceptable levels. Hoods would be effective for protection from fumes produced by in-flight fires provided that a sufficient, sustaining flow of oxygen is furnished to maintain oxygen and carbon dioxide levels within acceptable limits. Hoods would be useful for emergency evacuations provided that they are donned free of toxic fumes, contain sufficient oxygen, and have an internal volume large enough to allow dilution of carbon dioxide.

TABLE 11. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Open Ports.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)
1	404	240	35	10	385	259	36	7	13	379	265	34	12
2	609	37	34	11	582	61	36	7	12	534	110	33	12
3	636	12	34	11	614	30	35	6	11	544	100	33	12
4	642	6	34	11	610	26	34	6	13	544	102	32	13
5					625	19	35	8	11	544	102	32	13
6					625	19	35	7	13	552	95	32	13
7					629	17	32	8	15	552	94	31	13
8					630	16	33	7	14	542	105	31	13
9					636	10	33	8	14	544	103	31	14
10					634	13	33	8	14	562	84	31	14
12					637	11	32	7	14	564	83	31	14
15					634	14	31	6	15	563	84	36	14

*TSO approved configuration.

TABLE 12. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Open Ports.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)
1	400	247	33	11	366	278	36	10	11	319	330	31	12
2	610	40	32	11	568	77	36	10	11	470	178	31	12
3	639	12	32	11	604	43	36	11	11	482	167	31	13
4	646	6	31	11	618	28	36	13	12	517	132	30	13
5					620	26	35	12	11	506	143	30	13
6					624	23	36	13	12	499	150	30	14
7					620	27	35	14	12	495	155	29	14
8					618	28	35	14	12	497	153	29	14
9					611	36	35	13	12	500	151	29	14
10					609	37	34	13	12	513	139	28	15
12					615	33	34	12	13	504	147	29	14
15					616	32	34	12	12	501	149	28	15

*TSO approved configuration.

TABLE 13. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Open Ports.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	PO_2	PN_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	(RR)
1	348	290	40	10	305	333	40	10	11	266	375	38	8
2	573	69	40	11	504	132	42	15	11	461	179	39	8
3	623	21	39	10	556	82	43	15	11	454	186	38	11
4	636	9	38	11	560	75	43	13	11	441	199	38	10
5					552	85	42	15	11	463	175	39	9
6					554	83	42	14	10	458	182	37	10
7					543	93	42	15	11	452	188	37	11
8					543	95	42	17	11	433	207	37	12
9					553	85	41	16	11	424	216	36	11
10					560	78	41	16	11	429	212	36	12
12					562	77	41	18	11	429	210	37	12
15					558	81	40	17	11	433	208	37	11

*TSO approved configuration.

TABLE 14. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag Bag and Open Ports.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)
1	344	302	36	8	321	381	36	13	11	236	411	34	10
2	579	69	35	8	478	184	39	22	11	337	311	34	9
3	628	21	35	8	506	140	39	22	11	384	263	35	9
4	641	9	34	8	519	123	40	21	10	390	258	33	10
5					522	120	40	22	12	392	256	33	12
6					521	115	40	22	11	384	265	33	11
7					530	111	40	23	12	378	270	32	12
8					525	114	40	22	13	380	271	32	12
9					530	109	40	24	12	390	259	33	12
10					515	122	40	23	14	367	283	31	11
12					464	178	40	18	11	408	240	33	12
15					446	197	39	15	14	410	237	33	12

*TSO approved configuration.

TABLE 15. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Double Valve System.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	PO_2	PN_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	(RR)
1	394	252	34	9	396	249	36	5	11	381	266	33	10
2	598	51	33	9	586	59	36	2	10	569	81	33	11
3	633	17	33	10	613	34	35	4	11	580	69	33	13
4	642	9	33	10	622	27	35	5	12	564	85	32	13
5					632	23	36	6	12	571	79	32	13
6					626	22	34	6	12	568	81	32	13
7					626	22	34	6	12	564	85	31	13
8					627	21	34	6	13	565	86	30	13
9					626	22	33	6	12	567	82	31	12
10					625	22	33	6	13	575	75	31	13
12					625	22	32	5	13	566	83	31	14
15					626	23	32	6	13	562	87	30	14

TSO approved configuration.

TABLE 16. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Double Valve System.

Minute	Control: Crew Mask (E) PO_2	Control: Crew Mask (E) PN_2	Control: Crew Mask (E) PCO_2	Control: Crew Mask (RR)	Test With Rebreather Bag (E) PO_2	Test With Rebreather Bag (E) PN_2	Test With Rebreather Bag (E) PCO_2	Test With Rebreather Bag (I) PCO_2	Test With Rebreather Bag (RR)	Test Without Rebreather Bag* (E) PO_2	Test Without Rebreather Bag* (E) PN_2	Test Without Rebreather Bag* (E) PCO_2	Test Without Rebreather Bag* (RR)
1	382	265	32	9	335	149	34	10	9	361	285	32	9
2	600	50	32	10	569	38	34	9	10	568	79	32	10
3	636	15	31	9	595	30	35	10	10	526	122	31	12
4	642	10	30	9	606	22	35	8	11	512	136	30	12
5					617	24	34	11	11	519	128	30	13
6					620	21	34	12	13	534	114	31	14
7					623	23	33	13	12	520	128	30	14
8					627	22	34	11	12	515	133	30	13
9					625	24	33	12	12	521	128	30	14
10					630	21	34	12	12	521	127	30	13
12					630	21	34	11	13	530	119	30	14
15					628	20	34	13	13	536	114	30	14

*TSO approved configuration.

TABLE 17. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Double Valve System.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	P_{CO_2}	(RR)	P_{O_2}	P_{N_2}	P_{CO_2}	(RR)
1	346	301	35	7	309	336	36	12	10	320	326	34	9
2	582	67	34	9	515	129	37	12	10	482	165	34	11
3	630	21	33	8	551	95	37	16	10	488	161	33	11
4	641	10	33	9	574	71	36	18	11	479	168	33	11
5					583	64	36	18	11	496	152	33	11
6					595	53	36	19	10	493	154	33	11
7					601	46	36	20	11	488	160	33	11
8					604	44	36	20	11	490	160	32	12
9					608	41	36	19	12	487	160	33	12
10					600	49	36	19	11	472	177	32	11
12					603	45	36	19	11	485	163	33	11
15					598	49	36	18	12	490	158	33	12

*TSO approved configuration.

TABLE 18. Respiratory Rates (RR) in Breaths per Minute and End Expiratory (E) and Inspiratory (I) Gases in mmHg for the Sierra Mask with Rebreather Bag and Double Valve System.

	Control: Crew Mask				Test With Rebreather Bag					Test Without Rebreather Bag*			
	(E)				(E)			(I)		(E)			
Minute	PO_2	PN_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	PCO_2	(RR)	PO_2	PN_2	PCO_2	(RR)
1	396	254	32	8	288	357	36	14	9	312	333	33	11
2	604	49	31	9	459	184	38	21	10	410	236	33	11
3	640	14	31	9	498	147	38	22	10	389	258	33	11
4	646	8	31	9	511	134	38	24	11	398	250	33	12
5					530	113	38	25	11	381	267	32	12
6					539	105	38	26	10	384	265	32	11
7					540	105	39	26	12	387	262	32	11
8					521	125	38	25	13	410	237	32	11
9					524	122	38	26	13	397	252	32	11
10					521	124	38	27	13	405	244	32	10
12					532	114	38	26	14	412	235	32	12
15					529	117	38	26	15	382	217	31	13

*TSO approved configuration.

The use of a continuous-flow, phase-dilution, controlled-rebreather oxygen mask for passenger protection during decompressions appears to offer advantages over TSO-approved continuous-flow, phase-dilution type masks. These results should be verified by altitude chamber testing. Data indicate that masks of this design would provide respiratory protection from fumes produced during in-flight fires. The number of subjects tested with these masks should be increased to obtain a better representation of the population. The use of this type of mask for emergency evacuations would require that they be charged with oxygen and donned free of contaminants. This approach, however, would not provide visual protection from eye irritants.

Of the various devices tested, the passenger oxygen mask modified to incorporate a controlled-use rebreather reservoir in addition to but separate from the oxygen reservoir offers the best approach of the devices tested to achieve the desired objectives. This type mask would require a flow of approximately 5 L/min of sustaining oxygen. Most of the current in-use, passenger-activated oxygen systems, both compressed gas and chemical generators, deliver about 3.1 to 6.0 L/min for about 15 min. Some of the lower flows, therefore, would have to be increased to meet the 5 L/min needed flow rate.

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