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Performance Comparison of Rescue Breathing Apparatus

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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CONTENTS

ILLUSTRATIONS

CONTENTS—Continued

Page

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

breaths/min	breaths per minute	L/min	liter(s) per minute
ft	foot (feet)	min	minute(s)
hr	hour(s)	mm H_2O	millimeter(s) of water pressure
kg	kilograms(s)	psi	pound(s) per square inch
L	liter(s)	°C	degrees Celsius
L/breath	liter(s) per breath	%	percent

PERFORMANCE COMPARISON OF RESCUE BREATHING APPARATUS

By Nicholas Kyriazi[1]

ABSTRACT

A performance comparison of 14 rescue breathing apparatus was undertaken as an assessment of past and present worldwide technology. Rescue breathing apparatus are self-contained, closed-circuit breathing apparatus used for entry into areas having atmospheres that are immediately dangerous to life and health. Apparatus tested were the Biomarine BioPak 45, 60, and 240; the Draeger BG 4 and BG-174A; the Litton LITPAC II; the MSA Custom 4500 II Air Mask, Chemox, and McCaa; the Sabre Selected Elevated Flow Apparatus (SEFA); the Scott Rescue-Pak; the Siebe Gorman Aerorlox and Proto Ten; and the Survivair LP-120. The apparatus were tested on an automated breathing and metabolic simulator at the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH). Physiological parameters monitored during the testing were average inhaled CO_2 and O_2, minimum inhaled CO_2, inhaled wet- and dry-bulb temperatures, and peak inhalation and exhalation breathing pressures. The metabolic demand on the apparatus was 1.35 L O_2/min for most of the test with two 5-min intervals of 2.5 L O_2/min, the first beginning 10 min into the test and the second beginning 10 min before the end of the rated duration of the apparatus. Results presented include apparatus service life and test-averages of monitored physiological parameters. Schematic drawings and photographs of the apparatus are also included.

The Draeger BG-174A and BG 4 had the highest durations—295 and 291 min, respectively. The BG 4 had the lowest minimum inhaled CO_2 levels, attesting to the effectiveness of its CO_2-absorbent canister. The Sabre SEFA had the lowest *average* inhaled CO_2 levels, due mostly to the apparently low-dead-space mask and nose cup. The MSA Air Mask, the only open-circuit device tested, had the lowest wet- and dry-bulb temperatures, with the liquid-O_2-source Siebe Gorman Aerorlox having the next lowest temperatures. The only apparatus with a CO_2-absorbent not in a packed-bed design, the BG-174A, had the lowest exhalation pressures. The BG 4 had the highest level of positive pressure, with the Biomarine BioPak 60, Survivair LP-120, SEFA, and Litton LITPAC II nearly as high. The BG 4 had the lowest pressure swing, with the SEFA a close second.

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INTRODUCTION

In the event of a fire or explosion in underground coal mines, the air is likely to be irrespirable because of toxic gases or the absence of O_2. For this reason, all underground coal miners in the United States are required to have access to emergency escape breathing apparatus. Performance comparisons of such apparatus have been published by the author [Kyriazi and Shubilla 1984; Kyriazi 1996]. In order to recover the mine after a fire or explosion, or to rescue trapped miners, mine rescue teams use long-duration, closed-circuit, self-contained breathing apparatus for respiratory protection. These are commonly called rescue breathing apparatus (RBA), or entry, versus escape, apparatus.

In an effort to compare the performance of presently used, commercially available apparatus and those that have been used in the past, models of each type, which were either bought or borrowed, were tested on an automated breathing and metabolic simulator (BMS) [Kyriazi 1986]. Testing on a BMS enabled the apparatus to be evaluated with identical and repeatable inputs unlike human-subject testing. Although little attempt was made to analyze the designs of the apparatus, an apparatus designer can evaluate the effectiveness of the designs, which are shown in schematic form, by comparing the performance results. Consumers can use the performance results to help decide which apparatus best suits their needs.

DESCRIPTION OF APPARATUS

All of the apparatus tested are similar in their basic functions, which are to provide O_2 to, and absorb CO_2 produced by, the user. The standard parts of the breathing apparatus coming into contact with the user's exhaled air are the face mask, breathing hoses, CO_2-absorbent canister, and breathing bag. O_2 is stored in the apparatus as either a solid (potassium superoxide (KO_2)), a liquid, or a gas. The CO_2 absorbents used were lithium hydroxide (LiOH), calcium hydroxide (CaOH), sodium hydroxide (NaOH), or a combination of these usually simply poured into a canister (packed-bed design).

In general, exhaled air is channeled through the exhalation breathing hose to the CO_2-absorbent canister where the user's CO_2 is absorbed, and then to the flexible breathing bag. It is stored there until it is drawn through the inhalation hose and into the user's lungs upon inhalation. In most compressed-O_2 apparatus, the O_2 flows at a constant rate to the breathing bag and is supplemented at times of higher O_2 consumption by a demand valve triggered by either low bag volume or a threshold inhalation pressure. In contrast, when O_2 consumption is lower than the constant flow, the breathing bag fills to capacity and begins venting to ambient through a relief valve triggered by either high bag volume or a threshold exhalation pressure. Table 1 lists the apparatus tested. A description of each apparatus follows.

Table 1.—Rescue breathing apparatus tested

Apparatus	Rated duration, hr	Country of origin	Gas supply	Weight, kg
Biomarine BioPak 45	0.75	U.S.A.	Compressed O_2	7.7
Biomarine BioPak 60	1	U.S.A.	Compressed O_2	11.4
Biomarine BioPak 240	4	U.S.A.	Compressed O_2	17.7
Draeger BG-174A	4	Germany	Compressed O_2	15.8
Draeger BG 4	4	Germany	Compressed O_2	13.5
Litton LITPAC II	2	U.S.A.	Compressed gas	13.6
MSA Air Mask	1	U.S.A.	Compressed air	16.0
MSA Chemox	1	U.S.A.	Chemical O_2	6.1
MSA McCaa	2	U.S.A.	Compressed O_2	17.7
Sabre SEFA	2	U.K.	Compressed O_2	16.0
Scott Rescue-Pak	4	U.S.A.	Compressed O_2	15.9
Siebe Gorman Aerorlox	3	U.K.	Liquid O_2	13.4
Siebe Gorman Proto Ten	3	U.K.	Compressed O_2	15.0
Survivair LP-120	2	U.S.A.	Compressed O_2	10.0

BIOMARINE BIOPAK 45

The BioPak 45 (figures 1-2) is a compressed-O_2, closed-circuit apparatus with a disposable CO_2-absorbent canister. It was certified by the National Institute for Occupational Safety and Health (NIOSH) in 1973 as a 45-min unit when the O_2 cylinder is filled to 2,100 psi (at room temperature). The O_2 is delivered to the user at a rate of 3.6 L/min at ATPD (ambient temperature and pressure, dry) with no demand valve. The CO_2 absorbent is a form of soda lime (mostly calcium hydroxide). Unlike most of the other apparatus tested, the BioPak 45 is worn on the chest rather than the back. The face mask is equipped with a speaking diaphragm. The low-pressure alarm sounds at approximately 25% of capacity.

Exhaled air travels past the exhalation check valve in the face mask, through the exhalation hose, through the CO_2-absorbent canister, and into the breathing bag. Air is inhaled from the bag, through the inhalation breathing hose, past the inhalation check valve, and into the face mask. There is an optional coolant ring that surrounds the CO_2-absorbent canister.

BIOMARINE BIOPAK 60

The BioPak 60 (figures 3-4) is a compressed-O_2, closed-circuit apparatus with a refillable CO_2-absorbent canister. It was certified by NIOSH in 1978. It was certified again in 1988 as a positive-pressure device after that classification was added in 1985. It contains approximately 170 L of O_2 if filled to the recommended cylinder pressure of 2,250 psi.[2] A constant flow of 1.9 L O_2/min (ATPD) plus a volume-activated demand valve constitute the O_2-delivery system. The relief valve is also volume-activated. The CO_2 absorbent is Sodasorb, a form of soda lime. The low-pressure alarm sounds at approximately 25% of capacity.

The user exhales into the face mask containing both inhalation and exhalation check valves, through the exhalation hose, through the CO_2-absorbent canister, and into the breathing bag consisting of a spring-loaded, rigid diaphragm and a flexible sleeve. The CO_2-absorbent canister and breathing bag are contained within the breathing chamber, as Biomarine calls it. Upon inhalation, the air is drawn from the breathing bag through the inhalation hose and check valve, and then into the face mask. An anoxia-prevention valve, located in the exhalation hose at the point that it enters the breathing chamber, blocks exhalation flow unless opened by pressure provided by the O_2 cylinder. This prevents use of the apparatus unless the O_2 cylinder is opened and pressurized. It also signals the user when the cylinder is empty by preventing exhalation into the circuit.

The flow path through the breathing chamber is relatively complex. The exhaled air enters an inlet plenum between the CO_2-absorbent canister and a solid plate separating it from the breathing bag. The O_2 constant flow enters the circuit at this point, also. The exhaled air then travels through the absorbent to an outlet plenum formed by the canister and the lid of the breathing chamber. The exhaled air is then routed around coolant rings containing sodium phosphate crystals, through slots around the circumference of the housing, and into the breathing bag.

The spring-loading on the diaphragm results in a positive static pressure in the breathing circuit. The term "positive-pressure" is derived from this feature. When the user demands more air than is contained in the breathing bag, the diaphragm presses against a demand valve, which causes O_2 to flow into the bag. The flow of O_2 from the bypass valve is delivered to the bag at a location on its circumference. If more air is exhaled into the breathing bag than it can hold, the diaphragm presses against a relief valve and vents the excess volume.

[2]All volumes, unless otherwise noted, are listed at standard temperature and pressure, dry.

Figure 1.—Biomarine BioPak 45.

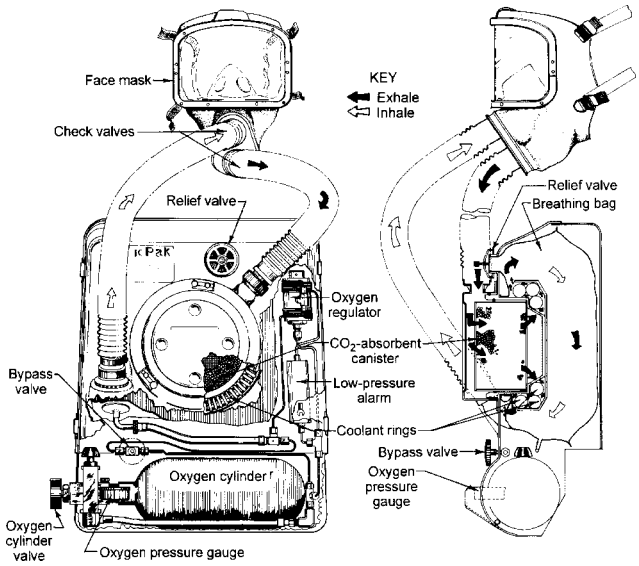

Figure 2.—Biomarine BioPak 45 schematic.

Figure 3.—Biomarine BioPak 60.

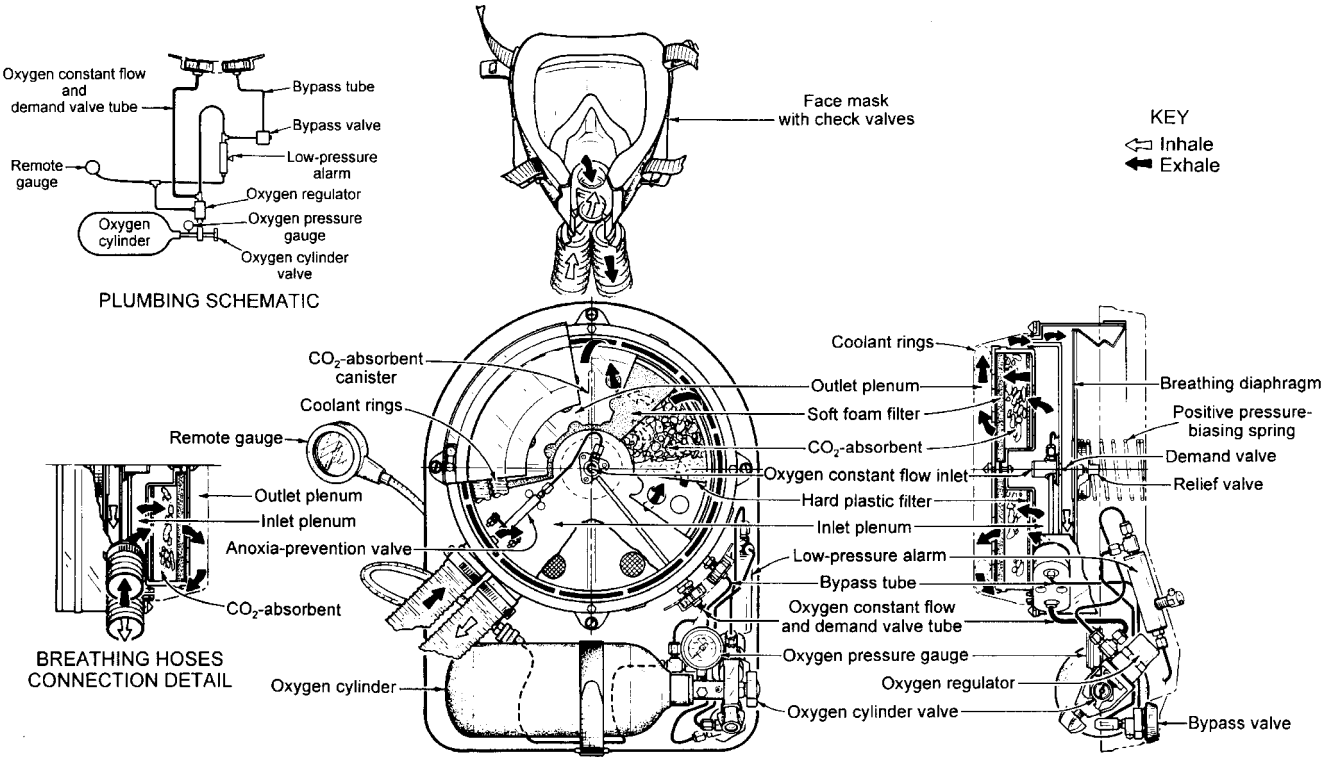

Figure 4.—Biomarine BioPak 60 schematic.

BIOMARINE BIOPAK 240

The BioPak 240 (figures 5-6) is a compressed-O_2, closed-circuit apparatus with a refillable CO_2-absorbent canister. It is NIOSH-certified (1985) as a 4-hr apparatus and is separately certified (1986) as a positive-pressure device. The fiberglass-wrapped aluminum O_2 cylinder contains approximately 535 L of O_2 at the recommended fill pressure of 3,000 psi at room temperature. The BioPak 240 has a constant O_2 flow of 1.65 L/min ATPD plus a volume-activated demand valve. The relief valve is also volume-activated. The CO_2 absorbent is called Rexsorb, a form of soda lime. The low-pressure alarm sounds at approximately 25% of capacity. Over the main viewing area, the face mask has a double lens, which is intended to minimize fogging.

The user exhales into the face mask containing the inhalation and exhalation check valves, through the exhalation hose, through the canister, and into a breathing bag. The configuration of the CO_2-absorbent canister/breathing bag component is the same as that of the BioPak 60. Upon inhalation, the user draws air from the breathing bag, through a heat-absorbent canister, and then through the inhalation hose and check valve back to the face mask.

DRAEGER BG-174A

The BG-174A (figures 7-8) is a compressed-O_2, closed-circuit apparatus with a disposable CO_2-absorbent canister. It is the most widely used long-duration closed-circuit breathing apparatus in the world. Originally certified in 1966 by the former U.S. Bureau of Mines (USBM) as a 2-hr apparatus, it was NIOSH-certified in 1975 as a 4-hr apparatus. The O_2 cylinder contains approximately 395 L of O_2 at the recommended fill pressure of 3,135 psi at room temperature. The BG-174A has a constant flow of O_2 of 1.5 L/min ATPD plus a pressure-activated demand valve. The relief valve is also pressure-activated. The CO_2 absorbent is NaOH suspended in

.

Figure 5.—Biomarine BioPak 240.

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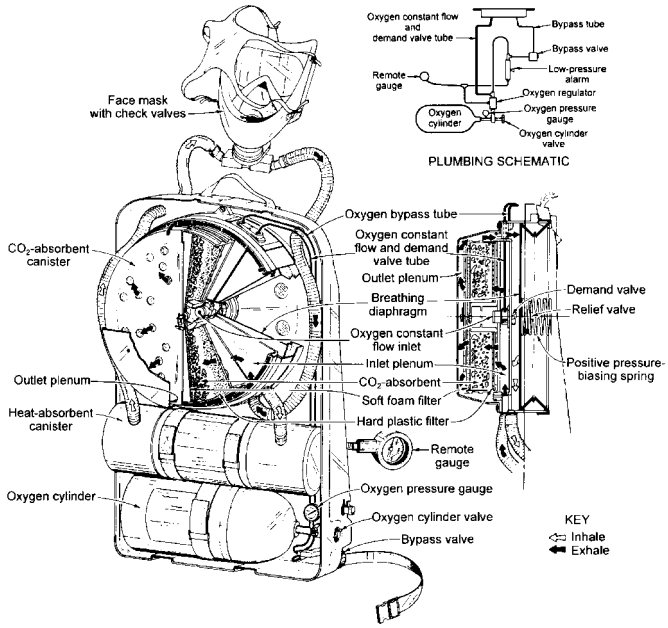

Figure 6.—Biomarine BioPak 240 schematic.

a crisscross, corrugated-screen bed (figure 9) designed to prevent the NaOH from melting into a solid mass during use

The user exhales into the face mask, through the exhalation hose, past the exhalation check valve, through the CO_2-absorbent canister, and into the breathing bag. Upon inhalation, the user draws air from the breathing bag, through the valve box and inhalation check valve, through the inhalation hose, and back to the face mask.

The face mask includes a wiper that removes condensation from the inside of the lens. A preflushing device operates when the O_2 cylinder is opened and fills the breathing bag with approximately 6 L ATPD of O_2, purging the circuit of a large quantity of N_2. If the user's O_2 consumption rate is higher than the O_2 constant flow rate and the circuit contains a large quantity of N_2, the O_2 concentration in compressed-O_2 apparatus can fall to subambient levels before the demand valve is activated.

Figure 7.—Draeger BG-174A.

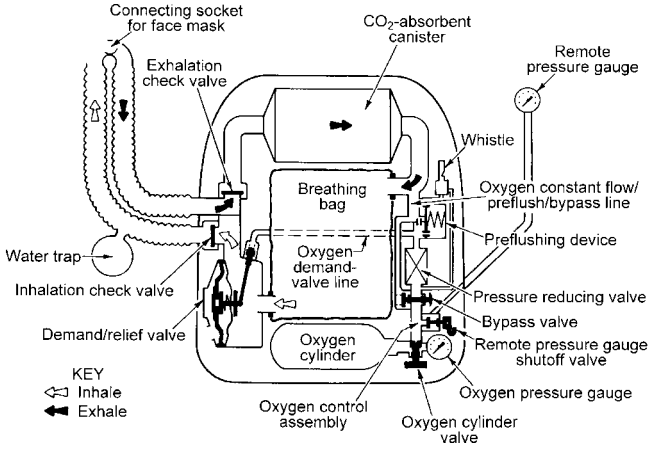

Figure 8.—Draeger BG-174A schematic.

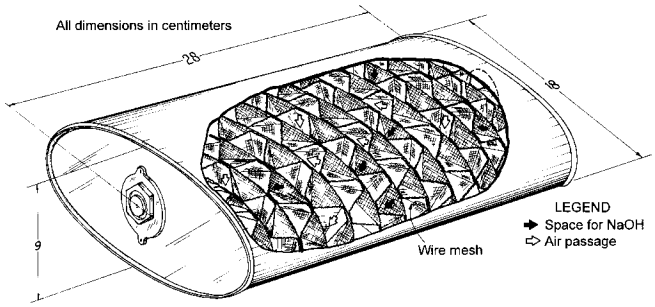

Figure 9.—Draeger BG-174A canister schematic.

DRAEGER BG 4

The BG 4 (figures 10-11) is a compressed-O_2, closed-circuit apparatus with a disposable soda lime CO_2-absorbent canister

Figure 10.—Draeger BG 4.

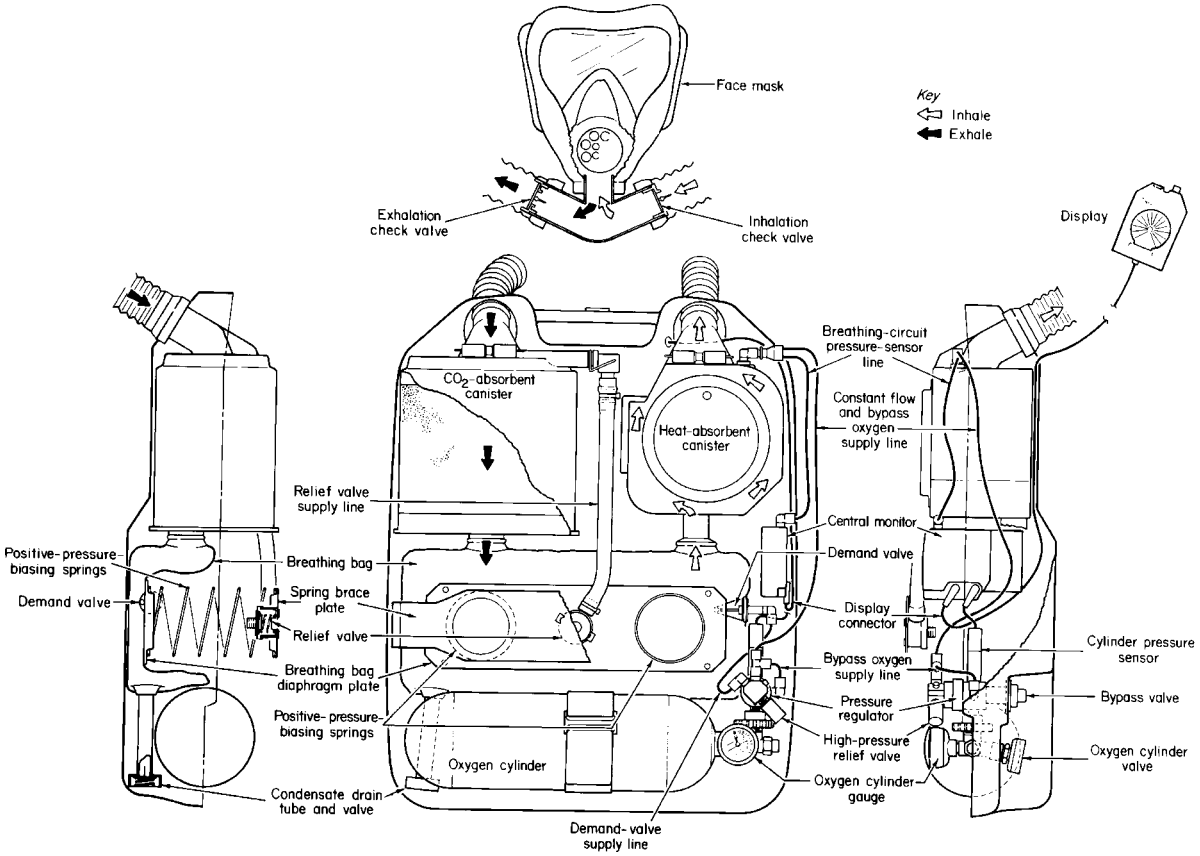

Figure 11.—Draeger BG 4 schematic.

It has been NIOSH-certified four times (1995) as both a 3- and 4-hr apparatus and a standard- and positive-pressure apparatus. The 4-hr, positive-pressure version of the BG 4 was tested using the same O_2 cylinder as that used for the BG-174A, which has the same recommended fill pressure of 3,135 psi at room temperature. The 3-hr version comes with a fiberglass-wrapped cylinder. The BG 4 has a constant flow of O_2 of at least 1.5 L/min ATPD plus a volume-activated demand valve. The relief valve is also volume-activated and purges exhaled air before it enters the CO_2-absorbent canister. The face mask is the same as that used with the BG-174A.

The user exhales into the face mask, through the exhalation check valve and breathing hose, through the CO_2-absorbent canister, and into the spring-loaded breathing bag. Upon inhalation, the user draws air from the breathing bag, through the heat-absorbent canister, the inhalation hose and check valve, and back to the face mask. The heat-absorbent canister works by routing inhalation air around a chamber containing a large cylinder of ice inserted just before use, formed in a separate ice mold.

LITTON LITPAC II

The LITPAC II (figures 12-13) is a positive-pressure, compressed-gas (39% O_2), closed-circuit apparatus with a refillable, CO_2-absorbent canister. It was certified by NIOSH in 1994 as a 2-hr, positive-pressure apparatus. Its targeted

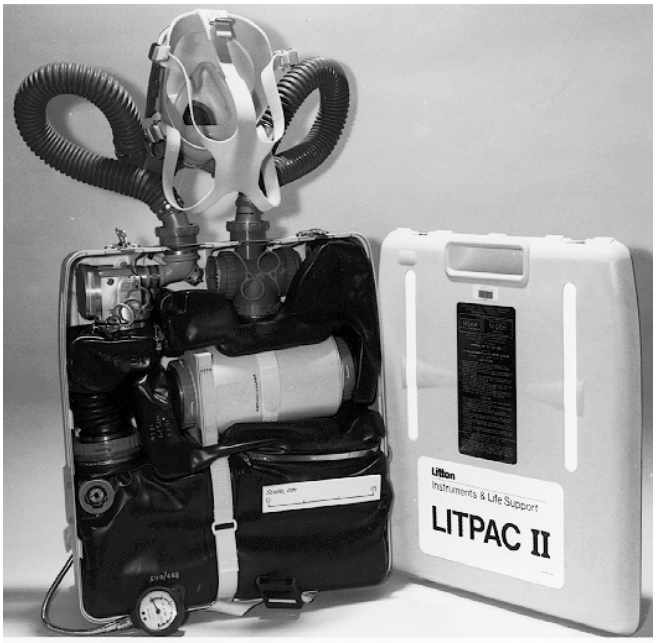

Figure 12.—Litton LITPAC II.

market is mainly the fire service and other users who require positive pressure even at high work rates. These users desire durations longer than open-circuit apparatus can provide, but do not want high O_2 levels in the breathing circuit. This apparatus was designed to pass the anticipated National Fire Protection Association 1984 standard for closed-circuit apparatus.

The two gas cylinders contain 1,036 L ATPD of gas when filled to 4,500 psi. The LITPAC II is a demand-only apparatus with approximately 20% of each breath coming from the cylinders through a positive-pressure-biased demand valve regulator. The same portion of exhaled air is vented out of the circuit on every exhalation through a pressure-biased exhalation/relief valve. This strategy spares the CO_2-absorbent to some extent and provides cooler breathing air, but requires a large quantity of supply gas. If one considers that open-circuit apparatus draw 100% of each breath from the gas supply versus approximately 4% for typical closed-circuit apparatus, this apparatus can be seen as a cross between open- and closed-circuit.

The user exhales into the face mask, through the exhalation breathing hose, into an exhalation/relief valve assembly containing a check valve and a relief valve, both of which are spring-loaded. The exhaled air then either exits the circuit via the relief valve or enters the scrubber inlet bag. The air that enters the scrubber inlet bag then passes through the CO_2-absorbent canister into a scrubber outlet bag, then into the pressure vessel bag, which encases the two compressed-gas cylinders. A small fourth bag made of thicker material, functioning more as a duct, connects the pressure vessel bag with the regulator. Inhalation draws air from the breathing bags and the gas cylinders. The gas from the cylinders enters the regulator through an injector nozzle, creating negative pressure in the regulator, which draws air in from the breathing bags, functioning as a sort of power-assist. This combination gas-cylinder/breathing-bag air is then drawn through the inhalation breathing hose and back into the face mask.

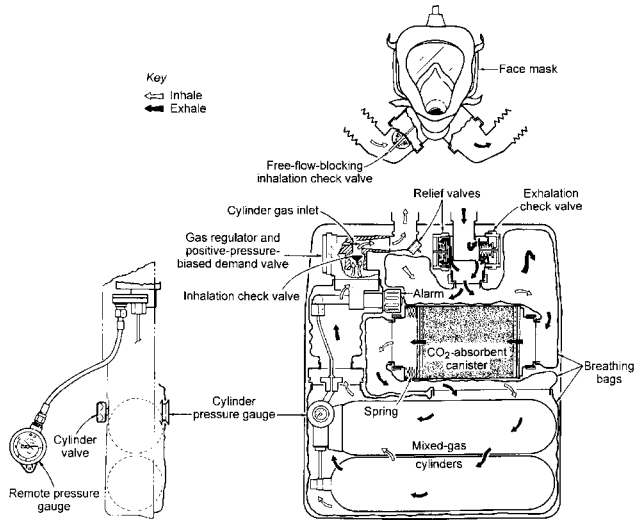

Figure 13.—Litton LITPAC II schematic.

MSA CUSTOM 4500 II AIR MASK

The Air Mask (figures 14-15) is a positive-pressure, compressed-air, open-circuit apparatus with a belt-mounted regulator. It is NIOSH-certified (1988) as a 1-hr apparatus. It contains approximately 2,300 L of air that is delivered to the user on a demand-only basis. As in all open-circuit apparatus, every inhalation draws air from the air cylinder and every

Figure 14.—MSA Custom 4500 II Air Mask.

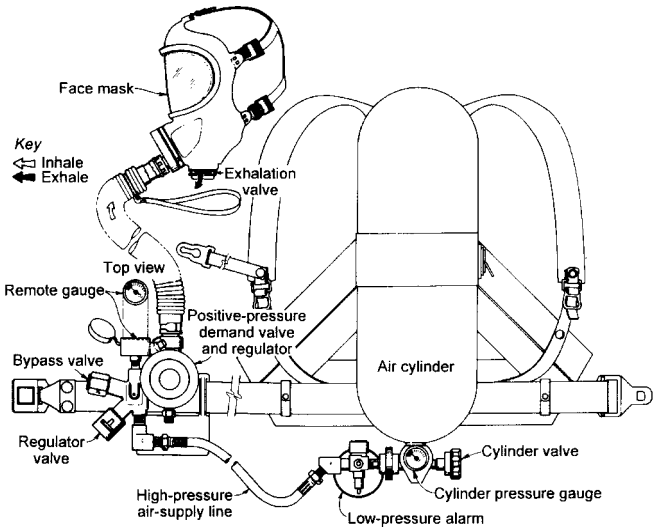

Figure 15.—MSA Custom 4500 II Air Mask schematic.

exhalation is vented to ambient. The face mask used for the performance comparison did not have the nose cup accessory.

MSA CHEMOX

The Chemox (figures 16-17) is a chemical-O_2, closed-circuit apparatus with a disposable KO_2 canister. It was certified by the USBM in 1946 as a 1-hr breathing apparatus. Because it was certified for less than a 2-hr duration, it was considered an auxiliary rescue apparatus. It has seen extensive use from 1946 to the present as the primary U.S. Navy shipboard firefighting apparatus progressing from the A-1 model to the presently used A-4. The early models had no chlorate candles and differed in the design of the breathing bag, relief valve, and the mechanism and procedures for loading. The U.S. Navy calls the device the OBA, short for O_2 breathing apparatus. Like the BioPak 45, it is worn on the chest rather than the back.

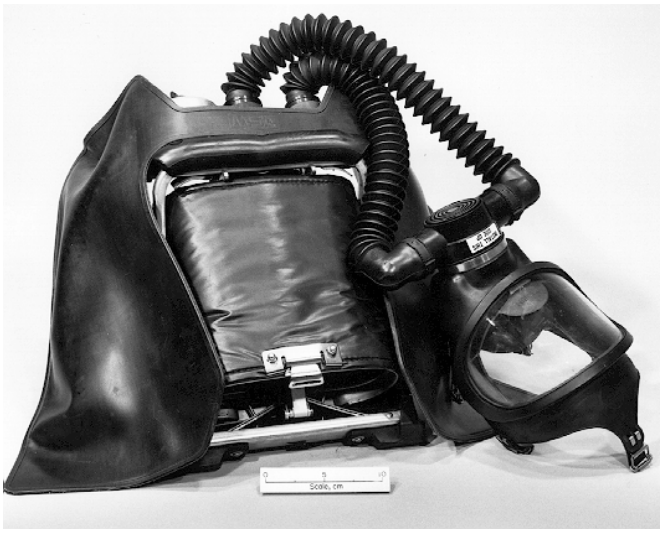

Figure 16.—MSA Chemox.

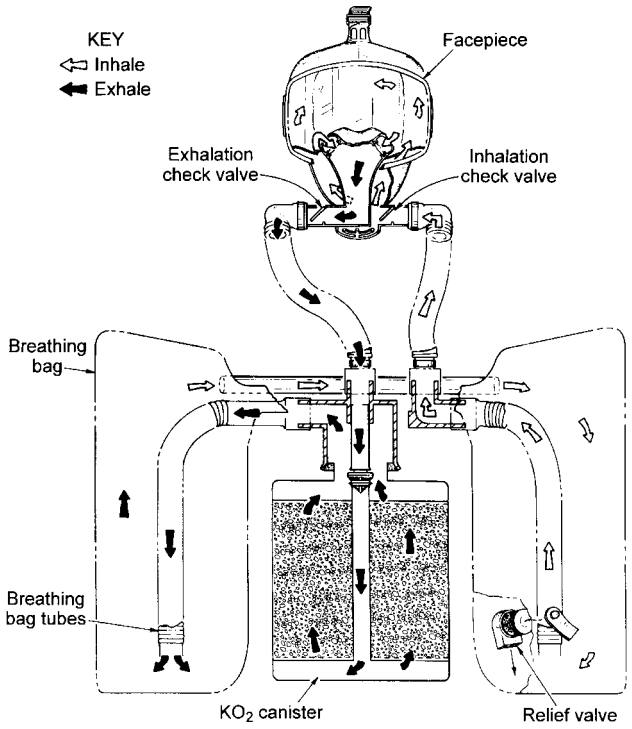

Figure 17.—MSA Chemox schematic.

KO_2 not only absorbs CO_2 but also produces O_2, so that a separate O_2 source is not needed. The new KO_2 canisters contain sodium chlorate "candles," which provide a quick source of O_2, permitting the apparatus to be worn immediately. Otherwise, the KO_2 needs three or four exhaled breaths, which provide not only the H_2O and CO_2 required for the chemical reactions, but also sufficient initial volume in the breathing bag to permit self-contained use of the apparatus. Since there is no O_2 cylinder and gauge to indicate quantity of O_2 remaining, a timer is provided that informs the user how long the apparatus has been in use. This allows for only a rough estimate of remaining duration, however, since KO_2 is strictly demand-responsive. KO_2 overproduces O_2 relative to human CO_2 production such that the breathing bag is always full and continually venting O_2 through the volume-activated relief valve. Earlier models had a manually activated relief valve. The model tested was the A-4 with an automatic relief valve and canisters containing chlorate candles.

Exhaled air goes through the exhalation check valve and hose, through a passageway down the middle of the KO_2 canister, up through the chemical bed, and is channeled to the bottom of one breathing bag, sweeping over the inner surface of the bag to a connecting tube terminating at the top of the other breathing bag. Upon inhalation, the air is drawn from the bottom of the second breathing bag, through the inhalation breathing hose and check valve, then back into the face mask.

MSA McCAA

The McCaa (figures 18-19) is a compressed-O_2, closed-circuit apparatus with a refillable CO_2-absorbent canister that is integral with the apparatus frame. It was originally approved by the USBM in 1925 as a 2-hr apparatus and is permitted by NIOSH to be used indefinitely as long as it is maintained in an approved condition. The O_2 cylinder contains approximately 243 L ATPD of O_2 when filled to 1,985 psi at room temperature. The McCaa does not have a constant flow of O_2; the demand valve regulator is activated by bag volume. The relief valve is functionally combined with a saliva trap release in the face mask and is manually activated. The CO_2 absorbent is called Cardoxide, which consists mostly of CaOH.

The user exhales into a face mask or a mouthpiece, through an exhalation check valve and hose, through the CO_2-absorbent canister, to the 8-L breathing bag. Inhaling draws air from the breathing bag, through a large plenum formed by the entire case housing that serves as a heat radiator, and through the inhalation

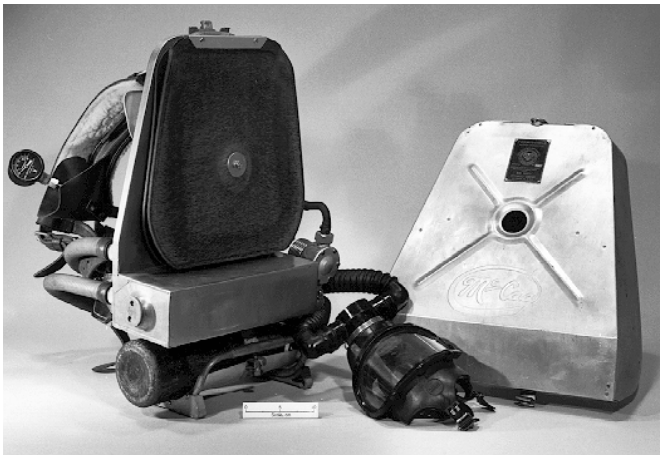

Figure 18.—MSA McCaa.

hose and check valve in the face mask or the mouthpiece.

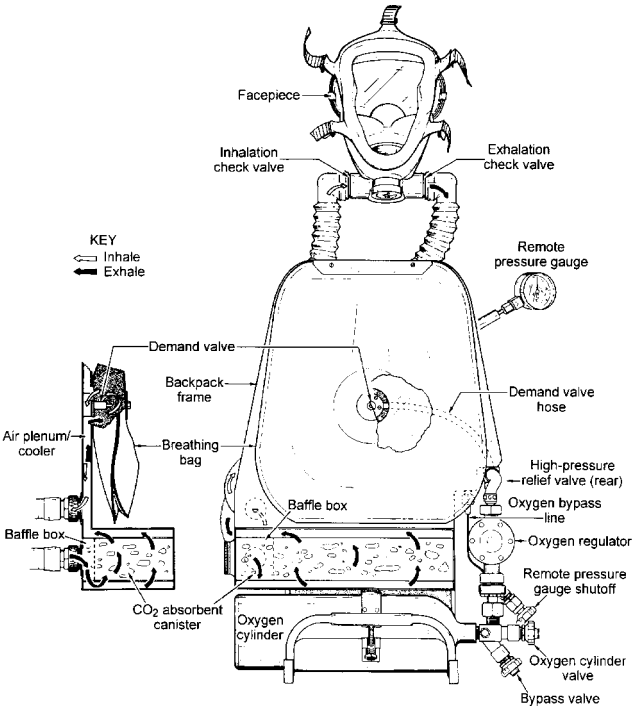

Figure 19.—MSA McCaa schematic.

A face mask without a nose cup was used in this testing.

This device is no longer used to any extent. It is claimed that this apparatus is positive-pressure with a static head pressure of about 6 mm H_2O. This claim is made by Grove [1941], but the breathing circuit pressure does not remain positive during inhalation and would certainly not qualify as positive-pressure by present standards.

SABRE SEFA

The SEFA (Selected Elevated Flow Apparatus) (figures 20-21) is a compressed-O_2, positive-pressure, closed-circuit apparatus with a refillable CO_2-absorbent canister. It

Figure 20.—Sabre SEFA.

was approved by the U.K. Health and Safety Executive in 1985 as a 2-hr apparatus in its low-flow mode, with a constant flow of O_2 of 5 L/min ATPD. In its high-flow mode—10 L/min ATPD—it is certified for 1-hr duration. It contains 750 L ATPD of O_2 at a pressure of 3,000 psi at room temperature. It has no demand valve. The pressure-activated relief valve is located upstream of the canister, venting exhaled air before it has been cleansed of CO_2 or enriched with O_2. The CO_2-absorbent canister is filled with SEFAsorb, consisting mostly of CaOH.

The user exhales into the face mask, through an exhalation check valve and hose, through the CO_2-absorbent canister, and through a heat exchanger to the 6-L breathing bag, consisting of a spring-loaded, rigid diaphragm connected to a flexible sleeve. Inhaled air is drawn from the bag, through the inhalation breathing hose and check valve, then back to the face mask.

The heat exchanger functions in tandem with the ambient-air chamber containing the breathing bag. The volume in the ambient-air side of the chamber increases when the breathing bag decreases, during inhalation, drawing ambient air through two check valves in the panel separating the chamber from the O_2 cylinder compartment. Upon exhalation, the breathing bag volume increases, forcing the ambient air in the chamber out through the outside and core of the wetted heat exchanger, drawing heat—through the evaporation of the water as well as direct conduction—from the hot exhaled air passing in the opposite direction through the middle plenum of the heat exchanger on the way from the canister to the breathing chamber. Two relief valves in the panel separating the ambient air chamber from the O_2 cylinder compartment permit ambient air in the chamber to escape if exhalation pressure becomes too high.

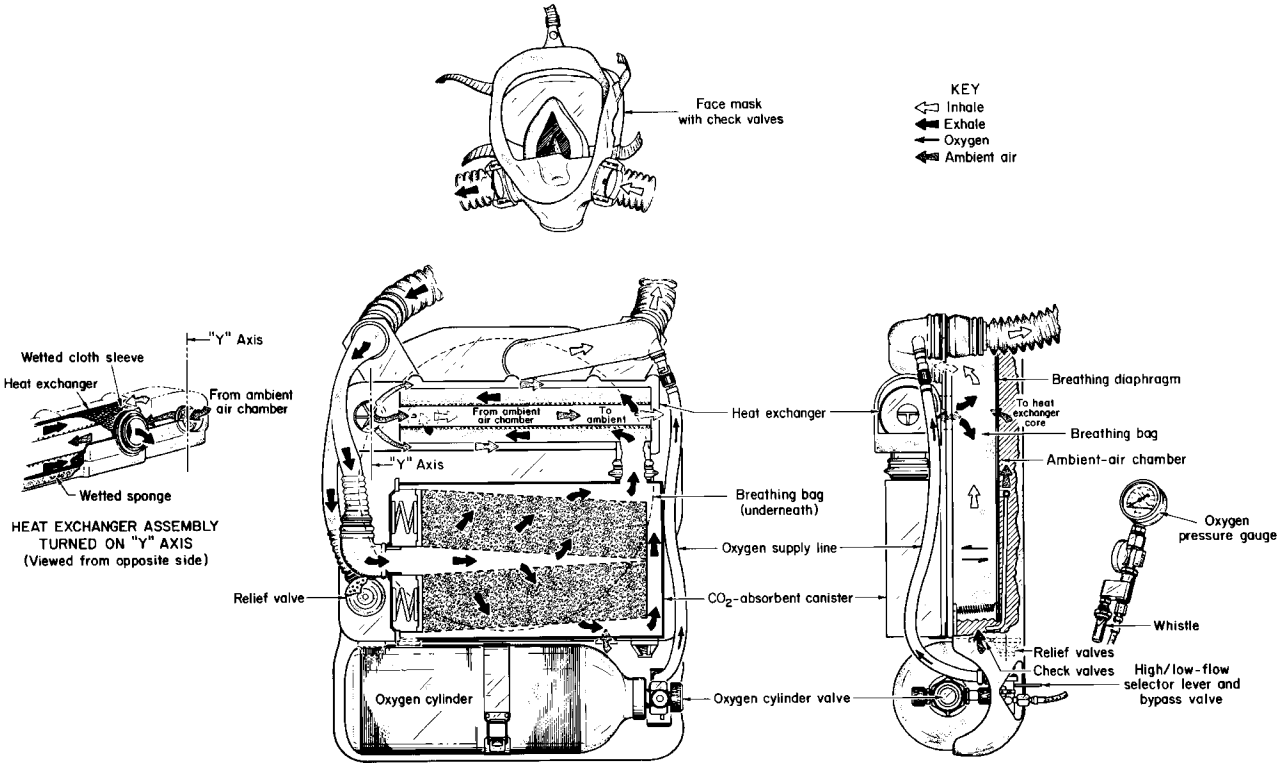

Figure 21.—Sabre SEFA schematic.

SCOTT RESCUE-PAK

The Rescue-Pak (figures 22-23) is a compressed-O_2, closed-circuit apparatus with a disposable CO_2-absorbent canister. It is NIOSH-certified (1975) as a 4-hr apparatus. The O_2 cylinder contains 435 L ATPD at a pressure of 1,980 psi at room temperature. A constant O_2 flow of 1.5 L/min ATPD is augmented by a volume-activated demand valve. The relief valve is also volume-activated and dumps exhaled air from the breathing circuit before it enters the CO_2-absorbent canister. The CO_2 absorbent is LiOH.

Exhaled air passes through the exhalation check valve and breathing hose, through the CO_2-absorbent canister, and into the breathing bag, which consists of a rigid diaphragm attached to a flexible sleeve. Air is inhaled from the breathing bag, through the inhalation breathing hose and check valve, then back to the face mask. The relief valve is activated by the movable diaphragm of the breathing bag, but channels the excess volume from the exhaled column of air just before it enters the CO_2-absorbent canister. This feature conserves both the absorbent and the O_2 supply, since the vented exhaled air has not yet been cleansed of CO_2 nor enriched with O_2.

SIEBE GORMAN AERORLOX

The Aerorlox (figures 24-25) is a liquid-O_2, closed-circuit apparatus with a refillable CO_2-absorbent canister. It is NIOSH-certified (1973) as a 3-hr apparatus. It is filled with 3 kg of liquid O_2 and provides a flow of between 6 and 12 L O_2/min to the breathing circuit. The pressure-activated relief valve continually vents the excess volume of breathing air in the circuit. The CO_2 absorbent is 8-12 mesh Protosorb, a soda lime that is mostly CaOH.

Figure 22.—Scott Rescue-Pak.

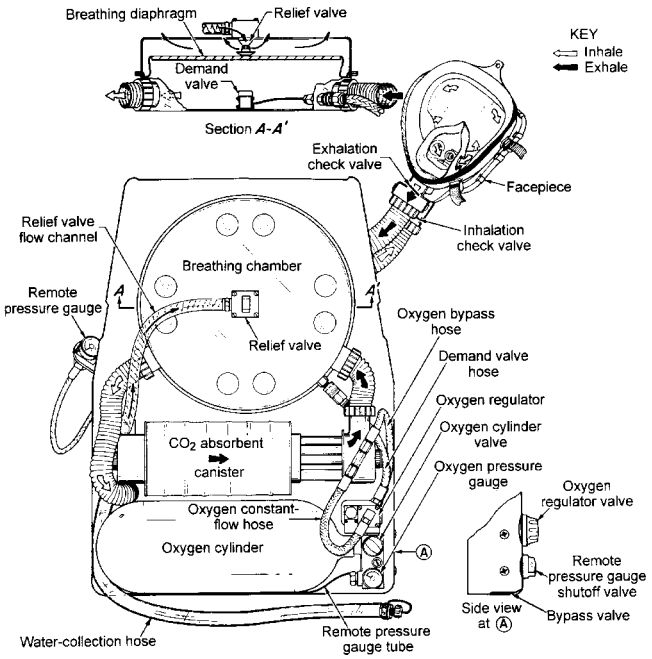

Figure 23.—Scott Rescue-Pak schematic.

Figure 24.—Siebe Gorman Aerorlox.

Exhaled air is channeled through a check valve in the face mask through the exhalation breathing hose, through the radial CO_2-absorbent canister, around the liquid-O_2 dewar (called an evaporator), which cools the air on its way to the breathing bag. The moisture that is condensed from the air as it passes over the evaporator collects in the breathing bag. The inhaled air is drawn from the breathing bag around the evaporator again, then through the inhalation breathing hose and back to the face

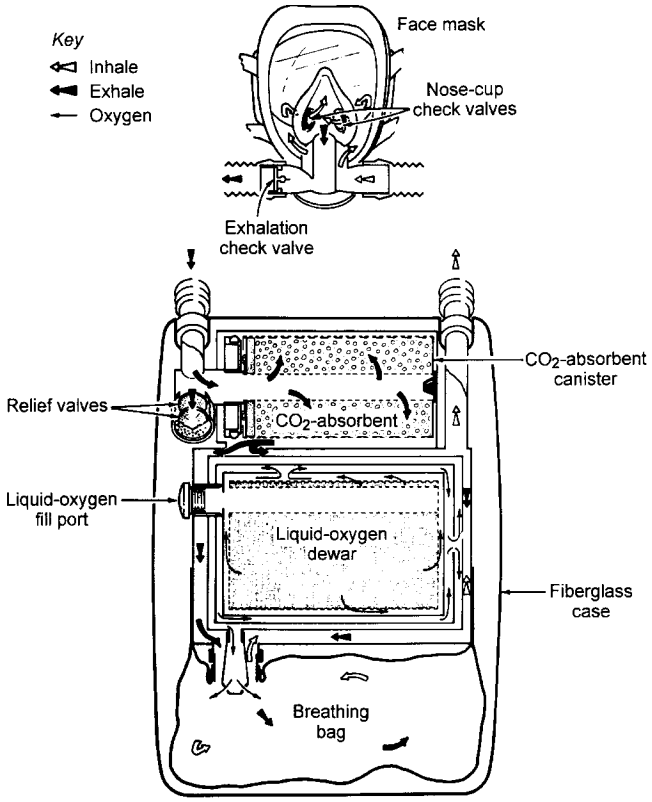

Figure 25.—Siebe Gorman Aerorlox schematic.

mask, through the nose cup, which contains two inhalation check valves. The O_2 flows from the evaporator into the breathing bag.

SIEBE GORMAN PROTO TEN

The Proto Ten (figures 26-27) is a compressed-O_2, closed-circuit apparatus with a refillable CO_2-absorbent canister. It was certified by the USBM in 1968 as a 3-hr apparatus. The cylinder contains 400 L ATPD of O_2 when filled to 2,840 psi at room temperature. A constant O_2 flow of 1.5 L/min ATPD is provided and augmented by a pressure-activated demand valve. The relief valve is also pressure-activated. The CO_2 absorbent is Protosorb, a soda lime composed mostly of CaOH.

Exhaled air from the face mask passes through the exhalation hose and check valve through the radial CO_2-absorbent canister housed in a metal shell, which also contains an inverse breathing bag, a heat-absorbent canister, and a warning whistle. The breathing circuit air is contained within the metal shell and contacts the exterior of the breathing bag, the interior of which is open to ambient. Air is inhaled from the shell interior, through a metal tube connected to the heat-absorbent canister, through the inhalation check valve and hose, and back to the face mask.

The inverse breathing bag design results in the breathing circuit air contacting the metal shell, enabling heat to be

Figure 26.—Siebe Gorman Proto Ten.

radiated to air in a plenum vented to ambient. A chamois cloth jacket covers the exterior of the metal shell. The jacket is wetted from water coming from the ice melting in the heat-absorbent canister, which is wicked through a hole in the canister to two positions on each side of the surface of the shell. The water in the chamois jacket evaporating to ambient cools the surface of the metal shell. Heat is transferred to ambient also through the breathing bag, which pulls ambient air into it with each breath. A sponge at the bottom of the inside of the metal shell, under the CO_2-absorbent canister, holds the water released by the chemical reaction.

SURVIVAIR LP-120

The LP-120 (figures 28-29) is a prototype, compressed-O_2, closed-circuit apparatus with a refillable, LiOH CO_2-absorbent canister. It is NIOSH-certified (1987) as a 2-hr apparatus. The O_2 cylinder contains 240 L ATPD at a pressure of 3,000 psi. O_2 is delivered on a demand-only basis by a positive-pressure-biased, pressure-activated, demand valve. The relief valve is also pressure-activated. The apparatus functions as a positive-pressure system, but was not submitted for certification under that category because of the use restrictions for pure-O_2 apparatus in the positive-pressure, closed-circuit apparatus category.

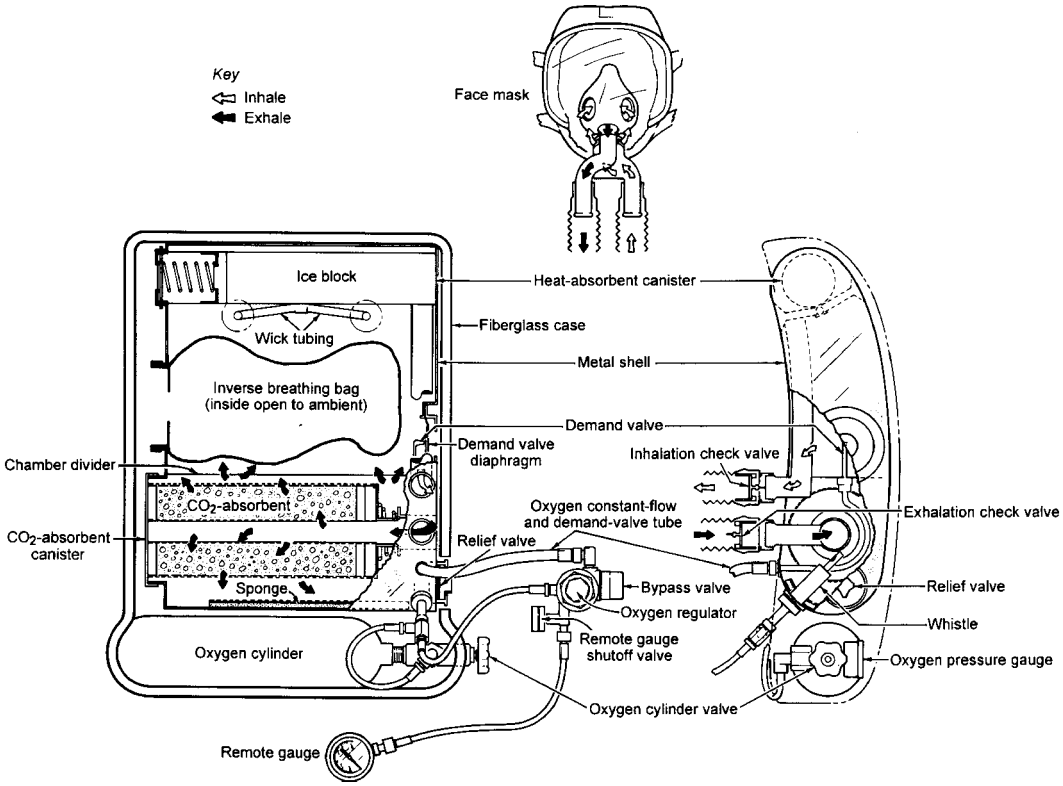

Figure 27.—Siebe Gorman Proto Ten schematic.

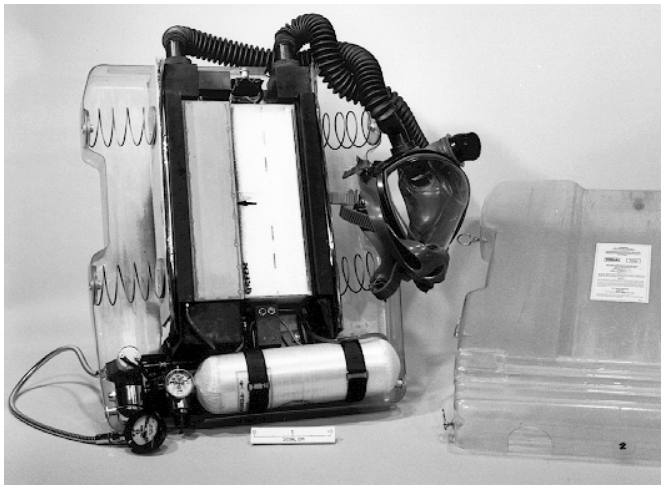

Figure 28.—Survivair LP-120.

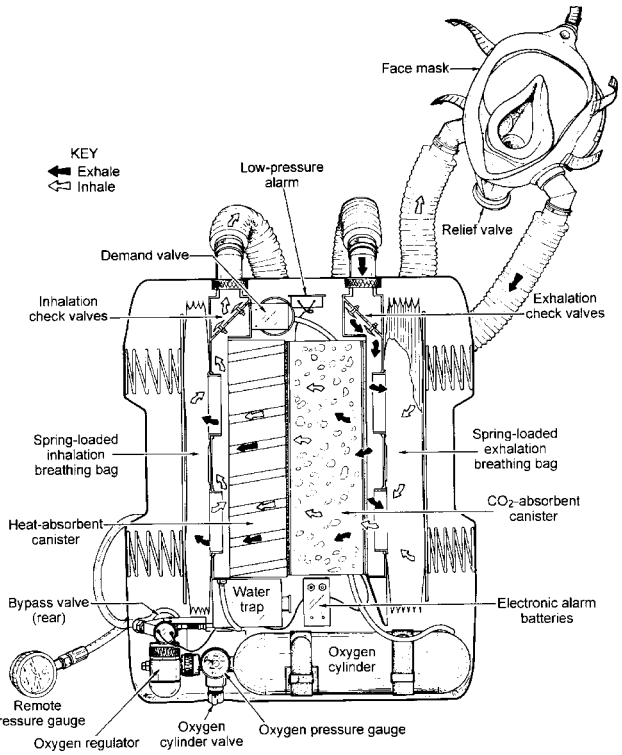

Figure 29.—Survivair LP-120 schematic.

The user exhales into the face mask, through the exhalation breathing hose, past the exhalation check valves, and into the exhalation breathing bag. Some of the exhaled air passes through the CO_2-absorbent canister and heat-absorbent canister, into the inhalation breathing bag. When the user inhales, some of the air is drawn from the inhalation breathing bag and some from the exhalation breathing bag, across the CO_2-absorbent and heat-absorbent canisters. The inhaled air continues through the inhalation check valves and breathing hose, then back to the face mask. The dual-breathing bag design splits the breathing pressures of the CO_2-absorbent canister between inhalation and exhalation rather than only on exhalation.

The heat-absorbent canister contains $LiNO_3$, a phase-change material that is formulated to melt at about 27 °C.

TEST APPARATUS AND EXPERIMENTAL PROCEDURE

Unlike human subjects, the BMS used in this study (figure 30) elicits a constant and repeatable metabolic demand on the breathing apparatus. Human-subject testing of a breathing apparatus is similar to evaluating the output of a black box with an unknown input. Use of the BMS provides a known input. The BMS simulates O_2 consumption and CO_2 production, reproduces humanlike waveforms, and heats and humidifies the inhaled air.

The metabolic work rates used in this study are:

Work rate 1

VO_2 (O_2 consumption) = 1.35 L/min
VCO_2 (CO_2 production) = 1.10 L/min
V_e (ventilation) = 30 L/min
V_t (tidal volume) = 1.67 L/breath
RF (respiratory frequency) = 17.9 breaths/min
Q_{peak} (peak flow rate) = 67 L/min (exhalation)
= 83 L/min (inhalation)

Figure 30.—Breathing and metabolic simulator.

Work rate 2

VO_2 (O_2 consumption) = 2.50 L/min
VCO_2 (CO_2 production) = 2.50 L/min
V_e (ventilation) = 54.8 L/min
V_t (tidal volume) = 2.45 L/breath
RF (respiratory frequency) = 22.4 breaths/min
Q_{peak} (peak flow rate) = 115 L/min (exhalation)
= 149 L/min (inhalation)

Most of the test consisted of work rate 1 with the addition of two 5-min intervals of work rate 2, the first beginning 10 min into the test and the second beginning 10 min before the end of the rated duration of the apparatus. This was done not only to evaluate performance at a higher work rate, but also to determine if this performance is maintained as the apparatus nears depletion.

The physiological parameters measured were average inhaled concentrations of CO_2 and O_2, minimum inhaled CO_2, end-of-breath inhaled wet- and dry-bulb temperatures, and inhalation and exhalation peak breathing pressures. Measure-ments were calculated over a two-breath period and averaged each minute. Test-averages were derived from the minute-averages, including the two high-work-rate periods. At least five tests were run on each apparatus.

The levels of the physiological parameters considered to be acceptable here are:

Average inhaled CO_2	<4%
Average inhaled O_2	>15%
Wet-bulb temperature	<50 °C
Exhalation pressure	<200 mm H_2O
Inhalation pressure	>−300 mm H_2O

The average inhaled gas concentrations include the contribution of any dead space in the face mask or hoses. (Dead space is that apparatus volume containing exhaled air that will be reinhaled.) All measurements were made at the mouth of the headform except the wet-bulb temperature, which, because of the configuration of the wet-bulb thermocouple [Kyriazi 1988], was placed at the back of the neck of the headform.

The wet-bulb temperature reflects both temperature and humidity. The wet-bulb temperature is the temperature actually perceived by the wearer with the wet human respiratory tract functioning essentially as a wet-bulb thermometer.

A test was terminated when the O_2 supply was exhausted, if average inhaled CO_2 reached 10%, or if average inhaled O_2 fell below 15%. A depleted O_2 supply is the preferred termination mode since this can be determined by the user without the aid of instrumentation. Termination under the other conditions is undesirable because the safety of the user may be compromised. In some cases, average inhaled CO_2 level was permitted to exceed 10% because the O_2 supply was nearly exhausted, and the test was permitted to continue until complete exhaustion.

RESULTS AND DISCUSSION

Table 2 lists the means of the test-average values of each physiological parameter for each model of apparatus. Figures 31-38 graphically illustrate the results of table 2. Figure 33 shows the differences between the average and minimum inhaled CO_2, which can be interpreted as some indication of quantity of apparatus dead space. If there were no dead space and the minimum inhaled CO_2 remained at a steady level from beginning to end of inhalation, average and minimum inhaled CO_2 would be equal. The greater the dead space, the higher the difference between the two values. It is not surprising, therefore, that the two apparatus with no face mask nose cups (MSA Air Mask and McCaa) have the highest dead-space values. A small difference between the wet- and dry-bulb temperatures, shown in figure 35, indicates that the air was humid; a large difference means dry air. Pressure swing, as depicted in figure 37, is the combination of inhalation and exhalation breathing pressures.

The duration obtained from a compressed-O_2 apparatus is entirely dependent upon how much O_2 is contained in the cylinder. Filling compressed-O_2 cylinders rapidly to high pressures results in the heating of both gas and cylinder. If filled exactly to the recommended pressure, the final pressure after cooling will be below this level, requiring additional filling. Final cylinder pressures varied based on filling procedures and ambient temperatures, with some settling below and some above the manufacturer's recommended pressure. The durations listed in table 2 for gaseous-O_2 apparatus were those actually attained, with the standard deviations reflective of the arbitrary differences in fill pressures, and the estimated durations for the apparatus if their storage vessels had been filled to their recommended levels.

In addition to the numerical results, discussions of unusual or notable behavior and/or comments about the testing follow the table and figures.

Table 2.—Means of average values of monitored physiological parameters (standard deviations)

Apparatus	Duration, min		Cause of termination	Average inhaled O_2, %	Average inhaled CO_2, %	Minimum inhaled CO_2, %	Exhalation pressure, mm H_2O
	Average of all tests	At recommended fill pressure					
Biomarine BioPak 45	51 (3)	51	Empty	80 (1)	1.7 (0.3)	0.8 (0.3)	46 (3)
Biomarine BioPak 60	80 (2)	80	Empty	88 (1)	0.8 (0.1)	0.1 (0)	82 (3)
Biomarine BioPak 240	264 (6)	264	High CO_2	87 (2)	1.4 (0.1)	0.6 (0.1)	69 (1)
Draeger BG-174A	295 (9)	298	Empty	62 (6)	1.2 (0.3)	0.4 (0.2)	26 (4)
Draeger BG 4	291 (17)	299	Empty	90 (2)	1.3 (0.1)	0 (0)	44 (1)
Litton LITPAC II	138 (15)	130	Low O_2	25 (1)	1.0 (0.2)	0.1 (0.1)	51 (1)
MSA Custom 4500 II Air Mask	62 (4)	66	Empty	19 (1)	1.8 (0)	0.1 (0)	63 (1)
MSA Chemox	70 (4)	—	Empty	76 (3)	3.6 (0.8)	3.0 (0.9)	93 (5)
MSA McCaa	130 (10)	137	Empty	60 (8)	4.0 (0.5)	1.6 (0.4)	42 (4)
Sabre SEFA	174 (3)	176	Empty	87 (2)	0.5 (0.1)	0.1 (0)	39 (1)
Scott Rescue-Pak	265 (18)	293	Empty	73 (4)	1.1 (0.2)	0.3 (0.2)	42 (3)
Siebe Gorman Aerorlox	228 (8)	216	Empty	96 (1)	1.0 (0.1)	0.1 (0)	51 (1)
Siebe Gorman Proto Ten	130 (13)	—	Empty	45 (17)	1.5 (0.6)	0.9 (0.7)	33 (3)
Survivair LP-120	141 (7)	137	Empty	63 (8)	1.6 (0.1)	1.0 (0.1)	58 (3)

Apparatus	Inhalation pressure, mm H_2O	High-demand 1 exhalation pressure, mm H_2O	High-demand 2 exhalation pressure, mm H_2O	High-demand 1 inhalation pressure, mm H_2O	High-demand 2 inhalation pressure, mm H_2O	Inhalation wet-bulb temperature, °C	Inhalation dry-bulb temperature, °C
Biomarine BioPak 45	−27 (2)	73 (10)	72 (9)	−46 (7)	−45 (3)	34 (0)	35 (1)
Biomarine BioPak 60	6 (2)	112 (2)	119 (1)	−18 (2)	−28 (2)	34 (1)	36 (1)
Biomarine BioPak 240	0 (3)	87 (1)	99 (3)	−31 (1)	−39 (6)	32 (1)	34 (1)
Draeger BG-174A	−26 (5)	47 (4)	70 (9)	−45 (2)	−56 (3)	36 (1)	39 (1)
Draeger BG 4	8 (2)	55 (3)	53 (2)	−6 (2)	−13 (3)	32 (1)	34 (1)
Litton LITPAC II	0 (1)	56 (2)	57 (2)	0 (3)	−12 (4)	29 (2)	31 (2)
MSA Custom 4500 II Air Mask	−20 (2)	66 (1)	68 (1)	−41 (3)	−44 (3)	14 (0)	18 (0)
MSA Chemox	−27 (2)	141 (8)	164 (13)	−65 (3)	−73 (3)	22 (1)	32 (1)
MSA McCaa	−42 (4)	90 (7)	121 (16)	−70 (1)	−141 (74)	34 (1)	38 (1)
Sabre SEFA	0 (1)	54 (2)	56 (2)	−23 (2)	−25 (1)	34 (1)	35 (1)
Scott Rescue-Pak	−33 (2)	78 (5)	92 (9)	−58 (2)	−68 (5)	35 (1)	38 (1)
Siebe Gorman Aerorlox	−26 (1)	92 (2)	87 (1)	−62 (2)	−58 (1)	16 (0)	20 (1)
Siebe Gorman Proto Ten	−70 (17)	66 (5)	—	−101 (8)	—	30 (3)	31 (1)
Survivair LP-120	2 (3)	84 (3)	84 (3)	−8 (4)	−12 (4)	34 (1)	35 (1)

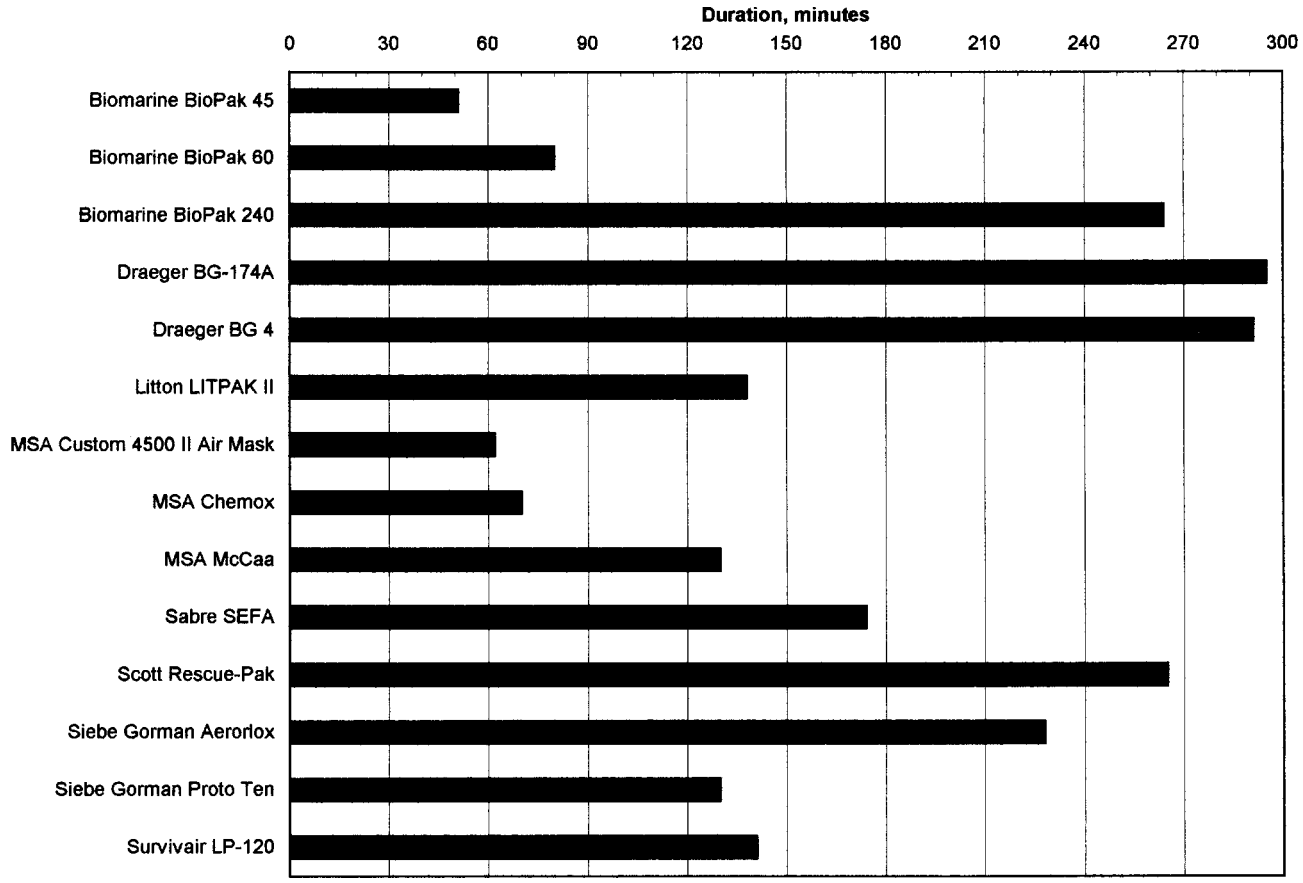

Figure 31.—Durations.

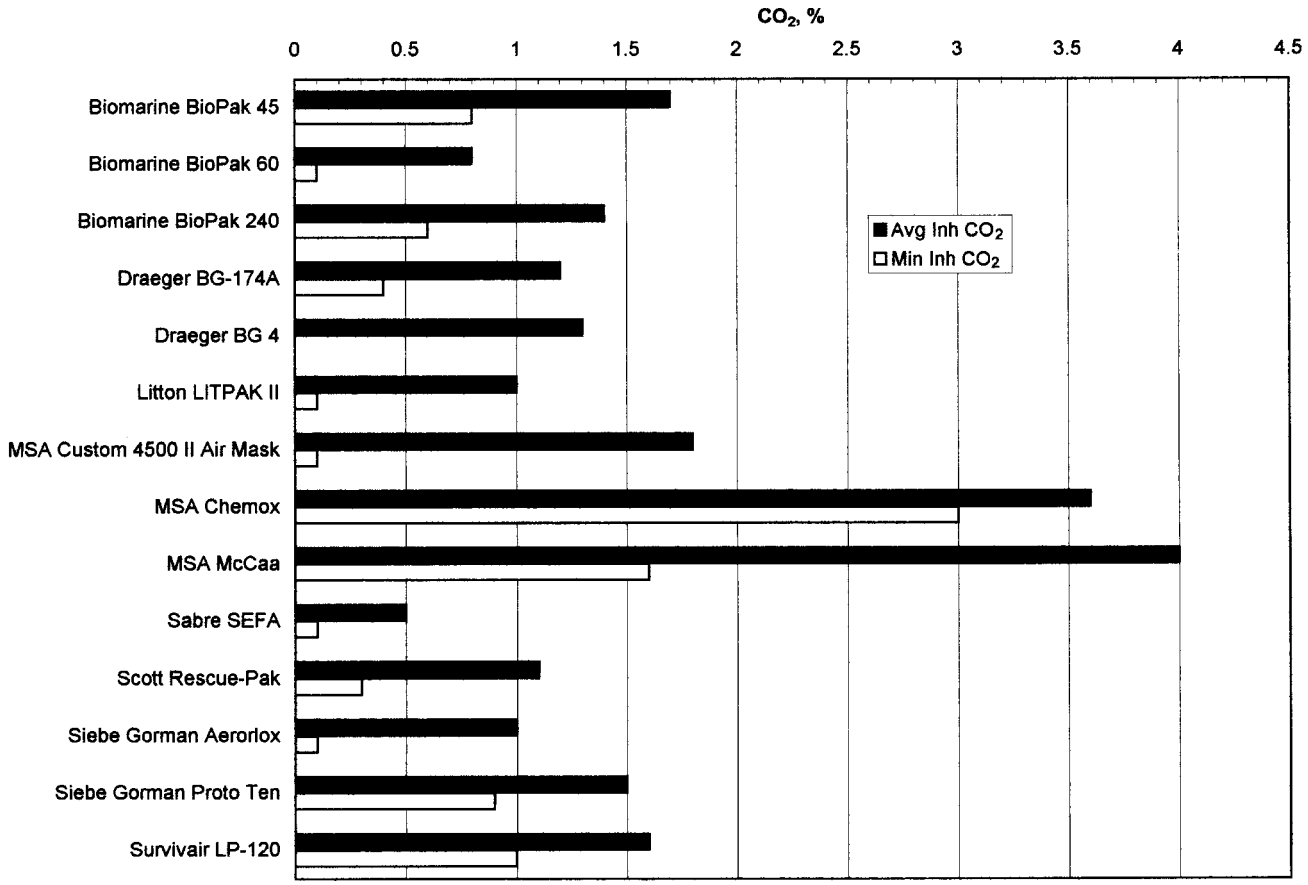

Figure 32.—CO_2 levels.

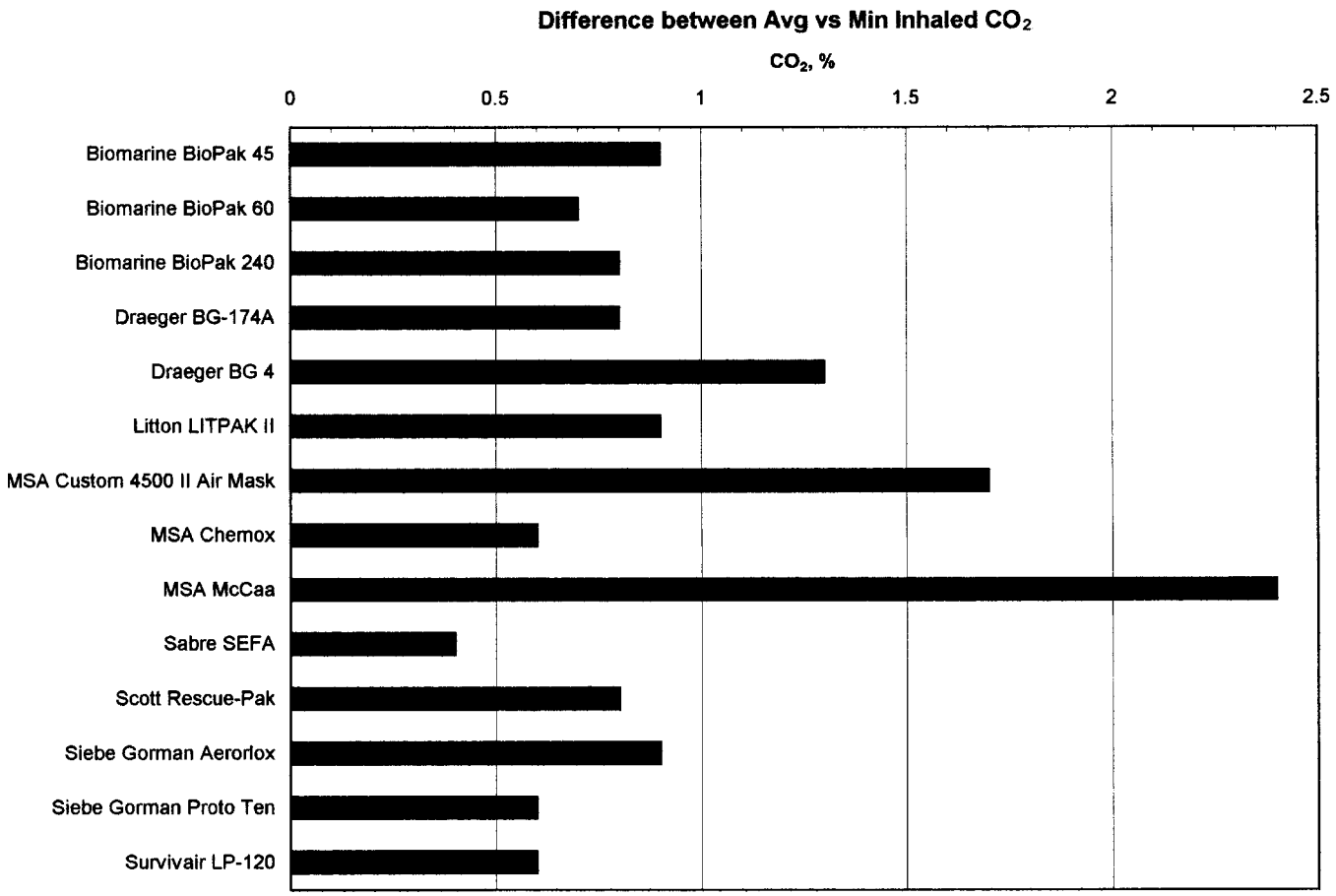

Figure 33.—Differences between average and minimum inhaled CO_2 levels.

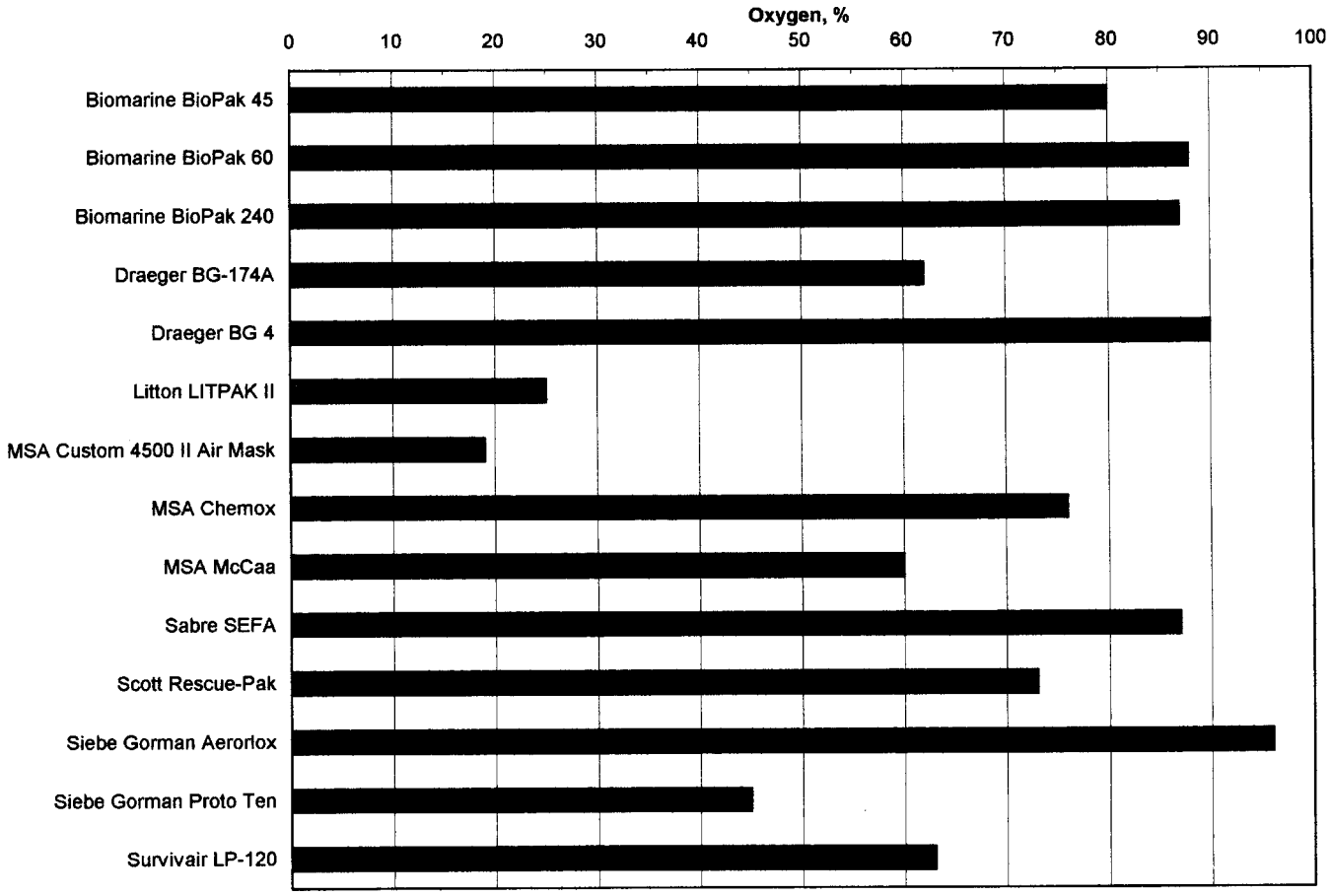

Figure 34.—O_2 levels.

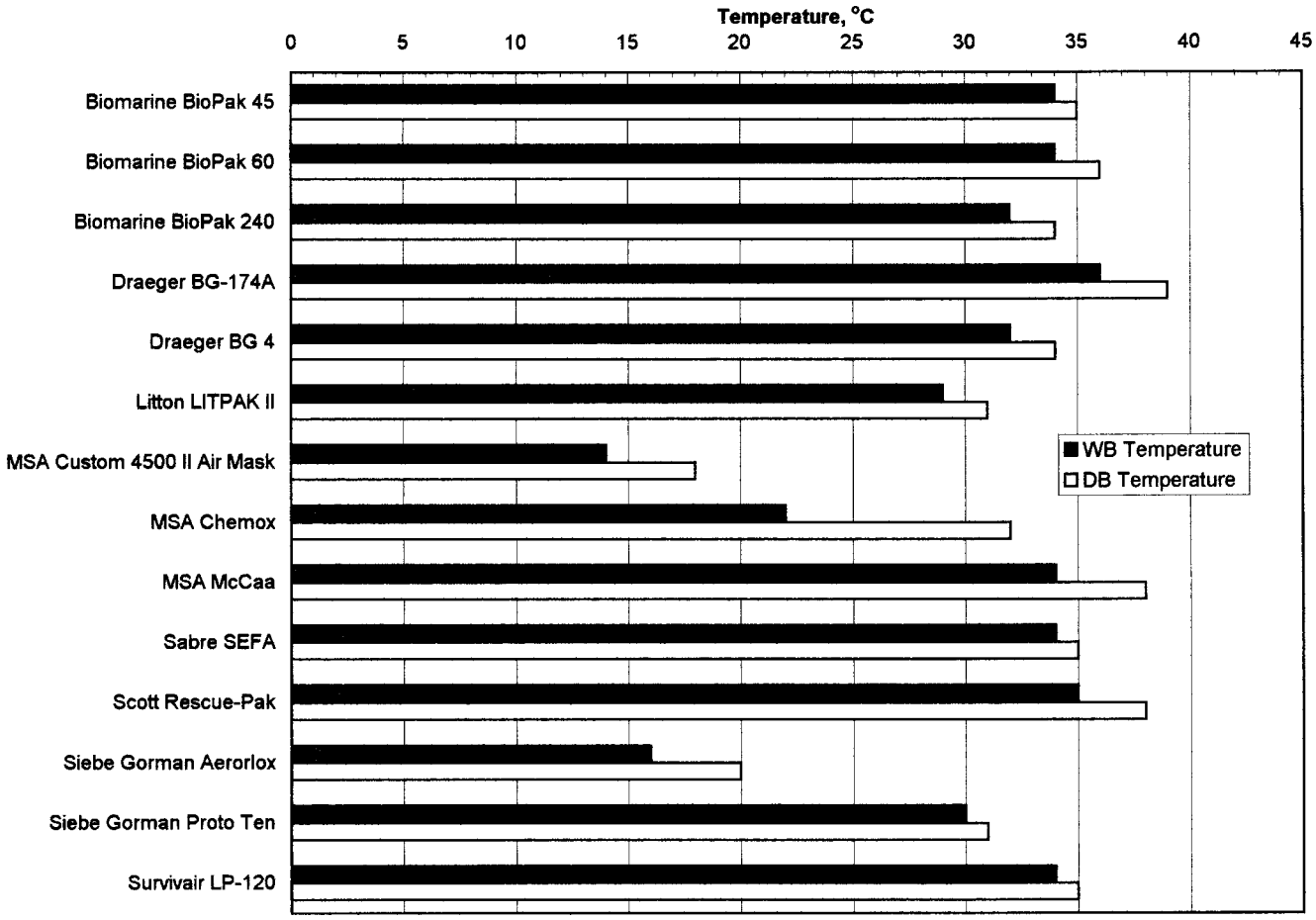

Figure 35.—Wet-bulb (WB) and dry-bulb (DB) temperatures.

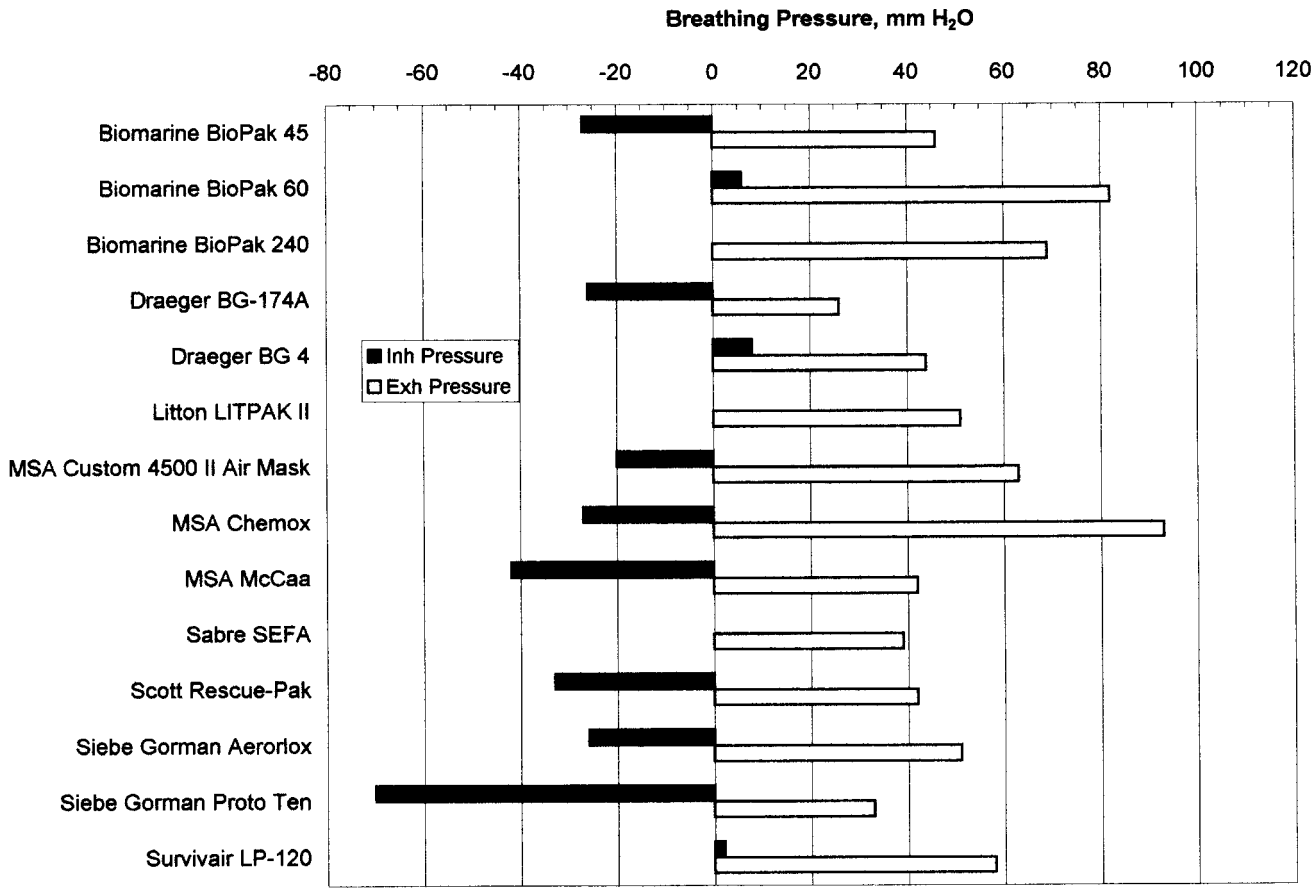

Figure 36.—Breathing pressures.

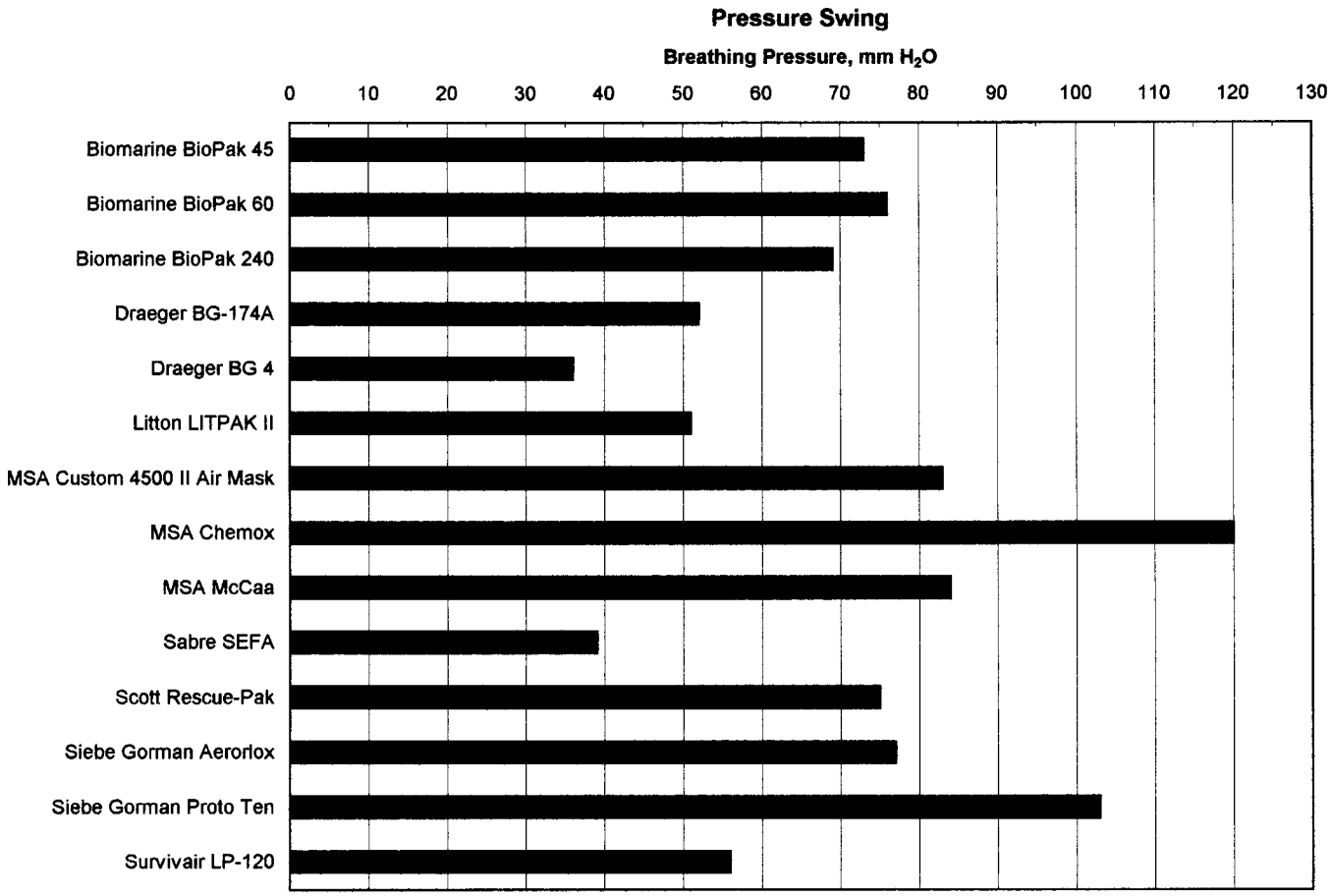

Figure 37.—Pressure swings.

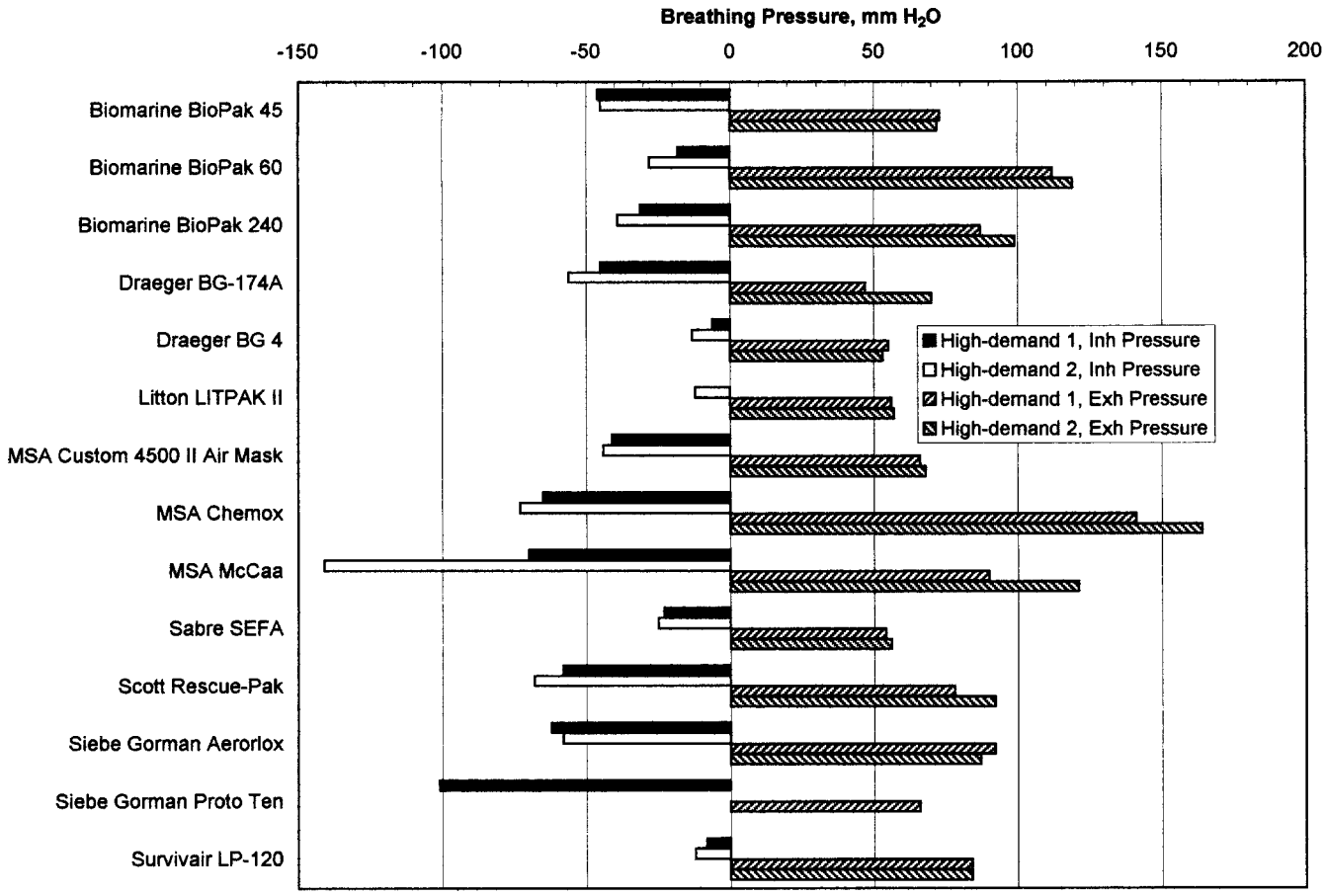

Figure 38.—Breathing pressures during high-work-rate intervals.

BIOMARINE BIOPAK 45

This apparatus is no longer being manufactured, and the apparatus tested was of advanced age. This was not particularly evident except for one peculiarity that surfaced after several tests had been performed. Either or both of the check valves in the face mask began to leak. Exhalation check valve leakage causes exhaled air in the exhalation hose to be reinhaled, effectively increasing the dead space and causing the average inhaled CO_2 to incrementally rise in value. Inhalation check valve leakage permits exhaled air to enter the inhalation hose. This high-CO_2 air is then reinhaled, again effectively increasing the dead space and causing the average inhaled CO_2 to incrementally rise in value. When the check valves leaked, average inhaled CO_2 values were approximately 3.5% compared with approximately 0.9% when they sealed properly. If this problem were to occur in actual use, a user would respond to the higher level of CO_2 by increasing his ventilation rate, which would result in the valves sealing better, thereby lowering the CO_2 level.

During the high work periods, the valves seemed to begin functioning again, with average inhaled CO_2 levels dropping. Presumably, the higher ventilation rates forced the valves to seat properly. At the manufacturer's suggestion, newer check valves from the face mask of the BioPak 240 were installed in the BioPak 45 face mask. These check valves sealed properly during the test performed immediately after their installation. After sitting over a weekend, however, they warped. This was discovered after the next test again showed high average inhaled levels of CO_2. The manufacturer later informed PRL that the check valves from the two apparatus were not identical. Biomarine then sent a new set of apparatus-specific check valves, which functioned properly in the remaining tests.

BIOMARINE BIOPAK 60

During the two periods of work rate 2, both the demand and relief valves were activated, indicating that the tidal volume (volume of a breath) was larger than the volume of the breathing bag. This is wasteful of the cylinder gas.

BIOMARINE BIOPAK 240

Throughout its *rated* duration, the average inhaled CO_2 of the BioPak 240 remained low and the O_2 high. Every test, however, was terminated due to high CO_2 (10%), with an average duration of 264 min with at least 600 psi left in the cylinder. High CO_2 level is not a positive indicator of end-of-life, i.e., it is not easily evident without instrumentation. A user would increase his ventilation rate at higher values of CO_2 and would increasingly desire to remove the apparatus. Ideally, the scrubber would be oversized relative to the quantity of available O_2. It could be that the manufacturer counts on a certain amount of outleakage of O_2 in normal use due to imperfect face mask sealing. In these tests, the face mask was sealed with putty to the headform with no leakage.

As with the BioPak 60, during the high-work-rate intervals, both the demand valve and relief valve were activated with each breath, which wastes cylinder gas. Possibly this is intentional, since reducing the gas supply brings it closer in capacity to that of the CO_2-absorbent canister.

DRAEGER BG-174A

The BG-174 had the lowest exhalation pressure of any apparatus tested here. This is due mostly to the CO_2 bed design, which suspends the chemical absorbent in a wire mesh rather than a packed bed.

DRAEGER BG 4

This apparatus had the lowest minimum inhaled CO_2 of any apparatus tested, including the open-circuit MSA Air Mask, testifying to both the efficiency of the canister and the fact that its face mask included a nose cup. In the Air Mask tests, the lack of a nose cup resulted in the nonzero minimum inhaled CO_2 level measured. In addition, the BG 4 had the lowest absolute pressure swing—exhalation and inhalation peak pressures combined—of any apparatus tested in this study.

LITTON LITPAC II

In the LITPAC II, the low-pressure alarm sounds at approximately 25% of capacity and continues until the cylinders are empty. Users should remove the apparatus when the alarm ceases because O_2 drops immediately thereafter. Although the user's manual states that it becomes difficult to inhale when the cylinders are empty, it was found that O_2 fell below 15% before inhalation pressure increased significantly. This occurred only after the low-pressure alarm stopped sounding, however.

Although this apparatus was designed so that face mask pressure never becomes negative relative to ambient, very short-duration inhalation pressure spikes occurred on every breath, eventually becoming negative toward the end of the test. These are the values measured and reported, but the inhalation face mask pressures, excepting these spikes, were ap-proximately 20 mm H_2O, remaining well above ambient even during the high-demand intervals. Although the reported positive-pressure performance of the LITPAC II is comparable to the Draeger BG 4 and Survivair LP-120 in being among the best performing apparatus during the high-demand intervals, measuring *average* inhalation pressures instead of *peak* inhalation pressures would undoubtedly improve the measured performance of this apparatus over that of the others.

MSA CUSTOM 4500 II AIR MASK

Very short-duration negative inhalation pressure spikes of approximately −15 mm H_2O occurred on every breath with this apparatus, but the inhalation pressure during most of the inhalation was approximately 15 mm H_2O. During the high-demand intervals, initial spikes of approximately −45 mm H_2O were followed by diminishing oscillations, with pressure stabilizing at approximately +20 mm H_2O. As with the LITPAC II, measuring *average* inhalation pressures instead of *peak* inhalation pressures would better reflect actual user impact since, in the event of a breathing circuit leak from ambient, the degree of in-leakage depends upon both the level and duration of the negative pressure.

It was somewhat surprising that the minimum inhaled CO_2 level was not zero for an open-circuit apparatus. This can be explained, however, by the fact that the face mask did not have a nose cup. Nose cups not only reduce the face mask dead space volume, reducing the average inhaled CO_2 level, but are also designed without remote corners so that CO_2 is swept cleanly at once from the contained space rather than trickling out a little at a time which seems to have happened here. Since the cylinder air contained no CO_2, this is the only possible explanation for a nonzero minimum inhaled CO_2 level.

MSA CHEMOX

Except for the Aerorlox, which has a cold O_2 source, and the open-circuit Air Mask, the Chemox provided inspired air with the lowest wet-bulb temperature of any apparatus tested. There was a large difference between wet- and dry-bulb temperatures, indicating relatively dry air. The low wet-bulb temperature is attributed to the inherently dry air produced by KO_2, causing heat of evaporation to be drawn from the respiratory tract. The low dry-bulb temperature can be attributed to the design feature of the apparatus that forces air to sweep over the inner surfaces of the exposed breathing bags from one end to the other, maximizing heat exchange with the cooler laboratory environment. Of course, in a warmer environment, this feature would be less effective and, with rising ambient temperature, would begin to add heat to the breathing-circuit air.

On the negative side, the CO_2 and breathing resistance levels were high. The second, 5-min, high-workload interval, beginning at 50 min, usually brought average inhaled CO_2 up to 10% and beyond. Since substantial recovery occurred after this interval, the test was permitted to continue, but CO_2 continued to rise after this recovery. Since the breathing bag volume was rapidly decreasing as average inhaled CO_2 levels reached 10%, the test was not terminated until the breathing bag was empty. High inhaled CO_2 concentration is not considered a positive indicator of end-of-life, nor desirable. A person would likely have removed the apparatus by the time CO_2 levels reached 10%. It should be noted, however, that the apparatus passes the standard U.S. Navy step test.

The performance of the Chemox is extremely dependent on the KO_2 canister, as might be expected. The canister determines the O_2 production and CO_2 absorption and greatly influences temperatures and exhalation pressure. Only inhalation pressure is related more to the rest of the apparatus than to the canister. The performance of the Chemox is, therefore, naturally dependent on the formulation of KO_2 used in the canisters. Canisters from three batches of KO_2 were used randomly in this study, with CO_2 and pressure seeming to be particularly batch-sensitive, and temperature and O_2 appearing to be less so.

On one apparatus from an old batch of canisters, the chlorate candle pull cord slipped out of the firing pin, requiring the candle to be activated by pulling the pin out with pliers. Assuming that under normal circumstances this action would be taken while still in good air, this is not considered to be a dangerous defect.

MSA McCAA

In order to test the McCaa, because of its aging and deteriorating parts, we had to have the O_2 cylinders hydrostatically tested and combine the good parts of two apparatus to make one functional unit. The regulator of one apparatus malfunctioned and caused a downstream O_2-supply line to burst. The CO_2-absorbent canister of the other apparatus, which is integral with the entire frame and body, had its lower screen excessively clogged with hardened absorbent. Because of this, after 20 to 40 min of use, the breathing pressures approximately doubled. The pressures remained at that level for the duration of the test. The visibly cleaner canister screen of the second apparatus did not experience this phenomenon and was used for all recorded tests.

The termination mode was low bag volume in every test, although average inhaled CO_2 levels were high in general, due in part to the lack of a nose cup in the face mask, and in two cases reached 10% in the second 5-min, high-work interval. The test with the longest duration, 144 min, reached average inhaled CO_2 levels of 10% at 135 min.

The demand valve was activated generally once every three breaths at the start of the tests. Later in the tests, as the pressure in the O_2 cylinder fell, the demand valve was activated generally once every two breaths. Near the ends of the tests, the demand valve was activated every breath. This phenomenon is attributed to the delivery of more O_2 than demanded at first, then less overdelivery as cylinder pressure decreased. The large variation in pressures experienced in the second, 5-min, high-work interval is believed to be a result of variations in the cylinder pressures. Lower cylinder pressure seemed to cause the demand valve to be less responsive, resulting in greater inhalation pressure. With higher cylinder

pressure during the second 5-min high-work interval, the inhalation pressure averaged in the −80 mm H_2O range; with lower cylinder pressure, this value increased to −250 mm H_2O.

SABRE SEFA

The SEFA was tested at the low-flow (5 L/min) regulator setting. Even the "low" O_2 flow rate, however, was much greater than the test O_2 consumption rate, so that the relief valve was activated on every breath. This characteristic spares the CO_2-absorbent canister by dumping high-CO_2 air, and ensures a high concentration of O_2 throughout the test. The SEFA had the lowest average inhaled CO_2 of any apparatus tested, as well as the lowest difference between average and minimum values, indicating low face mask dead space. The SEFA also had the lowest exhalation peak pressures of any positive-pressure apparatus.

SCOTT RESCUE-PAK

This apparatus is no longer being manufactured, so new CO_2-absorbent canisters were unavailable. The CO_2-absorbent canisters used for the Rescue-Pak varied in condition from questionably sealed to positively sealed, but all were past the recommended use date by nearly 2 years. LiOH does not degrade with age, however, so all the canisters were used. Although there was variation between individual canisters, all of them maintained very low CO_2 levels.

Two Rescue-Paks were tested. Five tests were run on one and three on the other. The data from both apparatus were combined since the differences between them were negligible.

The O_2 cylinder fill requirement was from 1,800 to 2,000 psi. This low pressure enabled them to be filled from standard 4.5-ft-tall cylinders. Since we did not yet have an O_2 pump on site, this expedited testing. As the supply cylinder was depleted, however, less O_2 was available to the apparatus cylinders, resulting in less duration and more variation in duration than would be seen if each cylinder had been filled by a pump to a targeted pressure. The average cylinder pressure achieved was approximately 1,780 psi on the first seven tests. The last test was with a cylinder at 2,000 psi filled by a pump. This test lasted 297 min compared with an average of 260 min for the first seven tests, with a standard deviation of 11 min. The average inhaled CO_2 concentration for the last test was only .01% higher than the average of the first seven tests indicating that the extended duration resulted in no CO_2 breakthrough.

The demand valve was usually activated during the tests, but did not seem to add to the inhalation pressure, probably because it is volume-activated, rather than pressure-activated.

SIEBE GORMAN AERORLOX

The most difficult challenge in testing this device was obtaining the liquid O_2 and filling the device. Once the apparatus had been filled, however, it became the simplest device to test. It has no demand valves, regulators, or gauges. It was certainly the coolest closed-circuit apparatus tested and had the highest O_2 concentration due to the high O_2 flow rate of 6-12 L/min, which mostly exited the relief valve.

The Aerorlox is no longer being manufactured, but Siebe Gorman will make custom replacement parts if desired for its remaining users.

SIEBE GORMAN PROTO TEN

This apparatus presented many obstacles to testing; some parts were missing while others had deteriorated, compromising performance. It is no longer being manufactured and Siebe Gorman had no spare parts. The inhalation check valve could not be located; a Rudolph 1800 check valve was used in its place. The metal frame of the apparatus, containing the CO_2-absorbent canister, the breathing bag and the heat-absorbent canister, had a crack in a weld joint which had to be repaired. The bypass valve kept opening on its own and had to be screwed down shut. We could not locate the ice mold to form a block of ice for the heat-absorbent canister, so small ice cubes were used instead. The most serious problem, however, was found after six tests had been performed. It was discovered that the O_2 supply lines were leaking along their entire lengths and could neither be repaired nor replaced. This resulted in a large quantity of the O_2 supply being lost to ambient, preventing the 3-hr-rated apparatus from attaining its intended duration. This means that the CO_2-absorbent canister was never pushed to its limit and that, in general, late test performance was not observed and averaged in with the early test data; this resulted in favorably biased average performance results. Given all these problems, the apparatus would not have been included in this study at all were it not for its unique design.

The test averages were calculated from the best four tests, all of which still suffered from one or more problems, compromising their validity to some extent. All the durations were short due to the leaky O_2-supply hoses, and some of the tests suffered from random activation of the bypass valve before it was permanently shut off. Durations ranged from 116 to 148 min. The first two tests had average inhalation pressures of −55 mm H_2O compared with −85 mm H_2O for the last two tests. This might be explained by differing use of the demand valve or by an actual change in performance characteristics after reassembly for cleaning. There were also large variations in both average and minimum inhaled CO_2 levels for unknown reasons.

The warning whistle is located inside the breathing circuit, presumably to make use of the O_2 vented from it when activated. Unless the user is working at a very high O_2 consumption rate, however, most of this O_2 is simply vented to atmosphere after the volume able to be contained in the breathing circuit is exceeded. Further, the sound made by the whistle is severely muffled by its placement inside the shell, compromising its intended purpose.

The areas in which the Proto Ten excelled were the exhalation pressure and both wet- and dry-bulb temperatures.

The temperatures would have been higher had the durations been longer, however. The low exhalation pressure was, presumably, the result of the low bed depth of the radial canister. It would not likely have changed much with longer durations.

SURVIVAIR LP-120

Four prototype apparatus were delivered to the USBM as part of the contract to develop a low-profile, lightweight, 2-hr-rated rescue breathing apparatus. Only one of the prototypes was used in the performance comparison so as to ensure that performance variation was a reflection of replaceable components rather than different apparatus, since the prototypes were all hand-built and not from a machine-tooled, assembly line.

The relief valve was originally placed in the exhalation breathing bag and was volume-activated. Our prototype, of a later design, had a pressure-activated relief valve in the face mask. This design, however, vented large volumes of air from the breathing circuit at high work rates. Between 30 and 40 L of air were vented during the first, 5-min, high-work-rate period. This resulted in severely reduced durations; therefore, the relief valve was plugged in subsequent tests. Since a relief valve serves little purpose in demand-only apparatus, this modification was considered an acceptable tradeoff in order to permit full evaluation of the apparatus.

SUMMARY

The Draeger BG-174A and BG 4 and the Scott Rescue-Pak had the highest durations. The Biomarine BioPak 240 contains more O_2, but the lower-capacity CO_2-absorbent canister does not permit its full use; average inhaled CO_2 concentrations reached 10% at 264 min with 600 psi remaining in the cylinder. The BG 4 had the lowest *minimum* inhaled CO_2 levels, attesting to the effectiveness of its CO_2-absorbent canister. The Sabre SEFA had the lowest *average* inhaled CO_2 levels, due mostly to the apparently low-dead-space mask and nose cup. Peculiarly, the face mask used on both the BG 4 and the BG-174A behaved differently on each apparatus, exhibiting higher dead space characteristics on the BG 4 than the BG-174A. Apparently, there is some interaction between the mask and the apparatus. The impact of having no face mask nose cup to reduce the quantity of reinhaled CO_2 is shown by the large difference between the average inhaled and minimum inhaled CO_2 levels in both the MSA McCaa and Air Mask. In fact, the Air Mask, with a completely CO_2-free inhalation source of breathing gas, had a nonzero minimum inhaled CO_2 level. This is due, presumably, to the exhaled CO_2 trapped in the recesses of the face mask, trickling out during the entire inhalation but never being completely washed out.

The Air Mask had the lowest wet- and dry-bulb temperatures, which is not surprising because it is an open-circuit device. The liquid-O_2-source Siebe Gorman Aerorlox had the next lowest temperatures. The only apparatus with a CO_2-absorbent not in a packed-bed design, the BG-174A, had the lowest exhalation pressures. The BG 4 had the highest level of positive pressure, with the Biomarine BioPak 60, Survivair LP-120, SEFA, and Litton LITPAC II nearly as high; the Air Mask and the LITPAC II would have been higher if the short-duration, inhalation-pressure spikes had been ignored. The BG 4 had the lowest pressure swing (36 mm H_2O), with the SEFA a close second (39 mm H_2O).

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