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# LIGHTWEIGHT RESCUE BREATHING APPARATUS FINAL REPORT

Bureau of Mines Open File Report 154-82

Contract H0262041
Mine Safety Appliances Company

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16. Abstract (Limit: 200 words)

A lightweight compressed oxygen rescue breathing apparatus (RBA) for rescue and recovery missions in mine rescue work was developed for the Bureau of Mines. The RBA is a positive pressure, closed circuit system that lasts 4 hours. The weight of the complete RBA, including an optional cooler, is slightly over 30 pounds. Weight reduction over currently available RBA's is achieved by using lithium hydroxide for scrubbing $CO_2$ instead of conventional chemicals and using a composite glass fiber-aluminum shell cylinder for oxygen storage instead of a steel cylinder. Positive pressure is maintained in the breathing circuit at all times by applying a constant spring force to the breathing bag. The harness was designed to reduce the work of the wearer by redistributing the weight of the RBA to the wearer's hips.

17. Document Analysis a. Descriptors

Mining

| | | |
|---|---|---|
| Lightweight compressed oxygen rescue breathing apparatus | | Breathing circuit |
| RBA | Weight reduction | Constant spring force |
| Positive pressure | Glass fiber-aluminum shell | Harness design |
| Closed circuit system | Positive pressure | Weight distribution |

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# FOREWARD

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## 1.0 Introduction

The objective of this program was to design, develop, fabricate, and test a compressed oxygen self-contained Lightweight Rescue Breathing Apparatus (RBA) suitable for four hours of mine rescue work. The apparatus was to weigh a maximum of thirty (30) pounds and have a simple cooling system to reduce heat stress.

Subject program was to be carried out in three distinct phases. Phase I (10 months) was to basically consist of designing and fabricating a bread-board prototype rescue breathing apparatus; this was to include component design and testing, system design, and machine and man tests. Phase II (6 months) was to consist of fabricating units for testing under Subpart H Part 11, Subchapter B, Chapter 1, Title 30, Code of Federal Regulations (CFR), as amended March 25, 1972; after successful completion of Title 30 CFR 11 H tests, the units were to be submitted to the National Institute for Occupational Safety and Health (NIOSH) for prototype approval. Phase III (6 months) was to consist of fabricating ten pre-production prototype RBA's and preparing an instruction and maintenance manual for the units.

Figures 1 and 2 on the following pages show the new Lightweight Rescue Breathing Apparatus developed by Mine Safety Appliances Company (MSA) under this program.

## 2.0 Design and Performance Requirements

The major design and performance requirements for the apparatus, as outlined in the original contract, were:

(1) The entire compressed oxygen RBA system shall weigh no more than 30 pounds when fully charged and ready to use. The weight shall be

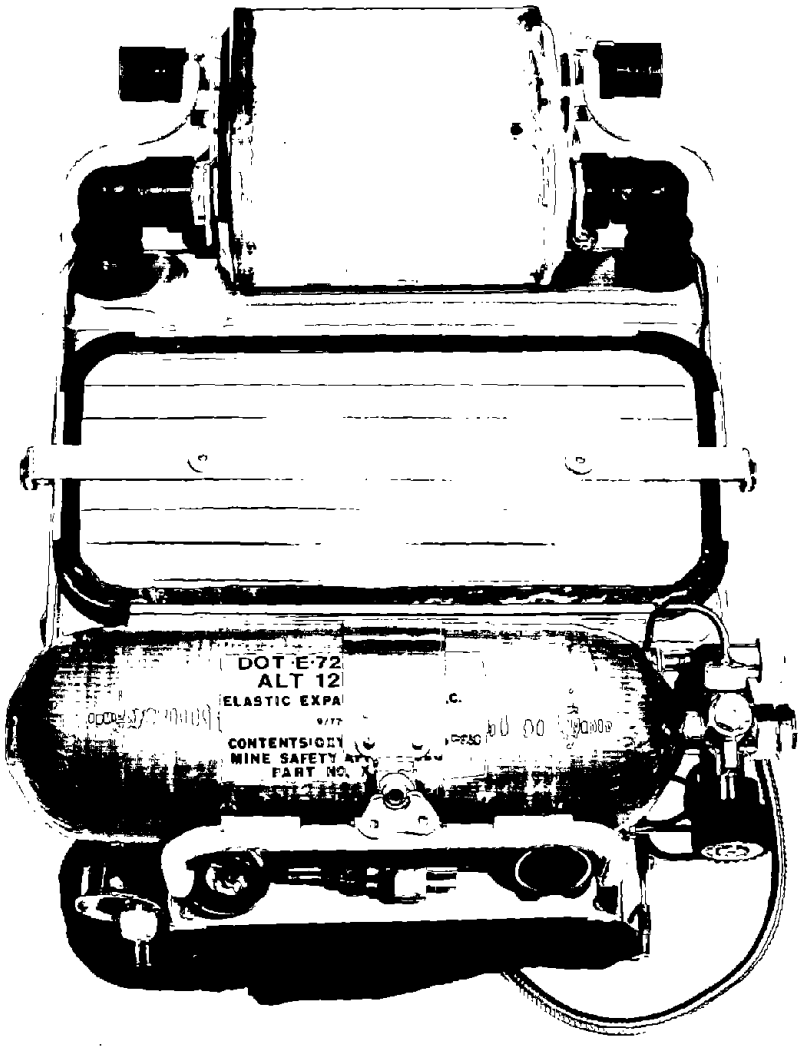




FIGURE 1.- Front View - 4 hour rescue breathing apparatus
(cover, ultravue facepiece assembly removed)

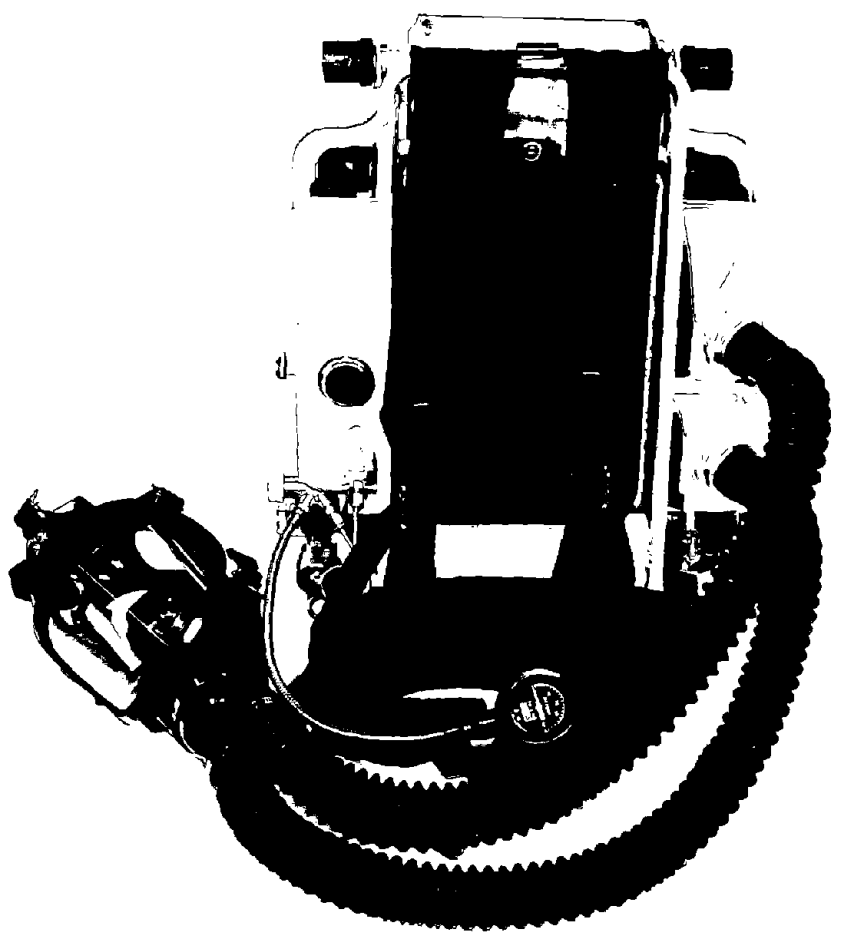



FIGURE 2.- Back View - 4 hour rescue breathing apparatus

distributed in the following manner:

(a) The RBA unit shall weigh a maximum of 23 pounds. The RBA unit includes the charged $CO_2$ scrubber and $O_2$ container, breathing bag, backpack cover and frame, and all other components normally included in RBAs.

(b) The facepiece, breathing hoses, and connections shall weigh a maximum of two pounds.

(c) The cooling system, including coolant, shall weigh a maximum of five pounds.

(2) The outer dimensions of the RBA backpack shall be no more than 19" x 17" x 6".

(3) A one-size full facepiece shall be supplied with the RBA and must be designed to prevent fogging. Windshield wipers are acceptable. Antifogging agents must be non-toxic and must not affect mask materials.

(4) The facepiece shall not cause any skin irritation or abrasion while being worn.

(5) The Contractor shall demonstrate that a one-size facepiece fits a wide range of head sizes. Typical head size range is described in the Los Alamos Scientific Laboratory Report LA-5488, December, 1973, "Selection of Respirator Test Panels Representative of U.S. Adult Facial Sizes."

(6) The RBA shall permit continuous voice communication by the user, shall not interfere with his hearing ability, and shall permit use of a mine rescue telephone during normal RBA operation.

(7) The cooling system shall provide at least 100 KCAL of cooling capacity in order to cool inspired gas and provide for heat loss from the rescue man.

(8) The cooling system shall be designed to be removable from the RBA.

(9) The cooling system shall not require any electrical power.

(10) The Contractor shall demonstrate the effectiveness of the cooling system with man tests. The results should show less physiological strain with employment of the cooling system. This can be measured as lower inspired gas temperatures, lower body core temperatures, and lower heart rates. It must be evaluated over a range of physiological stresses.

(11) Any part of the RBA which might incidentally come in contact with the wearer while in use shall not exceed a temperature of 50°C (122°F).

(12) The RBA shall be sufficiently simple to operate so that a person unfamiliar with breathing apparatus can operate it effectively upon completion of a training program of five 6-hour sessions or less.

(13) The RBA system shall be designed so that it can be refilled or that most repairs can be accomplished in the field. A maintenance and trouble shooting manual shall be incorporated into the instruction manual.

(14) The pre-production RBA shall be reusable at least 100 times with routine maintenance, without any deterioration in performance, function, or reliability.

(15) The design should reflect a simple, rugged, and reliable device while demonstrating a concern for the comfort and mobility of the user. Minimizing fatigue problems and providing adequate mobility in mines with less than 44 inches ceiling heights are important.

(16) The Contractor shall be responsible for obtaining a prototype approval of the RBA for four hour service life from NIOSH under Title 30 CFR 11 H.

3.0 Design Philosophy

Two primary improvements in the new apparatus over existing RBAs are a reduction in weight and the addition of a simple cooling system. Using a composite oxygen cylinder consisting of an aluminum shell wrapped with glass fiber and pressurized to 204 atmospheres results in a weight reduction of approximately 4 pounds over the more common steel cylinders pressurized to 120 to 160 atmospheres. Additional weight reduction has been accomplished by (1) simplification of the oxygen flow circuit, (2) use of a lightweight breathing bag material and (3) use of lithium hydroxide as the $CO_2$ adsorbent instead of soda lime or sodium hydroxide. The cooling system for the new apparatus has a cooling capacity of about 125 KCAL. Cooling of the breathing gas is aided by the addition of heat exchangers in the manifold assembly placed near the entrance/exit port of the breathing bag into the manifold assembly. A water ice cooler is placed adjacent to the heat exchangers (behind the manifold assembly) and conducts heat away from the breathing gas (see Figure 3).

An additional improvement, although not part of the original contract, is the incorporation of a positive pressure system into the apparatus design.

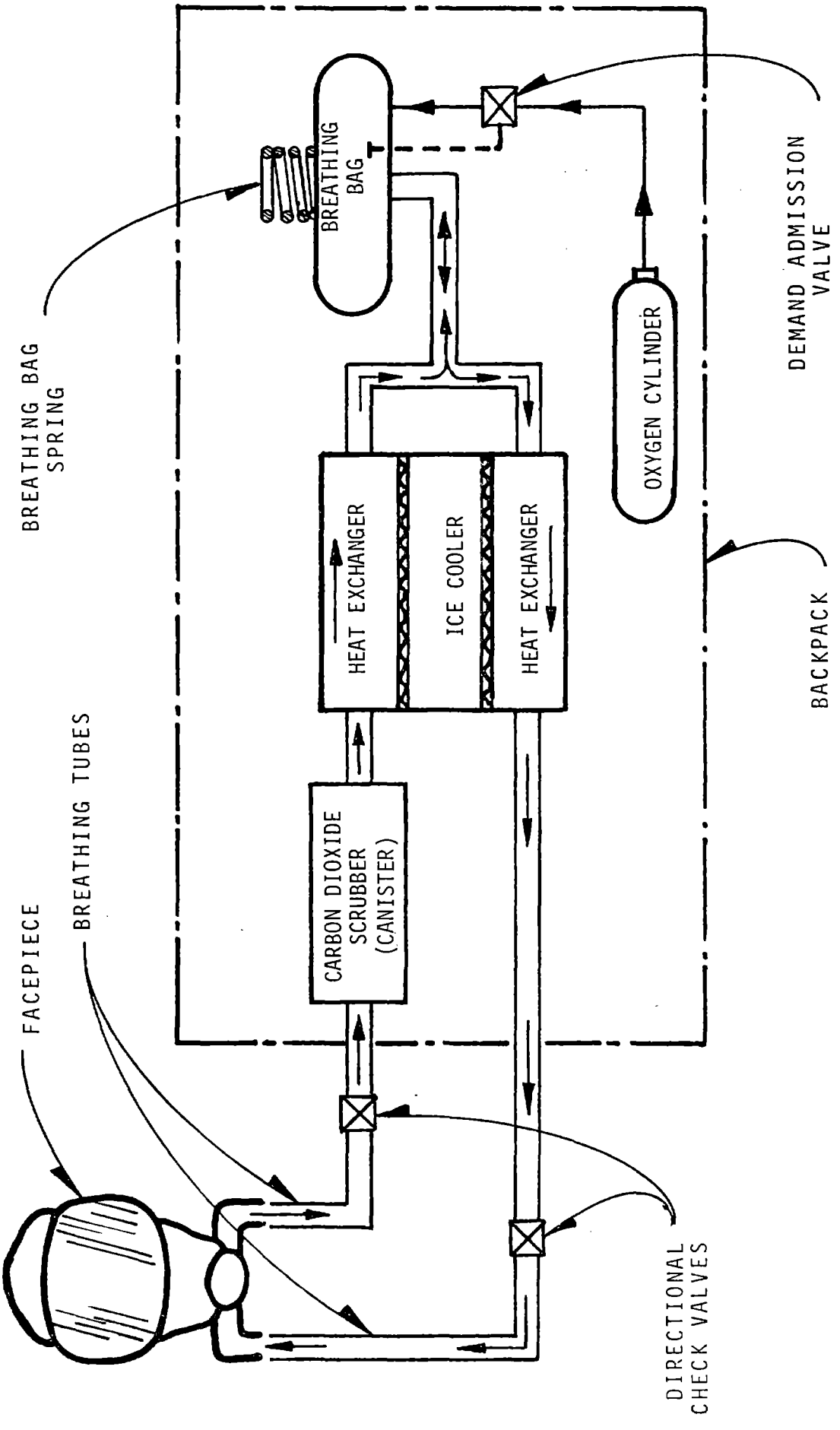


FIGURE 3.- Closed-circuit rescue breathing apparatus with cooling and positive pressure

The Bureau of Mines felt that the design of the new RBA should reflect the most recent technology, and it was verbally agreed between MSA engineering and the Bureau of Mines project officer that the new RBA would be designed as a pressure demand apparatus from the beginning of development. A positive pressure system was created by providing a constant external force to the breathing bag so that a pressure head, or static pressure, is developed throughout the system (see Fig. 3). This pressure head must be overcome on exhalation, so exhalation resistance is increased. On inhalation, flow is actually pushed to the facepiece, rather than being drawn by the user, so that there is no inhalation resistance, and, therefore, no negative facepiece pressure relative to ambient.

## 4.0 Phase I - Development

### 4.1 Component Layout

The first few months of development were spent determining the most desirable layout of the components with respect to the flow circuitry within the backpack, facepiece/hose connections to the backpack, heat convection from the canister, accessibility of the control valves, backpack profile, and backpack weight distribution. One layout considered mounting the major components (cylinder, $CO_2$ scrubber, and breathing bag) in the vertical position, rather than the conventional horizontal position. This was discarded due to problems in incorporating the desired flow circuitry and because of unequal weight distribution. Another concept which was discarded was stacking of components away from the body (breathing bag located behind the $CO_2$ scrubber). This concept was eliminated due to flow circuitry, $CO_2$ scrubber heat management, and addition of depth to the backpack profile.

As shown in Figure 4, the most desirable layout of major components was determined to be with the $CO_2$ scrubber at the top of the backpack, allowing heat to escape to the ambient without adding heat to the breathing circuit (as would occur if the scrubber were below the breathing bag). The breathing bag is located in the center of the backpack to allow a more direct, unrestricted path from the bag to the facepiece to aid in successful pressure demand operation. The oxygen cylinder is located at the bottom, making the control valves easily accessible and placing the heaviest component at the bottom for a lower center of mass (backpack). Flow within the backpack is controlled by two plenums (part of the manifold assembly) located behind the breathing bag and partially behind the $CO_2$ scrubber. The inlet plenum directs flow from the point of entry into the backpack to the scrubber. The outlet plenum directs flow from the scrubber to the breathing bag and from the bag to the backpack exit port.

As stated in the contract, the outer dimensions of the RBA backpack were to be no more than 19" x 17" x 6". However, as layout and mockup work progressed during Phase I, it became apparent that the 19" (height) and 6" (depth) dimensions would be exceeded, while the 17" (width) could be decreased. An allowance of more than 6" in total depth was necessary in the area of contact between the backpack and the lower part of the user's back to allow the use of a 4 1/2" diameter oxygen cylinder. An allowance of more than 19" in height was necessary when including the 1/2" dimension for the frame support located in the center of the backpack under the oxygen cylinder.

4.2 Oxygen Circuit

The oxygen circuit was felt to be an area where weight reduction could be accomplished by (1) eliminating unnecessary components, (2) conserving oxygen,

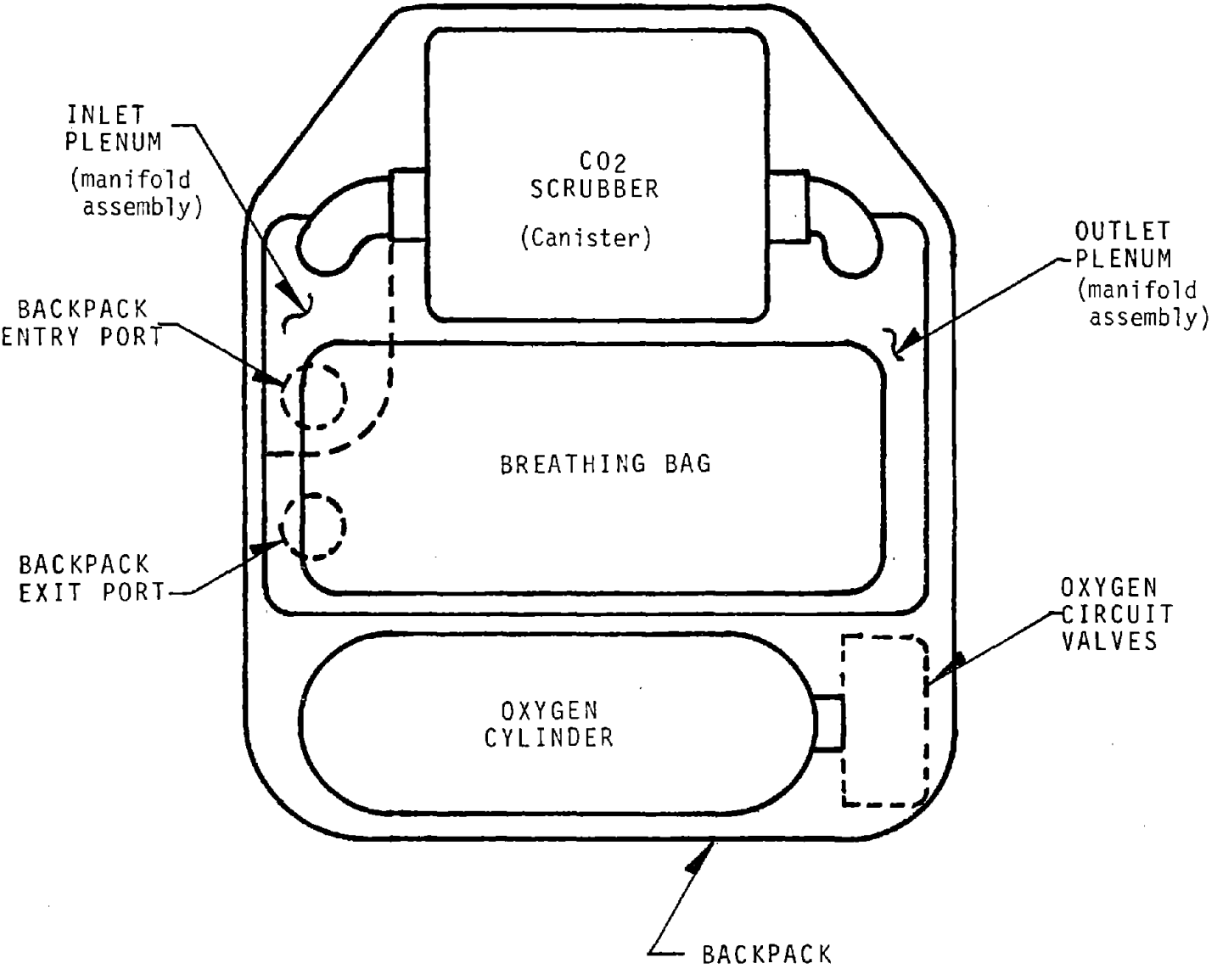


FIGURE 4.- Final layout of major components

and (3) reducing the weight of the actual components.

During Phase I, the thoughts on which components could be eliminated changed several times. An automatic preflush valve was one of the first items eliminated as it was felt flushing of the system could be accomplished by opening the Bypass Valve for several seconds. This action would also check the operation of the Bypass Line before each use. A pressure regulator was considered unnecessary during most of Phase I, but was added during the last few months as a precaution to prevent rapid oxygen depletion in the event of inadvertent opening of the admission valve. The oxygen mainline valve and cylinder valve were combined to eliminate two separate components.

Conservation of oxygen was accomplished by adding oxygen on a demand basis, rather than by constant-flow-plus-demand. The Title 30 CFR 11 schedule for a constant-flow-plus-demand system requires a minimum constant flow of 1.5 liters per minute. At moderate-to-low metabolic work rates, this requirement would result in considerable waste of oxygen. By using a straight demand system, only that amount of oxygen which is consumed will be added.

As stated previously in section 3, using a composite oxygen cylinder consisting of an aluminum shell wrapped with glass fiber and pressurized to 204 atmospheres results in a weight reduction of approximately 4 pounds over the more common steel cylinders pressurized to 120 to 160 atmospheres. However, a great deal of weight reduction in other oxygen circuit components is not realized because brass is used for all valve components.

The oxygen system circuitry as determined during Phase I is shown in Figure 5.

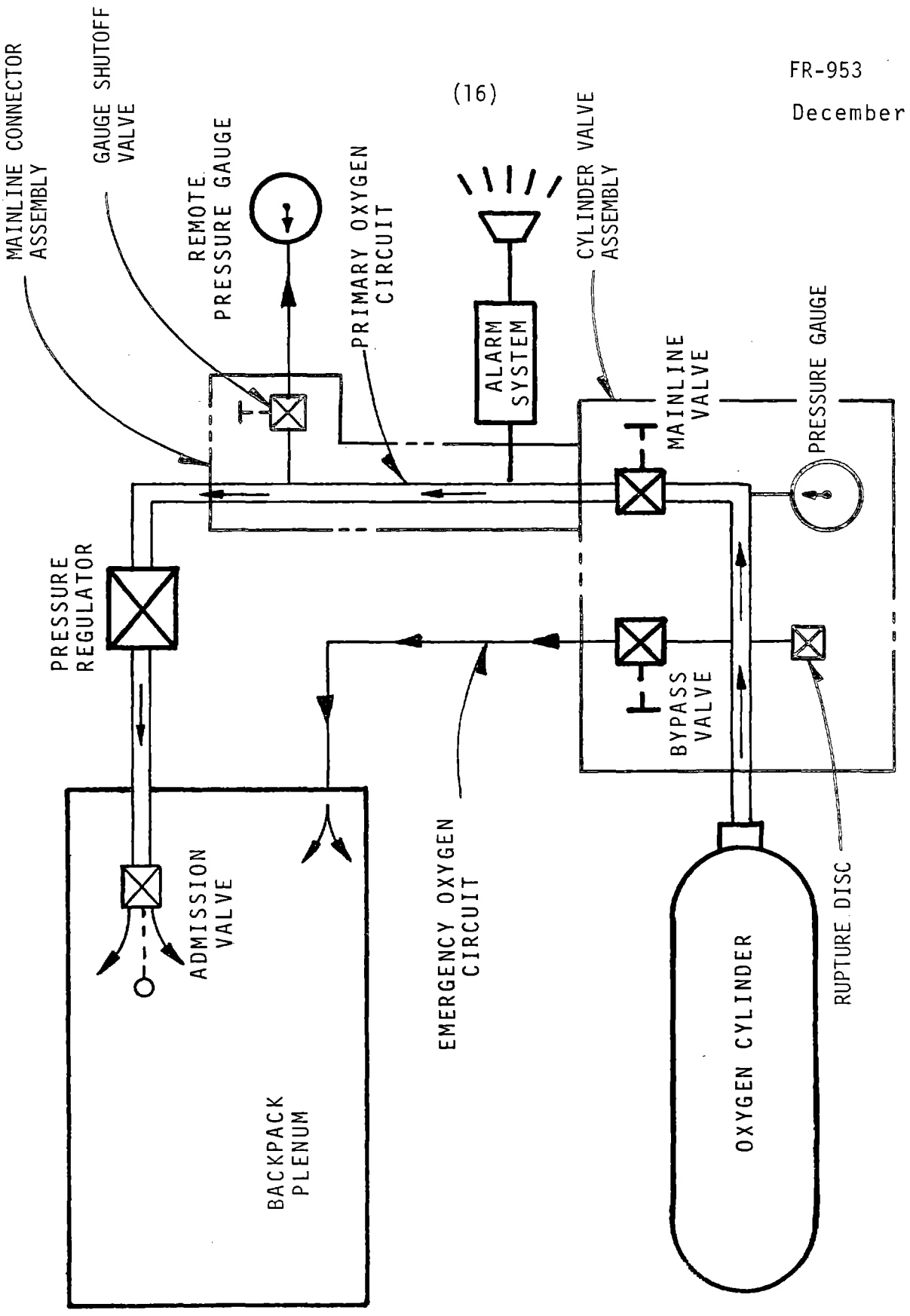


FIGURE 5.- Oxygen System Circuit

4.2.1 Cylinder Valve Assembly

The Cylinder Valve Assembly (see Figure 6) consists of four components: the Mainline Valve, the Bypass Valve, the Safety Rupture Disc, and the Pressure Gauge. The decision to incorporate the Bypass Valve at the cylinder was made early in the development and is a carryover from the design of the McCaa apparatus. Having the Bypass Valve at the cylinder, instead of downstream from the Mainline Valve as on most current RBAs, is felt to be the only true method of bypassing the system. In the event of any malfunction in the main oxygen line, the Mainline Valve can be turned off, isolating the system completely, and the Bypass Valve will still be functional.

The Bypass Valve handwheel is spring-loaded to return to the closed position when not held open manually. A number of pushbutton and pushbar concepts were looked at before the handwheel concept was used. Advantages of the handwheel are that it may be manually overridden in case of spring failure (pushbuttons or pushbars might stick open without overriding means), and the handwheel may be manually tightened by hand beyond the spring torque for long-term cylinder storage.

The Cylinder Pressure Gauge is mounted in the Cylinder Valve Body in a location where it can be easily read if the cylinders are in rack storage or from the side of the backpack by a second person while the apparatus is worn. The gauge uses a helically wound Bourdon Tube and has a 1 inch dial.

The Cylinder Valve Safety Disc is designed to rupture at a pressure of 4500 to 5000 psig at 160°F.

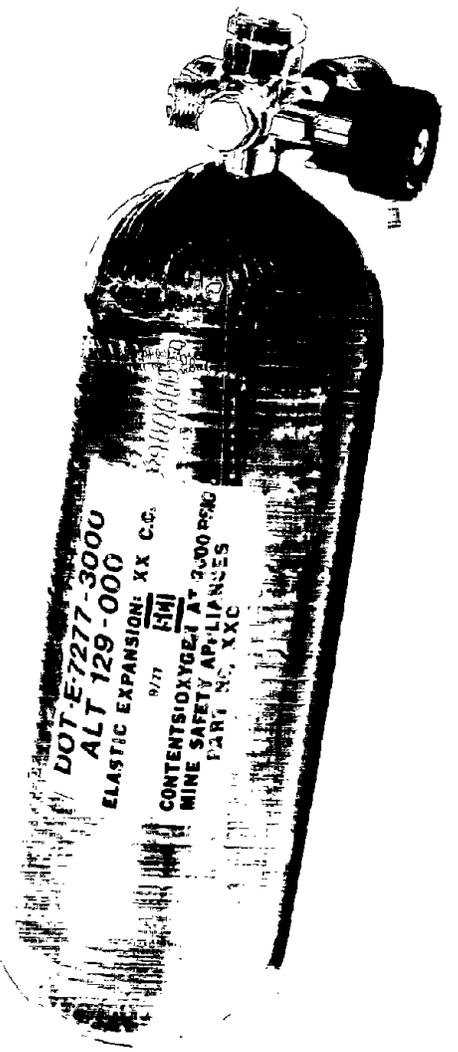




FIGURE 6.- Cylinder and Valve Assembly

4.2.2 Mainline Connector Assembly

The Mainline Connector Assembly (see Figure 7) serves to join the mainline outlet of the Cylinder Valve to the Pressure Reducing Valve, Audible Alarm and Remote Pressure Gauge (via the Gauge Shutoff Valve which is housed in the connector). The inlet to the connector is the oxygen nut and nipple in accordance with CGA Connection No. 540 for oxygen cylinders.

4.2.3 Remote Pressure Gauge

The Remote Pressure Gauge, like the Cylinder Gauge, uses a helical-wound Bourdon tube (see Figure 8). It has a 2 inch dial for easy reading during use, is housed in a glass filled-plastic case, and has a polycarbonate lens. The case is covered with a rubber boot to protect the gauge from damage. During Phase I, the high pressure hose to the gauge used a flexible Kevlar reinforced neoprene tube. After Phase I, hose construction was changed to a coiled capillary copper tube covered by a flexible stainless steel sleeve. This was done to eliminate the possibility of inadvertant severing of the hose during use of the RBA.

4.2.4 Pressure Reducing Valve

The Reducing Valve is similar in construction to that used in the MSA Air Mask. It uses an unbalanced poppet, and is a reverse acting pressure regulator, so that the reduced pressure increases as the cylinder pressure decreases. The reduced pressure will vary from about 55 psig at full cylinder pressure (3000 psig) to about 100 psig when the cylinder is essentially empty (100 psig).

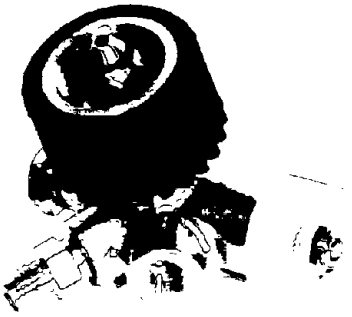

FIGURE 7.- Mainline Connector Assembly

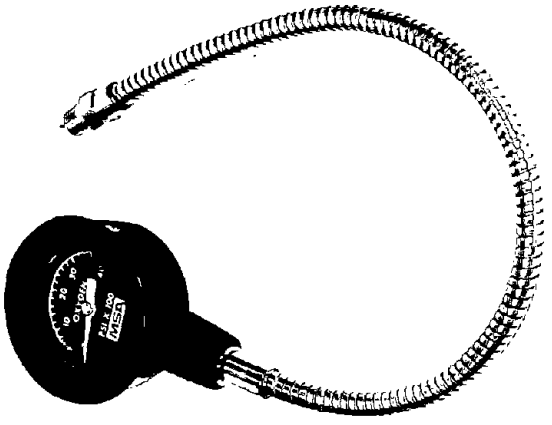

FIGURE 8.- Remote Pressure Gauge

4.2.5 Admission Valve

The demand admission valve adds oxygen to the breathing circuit when the breathing bag approaches a low volume (approximately 1 liter). The admission valve is located in the backpack manifold assembly and extends into the breathing bag. It is a spring-loaded tilt valve and is mounted at an angle to the top of the bag. As the bag volume decreases, the top plate of the breathing bag assembly comes in contact with and pushes on a teflon ball on the admission valve stem, thereby activating the valve and adding oxygen to the bag.

In a positive-pressure closed-circuit device, it is almost essential to operate the admission valve as a function of bag volume, rather than system pressure. Use of a volume-operated admission valve assures that the available gas in the breathing bag has been used before oxygen is added to the system.

4.2.6 Alarm System

The low-gas consumption alarm system developed for the RBA during Phase I is shown schematically in Figure 9. Although the alarm system for the RBA had to be redesigned during Phase II due to potential problems in the field, the principle of operation for the initial alarm system is explained herein as a reference base for comparison between the two systems (see Section 5.1.1).

The initial alarm system consisted of a spring-loaded piston which responds to cylinder pressure, an accumulator, and a small diaphragm horn. The principle of operation for the system was as follows: (1) When the cylinder valve is opened, the piston moves back to open a passage to the

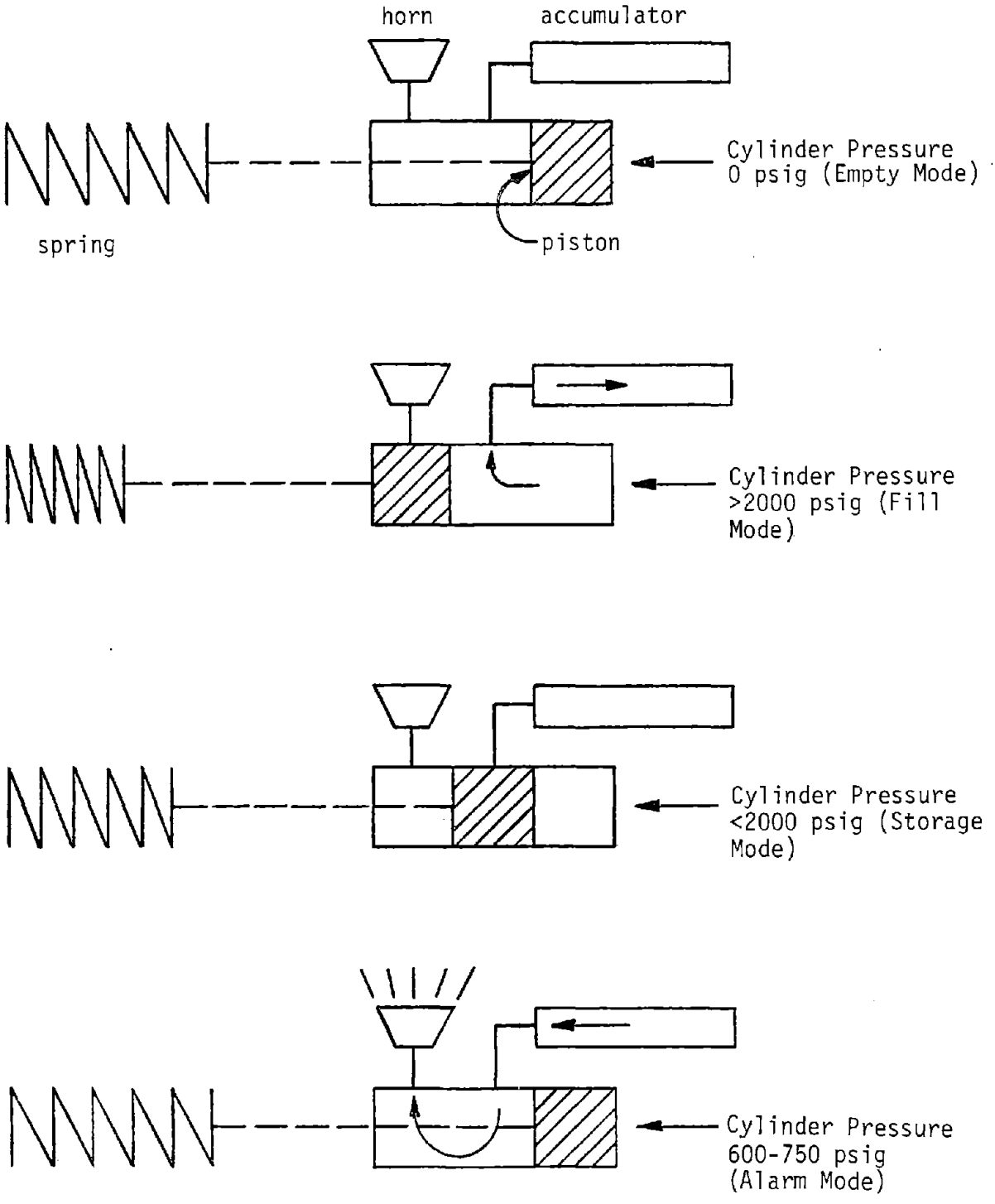


FIGURE 9. - Alarm System (Phase I)

accumulator; (2) As cylinder pressure drops during use, the piston responds and closes the opening to the accumulator; (3) When cylinder pressure reaches the alarm pressure, the piston moves past the passage to the accumulator, allowing oxygen to bleed from the accumulator thru the horn.

4.3 Breathing Circuit

The breathing circuit is shown schematically in Figure 10. It consists of the facepiece assembly, inhalation and exhalation tubes with directional check valves, manifold assembly (with inlet and outlet plenums), the $CO_2$ scrubber (canister) and the breathing bag.

Exhalation flow enters the facepiece and is directed through the exhalation tube by the directional check valves. Upon entering the backpack, flow is through the inlet plenum to the canister via the plenum-to-canister connector. The $CO_2$-scrubbed gas leaves the canister and enters the outlet plenum by means of a second canister to plenum connector. As flow passes through the outlet plenum, it traverses a heat exchanger (set of cooling fins on the plenum wall) which is adjacent to the conductive wall of the cooler and then travels into the breathing bag. Inhalation flow comes from the bag, through the outlet plenum with a second set of cooling fins, and back to the facepiece via the inhalation breathing tube.

During Phase I, the directional check valves were part of the inhalation and exhalation breathing tube assemblies. After Phase I, the location of the valves was changed to the entrance and exit ports in the manifold assembly. A system of mating slots incorporated into the directional check valve bodies and their corresponding receptacles in the manifold assembly insures proper direction of flow through backpack components even if the breathing tubes are

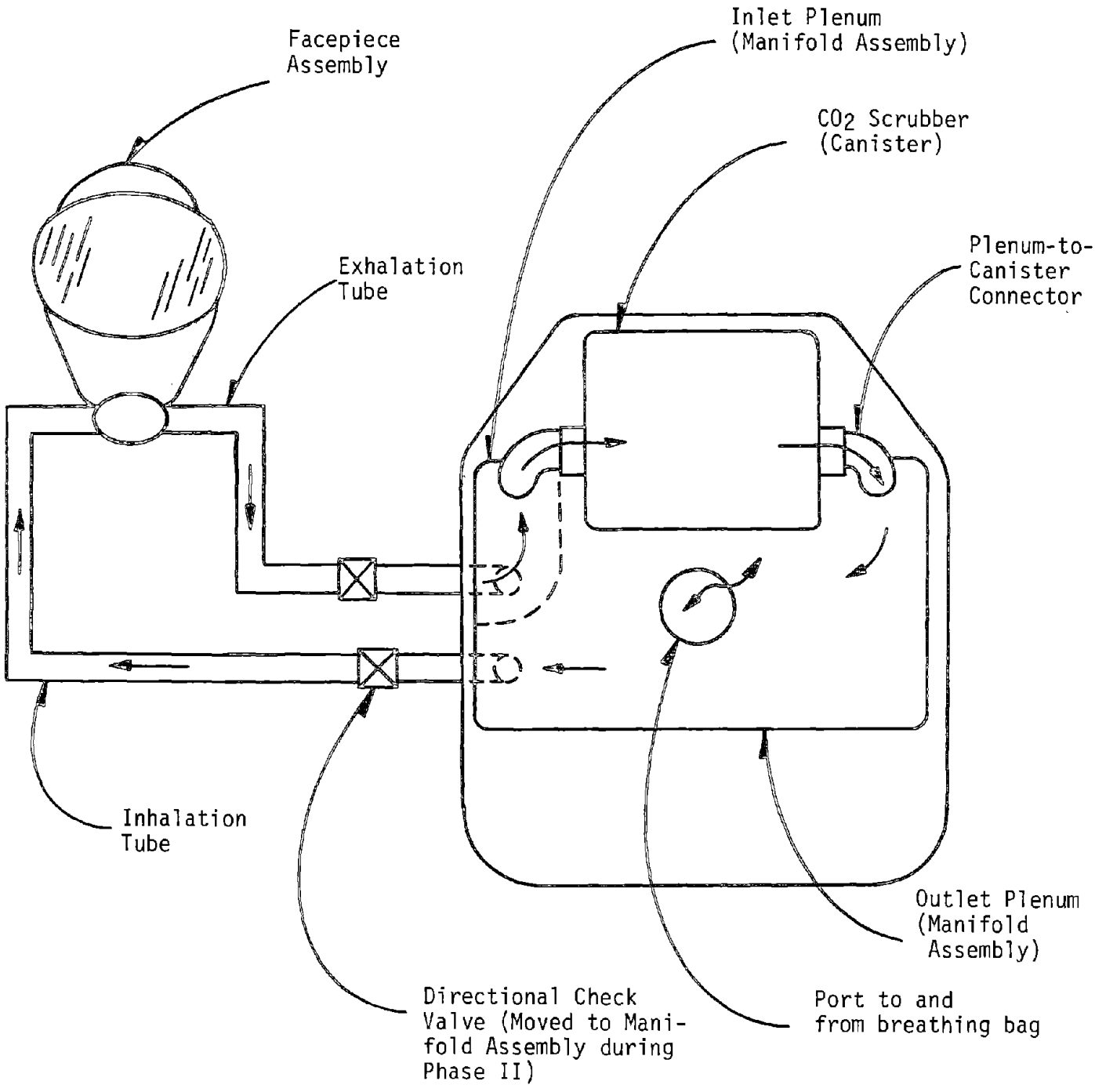


FIGURE 10.- Breathing Circuit

inadvertently crossed when they are hooked up to the manifold assembly.

4.3.1 Facepiece Assembly/Connector

MSA's standard "Ultravue" facepiece was incorporated into the apparatus design during Phase I (see Figure 2, page 7). This single size facepiece provides a positive facial seal on a wide range of facial sizes and shapes.[1]

A lens wiper assembly was added to the facepiece after man tests near the end of Phase I indicated that even with a heavy coat of the best available fog-preventative solution, condensate may accumulate on the lens after about 1 1/2 to 2 hours of use.

The connector, which serves to join the inhalation and exhalation breathing tube assemblies to the facepiece, is designed so that maximum downward head movement can be accomplished without interference between the tube assemblies and the user's chest. Voice communication through the facepiece is provided by a speaking diaphragm assembly housed in the connector.

4.3.2 Breathing Tube Assemblies

Through most of Phase I, the intended design for the inhalation and exhalation tube assemblies was that of flexible, corrugated tubes between the facepiece and chest position and wire-reinforced hoses between the chest and backpack. The wire-reinforced hoses were to prevent inadvertent collapse of the hoses as a result of arm movement. At the 1977 Mine Rescue Competition, where the first prototype of the RBA was shown, the

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1. Hyatt, E. C. and J. A. Pritchard and C. P. Richards. Respirator Efficiency Measurement Using Quantitative DOP Man Tests. American Industrial Hygiene Association Journal, October, 1972.

wire reinforced hoses were the most criticized feature of the device. Rescue team members felt that the hoses were too rigid and preferred corrugated tubes instead. They had not experienced tube collapse on other RBAs which used corrugated tubes under the arm. As a result of the unanimous objection to the reinforced hoses, they were eliminated from the apparatus design.

The flexible, corrugated breathing tubes are made of EPDM (ethylene propylene diene) rubber and have an inside diameter of 1.25 inches and an outside diameter of 1.85 inches over the corrugations (see Figure 2, page 7).

4.3.3 Directional Check Valves

The Directional Check Valves utilize a natural rubber V-shaped flapper which results in a low pressure drop at high flow rates (flow resistance at 120 liters per minute must not exceed 6.5 mm [.25 inches] of water).

4.3.4 Manifold Assembly

The Manifold Assembly consists of the inlet and outlet plenums, the plenum to canister connectors, the bypass tube assembly and the admission valve assembly. The inlet and outlet plenums, which are formed from .032" thick aluminum, control flow within the backpack. The outlet plenum also serves as:

(1) A housing for two sets of cooling fins (heat exchangers) used to cool the breathing gas.

(2) A water collector where condensate from the cooled breathing gas may accumulate.

(3) A housing for the demand admission valve (see 4.2.5).

(4) A connection point for the oxygen bypass line (see Figure 5).

The plenum to canister connectors, which consist of formed rubber tubes with hand-tightened nuts, are used at each end of the canister to permit easy canister replacement.

4.3.5 $CO_2$ Scrubber (Canister)

The $CO_2$ Scrubber (see Figure 11) consists of a kidney shaped canister with a chemical bed cross-sectional area of 25.4 square inches and a total length of 7.87 inches (excluding the inlet and outlet connectors). The canister contains 1350 grams of lithium hydroxide conforming to MIL-L-20213D. Lithium hydroxide (LiOH) was chosen as the $CO_2$ adsorbent due to its advantages in weight and efficiency over other known adsorbents such as soda lime or sodium hydroxide. Two sets of screens enclose non-woven polyester filter media at the top and bottom of the chemical bed.

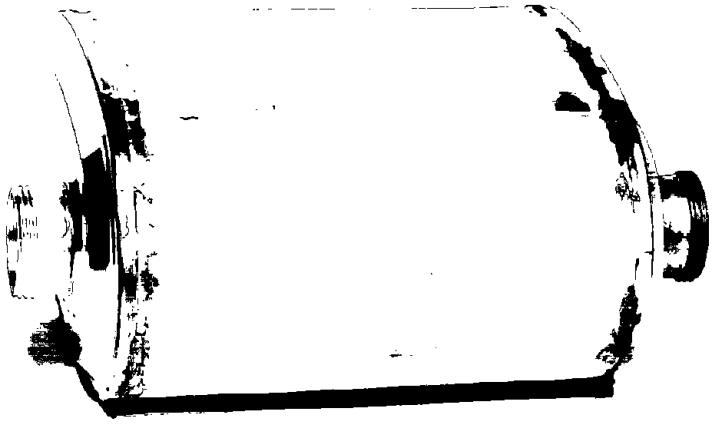



FIGURE 11.- $CO_2$ Scrubber (Canister)

4.3.5.1 Design Concepts (Canister)

Several canister designs were evaluated during Phase I. The first of these was a "radial flow" design, where the flow would enter the center of a cylindrical canister and flow radially outward to an outer ring plenum. This design was considered the optimum as far as breathing resistance, since it provided a very large cross-sectional flow area (about 40 square inches at the entrance to the chemical bed and 180 square inches at the bed exit). This was particularly desirable with the LiOH bed since filtering must be used to prevent LiOH fines from entering the breathing circuit, and the large filter surface area would minimize the pressure drop through the filter. This design, however, was eliminated because (1) the size and shape of the canister would have resulted in a bulky and cumbersome backpack; (2) the design showed poor LiOH utilization on machine tests; and (3) use of this design would have resulted in the heaviest canister of all the designs considered.

Three other canister designs were evaluated, each of which had a cubical chemical bed (see Figure 12). Each canister provided flow in a different orthogonal direction through the bed, and the bed size was defined by the available space within the backpack. These designs were:

(1) A "flat canister" having a large bed cross-sectional area and a shallow bed depth. A tube was located through the center of the bed so that the inlet and outlet ports would be on the same side of the canister.

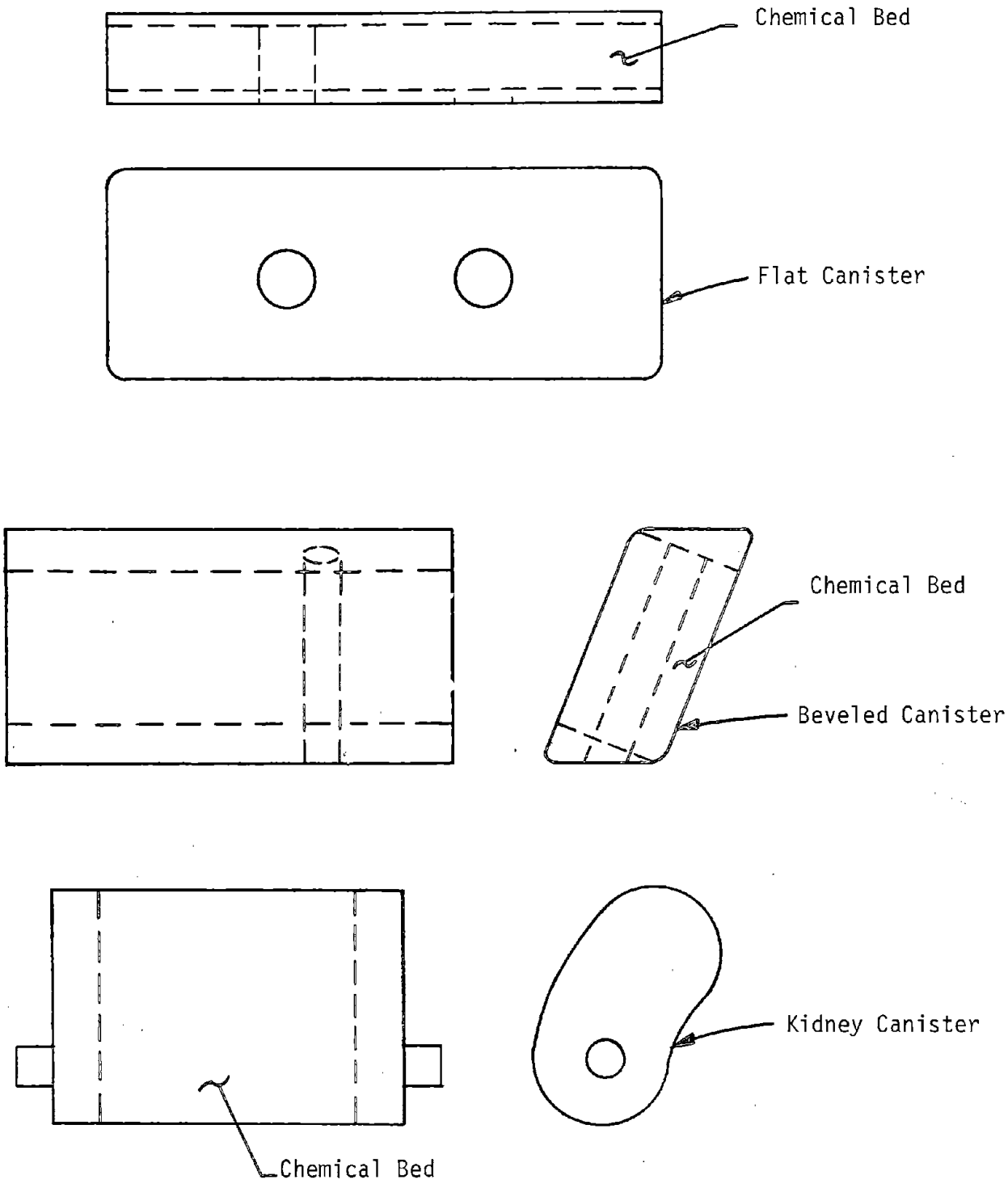


FIGURE 12.- Canister Design Concepts (Phase I)

(2) A "beveled canister" with flow in a vertical direction and beveled plenums on each end of the bed to reduce overall canister height. Again, a tube ran through the center of the bed so that the inlet and outlet ports would be on the same side of the canister.

(3) A "kidney canister" with horizontal flow through the face with the smallest cross-sectional area.

Early tests on the flat canister indicated that the shallow bed depth caused premature $CO_2$ breakthrough and that chemical efficiency was low. The beveled canister provided good chemical utilization, but was eliminated because of the difficulty in providing a satisfactory connection between the canister and backpack, and because of the complexity of the canister.

4.3.5.2 Breathing Resistance (Canister)

The kidney canister provided the optimum design as far as size, weight, canister cost, and ease of canister replacement. However, because it had the smallest cross-sectional area of the designs considered, it also had the highest pressure drop (breathing resistance). Attempts were made to reduce the pressure drop through the kidney canister by use of:

(1) Pleated screens within the chemical bed.

(2) Various size LiOH granules

(3) Various filter media

(4) A slight increase in the chemical bed cross-sectional area.

In general, the use of pleated screens not only resulted in a lower pressure drop, but also in a noticeable reduction in the

efficiency of the chemical bed. These screens would thus have added to the size, weight, complexity, and cost of the canister while providing little benefit as far as breathing resistance.

Tests using LiOH granules having a size other than that specified in MIL-L-20213D were conducted by both MSA and the Bureau of Mines Bruceton Facility. These tests indicated that the exclusive use of large size granules does result in a lower resistance, but this is also accompanied by a substantial reduction in the efficiency of the chemical bed. Additional tests conducted by MSA using only smaller size granules (6 x 8 mesh) showed no overall benefit.

Some improvement in the resistance through the bed was achieved by (1) use of nonwoven polyester filter media instead of glass fiber filter media; and (2) a slight increase in the cross-sectional area of the chemical bed. The addition of 1/8 inch to the periphery of the kidney canister increased the cross-sectional area from 24.2 square inches to 25.4 square inches. These two changes reduced the bed resistance approximately 0.4 inch of water at a flow rate of 120 liters per minute (resistance of smaller canister was 1 inch of water, resistance of larger canister was 0.6 inches of water).

4.3.5.3 Machine Test Results (Canister)

Table 1 on page 32 lists the results of some of the $CO_2$ scrubber machine tests conducted during Phase I. Each machine test consisted of passing a flow of 3.5 percent $CO_2$ in saturated air at 98°F through the canister using a breathing machine with a cam work rate of 622 Kg-m/min. (as defined in Title 30 CFR 11.85-3 [c]) and a minute volume displacement of 48 liters.

| Test Ref. No. | Canister Shape/Size | Internal Pleated Screen Configuration | Mesh Size of Lithium Hydroxide | Weight of LiOH (grams) | Bed Dimensions | | Duration (min.) (to 0.5% $CO_2$ at Canister Outlet) | Date Tested |
|---|---|---|---|---|---|---|---|---|
| | | | | | Cross Section ($in^2$) | Depth (Calculated) (in) | | |
| 1 | Kidney/Small | None | 4 thru 14 | 1,400 | 24.2 | 7.1 | 270 | 7/6/77 |
| 2 | Bevel | None | 4 thru 14 | 1,400 | 35 | 4.9 | 267 | 6/9/77 |
| 3 | Kidney/Large | None | 4 thru 14 | 1,350 | 25.4 | 6.5 | 250 | 12/6/77 |
| 4 | Kidney/Small | None | 4 thru 14 | 1,350 | 24.2 | 6.8 | 247 | 7/1/77 |
| 5 | Kidney/Small | None | 4 thru 14 | 1,350 | 24.2 | 6.8 | 240 | 10/6/77 |
| 6 | Bevel | None | 4 thru 14 | 1,200 | 35 | 4.2 | 174 | 6/3/77 |
| 7 | Kidney/Small | 3 Screens Staggered Config. | 4 thru 14 | 1,280 | 24.2 | --- | 213 | 10/11/77 |
| 8 | Kidney/Small | 4 Screens Inverted Config. | 4 thru 14 | 1,250 | 24.2 | --- | 157 | 10/13/77 |
| 9 | Kidney/Small | 4 Screens Crisscross Config. | 4 thru 14 | 1,300 | 24.2 | --- | 82 | 10/4/77 |
| 10 | Kidney/Small | None | 4 thru 6 | 1,400 | 24.2 | 7.1 | 190 | 7/12/77 |
| 11 | Kidney/Small | None | 6 x 8 | 1,000 | 24.2 | 5.0 | 126 | 12/1/77 |
| 12 | Kidney/Small | None | 6 x 8 | 1,000 | 25.4 | 4.8 | 70 | 12/1/77 |

TABLE 1.- $CO_2$ Scrubber Machine Tests

These machine tests indicated that the required four hour service life can be attained with 1350 grams of 4 through 14 mesh LiOH. Tests 1 and 2 used canisters having a 1400 gram, 4 through 14 mesh size LiOH charge. These canisters lasted for 267 to 270 minutes before the exit $CO_2$ concentration exceeded 0.5 percent (maximum allowable concentration per Title 30 CFR 11.85-12 [d]). Three canisters with 1350 grams of 4 through 14 mesh LiOH lasted for 240 to 250 minutes (Tests 3, 4, and 5). With 1200 grams of 4 through 14 mesh LiOH, the service life was reduced to 174 minutes (Test 6). Tests 7, 8, and 9 were run with various screen patterns in the chemical bed. Test 10 was run with 1400 grams of large size LiOH granules (4 through 6 mesh) and shows a substantial reduction in service life when compared with Test 1 (where 1400 grams of 4 through 14 mesh LiOH was used). Tests 11 and 12 were run with 1000 grams of 6 x 8 mesh LiOH.

4.3.6 Breathing Bag Assembly

The breathing bag assembly (see Figure 1, page 6) consists of .032 inch thick anodized aluminum top and bottom plates attached to a .025 to .030 inch thick neoprene latex bellows. Side and end edging strips made of .016 inch thick aluminum are used for external reinforcement of both plate to bellows connections. Three .032 inch thick polycarbonate rings are used for internal reinforcement of the bellows. The top plate assembly includes two studs which are used to attach the plate to the pressure support bar of the frame assembly (this bar transmits the external spring force to the breathing bag). The bottom plate assembly includes a relief valve assembly for the bag and a mounting ring for attaching the breathing bag assembly to the manifold assembly.

4.3.6.1 Design Concepts (Breathing Bag)

Three primary breathing bag designs were considered during Phase I. These designs were:

(1) A rectangular box - shaped compliant bladder type bag with a loading plate on the top to transmit the external spring force to the bag. A shield was to be placed around the sides of the bag to prevent excessive bulging or bag interference with other components. The main problem with this design was the possibility of bag abrasion from constant movement against the shield.

(2) A rectangular box - shaped bag with a loading plate on the top to transmit the external spring force to the bag. The sides of the bag were to use rubber or rubberized sheet with internal reinforcing plates to help control bag folding and shape. The main problems with this design were (a) the lack of bag compliance; (b) the difficulty of fabrication, and (c) the relatively heavy weight.

(3) A rectangular bellows type bag with a loading plate on the top to transmit the external spring force to the bag. This was the design concept chosen.

4.3.6.2 Breathing Bag Materials

Final selection of the material for the breathing bag was not completed until Phase II (see 5.1.3). The desired characteristics for the material, as established during Phase I, were as follows:

(1) Lightness of weight

(2) Ability to pass the gasoline vapor test delineated in Title 30 CFR 11.85-3 (less than 100 ppm gasoline vapor

penetration after 8 hours).

(3) Ability to be fabricated into a gas-tight bellows with adequate bag compliance.

The most promising fabrication technique for the bag near the end of Phase I appeared to be latex dipping. Natural latex, the most common dipping material, was used to produce a bellows type bag which was acceptable in all respects except for permeability. Nitrile latex was then tentatively selected as the first choice for the breathing bag material, while neoprene latex was selected as an alternate choice (both materials passed the permeability requirement).

4.3.7 Frame and Harness Assembly

The backpack frame assembly, constructed of 1/2" diameter aluminum tubing, includes hardware for securing the $CO_2$ scrubber (canister) and the oxygen cylinder (see Figure 1, page 6). It also includes two 1/2" diameter spring loaded arm assemblies which are joined by a pressure support bar at their ends. This bar transmits the external spring force to the breathing bag. The initial setting on the torsion springs determines whether the RBA is operated as a positive pressure device or as strictly a demand apparatus.

The harness assembly is designed to allow wearing of the backpack for the four hour service life without discomfort (see Figure 2, page 7). Padded shoulder straps and waist straps are used to prevent concentration of the load in any one area. Extension arms are used at the base of the backpack to distribute a large portion of the load to the user's hips, rather than requiring the whole load to be carried by the shoulders. Weight reduction is accomplished in the padded straps by the use of a tubular nylon webbing with internal foam pads which acts as both the

strap and pad, rather than using two separate components.

4.3.8 Cooler

The cooler, which consists of an .062 inch thick ABS (acrylonitrile-butadiene-styrene) body with an .032 inch thick aluminum back, has a cooling capacity of about 125 KCAL. Water ice is used as the cooling medium. The removable cooler is located behind the outlet plenum of the manifold assembly; this allows the cooler to provide some cooling to the user's back as well as the breathing gas. The aluminum back is used as the contact surface with the outlet plenum; the ABS body contacts the user's back. The cooler weighs slightly under 4.0 pounds.

4.3.9 Cover

The cover for the RBA is made from .125 inch thick ABS. During Phase II, a steel screen was added to the cover body (near the top) to allow convective heat transfer from the $CO_2$ scrubber (canister).

4.3.10 Water Accumulator

The water accumulator consists of a 1.75" diameter stainless steel canister located directly below the lower end of the outlet plenum in the manifold assembly. Condensate in the outlet plenum drains into the canister through a short section of 1/4" diameter tubing.

4.4 Man Tests (Prototype RBA)

Two man tests were conducted on the prototype RBA during Phase I in order to evaluate (1) the overall system performance and (2) the correlation between the machine tests and actual performance on humans. Both tests were Man Test 4 in accordance with Title 30 CFR 11.85-15, and the same 190 pound subject performed both tests. The first man test was run with the apparatus in the pressure demand mode, while the second test was run with the apparatus in the

demand mode. Also, the small kidney-shaped canister with 1,280 grams of LiOH and pleated screens in the chemical bed was used in the first test, while the second test was run with the small kidney canister having 1,400 grams of LiOH and no pleated screens in the bed (reference Table 1, page 32). The cooler was used in the second test only. However, problems in maintaining contact between the cooler and the outlet plenum prevented efficient cooling performance.

Tables 2 and 3 on page 38 show the breathing bag $CO_2$ concentration, the inhalation temperature, and the cumulative oxygen usage for the two man tests. Conclusions which were drawn from these tests are:

(1) The canisters performed in a similar manner during both the man tests and the machine test (described in 4.3.5.3). The canister with 1,280 grams of LiOH lasted for 213 minutes on the machine test before the exit $CO_2$ concentration had exceeded 0.5 percent, and it lasted for a little over 210 minutes on the man test before $CO_2$ concentration in the breathing bag reached the same level. The exit $CO_2$ concentration for the canister with 1,400 grams of LiOH never reached or exceeded 0.5 percent on either the machine test or the man test.

(2) The oxygen used in the pressure demand mode was approximately 40 percent higher than that used in the demand mode (439 liters in pressure demand versus 311 liters in demand). Reasons for this could have been: (a) a greater leakage rate from the system in the pressure demand mode; (b) a higher user work rate in the pressure demand mode due to higher exhalation resistance; (c) user acclimation to the 4-hour test; and (d) the cooler was used during the demand test and may have lowered the user work load. There were too many variables between the two tests to determine the reason for the wide variance

Table 2.- % $CO_2$ Concentration, Inhalation Temperature - Man Test 4 (Prototype RBA)

| Sampling Period (Time in Minutes) | MSA Test 390 (Pressure Demand Mode) | | MSA Test 391 (Demand Mode) | |
|---|---|---|---|---|
| | % $CO_2$ Concentration | Inhalation Temp. (°F) | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | .00 | 83 | .00 | 73 |
| 20 | .00 | 91 | .00 | 81 |
| 40 | .00 | 101 | .00 | 90 |
| 60 | .00 | 99 | .00 | 90 |
| 80 | .01 | 101 | .00 | 91 |
| 100 | .11 | 101 | .00 | 93 |
| 120 | .00 | 103 | .00 | 96 |
| 140 | .08 | 99 | .00 | 92 |
| 160 | .15 | 98 | .00 | 92 |
| 180 | .00 | 99 | .00 | 92 |
| 200 | .36 | 101 | .00 | 93 |
| 210 | .41 | 101 | .01 | 93 |
| 220 | .56 | 102 | .02 | 94 |
| 230 | .52 | 102 | .10 | 95 |
| 240 | .20 | 104 | .04 | 95 |

Table 3.- Cumulative Oxygen Usage - Man Test 4 (Prototype RBA)

| MSA Test 390 (Pressure Demand Mode) | | MSA Test 391 (Demand Mode) | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | Cumulative Oxygen Usage (Liters) | Sampling Period (Time in Minutes) | Cumulative Oxygen Usage (Liters) |
| 0 | 0 | 0 | 0 |
| 30 | 45.7 | 20 | 20.0 |
| 65 | 109.2 | 40 | 65.4 |
| 97 | 160.0 | 60 | 90.8 |
| 118 | 204.4 | 105 | 154.3 |
| 140 | 248.8 | 120 | 179.7 |
| 180 | 312.3 | 140 | 205.1 |
| 240 | 439.3 | 166 | 230.5 |
| | | 180 | 242.7 |
| | | 200 | 268.1 |
| | | 220 | 293.5 |
| | | 240 | 311.5 |

in oxygen used, but it appears that all of the factors listed above made some contribution.

(3) A considerable build-up of water in the system occurred in both tests. Of primary concern was the accumulation of condensate on the facepiece lens. In the two tests, different methods were used to prevent moisture accumulation on the lens, but neither proved completely satisfactory. In the first test, inhalation flow was directed over the lens (via the standard internal ducts on the Ultra-vue facepiece), but considerable condensate accumulated on the lens after about 1-1/2 hours. In the second test, the inhalation flow came directly into the facepiece nosecup without sweeping over the lens. Additionally, the lens in the second test did not have the abrasive-resistant coating normally added to the lens. The second test showed less water accumulation than the first test, yet it still showed a potential vision problem to a user on a long excursion. It was after the two man tests that the decision to add a lens wiper was made.

# 5.0 Phase II - Additional Development, Fabrication and Testing

## 5.1 Additional Component Design/Materials Investigations

### 5.1.1 Alarm System

During Phase II, tests on the alarm system showed that the minimum operating temperature of the diaphragm horn was +40°F (much too high). Other diaphragm materials (metal foils) were tried, but without success. It was also recognized, following the man tests, that the Phase I alarm concept could lead to an additional problem in the field. The Phase I alarm stored oxygen at a pressure relative to the initial cylinder pressure (the pressure available when the cylinder valve was opened). It then vented this stored pressure when the cylinder reached a pressure of 20 to 25 percent of that sensed when the cylinder valve was initially opened (750 psig nominal with a 3,000 psig cylinder). The alarm pressure was always relative to the cylinder pressure when the cylinder valve was last opened. If the Main Line Valve was ever closed during use, the alarm would sound as the line pressure dropped below the alarm pressure; but, when the Main Line Valve was reopened, the warning device would be set at a new alarm pressure which was considerably below the desired 750 psig trip point. It, therefore, became apparent that a different alarm concept, as well as a new sound-producing device, would have to be developed; this was done during Phase II.

MSA's standard "Audilarm" was used as the design basis for the Phase II alarm system - a schematic of the Audilarm is shown in Figure 13 on page 42. When pressure is applied to the system by opening the Mainline Valve on the cylinder, flow enters the alarm through opening A. Pressure builds up on the left side of the piston(1) causing it to move to the right against the spring(2). At the same time, a portion of the

flow enters the inside of the piston (Chamber B) - pressure builds up in this chamber and causes the striker(3) to oscillate as the pressure rises and falls due to venting of chamber B to the ambient (through opening C). The alarm continues to sound until the orifice in the piston moves further to the right past the seal(4). This shuts off high pressure flow to the system.

As the cylinder pressure decreases during use, the piston(1) gradually moves to the left. At the alarm pressure, the orifice in the piston passes over the seal(4) thus again allowing flow into chamber B. Pressure again builds up in this chamber, causing the striker to oscillate as before - the alarm will continue to ring until the cylinder pressure drops below 200 psig.

The Phase II alarm system uses this "Audilarm" concept along with the addition of a poppet within the piston to shut off the alarm after approximately 10 seconds. The Phase II alarm system solves both problems inherent in the Phase I system - first, the new system uses a striker and gong as the sounding device (instead of a diaphragm horn) - this sounding device will operate down to -25°F. Secondly, the new system is designed such that the alarm will always sound at a specified pressure - the alarm pressure is not dependent on what the initial cylinder pressure was when the Mainline Valve was opened.

5.1.2 $CO_2$ Scrubber (Canister)

At the end of Phase I, it was intended that the canister body for the $CO_2$ scrubber be made of aluminum. A Phase II evaluation showed, however, that the cost and time to develop a drawn aluminum canister would be excessive for the projected canister production. The material for the canister body was then changed to .015 inch thick tin-plated steel (as had been used for the prototype RBA).

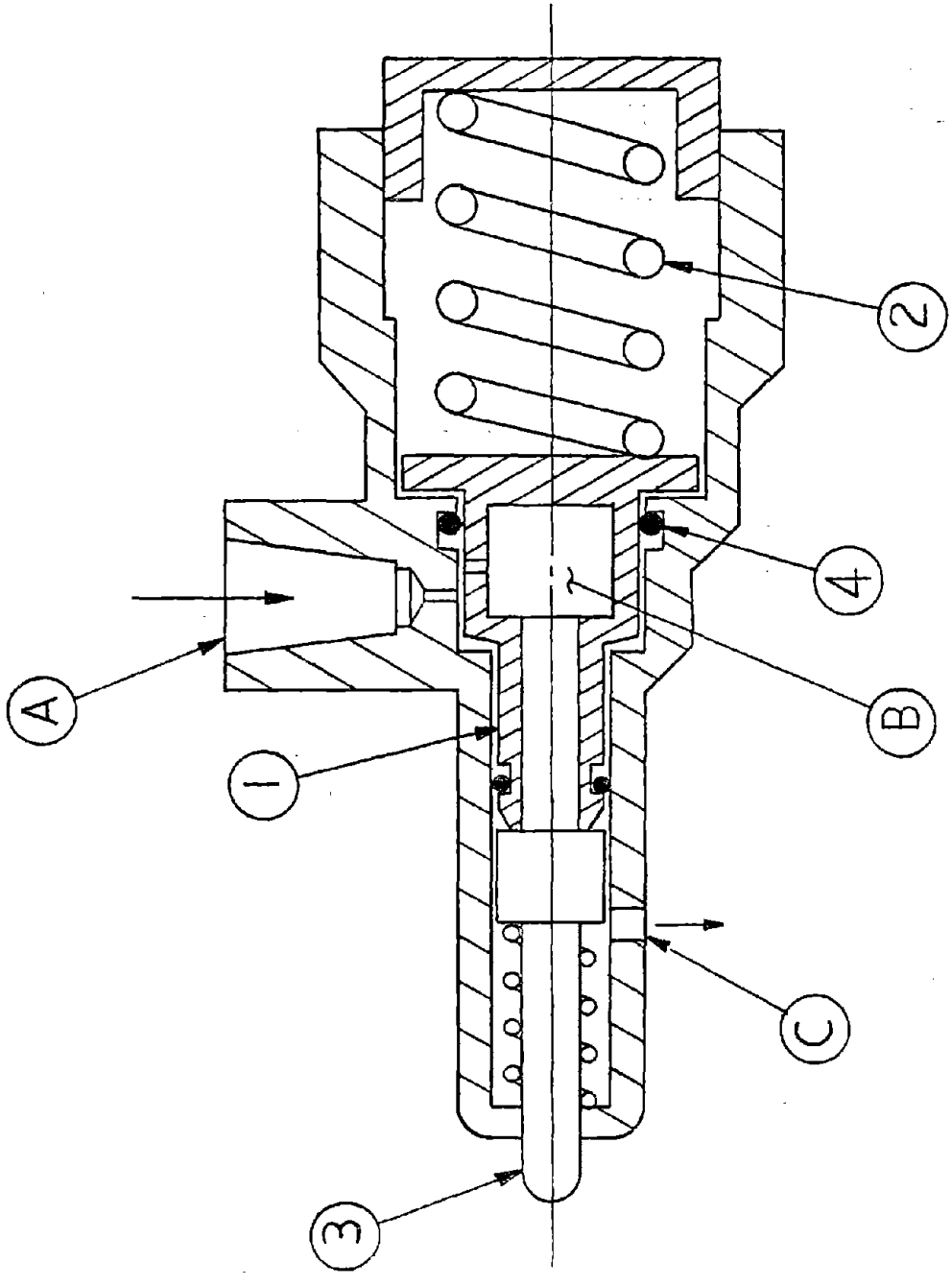


FIGURE 13.- MSA "Audilarm" (Schematic)

5.1.3 Breathing Bag

As stated previously in paragraph 4.3.6.2, final selection of the material for the breathing bag was not completed until Phase II. Materials and fabrication techniques considered for the breathing bag during Phases I and II were as follows:

(1) Compression molded rubber bag - efforts in this area resulted in producing sample bags which were much heavier and less compliant than those produced by latex dipping.

(2) Teflon - impregnated fiberglass (heat sealable) - bags produced from this type of material were found to be too stiff for the application.

(3) Urethane - coated fabric (heat sealable) - although a gas-tight heat seal could be produced on small samples of this type of material, complete gas-tight breathing bags could not be fabricated (difficulty in sealing over long seams).

(4) Latex dipping - efforts in this area showed that nitrile latex was very difficult to work with - MSA was unable to find any commercial fabricators who had been successful with this material. Neoprene latex, however, was found to possess all three desired characteristics (as established during Phase I) for the breathing bag material. These were:

   (a) Lightness of weight

   (b) Ability to pass the gasoline vapor test delineated in Title 30 CFR 11.85-3 (less than 100 ppm gasoline vapor penetration after 8 hours).

   (c) Ability to be fabricated into a gas-tight bellows with adequate bag compliance.

## 5.2 Man Tests (Phase II Units)

Additional units were fabricated during Phase II for the purpose of conducting man tests 1 through 5 in accordance with Title 30 CFR 11.85-15 and 11.85-16. Man tests 1 through 3 were each run twice with variations in the system (demand versus pressure demand, cooler versus no cooler) between the tests. Man test 4, the most rigorous work test, was run four times to check each system variable separately. Man test 5, the sedentary test, was run once using three test subjects.

Attempts were made to run the same work test on the same test subject so that the only variation between duplicate tests would be in the system. Although this was possible on Man tests 1 and 2, it was not possible on Tests 3 and 4 because of scheduling conflicts and because some subjects were unable to perform the tests without several days rest due to foot blisters developed during the tests.

### 5.2.1 Method of System Start-Up

On tests with the system in the pressure demand mode, no attempt was made to flush the system. After the test subject finished securing the facepiece, the cylinder Mainline valve was opened and the test was started. On tests with the system in the demand mode, the cylinder By-Pass Valve was opened for approximately 2 seconds to fill the system to the point where the breathing bag vented. Excess oxygen was not added beyond the initial bag venting to flush the system.

### 5.2.2 System Modifications

Three system modifications were made during testing to improve the comfort or performance of the apparatus. These three modifications were as follows:

(1) Addition of a pad between the backpack and shoulder blade area to improve comfort.

(2) Addition of a breathing tube support to reduce the pull of the facepiece.

(3) Removal of the steel screen on the backpack cover for some of the tests to determine the effect on the inhalation gas temperature.

5.2.3 Test Results (Man Test 1)

The 4 hour walk test was run by the same 130 lb. test subject in both the demand and pressure demand modes. Test results are shown in Tables 4 and 5. On the second test (see Table 5), the steel screen near the top of the cover was removed to improve heat convection from the $CO_2$ Scrubber. Both tests were without a cooler, but removal of the screen resulted in a temperature drop of about 2°F.

Table 4.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 1 (Phase II RBA)

| MSA Test 462 (Pressure Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 75 |
| 20 | 73.5 | .00 | 81 |
| 40 | 91.3 | .00 | 87 |
| 60 | 90.2 | .00 | 88 |
| 80 | 88.0 | .00 | 89 |
| 100 | 85.8 | .00 | 90 |
| 120 | 84.4 | .00 | 90 |
| 140 | 85.7 | .00 | 91 |
| 160 | 84.7 | .00 | 92 |
| 180 | 87.7 | .00 | 92 |
| 200 | 87.5 | .00 | 92 |
| 220 | 85.3 | .00 | 92 |
| 240 | 85.6 | .00 | 93 |

Table 5.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 1 (Phase II RBA)

| MSA Test 470 (Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 75 |
| 20 | 51.1 | .00 | 75 |
| 40 | 52.6 | .00 | 84 |
| 60 | 62.8 | .00 | 87 |
| 80 | 50.9 | .00 | 88 |
| 100 | 64.0 | .00 | 89 |
| 120 | 62.7 | .00 | 89 |
| 140 | 54.3 | .00 | 90 |
| 160 | 52.0 | .00 | 90 |
| 180 | 61.7 | .00 | 90 |
| 200 | 61.1 | .00 | 90 |
| 220 | 64.5 | .00 | 90 |
| 240 | 72.6 | .00 | 90 |

5.2.4 Test Results (Man Test 2)

Man test 2 was run twice by the same 150 lb. test subject, first in the pressure demand mode with no cooler, then in the demand mode with the cooler in place (see Tables 6 and 7). The screen near the top of the cover was in place on both tests. These two tests show similar results in the system $O_2$ and $CO_2$ concentrations and a temperature drop of about 10°F with the cooler installed.

Table 6.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 2 (Phase II RBA)

| MSA Test 465 (Pressure Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 75 |
| 20 | 34.3 | .00 | 78 |
| 40 | 30.8 | .00 | 96 |
| 60 | 38.5 | .00 | 96 |
| 80 | 46.6 | .00 | 96 |
| 100 | 48.3 | .00 | 97 |
| 120 | 49.4 | .00 | 97 |

Table 7.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 2 (Phase II RBA)

| MSA Test 467 (Demand Mode, With Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 72 |
| 20 | 46.3 | .00 | 71 |
| 40 | 45.3 | .00 | 87 |
| 60 | 46.7 | .00 | 87 |
| 80 | 52.0 | .00 | 86 |
| 100 | 59.4 | .00 | 87 |
| 120 | 57.8 | .00 | 88 |

5.2.5 Test Results (Man Test 3)

Man test 3 was run by two different test subjects who had similar oxygen consumption rates. During the first test (see Table 8) the screen near the top of the cover was in place, but on the second test (see Table 9) the screen was removed.

Table 8.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 3 (Phase II RBA)

| MSA Test 463 (Pressure Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 76 |
| 20 | 75.3 | .00 | 82 |
| 40 | 83.9 | .00 | 95 |
| 60 | 83.9 | .00 | 91 |
| 80 | 85.0 | .00 | 94 |
| 100 | 86.7 | .00 | 95 |
| 120 | 87.6 | .00 | 95 |

Table 9.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 3 (Phase II RBA)

| MSA Test 471 (Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 75 |
| 20 | 32.4 | .00 | 80 |
| 40 | 51.3 | .00 | 93 |
| 60 | 39.5 | .00 | 90 |
| 80 | 50.9 | .00 | 94 |
| 100 | 54.4 | .02 | 94 |
| 120 | 54.9 | .00 | 95 |

5.2.6 Test Results (Man Test 4)

Man test 4 was run four times by three different test subjects (see Tables 10, 11, 12, and 13). Tables 10 and 11 show the results with and without the cooler in the pressure demand mode, and Tables 12 and 13 show the same for the demand mode. The cooler reduced the inhalation temperature approximately 10°F during the first two hours of the test. During the second two hours in tests with the cooler, the temperature gradually rose, so that at the end of 4 hours, the temperature was about the same as without the cooler.

On the last of the Test 4 series (Table 13), the oxygen level in the system remained relatively low during most of the test. This was most apparent when the test subject rested following hard work and his breathing rate sharply decreased. It was apparent that during these rest periods, the subject was breathing from the residual volume in the breathing bag and failed to open the admission valve throughout the rest period. This low oxygen level in the demand mode was later shown to be a result of inadequate preflushing of the system.

Table 10.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 4 (Phase II RBA)

| MSA Test 460 (Pressure Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 26.9 | .00 | 76 |
| 20 | 74.0 | .00 | 86 |
| 40 | 83.5 | .00 | 92 |
| 60 | 86.0 | .00 | 93 |
| 80 | 88.4 | .03 | 96 |
| 100 | 87.2 | .05 | 96 |
| 120 | 86.6 | .01 | 96 |
| 140 | 87.0 | .04 | 96 |
| 160 | 86.0 | .04 | 95 |
| 180 | 88.3 | .02 | 94 |
| 200 | 87.9 | .06 | 94 |
| 220 | 88.7 | .12 | 94 |
| 238 | 81.8 | .02 | 94 |

Table 11.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 4 (Phase II RBA)

| MSA Test 464 (Pressure Demand Mode, With Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 75 |
| 20 | 47.8 | .00 | 73 |
| 40 | 53.5 | .00 | 82 |
| 60 | 56.2 | .00 | 83 |
| 80 | 64.7 | .00 | 87 |
| 100 | 82.0 | .00 | 87 |
| 120 | 78.6 | .00 | 88 |
| 140 | 73.0 | .00 | 89 |
| 160 | 70.0 | .00 | 92 |
| 180 | 68.3 | .00 | 91 |
| 200 | 64.6 | .01 | 94 |
| 220 | 71.6 | .01 | 95 |
| 240 | 68.9 | .02 | 95 |

Table 12.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 4 (Phase II RBA)

| MSA Test 466 (Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 70 |
| 20 | 34.9 | .01 | 76 |
| 40 | 30.4 | .01 | 90 |
| 60 | 28.5 | .01 | 91 |
| 80 | 44.8 | .01 | 96 |
| 100 | 89.7 | .00 | 99 |
| 120 | 82.5 | .00 | 97 |
| 140 | 74.6 | .00 | 95 |
| 160 | 70.5 | .00 | 94 |
| 180 | 61.8 | .00 | 94 |
| 200 | 66.7 | .03 | 94 |
| 220 | 57.4 | .15 | 94 |
| 240 | 58.2 | .00 | 95 |

Table 13.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 4 (Phase II RBA)

| MSA Test 469 (Demand Mode, With Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 72 |
| 20 | 26.6 | .00 | 71 |
| 40 | 26.0 | .00 | 82 |
| 60 | 20.3 | .00 | 84 |
| 80 | 26.9 | .00 | 89 |
| 100 | 23.5 | .00 | 90 |
| 120 | 31.4 | .00 | 90 |
| 140 | 25.3 | .00 | 89 |
| 160 | 32.7 | .00 | 90 |
| 180 | 28.7 | .00 | 91 |
| 200 | 29.8 | .00 | 92 |
| 220 | 38.5 | .00 | 93 |
| 240 | 40.0 | .01 | 93 |

5.2.7 Test Results (Man Test 5)

Table 14 shows test results for the sedentary man test. Three

test subjects were used and the apparatus lasted for more than 14 hours (843 minutes) at which time the oxygen cylinder was depleted. The average oxygen consumption for the three subjects during the test was slightly over 0.5 liters per minute.

Table 14.- % $O_2$, % $CO_2$ Concentration, Inhalation Temperature - Man Test 5 (Phase II RBA)

| MSA Test 472 (Demand Mode, No Cooler) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp. (°F) |
| 0 | 20.9 | .00 | 74 |
| 120 | 23.3 | .00 | 82 |
| 240 | 32.3 | .00 | 83 |
| 360 | 49.8 | .00 | 82 |
| 480 | 54.3 | .00 | 82 |
| 600 | 71.0 | .01 | 87 |
| 720 | 76.0 | .01 | 86 |
| 840 | 49.1 | .01 | 85 |
| 843 | 43.5 | .01 | 85 |

## 5.3 Low Temperature Operational Tests

Two low temperature operational tests were run during Phase II. Both tests were conducted in accordance with Title 30 CFR 11.85-13 at a temperature of -20°F. Test results are shown in Tables 15 and 16. Except for the alarm system (which at the time of these tests was still the Phase I design), the entire system functioned well.

Table 15.- % $O_2$, % $CO_2$, Inhalation Temperature - Low Temperature Operational Test (Phase II RBA)

| MSA Test 476 (Pressure Demand Mode) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp (°F) |
| 0 | 20.9 | .00 | 5 |
| 5 | 65.0 | .02 | 5 |
| 10 | 86.3 | .03 | 25 |
| 15 | 91.8 | .00 | 23 |
| 20 | 93.7 | .00 | 25 |
| 25 | 95.0 | .00 | 25 |
| 30 | 94.9 | .00 | 25 |

Table 16.- % $O_2$, % $CO_2$, Inhalation Temperature - Low Temperature Operational Test (Phase II RBA)

| MSA Test 477 (Demand Mode) | | | |
|---|---|---|---|
| Sampling Period (Time in Minutes) | % $O_2$ | % $CO_2$ Concentration | Inhalation Temp (°F) |
| 0 | 20.9 | .00 | -10 |
| 5 | 49.2 | .00 | 14 |
| 10 | 60.7 | .00 | 21 |
| 15 | 69.3 | .00 | 21 |
| 20 | 74.4 | .00 | 14 |
| 25 | 74.3 | .00 | 25 |
| 30 | 78.7 | .00 | 25 |

5.4 Gas Tightness Test

Six subjects wore the new apparatus in both demand and pressure demand modes in a chamber containing dioctyl phthalate (DOP) to measure the amount of leakage into the facepiece. (DOP leakage is generally used at MSA to measure facepiece leakage quantitatively, rather than the subjective isoamyl acetate test described in Title 30 CFR 11.85-19). The six subjects were chosen according to their facial size and shape to fit within the test panel chart instituted by Los Alamos Scientific Laboratories.

In the demand mode, facepiece in-leakage was generally less than .01%,

but rose to .1% on some subjects during certain tasks, such as loud talking. In the pressure demand mode, in-leakage values rarely exceeded .002 percent.

6.0 Miscellaneous Tests (Phase I/Phase II)

Table 17 shows test results for other tests (not covered previously in this report) conducted on the new RBA during Phases I and II.

7.0 NIOSH Approval

Two drawing packages (one for the pressure demand apparatus, one for the demand apparatus) were submitted to NIOSH in May of 1979, thus completing work under Phase II of the contract. Samples of the unit were not submitted since NIOSH was not ready for testing. Also, NIOSH representatives stated that they could consider approval only under the existing schedule, and that testing of the device in the pressure demand mode would not be performed (requirements for positive pressure closed circuit devices have as yet not been incorporated into the NIOSH approval schedule [Title 30 CFR 11H]).

8.0 Phase III

Not performed - Bureau of Mines terminated the contract at the end of Phase II.

9.0 Summary of Design and Performance Requirements

Table 18.0 lists all the design and performance requirements for the new RBA as specified in the contract (reference section 2.0) along with how the apparatus meets or modifies subject requirements.

10.0 Conclusions

The apparatus, with cooler installed, has met all design and performance requirements necessary for NIOSH approval as listed in Title 30 CFR 11 H. Although the maximum allowable inhalation temperature of 95°F (reference Title 30 CFR 11.85-18) was exceeded in Man Tests 2 and 4 (without the cooler installed), a decrease in the inhalation temperature is expected in production units since the opening for the screen near the top of the cover has been widened to 8.75 inches - this will allow for more convective heat transfer from the canister.

Table 17.- Miscellaneous Test Results - 4 Hour RBA

| Title 30 CFR 11 Section | Test | Requirement | Demand Apparatus | Pressure Demand Apparatus |
|---|---|---|---|---|
| 11.85-5 | Breathing Resistance Test, Inhalation | Not more than difference between exhalation resistance and 100 mm water col. ht. | Facepiece Pressure = -8 mm water column height | Facepiece Pressure = +2 mm water column height |
| 11.85-6 | Breathing Resistance Test, Exhalation | Not more than 51 mm water column height | 48 mm water column height | *71 mm water column height |
| 11.85-9 | Gas Flow Test, Closed-Circuit Apparatus | At least 30 lpm oxygen flow when fully open | 55 lpm at min. regulated pressure | 55 lpm at min. regulated pressure |
| 11.85-12 | Test for $CO_2$ in Inspired Gas | 1.0% $CO_2$ max allowable average | 1.0% | 1.0% |

*71 mm Exhalation Resistance is within proposed requirement for positive-pressure, closed-circuit devices.

Table 18.- Summary of Design and Performance Requirements - 4 Hour RBA

| Requirement | Actual |
|---|---|
| Weight of complete apparatus 30 lbs. maximum | 30.30 pounds* |
| Weight of Major Components | |
| a. Backpack components - 23 lbs. maximum | 24.00 pounds* |
| b. Facepiece, breathing hoses and connections - 2 lbs. max. | 2.56 pounds * |
| c. Cooling system - 5 lbs. maximum | 3.74 pounds |
| Backpack dimensions: 19" x 17" x 6" maximum | 20 7/8" x 16 1/4" x 6 1/2"* 6" dimension exceeded to allow use of 4 1/2" diameter $O_2$ cylinder. 20 7/8" dimension includes 1/2" for frame support located in center of backpack under $O_2$ cylinder. |
| One size full facepiece: | Apparatus uses Ultravue Facepiece with lens wiper assembly. |
| a. Designed to prevent fogging | |
| b. Shall not cause skin irritation | |
| c. Fits wide range of head sizes | |
| Voice communication | Speaking diaphragm included in facepiece connector. |
| Cooling system | |
| a. 100 KCAL capacity minimum | 125 KCAL capacity |
| b. Removable | Removable |
| c. No electrical power required | None required |
| d. Demonstrate effectiveness with Man Tests | See section 5.2 of report |
| No part of RBA in contact with wearer shall exceed a temperature of 122°F | Less than 122°F |

* Acceptable to Project Officer

Table 18.- Summary of Design and Performance Requirements - 4 Hour RBA (cont.)

| Requirement | Actual |
|---|---|
| Simple to operate (can be operated effectively upon completion of training program of five 6-hour sessions or less) | Yes |
| RBA can be refilled | $O_2$ cylinder can easily be removed and refilled; canister can easily be removed and replaced. |
| Reusable 100 times | Not tested |
| Design should reflect a simple, rugged, reliable device while demonstrating concern for comfort and mobility of wearer | Aluminum frame assembly used; harness assembly has padded shoulder and waist straps; extension arms at bottom of backpack distribute large portions of load to user's hips. |
| Positive Pressure System incorporated into design | Yes |
| Obtain NIOSH approval under Title 30 CFR 11 H | Submitted in both configurations:<br>a. demand apparatus<br>b. pressure demand apparatus<br>but not reviewed - Bureau of Mines terminated contract before NIOSH tested apparatus. |