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CO_2-Absorption Characteristics of Mine Rescue Breathing Apparatus

By T. E. Bernard, N. Kyriazi, and R. L. Stein

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CO_2-ABSORPTION CHARACTERISTICS OF MINE RESCUE BREATHING APPARATUS

by

T. E. Bernard,[1] N. Kyriazi,[2] and R. L. Stein[3]

ABSTRACT

The CO_2-absorbent canisters used in four approved rescue breathing apparatus were investigated. A breathing machine was used to simulate human expiration with gas flow rates of 26, 37, and 48 l/min of 3.5% CO_2 in air. The exit gas CO_2 concentration, the pressure drop across the canister, and the exit-gas temperature were monitored. The absorbent capacities of the packed-bed canister designs were found to be dependent on flow rate within the range studied, while the capacities of the other designs were less affected. The radial canister had the least resistance to breathing while the complex bed design proved to be the most effective in utilization of the chemical. The overall results indicated that LiOH (lithium hydroxide) has the highest capacity for CO_2 absorption among the absorbents tested. It can be used in a simple packed-bed design while maintaining acceptable levels of resistance and exit-gas temperature. Examination of oxygen supply with respect to CO_2-absorption capacity suggested that it is desirable to closely match CO_2-absorption capacity with the available O_2 supply to minimize the size and weight of rescue breathing apparatus.

INTRODUCTION

Rescue and recovery missions in underground mines normally require the use of respiratory protective equipment for protection against toxic gases or lack of oxygen in the underground atmosphere. Respiratory protection is usually achieved by using self-contained, closed-circuit breathing apparatus of 2 hours' or longer duration.

A schematic diagram of a typical closed-circuit system is shown in figure 1. The user's expired air is directed to the CO_2-absorption canister (CO_2 scrubber) where the CO_2 is removed from the air. The scrubbed, expired air then goes to

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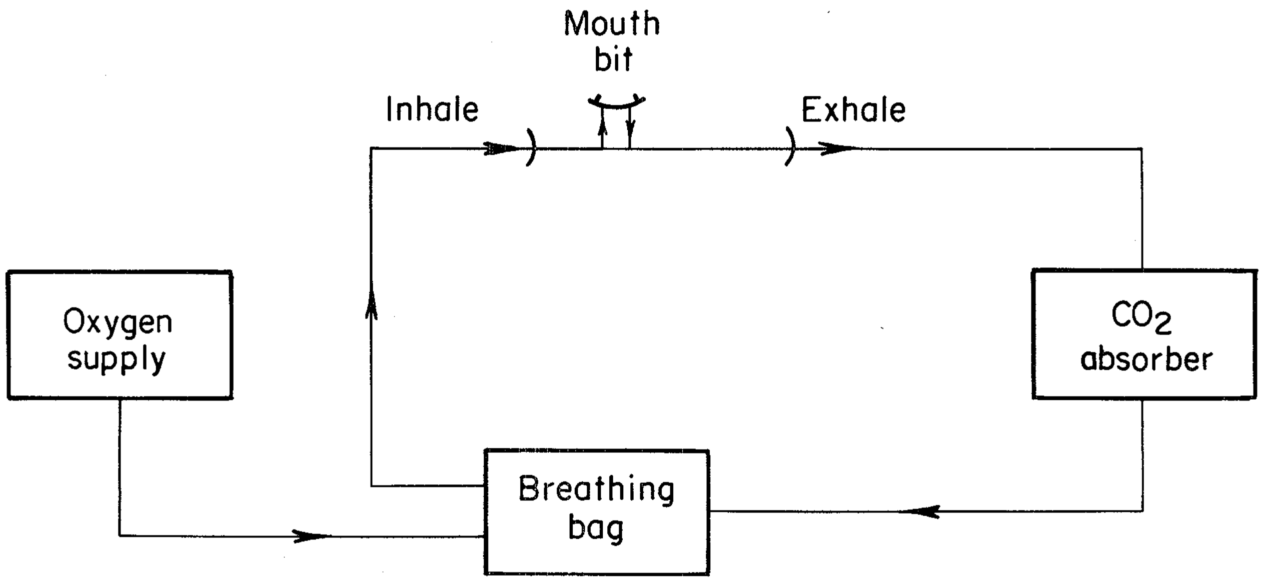

FIGURE 1. - Schematic diagram of a typical closed-circuit breathing apparatus.

a breathing bag from which the user inhales air free of CO_2. Replacement oxygen to support the user's need is metered into the breathing circuit from an oxygen supply. The replacement oxygen is added in one of three modes. One mode, called demand only, injects the oxygen when the breathing bag content reaches a low level indicating more gas is needed in the breathing circuit. A second mode, called constant flow, operates so that oxygen is added continuously at a flow in excess of 3 l/min. The third mode is a combination of the other two and is called constant flow plus demand. In this third mode, oxygen is added at a constant flow of at least 1.5 l/min and also allows for the addition of extra oxygen through a demand valve when the breathing bag content becomes low.

The CO_2-absorption process for all currently used scrubbing chemicals involves a reaction between the CO_2 and a hydroxide of a metal such as Na, Li, or Ca. The reaction is exothermic and generates between 14 and 22 kcal/mole CO_2.

The authors investigated the CO_2-absorption systems of several commercially available rescue breathing apparatus (RBA). This was done to determine the direction of development work on future RBA CO_2 scrubbers. This report provides information on flow rate dependence, absorption capacity, design philosophy, chemical effectiveness and canister efficiency, magnitude of pressure drops, and exit-gas temperatures.

DESCRIPTION OF APPARATUS

Four CO_2 scrubbing systems were studied. All of these scrubbers are used in RBA's of 2 to 4-hour duration. The scrubbers are briefly described as follows:

<u>Draeger BG-174A</u>--The BG-174A[4] is a 4-hour RBA. The unit provides 400 liters of compressed oxygen in a constant flow plus demand mode. The CO_2 scrubber employs 1.5 kilograms of anhydrous NaOH (sodium hydroxide), which is disposable after one use. The NaOH is packed in 2-cm-thick layers, each layer alternating a chemical space with an air space. A diagram of the canister is shown in figure 2. For training, the BG-174A employs a reusable canister filled with soda lime because it is less expensive than NaOH.

<u>Mine Safety Appliances (MSA) McCaa</u>--The McCaa is rated as a 2-hour RBA. The unit carries 250 liters of compressed oxygen available in the demand only mode. The CO_2 scrubber uses Cardoxide (MSA's formulation of soda lime) in a refillable container. The container is an integral part of the apparatus and is shown in figure 3. The air flows from the bottom plenum to the top. The total chemical charge is 1.8 kilograms.

<u>Scott Aviation Rescue-Pak</u>--The Rescue-Pak has a 4-hour approval. The RBA carries 400 liters of compressed oxygen which is delivered at 1.5 l/min constant flow plus demand. The scrubber is a disposable can filled with 1.4 kilograms of LiOH and is illustrated in figure 4.

<u>Siebe Gorman Aerorlox</u>--The Aerorlox has a 3-hour approval. The unit uses 2,400 liters of oxygen stored in cryogenic liquid form and provides a flow of 5 to 12 l/min. The CO_2 scrubber, which is a radial design (fig. 5), is refillable with 1.6 kilograms of 8-12-mesh Protosorb (Siebe Gorman's commercial formulation of soda lime).

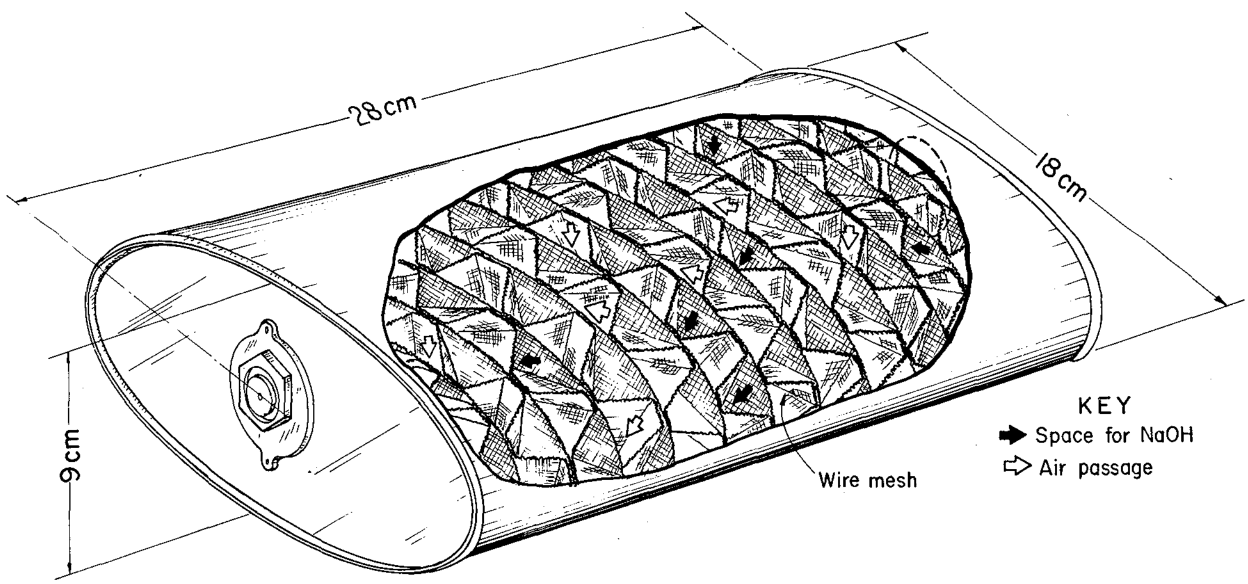

FIGURE 2. - Diagram of Draeger BG-174A CO_2 scrubber.

[4]Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

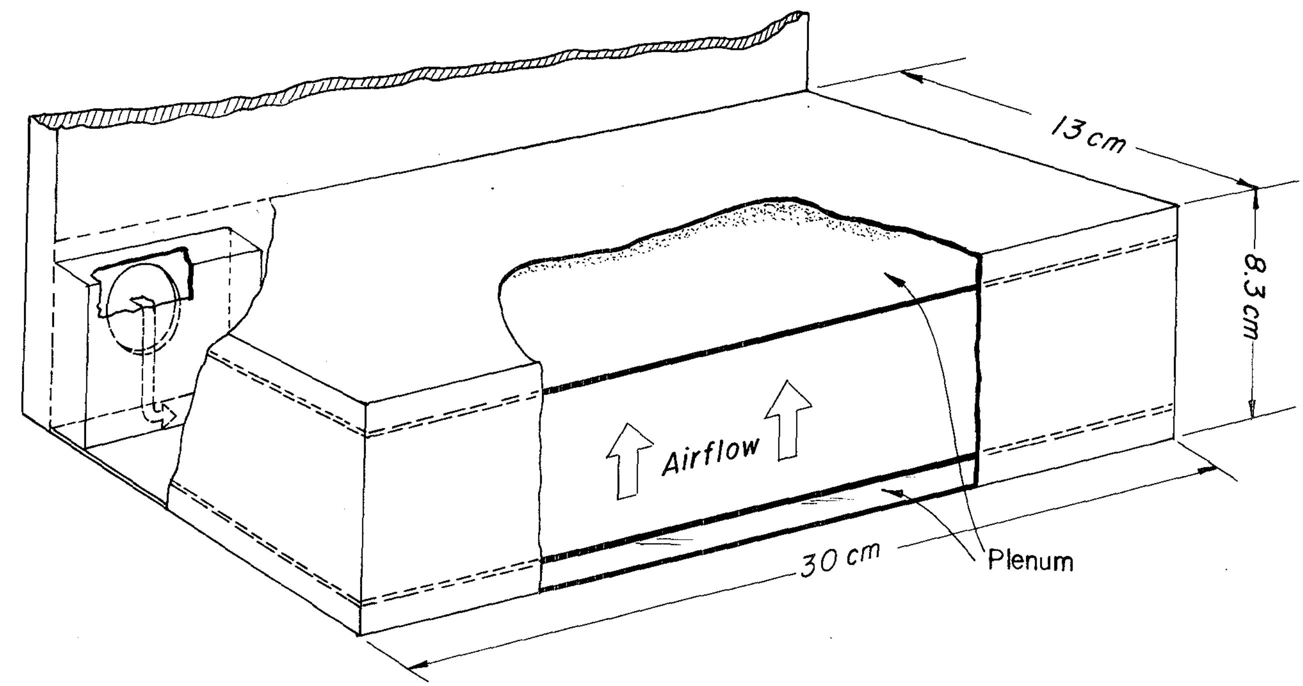

FIGURE 3. - Diagram of MSA McCaa CO_2 scrubber.

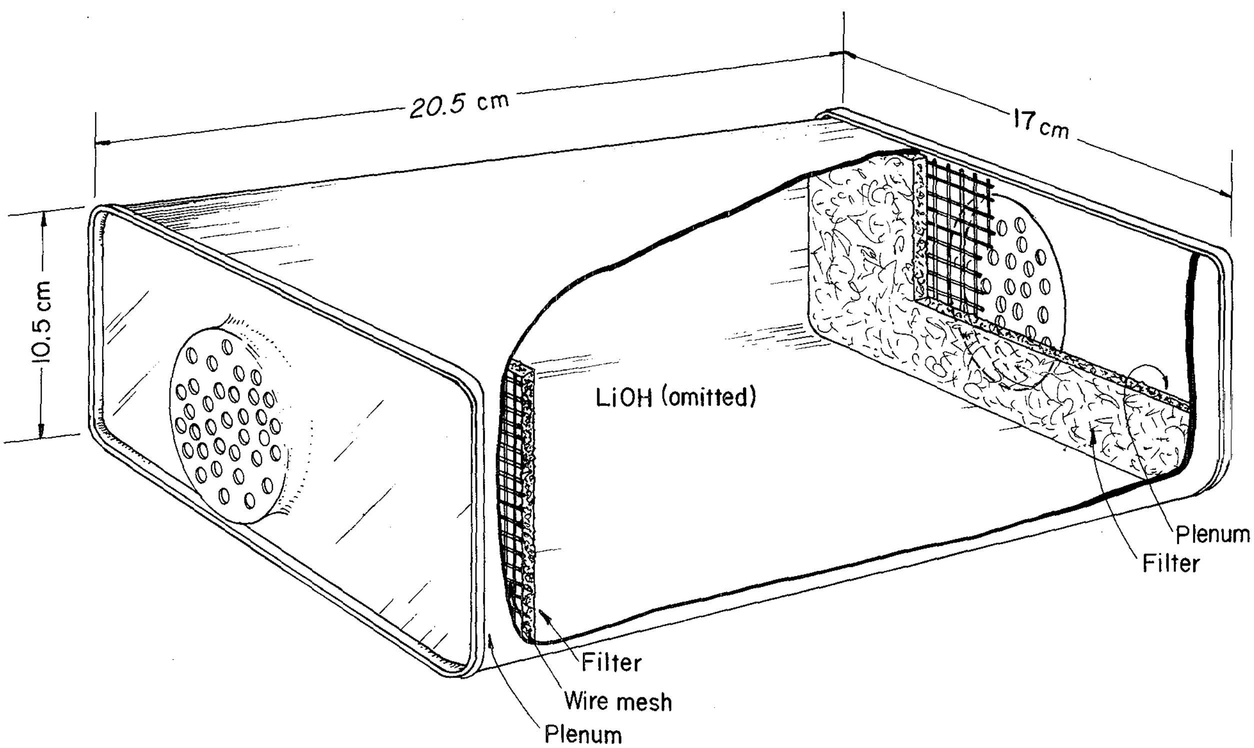

FIGURE 4. - Diagram of Scott Aviation Rescue-Pak CO_2 scrubber.

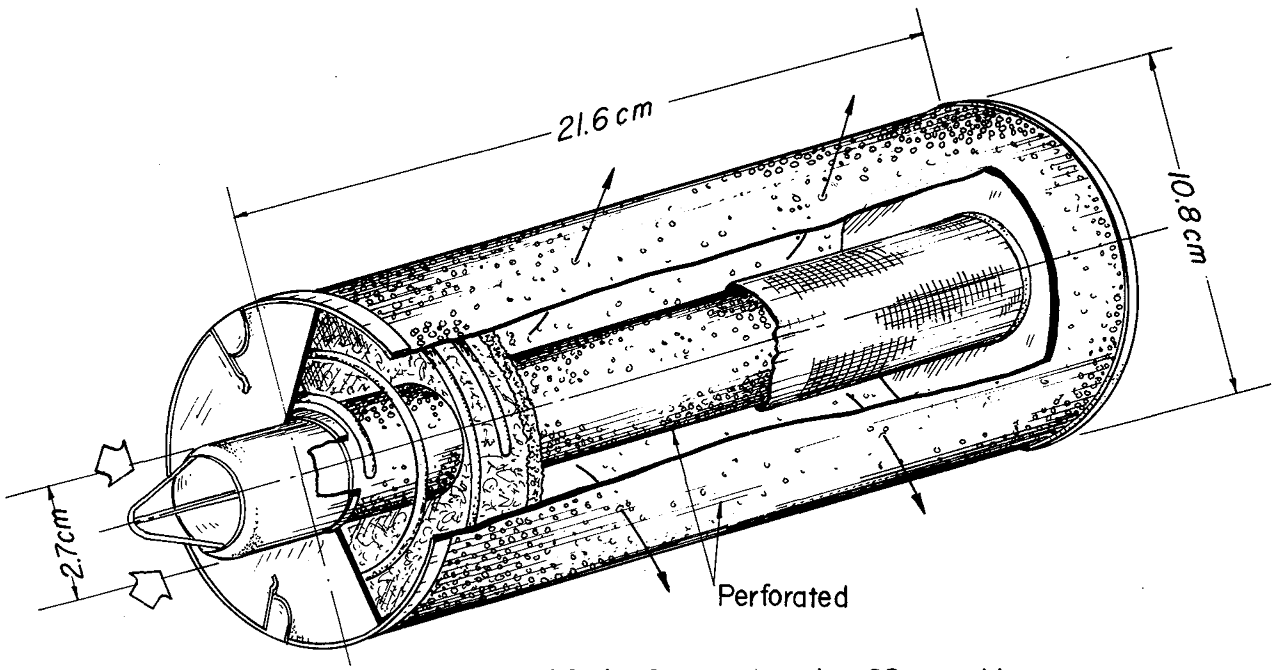

FIGURE 5. - Diagram of Siebe Gorman Aerorlox CO_2 scrubber.

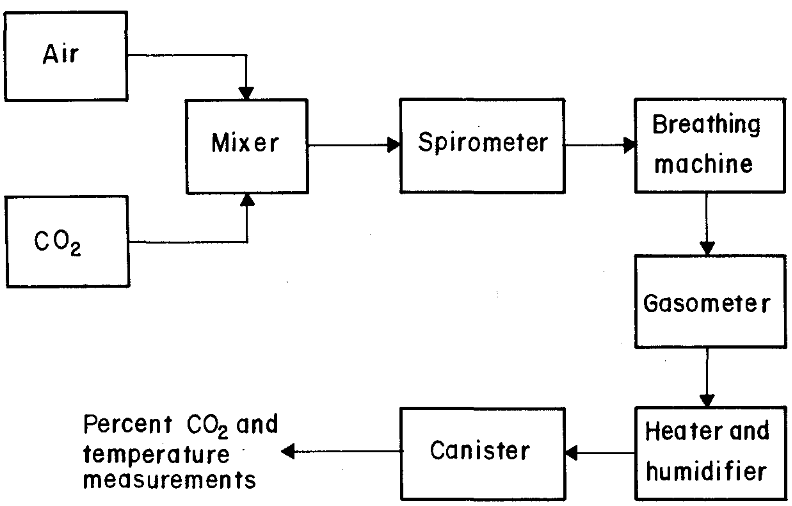

FIGURE 6. - Flow path for CO_2 canister testing system.

EXPERIMENTAL METHOD

The testing system is shown schematically in figure 6. A compressed-gas mixer supplied 3.5 percent CO_2 in air to a breathing machine designed to simulate the human breathing pattern at a moderate work rate.[5] The air from the breathing machine was then saturated with water vapor at 37° C and delivered to the canister. Measurements of CO_2 in the exit air, pressure drop across the canister, and temperature of the exit air were recorded at 15-minute intervals.

The commercial canisters were subjected to three flow rates of CO_2. These were selected to simulate light, moderate, and heavy work by a user. The test conditions are listed in table 1. Each of the four commercial canisters was tested three times at each flow rate. The three tests at each flow rate were then averaged together to yield a mean response for exit-air CO_2

[5]Kloos, E. J., and J. A. Lamonica. A Machine-Test Method for Measuring Carbon Dioxide in the Inspired Air of Self-Contained Breathing Apparatus. BuMines RI 6865, 1966, 11 pp.

concentration and temperature and for peak pressure drop. Maximum deviations about the mean were ±20 percent.

TABLE 1. - Test conditions used to investigate CO_2 scrubbers

Simulated activity level	Percent CO_2	Volume[1] flow rate, l/min	CO_2[2] flow rate, l/min STPD	CO_2 flow rate, g/min
Light.............	3.5	26	0.80	1.6
Moderate..........	3.5	37	1.14	2.2
Heavy.............	3.5	48	1.48	2.9

[1]Volume measured at ambient conditions.
[2]Volume at standard conditions (760 mm Hg, 0° C, dry).

The total amount of CO_2 absorbed by each canister was calculated from the integral of the mean concentration curve up to the time that 0.5 percent CO_2 was found in the exit air. This integral gives the amount of CO_2 that escaped the canister, and subtraction of this from the CO_2 entering the canister gives the amount absorbed during this period. The time to reach 0.5 percent CO_2 in the exit air was defined as the breakthrough time.

Analysis of variance (AOV) was used to determine if statistically significant differences occurred among measurements of the different canisters.

RESULTS AND DISCUSSION

Figures 7-10 show the mean CO_2 breakthrough versus time for the four canisters at each of the three flow rates used. Table 2 provides the mean breakthrough time for each canister at each flow rate.

TABLE 2. - Mean breakthrough time versus flow rate

	Time, minutes		
Flow rate, l/min.............	48	37	26
Canister:			
McCaa.....................	86	122	223
Aerorlox..................	124	166	242
BG-174A...................	182	249	339
Rescue-Pak................	216	318	495

For all canisters and flow rates, the CO_2 levels in the exit gas rose exponentially, with initial concentrations of CO_2 at or below 0.05 percent for the Rescue-Pak, Aerorlox, and McCaa. The BG-174A had initial exit CO_2 concentrations of approximately 0.1 to 0.2 percent. These values dropped after 45 minutes to concentrations of less than 0.05 percent. This initial rise has been previously observed by Hartwell and Senneck.[6] While the reason for the initial rise is not known, it will not, in any case, materially affect a wearer's breathing pattern.

[6]Hartwell, F. J., and C. R. Sennick. The Design of Closed-Circuit Breathing Apparatus for Mine Rescue Work. SMRE Res. Rep. No. 134, June, 1956, 41 pp.

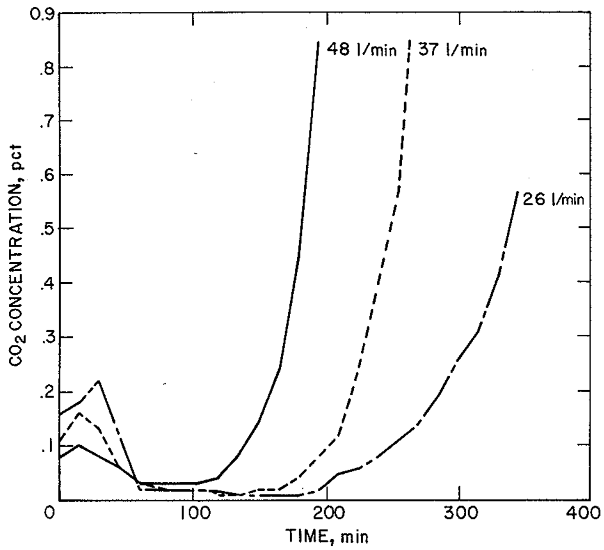

FIGURE 7. - CO_2 breakthrough curves for the BG-174A scrubber.

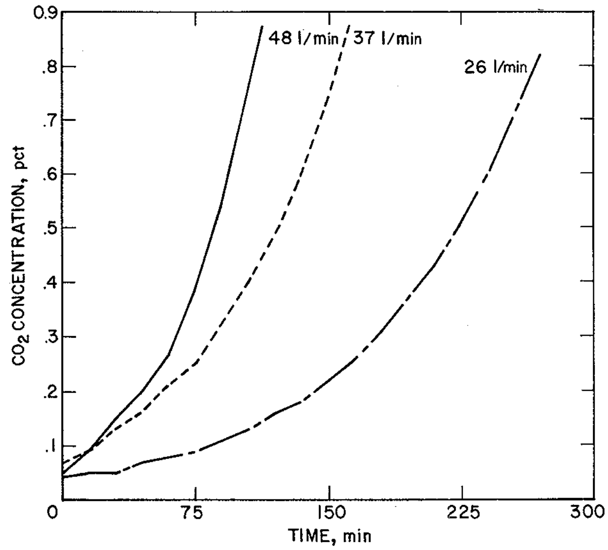

FIGURE 8. - CO_2 breakthrough curves for the McCaa scrubber.

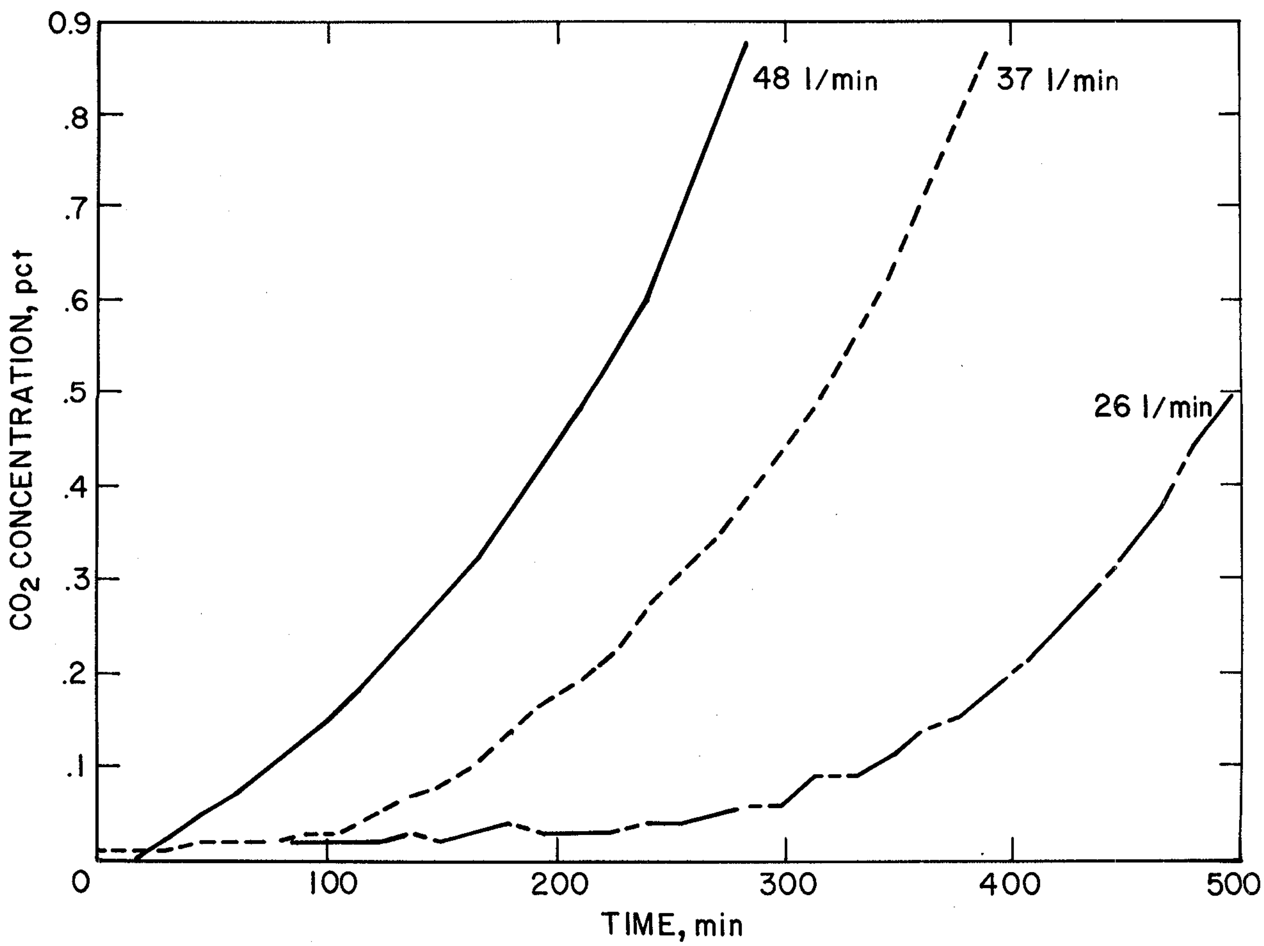

FIGURE 9. - CO_2 breakthrough curves for the Rescue-Pak scrubber.

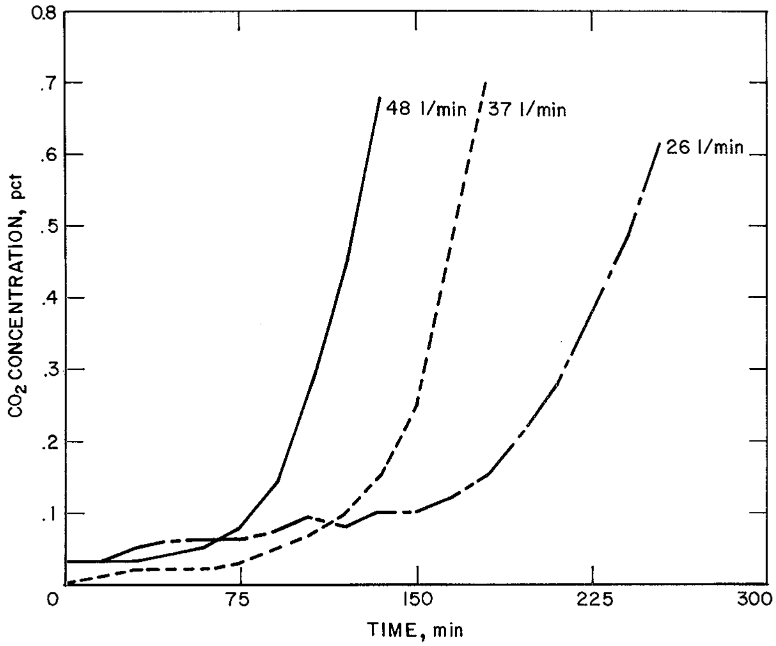

FIGURE 10. - CO_2 breakthrough curves for the Aerorlox scrubber.

Flow Rate Dependence

As would be expected, service time was longer at the lowest flow rate because the rate of CO_2 into the canister was low. To examine relative performance among canisters, an AOV of the product of the flow rate times service time was calculated. This product removes from consideration the primary effects of flow rate (a greater amount of CO_2 absorbed in a given period of time due to a greater amount of CO_2 administered to the canister in that period). Any other differences in absorption can then be attributed directly to secondary effects of flow rate, such as insufficient dwell time in the canister.

The AOV indicated that statistically significant differences ($p<0.05$) existed among canisters at a given flow rate and in some cases, flow rates for a single canister. There was also a significant interaction between flow rates and canisters. This indicated that there were basis differences in the performances of the four different canisters as well as an effect on performance due to flow rate on some of the canisters. Table 3 gives the mean value of flow rate times service time at each flow rate for each canister. While there was a general decreasing trend in the product with increasing flow rate, the two packed-bed designs (Rescue-Pak and McCaa) showed significant decreases. The packed-bed design thus seems to be sensitive to the secondary effects of flow rate, causing decreased performance with increasing flow rate.

TABLE 3. - Mean value of flow rate times service time, for each canister at three flow rates

Flow rate, l/min	Mean value of flow rate times service time, liters			
	Rescue-Pak	BG-174A	Aerorlox	McCaa
26..............	12,900	8,800	6,300	5,800
37..............	11,800	9,200	6,100	4,500
48..............	10,400	8,700	6,000	4,100

Absorption Capacity

The AOV on the service time-flow rate products also indicated basic differences among the canisters. To examine this phenomenon further, the average CO_2-absorption capacity of each canister was calculated and converted to STPD conditions of 760 millimeters of mercury at 0° C, dry. Because the four canisters were designed for different service lives, the capacities were computed as liters per hour of rated service life to yield the relative capacities. These relative capacities are given in table 4. The Rescue-Pak had the greatest relative capacity, with no significant differences ($p>0.05$) in the relative capacities of the other scrubbers.

TABLE 4. - Volume of CO_2 absorbed as liters (STPD) per hour of rated service life

RBA	Volume
Rescue-Pak	88 a
McCaa	71 a, b
BG-174A	68 b
Aerorlox	62 b

a = There is no statistically significant difference between numbers followed by a.
b = There is no statistically significant difference between numbers followed by b.

Design Philosophy

The absorption capacities of the canisters were compared to the volume of oxygen available in each RBA. Table 5 gives the ratio of the CO_2-absorption capacity divided by the available oxygen supply. This ratio, R', reflects the capacity of the RBA to remove the CO_2 produced by the user as he consumes the available oxygen. The analogous ratio for the user is the CO_2 produced divided by the O_2 consumed. This ratio, R, the respiratory quotient for humans, is about 0.9 during long duration rescue and recovery missions. For an apparatus to physiologically match a human user, R' would have to be equal to R. An R' greater than 0.9 means that the CO_2 scrubber has a greater capacity than is necessary to absorb the CO_2 that would be metabolically produced from the available oxygen. An R' value less than 0.9 indicates that more oxygen is available relative to the capacity of the scrubber and, therefore, the oxygen supply is oversized.

TABLE 5. - Volume ratios of CO_2-absorption capacity to O_2 available (R')

RBA	R'
Rescue-Pak	0.88
BG-174A	.68
McCaa	.57
Aerorlox	.08

The Rescue-Pak was the only RBA evaluated that nearly matched the O_2 supply to the CO_2 scrubber. The other three apparatus had ratios of less than 0.9, which suggests that CO_2 could accumulate before the oxygen supply was exhausted. In these three cases, however, the apparatus have passed Federal approval tests and have had extensive field experience with no indications of scrubber insufficiency. For the BG-174A and the McCaa units, this meant that the capacities of the scrubbers were adequate for current use and that an over-supply of oxygen was available for leakage, overpressure venting, and emergency bypass. The Aerorlox had a ratio of 0.08 due to the very large supply of liquid oxygen that flows into the breathing circuit at 5 to 12 l/min. Because of this high oxygen flow rate, the apparatus constantly vents gas to the environment. Some of the CO_2-laden exhaled air is also vented before it reaches the CO_2-absorption canister and, therefore, much of the demand on the scrubber is eliminated.

Insofar as R' did not equal 0.9 for demand systems, the sizing of the CO_2 scrubber to the oxygen supply was not optimized. The weight and size of the oxygen supply and CO_2 scrubber system can be minimized by carefully matching the two components after allowing for some gas loss due to preflushing, venting, and leakage.

Chemical Effectiveness and Canister Efficiency

The number of grams of CO_2 absorbed at the point when 0.5 percent was found in the exit air divided by the number of grams of chemical absorbent contained in the canister gives some indication of the effectiveness of the chemical and the canister design. These values were averaged and are given in table 6. The Rescue-Pak had the greatest capacity for CO_2 absorption. The BG-174A was shown to have three quarters of the CO_2-absorption capacity of the Rescue-Pak. The Aerorlox and the McCaa were not significantly different ($p>0.05$) and had capacities of less than 50 percent of that of the Rescue-Pak. These differences were due both to the inherent capacities of the different chemicals and to the effective utilization of the absorbents by the RBA design. The LiOH has a theoretical capacity for absorbing CO_2 of 0.9 gram of CO_2 per gram of LiOH; the NaOH has a capacity of 0.55 g/g and the soda limes, 0.49 g/g. Table 7 gives the percent utilization of the absorbents in the canisters, which is the actual capacity divided by the theoretical capacity. The percent utilization indicates how well each absorbent was used in the canister independent of the absorbent type. This reflects canister design efficiency. The BG-174A had the highest value, the Rescue-Pak and the Aerorlox were about the same, and the McCaa had the least effective utilization. The statistically significant differences ($p<0.05$) shown in the table occurred only between the BG-174A and the McCaa. In general, the differences in utilization were difficult to discern.

TABLE 6. - CO_2-absorbing capacity of RBA's

RBA	Gram of CO_2 absorbed per gram of chemical absorbent
Rescue-Pak..........	0.49
BG-174A.............	.36
Aerorlox............	.23
McCaa...............	.15

TABLE 7. - Percent utilization of the chemical absorbents in the canisters

RBA	Percent utilization
BG-174A.........................	65 a
Rescue-Pak......................	54 a, b
Aerorlox........................	47 a, b
McCaa...........................	31 b

a = There is no statistically significant difference between numbers followed by a.
b = There is no statistically significant difference between numbers followed by b.

Pressure Drops

The pressure drop across the canister was a measure of the resistance to flow through the canister and, thus, was an index to the amount of respiratory work necessary to breathe through the canisters. For increasing flow rates, the pressure drop increased as would be expected. Generally, there was a slight rise in pressure during the first 15 minutes. After the initial rise, the Rescue-Pak, McCaa, and Aerorlox canister pressure drops remained constant. The BG-174A canister with NaOH displayed a continuous rise but remained lower than the packed-bed designs. Figure 11 presents the highest peak pressure drop across each canister averaged at each flow condition. The Aerorlox had the smallest pressure drop, which was due to the radial flow design of the canister. This design provides a short path length and a large cross-sectional area. The BG-174A also had a low pressure drop across the canister because of the suspension of the chemical in a corrugated pattern with many air spaces. Both canister designs require a larger total volume to contain the same volume of chemical as used in a packed bed. The two packed-bed systems (Rescue-Pak and McCaa) have much higher pressure drops, but the pressure drops are physiologically acceptable. To minimize size of RBA's, packed beds are more desirable as long as the pressure drop is acceptable to the wearer.

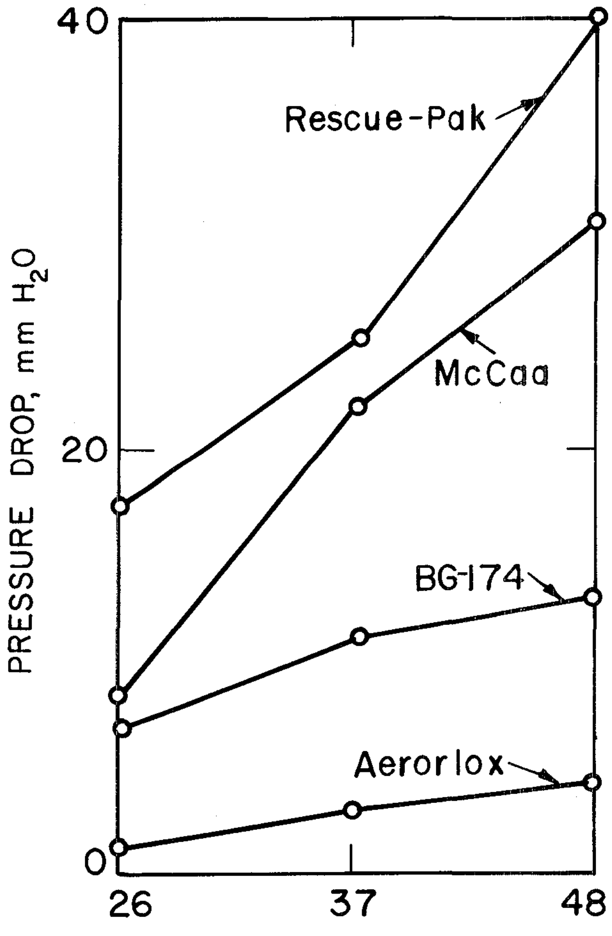

FIGURE 11. - Peak pressure drop versus flow rate.

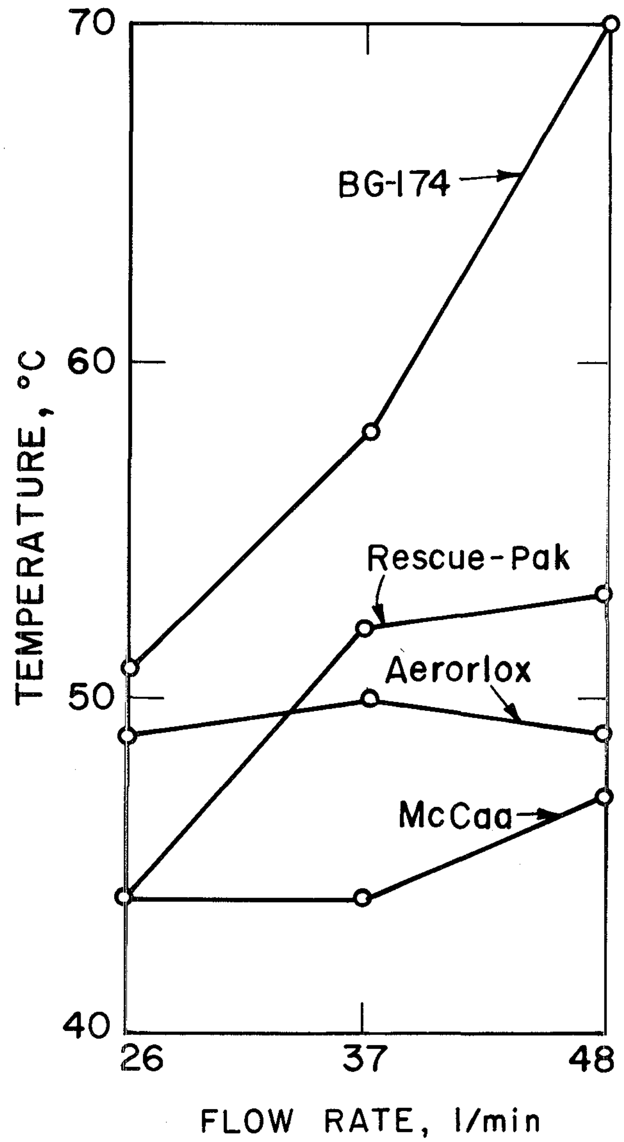

FIGURE 12. - Maximum exit temperature versus flow rate.

Temperature of Exit Gas

The absorption of CO_2 is an exothermic process which heats the exit air. The greatest exit-air temperature was noted for each of the three flow rates and is given in figure 12. In general, temperatures increased with increasing flow rate. Among the four RBA's, the BG-174A had the highest exit-gas temperature at each flow rate. The Rescue-Pak had exit temperatures which were not very different from the McCaa and Aerorlox soda lime canisters. The low temperatures for the Rescue-Pak were due to the exit air flowing through the exit connector, which was designed as a heat exchanger to dissipate some of the heat generated by the chemical reaction. The Aerorlox and McCaa canisters did not rise in temperature with increasing flow as much as the

Rescue-Pak or BG-174A; however, the exit air from the soda lime canisters of the Aerorlox and McCaa was nearly saturated with water, and, therefore, had a high heat capacity. The BG-174A NaOH canister, however, retained some of the water so that the exit air did not contain as much moisture. The result was a lower total heat capacity despite a greater exit temperature and, therefore, the air was more easily cooled in the breathing circuit after the canister. This was reported to be one of the advantages of NaOH over soda lime.[7] The anhydrous LiOH also had a lower water content in the exit air than the soda limes because of water retention. Heat generated in the Aerorlox canister is not sensed by the wearer because of the additional cooling provided by the liquid oxygen.

CONCLUSIONS

The Scott Rescue-Pak with LiOH as the CO_2 absorbent had the greatest capacity for CO_2 absorption. The temperature of the exit gas was high but the heat was dissipated by the heat exchanger. The packed-bed caused a high but acceptable pressure drop. The Draeger BG-174A with sodium hydroxide had the second greatest CO_2-absorbing capacity but required a complicated bed design to prevent caking of the chemical which occurs when it is exposed to water.[8] If used in a packed-bed design, this caking would result in an extremely high resistance to breathing. As a result of the bed design, the pressure drop was kept low and proved to be very effective in utilization of the absorbent. The Aerorlox and the McCaa with the soda limes had lower CO_2-absorption capacities than the other canisters along with lower exit-gas temperatures. The pressure drop for the radial flow design of the Aerorlox was very low; that of the packed-bed McCaa was high. LiOH is the most expensive chemical and the soda limes are the least expensive, although much more soda lime would be needed to absorb the same amount of CO_2 as did LiOH or NaOH.

In summary, LiOH can be used in a simple bed design with a high capacity for CO_2 absorption while maintaining acceptable levels of resistance and exit-gas temperatures. The result can be a smaller, lighter canister than those using NaOH or soda lime. The size of the scrubber should be closely matched to the supply of oxygen (R' = 0.9) to optimize the size and weight of these components. Finally, because of the expense of LiOH, a refillable canister with soda lime could be used for training.

The authors recommend that future work on closed-circuit, compressed-oxygen RBA's concentrate on LiOH as the CO_2 absorbent. Areas of consideration should be designs for increasing effectiveness, techniques to reduce resistance and close matching of oxygen supply and CO_2 scrubbers for RBA's. The results can lead to smaller, lighter CO_2 scrubbers for RBA's.

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[7] Stampe, G. Alkali oder Kalk zur Entfernung der Kohlensaure in Kreislaufgeraten? (Alkali or Lime for Removal of CO_2 from Closed Circuit Breathing Apparatus?). Draeger-Hefte, No. 218, 1951, pp. 4675-4677.

[8] Adriani, J., and E. A. Rovenstine, Experimental Studies on Carbon Dioxide Absorbers for Anesthesia. Anesthesiology, v. 2, No. 1, p. 12, January 1941, pp. 1-19.

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