

Effects of CO₂-Absorbent Canister Design on LiOH Efficiency in Closed-Circuit Breathing Apparatus¹

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It is of interest to know how to obtain as high an absorption efficiency as possible from a CO₂-absorption canister used in closed-circuit breathing apparatus. In this study, the Bureau of Mines found that varying the bed depth and the cross-sectional area of a canister changes its absorption characteristics. In tests using four, rectangular, variable-depth canisters with different cross-sectional areas, the Bureau found that, given a constant weight of the chemical absorbent, LiOH, and a constant CO₂ input, the canisters with a greater cross-sectional area reached CO₂ levels of 0.5 vol% in the effluent gas sooner than did the canisters with a greater bed depth. However, resistance to flow through the canister increases with bed depth, and a trade-off is inevitable. It was anticipated that the efficiency of a canister would increase with increasing intergranular air space, approaching the tidal volume of the breathing waveform and then level off at some point under 100%. This postulate was partially substantiated. Cylindrical and radial canisters were also tested and compared. It appears that shape is not as important a factor in absorption efficiency as bed depth, since neither canister differed significantly from rectangular canisters with regard to absorption efficiency values.

Introduction

Any type of closed-circuit breathing apparatus must have some way of ridding itself of expired CO₂ (carbon dioxide). This is accomplished, in the case of personal, bodily-carried rescue or escape breathing apparatus, by a CO₂ scrubber, which is a canister containing a chemical that absorbs CO₂. Lessening the weight is an important objective in breathing apparatus design; therefore, it is desirable to use as little absorbent as possible. Lithium hydroxide (LiOH) has been found to be the most efficient CO₂ absorbent; it absorbs more CO₂

per gram of chemical than any other absorbent readily available (Walker, 1941). More apparatus manufacturers are turning to LiOH for use in their scrubbers, and it is expected that LiOH use will be widespread in coming years. The Bureau of Mines therefore has chosen LiOH to be used exclusively in this study.

In previous work at the Bureau, we tested the CO₂-absorbent canisters of presently

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available, NIOSH-approved Rescue Breathing Apparatus (RBAs) [Bernard et al., 1979]. From these tests, we were led to do research on ways of maximizing the efficiency of the CO₂-absorbing process. We were interested in knowing if there were some critical amount of absorbent above and below which would be obtained a lesser absorption efficiency, and if there were some shape of canister that would be more conducive to CO₂ absorption than another. To these ends, single canisters were filled with varying amounts of LiOH to compare efficiencies, and different canister sizes and shapes were used with a given amount of LiOH to again compare efficiencies.

Description of Apparatus

Four rectangular, plexiglass canisters with different cross-sectional areas, one cylindrical-design, plexiglass canister, and one radial-flow-design, nonferrous-metal canister

were tested. The rectangular canisters and the cylindrical canister were built by the Bureau, while the radial-flow-design canister, in two sizes, is commercially available. The Bureau-built canisters had the advantage of allowing varying amounts of absorbent to be tested, but the radial-design canister did not lend itself well to this variable—thus two sizes were used. The rectangular canisters, which were of variable depth, will be referred to as “varicans” and are labeled according to their cross-sectional dimensions; hence, varican 10 (VC-10) is 10 by 10 cm, and we have VC-14, VC-17, and VC-7/28 (7 by 28 cm). The cylindrical canister will be referred to as CC, and the radial canister as RC. The canisters are depicted in Figures 1-6.

The rectangular canisters have cross-sectional dimensions as shown below:

Canister		VC-10	VC-15	VC-17	VC-7/28
Area	cm ²	100	196	289	196
Perimeter	cm	40	56	68	70

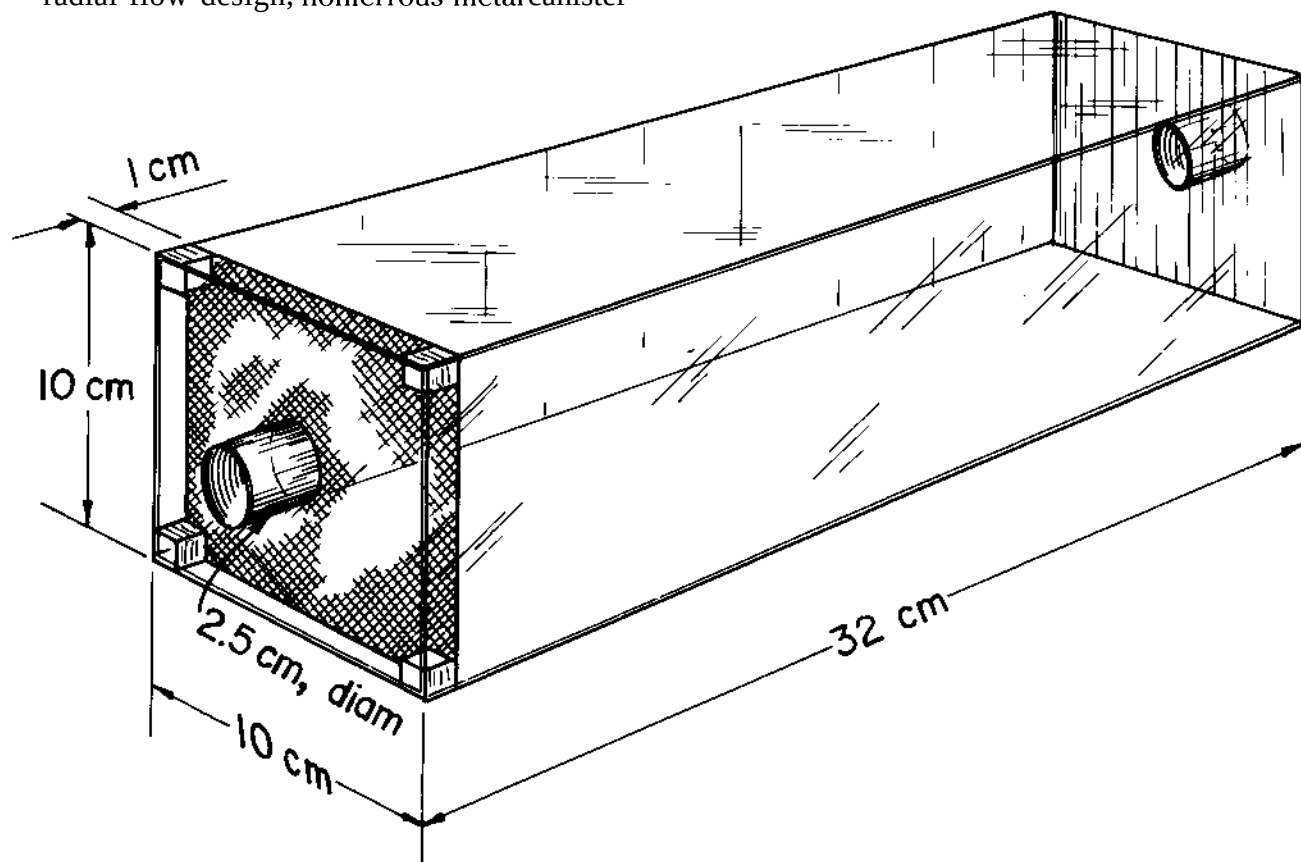


Figure 1. Varican 10.

Note that VC-7/28 has the same cross-sectional area as VC-14 and approximately the same cross-sectional perimeter as VC-17. These dimensions were chosen to determine which parameter is more important with regard to efficiency. By comparing efficiency values, we can tell if VC-7/28 aligns more closely with VC-14 or VC-17.

The canister assembly for varicans 10, 14, 17 and 7/28 is as follows: The airflow first enters a 1-cm-deep plenum in the case of varicans 10, 14, and 7/28 and a 2-cm-deep

plenum in varican 17. The larger plenum was used to compensate for the large cross-sectional area of the VC-17 to prevent possible channeling through the center of the canister. The airflow then passes through a 10-gage, wire mesh screen and a layer of gauze for bed retention and fine particulate filtration before reaching the LiOH. After passing through the absorbent, the air passes through another layer of gauze and screening before entering the exit plenum. A stiff spring was compressed between the wire screen and

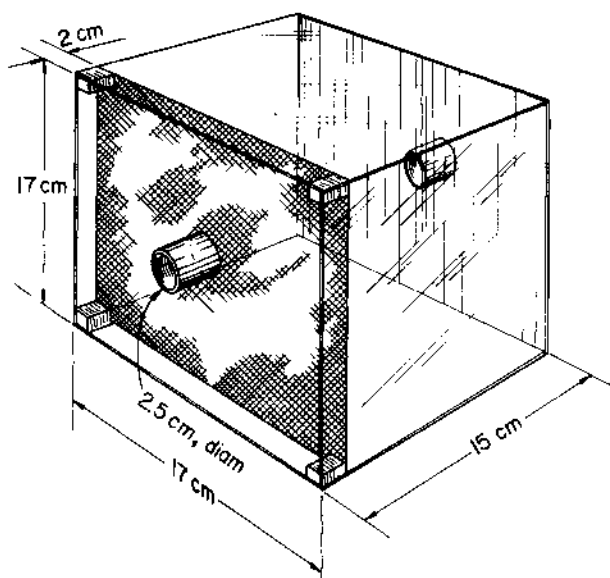


Figure 2. Varican 14.

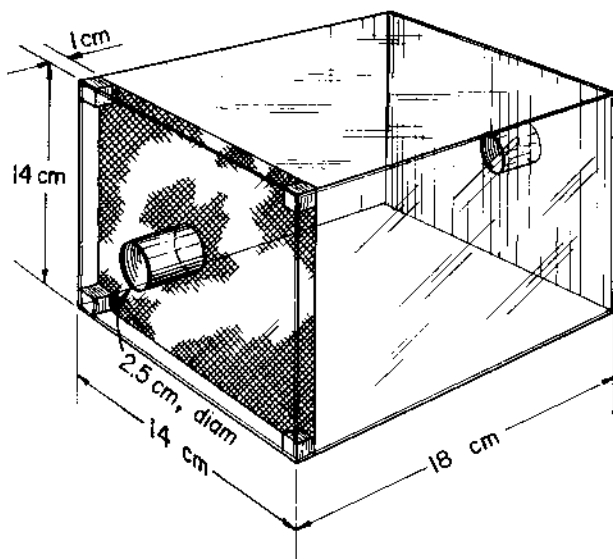


Figure 3. Varican 17.

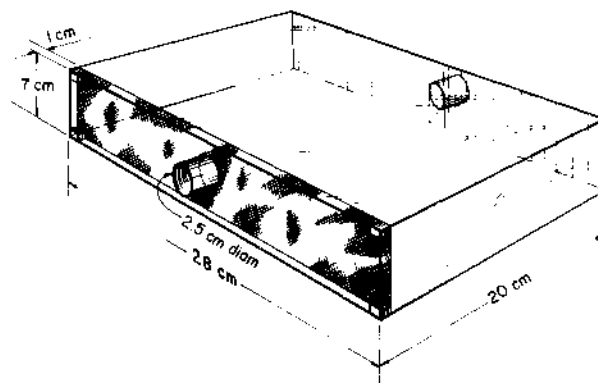


Figure 4. Varican 7/28.

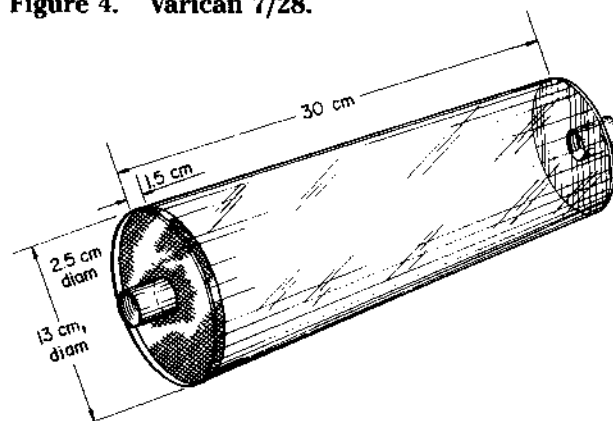


Figure 5. Cylindrical canister.

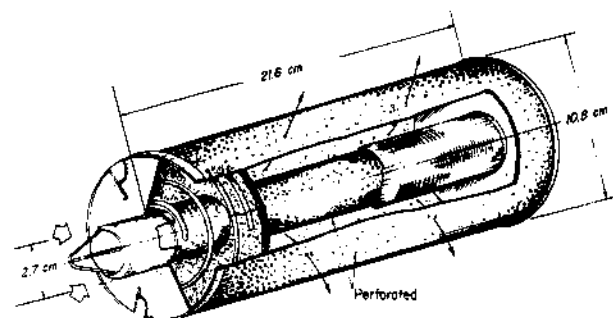


Figure 6. Radial canister.

a brace positioned against the insides of the canister to keep the LiOH under constant compression (Figure 7). The size of the exit plenum varied with the amount of chemical in the canister but was never smaller than 2 cm deep. The end plate was taped airtight at the far end of the canister so that with more or less chemical being tested, there was less or more air space, respectively, left over for the exit plenum. Exit plenum depth does not affect canister performance.

The canister assembly for the cylindrical canister is similar to that of the rectangular canisters and has a plenum depth of 1.5 cm.

The radial canister did not lend itself to varying the amount of absorbent, so two different sizes were used that held 800 and 1100 grams of LiOH (from the Siebe Gorman Aerorlox and Proto-10 RBAs, respectively*). Figure 6 shows the 800-gram-size canister. The airflow enters the radial canister axially, flows into the inner, cylindrical plenum, and then travels outward, radially, through the absorbent to the outer plenum formed by a plexiglass cylinder that channels the exit gas to the axial, exit port.

* Reference to specific makes or models of equipment is made for identification only and does not imply endorsement by the Bureau of Mines.

Experimental Methods

The testing system is shown schematically in Figure 8. A compressed-gas mixer supplies 3.5 vol% CO₂ in air to a breathing machine with a cam simulating a human breathing flow pattern at a work rate of 622 kg-m/min. The air from the breathing machine is then saturated with water vapor and delivered to the canister.

The exit gas from the canister enters a baffle box (Figure 9) where the fluctuating concentration values of CO₂ are averaged. From this box, a sample pump pulls some of the exit gas through a dryer to a small flask. The rest of the exit gas is vented to atmosphere. The small flask acts as a ballast further smoothing out the CO₂ values before being sampled by the CO₂ analyzer. Measurements of CO₂, both entering and exiting the canister, and the pressure drop (AP) across the canister are monitored continuously. The flow rate of the CO₂-air mixture, or ventilation rate, was 48 lpm, ATPD (ambient temperature and pressure, dry). The first phase of the experimentation studied the effects of varying the amount of LiOH in a given canister. Canisters VC-10 and VC-17

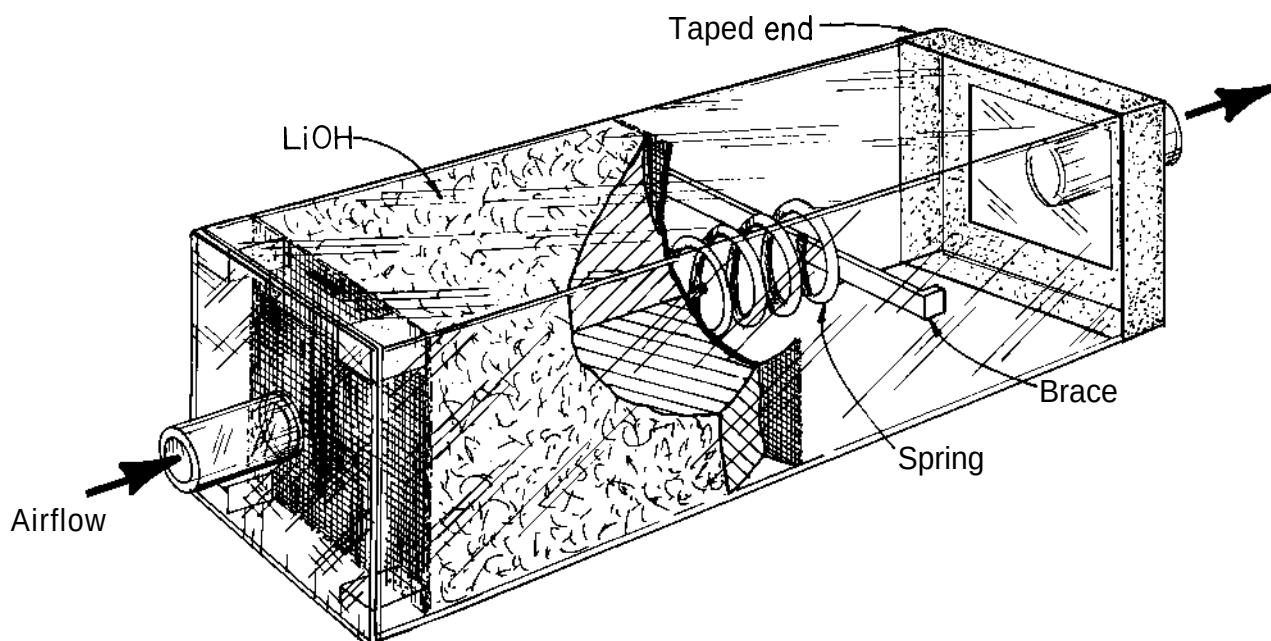


Figure 7. Spring-and-brace mechanism.

were loaded with 400 to 1400 grams of LiOH in increments of 200 grams. Two tests were run at each weight of LiOH for each canister. In the second phase, the varicans and the cylindrical canisters were loaded with 800 and 1200 grams of LiOH; however, tests with the radial canisters used 800 and 1100 grams of LiOH, since the larger radial canister could not accommodate more absorbent. Again, two tests for each canister at each weight were run.

The Code of Federal Regulations (CFR), Title 30, Part 11h, defines the test termination point, or canister life, as the point at which the concentration of CO₂ in the canister exit gas reaches 0.5%, for rescue breathing apparatus, and 1.5%, for escape apparatus. Efficiencies were determined for both points as the ratio of grams of CO₂ absorbed to grams of LiOH used in a particular test. Thus, it was necessary to find the area under the CO₂ breakthrough curve (Figure 10), translate this to liters of CO₂ *not* absorbed by the canister, and subtract this from the total amount of CO₂ entering the canister. This is the amount of CO₂ entering the canister. This is the amount of CO₂ absorbed, ATPD, which is then converted from ATPD to STPD, and then to grams.

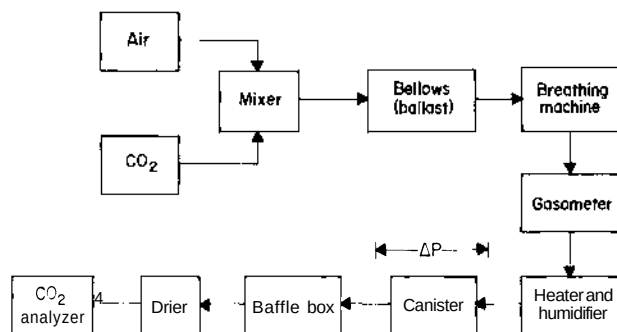


Figure 8. Flow path for CO₂-canister testing system.

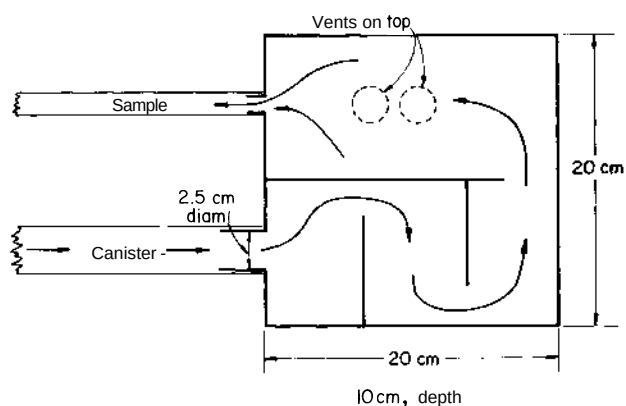


Figure 9. Baffle box.

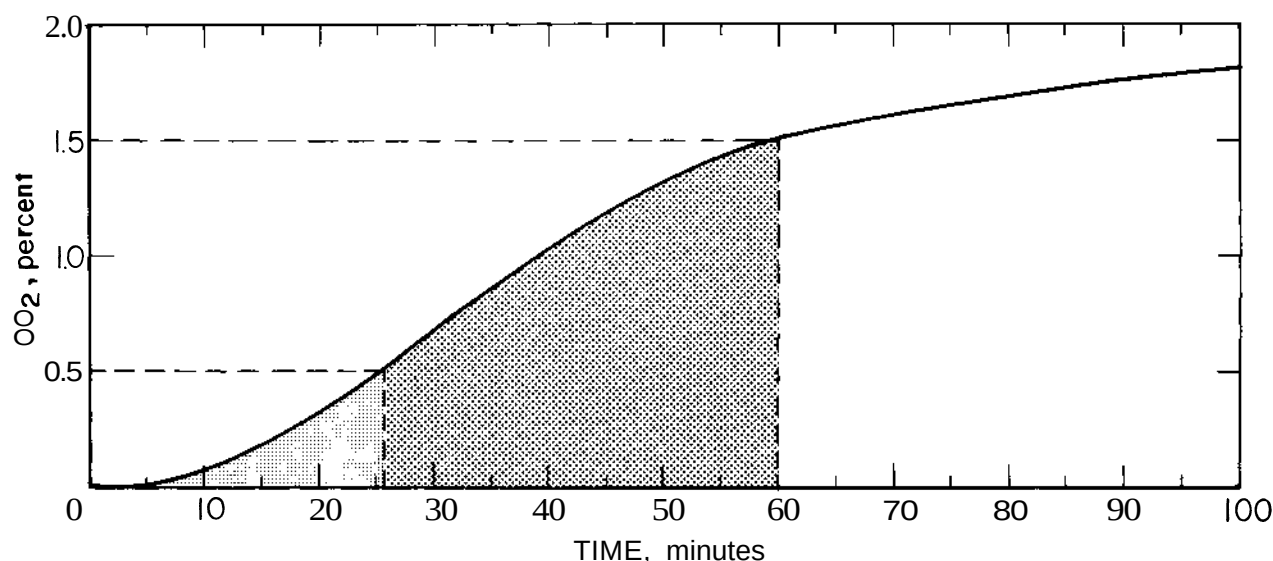


Figure 10. Sample effluent CO₂ breakthrough curve.

Results and Discussion

Phase 1

Figure 11 shows that efficiencies increased as weight of absorbent increased for both canisters at the 0.5% and 1.5% CO₂ termination points. At low weights of LiOH, efficiency does not vary a great deal with less or more LiOH. In the middle range of weights, efficiency increased tremendously with increasing amounts of LiOH. At higher weights, efficiency, again, is less sensitive to changes in weight of LiOH.

It was determined by laboratory measurement that the 4- by 14-mesh LiOH used has a density of 0.51 g/ml and that the intergranular air space is 53% of the total volume. With 1400 grams, the total volume of the LiOH would be 2745 ml, and 53% of this, the intergranular air space, is 1455 ml, or 1.46

liters. The tidal volume for these tests is approximately 1.52 liters, which is less than is found in standard breathing-machine setups, due to Bureau-developed modifications. It can be seen, then, that as the intergranular air space approaches the tidal volume, efficiency increases.

Adriani and Byrd (1941) indicated that efficiency drops when intergranular air space exceeds tidal volume. They explained the intergranular-space phenomenon as follows: When the tidal volume is greater than the air space in the canister (intergranular space), some CO₂-laden air is blown right through the canister with some of the CO₂ unabsorbed, not having had enough time to react with the LiOH. When the air space matches the tidal volume, dwell time in the canister is sufficient for complete absorption of the CO₂. When the tidal volume is less than the air space, Adriani and Byrd postulated that the front portion of the absorbent is expended but that the rear portion is left unused. We did not confirm the latter postulate, as any more than 1400 grams of LiOH would be unnecessary and impractical in most closed-circuit breathing apparatus applications.

Adriani and Byrd, in their research, were concerned with applications to anesthesiology, where weight and size of the apparatus are less significant and tidal volumes are consistent. They could apply their findings directly by using different-sized canisters for patients with different tidal volumes. In mine rescue work, however, this is not practical, and tidal volumes change with work rate. The best that could be done according to Adriani and Byrd's postulates would be to size the air space to the 50th-percentile worker at an average work rate. Other factors, however, would probably dictate the canister size rather than an attempt at optimal efficiency; for example, weight considerations—using as little absorbent as possible while meeting CFR Title 30, Part 11h requirements.

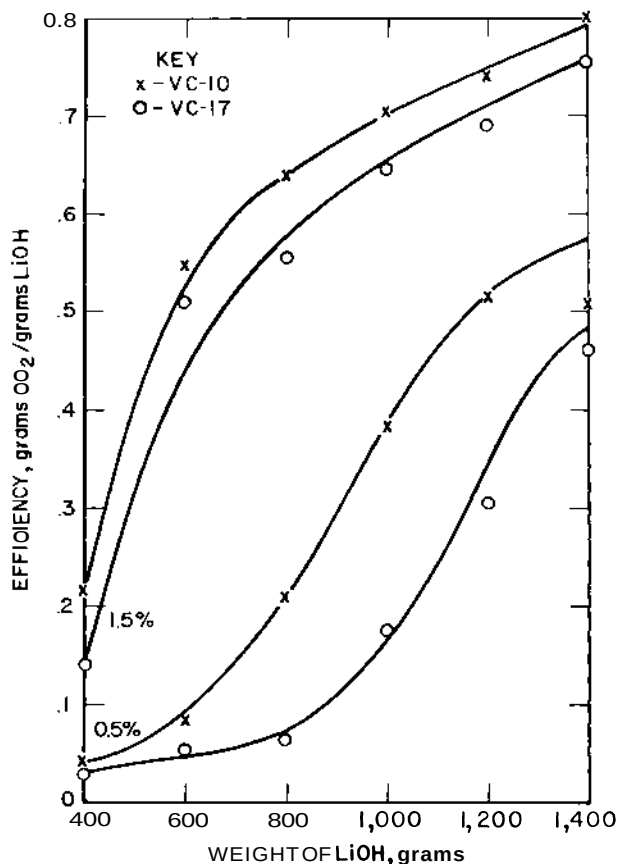


Figure 11. Weight of absorbent vs average efficiency for two canisters.

Phase 2

In Phase 2, six different canisters were tested with two weights of absorbent. From Figures 12 and 13, it appears there is strong

correlation between bed depth and efficiency at the 0.5% breakthrough point at both weights of absorbent and less correlation at the 1.5% breakthrough point. A logarithmic curve fit on the rectangular canisters gave coefficients of determination as follows:

Weight of LiOH	Breakthrough point	
	0.5% CO ₂	1.5% CO ₂
800 grams	0.70	0.46
1200 grams	0.85	0.68

Only the rectangular canister data were used for the curve fits, since it was necessary to keep all factors other than cross-sectional area constant. The efficiency differences in the various canisters are less pronounced at the 1.5% CO₂ level, as can be seen in Figures 12 and 13. It appears that the canisters with shallow beds are "catching up" to those with greater bed depths with regard to efficiency at higher effluent CO₂ levels. In terms of real time, although the shallow bed canisters broke through at 0.5% CO₂ relatively quickly their rates of breakthrough were lower, once they reached the 1.5% level, than those of the canisters with deeper beds. Indications are

that perhaps at higher levels of effluent CO₂, efficiencies will be equalized among the different canisters. This means that the canisters with shallow beds may take longer to reach higher levels of CO₂. Since, at moderate to heavy work rates, elevated CO₂ levels just become noticeable above 2.5%, it might be better physiologically, for long-term use, to use a shallow-bed canister (Menn et al., 1970). (It should be kept in mind that the test apparatus is an open-circuit one, and that the escaping CO₂ is not recirculated as it would be in a closed-circuit RBA. The effect in discussion may or may not be as significant in a closed-circuit situation.)

It seems, though, that at the 0.5% breakthrough point, a deep-bed canister makes better use of the available chemical absorbent, LiOH. But, we also have breathing resistance to consider. According to NIOSH regulations, the maximum peak-to-peak resistance for inhalation and exhalation is 100 mm H₂O at an instantaneous flow rate of 120 lpm. The varican 10, with a weight of 1200 grams LiOH at a flow rate of ~150 lpm, incurred a resistance of 98 mm H₂O representing exhalation

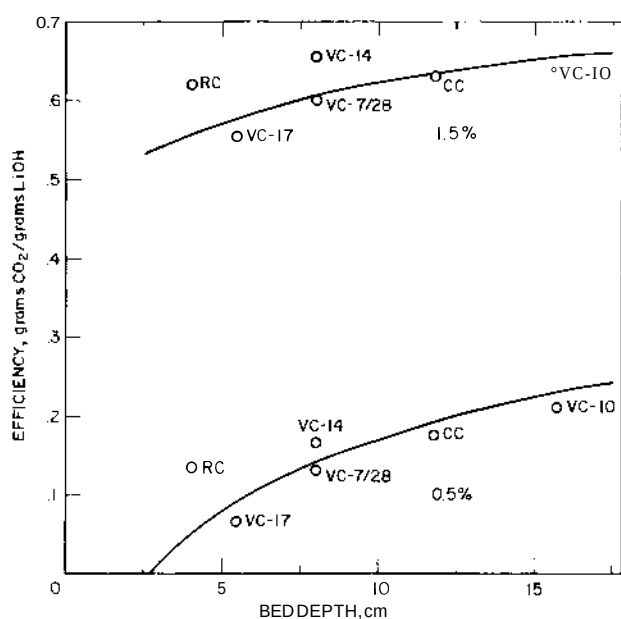


Figure 12. Absorbent bed depth vs average efficiency data points and logarithmic curve fits with 800 grams absorbent.

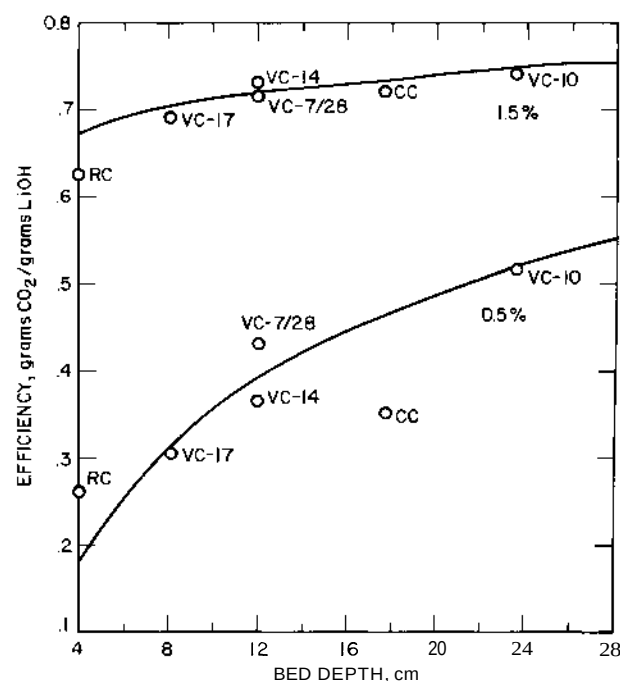


Figure 13. Absorbent bed depth vs average efficiency data points and logarithmic curve fits with 1200 grams absorbent.

only. This is clearly undesirable, and a trade-off is inevitable. The resistance at 1200 grams was 34 mm H₂O for the VC-14 and VC-7/28 and 22 mm H₂O for the VC-17.

In order to determine if cross-sectional perimeter and efficiency were related, the two factors were plotted and a least squares fit was performed (Figures 14 and 15). The coefficients of determination for the least squares fit were higher than those of either the logarithmic or exponential curve fits and are given below:

Weight of LiOH	Breakthrough point	
	0.5%	1.5%
800 grams	0.60	0.49
1200 grams	0.46	0.58

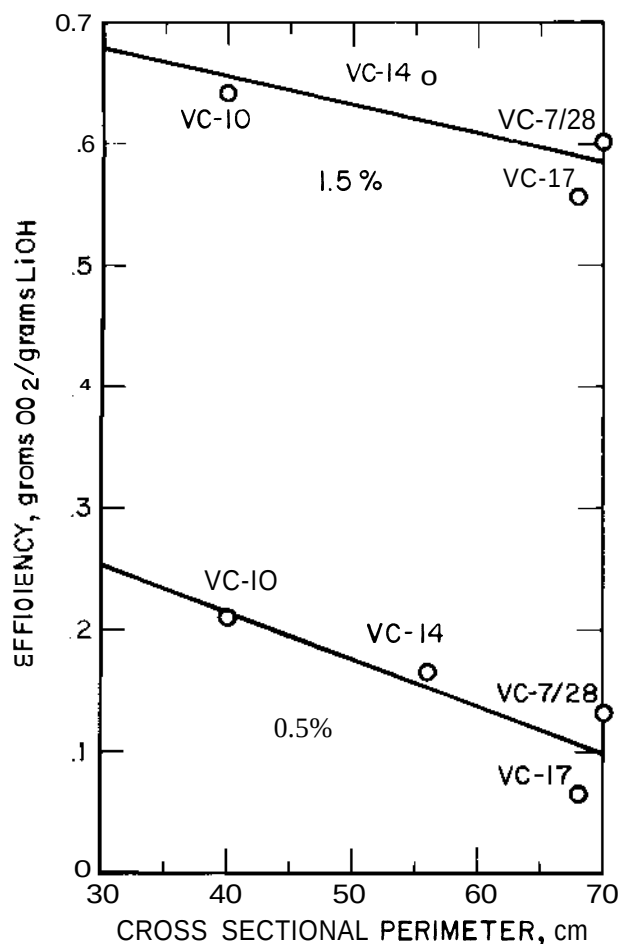


Figure 14. Canister cross-sectional perimeter vs average efficiency data points and least squares fit with 800 grams absorbent.

Comparing these values with those of bed depth versus efficiency, it appears that efficiency is more closely related to bed depth than to cross-sectional perimeter. Also, at the 0.5% breakthrough point, with 800 grams LiOH, the mean efficiency of the VC-17 was 9.3 standard deviations away from that of the VC-7/28, but the mean efficiency of the VC-14 was only 1.7 standard deviations away from that of the VC-7/28. At 1200 grams, the values were 5.9 and 3.1, respectively. This would give further support to the theory that efficiency is more closely correlated to bed depth than to perimeter.

From Figures 12 and 13, it appears that shape also is not as important as bed depth, as evidenced by the efficiency values of the cylindrical and radial canisters. A 90% confidence interval around each canister at each weight and breakthrough point places its true mean efficiency well within the range of the efficiencies of the rectangular canisters.

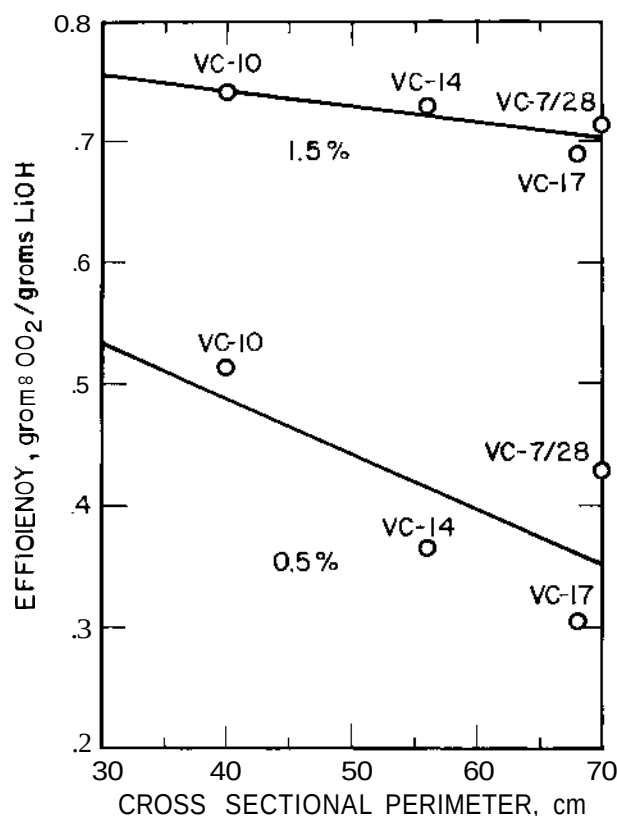


Figure 15. Canister cross-sectional perimeter vs average efficiency data points and least squares fit with 1200 grams absorbent.

Conclusions

In the design of CO₂-absorption canisters using LiOH, factors affecting efficiency are bed depth and amount of chemical used. A greater bed depth increases the efficiency of a canister in the range studied at the 0.5% breakthrough point, but as bed depth increases, so does breathing resistance,

eventually to intolerable levels, by NIOSH standards; therefore, a trade-off is necessary. Efficiency increases, also, with increasing amounts of chemical absorbent in the range of 400 to 1400 grams LiOH. This is attributed to the increase in intergranular space that is needed to enable sufficient dwell time in the canister for absorption of the CO₂. Factors not affecting efficiency to any significant degree are canister shape (rectangular, cylindrical or radial) and cross-sectional perimeter.

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