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CANISTER DESIGN CRITERIA OF CARBON DIOXIDE REMOVAL FROM SCUBA

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CANISTER DESIGN CRITERIA OF CARBON DIOXIDE REMOVAL FROM SCUBA

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8 MARCH 1957

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An empirical set of design criteria for a scuba carbon dioxide removal canister were derived from data obtained by a review of the pertinent literature. Such a device, presuming satisfactory performance for 180 min. at 30 ft and 30 min. at 180 ft, must be capable of absorbing a minimum of 600 gm. of CO_2. It must also remove 75-80% of the CO_2 from a mixture containing 0.5-2.0% CO_2 passing through it at a velocity of 55-90 L/min It must

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20. remove 70-75% of the CO_2 from a mixture containing 1.0 - 2.5% CO_2 passing through it at a velocity of 125-200 L/min. The breathing resistance must not exceed 1.5 cm. H_2O/L/sec. The inter-granular space must be at least 3.5 L.

ABSTRACT

An empirical set of design criteria for a scuba carbon dioxide removal canister were derived from data obtained by a review of the pertinent literature. Such a device, presuming satisfactory performance for 180 min. at 30 ft and 30 min. at 180 ft must be capable of absorbing a minimum of 600 gm of CO_2. It must also remove 75-80% of the CO_2 from a mixture containing 0.5-2.0% CO_2 passing through it at a velocity of 55-90 L/min. It must remove 70-75% of the CO_2 from a mixture containing 1.0-2.5% CO_2 passing through it at a velocity of 125-200 L/min. The breathing resistance must not exceed 1.5 cm H_2O/L/sec. The inter-granular space must be at least 3.5 L.

SUMMARY

PROBLEM

What are the design criteria for a carbon dioxide removal canister for use in closed or semi-closed circuit scuba which will have a duration of 180 min. at 30 ft and 30 min. at 180 ft?

FINDINGS

The total carbon dioxide absorption capacity must be between 600-800 gm. The CO_2 content of the gas leaving the canister under usual conditions (i.e. CO_2 production rate 2.5 gm/min., mean air flow 55 L/min., peak air flow 90 L/min.) must not exceed 0.5% effective. Under severe conditions, (i.e. production rate 6 gm/min.) the CO_2 content of the effluent gas must not exceed 1.5% effective. The breathing resistance must not exceed 1.5 cm H_2O/L/sec. (0.3 in H_2O/CFM). The inter-granular space must be between 3.5-4.5 liters. In addition, certain mechanical features affecting safety and convenience under field conditions must be included (see Art. 4.2.6). In section 4.3 of the report a set of tests and specifications are outlined by which any canister can be tested to determine whether or not it meets the above criteria.

RECOMMENDATIONS

(a) That the criteria, tests and specifications be adopted as tentative standards for CO_2 absorbent canisters for use in closed or semi-closed circuit scuba.

(b) When a canister is available which meets the tests and specifications, that subjective tests be conducted to determine whether or not it is completely satisfactory.

(c) That research be undertaken to determine whether or not the increased partial pressure at depth facilitates the reaction between CO_2 and the absorbent.

ADMINISTRATIVE INFORMATION

Ref: (a) BUSHIPS ltr ser 538-1776 dtd 6 July 1956

Reference (a) advised that a contract would be negotiated covering a design study of a carbon dioxide absorbent canister for use in self-contained underwater breathing apparatus and requested that specific criteria for such a study be established.

The estimated man-power requirements are as follows:

DESCRIPTION	MANHOURS
Establish bibliography	20
Review and research bibliography	175
Writing report	50
Publication	20
Total	265

The project outline was first prepared on 6 September 1956. Actual work on the project was started on 7 January 1957. Report was completed and submitted for approval on 8 March 1957.

CONTENTS

1. INTRODUCTION

1.1 Object

The objective of this project was to establish respiratory and physical criteria for the initiation of a design study to produce a standard carbon dioxide canister for scuba in the naval service.

1.2 Description

It was learned by conference with Bureau of Ships representatives that this canister was ntended principally for use with mixed-gas scuba. The canister desired was to have a duration of 180 minutes at 30 feet and a duration of 30 minutes at 180 feet. Since carbon dioxide production varies considerably w th swimming speed, the Bureau represent tives recommended assuming a swimming speed which a man could maintain for 180 minutes.

1.3 Scope

A p eliminary analysis of the problem revealed the amount and kind of information required to achieve the objectives of this study. It also soon became apparent that any study of this kind would have certain limitations due to gaps in our knowledge concerning some of the basic respiratory processes in underwater swimming.

1.3.1 Information to be furnished is:

(a) Total load of carbon dioxide which can be anticipated during 180 min. of underwater swimming.

(b) Average and peak rates of carb n dioxide output.

(c) Percentage of carbon dioxide in the gas entering the canister.

(d) Maximum allowable percentage of carbon dioxide in the gas leaving the canister.

(e) Rate of gas flow through the canister.

(f) Amount of breathing esistance which can be accepted.

(g) Desirable volume of inter and intra-granular space.

(h) Mechanical features which render canisters more convenient and useful.

1.3.2 The manner in which the carbon dioxide removal canister is placed in the scuba circuit has considerable bearing on some of the design criteria. Basically, there are two methods of placing a canister in a breathing circuit. First, one in which the respiratory mixture passes through the canister twice during each respiratory cycle. This is commonly known as the "to and fro" or "pendulum" canister. Second, one in which the respiratory mixturespasses through the canister only once during each respiratory cycle. This second method is commonly known s the "circle" type of canister. Further, it is conceivably possible to place the canister at one of three positions in relation to the swimmer and the breathing bag: (a) Between the exhalation valve and the breathing bag, (b) in the middle of the breathing bag, and (c) between the breathing bag and the inhalation valve. For purposes of this discussion, these will be called "near-circle", "split-bag" and "far-circle". The far-circle placement is not commonly used and will be not discussed further. (See figure 1.) Since the near-circle type of circuit is the most common one, the criteria were developed for that type of canister. Later in the report, the effect of placing the canister in either of the other two positions will be discussed.

1.3.3 The knowledge required to accurately specify canister design criteria is not readily available. Indeed, some of the most critical data is sadly lacking. In view of this situation, there was no alternative but to extrapolate the information on the basis of the best data available. The author wishes to make clear at the outset that the criteria specified in this report represent no more than the best estimates based on data available in the literature which in his opinion was the most reliable and applicable to the problem. Whenever possible, values will be specified in three alternative figures, "desirable", "acceptable" and "maximum" or "minimum" allowable. Every effort has been made to prescribe criteria which will produce maximum safety. In general, the "desirable" criteria will unquestionably meet the demands in section 1.2 with maximum safety. The "acceptable" criteria are believed to be reasonably safe but the canister may or may not entirely meet the duration and depth requirements. The "maximum allowable" values are borderline. To design solely on this basis is to gamble on a satisfactory canister.

1.3.4 For the sake of completeness, a chart indicating common defects and primary causes of failure in carbon dioxide absorption canisters have been included (Fig. 2). In order to render the report more generally useful, a glossary of respiratory terms is appended (Appendix A).

2. PROCEDURES

2.1 General

To collect the necessary information the following steps were undertaken: (a) limited search of the literature was completed, (b) An informative abstract was made of each article or report which contained data germane to the problem, and (c) Computations were made to produce the graphs and table.

2.2 Carbon dioxide production

Measurements of carbon dioxide production during underwater swimming in pen water have not been reported. Several studies of oxygen consumption are available (ref. 1, 2, 3). While there is some variance among the values reported by these investigators, they are generally of the same order of magnitude. Since the study of Dwyer and Lanphier (3) is the most complete and carefully controlled it was decided to rely principally on their data. In order to extrapolate carbon dioxide output from oxygen consumption it was first necessary to assume a realistic respiratory quotient (RQ)*.

Silverman, et al (4) have reported RQ at various oxygen consumption (work) rates. The oxygen consumption rates during underwater swimming reported by Dwyer and Lanphier were tabulated and multiplied by an RQ reported by Silverman at a similar rate of oxygen consumption (Table 1). This figure was divided by 1000 to determine the rate of CO_2 production in cc/min. Since Dwyer and Lanphier reported their values at STPD it was possible to change cc/min. to gm/min. by employing the density of carbon dioxide. At STPD 1 liter of carbon dioxide weighs 1.9768 gm. Therefore:

$$\frac{CO_2 \text{ production (cc/min.)}}{1000} \times 1.9768 = CO_2 \text{ prod. (gm/min.)}$$

The values in tAble 1 and figure 3 were arrived at by slide rule computation using a value of 1.975 for the density of CO_2.

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(Terms marked with an asterisk(*) are defined in the glossary (Appendix A).

2.3 Construction of flow curves

The construction of these curves (figure 4) was considerably more complicated. None of this data was available for underwater swimming and hence had to be extrapolated from other sources. In order to construct these curves the following data was needed: Respiratory Minute Volume (RMV)*, Respiration Rate*, Flow*, and time to reach maximum flow.

2.3.1 The RMV during underwater swimming has been reported (5, 6). As might be anticipated there is considerable variation among individuals both at he same and at different swimming speeds. In these same studies the respiration rate was also recorded but the oxygen consumption was not. It was therefore decided to extrapolate the RMV from the oxygen consumption rate using data contained in the Handbook of Respiratory Data on Viation (7). An examination of Table 1 will show that approximately 40% of the values for RMV are between 20 to 25 liters inclusive. They do, however, reach values as high as 66 liters. While there is a tendency for the RMV to rise with increased swimming speeds the relationship is by no means constant. Following an examination of all of the data available, it was concluded that to assume an RMV below 20 liters, while swimming, was not realistic. It was also concluded that the situation usually encountered in swimming at speeds between 0.7 and 1.0 knot could be described by assuming RMV's of 25, 26 and 35 liters. It is recognized that the value of 35 liters does not nearly approach the maximum value which could be attained. Shepard (8, 9) has reported maximum breathing capacities* for young men as high as 177 liters.

2.3.2 All of the data available (3, 5, 6) indicated that the respiration rate tended to increase with increasing swimming speed but was highly variable. Dwyer and Lanphier reported that the lowest average rate was 9/min. and the highest observed was 39/min. At swimming speeds between 0.7 to 1.0 kt. the majority of rates varied between 10 and 25 per min. For the purposes of constructing the flow curves it was therefore decided to assume three different respiration rates 10, 13, and 25 per minute.

2.3.3 In order to arrive at a realistic Tidal Volume the mean, high and low values for RMV at swimming speeds between 0.7 and 1.0 kt. (Table 1) were divided by 10 and 25. The results indicated that the Tidal Volume varied between 1 and 5.5 liters. In order to arrive at an "average" value, the mean, median and mode of these values was calculated and found to be 2.31, 2.20 and 1.98 liters respectively. An examination of the data in references 5 and 8 indicated that a tidal volume of approximately 2 liters could most commonly be expected. In view of the great variation in respiration rate it was decided that more realistic data could be obtained by assuming the respiratory pattern of swimmers could be described best by assuming three types: fast shallow breathers, slow deep breathers and an "average" between the two. For the purpose of constructing the flow curves, the following patterns were chosen (a) Respiration Rate 25/min., Tidal Volume 1 liter, (b) Resp. rate 10/min., Tidal Volume 3.5 liters and (c) Resp. rate 13/min., Tidal Volume 2 liters.

2.3.4 The remainder of the data required to construct the flow curves was derived from the work of Cain and Otis (10). This was done because it was the only study available which reported the effects resulting from very high resistance in respiration. Experience at this activity (5, 6, 11, 12, 13) has demonstrated that breathing resistance in all types of scuba is quite high, especially at depth. Tests using a mechanical respirator in a recompression chamber indicate that the usually encountered resitance to respiration is between 8 and 12 cm H_2O/liter/sec. at 130 feet. Cain and Otis studied the respiratory patterns of five resting subjects breathing against resistances of 7, 14.4 and 37.5 cm H_2O/lit r/sec. They found: (a) The total time of each phase of respiration was increased, (b) Maximum rate of flow was decreased, (c) Time required to reach maximum flow rate decreases, (d) Mean rate of air flow decreases, (e) Peak inspiratory and expiratory pressures increase, and (f) That the respiratory pattern becomes more rectangular, especially during the expiratory half-cycle.

2.3.5 Using the data described above, it was decided to assume that the time durations of the inspiratory and expiratory cycles were 39% and 61% of the total respiratory cycle, respectively.

2.3.6 The data of Cain and Otis also indicated that the maximum flow rate was reached in about 27.3% of the time duration of the cycle on inspiration and in about 23.2% of the time duration on expiration.

2.3.7 It is generally accepted by physiologists that there is a relationship between RMV and maximum rate of flow. It is recognized that in order for this to be true one must assume a regular and constant breathing pattern. Since the RMV was the only piece of data available it was decided to arrive at the maximum rate of flow found in the data of Cain and Otis. This was:

$$\frac{\text{Max. flow rate}}{\text{RMV}} \text{ equals, Inspiration 3.53, Expiration 2.59}$$

2.3.8 Putting all of the foregoing information together, we have the following:

TYPE OF RESPIRATORY PATTERN	Average	Rapid Shallow	Slow Deep
Total time of cycle (min)	0.077	0.01	0.1
Time of Inspiratory cycle	0.030	0.016	0.039
Time of expiratory cycle	0.047	0.0244	0.061
Time to reach maximum flow	0.0082	0.00246	0.01065
Max. rate of flow (L./min.)inspir.	92.0	88.2	123.0
Max. rate of flow (L./min.)expir.	67.5	64.7	90.6
Tidal Volume (liters)	2.0	1.0	3.5

2.3.9 The air flow curves (figure 4) were then constructed using the above values. A right triangle was first constructed the height of which represented the maximum rate of low and the base of which represented the time to reach maximum flow. Next a rectangle was constructed adjacent to the traingle the height of which was within 10% of the maximum flow rate and the base of which was 50% of the cycle. Others (4, 10) have reported that, on inspiration, the flow was maintained within 10% of the maximum for approximately 50% of the time and then shows a steady decline to zero. The areas of the triangle and rectangle were then calculated and subtracted from the tidal volume. A second triangle was next constructed adjacent to the rectangle, the base of which represented the remainder of the cycle and the weight of which was adjusted so that the area of this triangle was equal to the remainder of the tidal volume. The smoothest possible curve was then drawn above the resulting trapezoid. The area under the curve was checked by means of a planimeter and adjusted until it equaled the area equivalent of the tidal volume. In conducting the latter maneuver it was found necessary to adjust some of the values listed above.

3. RESULTS AND DISCUSSION

3.1 Total load of carbon dioxide

The studies o Dwyer and Lanphier (3) indicated that exp rienced swimmers could probably maintain a speed of 0.85 kt. for a considerable period of time. Employing the data from the above study, one concludes that in a 180 minute period a swimmer might produce between 340 and 570 gm of carbon dioxide. It is believed prudent to allow some margin for safety and to provide additional capacity for sudden bursts of swimming speed. The ideal canister should be capable of absorbing 800 gm of carbon dioxide. One which could absorb 700 gm would be considered acceptable and a canister which would absorb 600 gm would be the minimum acceptable.

3.2 Mean and peak rates of carbon dioxide output

It has been found (3) that swimmers experience considerable difficulty maintaining speeds slower than 0.7 kt. Since about 0.85 kt. is a comfortable speed the mean rate of carbon dioxide production which can be anticipated is about 2.5 gm per minute. It is also reasonably certain that men can maintain swimming speeds as high as 1.2 kt. for periods of ten minutes. Therefore, peak production rates as high as 6 gm per minute can be expected. Since men in good condition can maintain an oxygen consumption rate of 3500 cc/min. for short periods of time, peak rates of carbon dioxide output as high as 7 gm/min. are possible. Near the exhaustion period, canisters lose their ability to handle peak loads of carbon dioxide. Since this is the case, the design criteria are believed best expressed in terms of handling appeak load near the exhaustion period, i.e., the most difficult condition. These opinions will be developed in subsequent sections.

3.3 Percentage of carbon dioxide entering canister

Due to the nature of respiratory mechanics and the infinite variations in breathing patterns and carbon dioxide output, the percentage of carbon dioxide in the gas entering the canister covers a wide range. There is little if any carbon dioxide in the dead space air (the first part of the exhalation), most of the carbon dioxide being contained in the alveolar air (the last part of the exhalation). Under ordinary conditions the percentage of carbon dioxide in the gas entering the canister would vary from 0 to 5.5%.

It could vary from 0 to 8%. For the purposes of canister design, however, it is believed acceptable to assume that the gas is mixed and that the carbon dioxide is somewhat evenly distributed. In this case, the percentage of carbon dioxide in the gas entering the canister would vary from 4 to 5%, (Table 1). The effect of depth on this value is discussed in a subsequent section.

3.4 Rate of gas flow through canister

From an examination of figure 4, it will be noted that peak velocities of approximately 120 liters per minute can be anticipated during inhalation with peak velocities of approximately 88 L/min. occuring during exhalation. Under unusual circumstances such as physical exertion combined with rapid deep breathing, peak velocities in the range of 200 L/min. could occur. Cain and Otis (10) found that the ratio of mean rate of flow to maximum rate of flow was approximately 1:1.4 on inspiration and 1:1.6 on expiration. Considering the foregoing statements then, in the design of a canister one should anticipate mean air flows of 55 L/min. with peak flows as high as 200 L/min.

3.5 Percentage reduction in carbon dioxide content of gas mixture passing through canister

This is a quite critical value due to the role of carbon dioxide in precipitating oxygen convulsions. Certainly the ideal situation would be for the canister to remove all of the carbon dioxide at peak rates of production and air flow. To expect this may be unrealistic. The exact amount of carbon dioxide men can tolerate together with various oxygen tnesions in excess on one atmosphere has not been established. A number of workers have established that increasing the carbon dioxide content of an oxygen rich respiratory mixture under increased atmospheric pressure by even a small amount will precipitate a convulsion in an otherwise "safe" condition. It has also been found that oxygen convulsions are more likely to occur when men are breathing nitrogen-oxygen mixtures than would be expected on the basis of the oxygen tension alone (12). From a practical standpoint one must also realize that a swimmer would lose his life in the event of an oxygen convulsion occurred at any appreciable depth. In view of the foregoing one cannot gainsay the position that the carbon dioxide content of the breathing mixture must be kept as low as possible. An ideal value is considered to be of the order of 0.3% <u>effective</u>. It is believed that the value of 1.5% <u>effective</u> cannot be exceeded without encountering considerable risk of oxygen convulsions. Rickert (13) in the test of one semi-closed circuit scuba reported that the CO_2 concentrations in the breathing bag never exceeded 1.5% and the majority were below 0.5%. It would appear then that the values listed above were capable of being attained.

3.6 The effect of depth

The increased atmospheric pressures encountered at depth produce a series of related changes which increase the demands placed upon the performance of the canister and may or may not enhance it's performance. First, the molecular concentration of carbon dioxide in the mixture entering the canister is markedly reduced. Second, the amount of CO_2 present exerts a greater partial pressure. This means that the amount of CO_2 in the mixture leaving the canister produces a proportionally (greater) physiological effect. This picture can best be explained by an example.

3.6.1 Let us assume that a man is swimming at a depth of 165 feet (6 at. abs.) at a rate of 0.85 kt., producing CO_2 at a rate of 1260 cc/min. with an RMV of 35 liters. A volume of 35 L at 165 ft would be 210 L. (35 x 6) at the surface. Since the CO_2 in the mixture entering the canister would be 0.6%. However, since the pressure at this depth is 6 at. the effective percentage is 3.6% (0.6x6). Let us now assume that the canister removed two-thirds of the CO_2 from the mixture passing through it. The resulting percentage of CO_2 in the gas leaving the canister would be 0.2%. The effective percentage of the CO_2, since the swimmer is at 165 ft., would be 1.2% (0.2 x 6).

3.6.2 Since it is not established that the increased partial pressure of CO_2 at depth speeds up the chemical reaction in the canister, the safest assumption is that it will not. A canister for use with mixed gas scuba must then be expected to react with gas mixtures containing small molecular concentration of CO_2.

3.7 Tolerable respiratory resistance

Semi-closed circuit scuba apparatus is now available with respiratory resistances varying from 6.5 to 11.5 cm. H_2O/L/sec. (11, 13, 14). An examination of all of the evaluation reports available at this activity leads one to the conclusion that scuba divers will accept respiratory resistances up to 10 cm. H_2O/L./sec. without complaint. It is believed, however, that the canister should not contribute more than one-third of the resistance of the entire circuit. It must also be remembered that since the breathing mixture increases in density with depth, the resistance to respiration will also increase.

Marshall et al (15) reported that the resistance to respiration at 99 ft. guage was approximately two times that found at the surface. At 180 feet, then, the resistance can be anticipated to be 3 to 4 times that found at atmospheric pressure. Thus, a value of 5 cm. H_2O/L/sec at the surface would be between 15 and 20 at 130 feet. It appears then that the ideal canister should have resistance of no more than 0.5cm. H_2O/L/sec. at atmospheric pressure and that a resistance of 1.5 cm. H_2O/L/sec. would be the maximum allowable. This requirements is not unrealistic in view of the data reported by Leyden (16) who found resistances of 0.25 to 1 cm. H_2O/L./sec. in three typres of canisters, when tested at atmospheric pressure. The same report indicates that the resistance is increased between 3.5 and 6 times at 130 feet as comp red with the surface. In developing oxygen breathing equipment for use in aviation (18), it has been found desirable to have a linear relationship between the amount of pressure required and the airflow. One reason for this is immediately apparent. If the canister had a sudden peak in the "pressure-flow" curve, (fig. 5) the swimmer might have the uncomfortable experience of being suddenly blocked in the midst of a maximum exhalation. Just as if you were exhaling through a tube and someone suddenly occluded it.

3.8 Effect of inter and intra-granular space

Adriani and Rovenstime (17) reported that the more exactly the tidal volume was accomodated by the inter-granular space in the canister the better the carbon dioxide absorption. This was especially true of the pendulum type of canister. Since the tidal volume varies so widely in underwater swimming it is impossible to even remotely relate the tidal volume to the inter-granular space. It is desirable, however, that the canister be able to accomodate one complete exhalation. This would facilitate CO_2 absorption and prevent "blow through". The maximum exhalation would approximately 4.5 liters which is the usually encountered vital capacity* in healthy young men.

3.9 Effect of canister shape and placement

A report on this canister design criteria would not be com complete without a consideration of these two factors.

3.9.1 The shape of the canister seems to have considerable effect on the resulting resistance to air flows. Leyden (16) studied the breathing resistance in three different types of canisters: cylindrical, radial and rectangular. The radial canister appeared to offer the least resistance. The rectangular canister produced a breathing resistance which was between the other two. The values were of the following order of magnitude at 130 ft: radial 1.5 cm. H_2O/L/sec., rectangular 4.0 cm. H_2O/L/sec., cylindrical 3.25 cm. H_2O/L/sec.

3.9.2 A canister can be placed in the scuba circuit in one of three ways, known as pendulum, near circle and split-bag (fig. 1). On first thought, it might appear that the pendulum type of canister would offer many advantages. The principal one being that the respiratory mixture would pass over the absorbent twice and thus produce more efficient absorption of CO_2. It must be remembered, however, that the size of this canister is quite critical. For efficient operation, it should exactly accomodate the tidal volume. Since the tidal volume appears to vary so widely in underwater swimming this is almost impossible. If the canister is too small, it will be rapidly exhausted; if too large, it constitutes added dead space. It is probable that this canister would first be exhausted at either end. As a portion of the canister became exhausted, it would constitute dead space. In designing a pendulum canister, one would need to consider both inspiratory and expiratory air flows. Since the inspiratory air flows appear to be much greater (fig. 2), the resistance in the canister would need to be lower. In summary, while the pendulum canister might be of considerable value in anesthesia, where conditions are fairly constant, it seems to offer little to underwater swimming.

3.9.3 The near-circle canister cycle has several advantages over the pendulum canister. The inter and intra-granular space need not be matched so exactly with the tidal volume so long as it is of sufficient size and of such a shape as to prevent "blow through". In this canister one needs only to consider the expiratory cycle. Since expiration is prolonged the air flows are not as great and hence the resistance will not become intolerable at peak flows. The disadvantage of the circle type of canister is that the gas mixture passes through it only once and then at fairly high speeds.

3.9.4 On a theoretical basis the split-bag type of canister appears to offer some advantages which merit discussion and consideration. In this case, the exhaled gas would be mixed and a fairly uniform percentage of CO_2 would be found in the mixture entering the canister. Since the swimmer would be exhaling into the bag, the resistance in the canister itself would also be fairly uniform and slower, allowing more time for the CO_2 to react with the absorbent. It is recognized that some practical difficulties might be encountered in placing the canister in the circuit in this fashion. The merits of the split-bag type of canister can only be evaluated by further testing.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Design considerations

In formulating the design criteria for a CO_2 absorption canister for use in scuba, the factors listed below were considered.

4.1.1 The canister was to have a duration of 180 min. at 30 feet and 30 min. at 180 ft.

4.1.2 The mean rate of CO_2 production would be 2.5 gm./min. with peak rates of production of 6 gm./min. being probable.

4.1.3 The percentage of CO_2 in the gas entering the canister would be about 4% at mean rates of production and about 5% at peak rates of production.

4.1.4 The mean air flow rate through the canister would be about 55 L/min. (Approx. 2 CFM). Peak air flow rates as high as 200 L/min. (7 CFM) can be anticipated.

4.1.5 Due to the role of CO_2 in precipitating oxygen convulsions, the canister should be as effective as possible in removing CO_2 from the exhaled gas.

4.1.6 Due to the increased density of gases at depth, the molecular concentration of CO_2 in the exhaled gas would be relatively low.

4.1.7 It appears that swimmers will accept breathing resistances of 10 cm. H_2O/L/sec. It is concluded that the canister should contribute no more than one third of the entire resistance. From data available, it is also concluded that the resistance at 180 ft. would be from 3-4 times as great as on the surface due to the increased density of the exhaled gas.

4.1.8 To facilitate absorption of the CO_2 and to prevent "blow through", the inter-granular space should be nearly equal to the vital capacity.

4.1.9 The canister should have certain mechanical features which enhance its safety and convenience in use.

4.2 Canister design criteria

Below are listed the design criteria. Since the ideal may not be achievable, two alternate values are given in each case.

4.2.1 Total carbon dioxide absorption capacity:

(a) Ideal 800 gm.
(b) Acceptable 700 gm.
(c) Minimum 600 gm.

4.2.2 Allowable percentage of carbon dioxide in the gas leaving the canister under usual conditions, i.e. production rate 2.5 gm./min., mean air flow 55 L/min., peak air flow 90 L/min.

(a) Ideal 1.0% effective
(b) Acceptable 1.3% effective
(c) Maximum 1.5% effective

4.2.3 Allowable percentage of carbon dioxide in the gas leaving the canister under severe conditions, i.e. production rate 6 gm./min., mean air flow 125 L/min., peak air flow 200 L/min.

(a) Ideal 1.0% effective
(b) Acceptable 1.3% effective
(c) Maximum 1.5% effective

4.2.4 Breathing resistance is to conform to the values listed below and to be linear (fig. 5).

(a) Ideal 0.5 cm. H_2O/L/sec. (0.1 in.H_2O/CFM)
(b) Acceptable 0.1 cm. H_2O/L/sec. (0.2 in.H_2O/CFM)
(c) Maximum 1.5 cm.H_2O/L/sec. (0.3 in.H_2O/CFM)

4.2.5 The following mechanical features were largely obtained from <u>Submarine Medicine Practice</u> (19). The canister should:

(a) Utilize a non-caustic absorbent.
(b) Utilize an absorbent which is easily packaged, transported and readily obtainable.
(c) Be constructed so as to prevent the collection of leakage, saliva or condensate.
(d) Be readily opened.
(e) Be easy to fill without excessive shaking.
(f) Keep the absorbent from settling and channeling.
(g) Be of such size and shape as to prevent "blow through".
(h) Be easy to seal, with minimum likelihood of leakage.
(i) Be easy to empty and clean.

4.3 Tests and specifications

This section describes a procedure by wh ch any canister can be tested to determine whether or not it meets the criteria set forth in this report. It is recognized that these tests neglect the fact that under operational conditions the gas will be fully saturated with water vapor and will be at body temperature. It is believed, however, that experience will prove that these factors can be neglected in bench tests.

4.3.1 First inspect the canister and determine how nearly it conforms to the criteria in article 4.2.6 above.

4.3.2 Next, fill and empty the canister. Weigh the absorbent and calculate the number of grams of CO_2 with which it will combine. If possible, use actual test rather than theoretical values. For example, McConnaughy found that there was a considerable difference between the theoretical and actual performance of Baralyme. One pound of Baralyme should absorb 1/2 lb. of CO_2, but in actual tests it was found that would only absorb about 0.2 lb. If the amount of absorbent in the canister will not abosrb 600 gm. of CO_2, the canister is unacceptable.

4.3.3 The next logical step is to check the canister for breathing resistance. For this one needs a dry gas meter and a water manometer. Attach a source of compressed air to the inlet of the gas meter. Attach the outlet of the meter and the canister and arrange a water manometer between the meter and the canister inlet. Pass air through the canister at flow rates from 20 to 170 L/min. (1 to 60 CFM) and plot the pressure developed on graph paper (fig. 5). If the pressure developed exceeds 1.5 cm. H_2O/L/min. (0.3 in. H_2O/CFM) or if the relationships between the pressure and flow rate is not linear the canister is unacceptable.

4.3.4 The next series of tests is designed to determine the performance of the canister under the conditions which will be imposed on it during actual use. For these tests the following material will be required: (1) A gas mixture containing 10% CO_2 in either air or oxygen, (2) A large spirometer, and (3) A mechanical respirator which produces a sinuous breathing pattern and in which the tidal volume and respi atory rate can be varied. It is recognized that these tests will require quite large amounts of CO_2 mixtures and to do them in sequence would be almost impossible. It is believed that the tests should and can be accomplished in one working day. These tests must be done on the same canister without refilling or disturbing the absorbent.

(a) The first step is to exhaust the canister to one-half to two-thirds of its capacity. Using the respiratory set at tidal volume of 2 L. and rate of 20/min., pass 2500 liters of 10% CO_2 through the canister.

(b) Set the respirator at a tidal volume of 2 L. and the rate at 15/min. and pass 100 L. of 2% CO_2 through the canister. Collect a 10 L. sample at the end of the test and analyze it for CO_2. If the CO_2 content exceeds 0.25% the canister is unacceptable.

(c) Using the same settings on the respirator, pass 100 L. of 0.5% CO_2 through the canister. Collect a 10 L. sample at the end of the test and analyze. If the CO_2 content exceeds 0.25% the canister is unacceptable.

(d) Set the respirator at a tidal volume of 3 L. and the rate at 25/min. Pass 100 L. of 2.5% CO_2 through the canister and collect a 10 L. sample at the end of the test. If the CO_2 content exceeds 0.75% the canister is unacceptable.

(e) Using the same settings, pass 100 L. of 1% CO_2 through the canister. Collect a 10 L. sample at the end of the test and analyze. If the CO_2 content exceeds 0.25% the canister is unacceptable.

4.3.5 To determine the tendency of the canister to leak, remove the absorbent, secure the inlet and outlet with stoppers and submerge the canister in water for a period of 1 hour. At the end of this period empty the water, if any, from the canister and measure it. A leakage rate of 10 cc. per hour will be tolerated.

4.3.6 Next, fill the canister with absorbent. Secure one end and fill the canister with water. Empty the water from the canister and measure it. If the volume is less than 3.5 liters the canist r is unacceptable.

4.4 Recommendations

The following action is recommended:

(a) That the criteria, tests and specifications be adopted as tentative standards for CO_2 absorbent canisters for use in closed or semi-closed circuit scuba.

(b) When a canister is available which meets the test and specifications, that subjective tests be conducted to determine whether or not it is completely satisfactory.

(c) That research be undertaken to determine whether or not the increased partial pressure at depth facilitates the reaction between CO_2 and the absorbent.

TABLE 1. DERIVATION OF PRINCIPAL DATA

1 Swim Speed (kts)	2	3 Oxygen Consumed (L/min.)	4 Assumed Resp. Quotient	5 Carbon Dioxide Production cc/min	 gm/min	6 Resp. Minute Volume	7 % CO_2 Entering Cannister
0.5	Mean	0.82	0.87	714	1.41	20.0	4.05
	High	1.00	0.87	870	1.72	24.5	4.02
	Low	0.67	0.86	576	1.14	17.0	3.84
0.6	Mean	0.96	0.87	835	1.65	24.5	3.86
	High	1.14	0.87	991	1.96	25.0	4.50
	Low	0.83	0.87	721	1.43	20.0	4.10
0.7	Mean	1.14	0.87	991	1.96	25.0	4.50
	High	1.35	0.91	1228	2.43	34.0	4.10
	Low	0.96	0.87	835	1.65	24.5	3.87
0.8	Mean	1.30	0.91	1181	2.34	31.0	4.32
	High	1.58	0.93	1469	2.90	38.0	4.39
	Low	1.04	0.87	905	1.79	24.5	4.19
0.9	Mean	1.53	0.91	1391	2.75	37.0	4.26
	High	1.90	0.93	1768	3.49	49.0	4.19
	Low	1.13	0.87	982	1.94	25.0	4.45
1.0	Mean	1.83	0.93	1701	3.36	44.0	4.38
	High	2.26	0.97	2190	4.33	55.0	4.51
	Low	1.34	0.91	1219	2.43	34.0	4.03
1.1	Mean	2.10	0.97	2035	4.02	50.0	4.61
	High	2.64	0.97	2560	5.06	60.0	4.86
	Low	1.56	0.93	1450	2.97	38.0	4.33
1.2	Mean	2.50	0.97	2425	4.79	60.0	4.60
	High	3.03	1.00	3030	5.99	66.0	5.21
	Low	1.87	0.93	1738	3.43	45.0	4.39
Rest	Mean	0.34	0.85	289	0.57	9.0	3.64
	High	0.42	0.85	357	0.70	11.0	3.68
	Low	0.26	0.85	221	0.44	7.0	3.57

APPENDIX A

GLOSSARY

BREATHING RESISTANCE	- Expressed in centimeters and measured by the height of a water column at a flow of one liter per second.
FLOW CURVE	- Curve of velocity of air flow in relation to time.
MAXIMUM BREATHING CAPACITY	- The maximum volume of air a subject is capable of moving in and out of his lungs, expressed in liters per minute.
MAXIMUM FLOW	- The peak rate of air flow, expressed in liters per minute, which occurs during either the inspiratory or expiratory cycle.
RESPIRATORY RATE	- Number of breaths per minute.
RESPIRATORY CYCLE	- One complete breath. It consists of an inspiratory and expiratory cycle.
RESPIRATORY MINUTE VOLUME (RMV)	- Volume per minute of air moved in and out of the lungs.
RESPIRATORY QUOTIENT (RQ)	- The ratio $\frac{\text{vol. } CO_2 \text{ expired}}{\text{vol. } O_2 \text{ consumed}}$
TIDAL VOLUME	- Volume of air inspired or expired during a single respiration.
VITAL CAPACITY	- A term used to indicate the maximum volume (liters) of air that a subject is capable of exhaling after inflating the lungs to their maximum capacity.

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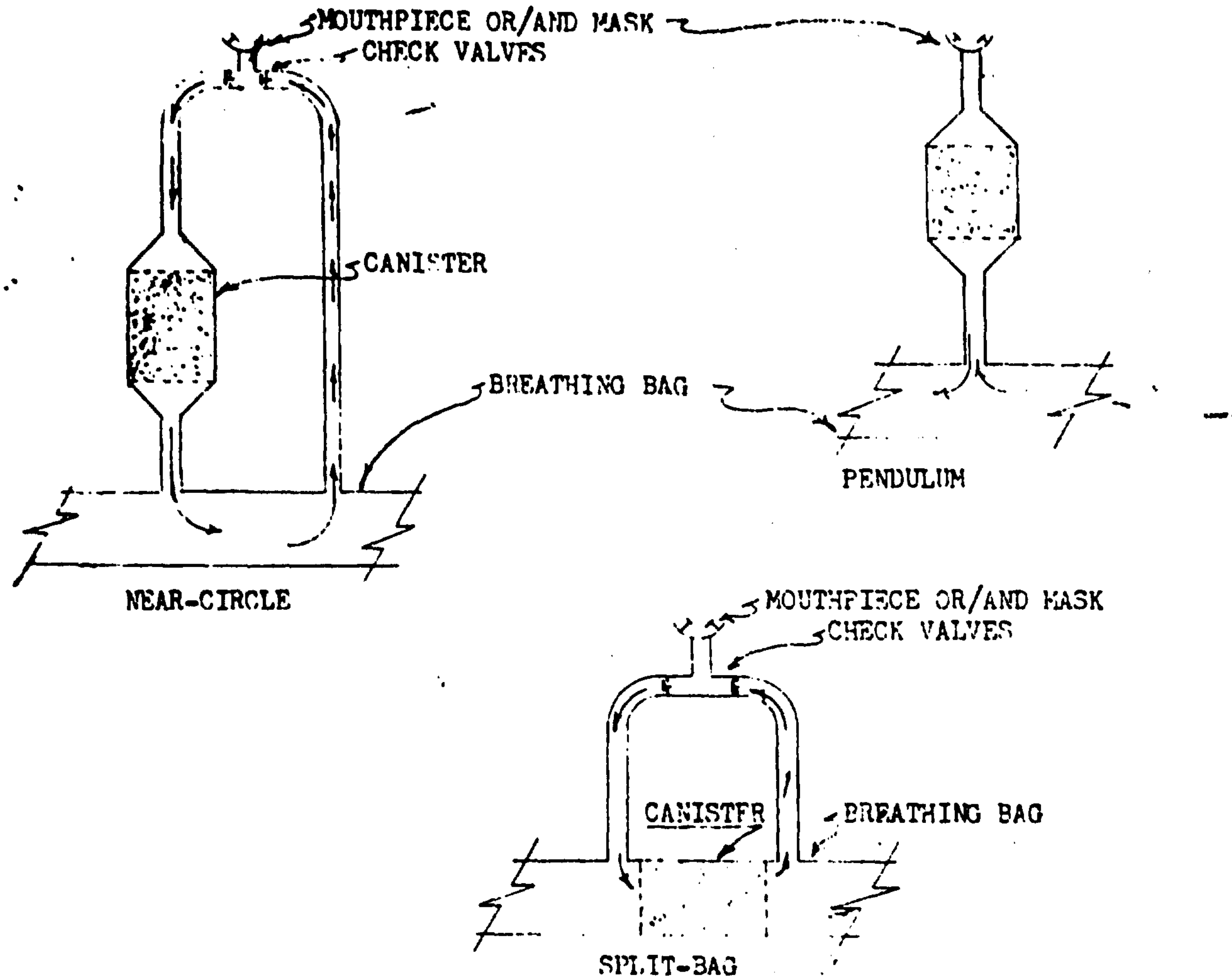
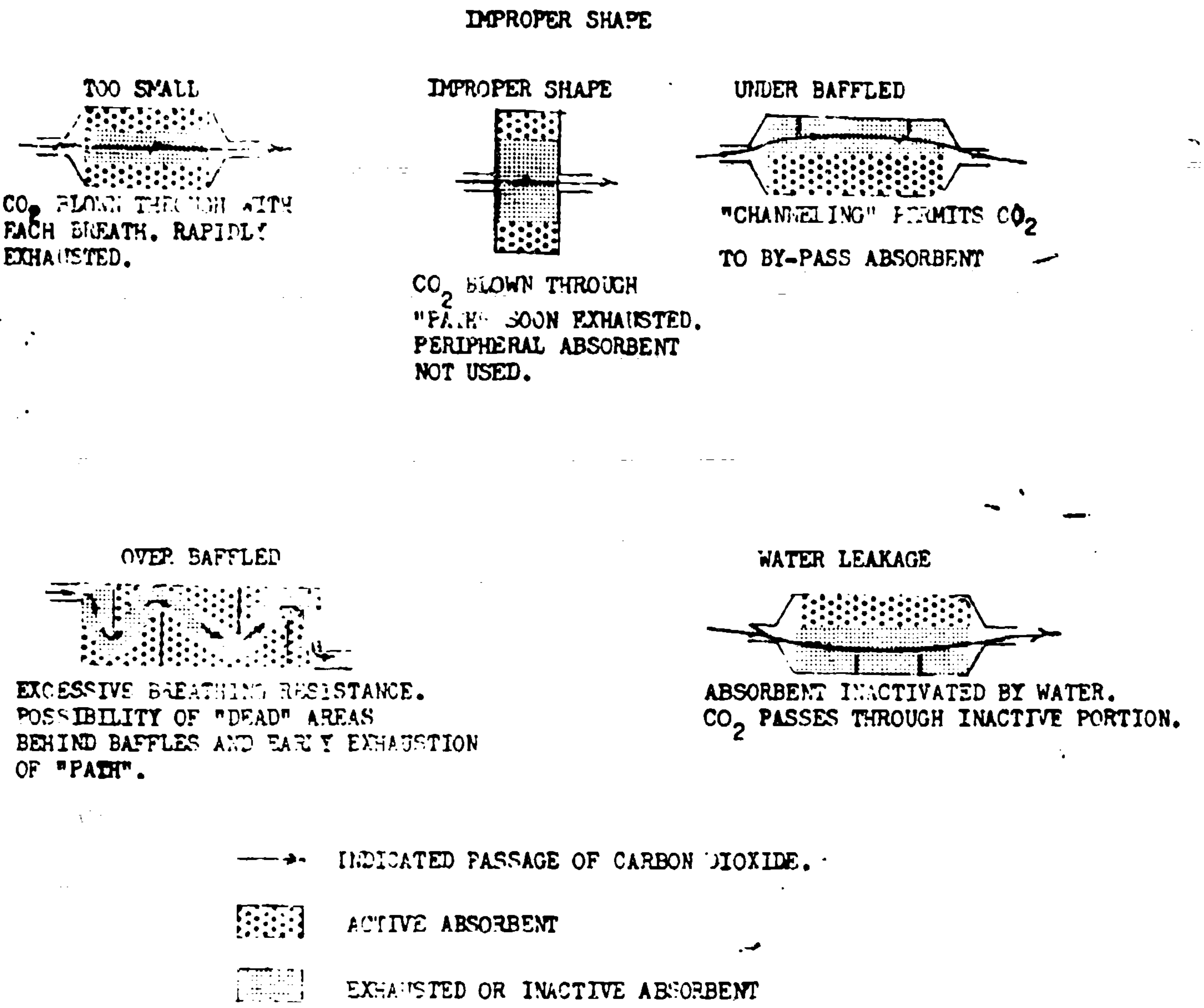


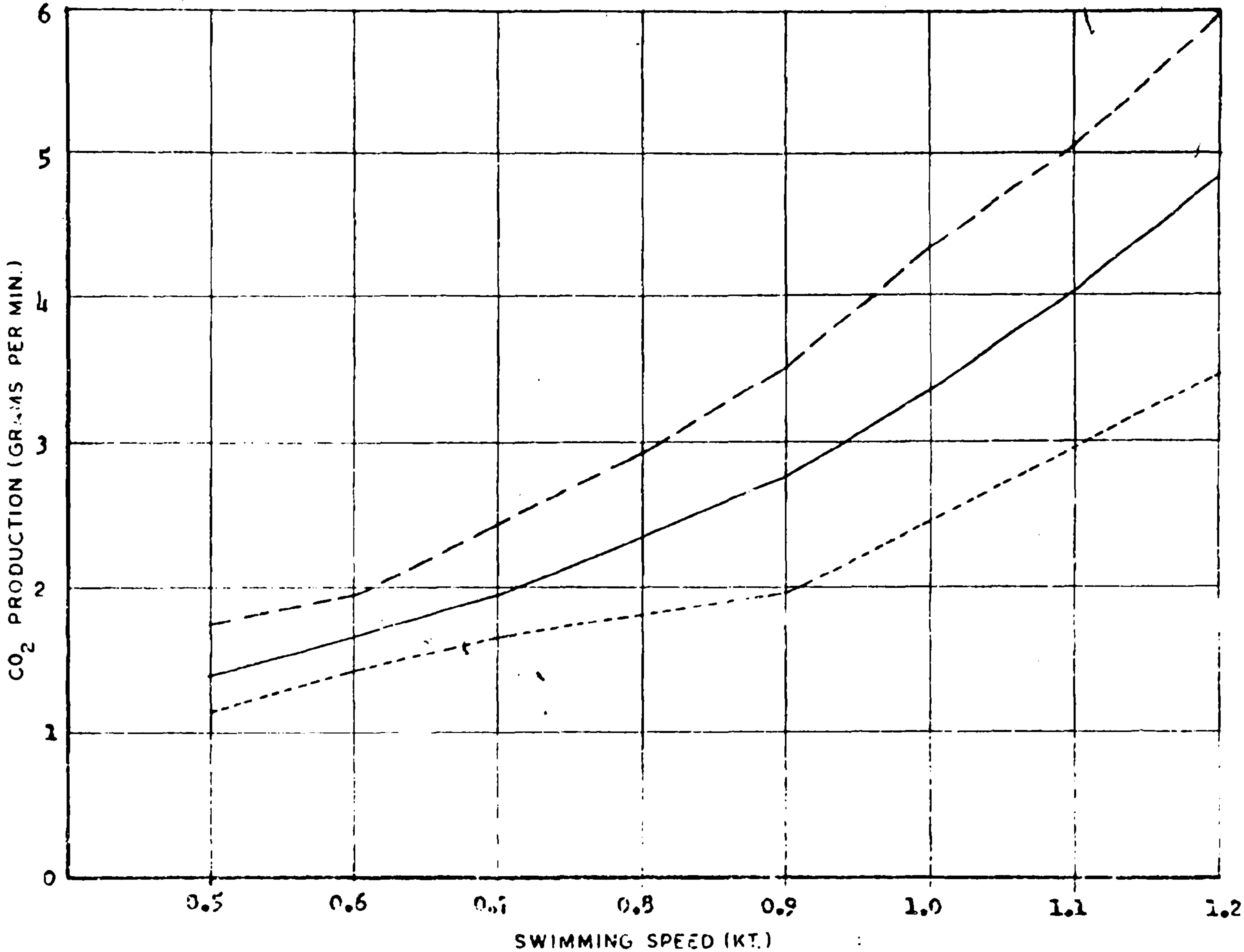
THREE ALTERNATIVE METHODS OF PLACING THE CARBON DIOXIDE ABSORBENT CANISTER IN THE S C U B A BREATHING CIRCUIT.

FIGURE # 1



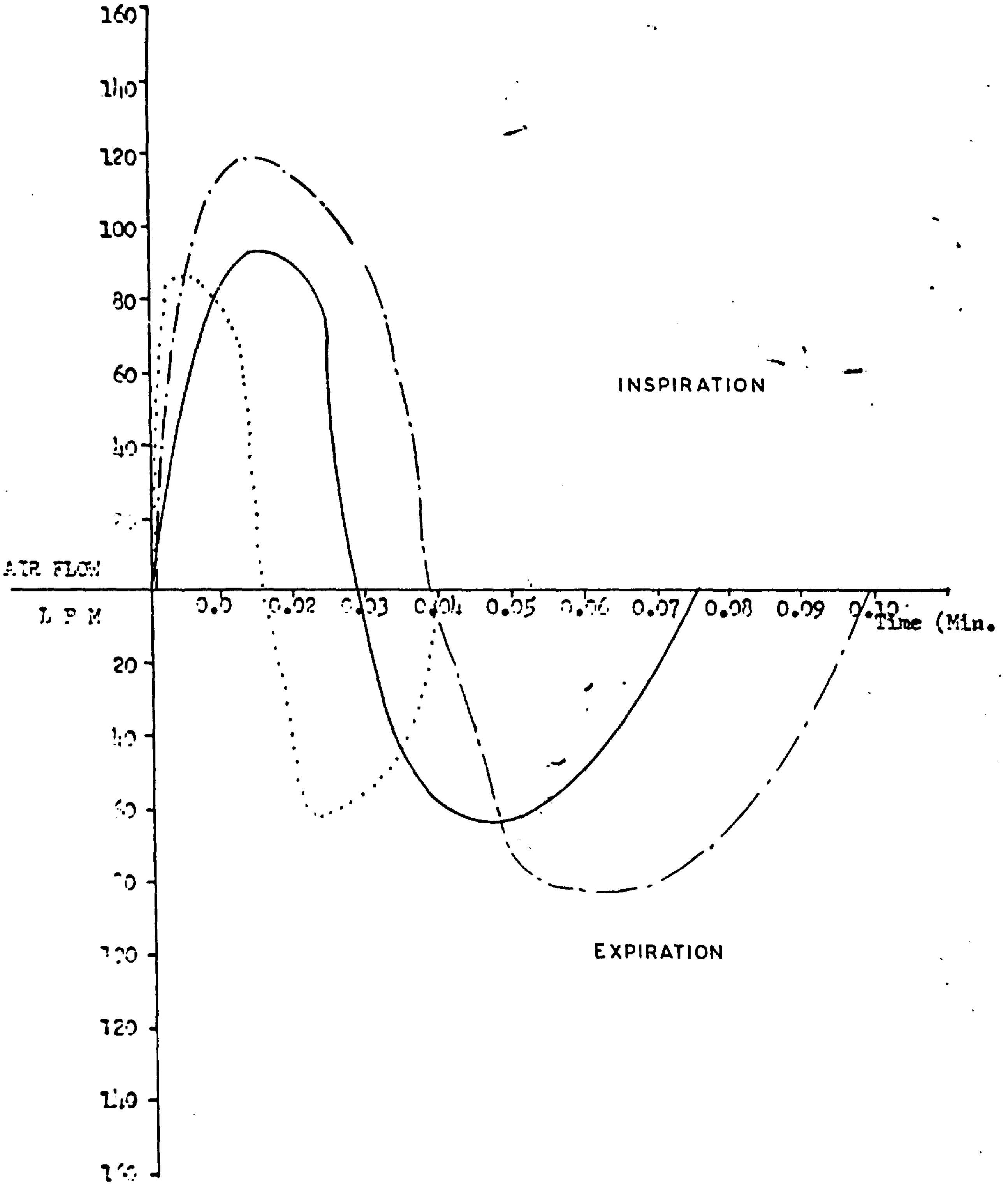
COMMON DEFECTS AND PRIMARY CAUSES OF FAILURE IN CO_2 ABSORPTION CANISTERS.
(From "Submarine Medicine Practice)

FIGURE # 2



CARBON DIOXIDE PRODUCTION RATES AT VARIOUS SWIMMING SPEEDS.

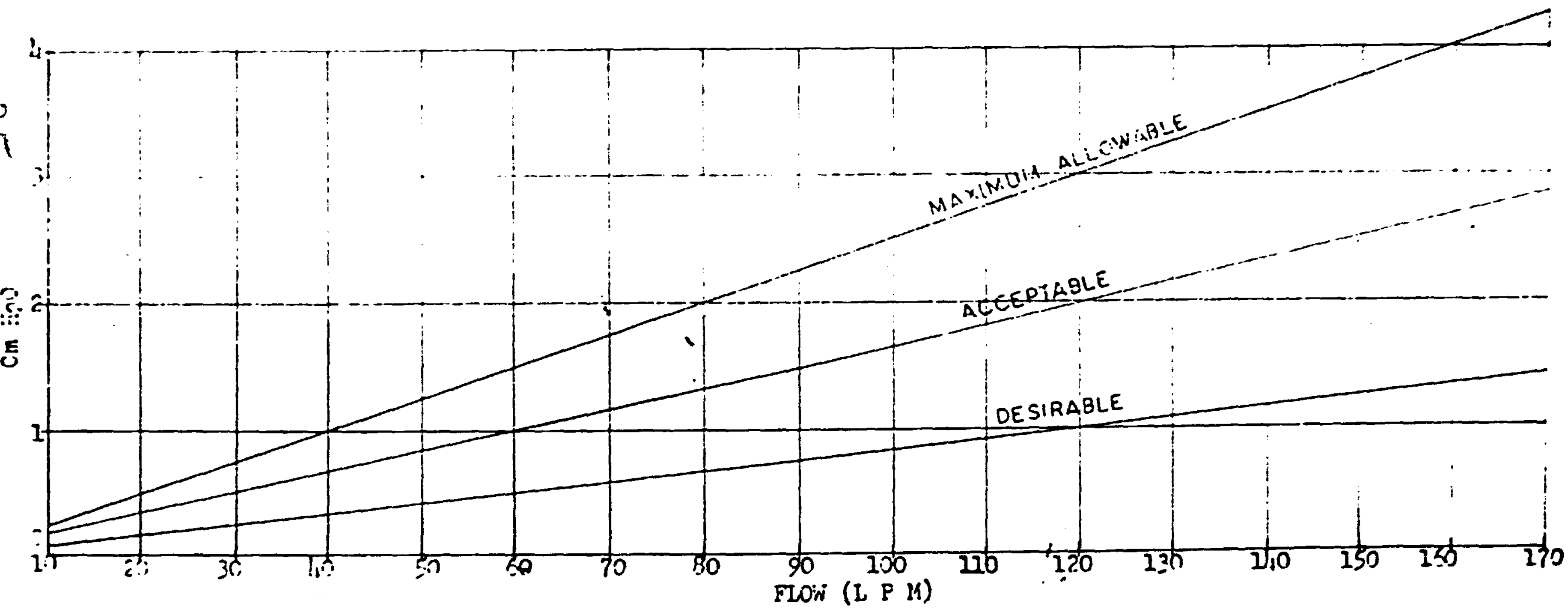
FIGURE # 3



AIR FLOW CURVES WHICH CAN BE ANTICIPATED DURING USUAL UNDERWATER SWIMMING ACTI

FIGURE #4

25



BREATHING RESISTANCE WHICH CAN BE ACCEPTED IN CARBON DIOXIDE ABSORPTION CANISTERS IN S C U B A.

FIGURE # 5