U. S. NAVY EXPERIMENTAL DIVING UNIT
WASHINGTON NAVY YARD
WASHINGTON, D. C. 20390

RESEARCH REPORT 3-64

CARBON DIOXIDE ABSORPTION SYSTEMS FOR SCUBA. 1. QUANTITATIVE CONSIDERATIONS OF DESIGN AND PERFORMANCE OF CYLINDRICAL CANISTERS

PROJECT S-F011-06-03, TASK 3380, TEST 8

by

LCDR M.W. GOODMAN (MC) USN

15 January 1965

AD 615 771

SUBMITTED:	APPROVED:	APPROVED:
M. W. GOODMAN	R. D. WORKMAN	C. H. HEDGEPETH
LCDR (MC) USN	CAPT (MC) USN	CDR USN
ASS'T SUB MED RESEARCH	SUB MED RESEARCH	OFFICER IN CHARGE

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Officer in Charge
U. S. Navy Experimental Diving Unit, Washington Navy Yard, Washington, D. C. 20390

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
Carbon Dioxide Absorption Systems for Scuba
1. Quantitative Considerations of Design and Performance of Cylindrical Canisters

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Interim

5. AUTHOR(S) *(Last name, first name, initial)*
LCDR M. W. GOODMAN, MC, USN

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 January 1965	38	77

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.
S-F011-06-03

c. TASK 3380
TEST 8

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
Research Report 3-64

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES
U. S. Government Agencies may obtain copies of this report directly from Defense Documentation Center. Other qualified DCC users shall request through Office of Technical Services, Department of Commerce, Washington, D. C.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Cylindrical SCUBA canisters, packed with granular Baralyme, were tested with a mechanical respirator. Breathing resistance was observed to vary linearly and in direct proportion to the length-diameter ratio when airflow was of less than critical or pre-critical magnitude. Duration of useful canister life (end-point at 0.5% CO_2) was determined to be a function of canister size, i.e., volume and quantity of absorbent. Efficiency, however, correlates closely with the packed granular column length of iso-diameter, adequate-size canisters.

Dimensions of low-flow-impedance, minimal-capacity canisters are governed by the absorptive wave-reactive-zone volume and the empirically-stipulated diameter. Methods for determining size, capacity and dimensional ratios of low resistance, efficient, duration-specific canisters are considered, together with the gas flow and composition parameters, the specific environmental hazards facing closed-circuit oxygen swimmers, and related factors of significance in these respects.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Carbon dioxide absorption systems						
SCUBA, semi-closed and closed circuit						
Breathing resistance						
Carbon dioxide absorbent characteristics						
Gas-fluid dynamics						
Mechanical respirator simulation						
Life support systems						
Biolography						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

ABSTRACT

Cylindrical SCUBA canisters, packed with granular Baralyme, were tested with a mechanical respirator. Breathing resistance was observed to vary linearly and in direct proportion to the length-diameter ratio when airflow was of less than critical or pre-critical magnitude. Duration of useful canister life (end-point at 0.5% CO_2) was determined to be a function of canister size, i.e., volume and quantity of absorbent. Efficiency, however, correlates closely with the packed granular column length of iso-diameter, adequate-size canisters.

Dimensions of low-flow-impedance, minimal-capacity canisters are governed by the absorptive wave-reactive-zone volume and the empirically-stipulated diameter. Methods for determining size, capacity and dimensional ratios of low resistance, efficient, duration-specific canisters are considered, together with the gas flow and composition parameters, the specific environmental hazards facing closed-circuit oxygen swimmers, and related factors of significance in these respects.

SUMMARY

PROBLEM

1. Determination of the factors which govern the function of SCUBA CO_2 absorbent canisters, and the quantitative manner of their interdependence.

2. Derivation of specifications for both small canisters and those with unconventionally-great capacity; fabrication and testing of prototypes suitable for concurrent, "bread-board" stage, rigs.

3. Coincidental evaluation of proprietary components, submitted for that purpose.

FINDINGS

1. Breathing resistance, duration of useful canister life, and efficiency of absorbent utilization depend upon, respectively, the length to diameter ratio, reactive zone volume, and packed-column length.

2. Empirical methods for prediction of cylindrical canister dimensions have been derived.

3. The performance of granular Baralyme-packed canisters of USN closed and semi-closed apparatus is, overall, satisfactory. For deployments with extended depth and duration challenges, gasflow resistance will attain unfavorable levels, particularly when oxygen or nitrogen-oxygen mixtures are respired.

RECOMMENDATIONS

1. That specifications for SCUBA components be formulated with reference to duration requirements and breathing resistances for the most severe pressure-duration-gas mixture density spectrum of anticipated exposure.

2. In addition to the planned studies of alternative geometrical configurations for canisters, alternative methods for CO_2 elimination should be investigated.

ADMINISTRATIVE INFORMATION

Authorization: By Head, Code 636 BUSHIPS

Designation: Project S-F011-06-03, Task 3380, Test 8, "Carbon Dioxide Absorption Systems for SCUBA"

Chronology: Project outline submitted 3 August 1964; Project report no. 1 submitted 15 January 1965

Personnel: Investigator: LCDR M. W. GOODMAN (MC) USN

Project Engineers: C. W. DUFF, HMCA(DV) USN

T. W. JAMES, HM1(DV) USN

P. LAFERRIERE, HM1(DV) USN

(Experimental and prototype canisters were fabricated by HM1 JAMES)

MANPOWER EXPENDITURES

DESCRIPTION	MANHOURS
(1) Mechanical respirator evaluation series	80
(2) Swimming evaluation series: Subjects, 20 Project Engineers, 40	60
(3) Fabrication of prototype canisters	40
(4) Calculations and data analysis	200
(5) Preparation of report	100
(6) Drafting and typing services	35
TOTAL	515

(Project report number 2 will discuss and evaluate experiences (respiratory tests and underwater swimming runs) with a tetrahedral, low-resistance canister)

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF FIGURES AND TABLES

FIGURES

TABLES

1. INTRODUCTION

1.1 Background. Research and developmental efforts related to the problems of carbon dioxide removal from the gaseous atmospheres of mobile closed-circuit life-support systems have, in recent years, been referenced almost exclusively to true submersibles and aerospace-vehicle crew modules (20) (21) (22) (23) (42) (49) (53) (64). There have been no fruitful applications of these sophisticated procedures and complex hardware to the closed-circuit respiratory environments of self-contained, surface-based divers and underwater swimmers. Apparatus-platform spatial dimensions and weight-in-air (mass) have not been compatible with specifications for simple, hydrodynamically-streamlined compact packages for the non swimmer-propulsion-unit- mounted SCUBA swimmer (28) (36) (37) (45) (66). A second generic source of information, particularly with regard to physical dynamics and chemical kinetics of carbon dioxide absorption, and prototype-canister design, is the relevant body of anesthesia literature. Inadequate carbon dioxide elimination capabilities, specifically suitable for the stresses of the environment, could retard the exploitation of opportunities provided by hyperbaric physiological competence and the bio-engineering development of other items of apparatus.

1.2 Objectives. These can be summarized by brief reference to project outline number one:

(1) basic studies of absorption systems
(2) departures from conventional SCUBA canister designs
(3) examination of heretofore untested chemical absorbents
(4) accumulation of performance data of canisters submitted for concurrent evaluation

1.3 Report Scope. Proprietary devices and locally-fabricated cylindrical canisters have been evaluated in order to relate morphological and functional data and to derive empirical descriptions of optimal systems. Granular Baralyme absorbent was employed. Subsidiary interpretations of evaluation data, and alternative end-point functional indices are discussed.

1.4 Appended Information. A synopsis of representative chemical, pneumatic, physiological and geometric information pertinent to canister design has been appended in response to requests and in order to provide a handy reference source. Definitions of technical expressions have been condensed in a glossary. A glossary of abbreviations and symbols includes and identifies all terms employed in the mathematical treatments.

1.5 Reference Sources. An extensive reference list (68 entries) has been included not only for specific, intrinsic value and utility, but to bring emphasis to the call for correlated, inter-disciplinary work on problems such as the present ones. Grouping into categories by topics and literature source areas gives the following (numbers are those of the reference list):

(1) ABSORBENTS: CAPACITY, CHEMISTRY, COMPOSITION, ETC: 1, 4, 9, 11, 14, 52

(2) ABSORBENTS: GRANULARITY, POROSITY, FLUID FLOW: 10, 12, 13, 26, 31, 58

(3) ABSORPTION, GENERAL: 2, 8, 24, 54

(4) CANISTERS: 3, 15, 30, 47, 48

(5) CHEMICAL ABSORBERS OTHER THAN ALKALINE-ALKALINE EARTH METAL HYDROXIDES: 6, 27, 49, 62, 63

(6) DIVING, ALL SPECIFIC REFERENCES: 28, 36, 37, 40, 41, 45, 46, 65, 66

(7) ENGINEERING HANDBOOKS AND FLUID MECHANICS REFERENCES: 5, 16, 29, 35, 38, 55, 60, 61, 68

(8) HANDBOOKS, SYMPOSIA, BIBLIOGRAPHIES: 20, 21, 34, 43, 50, 57, 67

(9) METHODS AND TECHNIQUES OF INVESTIGATION: 7, 32, 33, 39, 44, 56

(10) PHYSIOLOGICAL REFERENCES: 17, 18, 19, 25, 51

(11) SUBMARINE ATMOSPHERE-AEROSPACE VEHICLE ATMOSPHERE REFERENCES: 22, 23, 42, 53, 59, 64

2. METHODS

2.1 General. All methods and procedural practices have been heretofore described in reports from this laboratory (36) (41). Table two lists the observations obtained for the parameters of water-bath and canister inlet gas temperature, volume input of carbon dioxide per minute ("CO_2 output") and total volumetric delivery of gas per minute ("minute volume"). The mixed expired gas (air-CO_2) was humidified at body temperature, 37°C. The piston respirator was always operated at 10 cycles per minute, and the sine-wave flow pattern was verified with a Fleisch pneumotachograph - differential pressure transducer array.

2.2 Mathematical Handling of Data.

2.2.1 Fluid Dynamics. Computations for Reynolds numbers, mass velocity, critical velocity, etc., have been in accordance with porous media flow theory (5) (16) (34) (56) (68). Appendix C includes resumes of several procedures and formulae (Appendix C, sections 7, 8, and 10).

2.2.2 Statistical Treatment. Only the major structure-function correlations are reported, having been selectively chosen from an 8 X 8 Pearson product moment intercorrelation matrix.

2.3 Canister Fabrication. Construction materials included cylinders of acrylic plastic, of specified wall thickness and internal diameter; four centimeter (O.D.) acrylic tube segments for hose fittings; 63 percent void area perforated metallic screens; and Masco Chemical Company MC-25 acrylic plastic cement adhesive, used with admixed acrylic dust.

3. RESULTS

3.1 Data Identification. Code designations have been applied in the place of standard nomenclature or proprietary identifications. Much of this test data will be incorporated into the appropriate Experimental Diving Unit Evaluation Reports, which are for limited dissemination of proprietary-apparatus test results.

3.2 Reporting and Analysis. All observed variables, computed functions and controlled inputs felt to be pertinent to both chemical and pneumatic functions have been listed in the following tabulations. Illustrations and graphs have not been employed to illuminate these data, because these observations were made to generate a reservoir of information for further empirical study, rather than for direct reporting. Six experiments with modified F-series canisters (internal circumferential and longitudinal baffles, fins, etc.) have not been reported, because each test was productive of similiar, highly unsatisfactory duration parameters. In one, of the total of four, swimming trials with "F" canisters, duration exceeded that reported for the mechanical respirator runs. The swimmer experienced a moderately severe, typical carbon dioxide headache, just prior to swim termination.

3.3 Table 1: Packed Canister Dimensions

CODE	LENGTH (CM)	DIAMETER (CM)	1/D RATIO	AREA (CM2)	VOLUME (LITERS)	GRANULAR (GRAMS)	BARALYME (POUNDS)	BULK DENSITY (GM/100CM3)
A1	39.9	10.5	3.80	86.59	3.455	3486	7.68	100.9
A2	39.9	10.5	3.80	86.59	3.455	3487	7.68	100.9
B1	42.5	9.1	4.67	65.04	2.664	2935	6.45	110.1
B2	42.5	9.1	4.67	65.04	2.664	2985	6.58	112.0
B3	42.5	9.1	4.67	65.04	2.664	2910	6.41	109.2
C1	37.5	9.0	4.17	63.62	2.386	2570	5.69	107.7
D1	43.2	13.2	3.27	136.85	5.815	5590	12.37	94.5
D2	34.5	12.7	2.72	126.68	4.379	4700	10.35	107.6
D3	31.4	12.7	2.47	126.68	3.978	4270	9.41	107.3
E1	35.1	7.8	4.51	47.78	1.677	1640	3.63	97.0

CODE	LENGTH (CM)	DIAMETER (CM)	L/D RATIO	AREA (CM^2)	VOLUME (LITERS)	GRANULAR BARALYME (GRAMS)	(POUNDS)	BULK DENSITY ($GM/100CM^3$)
E2	42.5	9.3	4.38	67.93	2.765	2670	5.88	96.6
F1	18.1	9.2	1.97	66.44	1.203	1080	2.38	89.8
F2	18.1	9.2	1.97	66.44	1.203	1100	2.42	91.4
F3	18.1	9.2	1.97	66.44	1.203	1120	2.47	93.1
F4	18.1	9.2	1.97	66.44	1.203	1080	2.38	89.8
G1	20.6	9.2	2.24	66.44	1.369	1370	3.02	100.0
H1	25.5	9.5	2.68	70.85	1.807	1920	4.23	106.2
H2	25.5	9.5	2.68	70.85	1.807	1960	4.32	108.5
I1	25.4	9.2	2.76	66.44	1.689	1655	3.65	102.1

3.4 Table 2: Ventilation, CO_2 Output

CODE	MINUTE VOLUME (LPM, STPD)	PEAK FLOW (LPM, STPD)	"CO_2 OUTPUT" (LPM, STPD)	TEMPERATURE (°C) AMBIENT	TEMPERATURE (°C) INPUT GAS	TOTAL CO_2 DELIVERED (L, STPD)
A1	26.10	81.95	1.175	24.5	27.9	322
A2	24.90	78.19	1.121	23.0	27.5	273
B1	26.70	83.84	1.202	21.5	25.0	215
B2	26.20	82.27	1.175	21.0	27.4	295
B3	26.05	81.80	1.172	24.5	28.0	265
C1	25.50	80.07	1.148	21.3	26.7	182
D1	26.10	81.95	1.175	21.3	27.9	599
D2	26.05	81.80	1.172	27.0	29.1	381
D3	26.15	82.11	1.177	24.4	27.5	351
E1	26.10	81.95	1.175	25.3	29.0	64
E2	26.60	83.52	1.197	25.0	28.5	238
F1	23.10	72.53	1.040	22.1	27.6	(MEAN
F2	23.80	74.73	1.071	24.4	31.5	OF
F3	25.70	80.70	1.157	21.0	26.8	F-SERIES:
F4	25.60	80.38	1.152	22.0	27.8	22)
G1	26.20	82.27	1.175	25.3	29.0	19
H1	26.55	83.37	1.208	22.5	27.1	101
H2	26.52	83.27	1.193	23.3	26.8	119
I1	25.85	81.50	1.137	21.5	26.4	40

3.5 Table 3: Duration and Efficiency

CODE	TIME IN MINUTES TO FIRST TRACE	0.25%	0.50%	MIN TO 0.5% PER 100 GM	LITERS CO_2 PER 100 GM	TOTAL CO_2 ABSORBED(L)	EFFICIENCY (%)
A1	70	222	274	7.86	8.69	303	35.8
A2	76	198	244	7.00	7.14	259	30.6
B1	72	147	180	6.13	7.17	211	29.6
B2	93	214	251	8.40	9.54	285	39.8
B3	110	208	226	7.77	8.79	256	36.2
C1	56	120	159	6.19	6.70	172	27.5
D1	360	480	510	9.12	10.55	590	43.5
D2	160	279	325	6.92	7.23	340	29.8
D3	155	252	298	6.98	7.95	340	32.7
E1	1	13	54	3.30	3.74	61	15.4
E2	60	164	199	7.45	8.63	231	35.5
F SERIES	6	13	21	1.62	1.83	22	8.2

CODE	TIME IN MINUTES TO FIRST TRACE	0.25%	0.50%	MIN TO 0.5% PER 100 GM	LITERS CO_2 PER 100 GM	TOTAL CO_2 ABSORBED (L)	EFFICIENCY (%)
G1	4	12	16	1.18	1.03	15	6.6
H1	8	64	84	4.38	5.13	99	21.1
H2	10	77	100	5.10	5.91	116	24.3
I1	8	26	35	2.11	2.30	38	9.5

EFFICIENCY = (Liters CO_2 absorbed/liters CO_2 capacity) (100)

3.6 Table 4: Gas Flow and Flow Impedance

CODE	PRESSURE (CMH_2O) INITIAL	AT 0.25%	BREATHING RESISTANCE (CMH_2O/L/SEC) PEAK FLOW	VELOCITY AT PEAK FLOW LINEAR (CM/SEC)	MASS (GM/SEC)
A1	3.9	6.0	4.4	15.77	1.77
A2	5.4	6.5	4.9	15.05	1.69
B1	6.5	8.7	6.2	21.48	1.81
B2	7.6	9.2	6.7	21.08	1.77
B3	6.5	10.3	7.6	20.96	1.76
C1	4.1	5.2	3.9	20.98	1.73
D1	3.4	4.1	3.0	9.98	1.77
D2	3.9	4.4	3.2	10.76	1.76
D3	3.3	4.4	3.2	10.78	1.77
E1	7.6	8.2	6.0	28.59	1.77
E2	7.6	8.2	5.9	21.40	1.80
F SERIES	2.9	3.5	2.8	19.29	1.66
G1	3.3	3.5	2.7	20.63	1.77
H1	5.4	7.0	5.0	19.60	1.80
H2	4.9	5.4	3.9	19.59	1.68
I1	17.7	19.0	14.0	20.42	1.65

Breathing resistances are for peak flow, at time of CO_2 = 0.25%; linear velocity = peak flow (CM^3/SEC) area; mass velocity = volume flow (CM^3/SEC) X density (GM/CM^3)

3.7 Table 5: Miscellaneous Parameters

CODE	ABSORPTION CAPACITY (L, CO_2)	REYNOLDS NUMBER	CRITICAL VELOCITY (CM/SEC)	VOID SPACE VOLUME (L)
A1	847	1182	28.3	1.727
A2	847	1127	28.3	1.727
B1	713	1395	32.6	1.465
B2	725	1369	32.6	1.490
B3	707	1361	32.6	1.455
C1	625	1347	33.0	1.285
D1	1358	940	22.5	2.895
D2	1142	975	23.4	2.450
D3	1038	976	23.4	2.135
E1	399	1591	38.1	0.820
E2	649	1420	31.9	1.335
F SERIES	265	1266	32.3	0.548
G	328	1354	32.3	0.680

CODE	ABSORPTION CAPACITY (L. CO_2)	REYNOLDS NUMBER	CRITICAL VELOCITY (CM/SEC	VOID SPACE VOLUME (L)
H1	467	1376	31.3	0.905
H2	476	1232	31.3	0.905
I1	402	1260	32.2	0.845

Theoretical absorption capacity = 24.3L. CO_2/100GM granular Baralyme; Reynolds number = (4) (mass velocity)/(3.14) (diameter) (viscosity); void space = ± 50 CM^3/100 GM; critical velocity computed for air, 1 atm. abs., 20°C = 297/diameter

3.8 Table 6: Statistical Appraisal Experiments A1, A2, B1, C1, D1, D2, D3, E2

(1)

PARAMETER	MEAN	RANGE	STD. DEVIATION
TIME TO TRACE CO_2 (MIN)	131	56-360	
TIME TO 0.25% CO_2 (MIN)	240	120-480	
TIME TO 0.50% CO_2 (MIN)	279	159-510	
MIN/100 GM	7.42	6.19-9.12	0.81
LITERS/100 GM	8.25	6.68-10.56	
EFFICIENCY, %	34.0	27.5-43.5	
LITERS ABSORBED	311	172-590	
LITERS CAPACITY (THEORETICAL)	902	625-1358	
RATIO, LENGTH/DIAMETER	3.66	2.47-4.67	0.73
WT. GRANULAR BARALYME (GM)	3710	2570-5590	999
WT. GRANULAR BARALYME (LB)	8.18	5.69-12.37	2.2
BULK DENSITY, GM/100CM^3	103.1	94.5-109.2	5.2
INT. DIAMETER (CM)	10.9	9.0-13.2	1.6
CROSS SECTIONAL AREA (CM^2)	95.00	63.62-136.85	32.4

(2) PEARSON PRODUCT MOMENT INTERCORRELATION MATRIX (SELECTED CO-VARIABLES FROM A 7 X 7 TABLE):

VARIABLES	COEFFICIENT OF CORRELATION
Ratio of length/diameter and breathing resistance	+.86
Efficiency (min./100GM) and length	+.63
Absorbent weight and duration	+.99
Diameter and breathing resistance	-.79

3.9 Descriptive Remarks

(1) "Longest and narrow" canisters: A1-2, B1-2-3, C1, E2: These four canisters (C1 and E2 are operational) are similiarly configured and have been used or proposed for use in similiar kinds of closed or semi-closed apparatus.

(2) "Long and very narrow" is the phase which seems specifically applicable to canister E1. Both unfavorable airflow impedence and compromised duration were noted with this granular Baralyme-filled cartridge insert for canister E2.

(3) Canister D1 (proprietary) is the sole "long and wide" specimen. The capacity of this canister is enough for about seven to eight hours actual swimming utility.

(4) "Short and wide" canisters are D2 and D3 (prototypes fabricated in the NAVXDIVINGU laboratory by HM1 JAMES).

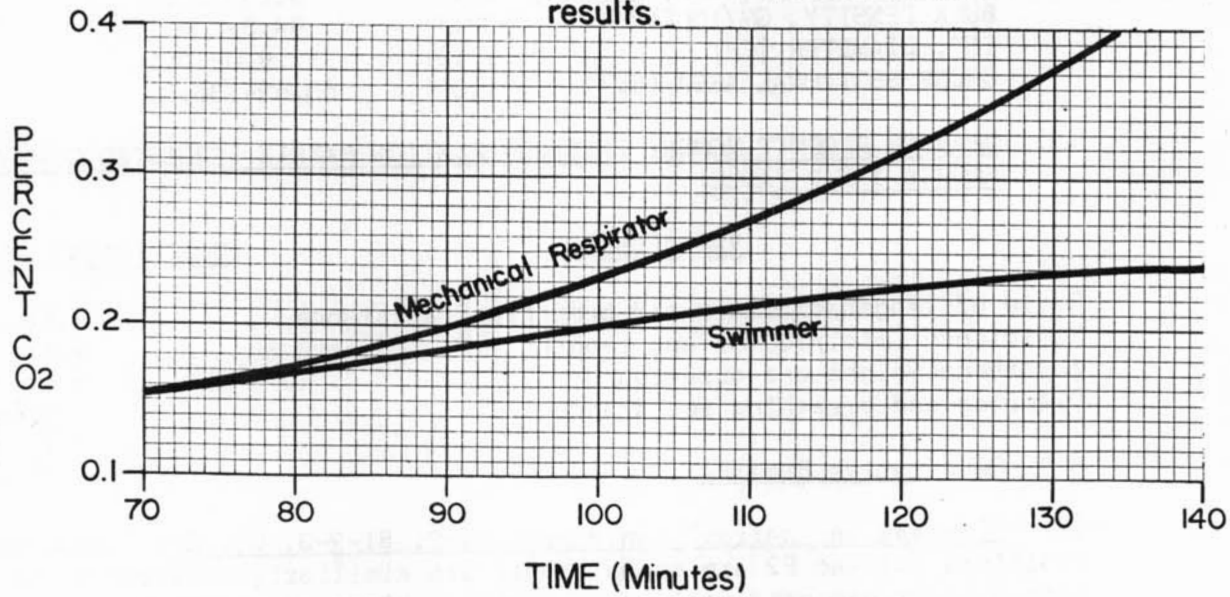
(5) Canisters of F-G Series are obviously too small, too short, and hazardous for use with closed-circuit oxygen systems.

(6) The H-Series canisters, the "theoretical minimal cylindrical canister" of paragraph 4.11, is, in the contex of these descriptors, "short and narrow".

(7) Canister I-1 is a proprietary prototype, notable for the incorporation of hemispherical inlet and exit channels with a total of six ninety-degree bends. Note consequences (Table 4).

FIGURE I.

CO2 Absorption System Evalation: Representative performance curves comparing mechanical respirator & underwater swimmer test results.



4. DISCUSSION

4.1 Men, Machines and Methodology

4.1.1 The curvilinear lines which comprise Figure 1 are idealized representations of the trends in observations of a large panel of tests. The mechanical ventilatory system analog delivers its preselected profile of expired volume, expired volume flowrate, and expired carbon dioxide content to the test absorption system in a redundant, tireless manner. Quite distinct from this situation are canister tests in which attempts have been made to swim, without intermission, until the establishment of a breakthrough pattern. This is almost certain to create a phase of progressively-diminishing time-unit delivery of carbon dioxide to the canister, because energy expenditures of the subject will diminish, i.e., he will probably swim at a speed less than 0.8 knots.

4.1.2 Mechanical respirator data is valuable for comparative (one canister to another) studies and for establishing adequacy of absorption system duration. There cannot be an unlimited, simple extrapolation to actual conditions of an operational profile. Predictive areas of greatest validity include, (a) breathing resistance; (b) efficiency; (c) detection of grossly inadequate systems; (d) duration of useful canister life, the estimate of which becomes progressively more conservative as duration becomes greater and greater.

4.1.3 Because most of the patho-physiological phenomena encountered in diving situations have not yet been satisfactorily explained, the largely empirical nature of hyperbaric bioengineering imposes substantial responsibility upon those environmental specialists who are engaged in the design and evaluation of life-support gear. Being remote from the operational groups who regularly deploy such gear tends to exaggerate any artificialities of the model system. The designer-evaluator must account for the safety of all users of the gear. Therefore, the frame of reference must encompass the least-experienced, least-competent, least-confident and most-anxious of the closed-circuit underwater swimmers. Obviously, this restrictive standard will penalize others. Therefore, some indications of the nature or military character of the mission, the most arduous depth-time patterns to be encountered, and the approximate physiological stature of the intended users could legitimately affect the conduct and interpretation of evaluations. However, no amount of erudition and information can conceal the nature of these decisions, which are not firmly rooted in complete comprehension of fundamental physiologic factors. All canister performance standards are alike to the extent that they are arbitrary. Differing standards of judgement, then, reflect only the differing degrees of risk which are assumed.

4.2 Table 7: Regulated Conditions of the Evaluation Procedure

		MEAN	RANGE
(1)	Carbon dioxide production (LPM, STPD):	1.167	1.121 - 1.197
(2)	Carbon dioxide fraction of expired gas:	4.50%	4.48 - 4.55
(3)	Expired tidal volume (L, STPD):	2.60	2.49 - 2.66
(4)	Peak expiratory flowrate (LPM, STPD):	81.42	78.19 - 83.52
(5)	Frequency (BREATHS/MIN):	10.00	
(6)	Exhaled gas saturated with water vapor at 37°C		
(7)	Temperature of exhaled gas entering breathing bag: 25 - 29°C		
(8)	Ambient water temperature: 21 - 27°C		
(9)	Greatest linear dimension of absorbent granules (CM): 0.35; (N=25) SD, 0.74 (4 - 8 mesh granules)		

4.3 SUMMARY: Data Analysis and Evaluation Assumptions

(1) Respiratory gas flow, as a function of time, is described by a sinusoidal curve.
(2) Peak expiratory flow $\cong$ (π) (RMV)
(3) Mean expiratory flow $\cong$ (0.637) (π) (RMV)
(4) Absorption wavefront volume $\cong$ (0.01) (π) (RMV)
(5) Gasflow through a charged canister behaves according to the laws governing non-uniform, steady, viscous flow of a non-compressible fluid through a granule-packed cylindrical pipe.
(6) The absolute volumetric quantity of carbon dioxide absorbed per exhaled breath is a small proportion of the total volume of the exhaled breath and, essentially, the gas volume exiting the canister per unit time is equal to that introduced.
(7) The intergranular space volume of cylindrical canisters charged with granular Baralyme $\cong$ 0.050L/100 GM.
(8) Granular Baralyme, in theory, is chemically capable of combining with carbon dioxide to a maximal capacity of 24.3 LITERS(STPD)/100 GM.
(9) The pressure drop, frictional effects, and flowrate through packed cylindrical canisters are quantitatively described by the Darcy relationship, which can be stated as follows: frictional pressure drop is directly proportional to the product of linear velocity of gasflow, mean granular diameter, gas viscosity and a resistance or permeability factor, and is inversely proportional to the product of the gas density and the second power of the diameter of the granules (Appendix C, para 10.6).
(10) For air-breathing, at sea level, if peak (instantaneous) expiratory volume flowrate reaches 90 LPM, and linear velocity approaching the canister approximates 15 CM/SEC, then at 20°C the Reynolds number will be about 1895. The critical velocity, which in this situation must approximate 27 CM/SEC, could not be reached until $\dot{V}_M$ = 162 LPM. Therefore, the overall flow of gas traversing the canister should not be (sustained) turbulent.

4.4 Qualitative Summary of Desirable Functional and Morphological Features of Cylindrical Canisters

(1) Split-bag location of canister.
(2) Circular pathway for gasflow.
(3) Overall construction and final configuration should facilitate routine care and maintenance requirements, which ought to be simple and infrequent.
(4) Emptying, cleaning, packing and sealing should be simple, requiring minimal time and few adjuvant tools.
(5) Entry of extraneous fluids, e.g., saliva or condensate from the exhalation bag, should be prevented, preferably by spatial arrangement of components.
(6) The freshly-charged canister, considered as an individual package, probably should have minimal weight and volume magnitudes, which are best determined specifically for the type of exposures to be encountered.
(7) The effective life of the absorption system should exceed the presumptive operational requirements, for any ambient temperature.
(8) Breathing resistance, at peak flowrate, should not be of sufficient magnitude to generate untoward physiological consequences or subjective discomfort. The percentage of the void area of retaining screens and springs, at the inlet and exhaust, however, have not been shown to be critical in this respect.
(9) All exhaled carbon dioxide should be absorbed, breath by breath, until the breakthrough pattern supervenes.

4.5 Resistance, Duration and Efficiency

4.5.1 Breathing resistance will be considered as a primary quantitative factor in canister design, and as the decisive quantitative characteristic for comparative judgement of functional canisters intended for closed-circuit oxygen SCUBA circuits. For all rigs for which the calculated Reynolds numbers are not in excess of the laminar airflow limit, the Poiseuille-Hagan expression indicates proportionality of resistance to length:diameter ratio.

4.5.2 Duration to the selected endpoint varies directly with each of several indices of overall system magnitude, e.g., absorbent charge weight, absorbent space volume, absorption capacity.

4.5.3 For a condition of constant linear airflow velocity, the parameters of efficiency and canister length vary together in direct fashion.

4.5.4 Tabular handling of the experimental data, in sequences of high-low magnitudes, gives the following:

RANK	RESISTANCE	DURATION	EFFICIENCY	L/D RATIO	VOL-WEIGHT	LENGTH
1	B3	D1	D1	B SERIES	D1	D1
2	B2	D2	B2	B SERIES	D2	B SERIES
3	B1	D3	B3	B SERIES	D3	B SERIES
4	E1	A1	A1	E1	A SERIES	B SERIES

RANK	RESISTANCE	DURATION	EFFICIENCY	L/D RATIO	VOL-WEIGHT	LENGTH
5	E2	B2	E2	E2	A SERIES	E2
6	A2	A2	B3	C1	B2	A SERIES
7	A1	B3	A2	A SERIES	B1	A SERIES
8	C1	E2	D2	A SERIES	B3	C1
9	D3	B1	B1	D1	E2	E1
10	D2	C1	C1	D2	C1	D2
11	D1	E1	E1	D3	E1	D3

4.5.5 By discarding, from the derivation sequences to follow, data sets for which resistance attained or exceeded 5 CM H_2O/L/SEC:

RANK	RESISTANCE	DURATION	EFFICIENCY	L/D RATIO	SIZE	LENGTH
1	A2	D1	D1	C1	D1	D1
2	A1	D2	A1	A SERIES	D2	A SERIES
3	C1	D3	D3	A SERIES	D3	A SERIES
4	D3	A1	A2	D1	A SERIES	C1
5	D2	A2	D2	D2	A SERIES	D2
6	D1	C1	C1	D3	C1	D3

4.6 Specified Duration - Weight: First Approximations

4.6.1 Swimming-time specifications are presumed to originate within the operational proposals for which a wholly-compatible apparatus is to be designed.

4.6.2 For a given performance efficiency plateau, with mean (N=8) CO_2 output, the gravimetric requirements for granular Baralyme are estimated in the following tables:

TABLE 8

0.8 K. SWIM TIME (MIN)	CO_2 OUTPUT (L, STPD)	GRANULAR BARALYME WEIGHT 7.4 MIN/100GM (GRAMS) - (POUNDS)	GRANULAR BARALYME WEIGHT 8.25L.CO_2/100GM (GRAMS) - (POUNDS)
30	35.10	405.4 - 0.89	425.5 - 0.94
60	70.20	810.8 - 1.78	850.9 - 1.88
90	105.30	1216.2 - 2.67	1276.4 - 2.82
100	117.00	1351.3 - 2.98	1418.2 - 3.12
120	140.40	1621.6 - 3.56	1701.8 - 3.76
150	175.50	2027.0 - 4.45	2127.3 - 4.70
180	210.60	2432.4 - 5.34	2552.8 - 5.64
210	245.70	2837.8 - 6.23	2978.3 - 6.58
240	280.80	3243.2 - 7.12	3403.6 - 7.52
360	421.20	4864.8 - 10.68	5105.6 - 11.28
480	561.60	6486.4 - 14.24	6807.2 - 15.04

4.6.3 Absorption system efficiency (expressed as the number of minutes of swimming time per 100 gram unit of absorbent) cannot, of course, be a physical constant. Changing absorbent quantity requirements for the (from above) 30 and 360 minute hypothetical swims are shown below to be inversely proportional to the varying efficiency.

TABLE 9

TIME EFFICIENCY (MIN/100GM)	GRANULAR BARALYME WEIGHT 30 MIN (GRAMS)	(POUNDS)	100 MIN (GRAMS)	(POUNDS)	360 MIN (GRAMS)	(POUNDS)
2.0	1500	3.31	5000	11.01	18000	39.64
4.0	750	1.65	2500	5.50	9000	19.82
6.0	500	1.10	1667	3.67	6000	13.22
8.0	375	0.83	1250	2.75	4500	9.91
10.0	300	0.66	1000	2.20	3600	7.92

4.6.4 Absorption system "mechanical efficiency" equivalent (liters of carbon dioxide absorbed/capacity to absorb carbon dioxide), has been (above) expressed as the "number of minutes of swimming time per 100 grams of granular Baralyme", without disturbing relative ranks within a series of comparable tests. Moreover, since it is not a dimensionless quantity, it serves as a handy index of the single functional parameter of greatest interest: duration. Within the calculation protocol to follow, this latter teminology will be employed. Equivalence of these efficiency expressions can be shown as: $Y=0.19\ X + 0.32$, which is the regression equation of time efficiency upon observed mechanical efficiency.

TABLE 10

MECHANICAL EFFICIENCY % (L. ABS./ L. CAPACITY)	TIME EFFICIENCY (MINUTE/100 GM)	LITERS CO_2 ABSORBED PER 100 GM(V_{CO_2}=1.17)	GRANULAR BARALYME WT(GM) 30 MIN.	360 MIN.
10	2.22	2.60	1350	16,200
20	4.12	4.82	728	8,738
25	5.07	5.93	592	7,103
26	5.26	6.15	571	6,849
27	5.46	6.38	550	6,602
28	5.64	6.60	532	6,382
29	5.83	6.82	515	6,176
30	6.02	7.04	499	5,983
31	6.21	7.26	484	5,802
32	6.40	7.48	469	5,631
40	7.92	9.25	379	4,554
50	9.82	11.48	306	3,669

4.7 Intracanister Volume Requirements: First Approximation

4.7.1 Any estimate of absorbent quantity simultaneously supplies the corresponding first approximation of absorbent compartment volume magnitude, with the reciprocal of bulk density employed as the constant of proportionality:

$$\text{VOLUME} = (\text{WEIGHT})\ (\text{VOLUME/WEIGHT})$$
$$\text{CM}^3 = (\text{GRAMS})\ (100\ \text{CM}^3/\text{GRAMS})$$

4.7.2 The following tabulation was computed, with a factor of 103.1 GM/100 CM^3 for bulk density, from the initial weights listed in paragraph 4.6.2, above:

TABLE 11

0.8 K. SWIMMING TIME (MIN)	GRANULAR BARALYME WEIGHT (GRAMS)	INTRACANISTER VOLUME (LITERS)
30	425.5	0.413
60	850.9	0.825
90	1276.4	1.238
100	1418.2	1.376
120	1701.8	1.651
150	2127.3	2.063
180	2552.8	2.476
210	2978.3	2.889
240	3403.6	3.301
360	5105.6	4.952
480	6807.2	6.603

4.8 Concepts of Reactive Space and its Estimation

4.8.1 A minimal absorbent compartment volume (above) can be defined for any functional duration because a gravimetric unit of absorbent occupies a volume which is finite and which has been identified. However, the absolute minimal absorbent compartment volume is defined in a different manner, and it cannot be diminished with respect to successively-smaller desired durations. Therefore, specifications for absorption system duration affect canister dimensions only when this minimal intracanister volume has been surpassed.

4.8.2 From assumptions related in paragraph 4.3, and by equating minimal intracanister volume with intergranular space volume plus volume occupied by the granules, an initial trial tabulation is obtained as follows:

TABLE 12

TIDAL VOLUME (L, STPD)	OPTIMAL INTERGRANULAR SPACE VOLUME (LITERS)	MINIMAL ABSORBENT COMPARTMENT VOLUME (LITERS)	WEIGHT OF GRANULAR BARALYME (GRAMS)(POUNDS)
1.00	1.00	2.00	1031;2.27
1.50	1.50	3.00	1547;3.41
2.00	2.00	4.00	2062;4.54
2.50	2.50	5.00	2578;5.66
3.00	3.00	6.00	3083;6.81

4.8.3 Assumptions of paragraph 4.3 apply also to pore volume estimations. Experimental procedures for the laboratory determination of pore volume per weight unit of absorbent are available (10) (36). It is prudent to disregard this parameter when computing canister dimensions, because the pore volume is unstable and progressively diminishes as canister use time increases. The following table employs values already utilized in paragraph 4.7.2:

TABLE 13

WT. GRANULAR BARALYME (GM)	PORE SPACE VOL.(LITERS)	VOID + PORE VOL.(LITERS)
1031	2.062	3.062
1547	3.094	4.594
2062	4.124	6.124
2578	5.156	7.656
3093	6.186	9.186

4.8.4 As expired gas passes through the packed canister it may present a peak CO_2 concentration front as a function of the instantaneous flowrate. This has been called the "absorption wave" (12)(14). Large tidal volumes and high peak flows can deposit this wave beyond the absorbent bed if the absorbent compartment volume is insufficient. However, targeting the wave front within the absorbent mass does not, of itself, provide acceptable function, because duration of reactant contact time governs the breath-by-breath extent of the reaction. As absorption progressively exhausts the stationary-phase reactant and the surface area for reaction (with respect to the finite absorption wave volume) shrinks because pore space volume is occupied by water of reaction, the locus or site of active function will migrate along the column. When the exhaust plenum is reached, the canister effective capacity has been attained. The theoretical chemical capacity-maximal effective capacity difference expresses the proportion of unused absorbent. The zone of changing indicator color follows directly upon the locus of the wavefront. Therefore, those canisters which fail most rapidly would be unlikely to exhibit any visible indicator shift whatsoever, and in fact, none was observed (canister F-G series).

4.8.5 Estimation of minimal reactive volume from ventilatory data:

TABLE 14

RMV (LPM, STPD), &	V_T(L, STPD) @ f=10	PEAK EXPIRATORY FLOW (LPM)=(π)(RMV)	ABSORPTION WAVE VOLUME (L)=(0.01)(π)(RMV)
10	1.0	31.42	0.314
15	1.5	47.13	0.471
20	2.0	62.84	0.628
25	2.5	78.55	0.786
26	2.6	81.69	0.817
27	2.7	84.83	0.848
28	2.8	87.97	0.880
29	2.9	91.11	0.911
30	3.0	94.25	0.943
35	3.5	109.90	1.099

4.9 Dimensions, Density, and Airflow Impedance

4.9.1 Breathing resistance and length/diameter ratio show significant positive correlation (Pearson product moment coefficient = 0.86). This surpasses other correlations relating air flow impedance to packed-canister physical dimensions. Semi-logarithmic plots of observed pressures (log CM H_2O), as dependent functions of the lenght-diameter ratio prove to be linear. Minimal resistive pressures occurred in association with length-diameter ratios over the range 1.5 - 2.0 However, these canisters uniformly exhibited unsatisfactory time efficiency and insufficient duration.

4.9.2 The pressure drop (ΔP), or driving force for gasflow, which occurs as the result of frictional factors, varies in direct proportion with the length and by an inverse relationship with the diameter of the channel. Direct variation occurs with velocity and viscosity, as well as with a dimensionless factor which expresses the circumferential bulkhead influences.

4.9.3 No reliable estimates to quantitate the effect of ambient pressure upon tran-canister airflow impedence and absorption system functional indices can be ventured until suitable data is generated and analyzed. In the interim, therefore, it is necessary to employ Graham's Law expressions, as follows:

(a) DIFFUSION, i.e., FLOW = K/SQUARE ROOT OF DENSITY
(b) RESISTANCE, i.e., RECIPROCAL OF FLOW = (K)(SQ. ROOT OF DENSITY)

This may provide a relative index of change of resistance to airflow, for a specific gas mixture, as a function solely of the change of ambient pressure.

4.9.4 Exhalation airflow resistance is not likely to be subjectively discomforting until the order of magnitude exceeds about 7.0 - 7.5 CM H_2O per liter per second. (It is fortunate that, as a group, NEC-5342 exhibits sufficient ingenuity to avoid the regular use of gear which is not subjectively acceptable). Compensatory responses to increased resistance are usually manifested by gradual shifting of the equilibria levels of alveolar ventilation- arterial carbon dioxide tension-carbon dioxide tolerance, and rate-depth-mechanical work of breathing. Discussion of these mechanisms falls outside the scope of this paper. Therefore it is merely noted, however briefly, that since the potential climactic catastrophe with high-pressure oxygen breathing is an underwater convulsive episode, there is a need for apparatus design, in all respects, to be influenced by the physiological consequences of the architecture.

4.9.5 It has been estimated (49) that the proportionality factor relating exhalation resistance and density is 0.75. Air density at one atmosphere absolute, 20°C. = 1.204 grams/liter. Therefore, in the following table, resistance is the product of resistance at one atm., the square root of 2.408, and the constant 0.75. Assuming that ventilation volume does not change, an estimate of ΔP can be obtained from the expression $(\Delta P_1)(R_2)/(R_1)$, and the following extrapolations of test results (paragraph 3.6 - 3.7) to two atmospheres (33 feet) pressure are computed. It is observed that in all but three cases, D1, D2, D3, the projected Reynolds number suggests that transitional or turbulent flow should occur.

Table 15: Extrapolating Airflow and Impedance Parameters to 33 ft.

	RESISTANCE (CMH_2O/L/SEC)		EXHALATION ΔP (CMH_2O)		MASS VELOCITY (GM/SEC)	
CODE	OBSERVED(1 ATM)	33 ft.	OBSERVED(1 ATM)	33 ft.	OBSERVED(1 ATM)	33 ft.
A1	4.4 (+0.7)	5.1	6.0	6.9	1.77	3.31
A2	4.9 (+0.8)	5.7	6.5	7.6	1.69	3.20
B3	7.6 (+1.2)	8.8	10.3	11.9	1.76	3.31
C1	3.9 (+0.6)	4.5	5.2	6.0	1.73	3.22
D1	3.0 (+0.5)	3.5	4.1	4.8	1.77	3.31
D2	3.2 (+0.5)	3.7	4.4	5.1	1.76	3.30
D3	3.2 (+0.5)	3.7	4.4	5.1	1.77	3.31
E2	5.9 (+0.9)	6.8	8.2	9.5	1.80	3.35

REYNOLDS NUMBERS

CODE	COMPUTED FOR 1 ATM	COMPUTED FOR 33 ft.
A1	1182	2217
A2	1127	2145
B3	1361	2751
C1	1347	2511
D1	940	1763
D2	975	1880
D3	976	1885
E2	1420	2534

4.10 Dimensions and Resistance

4.10.1 Resistance varies directly with canister length and inversely with the cross-sectional diameter, i.e., directly with the length to diameter ratio (correlation coefficient, +0.86).

4.10.2 With canister diameter less than 9.5 centimeters, there would appear to be an expectation of encountering physiologically-unfavorable breathing resistance at depth. The only structural compensation, of course, would be to foreshorten the packed granular column, an act which would probably provoke early failure of the canister function.

4.10.3 Diameter magnitude is, therefore, of signal significance in regard to airflow impedance characteristics. It is well to recall that it is the geometric plane of cross-sectional area which reflects any adjustments of the diameter dimension, and that any seemingly trifling design change will exert its effect according to the product, $AREA = (DIAMETER)^2(0.7854)$.

4.10.4 Empirical projections of simple ratios have, (or so it is commonly held), been employed by apparatus designers (e.g., the weight of absorbent required for a four-hour duration canister = 2 X weight for a two-hour duration canister). Disregarding the nonvalid situations when gravimetric quantity of absorbent does not govern duration, the duration is still affected by canister geometry. In other words, only if efficiency remains constant can such durational estimates prove to be useful.

4.10.5 Whereas resistance relates to the proportional magnitudes of cross-sectional and length dimensions, and duration correlates with gross size (i.e., volume and the contained amount of absorbent), efficiency appears to depend upon length and packed-canister air space-volume factors. Although the absorbent weight-volume index, (bulk density), is not an architectural item, it does merit comment here: objectives of careful canister-packing routines are twofold, (a) avoidance of dusting and of particle disruption by fragmenting, and (b) the prevention of channeling subsequent to shifting of the granular mass. Both objectives are attained when the bulk density approximates 100-103 grams per 100 cubic centimeters, with granular Baralyme of MILSPEC density (52).

4.11 Canister Dimensions: Minimal Magnitudes

4.11.1 Manipulations with the experimental data must adhere to the framework of limitations set by the spectrum of fixed circumstances: lung-power as the system prime mover; specified granular absorbent (52); underwater hazards associated with breathing-mixture composition and density.

4.11.2 The hypothesis which proposes that an entire exhaled tidal volume must be held within the packed canister (3) (4) (10) can be pre-emptorily discarded, as inspection of the data illustrates that this is not a requirement with respect to a minimal-size canister which functions to the satisfaction of the test criteria.

4.11.3 Considering the simplest system, a single, finite, exhaled wave of gas, it is clear that:

(a) The gas first entering into the absorbent mass will lose nearly all its carbon dioxide in the vicinity of the canister inlet.

(b) The chemical reactions, which are designated "absorption" are finite, and are governed, in part, by the concentrations of the reactants.

(c) Therefore, a requirement for a finite linear dimension, length, of the absorbent column must exist.

(d) The rate of reaction also defines a "reactive volume", a three-dimensional unit situated at the indefinitly-demarcated interface between exhausted and fresh absorbent. It gradually moves from the inlet and toward the exhaust, and may be topographically equated with the advancing indicator color-change zone, as noted with transparent lucite-bulkhead canisters (12) (14). This concept is analogous to gas absorption chromatographic and distillation column theories of individual reacting plates.

4.11.4 Shortly after the distal granular column boundary has been reached, inhaled or post-canister gas carbon dioxide concentration begins to rise, and the rate of rise accelerates as well; when inlet concentration is reached, a plateau should occur. The rate of flow through the packed canister is a determinant of the contact time for absorption, and therefore, efficiency of any canister will be impaired, progressively, with increasing velocity. Because efficiency is proportional to length, the flow or velocity parameters are factors which affect the selection criteria for packed-column length.

4.11.5 Minimal reactive volume is selected from the assumptive criteria of paragraph 4.3: RV = $(0.01)(\pi)$(RMV), and, since RMV has been fixed, according to criteria separately derived from observations of 0.8 knot swims (28) (65), RV = (0.01)(3.14)(30) = 0.943L.

4.11.6 Equating this estimate of minimal reactive volume to minimal intergranular space volume, and applying assumption 7 of paragraph 4.3, GRAMS OF GRANULAR BARALYME = 943 $CM^3/(0.5\ CM^3)(GM^{-1})$= 1886 GM. Observed density (paragraph 3.8) was 103.1 grams/100 CM^3 and, therefore, compartment volume is, VAS = (1886/103.1)(100) = 1827 CM^3.

4.11.7 Minimal diameter can be estimated from one of several relationships, e.g., by derivation from Poiseuille's Law (56), RESISTANCE = (FRICTIONAL FORCE) (π) (DIA) (ℓ), or again with reference to breathing resistance and the maintenance of viscous flow, by the following derivation, when Reynolds number = 2000 (Air, one atm. abs., 30°C): CRITICAL FLOW (LPM) = (0.784) $(D)^2(19{,}410/D)(1/1000)$ = 15.2D.

(a) Ideally, any system critical flow rate will not be attained when physiological peak flow rates occur. Using the second assumption of paragraph 4.3 to derive peak flow when minute volume approximates 30 LPM, rearranging the above equation, and employing a constant which arbitrarily increases flow by one-half,

$$\text{DIAMETER} \cong (\text{FLOW})\ (k)/15.2$$
$$\text{DIAMETER} \cong (94)\ (1.5)/15.2$$
$$\text{DIAMETER} \cong 9.5\ \text{CM}$$

Therefore, critical flow rates for sustained turbulence should not occur unless 150 percent of maximal anticipated peak instantaneous volume flow was to be reached.

(b) Having established trial values for volume and diameter, length is fixed, according to the equation for the volume of a cylinder:

$$V = \pi r^2 \ell$$
$$\ell = V/(0.784)(D)^2$$
$$\ell = 1827/(0.784)(9.5)^2 = 25.8\ \text{CM}$$

4.11.8 Summary of estimates of minimal canister size and dimensions:

VOLUME: 1827 CM^3
ABSORBENT: 1886 GM (4.2 LB)
DIAMETER: 9.5 CM
LENGTH: 25.8 CM
RATIO LENGTH/DIAMETER: 2.71

4.11.9 Regression equations are computed, with data sources limited to the canister units tabulated in paragraph 4.5.5 , to describe the nearly linear curves of resistance as a function of length-diameter ratio, duration as a function of size, and efficiency as a function of length (air, one atm. abs., $0^{\circ}C$).

(a) RESISTANCE (CM H_2O/L/SEC) = (1.23)(ℓ/D) + 0.49
(b) DURATION TO 0.5% CO_2 (MINUTES) = (44.5)(WT in LB of granular Baralyme) - 88.5
(c) EFFICIENCY (MINUTES/100 GM) = (0.2)(LENGTH IN CM) + 0.83

4.11.10 Data, identified with "H"-series designators (see Results), obtained while testing the prototype "minimal" canister, compare reasonably well to predictions derived by regression:

	DURATION (MINUTES)		EFFICIENCY (MIN/100 GM)		RESISTANCE (CM H_2O/L/SEC)	
	OBSERVED	PREDICTED	OBSERVED	PREDICTED	OBSERVED	PREDICTED
H1	84	100	4.38	5.93	5.0	3.8
H2	100	104	5.10	5.93	3.9	3.8

4.11.11 Alternative procedures, perhaps exhibiting greater degrees of validity, and certain to reflect professional sophistication could be employed in these derivations, in the hands of an engineer with a suitable background in the relevant fluid dynamics. Among these potentially useful methods, and requiring prior stipulation of either flow rate, velocity or resistance boundaries, are computations according to the Poiseuille-Hagan or Darcy Law expressions, and contact time-flowrate-reactive volume relationships. Following is an example of the latter (5)(48):

(a) K = (Flow, in LPM)(ln $F_{CO_{2_I}}/F_{CO_{2_E}}$)/($P_B$, ATM)(AREA/UNIT VOL.)(VOLUME)

(b) Dimensional analysis and units of the velocity constant, K:

$$CM \cdot ATM^{-1} \cdot MIN^{-1} = (L \cdot MIN^{-1})/(ATM)(CM^2 \cdot CM^{-3})(LITERS)$$

(c) Solving for volume, when $F_{CO_{2_I}} = 0.045$; $F_{CO_{2_E}} = 0.005$;
P_B = 1 ATM. ABS; RMV = 26.0 LPM, STPD; MEAN GRANULAR AREA = 290 $CM^2/100\ CM^3$;
V = (26)(23) (antilog 0.95243)/(1) (290/100)(1)
V = 1.855 LITERS

4.12 Duration - Dimensions - Size Expressions

4.12.1 One or two of the canisters were observed to be about equally unsatisfactory, with regard to the duration parameter, in both swimmer and mechanical ventilator testing. For "small" canisters (para. 3.9), the 0.8 knot swim durations to the endpoint are, referenced to safety and utility factors, tantamount to zero duration for the imposed conditions.

4.12.2 Canisters coded with A, B, C, D1 and E2 designators have been tested by experienced diver subjects, swimming at subsurface depth (3-4 feet), according to the following protocol:

(a) 10-15 minutes swimming with trapeze-ergometer rigged for 0.8 knot load;
(b) 5 minute rest intervals;
(c) rapid changeover to fresh, rested swimmers when indicated by the subject himself or by the Master Diver.

4.12.3 Each operational-rig canister and advanced developmental-rig canister was shown to absorb all carbon dioxide introduced into the closed system for 120 minutes swimming time. The conservative factor which relates the long-swim data to mechanical ventilation analog data has not been quantified. Predictions following, are assumed to be influenced by this factor.

4.12.4 The following cylindrical-canister construction guides are based upon the minimal canister concept, the breathing resistance magnitude influence, and the experimental observations of size, dimensions and duration for canisters with not less than 9.5cm. diameter.

(a) Minimal cylindrical canister, DURATION 90 MIN.

VOLUME 1800 CM3
DIAMETER 9.5 CM
LENGTH 25.5 CM

(b) For 0.8 K. swim durations 90-140 MIN.

VOLUME = 1800 CM3 + 100 CM3 per 12.5 MIN.
DIAMETER = 9.5 CM + 0.1 CM per 12.5 MIN.
LENGTH = 25.5 CM + 0.75 CM per 12.5 MIN.

(c) For 0.8 K. swim durations 140-200 MIN.

VOLUME = 2200 CM3 + 100 CM3 per 10 MIN.
DIAMETER = 9.9 CM + 0.1 CM per 10 MIN.
LENGTH = 28.6 CM + 0.65 CM per 10 MIN.

(d) For 0.8 K. swim durations 200-250 MIN.

VOLUME = 2800 CM3 + 100 CM3 per 10 MIN.
DIAMETER = 10.5 CM + 0.1 CM per 10 MIN.
LENGTH = 32.3 CM + 0.45 CM per 10 MIN.

(e) 250-300 MIN.

VOLUME = 3300 CM3 + 100 CM3 per 10 MIN.
DIAMETER = 11.0 CM + 0.1 CM per 10 MIN.
LENGTH = 34.7 CM + 0.40 CM per 10 MIN.

(f) 300-364 MIN.

VOLUME = 3800 CM3 + 100 CM3 per 8 MIN.
DIAMETER = 11.5 CM + 0.1 CM per 8 MIN.
LENGTH = 36.7 CM + 0.30 CM per 8 MIN.

(g) 364-396 MIN.

VOLUME = 4600 CM3 + 100 CM3 per 8 MIN.
DIAMETER = 12.3 CM + 0.1 CM per 8 MIN.
LENGTH = 38.7 CM + 0.20 CM per 8 MIN.

(h) 396-500 MIN.

VOLUME = 5000 CM3 + 100 CM3 per 8 MIN.
DIAMETER = 12.7 CM + 0.1 CM per 8 MIN.
LENGTH = 39.5 CM + 0.1 CM per 8 MIN.

4.12.5 Specimen Calculations:

(a) operational duration: 360 minutes
(b) from rule (f), volume = 3800 CM^3 plus 100 CM^3 per each 8 minutes from 300 - 364 min.
(c) 60/8 = 7.5; therefore, volume = (7.5)(100) + 3800 CM^3, or 4550 CM^3
(d) by the same rule, diameter = 11.5 CM + 0.1 CM per 8 MIN, or (7.5)(0.1) + 11.5 = 12.25 CM
(e) length = 36.7 CM + 0.3 CM per 8 MIN, or (7.5)(0.3) + 36.7 = 38.95 CM
(f) length to diameter ratio = 38.95/12.25 = 3.18
(g) this volume, 4550 CM^3, represents only the absorbent compartment, and does not reflect total displacement volume of a canister, since this also incorporates the inlet and exhaust plenum chamber volumes.
(h) assuming that packing with granular Baralyme was performed so that bulk density = 103 grams of absorbent per 100 CM^3 volume, this canister would contain 4687 grams (10.32 pounds) of the granular absorbent.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Cylindrical canisters, carefully packed with granular Baralyme and subjected to closely-similar stresses of gas flow, carbon dioxide content and temperature, will behave in predictable fashion.

5.2 A minimal-duration canister, fabricated according to theoretically-established dimensions, has been tested and described.

5.3 Approximate overall size and length-diameter ratio limits have been suggested for "duration-oriented" canisters.

5.4 The airflow impedance characteristics of certain proprietary canisters appear to be unfavorable. A method of experimental examination, applicable at simulated depths, will be developed, and the required inquiries pursued.

5.5 It is recommended that:

5.5.1 Specifications for SCUBA components be formulated with reference to duration requirements and to physiologically-realistic breathing resistance magnitudes for the most stressful pressure-duration-gas mixture density-activity spectrum of an operation;

5.5.2 The presumptive order of project work as specified in the project outline be altered, and a method of testing be developed for use at simulated depths in a recompression chamber;

5.5.3 Canisters which were designed and tested according to the methods here reported be adopted as components of the pre-operational equipments for which they were specifically created;

5.5.4 Studies be initiated, possibly by contract with an industrial or university group, to explore the feasibility of several radical modifications and alternative methods for carbon dioxide elimination, including: other expendable chemical absorbents; regenerative chemical absorbents; regenerative adsorbent systems; liquid chemical systems; physical and electro-catalytic systems. Ultimately, consideration should be given to systems in which sea water is exploited for the non-stationary absorption phase component of a life-support system for which it is, as well, the source of both the oxygen and the diluent gas of the respired atmosphere.

6. REFERENCES

1. Adriani, J. Effect of varying moisture content of soda lime upon efficiency of carbon dioxide absorption. Anesth. 6:163, 1945.

2. Adriani, J. Disposal of carbon dioxide from devices used for inhalation anesthesia. Anesth. 21:742-758, 1960.

3. Adriani, J. and M. Byrd. A study of carbon dioxide absorption appliances for anesthesia: the canister. Anesth. 2:450-455, 1941.

4. Adriani, J. and E.A. Rovenstine. Experimental studies on carbon dioxide absorbers for anesthesia. Anesth. 2:1-19, 1941.

5. Albertson, M.L., J.R. Barton and D.B. Simons. Fluid Mechanics for Engineers. Englewood Cliffs, N.J. : Prentice-Hall, 1960.

6. Allen, J.P. Carbon dioxide absorption by amine solutions. Air Force Flight Dynamics Laboratory, TDR 64-27, 1964.

7. Allen, J.P. Technique for carbon dioxide absorber analysis. Air Force Flight Dynamics Laboratory, TDR 64-67, 1964.

8. Batten, D.H. The absorption of carbon dioxide from anesthesia apparatus. N.Y.S.J. of Med. 43:539-543, 1943.

9. Brown, E.S. Certain physical properties and reaction kinetics of carbon dioxide absorbents. USAF School of Aviation Medicine report, un-numbered, May 1954.

10. Brown, E.S. Voids, pores and total air space of carbon dioxide absorbents. Anesth. 19:1, 1958.

11. Brown, E.S. The activity and surface area of fresh soda lime. Anesth. 19:208-212, 1958.

12. Brown, E.S. Performance of absorbents; continuous flow. Anesth. 20:41-44, 1959.

13. Brown, E.S. Factors affecting the performance of absorbents. Anesth. 20:198-203, 1959.

14. Brown, E.S., V. Bakamjian and A.M. Seniff. Performance of absorbents: effect of moisture. Anesth. 20:613-617, 1959.

15. Brown, E.S., A.M. Seniff and J.O. Elam. Carbon dioxide elimination in semi-closed systems. Anesth. 25:31-36, 1964.

16. Brown, G.G., editor, Unit Operations. New York: John Wiley & Sons, 1950.

17. Burns, H.L. Mechanical resistance in breathing systems: a theoretical analysis. WADC Tech. Note 55-218, 1955.

18. Cain, C.C. and A.B. Otis. Some physiological effects resulting from added resistance to respiration. J. Aviation Med. 20:149, 1949.

19. Campbell, E.J.M. The Respiratory Muscles and the Mechanics of Breathing. London: Lloyd-Luke, LTD., 1958.

20. Closed Ecological Systems: A Literature Survey. Technical Information Center, North American Aviation, Inc., 1961.

21. Closed-Circuit Respiratory Systems Symposium. WADD Technical Report 60-574, 1960.

22. Coe, C.S., and G. Christensen. Carbon dioxide management in spacecraft atmospheres. Aerospace Med. 35:110-115, 1964.

23. Coe, C.S., J. Rousseau and A. Shaffer, editors, Analytical methods for space vehicle atmospheric control processes. Part II. ASD Tech. Rept. 61-162, 1962.

24. Conroy, W.A. and M.H. Seevers. Studies in carbon dioxide absorption. Anesth. 4:160-173, 1943.

25. Cooper, G.A. Suggested methods of testing and standards of resistance for respiratory protective devices. J. Appl. Physiol. 15:1053-1061, 1960.

26. Danby, C.J., J.G. Davoad, D.H. Everett, C.N. Hinshelwood and R.M. Lodge. The kinetics of absorption of gases from an air stream by granular reagents. J. Chem. Soc. (London), 918-934, 1946.

27. Derrick, W.S. and R.C. Smart. Carbon dioxide absorption properties of monoethanolamine. Anesth. 18:551, 1957.

28. Duffner, G.J. Canister design criteria of carbon dioxide removal from SCUBA. USN Experimental Diving Unit Research Report 9-57, 1957.

29. Eagleton, L.C. and H. Bliss. Drying of air in fixed beds. Chem. Eng. Prog. 49:543-548, 1953.

30. Elam, J.O. The design of circle absorbers. Anesth. 19:99, 1958.

31. Elam, J.O. Channeling and overpacking in carbon dioxide absorbers. Anesth. 19:403, 1958.

32. Elam, J.O., E.S. Brown and J.D. Elder, Jr. A mechanical ventilation analogue. USAF School of Aviation Medicine, unnumbered report, May 1954.

33. Elam, J.O., E.S. Brown and R.H. Ten Pas. Carbon dioxide homeostasis during anesthesia. I. Instrumentation. Anesth. 16:876-885, 1955.

34. Eshbach, O.W. (ed). Handbook of Engineering Fundamentals. New York: John Wiley and Sons, 1952.

35. Goldstein, S.A. On the mathematics of exchange processes in fixed column. Proc. Roy. Soc., A., 21:9 151-185, 1963.

36. Goodman, M.W. A study of carbon dioxide elimination from SCUBA, with standard and modified canisters of the U.S. Navy closed-circuit oxygen rig. USN Experimental Diving Unit Research Report 1-64, 1964.

37. Goodman, M.W., R. D. Workman and K.W. Wallace. Evaulation of granular Baralyme carbon dioxide absorbent in place of Shell Natron for use with deep-sea helium-oxygen diving outfit. USN Experimental Diving Unit Evaulation Report 1-64, 1964.

38. Hacker, P.T., R.J. Brun and B. Boyd. Inpingement of droplets in 90o elbows with potential flow. NACA TN 2999, Sept. 1953.

39. Hammond, W.A. Drierite and Its Applications. Xenia, Ohio: The W.A. Hammond Drierite Co., 1961.

40. Huseby, H.W.S. and E.J. Michelsen. Carbon dioxide absorbent evaluation and canister design. USN Experimental Diving Unit Research Report 1-60, 1959.

41. Janney, G.M. Evaluation of a new positive displacement mechanical respirator for use in the testing of breathing apparatus. USN Experimental Diving Unit Research Report 2-61, 1960.

42. Kincaide, W.C. Development of the APOLLO portable life support system, in Lectures in Aerospace Medicine. USAF School of Aerospace Medicine, Feb 1964.

43. Kinslow, M. and B.M. Majors. Systems of units and conversion tables. AEDC Tech. Doc. Rept. 62-6, 1962.

44. Kubiak, E. J., J. Rest and R.A. Bambenek. A closed respiratory system evaluator. ASD Tech. Rep. 61-512, 1961.

45. Lanphier, E.H., C.P. Norton, P.A. Violich and T.A. McAllister. Modification of standard Draeger carbon dioxide absorbent canister. UDU2 Evaluation Report 1-60, 1960.

46. Leyden, C.J. Breathing resistance in SCUBA components. USN Experimental Diving Unit Research Report 4-57, 1956.

47. Lueden, M. Experimental investigations on soda lime using double absorbers. Der Anesthestitist 12:297, 1963.

48. Margaria, R., E. Galante and P. Cerretelli. An efficient carbon dioxide absorber for experiments on metabolism. J. Appl. Physiol. 14:1066-1068, 1959.

49. Markowitz, M.M., D.A. Boryta and H. Stewart, Jr. Concurrent carbon dioxide absorption and oxygen evolution by lithium peroxide. J. Inorg. Nucl. Chem. 26:2028-2033, 1964.

50. Marks, L.S. (ed). Mechanical Engineer's Handbook. New York: McGraw-Hill Book Co., 1941.

51. Mead, J. Resistance to breathing at increased ambient pressure, in Goff, L. (ed). Proceedings of the Underwater Physiology Symposium. Publication 377, National Academy of Sciences - National Research Council, 1955.

52. Military Specification MIL-B-36212 (DM), dtd 25 May 1964: Barium Hydroxide Lime, USP, Granular. Defense Supply Agency, Defense Medical Supply Center, Directorate of Technical Operations (Code T-M2), Brooklyn, New York, 11232.

53. Miller, R.R. Comparison of carbon dioxide removal systems, in Carhart, H.W., and V.R. Piatt (editors), Present Status of Chemical Research in Atmosphere Purification and Control on Nuclear-Powered Submarines. Naval Research Laboratory report 6053, 1963.

54. Nealon, T.F., Jr., H.F. Chase and J.H. Gibbon, Jr. Factors influencing carbon dioxide asborption during anesthesia. Anesth. 19:75-81, 1958.

55. O'Rourke, C.E. (ed). General Engineering Handbook. New York: McGraw-Hill, 1940.

56. Ower, E. The Measurement of Air Flow. London: Chapman and Hall, Ltd., 1933.

57. Report Bibliography: Absorbents for gases (oxygen and carbon dioxide), 1953-1962. AD 446936, Defense Documentation Center, 1964.

58. Scheidegger, A.E. The Physics of Flow Through Porous Media. New York: MacMillan, 1960.

59. Shaffer, A., (ed). Analytical methods for space vehicle atmospheric control processes. Part 1. ASD Tech. Rept. 61-162, 1961.

60. Shapiro, A. The Dynamics and Thermodynamics of Compressible Fluid Flow. New York: Ronald Press Co., 1953.

61. Sherwood, T.K. and R. L. Pigford. Absorption and Extraction. New York: McGraw-Hill, 1952.

62. Smart, R.C. and W.S. Derrick. Carbon dioxide absorption by ion exchange resins. Aneth. 18:216, 1957.

63. Sodasorb Manual of Carbon Dioxide Absorption in Inhalation Anesthetic Apparatus. Dewey and Almy Chemical Division of W.R. Grace and Co., 1962.

64. Submarine Atmosphere Habitability Data Book, NAVSHIPS 250-649-1 (Revision-1). Washington, D. C., Navy Department, 1962.

65. Submarine Medicine Practice, NAVMED-P5054. Washington, D.C.: U.S. Government Printing Office, 1956.

66. U. S. Navy Diving Manual, NAVSHIPS 250-538. Washington, D.C.: U.S. Government Printing Office, 1964.

67. Van Patten, R.E. An annotated bibliography on biomedical (animal) satellite vehicles, life support systems and related technology. AMRL-TDR 63-126, 1963.

68. Walker, J.H. and S. Crocker. Piping Handbook. New York: McGraw Hill, 1939.

ADDITIONAL REFERENCES

69. Air Reduction Company, Inc. Closed circuit respiratory/ ventilation system, phase 1. WADD Tech. report 60-33, 1960.

70. Burgess, D. Review of canister developmental tests using alkali oxides. Naval Research Laboratory report P-2153, 1943.

71. Chandler, H.W. and W. Oser. Study of electrolytic reduction of carbon dioxide. MRL Tech. Doc. report 62-16, 1962.

72. Christensen, G. and J.R. Wenker. Low temperature adsorption of carbon dioxide. ASD Tech. report 62-560, 1962.

73. Gustafson, P. and S.H. Smith, Jr. Removal of organic contaminants from air by type 13X molecular sieve. Naval Research Laboratory report 5560, 1960.

74. Pierce, C.M. The biology of space flight: an annotated bibliography. SB-63-20, Lockheed Missles and Space Company, 1963.

75. Silverman, L., G. Lee, T. Plotkin, L.A. Sawyers and A.R. Yancy. Airflow measurements on human subjects with and without respiratory resistance at several work rates. Arch. Ind. Hyg. 3:461, 1951.

76. Smith, S.H., Jr. A dry chemical system for carbon dioxide removal from submarines. Naval Research Laboratory report 5563, 1960.

77. Zechman, F., F.G. Hall and W.E. Hull. Effects of graded resistance to tracheal airflow in man. J. Appl. Physiol. 10:356-362, 1957.

APPENDIX A: GLOSSARY OF ABBREVIATIONS AND SYMBOLS

ATPS	: Ambient conditions of temperature and pressure, saturated with water vapor
^oC	: Centigrade degrees
CM	: Centimeter
CM H_2O	: Centimeters of water, pressure
CM H_2O/L/SEC	: Centimeter of water per liter per second, breathing resistance
cos	: Cosine
d	: Density
D	: Diameter
DIA	: Diameter
D_G	: Diameter of granule
f	: Respiratory frequency, breaths per minute
fc	: Resistance coefficient
F_{CO_2}	: Percent (fraction) carbon dioxide
GM	: Gram
h	: Height
l	: Length
L	: Liter
LPM	: Liter per minute
MHR	: Mean hydraulic radius
MIN	: Minute
mm Hg	: Millimeters of mercury, pressure
N	: Number
P	: Pressure
r	: Radius

Re	: Reynolds number
RMV	: Respiratory minute volume, liters per minute
SD	: Standard deviation
SEC	: Second
STPD	: Standard conditions of temperature and pressure (0°C, 760 mm Hg), dry
t	: Time
v	: Viscosity
V	: Volume
$\dot{V}$	: Volume per unit time
VAS	: Volume of the absorbent compartment
V_D	: Volume of the dead space
$\dot{V}_E$	: Volume flowrate at any instant
VIGS	: Volume of the intergranular space
$\dot{V}_M$	: Maximal volume flowrate
V_O	: Linear velocity
V_T	: Tidal volume
W	: Mass velocity
Δ	: (delta); a difference
π	: (pi); 3.1416, the ratio of circumference and diameter of a circle
ω	: (omega); angular velocity

APPENDIX B: GLOSSARY

Baffle: Simple architectural feature, within a canister, which deflects the flow of gases.

Breakthrough: The point, in the use span of a canister, which is followed by exponential deterioration of function.

Breathing resistance: Impedance to the flow of respired gas, usually expressed as centimeters of water/liter/second.

Canister duration: Useful life of the absorption system, referenced to specific conditions of CO_2 output, ventilation and temperature.

Causticity: Ability to damage or destroy living tissue by chemical action.

Contact time: The time span during which the exhaled gas is within the reaction zone within the packed canister. Effectively, it is the time period between successive expirations, and it varies inversely with the flow rate and the breathing resistance, and is frequently computed as space velocity.

Dead space: With respect to the canister, the dead space consists of the hose volume from the exhalation check, and the input plenum chamber volume.

Efficiency: Performance output referenced to performance capacity. 100 grams of granular Baralyme has, theoretically, capacity for absorbing 24.3 liters CO_2.

Exhaustion: The point, in the use span of a canister, which marks the cessation of function, insofar as human respiration of oxygen under pressure, and underwater, is concerned.

Flow director: Complex geometric form used to direct the path of gasflow in a defined, circuitous route.

Functional reserve interval: The period of canister use span between breakthrough and exhaustion.

Hydraulic radius: Cross-sectional area of a fluid-filled channel, divided by the length of the contacting perimeter. For cylinders, MH R = (DIAMETER)(0.25).

Intergranular space: The void space, consisting of that part of the intracanister volume not taken up by absorbent particles.

Mean mass velocity: The weight rate of flow divided by cross-sectional area, with reference to flow through an apparatus.

Reynolds number: Any of several dimensionless quantities, which are encountered in the theory of fluid motion, and are of the general form: (length) (velocity) (density)/(viscosity).

Pore space: The microscopic spaces, within granules, which provide much of the surface area required for the chemical reactions which comprise absorption. Pore space volume varies inversely with particle density, and it progressively diminishes with increasing canister use time.

Space velocity: Volume of gas passing through a given volume of reaction space in unit time, divided by the latter, i.e., space velocity = V/VIGS.

Space-time-yield: Yield of product in unit time per unit volume of reactant per passage. S.T.Y. = F(V/VIGS).

APPENDIX C: SYNOPSIS OF CHEMICAL, PNEUMATIC, PHYSIOLOGICAL AND GEOMETRICAL INFORMATION PERTINENT TO SCUBA CANISTER DESIGN AND CARBON DIOXIDE ELIMINATION

1. HYDROXIDES OF ALKALINE AND ALALINE EARTH METALS

NAME AND FORMULA	MOLECULAR WEIGHT	MOL. WT. OF ANION METAL	SOLUBILITY IN WATER(GM/100CC)	CO_2 CAPACITY (GM CO_2/100 GM)
POTASSIUM HYDROXIDE KOH	56.10	39.102	115 - 20°C 178 - 100°C	47
SODIUM HYDROXIDE NaOH	40.01	22.989	109 - 20°C 347 - 100°C	54
LITHIUM HYDROXIDE LiOH	23.95	6.939	13.0 - 20°C 17.5 - 100°C	92
BARIUM HYDROXIDE $Ba(OH)_2.8\ H_2O$	315.51	137.34	5.6 - 15°C	-
CALCIUM HYDROXIDE $Ca(OH)_2$	74.10	40.08	0.183-10°C 0.077-100°C	59
MAGNESIUM HYDROXIDE $Mg(OH)_2$	58.34	24.312	0.0009-18°C 0.0004-100°C	76

(references: 2, 6, 59)

2. BARALYME: COMPOSITION AND PROPERTIES

GRANULAR BARALYME			PELLET BARALYME	
$Ca(OH)_2$	74%		$Ca(OH)_2$	80%
$Ba(OH)_2 \cdot 8H_2O$	11%	(a) COMPOSITION	$Ba(OH)_2 \cdot 8H_2O$	20%
KOH	5%			
MOISTURE	10%			
24.3L CO_2/100 GM		(b) CO_2 CAPACITY	25.6L CO_2/100 GM	
48.03 GM CO_2/100 GM			49.7 GM CO_2/100 GM	

(c) PHYSICAL PROPERTIES

PROPERTY	GRANULAR	PELLET
Pore volume per gram (CM^3/GM):	0.043	0.137
Granule volume per gram (CM^3/GM):	0.673	0.646
Apparent density ($GM/100\ CM^3$):	178.0	173.0
Bulk density ($GM/100\ CM^3$):	104.0	103.2
Specific gravity ($GM/100\ CM^3$):	191.0	202.0
voids (%):	41.6	41.7
pores (%):	3.7	20.1
total air space (%):	45.3	61.8

(references; 9, 10, 52)

3. RELATIVE HAZARD OF CAUSTIC INJURY OF ALKALINE METAL AND ALKALINE EARTH METAL HYDROXIDES, ESTIMATED FROM SOLUBILITY DATA (RELATIVE TO KOH = 1.000, 20°C)

KOH	=	1.000
NaOH	=	0.950
LiOH	=	0.110
$Ba(OH)_2$	=	0.050
$Ca(OH)_2$	=	0.0015
$Mg(OH)_2$	=	0.0000007

4. PHYSICAL PROPERTIES, CONVERSION FACTORS AND UNITS: GASES

(a) PHYSICAL PROPERTIES	CO_2	OXYGEN	AIR
dynamic viscosity (POISE x 10^7) (STP):	1420	1890	1708
(20°C):	1463	2031	1813
density (GM/L) (STP):	1.9769	1.42904	1.2929
(20°C):	-	-	1.2047
kinematic viscosity (STOKE x 10^3)(STP):	-	179.7	-
(20°C):	79.4	-	150.5

(b) CONVERSION FACTORS

ABSOLUTE VISCOSITY: 1 centipoise = 0.01 poise = 0.001 kg/ meter·sec
KINEMATIC VISCOSITY: 1 stoke = 1 cm^2/sec = 1/929 ft^2/sec

(references 34, 43, 50)

5. RESISTANCE TO EXHALATION: PACKED CANISTERS, AMBIENT PRESSURE 1-5 ATM.ABS.

CANISTER TYPE	CM H_2O ΔP AT EACH AMBIENT DEPTH (FT. S.W.) 0	33	66	99	132
Cylindrical (DIA 9.8 CM, 24 CM long)	2	4	5	6	7
Rectangular (30 CM x 19 CM x 6 CM)	2	4	6	8	10
Radial (DIA 16 CM, depth 8 CM)	1	1	2	2.5	3

(reference 46)

6. BREATHING RESISTANCE OF THE EXTERNAL AIRWAY: SUGGESTED LIMITING MAGNITUDES

Desirable limit, added exhalation resistance: 3.0 CM H_2O/L/SEC
Desirable limit, added inhalation resistance: 7.5 CM H_2O/L/SEC
Desirable limit, anatomical plus apparatus resistance: 12 CM H_2O/L/SEC
(references 17, 18, 19, 24)

7. DERIVATION OF PEAK VOLUME FLOWRATE FROM VENTILATORY VOLUME BY ASSUMING SINUSOIDAL FLOW

(refer to Appendix 1 for glossary of symbols and abbreviations)

(a) $\dot{V}_E = \dot{V}_M \sin\omega t$
when $d\dot{V}_E/dt = 0$, $\omega t = 90^\circ$, and $\sin \omega t = 1$, $\omega t = \pi/2$
therefore $\dot{V}_M = \dot{V}_E \sin\pi/2$; $\sin \pi/2 = 1$,
and $\dot{V}_M = \dot{V}_E$ under these conditions

(b) $RMV = (V_T)(f)$; $V_T = \int_0^{\pi} \dot{V}_E \sin\omega t dt = (\dot{V}_E)\left[-\cos\omega t\right]_0^{\pi} = 2\dot{V}_E/\omega$
$\omega = 2\pi f$
therefore $V_T = 2\dot{V}_E/2\pi f = \dot{V}_E/\pi f$
since $RMV = (V_T)(f)$, $RMV = (\dot{V}_E/\pi f)(f) = \dot{V}_E/\pi$
$\dot{V}_E = (\pi)(RMV)$
when $\dot{V}_E = \dot{V}_M$, $\dot{V}_M = (\pi)(RMV)$

8. ESTIMATION OF TOTAL VOLUME OF CARBON DIOXIDE ABSORBED WHEN VENTILATION AND CO_2 OUTPUT ARE CONTROLLED DURING A TIMED INTERVAL

(a) $\dot{V}\int_{t1}^{t2} f(t)\,dt = \dot{V}\int_{t1}^{t2} FCO_{2_E}$

(b) $\int_{t1}^{t2} FCO_{2_E} = (x_1 - x_o/3)(y_o + 4y_1 + 2y_2 + 4y_3 + 2y_4 + 4y_5 + y_6)$

(c) $(\dot{V})\ (FCO_{2_I}) - (\dot{V})\ (FCO_{2_E}) = (\dot{V})\ (FCO_2\ ABS)$

(d) $(\dot{V})\ (FCO_2\ ABS)\ (\Delta t2\text{-}1) = V_{CO_2}\ ABS\ (t_2 - t_1)$

(e) $(\dot{V})\ (FCO_{2_I})\ (\Delta t_1 - 0) = V_{CO_2}\ ABS\ (t_1 - t_o)$

(f) $V_{CO_2}\ ABS\ (t_2 - t_1) + V_{CO_2}\ ABS\ (t_1 - t_o) = V_{CO_2}\ ABS\ (total)$

9. GEOMETRICAL FORMULATIONS

(a) volume, right circular cylinder

$V = 0.7854\ D^2h$

(b) volume, frustum of a rectangular pyramid

$V = (h/6)\ [(2a + a_1)\ b + (2a_1 + a)b_1]$

(c) volume, truncated right circular cone

$V = (0.7854h)[(r + r_1)^2 + (r - r_1)\ ^2/3]$

(d) area, circle

$A = 0.7854\ D2$

(e) area, isosceles trapezoid

$A = (a + b)\ h/2$

(f) mean hydraulic radius, circular cross-section

$m = D/4$

(g) mean hydraulic radius, rectangular cross-section

$m = (ab)/2(a + b)$

/

10. GASFLOW THROUGH SMOOTH-SURFACE CYLINDERS AND PACKED CYLINDRICAL CANISTERS

(1) POISEUILLE LAW

(a) $\dot{V}_E = (\Delta P)(\pi/8)(1/\nu)(r^4/l)$

(b) MOLES/SEC $= (P_2^2 - P_1^2$, DYNE/CM$^2)(\pi)(d/2)^4/16l\nu RT$;

($R = 8.313 \times 10^7$ erg/degree-mole)

(2) RESISTANCE TO FLOW (RATIO OF ΔP TO FLOW)

$R = \Delta P/\dot{V}_E = (8/\pi)(\nu)(1/r^4)$

Throughout the lower ranges of flow velocity, the flow of a viscous, noncompressible fluid, through a circular cross-section pipe, is laminar; the velocity profile is parabolic; the relation between volume flow and driving force is: $\dot{V}\pi r^2 = (\Delta P)(\pi r^4)/8\nu l$

(3) REYNOLDS NUMBER

$Re = D\, V_o d/\nu$

$Re = 4W/\pi D\nu$

$Re = D_G V_o d/\nu$

(4) LINEAR VELOCITY AND MASS VELOCITY

(a) $V_o = \dot{V}_E/(\pi)(D2/4)$

(b) $V_o = 21.2\ \dot{V}_E/D^2$, when V_o = CM/SEC, $\dot{V}_E$= LPM and D = CM

(c) $W = (\dot{V}_E)\ (d)$

(d) $W = 0.02155\dot{V}_E$, when W = GM/SEC, $\dot{V}_E$ = LPM, and d = GM/CM^3, for air at STP

(5) CRITICAL VELOCITY AND CRITICAL FLOW

(a) Re = (GM/CM)(CM/MIN)(CM) / (GM/CM·MIN)

(b) Re = 2000 (air, 1 atm. abs., 30°C) = criterion of criticality

(c) CRITICAL VELOCITY = 19, 410/DIAMETER, when V_c = CM/MIN;

(d) CRITICAL VELOCITY = 323.5/DIAMETER, when V_c = CM/SEC;

(e) FLOWRATE = (AREA)(VELOCITY) = (CM^2)(CM/MIN)(L/1000CM^3)= LPM

(f) CRITICAL FLOW = (0.784)(DIAMETER^2)(19,410/D)(1/1000) = 15.2D when FLOW = LPM

(6) DARCY LAW EXPRESSIONS GOVERNING FLOW THROUGH GRANULAR MEDIA

$$\Delta P = \frac{(V_o)(D_G)(\nu)(fc)}{(D_G^2)\ (d)}; \quad V_o = \frac{(d)(D_G)(\Delta P)}{(fc)(\nu)(\ell)}$$

D_G/D	fc (viscous)	fc (turbulent)
0.01	10.0	10.0
0.03	9.4	8.8
0.05	9.0	8.3
0.10	8.2	7.4
0.15	7.7	6.5
0.20	7.5	6.0
0.25	7.4	5.7