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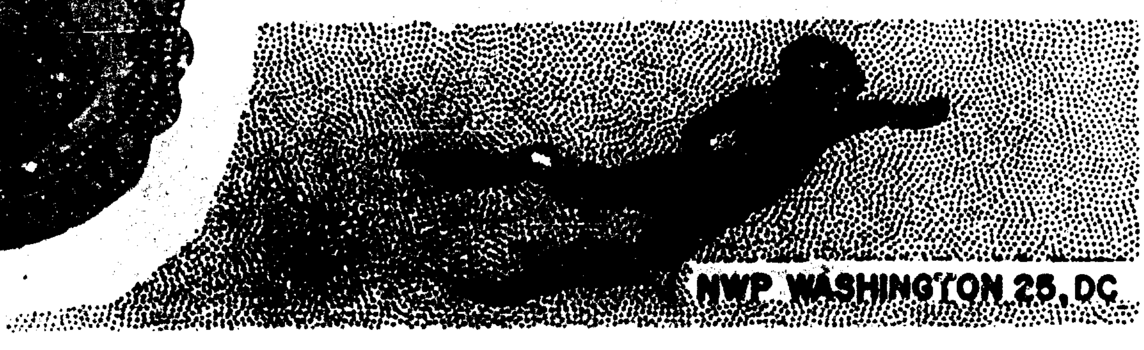
U. S. Navy Experimental Diving Unit



U. S. NAVY EXPERIMENTAL DIVING UNIT
U. S. NAVAL STATION
(WASHINGTON NAVY YARD ANNEX)
WASHINGTON, D.C. - 20390

RESEARCH REPORT 1-64

A STUDY OF CARBON DIOXIDE ELIMINATION FROM SCUBA, WITH STANDARD AND MODIFIED CANISTERS OF THE U. S. NAVY CLOSED-CIRCUIT OXYGEN RIG

PROJECT F-011-06 TASK 3380 TEST 6

by
LCDR M. W. GOODMAN, (MC), USN

1 May 1964

SUBMITTED:	APPROVED:	APPROVED:
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ASS'T SUB. MED. RESEARCH	SUB. MED. RESEARCH	OFFICER IN CHARGE

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ABSTRACT

The canister from a U. S. Navy Standard Oxygen Closed-Circuit Breathing Apparatus was modified to accomodate reduced loads of pellet Baralyme. Polystyrene rods, inserted longitudinally, were used to occupy the vacated intracanister space. In a controlled laboratory environment, and with a mechanical respirator for the simulation of respiratory and CO_2 production values, the relationships between absorbent weight and swimming duration were determined. A number of canister design and absorbent function characteristics were concurrently studied.

Reducing the weight of the absorbent charge by not more than about one-half pound did not appear to significantly affect functional duration. Any further reduction of the standard pellet Baralyme load, however, cannot be recommended for use. This conclusion is based upon the experimental observations that decrements of absorbent weight cause corresponding greater reductions of the modest functional reserve time period, as measured from the swimming duration limit at the breakthrough event, to the point of total absorbent exhaustion. If this important effect of smaller absorbent charges is superimposed upon planned operational swimming times chosen to correspond with the canister functioning time, the occurrence of casualties due to acute CO_2 retention must be anticipated. Any beneficial result which might be expected from these smaller pellet Baralyme charges, therefore, should be of sufficient significance to compensate for the added hazards to individual swimmers and to mission completion. Fiscal advantages were postulated and examined. The limited economies were not felt to be of importance.

Segregated from the report proper, as appendices to it, are subject areas of limited or special interest which relate to the study thesis, but are peripheral to it.

SUMMARY

PROBLEM:

To determine the amount of CO_2 absorbent required for 0.5, 1, 1.5 and 2 hours swimming, using the U. S. Navy Standard Oxygen Closed-Circuit Breathing Apparatus.

FINDINGS:

With reference to the canister environment and the stresses used, the requested curve of swimming duration - pellet Baralyme weight has been derived. Employing polystyrene rods of varying diameter, to occupy intracanister volume in place of portions of the absorbent, the resistance to passage of air through the canister was observed to rise toward unacceptable levels as the tests progressed to their endpoints. The time span from breakthrough to absorption system exhaustion was noted to decrease logarithmically with each successive absorbent weight reduction. The operational risks thereby entailed are clear. Problems of individual response uncertainties are an important limiting aspect of absorption system testing validity.

RECOMMENDATIONS:

(1) That the swimming duration-reduced canister load data be considered, primarily, as an addition to the fund o knowledge in this area, but that operational employment of reduced absorbent loads be dismissed. The sole exception to this suggestion is an approximate 0.5 lb. absorbent decrement from maximally-loaded systems.

(2) That a concept of absorption systems be adopted by apparatus designers, so that canister specifications and specific absorbent characteristics can be planned to complement each other in all respects. Appendix C deals with these concepts.

(3) That a project be established to authorize basic studies of absorption system design, with the expectation that the dimensions and specifications for an optimal system will result therefrom. Alternatives to the conventional chemical CO_2 removal methods might concurrently be examined.

(4) That underwater swimming studies of CO_2 elimination systems be conducted with numbers of subjects exceeding customary sampling limits.

ADMINISTRATIVE INFORMATION

Authorization: Bureau of Ships ltr C-9940 ser 638-03 of 24 Jan 1963

Chronology: Project outline submitted - 12 June 1963
Experimentation commenced - 15 July 1963
Experimentation completed - 17 Feb 1964
Project report submitted - 1 May 1964

Personnel: V.E. SHEEHAN, HMC(DV), USN and C.W. DUFF, HMCA(DV), USN were designated as project engineers. They designed and fabricated the testing apparatus, conducted all the laboratory runs and underwater swimming trials, and performed the preliminary data computations. A comprehensive evaluation of the mechanical respirator was conducted by Chief SHEEHAN.

LCDR M.W. GOODMAN, (MC), USN, as cognizant project officer, prepared the project outline and the project report, designed the experiment and evaluated the data, and is solely responsible for its validity and applicability.

The manpower investment in this project is as follows:

DESCRIPTION	MANHOURS
(1) planning, literature review and experimental design	30
(2) testing, assembling apparatus and modifying canisters	60
(3) preparation and calibration of flowmeters, pressure transducers, CO_2 analyzers, volume-measuring devices and the mechanical respirator	75
(4) experimentation, laboratory runs	80
(5) experimentation, underwater runs	10
(6) data analysis and preparation of report	50
(7) drafting	20
(8) typing	35
TOTAL	360

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

ATPS: Abbreviation which signifies that a given volume of a gas was affected by ambient conditions of temperature and barometric pressure during the measurement procedure, and that the gas is saturated with water vapor at that ambient temperature.

BREAKTHROUGH: Multiple connotations attend this word. Generally it is taken to mean the graphically intersecting (% CO_2 - time) point after which canister function deterioration accelerates. Throughout this report this breakthrough point has been defined as occurring when 0.25% CO_2 concentration appears in the canister exhaust gas.

BREATHING RESISTANCE: The impedance to a gas flow phase (inhalation or exhalation), expressed in units of centimeters of water per liter of flow per second: added respiratory work efforts may be required of the diver.

EFFECTIVE % CO_2: The CO_2 concentration which actually occurs or exerts an effect at a depth, e.g., 4% CO_2, at 99 ft., would be analyzed at surface pressure as 1%; the effects of the gas, of course, are important with reference to the diver at depth.

EFFICIENCY OF CO_2 ABSORPTION: This phrase has been used to express percentage of the total absorption capacity for CO_2 actually used during a specified time.

ERGOMETER: An apparatus for the study of oxygen consumption and the physiology of muscular exercise. The U. S. Navy Experimental Diving Unit trapeze swim ergometer [illegible] in terms of the work [illegible].

FUNCTIONAL RESERVE INTERVAL: The elapsed time period between the breakthrough event and the frank loss of the CO_2 absorption function as defined by detection of a mean concentration of 0.5% CO_2 passing through the canister.

INTERGRANULAR SPACE: The "void" space between particles of absorbent, and between particles and the canister bulkhead.

LPM: Abbreviation for liters per minute.

RMV: Abbreviation for respiratory minute volume, generally measured as total gas expired per measured minute.

RQ: Abbreviation for respiratory quotient, the ratio of CO_2 produced to oxygen consumed.

STPD: Abbreviation which signifies that a given gas volume value has been adjusted to its corresponding volume at 0°C (standard temperature), 1 atm. pressure (std. pressure), with no water vapor effect.

SWIMMING DURATION LIMIT: For reporting purposes this has been defined as a specified time (in minutes) for which a specified pellet Baralyme quantity can, theoretically, be used under ideal conditions. The limit occurs when 0.25% CO_2 (effective) is the consistent canister exhaust gas concentration.

V_{CO_2}: Abbreviation for CO_2 production, expressed as volume of CO_2 (liters) per unit time (one minute).

V_{O_2}: Abbreviation for oxygen consumption expressed as volume of oxygen (liters) per unit time (one minute).

1. INTRODUCTION

1.1 General

1.1.1 Concept and Status of CO_2 Absorption Systems in Diving

(1) A characteristic common to all U. S. Navy closed circuit and semi-closed circuit diving rigs is that their ultimate utility and operational duration are limited by their CO_2 removal capability. Within the scope of diving depth and time situations generally encountered in self-contained underwater swimming, the CO_2 absorption ability is usually adequate, but it stands apart as the most significant single factor obstructing any increasingly efficient safe exploitation of other apparatus components. Recent developments and foreseeable advances in compressed-gas cylinder technology, cryogenic gas storage technics, portable efficient energy sources, body heat conservation methods and devices, swimmer underwater-propulsion systems, sensor-servomechanism gas supply controls, and diver-carried decompression computers have been widely discussed and eagerly anticipated. However, our limited absorption system technology may well prove to be a source of intolerable irritation and inertia when concerted efforts to extend operational diving limits are initiated.

(2) An obvious corollary to this evaluation is that the absorption systems in current use represent neither the application of thorough research investigation results, nor even an empirical synthesis of the best information from diving and anesthesia-canister literature. These sources (in particular the extensive closed-circuit anesthesia system data) strongly support the "absorption system" concept. As employed in this report, the word "system" is intended to denote the structural and functional interaction of a specific type and amount of absorbent, within a canister especially designed for it. A notable example of an effective absorption system is the Roswell Park anesthesia canister charged with high-moisture soda lime. Modifications of such proven, established systems are unlikely to trigger significant improvements in performance. The outcome, rather, may be a decrement in some basic performance parameter, and a resultant, avoidable, danger to the user.

1.1.2 Carbon Dioxide and the Underwater Swimmer. As essential to the maintenance of health and life as oxygen, the carbon dioxide content of tissues, blood and alveolar gas must not depart from the normal by more than a few millimeters mercury partial pressure. The subjective symptoms of CO_2 retention and of CO_2 loss (hypercapnia and hypocapnia, respectively) may be remarkably similar at first. Acute carbon dioxide retention has been implicated in the mechanism responsible for sudden loss of consciousness during underwater exertion. Perhaps of most unfortunate significance for the closed-circuit rig underwater swimmer is the insidious, covert nature of progressive CO_2 intoxication, and the nonspecific nature of its clinical profile. If early CO_2 poisoning could consistently announce its presence as dramatically as does, for example, acute appendicitis, the reasons for concern in these respects would largely cease to exist.

1.1.3 Selection of the Canister Functional Endpoint. Duffner (7) suggested that, with specified swimming conditions prevailing, 1.0 percent (effective) carbon dioxide concentration in the gas passing through and exiting the canister constituted the ideal functional state. In the omnibus NAVXDIVINGU Research Report 1-60 (13), Huseby considered the terminus of his test runs to have occurred when 0.5% CO_2 was detected distal to the canister. In this present report the appearance of a consistent concentration of 0.25% CO_2 passing through the canister has been designated as the functional endpoint. While this may seem artificial and arbitrary in some respects, several factors governed the choice:

(1) Correspondence (4) specifying the primary objective of this study did not prescribe any limiting parameters, thereby reserving freedom of choice to the cognizant investigator.

(2) Tolerance to the pathophysiological effects of CO_2 is noted for broadly varying individual susceptibility. There are indications that individuals might, theoretically, be placed in categories according to their respiratory responses to inhaled CO_2 (15). This is not yet practical, but the existence of broadly-varying tolerances to CO_2 has been established among healthy young males.

(3) The suspicions, long held (19), that retention of carbon dioxide by the body could be facilitated by the breathing of oxygen at increased pressures has recently been quantitatively reported (16). Therefore, in selecting performance standards for these tests, and in reference to these several reasons, an effective percent CO_2 of insufficient magnitude to harm any individual underwater swimmer has been selected.

(4) This functional endpoint is felt to be one of two conservative safety factors engineered into the experimental design. It is hoped that any undetected systematic error, if present, might thereby be counterbalanced in the direction of swimmer protection.

(5) The structural characteristics of this canister, when subjected to respiratory volume and frequency challenges equal to or exceeding those here reported, are such that progress from the breakthrough event to complete exhaustion should be rapid. Therefore, reduction of the absorbent weight ought to be associated with further losses from this small functional reserve. An effective concentration of 0.5% CO_2 in the canister exhaust gas may, therefore, be considered to represent impending, if not actual, loss of the absorption function. These relationships have been thoroughly explored (3)(17)(18).

1.2 Objectives

1.2.1 Specific Objective. This project was performed and is reported in compliance with a Bureau of Ships request for determination of, "the amount of CO_2 absorbent required for 0.5, 1, 1.5 and 2 hours swimming, using the U. S. Navy Standard Oxygen Closed-Circuit Breathing Apparatus," (4). The data is presented in tabular format and graphically. Conclusions and recommendations as to the utility-safety aspects of operational applications are noted where appropriate.

1.2.2 Collateral Objectives. Within the limits imposed by the primary objective and the assigned project priority, the particulars and parameters listed in paragraph D2 of the project outline (5) have been explored. This data, and the following interpretative discussion, provide additional knowledge referable to the test canister, and to future design research efforts.

1.3 Scope

1.3.1 Mechanical Respirator Studies. The bulk of the reported data was generated during test runs utilizing a positive displacement mechanical respirator (14) to deliver sine-wave flow tidal volumes at preselected fredquencies. All recognized variables relating to canister-absorbent function were regulated or monitored. Details of the test environment design and control are discussed in succeeding sections, and are summarized in Table I.

1.3.2 Underwater Swim Studies. The number of working swim-dives was not expanded because of the observed influence of individual variability factors which appeared. Additional manhour expenditures in these efforts also seemed not to be indicated by the emerging pattern of laboratory testing results. A recent series of dives employing the closed-circuit oxygen rig, but with granular Baralyme in the canister, is partially reported for interest and contrast to the pellet Baralyme absorbent data.

2. PROCEDURE

2.1 The Basis of Experimental Design

2.1.1 Application and Limitation of Laboratory Data. The diversity of the multiple factors affecting canister-absorbent systems is generally appreciated. However, some distinction is required when laboratory experimental influences are applied to these factors. Fundamental to the interpretation of the project results is the realization that they have been induced by influential elements which may not relate, directly, to any conceivable operational situation. The basis of laboratory testing resides in the ability to control the inputs to the test object, so that its responses can be studied in more-or-less pure form. Therefore, in terms of general applicability, the project data can be related to every conceivable operational situation. This requires the use of suitable correction factors to compensate for the specific actions of any encountered conditions, e.g., water temperatures. This extrapolation from the artificially-controlled, unrealistic atmosphere of the experiment, to the comprehensive spectrum of operational stresses and circumstances, is valid and can be accepted with confidence when the correction factors are supplied by logic and the experienced judgment of senior divers. (Generalization in this fashion is, of course, the inductive reasoning method, which is fundamental to the formation of technological systems from elemental research contributions.)

2.1.2 Factors Known to Influence CO_2 Absorption

(1) Design and Canister Modifications. Rods of polystyrene plastic, oriented centrally in the long axis of the canister (Fig. 1), were chosen to compensate for the vacated volume of the displaced Baralyme. Broomsticks, or any similar roughened or coarse-surfaced round or oval rod could be identically employed, provided that it did not react chemically with the absorbent. The method of accomplishing the modification, as distinct from the reduced absorbent mass itself, affects the final performance by virtue of the disturbed gas-flow, as a consequence of induced channelling pathways, and by breathing resistance increments. Imagination as well as sound judgment can, with justification, be employed in these manipulations because the reservoir of basic information on canister design is not extensive. What must be appreciated is the potentially decisive effect due solely to the method of reducing the canister load.

TABLE

EXPERIMENTAL

CANISTER CONFIGURATION	TEST NO.	RESPIRATORY MINUTE VOLUME (LPM , STPD)	TIDAL VOLUME (LITERS , STPD)	FREQUE (BREATI MINUTI
UNMODIFIED	1	23.5	2.35	10
UNMODIFIED	2	24.2	2.42	10
UNMODIFIED	3	26.8	2.68	10
MEAN		24.8	2.48	10
STD. ERROR		1.8	0.18	-
1" CENTRAL ROD	1	22.5	2.25	10
1" CENTRAL ROD	2	21.6	2.16	10
1" CENTRAL ROD	3	21.0	2.10	10
MEAN		21.7	2.17	10
STD. ERROR		0.8	0.08	-
1.5" CENTRAL ROD	1	25.8	2.58	10
1.5" CENTRAL ROD	2	29.1	2.91	10
1.5" CENTRAL ROD	3	28.3	2.83	10
MEAN		27.7	2.77	10
STD. ERROR		1.7	0.17	-
1.75" CENTRAL ROD	1	26.2	2.62	10
1.75" CENTRAL ROD	2	25.7	2.57	10
1.75" CENTRAL ROD	3	26.7	2.67	10
MEAN		26.2	2.62	10
STD. ERROR		0.5	0.05	-
2" CENTRAL ROD	1	26.6	2.66	10
2" CENTRAL ROD	2	26.0	2.60	10
2" CENTRAL ROD	3	26.1	2.61	10
MEAN		26.2	2.62	10
STD. ERROR		0.5	0.05	-

3LE I

ıL CONDITIONS

ıUENCY :ATHS/ UTE)	CARBON DIOXIDE PRODUCTION (LPM , STPD)	MAXIMAL INSTANTANEOUS FLOW (LPM)	INPUT GAS TEMPERATURE (°C)	AMBIENT WATER TEMPERATURE (°C)
0	1.06	73.88	27.1	19.9
0	1.09	76.08	26.9	20.7
0	1.21	84.26	26.9	20.1
0	1.12	78.07	27.0	20.2
.	0.08	5.5	0.2	0.4
)	1.01	70.74	27.3	21.5
)	0.97	67.91	27.1	21.5
)	0.95	66.02	26.2	19.6
)	0.98	68.22	26.9	20.9
	0.03	2.3	0.6	1.1
	1.16	81.12	23.2	14.2
	1.30	91.49	27.0	20.0
	1.27	88.98	25.9	19.8
	1.24	87.20	25.4	18.0
	0.07	5.4	1.5	3.3
	1.18	82.37	23.2	17.3
	1.16	80.80	23.9	17.7
	1.20	83.94	24.0	15.7
	1.18	82.37	23.7	16.9
	0.02	1.1	0.4	1.1
	1.17	83.63	26.3	19.1
	1.20	81.74	25.6	18.5
	1.17	82.06	23.1	17.0
	1.18	82.48	25.0	18.2
	0.02	0.1	0.6	0.4

CANISTER DESIGN AND MODIFICATION FACTORS

Capacity for the absorbent

Shape of the canister

Length of the canister

Diameter (both I.D. and E.D.) of the canister

Length:Diameter ratio

Intergranular space: tidal volume ratio

Canister internal surface characteristics: airflow resistance: airflow turbulence

Exhalation hose length and diameter

Exhalation bag-canister check valves

Baffles and screens

Plenum chambers

Insulation

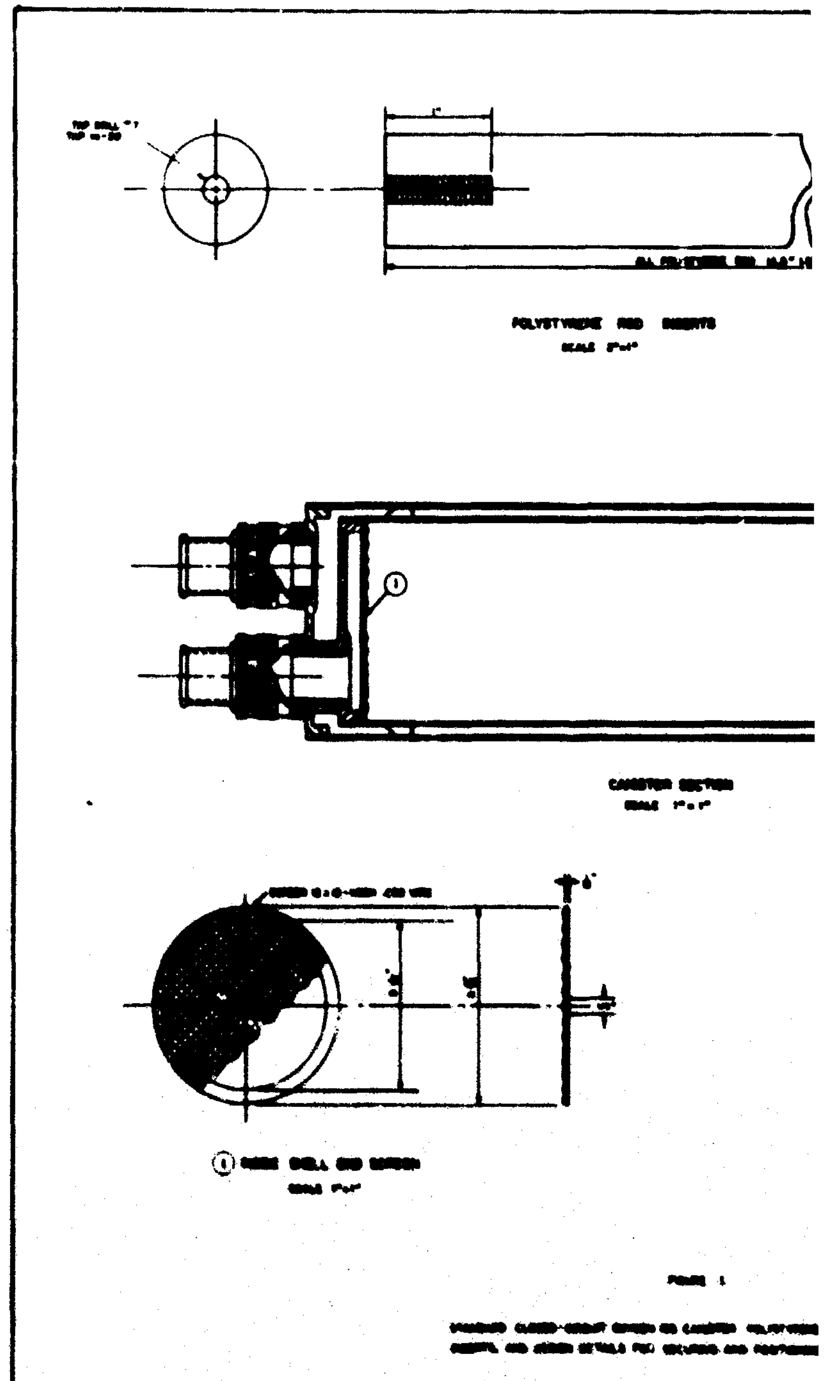
Orientation of canister and exhalation bag

(2) Ambient Conditions. Efforts were directed to the maintenance of constant canister conditions during each test, and for the entire sequence. Reasonable values which could be achieved, monitored, and adjusted within the limits of the equipment at hand were selected and maintained. The impossibility of finding representative canister environment values for simultaneous direct application to, e.g., Arctic and Tropical conditions, has been acknowledged.

AMBIENT FACTORS AND PELLET BARALYME FUNCTION EFFECTS

Water temperature:	tendency to diminish efficiency in cold water
Depth(pressure):	tendency to diminish duration as pressure increases
Input gas temperature:	tendency to diminish rate of absorption as temperature drops
Input gas humidity:	tendency to diminish rate of absorption as humidity falls

(3) Diver-Dependent Factors. This category of canister-absorbent stresses is the least-firmly predictable of the recognized influences. For this reason, and in view of the paramount requirement for safety, the respiratory challenges delivered to the test canister were consistently severe. Calculations were based upon a constant swim at 0.8 knots for the entire duration of each test run.


POLYSTYRENE ROD INSERTS
CANISTER SECTION

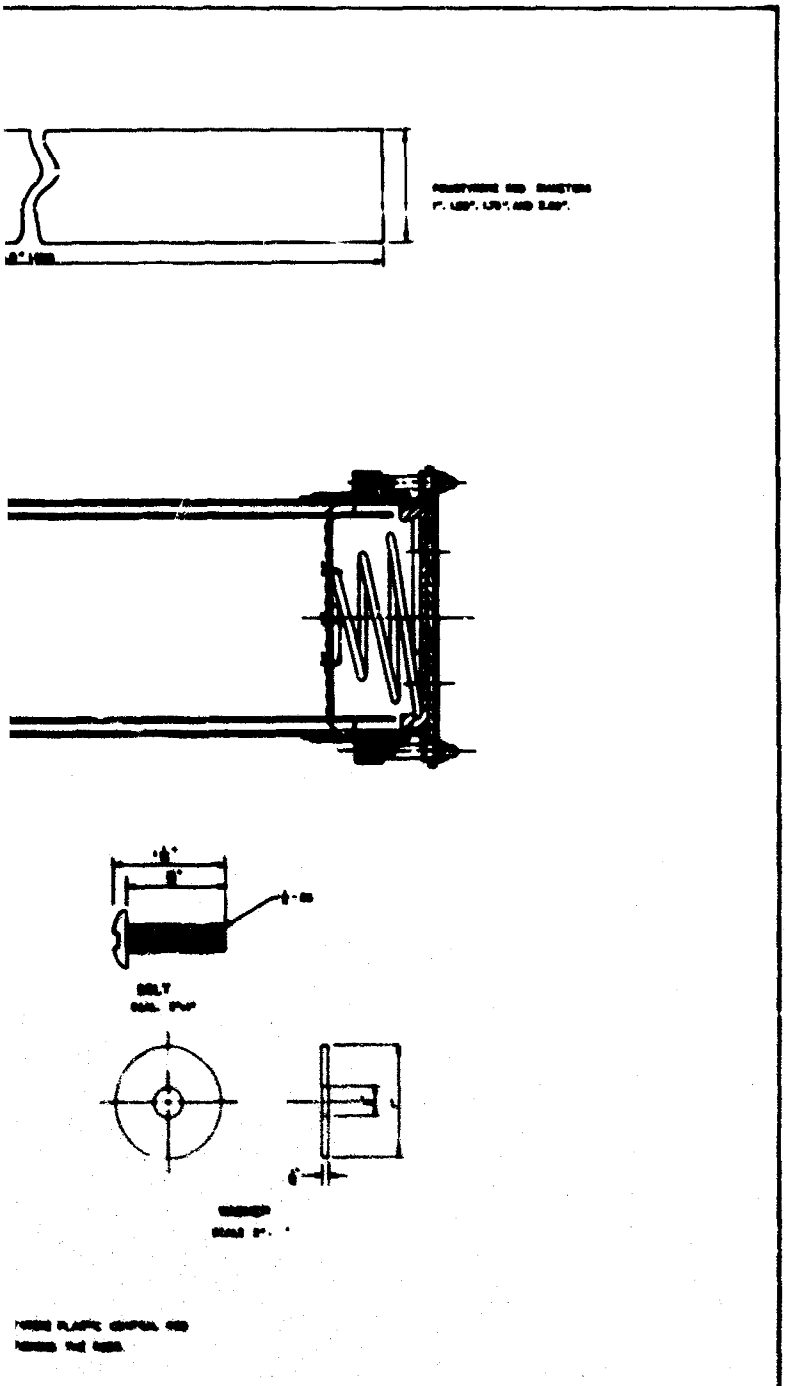

BOLT

FIGURE 1. CANISTER MODIFICATION SCHEMATIC. The upper all the cylindrical-plastic rod inserts. Superimposit full-scale, saggital-section canister schematic would and screen (left, lower) is secured to the rod, ensuri rod. Exhaled gas enters the canister through the uppe the peripheral, concentric channel between the inner a finally, against and into the absorbent mass. The full surface of the absorbent is presented to the entering the lower hose adaptor.

The upper, double-scale sketch represents
uperimposition of the rod directly onto the
atic would emphasize that the inner shell
od, ensuring central orientation of the
h the upper hose fitting, is directed via
he inner and outer canister shells, and,
. The full, circular cross-sectional
entering gas. Exhaust gas exits by

BREATHING PATTERN-CO_2 PRODUCTION FACTORS AND THEIR EFFECTS

Tidal Volume:	Irregularity and excess over canister gas volume tend to diminish efficiency
Respiratory frequency:	Increase and irregularity tend to diminish efficiency
Expiratory flow rate:	Increases tend to diminish efficiency due to decreasing gas-absorbent contact times
CO_2 Production:	Canister duration varies directly with this parameter

(4) Canister-Packing Factors. Each canister modification was processed according to predetermined routines. Canister filling was performed by a standard technique so as to insure uniform filling and minimal dusting. All pellet Baralyme came from one manufacturer's lot, and was screened prior to use (common window screen). These procedural pattern excerpts are cited as typical laboratory control factors.

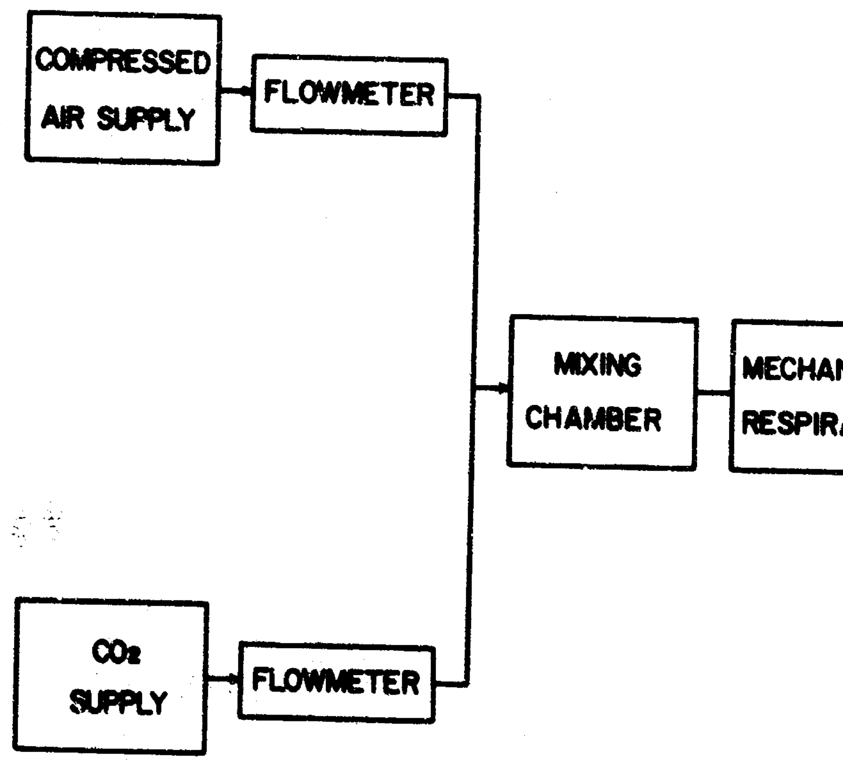
CANISTER-PACKING FACTORS AND EFFECTS

Canister packing technique:	Influences absorbent weight, void space, dusting
Packed canister breathing resistance:	Increases as absorbent is consumed; may become severe enough to provoke added CO_2 production and retention

2.2 Mechanical Respirator Studies

2.2.1 Gas Supply and Flow Path. Figure 2 has been designed as an illustrative block-diagram summary of the basic apparatus components in their flow-path functional sequence.

Compressed air, supplied by the high-pressure storage banks, was blended with 100% CO_2 from cylinders, in a 120 liter meteorological balloon. Gas flow rates and relief valve settings were empirically adjusted for maintaining uniform production of a 4.5% CO_2 in air mixture. The mechanical respirator "inhaled" this gas from the mixing balloon, and "exhaled" it into the canister via a humidifier (in which the gas was warmed to body temperature, 37°C, and saturated with water vapor) and an exhalation hose (immersed with the canister in a temperature-regulated water bath) into the apparatus expiratory bag (also immersed; oriented to swimming posture position) and then into the immersed canister. Exhaust gas was directed above the water surface through a 1½" I.D. smooth-bore, minimal-resistance tubing segment. The average bath temperature, for all runs, was 18.8°C. The warmed "exhaled" gas dropped in temperature by at least 10°C during its passage through the expiratory hose and the breathing bag. Barometric pressure was measured with a cistern mercury barometer, and the readings were subjected to conventional correction processes.



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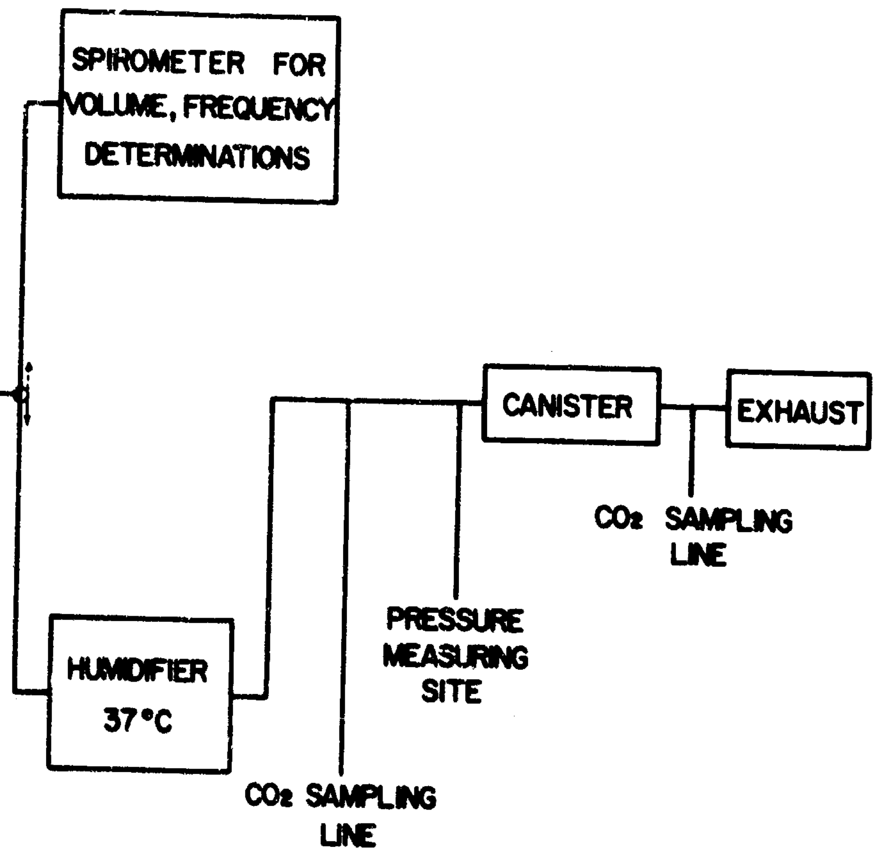
CANISTER STUDY A



TUS BLOCK DIAGRAM.

2.2.2. Flow, Temperature and Pressure Monitoring. The dual-source gas supply was directed through Schutte and Koerting flowmeters, appropriately calibrated. Humidifier and canister water-bath temperatures were measured with precision immersion thermometers graduated in 0.2°C divisions. These were checked for accuracy with a National Bureau of Standards certified Beckman differential thermometer. Submersible pumps and immersion heaters were used to maintain the designated temperature limits. A resistance bridge differential pressure transducer (Statham Instrument Co. Model PR23-10-300) sensed gasflow resistance at a site immediately adjacent to the canister input fitting. The transducer signal was directed to a Sanborn Model 350-1100B carrier preamplifier and was recorded on the strip-chart of a Sanborn model 964-100 direct writing galvanometric recorder.

2.2.3 Carbon Dioxide Analysis. The input gas mixture composition was sampled and analyzed periodically during the test runs. Canister exhaust gas monitoring was continuous, interrupted only by periodic calibration checks. The sampling lines (small-bore, thick-walled polyethylene tubes) delivered their gases to a Beckman Spinco model LB-1 medical gas analyzer via a system of pressure-control valves and a Brooks rotameter flowmeter. A Beckman microcatheter sample pump was employed. An Esterline-Angus 0-5 milliampere span strip-chart recorder received the LB-1 amplifier output. Optimal and consistent pressure-flow dynamics were thereby attained for both the calibration and the analysis. Complete, formal calibration was performed prior to and following each experiment. Calibration mixtures were prepared in 200 cubic foot gas cylinders with a Pressure Products Industries diaphragm compressor, mixing being facilitated with a motorized gas cylinder roller. CO_2 concentrations were established when micro-Scholander analysis of four consecutive samples did not vary by more than ±0.02%. Details of all analysis procedures and instrumentation methods are described in the Experimental Diving Unit Standard Analytical Practices Manual (10).

2.2.4 Gas Volume, Flow Pattern and Delivery Frequency. Simulation of human respiratory parameters was performed with a positive displacement mechanical respirator. The recommendation of Duffner (7) that respiratory volumes be of sufficient magnitude to exceed established underwater swim values has been followed. All gas volumes were measured with a Collins 100 liter spirometer, and were reduced to standard conditions. Incompetancy of the O-ring seals of the respirator cylinders caused variations in delivered volumes. The basic values desired at ambient conditions were:

Respiratory minute volume:	30 LPM
Respiratory frequency:	10 breaths/min.
Tidal volume:	3 liters

Meticulous measurements of all aspects of the mechanical respirator performance were required to prepare it for use. Transmission of shaft power to the cylinder thrust rod was accomplished with a positive-motion grooved cam. The tidal volume outputs were thereby given sine-wave flow character. This provided the capability to deliver stroke volumes with instantaneous flow values which actually represent those produced during hard-work efforts. The range of maximum instantaneous flows achieved was 66-91 liters per min., the mean value being about 80 LPM.

2.2.5 Calculations and Miscellaneous Procedural Methods

(1) CO_2 Production. For a constant-rate, sustained, 0.6-0.8 knot swim, the oxygen consumption was assumed to be constant at 1.30 LPM (STPD). This value was selected as representative for the steady-state energy expenditure plateau and was derived from a study of several sources (6)(8)(9)(20). This value was processed as shown below, and a "carbon dioxide production" value obtained. From this the actual test gas mixture composition was derived.

$V_{O_2} = 1.30$ LPM(STPD) $\qquad V_{CO_2} = 1.12$ LPM(STPD)

R.Q. = 0.85 (assumed)

$$V_{CO_2} = (R.Q.)(V_{O_2})$$

$$V_{CO_2}(ATPS) = V_{CO_2}(STPD) \times \frac{P_1}{P_2 - W_2} \times \frac{T_2}{T_1}$$

$$V_{CO_2}(ATPS) = (1.30)\left(\frac{760}{760-47}\right)\left(\frac{37+273}{273}\right)$$

$V_{CO_2}(ATPS) = 1.35$ LPM (1 atm. pressure, body temp.)

$$\%CO_2 \text{ of "exhaled" gas} = \left(\frac{V_{CO_2}}{RMV}\right)(100)$$

$$\%CO_2 = \frac{1.35}{30} \times 100$$

$$\%CO_2 = 4.50$$

(2) Absorbent Weight and Volume, Canister Packing. Weights of both empty and packed canisters were estimated with a platform beam balance. Each Baralyme weight was established by simple subtraction. Intra-canister floodable volume was determined by filling with water. The volume occupied by each weight allotment of Baralyme was measured by packing in a 2000 ml. graduated cylinder. The accuracy of these weight and volume determinations is not likely to be very high, but the measurements do relate one to another. Calculations of bulk and apparent density of the packed canister loads suggests that the Baralyme was of uniform hardness and that despite efforts to pack each canister in an identical manner, there was some variation in space-weight distribution. The uniform packing procedure is described below. (No particular importance is attached to this procedure other than the impression that it appeared to be effective in minimizing dusting, and that it was used for all the runs.):

Baralyme cartons were opened carefully to avoid shedding wax particles onto the contents or the screen.

About one-third of the contents were dumped onto the screen. Alternating shaking and rotatory movements were used to isolate dust and fragmented pellets.

Screened pellets were swept into the canister.

The canister was rotated and repeatedly struck with the flat of the hand.

2.3 Underwater Swim Studies

2.3.1 Subjects. Each participant was a NAVXDIVINGU enlisted diver (NEC 5342) who was proficient in closed-circuit rig diving, and who was familiar with the work-rest routines and the NAVXDIVINGU underwater trapeze ergometer (20).

2.3.2 Canister Modifications. (See Table II). Three underwater swims were performed with the minimal absorbent weight loading (2" central rod) in the modified closed-circuit canister. One swim test of the un-modified rig is reported. For each one of these swims pellet Baralyme charges were employed.

2.3.3. Ambient Conditions. The following test conditions were common to all four of these experiments:

Water Temperature:	30.0 - 32.2°C
Depth:	20 ft. S.W.
Ergometer Work Load:	8 lb. pull (0.9 knot swim)
Swim-Rest Sequence:	30 min. work - 5 min. rest

2.3.4 Carbon Dioxide Analysis. Continuous monitoring of gas composition at a sampling site adjacent to the canister exhaust fitting was performed routinely. The Experimental Diving Unit wet pressure tank dual gas-monitoring setup was employed. Except for the necessary underwater fittings, and a somewhat more complex pressure-flow regulation manifold, the apparatus configuration adheres to the description already presented.

2.3.5 Granular Baralyme Closed-Circuit Rig Swims. Six representative working dives, varying in depth from one to 120 feet, have been reported because the standard oxygen closed-circuit apparatus was used for each. The work-rest sequence was a 10 min.-5 min. pattern in every case, and bottom times were of planned specific duration, in distinction to the dives for which absorption-system parameters triggered the terminal events of each dive. Granular Baralyme absorbent was used in each unmodified canister. Note that dives #2 and #6 (Table III) were made with the identical absorbent portion in the canister. A total of 4 hours exposure (10 min.-5 min. pattern), without detectable CO_2 passage through the Baralyme, was observed.

TABLE II

CANISTER MODIFICATIONS AND PELLET BARALYME ABSORBENT CHARGE WEIGHT

CANISTER CONFIGURATION	WEIGHT OF ABSORBENT	
	GRAMS	POUNDS
UNMODIFIED 1.	2480	5.48
UNMODIFIED 2.	2445	5.42
UNMODIFIED 3.	2450	5.43
MEAN	2458	5.44
STD. ERROR	19	.04
1" CENTRAL ROD 1.	2224	4.92
1" CENTRAL ROD 2.	2210	4.89
1" CENTRAL ROD 3.	2190	4.84
MEAN	2212	4.89
STD. ERROR	18	.06
1.5" CENTRAL ROD 1.	2020	4.46
1.5" CENTRAL ROD 2.	1970	4.35
1.5" CENTRAL ROD 3.	1990	4.40
MEAN	1993	4.41
STD. ERROR	25	0.05
1.75" CENTRAL ROD 1.	1830	4.05
1.75" CENTRAL ROD 2.	1830	4.05
1.75" CENTRAL ROD 3.	1830	4.05
MEAN	1830	4.05
STD. ERROR	0	0
2" CENTRAL ROD 1.	1635	3.62
2" CENTRAL ROD 2.	1610	3.56
2" CENTRAL ROD 3.	1640	3.63
MEAN	1628	3.60
STD. ERROR	16	.03

UNDERWATER SWIMS WITH THE U.S. NAVY S

FULL AND (

CANISTER CONFIGURATION	ABSORBENT WEIGHT (LBS)	WATER TEMP. °C	DEPTH FEET S.W.	SWIM – R PATTERN WORK LO
UNMODIFIED	5.00	30.0	20	CONTINUOU 8 POUND PI
2" CENTRAL ROD	3.72	31.1	20	30 MINUTE W
2" CENTRAL ROD	3.85	31.1	20	5 MINUTE RI
2" CENTRAL ROD	3.87	32.2	20	28 POUND P
1. UNMODIFIED	5.65	30.0	0	
2. UNMODIFIED	5.65	30.0	0	10 MINUTE SV
3. UNMODIFIED	5.78	30.0	[illegible]3	5 MINUTE RE
4. UNMODIFIED	5.71	30.0	33	
5. UNMODIFIED	6.20	30.0	120	28 POUND PU
6. UNMODIFIED	6.20	30.0	120	

TABLE III

Y STANDARD OXYGEN CLOSED-CIRCUIT BREATHING APPARATUS WITH

ND REDUCED ABSORBENT CHARGES.

- REST N AND LOAD	TIME (MINUTES) TO DETECTION OF CO_2 PASSING THRU CANISTER							ABSORBENT USED	REMARKS
	TRACE	0.1%	0.2%	0.25%	0.3%	0.4%	0.5%		
UOUS;) PULL	—	—	—	—	—	—	162	PELLET BARALYME	TERMINAL % CO_2 ONLY VALUE OBTAINED
E WORK.	86	95	122	123	—	—	—	PELLET BARALYME	NOTE END-POINT TIME VARIABILITY
: REST.	20	42	57	63	66	—	—		
PULL	54	98	120	122	124	—	—		
	100	—	—	—	—	—	—	GRANULAR BARALYME	1.
SWIM;	—	—	—	—	—	—	—		2. SAME ABSORBENT USED IN NO. 1. NO CO_2 - 120 MINUTES
	—	—	—	—	—	—	—		3. NO CO_2 - 180 MINUTES
REST.	—	—	—	—	—	—	—		4. NO CO_2 - 120 MINUTES
PULL	—	—	—	—	—	—	—		5. NO CO_2 - 60 MINUTES
	—	—	—	—	—	—	—		6. SAME ABSORBENT USED IN NO. 5. NO CO_2 - 60 MINUTES

3. RESULTS

3.1 Statistical Testing. An estimate of reliability has been obtained for each group of data by applying the standard error of the mean. This statistical expression of reliability is used as shown in the following example:

> Table II shows the weights of pellet Baralyme used in the unmodified canister to be 5.48, 5.42 and 5.43 pounds, and the mean weight is, therefore, 5.44 lbs. How reliable is this number? The standard error of the mean is 0.04 lbs. The probability is two to one that the real, actual value falls in the range of ± one std. error. The probability that it is within the range of ± two std. errors is 9 to 1. Therefore:
>
> range 5.40-5.48 lbs: 2 to 1 probability that the "real" value is included
>
> range 5.36-5.52 lbs: 9 to 1 probability that the "real" value in included
>
> This indicates that our weight data is highly reliable and accurate to within a tolerance of better than 0.2 lbs. in 5½ pounds total (11).

3.2 Relationship of Canister Load and Swim Duration. Step-by-step reductions of the pellet Baralyme load were not made because the size of the plastic rod inserts determined the loading magnitude, not vice-versa (Table II). The effectiveness of each modification was checked, however, in a step-wise, serial manner (Table IV). Data is reported for CO_2 concentrations at 10 min. intervals, and time data was noted for selected concentration interval. Combining the weight information and the performance information (Table V and Fig. 3) fulfills the basic project objective. Figure 3 is used in this manner: enter with a proposed underwater swim duration to obtain the corresponding pellet Baralyme weight requirement. The vertical distance (time units) between the swimming duration curve and the absorption system exhaustion curve provides an estimate of canister time remaining once the weight-duration point has been reached.

3.2.1 120 min. Duration Absorbent Load. It is possible that pellet Baralyme loadings may be reduced by up to one-half pound before measurable functional losses occur. There are indications that the minimal modification is, fortuitously, a more effective system than the standard canister, as judged by duration and gas flow resistance characteristics. The "120 min. duration load" is the mean value of six experimental determinations, and is firmly established at 5.17 pounds (4.89-5.45 pounds for 2 to 1 probability).

3.2.2 90 min. Duration Absorbent Load. The curve of figure 3 indicates this to be 4.65 lbs. of pellet Baralyme. This is 0.79 pounds less than the established mean full loading capacity, and 0.52 pounds less than the 120 min. duration requirement.

TABL

EFFECT OF MODIFICATION UPON TIME COU

CANISTER CONFIGURATION	TIME (MIN) TO DETECTION OF CO_2 PASSING THRU CANISTER										
	TRACE	0.1 %	0.2 %	PEAKS 0.25 %	CONSIST. 0.25 %	0.3 %	0.4 %	PEAKS 0.5 %	CONSIST. 0.5 %	10	20
UNMODIFIED 1.	95	112	129	130	138	140	151	155	158	-	-
UNMODIFIED 2.	80	104	116	120	124	128	138	145	148	-	-
UNMODIFIED 3.	67	87	101	84	108	111	120	114	126	-	-
MEAN	81	101	115	111	123	126	136	138	144	-	-
STD. ERROR	14	13	14	24	14	15	16	16	16	-	-
1" CENTRAL ROD 1.	80	90	109	110	114	118	127	130	135	-	-
1" CENTRAL ROD 2.	70	118	135	127	139	143	152	150	162	-	-
1" CENTRAL ROD 3.	83	111	121	125	129	131	149	139	149	-	-
MEAN	78	108	122	[illegible]	127	131	139	140	149	-	-
STD. ERROR	8	15	13	9	13	12	12	10	14	-	-
1.5" CENTRAL ROD 1.	25	51	72	75	82	85	90	86	96	-	-
1.5" CENTRAL ROD 2.	20	47	59	60	67	74	78	75	86	-	0.04
1.5" CENTRAL ROD 3.	30	61	75	76	77	81	88	82	100	-	-
MEAN	25	53	69	70	75	79	85	81	94	-	-
STD. ERROR	5	[illegible]	8	9	8	7	6	6	7	-	-
1.75" CENTRAL ROD 1.	26	51	58	49	63	68	72	80	78	-	
1.75" CENTRAL ROD 2.	20	27	37	40	42	44	49	50	55	-	0.04
1.75" CENTRAL ROD 3.	20	34	45	50	55	60	65	70	75	-	-
MEAN	22	37	47	46	53	57	62	66	69	-	-
STD. ERROR	3	12	11	6	10	12	11	10	12	-	-
2" CENTRAL ROD 1.	25	41	47	40	52	54	59	55	63		-
2" CENTRAL ROD 2.	10	40	52	40	57	60	67	54	70	-	0.04
2" CENTRAL ROD 3.	20	44	52	43	56	58	64	60	68	-	-
MEAN	18	42	50	41	55	57	63	56	67	-	-
STD. ERROR	5	0.7	0.9	1.7	2	0.9	4	3	3	-	-

ABLE IV

OURSE OF ABSORBENT SYSTEM FUNCTION.

% CO_2 PASSING THRU CANISTER AT LISTED ELAPSED TIMES (MIN)													
20	30	40	50	60	70	80	90	100	110	120	130	140	150
-	-	-	-	-	-	-	-	0.04	0.08	0.12	0.20	0.30	0.38
-	-	-	-	-	-	-	-	0.08	0.14	0.24	0.32	0.44	0.52
-	-	-	-	-	-	0.04	0.10	0.16	0.28	0.40	0.56	-	-
-	-	-	-	-	-	-	-	1.10	0.17	0.25	0.30	0.37	0.45
-	-	-	-	-	-	-	-	0.07	0.03	0.14	0.18	-	-
-	-	-	-	-	-	-	0.10	0.20	0.20	0.30	0.40	0.50	-
-	-	-	-	-	-	-	-	-	0.08	0.10	0.18	0.28	0.36
-	-	-	-	-	-	-	-	0.08	0.09	0.18	0.28	0.40	0.54
-		-	-	-	-	-	-	0.13	0.13	0.19	0.29	0.39	0.46
-	-	-	-	-	-	-	-	-	0.07	0.10	0.12	0.11	-
-	0.04	0.08	0.09	0.13	0.18	0.26	0.36	0.46	0.60	0.76	-	-	-
0.04	0.08	0.08	[illegible]	0.20	0.20	0.40	0.50	-	-	-	-	-	-
-	0.04	0.05	0.08	0.11	0.19	0.32	0.41	0.59	-	-	-	-	-
-	0.05	0.08	0.08	0.15	0.25	0.33	0.42	0.53	-	-	-	-	-
-	0.01	0.01	0.02	0.04	0.06	0.07	0.07	0.09	-	-	-	-	-
	-	0.04	0.08	0.22	0.34	0.56	-	-	-	-	-	-	-
0.04	0.12	0.23	0.41	0.63	0.81	-	-	-	-	-	-	-	-
-	0.07	0.15	0.25	0.38	0.57	0.84	-	-	-	-	-	-	-
-	0.09	0.14	0.25	0.41	0.57	0.70	-	-	-	-	-	-	-
-	-	0.09	0.16	0.20	0.17	-	-	-	-	-	-	-	-
-	0.04	0.08	0.22	0.42	-	-	-	-	-	-	-	-	-
04	0.08	0.12	0.18	0.30	0.50	-	-	-	-	-	-	-	-
-	0.04	0.08	0.16	0.34	0.56	-	-	-	-	-	-	-	-
-	0.05	0.09	0.18	0.35	0.93	-	-	-	-	-	-	-	-
-	0.01	0.01	0.03	0.02	-	-	-	-	-	-	-	-	-

3.2.3 60 min. Duration Absorbent Load. The appropriate Figure 3 intersecting point falls at 4.00 pounds.

3.2.4 30 min. Duration Absorbent Load. The results verify the anticipation that this relationship is non-existent. When absorbent weight has been reduced until about 3.5 pounds remain, the expired gas CO_2 wavefront will, in all cases, be deposited directly into the inhalation bag.

3.3 Effects of Modifications Upon Minute-to-Minute Functional Indices. Figure 4 illustrates the relationships of three sets of data. Reductions of absorbent load have two effects: the curve is shifted to the left (decrease) on the time scale, while it becomes increasingly steep, in other words, with a lesser absorbent mass, the time to the breakthrough point shrinks, and, once breakthrough is reached, deterioration to the non-functional state accelerates:

ABSORBENT WEIGHT(LB)	SWIM DURATION(MIN)	RESERVE DURATION(MIN)
5.44	123	21
4.41	75	19
3.60	41	12

3.4 Gasflow Resistance. Static pressures measured at the canister entrance fitting are listed in Table VI. The differences between observed values for empty and freshy-packed canisters indicate contributions of the absorbent load to the total resistance. Two patterns emerge as use time increases: pressures either stabilize and remain largely constant, or they increase steadily. Figure 5 was constructed by plotting calculated gas-flow resistances (cm H_2O/liter/sec.) against elapsed use time. All values of gasflow resistance pertain to the mean expired gas flow rate only, and the shape of each curve, therefore, has been determined by the observed resistance figures. Variations of flow rates perhaps influenced the relative positions of the curves, but this is not so readily accessed.

3.5 Underwater Swimming Tests. For reasons heretofore examined, the limited number of these runs with diver-subjects was not expanded. Table III includes the data for surface swims with an unmodified, standard canister, and for three tests with the minimal absorbent weight (2" rod) modification. A series of six working dives using routinely-prepared, fully-charged canisters and granular Baralyme absorbent has been reported for relevant interest. Three fundamental observations derive from the listed results:

(1) There is a 50% variability from one swimmer to another, despite identical ambient stress factors and work load imposition.

(2) Variability of this degree, appearing in a small sample panel, was not anticipated.

TABLE

PREDICTED PELLET BARALYME RE
SWIMMING

(USING MODIFICATIONS OF THE U.
CLOSED CIRCUIT RIG CANISTE

SWIMMING DURATION LIMITS (MINUTES)	PELLET B WEIGHT (
120	5.17
110	4.9
100	4.8
90	4.6
80	4.4
70	4.2
60	4.0

E V

EQUIREMENTS FOR SPECIFIED
DURATIONS.

J. S. NAVY STANDARD OXYGEN
TER AS DESCRIBED.)

BARALYME (POUNDS)	PELLET BARALYME LOAD REDUCTION (LB.)
17	0
97	0.20
82	0.35
55	0.52
49	0.68
27	0.90
00	1.17

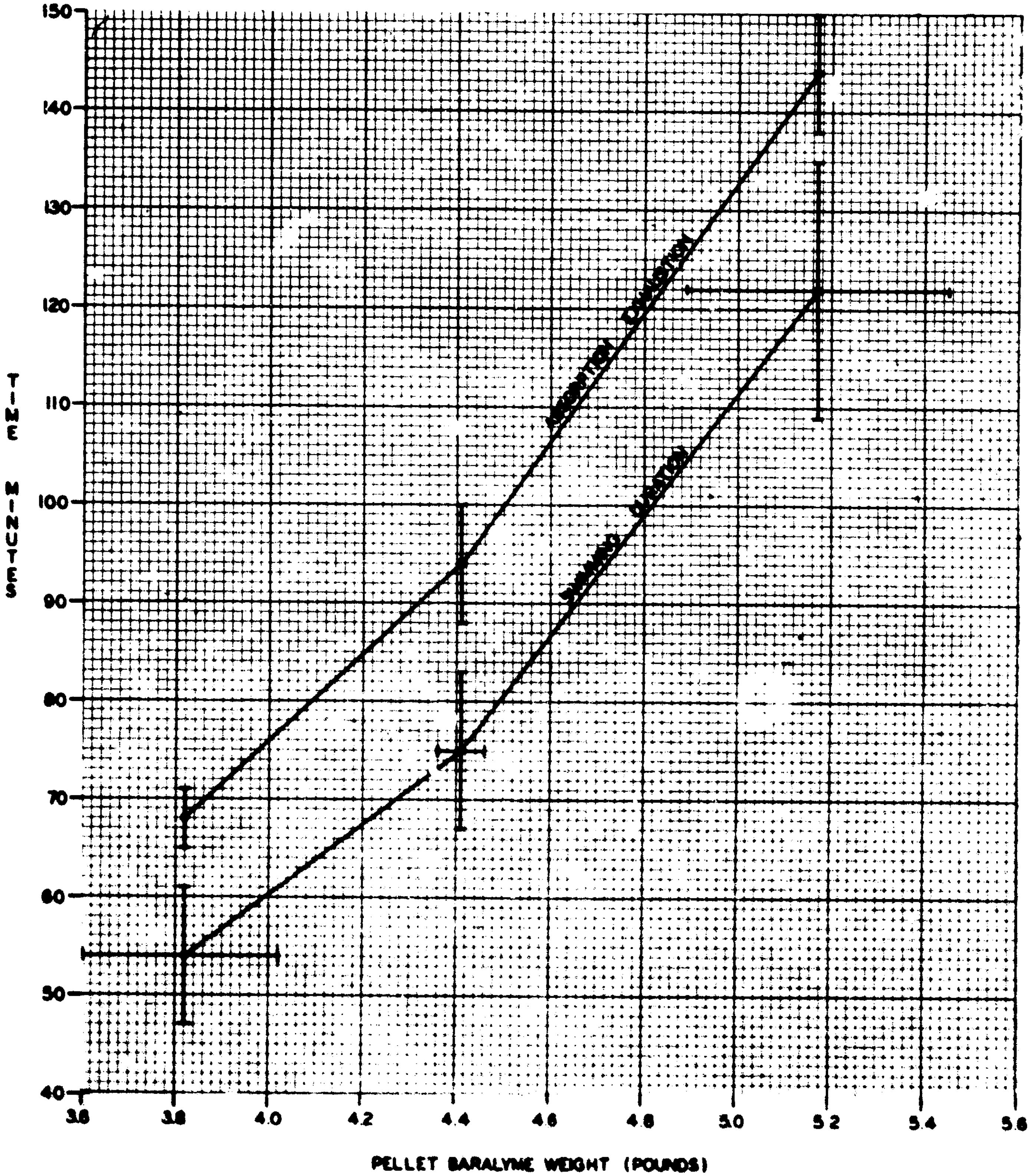


FIGURE 3. ABSORBENT WEIGHT - DURATION CURVES. ENTERED WITH SWIM DURATION, OR ABSORBENT WEIGHT, THE OTHER IS FOUND INTERSECTING ON THE DURATION LIMIT CURVE. ONE STANDARD ERROR OF THE MEAN IS IDENTIFIED. RESERVE TIME (BREAKTHROUGH TO FAILURE) IS THE VERTICAL DISTANCE BETWEEN CURVES.

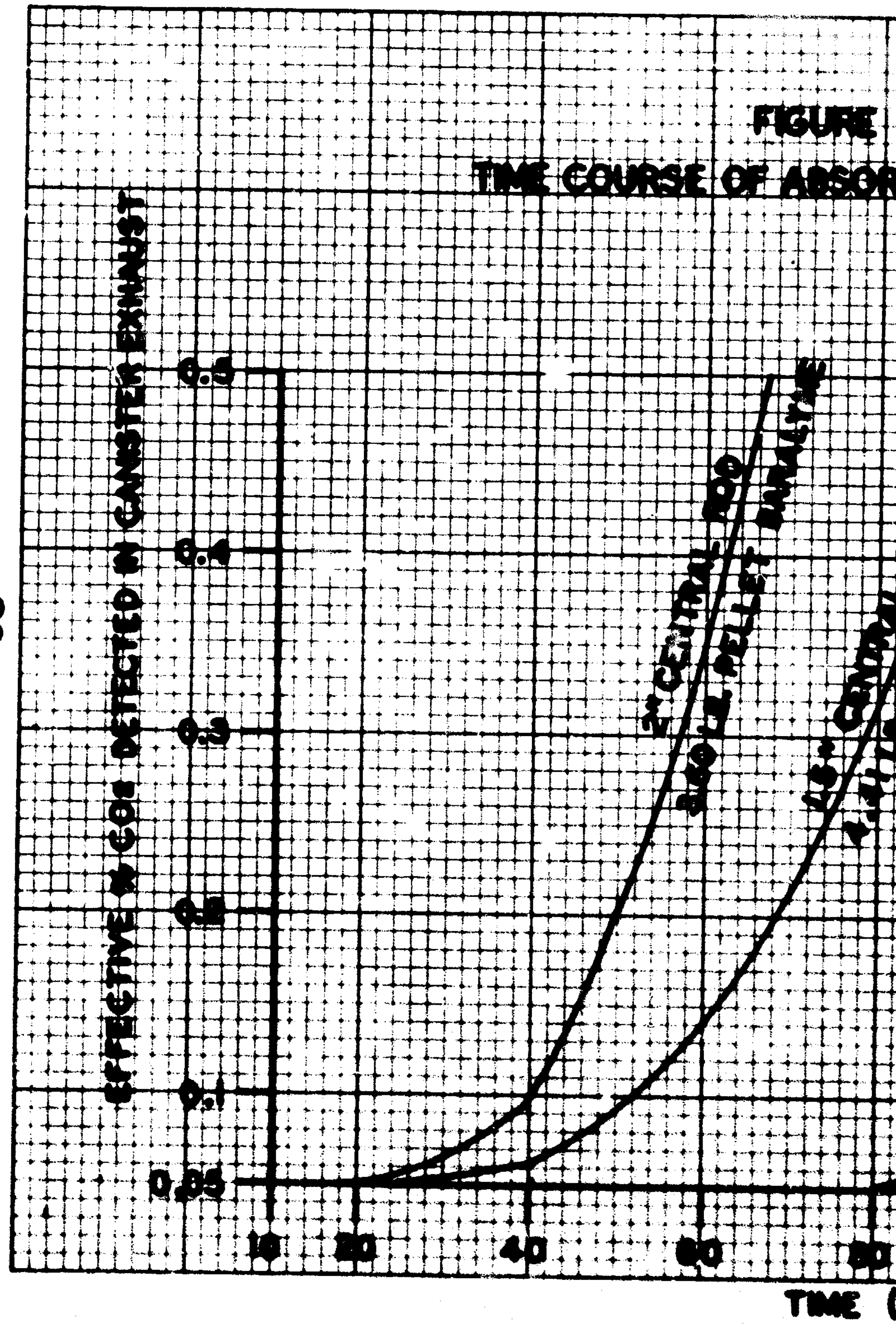
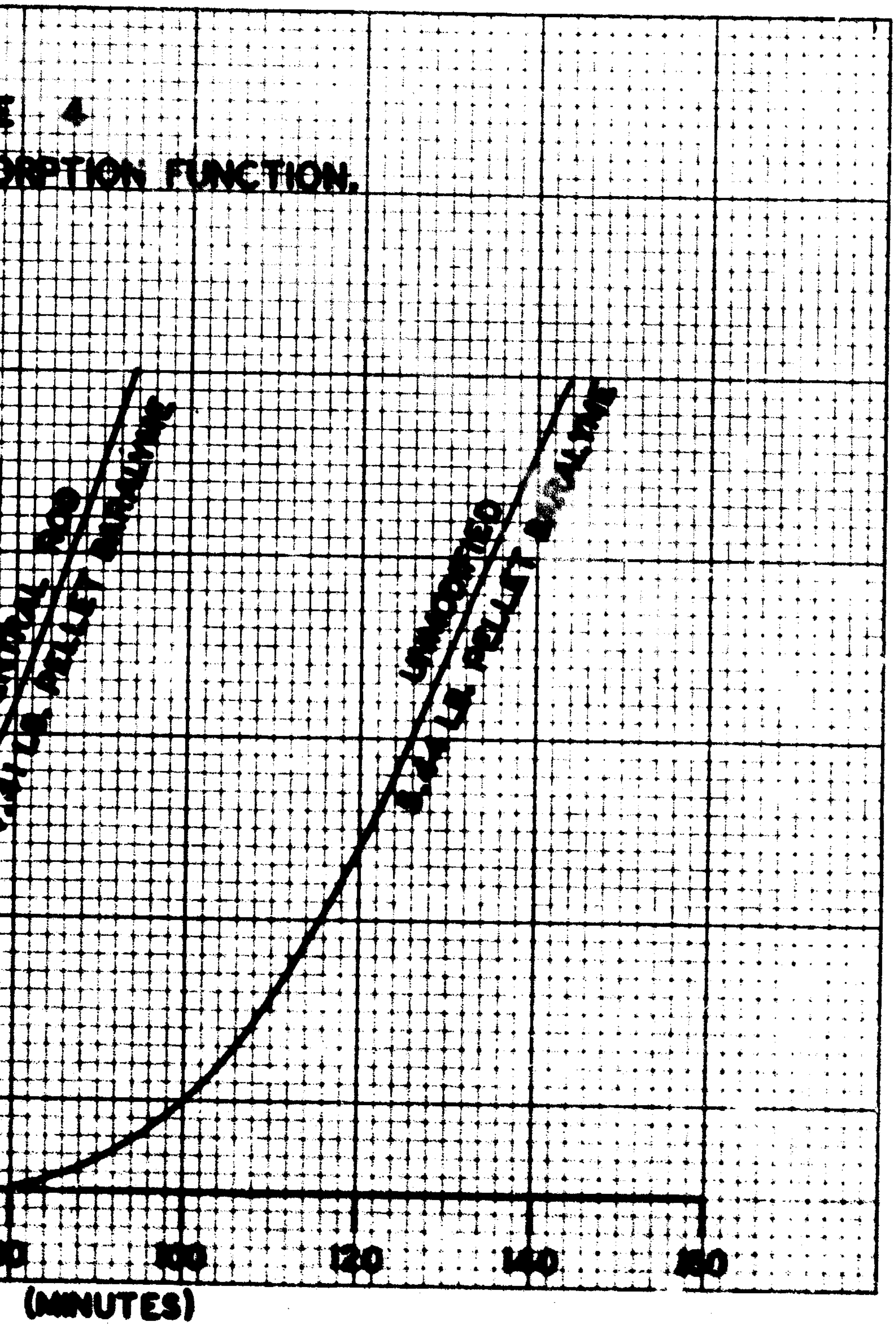


FIGURE
TIME COURSE OF ABSOR
EFFECTIVE % CO_2 DETECTED IN CANISTER EXHAUST
0.5
0.4
0.3
0.2
0.1
0.05
10
20
40
60
80
2" CENTRAL ROD
3.60 LB. PELLET BARALYME
1.5" CENTRAL
TIME (



ORPTION FUNCTION.
URANIUM ROD
PELLET PARALYNE
UNCOATED
PELLET PARALYNE
100
120
140
160
(MINUTES)

(3) The dive which produced a duration endpoint nearly identical to the mechanical-respirator endpoint constitutes an unexpected result, suggesting that only guarded trust be placed upon the conservative biases designed into the laboratory experiments. To promote a state of maximal diver safety and effectiveness, and in view of the sparse subject panels generally available for testing procedures, the largest number of subjects which can be assembled should be tested. Rigid control should be maintained on the applications of mechanical test results.

4. DISCUSSION

4.1 Reduced Canister Loading, Experiences Previously Reported

4.1.1 Drager Closed-Circuit Oxygen Rig. Lanphier (17) concluded that reduction of either the canister volume capacity of the normal full-charge weight of pellet Baralyme rendered the unit practically non-functional. Canister loads approximately 43-48% of full weight capacity were consistently associated with reduced swimming durations of 85-90% magnitude. Three distinct approaches to structural alteration methods, productive of equal load reductions, were attempted. All resulted in uniformly inadequate and hazardous duration characteristics.

4.1.2 U. S. Navy Experimental Diving Unit Research Report 1-60 "Standard" Canister. An insulated, 2.35-liter volume, 2500-gram capacity (5.5 lb) evaluation canister was tested by serially reducing the granular Baralyme loadings (13). Observations reported may be expressed as follows:

ABSORBENT WEIGHT (LB)	SWIM DURATION (MIN)	% REDUCTION OF FULL WT.	% REDUCTION OF FULL TIME
5.52	200	0	0
3.85	91	35	55
2.65	31	52	85

This study suggests that the effect upon duration caused by reduced loading will be in terms of some multiple of the weight reduction unit. The relationship, one to the next, of the serial weight reductions is not linear, and therefore, one tentatively concludes that all such initial steps are almost certain to be in the direction of increased hazard. Referencing Huseby's values to the greater stresses of the present test suggests that lower duration results would be observed. It seems justified to presume that all attempts to manipulate absorption systems in this manner will be rewarded with similar geometrically greater functional losses.

4.2 Resistance Characteristics and the Physiology of CO_2 Intoxication.

Accumulated knowledge of the spectrum of responses of working underwater swimmers to physiological stresses occurring when high-oxygen breathing mixtures are respired, indicates that complex mechanisms are operative. Canister functioning can influence these mechanisms by either of two discrete effects, singly or by interaction. CO_2 passage through the canister into the inhaled gas is the patently obvious influence.

TABLE III

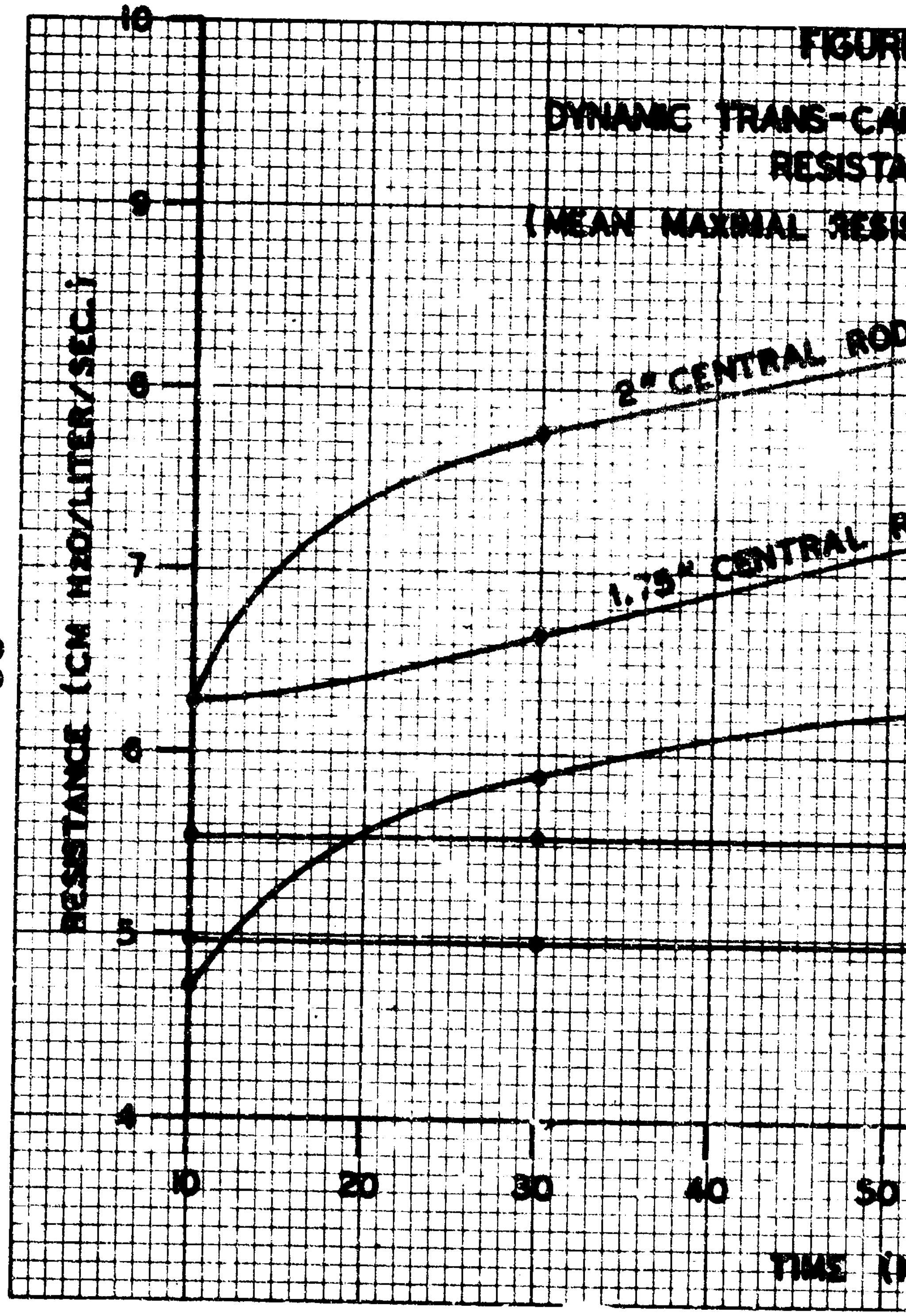
EFFECT OF MODIFICATION UPON RESISTANCE, ABSORBENT VOLUME AND INTER-GRANULAR SPACE VOLUME

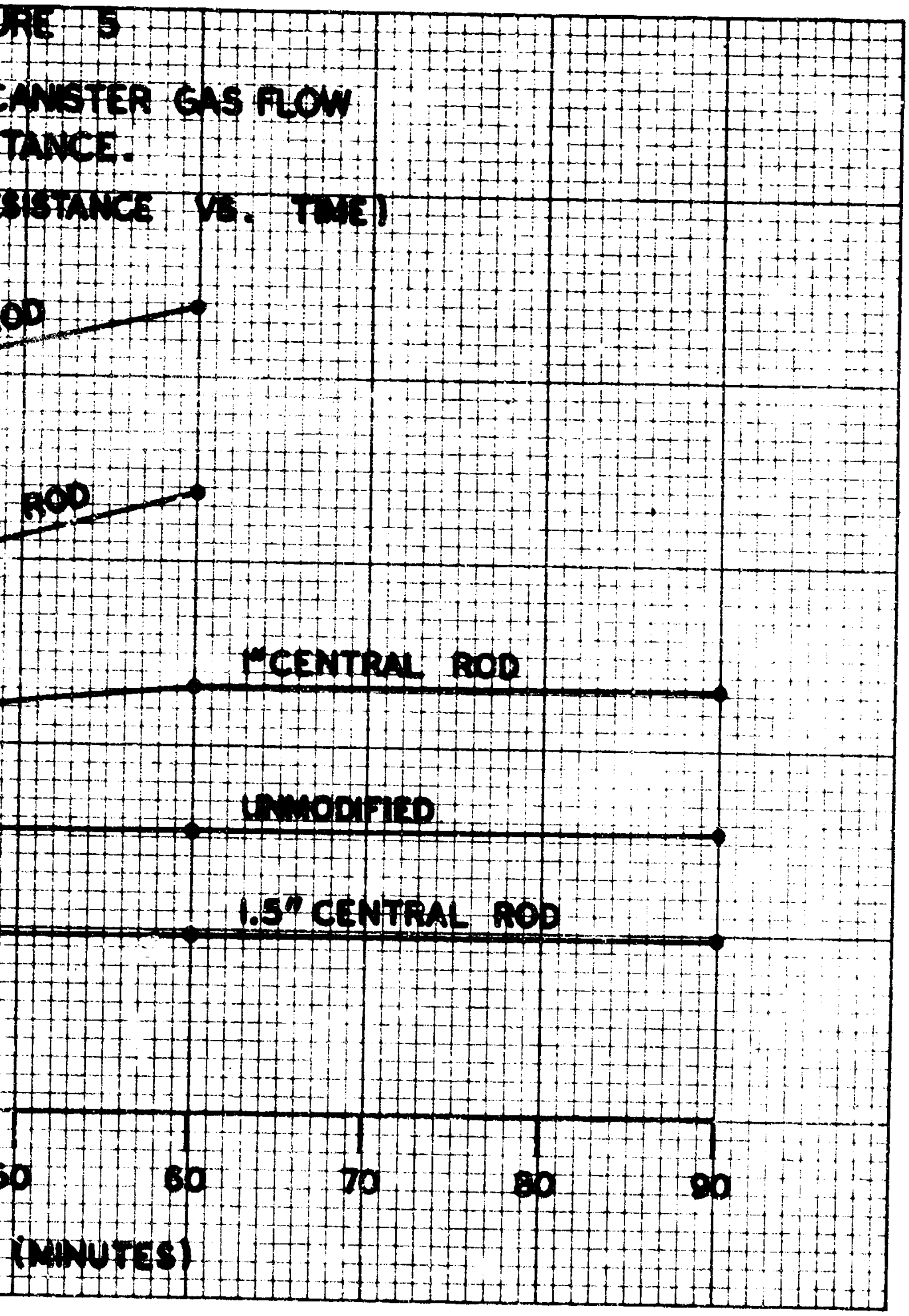
CANISTER CONFIGURATION	MEAN GAS-FLOW RESISTANCE (CM H_2O)						EI...
	EMPTY	PACKED	10 MINUTES	30 MINUTES	60 MINUTES	90 MINUTES	CAN...
UNMODIFIED	0.7	4.8	7.2	7.2	7.2	7.2	3.[illegible]
1" CENTRAL ROD	0.7	4.3	—	8.7	·	7.2	3.[illegible]
1.5" CENTRAL ROD	0.9	4.3	7.2	7.2	7.2	7.2	2.[illegible]
1.75" CENTRAL ROD	1.0	4.8	8.6	9.1	10.1	—	2.7[illegible]
2" CENTRAL ROD	1.2	5.7	7.7	10.6	11.5	—	2.5[illegible]

VI

MEAN BULK AND APPARENT DENSITY RELATIONSHIPS

MEAN VOLUME DATA (LITERS)			BULK DENSITY GRAMS ABSORBENT/ CC. VOLUME	APPARENT DENSITY GRAMS ABSORBENT/ CC. ABSORBENT
EMPTY CANISTER	ABSORBENT CHARGE	INTER-GRANULAR SPACE		
3.350	2.600	0.750	0.732	0.948
3.150	2.320	0.830	0.701	0.952
2.910	1.980	0.930	0.686	1.005
2.750	1.850	0.880	0.674	0.984
2.560	1.707	0.853	0.636	0.954


FIGUR
DYNAMIC TRANS-CA
RESISTA
(MEAN MAXIMAL RESIS
2" CENTRAL ROD
1.75" CENTRAL R
RESISTANCE (CM H2O/LITER/SEC.)
10
9
8
7
6
5
4
10
20
30
40
50
TIME (



...URE 5
...CANISTER GAS FLOW
...TANCE.
...SISTANCE VS. TIME)
...OD
ROD
1" CENTRAL ROD
UNMODIFIED
1.5" CENTRAL ROD
...0
60
70
80
90
(MINUTES)

Significant resistance to gas flow through the canister is the other. Reference to the data of Table VI and Figure 5 illustrates that resistance increases toward a maximum as swim time increases and, therefore, exerts its greatest effects when the tired diver may be least able to supply the compensatory ventilatory responses. Zechman (21) and others have shown that compromised alveolar ventilation occurs when expiratory resistance mounts. With this foundation, it can be postulated that a diver using the so-called "60 minute load," for example, can become a victim of acute CO_2 intoxication even though this obviously-inadequate canister still removes most of the carbon dioxide. Sufficient experimental data to estimate how much real potential risk is involved is not now available. However, the concept here emphasized is that canister influences may be exerted by multiple mechanisms.

4.3 Unanticipated Aspects of the Experimental Data. The observed acceleration of progress from breakthrough to exhaustion which was seen to characterize successive reductions of the absorbent weight exceeded pre-test expectation. Retrospectively, this strengthens the 0.25% CO_2 endpoint selection. It also compromises the conservative bias factors of experimental design. The range of variation, "individual variability," occurring in the underwater swim tests far exceeded the anticipated magnitude. Presumably, we are hereafter obligated to assume that, should the test population be sufficiently large, some examples of absolute canister exhaustion will occur very early in the time span of the stress. It is axiomatic that individuals are, after all, individual. However, the basic mechanisms of life processes and the limits imposed by physiological regulation are common to all members of a species. and are basic to the universally-encountered similarities of the species. It is recognized however, that some healthy people consistently respond to stresses in a manner or degree which is abnormal, i.e., outside the "normal range." For any individual, it is just about impossible to predict that this can occur. There are a number of well-known factors which are universally recognized as significant for the diver and his safety underwater: degree of training, proficiency and self-confidence, motivation, anxiety, experience, etc. It seems inescapable to conclude that sooner or later the chance meeting of a reduced-load canister which fails too rapidly, with a diver who exhibits responses outside the "normal range" will occur. A fatality may result. This conclusion, of course, leads to an equally inescapable recommendation: there is no justification whatsoever for utilization of the reduced canister load concept.

4.4 Canister Testing Methods. There is no doubt that laboratory evaluations are as basic to canister study as they are to the entire effort to advance any technology. Primarily, however, this should be limited to basic design studies. Full evaluation requires human testing. This is essential and cannot be overemphasized. It is equally essential to employ the largest possible groups of subjects in working, swimming trials.

4.5 Fiscal Motivation for Deployment of Modified Canisters. A group of 50 dives made with the specified 90-minute absorbent loading (Figure 3) will necessitate the obligation of about $75.00 for pellet Baralyme purchases (at $-.32/lb). If the maximally obtainable packed-canister weight was employed for each one of a second group of 50 dives, with the unmodified, standard apparatus, the comparative expense would approximate $87.00. Budgetary impact, would, therefore, be somewhat less than $250 per 1000 dives. Not considered, but worthy of mention, is the expectation that modification costs could be substantial, e.g. at least $2-$3 per canister per plastic rod.

5. CONCLUSIONS

5.1 Reduced Canister Loading: Concept and Practice. No consistently-beneficial effects upon performance have been shown to occur with these canister modifications whereas, conversely, progressively-mounting compromise of the system seems to be inevitable. Fiscal advantages are quite limited. In the absence of convincing justification for acceptance of the increased risks to personnel, it is concluded that condemnation of this as a practice can hardly be overemphasized.

5.2 Reduced Canister Loading: Data. A potentially-useful body of data has been generated. This data lends credence to, for example, the claim that canister function and canister-volume capacity for the expired tidal breath are closely linked (Appendix A). The total impact of the data is, of course, of greatest pertinent importance: it is the basis for conclusions that these canisters ought not to be so modified.

5.3 Standard Closed-Circuit Rig Canister. Provision of a starting point for this study required that the unmodified canister be subjected to the same stresses as used throughout all the runs. Results of runs made with the standard canister lead to the following conclusion: when used with pellet Baralyme, in manner similar to that herein described, the canister function is adequate for at least two hours of continuous underwater swimming.

5.4 Future Canister Design-Function Studies

(1) While laboratory-type investigators will continue to contribute to the fund of knowledge, it is concluded that underwater swimming studies, with the largest possible number of subjects are essential.

(2) No blanket condemnation of attempts to modify existing canister-absorbent systems would be sensible, but this is probably not the most rewarding approach to the task. Establishment of project designation and status for on-going canister study and development is suggested. A mode of canister modification which could prove to be fruitful, and which deserves feasibility testing, is the use of venturi-systems with scuba canisters. This approach might elevate the present 25-30% efficiency ceiling to the neighborhood of 90-100% (see Appendix C: Carbon Dioxide Absorption System Design Concepts - Suggestions).

5.5 Future Physiological Studies. Full exploitation of absorption systems information is prevented by the absence of a firm understanding of several human factors. Studies such as those listed, following, are suggested to narrow the information gap which separates engineering and physiological sciences:

(1) Tolerance to breathing resistance loads should be investigated so that apparatus specifications can be established on a firm and rational basis.

(2) Concurrent quantitative study of the effects of expiratory resistance upon alveolar ventilation and carbon dioxide elimination could be undertaken.

(3) Verification of the predisposition for CO_2 retention and acute respiratory acidosis when 100% oxygen is breathed during underwater swimming is long overdue.

(4) Inquiry into the mechanisms governing the phenomena of response variability to respiratory gas tension and breathing resistance stresses is needed to define feasible selection characteristics.

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APPENDIX A: CALCULATED INDICES OF ABSORPTION SYSTEM FUNCTION

1. Intracanister Accomodation of Expired Gas.

(1) The center grouping of figures of Table VI includes the mean data for: measured canister floodable volumes; measured pellet Baralyme absorbent charge volumes; computed intergranular space volumes. Although the last-noted parameter has been presented as if it was equivalent to the simple arithmetic difference of the first two volumes, this is not completely accurate. It has proven to be a useful compromise, however, in studying the relations of the several canister modifications one-to-another insofar as this particular parameter is concerned. The complexities which would be encountered in an effort to measure the true void space of a packed canister are appreciative. The method is in part analagous to the pore space estimation related in paragraph 1.2. It has been suggested by Adriani (1) and others that intracanister-gas space should be of such capacity to accomodate any expired tidal volume. This would ensure that the whole of any expired breath (except the end-tidal portions) would be exposed to and acted upon by the chemical absorbent during the succeeding inhalation and post-inspiratory pause phases of the respiratory pattern. Occurring as a function of the normal expired breath flow pattern is an advancing wavefront of considerable carbon dioxide content. High peak expiratory flows and large expired tidal volumes may in some circumstances, therefore, lead to actual dumping of CO_2-rich gas beyond the active absorbing surfaces. An example of such a situation has, in this study, proven to be the reduced canister load.

(2) The total intracanister space available within the packed canister is conventionally divided into two subvolumes.

1.1 Void Space. The spaces between adjacent absorbent particles, and between particles and canister structures are regulated primarily by particle size, particle shape, and the methods employed in canister packing. A column of Table VI headed, "Intergranular Space" reports these computed values.

1.2 Pore Space. The microscopic-dimension channels which invade and indent the surface of each pellet summate for all the pellets present into the pore space volume. This volume is determined primarily by the manufacturing process, as it varies inversely with the absorbent density. Since the surfaces at which the chemical reactions of CO_2 elimination take place are those which surround and form the pore spaces, it follows that pore-space volume will decrease as usage time mounts and the water of reaction collects. Brown's method (2) for determination of the pore-space volume per gram of absorbent was employed to evaluate a representative pellet Baralyme sample. The details of this procedure will not be reproduced, because the methods employed by Brown are so comprehensively related in his reports. In general, the order of events is to first determine the weight of the sample of absorbent, then the volume of the same sample and, finally, the pore volume of the sample. The pore-volume estimation requires the assumption that the pores can be filled with selected organic fluids of known specific gravity (capryl alcohol, S.G.=0.820)

MEASUREMENT OR CALCULATION	RUN #1		RUN #2
weight of volumetric flask, grams	18.205		17.355
weight of flask & absorbent, grams	31.800		30.510
weight of absorbent, grams	13.595		13.155
weight of flask filled with absorbent and capryl alcohol, grams	46.605		45.465
volume of capryl alcohol, ml.	18.055		18.235
volume of absorbent sample, ml.	6.945		6.765
computed specific gravity of absorbent	1.958		1.945
(mean)		(1.952)	
weight of flask and dried absorbent sample, grams	32.875		31.845
weight capryl alcohol retained in pores, grams	1.075		1.335
pore volume	1.311		1.628
pore volume per gram of absorbent, ml.	0.096		0.123
(mean)		(0.110)	

1.3 Estimation of Total Intracanister Gas Volume

(1) Computed values for the pore space of the absorbent, and for the void space of each canister-absorbent modification can now be presented. Without regard to the degree of precision which characterizes these numbers, their application to absorption system design will also be illustrated.

CANISTER CONFIGURATION	PELLET BARALYME WEIGHT, GRAMS	PORE VOL. LITERS	VOID VOL. LITERS	TOTAL, PORE & VOID VOL., LIT.
unmodified	2458	0.270	0.750	1.020
1" central rod	2212	0.243	0.830	1.073
1.5" central rod	1993	0.219	0.930	1.149
1.75" central rod	1880	0.201	0.890	1.091
2" central rod	1628	0.179	0.853	1.032

(2) Comparisons of the total intracanister gas volumes thus computed with the expired tidal volumes presented to the canisters shows that, in all cases, the volume requirement was more than twice the volume capacity. The basis for this emphasis rests on the validity of the canister design precept regarding capacity to contain the whole of an expired tidal volume.

CANISTER CONFIGURATION	TOTAL INTRA-CANISTER GAS VOL. (LITERS)	MEAN TIDAL VOL., LITERS	RATIO TIDAL VOL. TO GAS VOL.
unmodified	1.020	2.48	2.43
1"	1.073	2.17	2.02
1.5"	1.149	2.77	2.41
1.75"	1.091	2.62	2.40
2"	1.032	2.62	2.54

Unfortunately, no firm conclusion can be founded upon these figures because of the variations in tidal volumes which occurred. Several criteria of good absorption system performance, as reported in this study, were best satisfied by the one-inch central rod modification. However, the smallest tidal volume stresses also were observed in this category.

2. Basic Considerations of CO_2 Elimination. The factors which interact to determine the system performance characteristics can themselves be combined and condensed to four entries. These are:

(1) gas-stream concentration of the component to be eliminated

(2) component-absorbent contact time

(3) physical state of the absorbing surface

(4) rate constant governing the gas-solid chemical reaction kinetics

The first two entries of this tabulation have just been discussed. A brief consideration of the remaining pair of factors, in terms of the values of absorption efficiency here observed follows (below).

3. Capacity and Efficiency Computations

3.1 Baralyme-Carbon Dioxide Reaction. Pellet Baralyme is a proprietary mixture of 20% barium hydroxide octahydrate and 80% calcium hydroxide. The compressed pellets are formulated without inert binder. The reaction sequence is:

(1) $Ba(OH)_2 \cdot 8H_2O + CO_2 \longrightarrow BaCO_3 + 9H_2O$

(2) $9H_2O + 9CO_2 \longrightarrow 9H_2CO_3$

(3) $9H_2CO_3 + 9Ca(OH)_2 \longrightarrow 9CaCO_3 + 18H_2O$

Practical significance attends that last noted reaction product: water. Depending on canister design, it may become an important progenitor of trans-canister gas flow resistance, caused by caking of wet contiguous masses of the chemical. The theoretical absorption capacity of pellet Baralyme can be shown to approximate 225 grams of CO_2 per pound of pellet Baralyme or 0.497 grams CO_2/gram pellet Baralyme. (Additional discussion of the importance of the water of reaction and of other chemical properties can be found in Appendix C.)

3.2 Calculation of Absorption Efficiency

3.2.1 Method. Table VII lists values for efficiency of CO_2 absorption calculated from the experimental data. For purposes of the computation it was necessary to assume a time limit for 100% absorption reacting. The observed time to breakthrough was applied in each case. The calculation protocol consisted of the following steps:

(1) (CO_2 production LPM, STPD)(Time, min.) = CO_2 absorbed, LITERS, STPD

(2) (CO_2 absorbed, liters, STPD)(1.9768 gm. CO_2/liter CO_2) = CO_2 absorbed, grams

(3) (Pellet Baralyme Wt., grams)(0.497 Gm CO_2/Gm. Baralyme) = CO_2 absorption capacity, grams

(4) (CO_2 absorbed, grams/CO_2 absorption capacity, grams)(100) = % absorption efficiency

3.2.2 Results. These are reported in Table VII. Obviously, these calculated quantities representing total CO_2 absorbed have meaning only in a relative sense. It is seen that the efficiency values fall within the customary range and, perhaps, this suggests that the calculated totals for CO_2 absorption used in these computations can be taken as estimates of the true values. Attention is called to the 23% absorption efficiency level of the one-inch central rod modification. This is, essentially, unchanged from the control quantity.

COMPUTED INDICES OF ABSORBENT SYSTEM FUNCTION

CANISTER CONFIGURATION	TEST NO.	TOTAL CO_2 ABSORBED		ABSORBENT LOAD CO_2 CAPACITY (GRAMS CO_2)
		LITERS (STPD)	GRAMS	
UNMODIFIED	1.	144.2	286	1240
UNMODIFIED	2.	135.2	268	1223
UNMODIFIED	3.	130.7	258	122[illegible]
	MEAN	136.7	271	1229
1" CENTRAL ROD	1.	115.1	229	[illegible]12
1" CENTRAL ROD	2.	134.8	266	1105
1" CENTRAL ROD	3.	122.6	242	1095
	MEAN	124.[illegible]	[illegible]	[illegible]
1.5" CENTRAL ROD	1.	95.1	175	1010
1.5" CENTRAL ROD	2.	[illegible]	172	985
1.5" CENTRAL ROD	3.	97.6	176	995
	MEAN	92.9	175	997
1.75" CENTRAL ROD	1.	[illegible]	[illegible]	915
1.75" CENTRAL ROD	2.	[illegible]	13[illegible]	915
1.75" CENTRAL ROD	3.	48.7	96.8	915
	MEAN	53.0	[illegible]	815
2" CENTRAL ROD	1.	[illegible]	[illegible]	815
2" CENTRAL ROD	2.	[illegible]	[illegible]	[illegible]
2" CENTRAL ROD	3.	65.5	129	[illegible]
	MEAN	64.5	123	814

TABLE VII

DERIVATION DATA FOR WEIGHT–DURATION CURVES

EFFICIENCY % CO_2 ABSORBENT / CAPACITY	MEAN ABSORBENT WEIGHT (POUNDS) AND STANDARD ERROR	MEAN DURATION (MINUTES) AND STANDARD ERROR	MEAN RESERVE TIME (MINUTES) AND STANDARD ERROR
23			
22			
21			
22	5.17	122	22
21	± 0.28	± 13.3	± 7.2
24			
22			
23			
17			
20	4.41	75	18
18	± 0.05	± 8.0	± 5.5
18			
15			
14			
11			
13	[illegible]	54	14
15	± 0.24	± 6.9	± 3.2
17			
16			
16			

APPENDIX B: DERIVATION OF AN EQUATION TO RELATE ABSORBENT WEIGHT AND DURATION

1. Data for Weight-Duration Curve Plotting. The general shape of each of the curves reproduced in Figure III suggests that a linear plot would result from a log-log paper data fit. Preliminary to this additional study was the need to select a suitable series of co-ordinates. Ten absorbent weight data points where chosen from the experimental results. The only standard employed for the selection was the desire to use both extremes of observed weight magnitude, and between them to obtain representative intervals of weight changes. Following, below, is a table which lists these data points. Ranking is from highest to lowest measured absorbent weight. The right-hand columns report changes of a parameter, e.g., weight, both as an absolute reduction of the full load (pounds) and as a proportion of the full load (percent). It was noted, empirically, that curves or equations for these values express the interrelationships of weight and duration accurately, while supplying added attention to the terminally-accelerating functional reserve duration shrinkage observed with the smaller absorbent loadings.

ABSORBENT WEIGHT(LB)	SWIMMING DURATION(MIN)	RESERVE DURATION(MIN)	WEIGHT REDUCTION	SWIM DUR REDUCTION	RESERVE REDUCTION
5.48 lb.	136 min.	22 min.	0 lb(0%)	0 min(0%)	0 min(0%)
5.44	123	19	0.04(0.7)	13(9.5)	3(14)
5.17	122	22	0.31(5.7)	14(10)	0(0)
4.84	114	21	0.64(12)	22(16)	1(4.5)
4.46	82	14	1.02(19)	54(40)	8(36)
4.41	75	19	1.07(20)	61(45)	3(14)
4.35	67	[illegible]	1.1[illegible](21)	69(51)	3(14[illegible]
4.05	63	[illegible]	1.43(26)	73(54)	7(32)
3.84	54	14	1.64(30)	82(60)	8(36)
3.62	52	11	1.86(33)	84(65)	11(50)

2. Derivation Method. Weight-duration plots were placed on 2 cycle X 3 cycle logarithmic paper. Although a simple method-of-estimates procedure was employed, the observed linear data fit was assumed to represent at least a parallel approximation of some true fit. Therefore, the pellet Baralyme weight-swimming duration relationship should be described by an equation based upon the general expression for a logarithmic curve:

$$Y = aX^n$$

By taking the base ten logarithms of each factor the expression can be made to adhere to the form of the general linear expression ($Y = a + mX$):

$$\log Y = \log a + n\log X$$

Processing of matched data pairs enabled slope factors (m) and y-axis intercept factors (a) to be derived. The equation predicting duration as a result of pellet Baralyme weight was determined to be:

log time, min. = (1.354)(2.740 log weight, lb.)

3. <u>Application Validity</u>. Two independent sets of data which were produced by experiments comparable to those of the present study were used to examine the validity of this expression. It appears that this simple, non-rigorous treatment does predict the direction and intervals of a series of changes superimposed upon a common, basic system structure. Emphasizing that absorption system design is susceptible to orderly treatment, based upon firm bioengineering data, was the fundamental objective of these computations, and mathematical sophistication was not attempted. That a logarithmic relationship characterizes the weight charge-swim duration curves is of itself, of course, of the utmost importance to any swimmer contemplating open-sea deployment of a compromised absorption system.

APPENDIX C: CARBON DIOXIDE ABSORPTION SYSTEM DESIGN CONCEPTS: SUGGESTIONS

1. Conventional and Theoretical Chemical CO_2 Absorbents. Primarily by virtue of a chemical-family grouping, it is convenient to classify chemical CO_2 removing agents into four categories. The causticity properties typical of these groups, together with the cumulative practical experience in the utility of certain chemicals, provides a basis for group study of numerous individual substances.

(1) HYDROXIDES OF ALKALINE METALS	MOL. WEIGHT OF THE METALIC ELEMENT	SOLUBILITY (GM/100 ML.) COLD WATER	HOT WATER
cesium, CsOH	132.905	395.5(15°C)	- - -
rubidium, RbOH	85.47	180.0(15°C)	- - -
potassium, KOH	39.102	107.0(15°C)	178.0(100°C)
sodium, NaOH	22.989	42.0(0°C)	347.0(100°C)
lithium, LiOH	6.939	12.7(0°C)	17.5(100°C)

(2) HYDROXIDES OF ALKALINE EARTH METALS			
barium, $Ba(OH)_2 \cdot 8H_2O$	137.34	5.6000(15°C)	94.700(78°C)
strontium, $Sr(OH)_2$	87.62	0.4100(0°C)	21.830(100°C)
calcium, $Ca(OH)_2$	40.08	0.1850(0°C)	0.077(100°C)
magnesium, $Mg(OH)_2$	24.312	0.0009(18°C)	0.004(100°C)

(3) ADSORBING AGENTS

silica gel, anhydrous
charcoal, activated
molecular sieves

(4) MISCELLANEOUS

ammonia
organic amines
ion-exchange resin

2. Summary of CO_2 Absorption Chemistry. The affinity of a base (alkali) to react with carbon dioxide is a property of the metalic element involved in hydroxide formation. This, in turn, is determined by the position of the metal in the electromotive series. The alkaline metals (group 1, above) include the most active hydroxides because they occupy superior positions in the electromotive series. Common to most of the reaction sequences is the preliminary step of water-CO_2 combination, yielding carbonic acid. (Therefore, some water ought to be available from the absorbent itself, at least at the start.) Dissociation of carbonic acid into hydrogen and bicarbonate ions occurs, while hydroxyl ions are supplied by the ionized alkaline absorbent. The neutralization of carbonic acid is typically exothermic. Thus, the familiar absorption reaction characteristics of exothermia and water accumulation are not unanticipated. Deserving of emphasis is the high solubility in water of both sodium and potassium hydroxides; given a source of humid gas, saturated solutions can be produced. Barium hydroxide, conversely, while known to ionize to an extent similar to that of sodium hydroxide, does not produce highly caustic solutions with water because it is, comparatively, rather poorly soluble. Observed degrees of causticity relate directly to solubility.

2.1 Alkaline Metals. Although it contains one of the less reactive elements of this group, sodium hydroxide is extensively utilized because it is relatively inexpensive and easy to produce. Potassium hydroxide possesses a comparable degree of causticity, but it is probably somewhat less desirable for CO_2 absorption purposes because of its hygroscopic properties. Lithium hydroxide has been extensively applied to fulfill closed-atmosphere system CO_2 absorption requirements in submarines. This chemical is less soluble and loses activity as the water of reaction accumulates. It has proven satisfactory for submarine requirements and may be used either within the canisters of portable blower assemblies or by manual spreading techniques. The low molecular weight of lithium may make this absorbent particularly suitable for scuba applications. It is, relatively, non-caustic, but is well known to produce an irritating chemical dust.

2.2 Alkaline Earth Metals. Barium and calcium are widely applied for CO_2 absorption purposes. Although strontium is more active, chemically, than calcium, it is far less abundant in nature. Magnesium (as well as aluminum, zinc, copper, silver and gold) hydroxide is too relatively inactive to be suitable.

2.3 Adsorbing Agents and Miscellaneous Absorbent Groups. Attending practically each agent listed are objections to its applicability for use in SCUBA canisters. This is especially in reference to contemporary canister system characteristics, which are probably not adaptable for use with these chemicals. The properties of causticity, toxicity or efficiency are not uniformly optimal either.

2.4 Suggested Parameters for an Improved Absorbent for Scuba. The objections to using hydroxides of alkaline metals rests with their potential to react with (dissolve in) water, producing dangerously caustic solutions. Pellet Baralyme, $Ba(OH)_2 \cdot 8H_2O\text{-}Ca(OH)_2$, is practically free of the risk just noted. The caustic chemicals readily bind all available water in solutions. In comparison, the water of reaction liberated by Baralyme often initiates faceplate condensation when employed with the U. S. Navy deep sea Helium-Oxygen canister. It has been suggested to the author (CDR R.D. WORKMAN, (MC), USN, personal communication) that the possibility of combining a less-caustic alkaline metal hydroxide with a proven moisture absorbent could produce an advanced absorption material. Lithium hydroxide and activated charcoal might be thusly investigated. Absorbent characteristics of shape, e.g., pellets or granules, hardness, dusting proclivities, etc. retain their significance and should be considered as influencing channeling tendencies and resistance effects when mated to a canister.

PROPERTIES OF A POSTULATED IDEAL SCUBA CO_2 ABSORBENT

rapid CO_2 neutralizing capability
moderate exothermia
no excess of water removal or addition
resistant to waterlogging with continued use
light to moderate weight (absorbent wt./volume)
sufficient hardness and density to resist dusting, breakage, while maintaining pore volume
large CO_2 absorption capacity
low order of causticity; no toxicity; odor free
long shelf life; economical cost

3. Canister Design Considerations

3.1 U. S. Navy Experimental Diving Unit Studies. Duffner's impressive theoretical treatment has been cited more than once in this report. Suggestions for canister design criteria were coupled with functional parameter estimates and recommendations for testing procedures. As noted earlier the end-points promulgated by Duffner seemed excessive, and were disregarded, but the greater portion of his ideas are valid and important, and could have been applied to the closed-circuit rig canister.

3.2 Canister Size and Shape: Design Considerations and Suggestions. The primary factor within this category, and which is of equal importance for all canisters irregardless of shape configuration, is the provision of an intracanister gas space equal to any encountered tidal volume. Because the pore space volume is not a constant quantity, diminishing with use time, it ought not to be included in considering available intracanister space. Provision of sufficient intracanister gas volume exerts priority over all other design parameters. Total size can now be as large or as small as desired. Canister orientation (vertical or horizontal) is immaterial if the absorbent is firmly packed; the direction of gas flow passage, and the provision of baffles, bypasses, and insulation are each of optional significance. Factors which may influence these decisions will, of course, include the tendency of the absorbent to cake and other related absorbent-canister interacting mechanisms which determine channeling potentials and the development of gasflow resistance to other than the most minimal magnitude.

3.3 Specific Suggestions for Study. Two radical departures from current U. S. Navy scuba rig canisters would appear to be worthy of study. Each can, potentially, provide prolonged durations for use, but by differing means. Two canisters, end-to-end, in a series arrangement, might postpone the first trans-canister passage of important concentrations of CO_2. The distal canister would not be expected to participate in CO_2 elimination until failure of the upstream one was progressing. The second approach to be considered would be based upon a Venturi recirculation device. It might be learned in this manner, if 90-100% of the absorbent capacity for CO_2 could be utilized. Current canister systems commonly realize only 25-30% of their potential.

APPENDIX D: EVALUATION AND APPLICATION OF THE U. S. NAVY EXPERIMENTAL DIVING UNIT MECHANICAL RESPIRATOR

1. Estimation of Peak Flow Values. The sole existing reference source for all descriptive and operational information pertaining to this device is U. S. Navy Experimental Diving Unit Research Report 2-61 by Janney, Gwinn and Avila (14). The authors' intent was to mimic human expiratory flow patterns by superimposition of the effects of a positive motion cam upon the sinusoidal flow pattern of the thrust arm. However, no actual flow pattern data was reported. Estimation of the peak, instantaneous flow values characteristic of sinusoidal gas-flow delivery was performed with the sinusoidal waveform curve, expressed by:

E(max) = E(average)/0.637

E(max) = amplitude of sinusoidal cycle

E(average) = average amplitude of the cycle

The constant, 0.637, is pi (π) divided by two. Since the average value must be defined for half-periods the $\pi/2$ constant is used (the average value of a full period is zero for true sinusoidal waves). Rearranging and defining terms gives:

V(max) = V(mean)/0.637, in which

V(max) = peak expiratory flow (LPM, STPD), and

V(mean) = mean expiratory flow (LPM,STPD)

The product of tidal volume and time period needed for its delivery (half cycle) is equal to mean flow. This is seen, as follows:

V(max) = (V_T)(Time)/0.637, in which

V_T = liters/breath

Time = (breaths/second)(60 sec/min)

Respiratory frequency was constant at 10 breaths per minute for all runs. The half-cycle time corresponding to this is 0.334 breaths per second. Maximum flow, then, was computed according to:

V(max) = (V_T)(0.334)(60)/0.637, or

V(max) = $31.4V_T$

Values calculated for each run are listed in Table I. The largest of the three positive motion cams was utilized exclusively, and the computed delivered flow maxima which resulted are judged to be representative of real values. This constitutes a stress to the canister-absorbent system in excess of that occuring when only square-wave flow is produced.

2. Expectations of Respirator Output. Following is a brief listing of information, of parochial value, to guide in the selection of respirator variables. The reasons for presenting approximate delivery predictions only will be discussed in the final paragraph below.

CAM	NO. CYLINDERS	APPROX. OUTPUT: LITERS/CYCLE
small	1	0.5
small	2	1.0
small	3	1.5
medium	1	1.0
medium	2	2.0
medium	3	3.0
large	1	1.2
large	2	2.4
large	3	3.6

3. Experiences with the Mechanical Respirator, and Suggestions for Redesign

3.1 "O" Ring Seals and Lubrication. Without meticulous lubrication with a moderately viscous fluid, failure of the "O"-ring seals soon occurs, especially if the machine output is encountering any flow resistance at all. Series 10-25 halocarbon oil was empirically determined to be satisfactory, and was applied by rotating the rings in shallow dishes of the oil. The horizontal disposition of the three parallel cylinders seemed to predispose, as a gravity effect, to loss of the lubricant from the superior arcs of the rings. The resulting relative incompetence of the piston seal will diminish the stroke volume output of the respirator.

3.2 Cycle Counting and Recording. Mention of the convenience and utility to be derived from a simple digital counting device is appended here in order to record the impression of its worth, per se, and to note the ease with which it could be adapted and attached.