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# NITROGEN-OXYGEN MIXTURE PHYSIOLOGY, PHASES 1 AND 2

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Navy Experimental Diving Unit
Washington, D. C.

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This report covers the first two phases of a study to determine the answers to four sequentially related problems:

(1) Whether carbon dioxide retention is a mechanism for unusual susceptibility to oxygen poisoning and other untoward effects of exposure to nitrogen oxygen mixtures in diving.

(cont)

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20. (2) Whether individuals with unusual retention characteristics for a definite group standing apart from the rest.

(3) Whether there is any simple screening test which will separate the two groups.

(4) Whether elimination of the "retentive" group permits worthwhile extension of depth and time limits for oxygen tolerance in nitrogen oxygen diving.

By measurement of respiratory variables and carbon dioxide levels, exposure to nitrogen oxygen mixtures at depth during exertion was found to result in carbon dioxide levels well above these encountered in other conditions. Some individuals showed levels consistent with symptoms of carbon dioxide intoxication, although few actual symptoms related either to oxygen poisoning or to carbon dioxide excess were reported. The results suggest, but do not conclusively show, a definite relationship between symptoms and carbon dioxide levels. The results strongly indicate that individuals tending to show high carbon dioxide levels do not fall into a discrete group. At present, personnel selection does not appear promising for extension of nitrogen oxygen diving limits. The mechanism responsible for the observed phenomena remains obscure, but appears to involve loss of respiratory responsiveness to carbon dioxide. This may have important implications in other aspects of diving.

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FORMAL REPORT 7-55

# NITROGEN-OXYGEN MIXTURE PHYSIOLOGY PHASES 1 AND 2

PROJECT NS185-CO5
SUBTASK 5
TEST 4

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## FOREWORD

Occurrence of untoward symptoms well within presumably safe limits of exposure to nitrogen-oxygen mixtures has seriously limited the utility of such mixtures in diving. Consideration of the symptoms indicated that they might result from carbon dioxide retention secondary to significant respiratory depression in a minority of individuals. It appeared possible that elimination of susceptible individuals might permit worthwhile application of nitrogen-oxygen mixtures, if a practical screening test could be devised. With this possibility in mind, the Bureau of Ships authorized a study of respiratory phenomena associated with nitrogen-oxygen diving.

The project outline, dated 25 February 1955, divided the study into four phases. Equipment work on phases 1 and 2 started 10 January, runs started 16 March and analysis of the results was completed 15 June. The manuscript was submitted for review on 28 June.

All of the work originally indicated for Phase 1 and Phase 2 is finished, and is described herein. This is the first interim report for the project. Two other interim reports are contemplated for Phase 2:

(1) A report describing the carbon dioxide sampling system and discussing the significance of the data obtained therefrom.

(2) A report presenting the individual graphs which were made to summarize each run, minute by minute.

## ABSTRACT

This report covers the first two phases of a study to determine the answers to four sequentially related problems:

(1) Whether carbon dioxide retention is a mechanism for unusual susceptibility to oxygen poisoning and other untoward effects of exposure to nitrogen-oxygen mixtures in diving.

(2) Whether individuals with unusual retention characteristics form a definite group standing apart from the rest.

(3) Whether there is any simple screening test which will separate the two groups.

(4) Whether elimination of the "retentive" group permits worthwhile extension of depth and time limits for oxygen tolerance in nitrogen-oxygen diving.

By measurement of respiratory variables and carbon dioxide level well above those encountered in other conditions. Some individuals showed levels consistent with symptoms of carbon dioxide intoxication, although few actual symptoms related either to oxygen poisoning or to carbon dioxide excess were reported. The results suggest, but do not conclusively show, a definite relationship between symptoms and carbon dioxide levels. The results strongly indicate that individuals tending to show high carbon dioxide levels do not fall into a discrete group. At present, personnel selection does not appear promising for extension of nitrogen-oxygen diving limits. The mechanism responsible for the observed phenomena remains obscure, but appears to involve loss of respiratory responsiveness to carbon dioxide. This may have important implications in other aspects of diving.

CONTENTS

# 1. OBJECT

## 1.1 OBJECTIVES

(1) The basic objective of this project is to find means of extending the safe range of application of nitrogen-oxygen mixtures in diving.

(2) The immediate objective of this project is to determine whether personnel selection procedures can provide a reliable and practical means of achieving such extension.

(3) The objective of this report is to present results obtained to date in experimental work directed toward the basic and immediate objectives.

## 1.2 Scope

This report covers only Phase 1 and Phase 2 of the project outline. Phase 1 was the analysis of existing respiratory data, and Phase 2 was a series of special runs by divers breathing various mixtures at certain depths under specific working conditions.

# 2. DESCRIPTION

## 2.1 Background

2.1.1 Establishment of safe tables for diving with nitrogen-oxygen breathing mixtures required consideration of limits imposed by both nitrogen (decompression) and oxygen (oxygen toxicity). It was possible to base the nitrogen limits on the Standard U.S. Navy Decompression Table for air diving, but no comparable body of information existed concerning oxygen tolerance.

2.1.2 The oxygen limits were based on a limit curve derived from the small amount of existing information. This curve was tested by using cylinder oxygen at various depths producing the range of oxygen partial pressures in question. (The details and results of the test are presented in Special Report 8-54). The curve was accepted pending further testing with actual nitrogen-oxygen mixtures at corresponding oxygen pressures.

2.1.3 The tests using nitrogen-oxygen mixtures produced a variety of symptoms well within the limits which had been presumed safe. Reestablighing the limits in accordance with those results would largely defeat the purpose of using nitrogen-oxygen mixtures in diving. Consequently, an explanation for the unexpected toxicity of these mixtures was sought in the hope of circumventing the phenomenon in some way.

2.1.4 Although the symptoms observed included a major convulsion, some of the symptoms occurred very early and were suggestive of carbon dioxide effects rather than oxygen toxicity. Unusually high carbon dioxide levels in the diver, if present, could explain not only these symptoms but also the apparent increase in susceptibility to oxygen poisoning. It thus offered a possible explanation for the symptoms observed. However, an open circuit system had been used; and there was no carbon dioxide in the gas mixture supplied. For this reason, only abnormal retention of carbon dioxide by the diver could account for the postulated increase of carbon dioxide tension in his body.

2.1.5 Previous studies (see Special Report Series of 1954, sections 5.6.0, 6.3.3, 6.3.4, 6.5.0, 6.6.4, 6.6.5, 8.3.0) have indicated that under certain conditions involving exertion and increased oxygen partial pressures, some individuals experience a relative decrease both in pulmonary ventilation and in respiratory response to carbon dioxide. "Shallow water blackout" has been attributed to this effect, and the casual relationship is relatively well-established. A decrease in ventilation due to increased oxygen pressure alone could not, however, explain the apparently greater toxic effects of mixtures as compared to those of similar oxygen pressures alone. The mechanism should be operating equally in both situations.

2.1.6 One of the studies of the CUSP project (discussed in the references given) indicated that exposure to increased ambient pressure during exertion while breathing air produced a drop in ventilation in some individuals greater than could be explained on the basis of the coincident increase in oxygen pressure. This suggested that some effect of increased nitrogen pressure, or of depth itself, added to the apparent respiratory depression.

2.1.7 If a "nitrogen" or "depth" effect exists, whatever its mechanism may be, it should certainly be operative during nitrogen-oxygen exposures where not only increased oxygen pressure but also increased ambient and nitrogen pressures are encountered. Such an effect may offer an explanation for the observed toxicity of mixtures.

2.1.8 Whatever the cause behind the apparent toxicity of nitrogen-oxygen mixtures, it appears that unusual susceptibility may be confined to a few individuals, although a large degree of individual variation has been noted in previous studies. If unusually susceptible individuals were identified and eliminated, nitrogen-oxygen mixtures could be used safely through a much greater range than currently appears possible.

2.2 Statement of the problem

2.2.1 The concept which underlies this project has four major aspects which are reflected in the following questions:

(1) Is the peculiar toxicity of nitrogen-oxygen mixtures directly related to unusual retention of carbon dioxide, secondary to relative inadequacy of pulmonary ventilation?

(2) Is carbon dioxide retention under nitrogen-oxygen diving conditions a consistent characteristic of a circumscribed minority of divers?

(3) Can this minority be identified reliably by means of any simple test?
(4) Does elimination of this minority permit significant extension of the safe application of nitrogen-oxygen mixtures in diving,

2.2.2 The specific problem of the project is to answer these questions.

## 2.3 Approach

2.3.1 The questions listed above suggested four logical phases of study. Phase 1 involved analysis of existing respiratory data for information bearing on the above questions.

2.3.2 Phase 2 consisted of a series of special runs on air, oxygen, nitrogen-oxygen and helium-oxygen mixtures, with measurement of RMV and alveolar (end-tidal) carbon dioxide tension, using all available EDU subjects. Analysis of data was similar to that of Phase 1, with the addition of emphasis on differences in carbon dioxide levels and their correlation with ventilation and toxicity.

2.3.3 Phase 3 is to be a study of the relationship between respiratory responses in actual runs and those elicited by a variety of respiratory procedures which might form the basis of practical tests. This study may also help clarify the mechanisms involved. The phase breaks into two steps:

(1) Study a small group of individuals representing the major types of response noted in actual runs.

(2) If any of the procedures correlate well with run observations on these men, extend testing to as many subjects as possible. Check correlations by comparison with run values for the large group.

2.3.4 Phase 4 will consist of an extension of testing of nitrogen-oxygen diving limits with many of the measurements applied in Phase 2. This phase is expected to shed additional light on the cause of toxicity as well as to define the actual limits for these conditions more clearly.

2.3.5 Phases 1 and 2 have been completed and are the subject of this report.

# 3. PROCEDURE

## 3.1 Phase 1: Analysis of existing data

3.1.1 The purposes of Phase 1 were:

(1) to determine whether a definite decrease in ventilation occurs during work while breathing nitrogen-oxygen mixtures at depth, and
(2) to determine whether such a decrease is characteristic of individuals who tend to show untoward symptoms.

3.1.2 Data on respiratory minute volume and respiratory rate, obtained from table-testing runs (Project NS185-005, Subtask 5, Test 1) and open circuit scuba evaluations, were analyzed in conjunction with reported symptoms.

## 3.2 Phase 2: Wet tank studies

3.2.1 Phase 2 had the same purposes as Phase 1 (see 3.1.1), and the following as well.

(1) To determine whether any subject showed an elevation of end-tidal carbon-dioxide level consistent with symptoms.

(2) To determine whether such elevations occurred consistently in specific individuals under certain conditions.

(3) To determine whether symptoms, if they occurred were associated with unusual carbon dioxide levels.

3.2.2 The following procedure was employed:

(1) All available E.D.U. subjects were studied. A complete series of runs was obtained with each of 17 subjects. Four men were studied less completely.

(2) Where possible, at least one run with each subject was conducted under each of the following conditions.

(2.1) Breathing air at surface.

(2.2) Breathing oxygen at 26 feet.

(2.3) Breathing a 55/45 nitrogen-oxygen mixture (45% oxygen) at 99 feet. (A few of these runs were repeated as an index of variability.)

(2.4) Breathing a 55/45 helium-oxygen mixture (45% oxygen) at 99 feet.

(2.5) Breathing air at surface (repeat-runs at end of series).

3.2.3 The following apparatus was employed:

(1) Scott "Hydro-Pak" mask with built-in mouthpiece and arrangements for end-tidal gas sampling.

(2) Pneumatic end-tidal gas sampling system.

(3) "Bubble catcher" and gas meter, recording by means of event-marker on Brush recorder.

(4) "Mixing chamber" arrangement in breathing circuit to permit sampling of mixed expired gas (some runs).

(5) Strain gage pressure transducer "breathing resistance" setup.

(6) Liston-Becker carbon dioxide analyzer Model 11 with special pick-up unit and appropriate sample cells.

(7) Esterline-Angus recorder for carbon dioxide percentage.

(8) Beckman oxygen analyzer for monitoring breathing mixtures.

(9) Brush oscillograph for RMV, respiratory pressures, and respiratory rate.

3.2.4 The following data were obtained:

(1) Respiratory Minute Volume

(2) Respiratory rate

(3) End-tidal carbon dioxide percentage, computed to tension.

(4) Mixed expired gas carbon dioxide percentage (some runs).

3.2.5 The following special notes apply to the procedures used in Phase 2.

(1) With few exceptions runs were made in the order listed (3.2.2 (2)).

(2) In all "surface" runs (3.3.3: (2.1), (2.3), (2.4)) depth-pressure was measured at the level of the subject.

(4) Details of carbon dioxide sampling and analysis (3.2.3) and significance of the measurements will be the subject of a separate report.

(5) In addition to the data listed (3.2.4), inspiratory and expiratory pressure ("breathing resistance") was measured continuously. However certain errors in technique, discovered later, rendered the results questionable in significance.

## 4. RESULTS

### 4.1 Phase 1 - Analysis of existing data

4.1.1 Respiratory measurements which had been obtained in the course of studies conducted prior to this project are presented in Table 1. The unreliability of such heterogeneous data is apparent. However, Table 1 indicates the following:

(1) Certain subjects appear to experience a decrease in ventilation when breathing nitrogen-oxygen mixtures at depth. Those showing such a change (as compared with their ventilation when breathing air close to the surface) include:

Funderburk

Miller

Rickert

Willoughby

Note that although they both show a change, neither Rickert nor Willoughby has exceptionally low RMV's under any of the conditions.

(2) Despite the higher work rate, ventilation during air-breathing at 150 feet shows a further decrease in the case of Funderburk. (Corresponding values are not available for Miller and Willoughby, while Rickert shows a considerable increase over his nitrogen-oxygen values.)

(3) Some of the figures suggest an actual inadequacy of ventilation. The minimum carbon dioxide output likely to be associated with 7 or 8 pound trapeze swimming would require at least 20 liters per minute of net ventilation to maintain normal carbon dioxide levels in the body. The following subjects appreach or go below this "critical level":

Lewis ( all conditions)

Funderburk (nitrogen-oxygen, air at 150 feet

Hollingsworth (air at 150 feet)

Miller (nitrogen-oxygen)

Cirelli (air at 150 feet - no measurements under other conditions)

4.1.2 Since low ventilation or high carbon dioxide levels are significant only in terms of symptoms which they may produce, a review of symptoms encountered in the course of various runs may be of interest.

(1) LEWIS reported no symptoms except one episode of transient dizziness early in the course of a run breathing 49% oxygen at 110 feet. (No respiratory measurements were being made at the time.)

(2) FUNDERBURK reported no symptoms other than a marked tendency to have severe headaches following runs of almost any kind.

(3) HOLLINGSWORTH reported severe fatigue and dizziness after 16 minutes of breathing 40% oxygen at 110 feet and "waves of fatigue" on a subsequent similar run. His "steady state" net ventilation during the later run was 31 liters perminute. Following his 200-foot run breathing air (see Table 1), he complained of severe headache lasting several hours. His RMV was 14 liters during that run.

(4) MILLER has been free of symptoms except for nausea reported after 23 minutes on 40% oxygen at 110 feet.

(5) CIRELLI had a grand mal convulsion after 20 minutes breathing 47% oxygen at 100 feet, and reported nausea after 45 minutes breathing 50% oxygen at 90 feet. (No respiratory data were obtained in either case.)

(6) RICKERT experienced uncontrollable trembling (distinct from twitching and apparently not of emotional origin) after 4 minutes breathing 40% oxygen at 140 feet. (No respiratory data were obtained) He also developed headache and nausea after 35 miutes on 40% oxygen at 110 feet. (His net ventilation was 31 liters per minute.)

(7) WILLOUGHBY reported no symptoms except considerable fatigue on his first trapeze swimming run (40% oxygen at 110 feet).

(8) CARROLL reported severe nausea after 36 minutes of breathing 40% oxygen at 110 feet.

(9) CARR, GRIFFITH, KELLEY, KISSEE, and MANNAN were free of symptoms.

(10) Subjects for whom no respiratory data are available but who participated in similar runs are McARDLE and McKENZIE. Of these, McARDLE experienced severe fatigue very early in a run breathing 47% oxygen at 100 feet, but was otherwise symptom-free.

4.1.3 It is impossible to derive a convincing correlation between ventilation and symptomatology from these data. However, subjects showing low ventilation throughout or a decrease on nitrogen-oxygen or air depth appear much more likely to report symptoms of one kind or another than those who maintained relatively high ventilation.

4.1.4 The data summarized here are too incomplete to be subject to satisfactory averaging. The amount of inter- and intra-individual variation shown is impressive.

4.2 Phase 2 - Special runs under various conditions.

4.2.1 The volume of complete individual run data and the number of individual graphs for Phase 2 precluded reproduction for this report because of time and cost considerations. It is planned to issue at least the graphs in a later report.

4.2.2 The results of Phase 2 of the project are summarized in Table 2 and Figure 1. The average values for the last 5 minutes of work and of rest in each of the 5 sets of runs are the basis of summaries. These average values are presented in detail for each subject in Tables 3 to 12. An explanation of the tabulated values is presented on the page preceding Table 3.

4.2.3 Only the results for the 17 subjects in whom a complete series of runs was obtained were employed for averaging. Data from subjects who did not complete the series are tabulated separately in Tables 3 to 12.

4.2.4 The "Surface-Air #1" set was conducted at the outset of the study when all subjects were unfamiliar with the breathing system used and a few were doing "trapeze swimming" for almost the first time. The "Surface-Air #2" set was run at the conclusion of the study when all of the subjects were presumably well-accustomed to the conditions. For this reason, "Surface-Air #2" is probably the most appropriate for comparative purposes.

4.2.5 Runs at 99 feet breathing nitrogen-oxygen were repeated in a few subjects to obtain an indication of intra-individual variability (that is, reproducibility of values). Where such repeat runs were made, the average of the two runs was used for tabulation and averaging in Tables 3 to 12. However, values for both such runs are presented in Tables 3 to 12.

However, values for both such runs are presented in Table 16, "Reproducibility".

4.2.6 Symptoms reported during the study are summarized in Table 14. Individual runs which produced symptoms are indicated by numbers in parentheses in Tables 3 to 12. These numbers correspond to the entries in Table 14.

4.2.7 Table 13 presents the relative position of the various subjects as to their end-tidal carbon dioxide levels during work under the various conditions.

4.2.8 The oxygen consumption values obtained during a separate series of runs at the same work-rate are presented in Table 15.

4.3 Comments

4.3.1 In the "work" data, the only group mean value which is clearly different from those obtained under other conditions is the end-tidal carbon dioxide tension recorded for 99-foot nitrogen-oxygen.

(1) The mean value derived from "last 5 minute averages", 53.5 mm Hg, is well above the highest recorded under other conditions. It is 7.4 mm Hg above that for 26-foot oxygen, and this difference is highly significant statistically. (There is considerably less than one chance in 1000 that such a difference would occur by chance). The maximum carbon dioxide tension (highest recorded for any given minute of a run) is even more strikingly above the corresponding values for other conditions.

(2) The mean respiratory minute volume (RMV) for 99-foot nitrogen-oxygen (24 liters) is below corresponding values. The difference is small (roughly 10%) if "Surface-Air #1" is omitted from consideration. Nevertheless, calculation based on average values for the significant variables indicates that this RMV is of the proper order of magnitude to explain the higher corresponding carbon dioxide value. Note, however, that the RMV for 99-foot helium-oxygen is also low while the corresponding carbon dioxide level is unexceptional. In many cases, individual RMV values showed variations quite unrelated to corresponding changes in end-tidal carbon dioxide.

(3) Carbon dioxide values recorded during exertion were invariably higher than those of rest. The difference averaged 11.5 mm Hg.

4.3.2 In the "rest" data, the low end-tidal carbon dioxide pressures for 26-foot oxygen and 99-foot helium-oxygen are distinctive. The corresponding RMV's are higher as might be expected although not enough so to be noteworthy in the case of helium.

4.3.3 Examination of individual carbon dioxide data reveals several facts of interest.

(1) The range of individual values is tremendous. For example, during work, it extends from 40 mm Hg to 70 within the 99-foot nitrogen-oxygen series (Table 13, Table 16).

(2) High values (above 55) are not uncommon, and levels of 60 or above were recorded for no less than 4 individuals during nitrogen-oxygen exposure.

(3) Individuals who had high (or low) carbon dioxide levels under one condition tended to do so under all conditions. Seven subjects were above the mean in at least 90% of their runs, and two were almost invariably more than one standard deviation above the mean. In the opposite direction, two were consistently one to two standard deviations below the mean.

(4) Despite the wide range of observed values, there is a relatively smooth graduation from low to high except for the lowest values, which tend to stand alone.

(5) Although "high" individuals tended to show a greater relative rise when exposed to nitrogen-oxygen during exertion, there is also a relatively smooth gradation in this sense.

(6) Examination of data for subjects who showed a tendency toward decreased ventilation when breathing nitrogen-oxygen mixtures or air at depth in Phase 1 measurements indicates the following:

(6.1) FUNDERBURK and MILLER Show carbon dioxide levels in the higher range while WILLOUGHBY and RICKERT are unexceptional.

(6.2) Among these who showed probable inadequacy of ventilation in Phase 1, all but MILLER show high carbon dioxide levels in Phase 2.

4.3.4 The reproducibility of values obtained in check-runs for 99-foot nitrogen-oxygen (Table 16) is reasonably good (within 5 mm Hg high or low), except in the cases of HOLLINGSWORTH and DWYER. HOLLINGSWORTH is and excellent swimmer with 7 years UDT experience. He was trained to use "controlled breathing" for conservation of air and tends to do this consistently. He did so during the first 99-foot nitrogen-oxygen run but deliberately avoided "control" during his second run under those conditions. The difference in both RMV and carbon dioxide level is apparent. DWYER, however, was conscious of no effort at control or of any difference in his breathing during the working phase of either run, yet an even larger difference is evident in his case. He reached a peak of 72 mm Hg during the second run - the highest recorded value of the study - and experienced symptoms (Table 14).

4.3.5 The symptoms reported during this study (Table 14) were few in number. Those strongly suggesting carbon dioxide excess were confined to Nitrogen-oxygen exposure. The only one presumed indicative of incipient oxygen poisoning was that reported by FUNDERBURK on helium-oxygen. Note that the subject had been ill. Omitting FUNDERBURK's case, symptoms were reported only in the presence of exceptionally high carbon dioxide levels.

4.3.6 The oxygen consumption values (Table 15) were obtained in a separate series of runs since this measurement was impractical during the regular experiments. The mean value of 1.40 liters per

per minute for 8-pound trapeze swimming compares to 1.42 l/min. obtained during a previous study (Formal Report 1-55) with an almost totally different group. The range of values is also almost identical. The corresponding speed of free swimming (Formal Report 14-54) for the mean value is 0.85 knot. This is believed to be the "natural pace" of the average underwater swimmer.

4.3.7 Toward the end of the study, a technique for obtaining simultaneous measurement of carbon dioxide output was developed. A complete set of these measurements was obtained only for the Surface-Air #2 series (Table 5). The values for rest (Table 6) are probably falsely high due to post-exercise recovery and the lag of the "mixing chamber" involved, but the work values should be accurate. The mean was 1.19 liters per minute.

4.3.8 Calculation of the respiratory quotient (R.Q.) using the mean oxygen consumption (1.40 l/min STPD) and mean carbon dioxide output (1.19 l/min., ambient conditions, 1.09 l/min. STPD) yields a value of 0.77 which is somewhat lower than might be expected but probably a good approximation considering the use of mean data.

## 5. DISCUSSION

### 5.1 Phase 1 - Existing Data

Available information from runs made prior to the beginning of this project was not adequate for confident analysis along the intended lines. However, it provided some evidence of decreased ventilation and probably inadequate ventilation in some subjects during exposure to nitrogen-oxygen mixtures or air at depth. There was also some evidence of correlation between a tendency toward low ventilation and reported symptoms.

### 5.2 Phase 2 - Special Runs

5.2.1 The study conducted in Phase 2 provided a much more adequate array of data for analysis. It presents, in fact, a unique body of information concerning respiration and carbon dioxide levels under a variety of diving conditions never before subjected to such study.

5.2.2 Unfortunately, the sheer bulk of the data precluded reproduction of more than a fragment for this report; and because of limited time, analysis had to be limited severely in its scope. This situation may have the effect of obscuring factors of unsuspected importance. For example, the necessity of adopting "last 5-minute averages" as the basis of analysis has left the entire subject of rate of adjustment from rest to work and vice versa untouched; and the marked differences in moment-to-moment respiratory regulation also remain uncorrelated and unexplained.

5.2.3 Analysis of the results, as far as it has proceeded, can be discussed best by physiological categories.

## 5.3. Respiratory Minute Volume (RMV)

5.3.1 Although the group mean RMV's for nitrogen-oxygen exposure during both rest and work were appropriate for the corresponding end-tidal carbon dioxide values, differences were too small and too variable among the individual subjects to show statistical significance. Consequently, RMV measurements alone would have been inconclusive as an indication of changes in effective ventilation; and consideration of the values for any given individual could be positively misleading.

5.3.2 Respiration is strongly influenced by work rate. Minor variations in the degree of exertion, even these noted while working against the same nominal"load", and probably produce relatively large changes in RMV. These changes are no doubt often greater than those associated with abnormal retention or blow-off of carbon dioxide. Since it is impossible to maintain or reproduce an exact work-rate, a difference in an individual's RMV could signify either a change in exertion or a change in effective ventilation. Unless oxygen consumption or carbon dioxide output were measured simultaneously, it would be impossible to differentiate; and even carbon dioxide output measurement could be misleading during the course of progressive retention or blow-off. A more direct measure of carbon dioxide levels in the body is clearly needed. End-tidal gas sampling represents an attempt to obtain such a measure.

## 5.4 End-tidal gas sampling

5.4.1 Comprehensive discussion of end-tidal sampling and the exact significance of the carbon dioxide measurements obtained in this way must be deferred to a subsequent report. However, the essence of the matter may be stated as follows.

5.4.2 In connection with oxygen tolerance, the carbon dioxide tension of arterial blood is considered the most crucial of the body's various carbon dioxide levels. Measurement of arterial carbon dioxide tension requires actual drawing of blood samples and elaborate analysis. Having to do this in men who are under increased ambient pressure complicates the problem severely. Even where such sampling and analysis can be accomplished, the results will be quite discontinuous unless an extremely large number of samples can be obtained and analyzed.

5.4.3 As far as carbon dioxide is concerned, arterial blood is believed to be in equilibrium with alveolar gas. Thus, sampling and analysis of alveolar gas should theoretically provide an almost exact indication of arterial carbon dioxide tension. Unfortunately, alveolar gas is not homogeneous throughout the respiratory cycle, and it is impossible to obtain a perfectly representative sample of "mean" alveolar gas. Nevertheless, according to Rahn and others, end-tidal samples - those drawn from the last portion of normal expirations - provide a very satisfactory indication. The value of such sampling is widely accepted.

5.4.4 It is recognized that such samples will yield carbon dioxide values slightly in excess of the true arterial tension during exertion, but the approximation is considered close enough for most purposes. It is possible that the factors operating in this study may have increased the difference between end-tidal and arterial tensions. However, the end-tidal levels should continue to provide a reasonable indication of arterial tension. At worst, they should remain a valuable index of relative level and of change.

5.5 Normal carbon dioxide values

5.5.1 The accepted range of normal values for arterial carbon dioxide tension during rest (while breathing air at one atmosphere on dry land) is from 35 to 45 mm Hg. The traditional "average" is 40 mm Hg. "Tension" is equivalent to partial pressure. Expressing carbon dioxide tension in millimeters of mercury is universally standard among physiologists. Although many people are more familiar with expression of carbon dioxide levels by percentage, conversion of tension to the equivalent "percent" can actually confuse the issue severely. Throughout this report carbon dioxide tension is given only in millimeters of mercury, except for mixed expired gas (where percentage is needed to calculate carbon dioxide output). There is surprising lack of unanimity concerning normal values during exertion. The confusion may possibly stem from differences related to work rate itself.

5.5.2 Some idea of the consequences of variations from "normal" values may be gained from the following:

(1) Lowering the tension to 20 mm Hg (as by hyperventilation) generally produces definite light-headedness, and the limit for voluntary hyperventilation is said to be 15 mm Hg.

(2) Increaded levels, if caused by adding carbon dioxide to the inspired gas, normally cause increased respiration. For example, a 3-fold increase in breathing is about average for a (resting) subject with an arterial carbon dioxide tension of 50 mm Hg. Definite signs of central nervous system depression generally occuf when the tension is as high as 60 mm Hg for any reason.

5.6 Observed carbon dioxide levels

5.6.1 Group-mean values

(1) The fact that carbon dioxide values obtained during exertion with exposure to nitrogen-oxygen at 99 feet were so much higher than those measured under other conditions is of great interest. That they were so consistently above those obtained at work breathing oxygen at 26 feet seems especially important. A definite tendency to retain carbon dioxide appears to be characteristic of nitrogen-oxygen exposure in working divers.

(2) The "rest" data is also of interest. It indicates that increased oxygen tension tends to cause a "blowing off" of carbon dioxide under resting conditions but that the presence of nitrogen offsets this tendency.

(3) The difference between carbon dioxide levels at rest and at work is striking. Higher values during exertion were observed in all individuals under all conditions. The lack of agreement concerning "normal" carbon dioxide tensions during work makes evaluation of this difference difficult. That a portion of the difference may be an artifact of end-tidal sampling must be kept in mind. The mean value for rest (40.7 mm Hg) in Surface-Air #2 is certainly "normal", while the corresponding value for work (46.7) is slightly above the upper limit of "normal" for rest.

5.6.2 Individual values

(1) The individual carbon dioxide values recorded, especially those obtained during exertion, are impressive not only because of the observed range but also because of the deviations from "normal". Individual differences are clearly great. It is also noteworthy, however, that almost all individuals showed the same type of response to the various conditions and tended to retain roughly the same "rank" in the group. This individual consistency suggests two things:

(1.1) An increase in carbon dioxide level is an almost universal response to nitrogen-oxygen exposure during work.

(1.2) A man who shows an exceptionally high carbon dioxide level in a nitrogen-oxygen exposure during work will also show relatively high values under other conditions.

(2) The data on reproducibility of carbon dioxide levels in exposures to nitrogen-oxygen (Table 16) is admittedly limited. However, it does suggest that a man is not likely to have a very low carbon dioxide level on one occasion and a very high level on another, and that most men will, in fact, stay fairly close to the same level. At the same time, the possibility of considerable variation due to either conscious or unconscious factors was demonstrated. DWYER's performance should caution one not to assume that a man who has a near-average carbon dioxide level during a single test is incapable of having exceptionally high values on other occasions. HOLLINGSWORTH's runs are interesting since they indicate that "controlled breathing" can apparently be carried to the point of causing considerable carbon dioxide retention.

(3) The absence of any sharp demarcation between "average" and "high" carbon dioxide values does not substantiate the hypothesis of a discrete group of "susceptible" individuals. The fact that no individuals showed an exceptional relative degree of change on exposure to nitrogen-oxygen is also discouraging from the standpoint of personnel selection.

5.6.3. Symptoms

(1) Untoward symptoms were reported so infrequently in this study that there is no conclusive relationship between symptoms and measured data. It is interesting, however, that no

symptoms at all were reported in the presence of low carbon dioxide levels.

(2) The oxygen partial pressure employed was not high enough and the exposures were not long enough to produce symptoms of oxygen poisoning frequently. It is uncertain symptoms suggesting carbon dioxide intoxication would have been more frequent with greater depth or different mixtures.

### 5.6.4 Implications

(1) Oxygen tolerance

The study unfortunately sheds no light upon the relationship between oxygen tolerance and carbon dioxide retention. However, one thing appears highly probable: if carbon dioxide retention of any degree does tend to reduce oxygen tolerance, all individuals should prove less tolerant when a given partial pressure of oxygen is administered in the presence of nitrogen than when the breathing medium consists of oxygen alone. This statement should at least be true for the general range of depth and mixture composition employed in the study.

(2) "Carbon dioxide symptoms"

The study also fails to prove that "symptoms suggestive of carbon dioxide intoxication" are actually associated with unusually high carbon dioxide levels. It is difficult to specify a dividing line beyond which carbon dioxide levels would definitely be considered "consistent with symptoms". It seems likely that 60 mm Hg would be a reasonable value. If so certain subjects of this study were certainly "eligible" for symptoms during nitrogen-oxygen exposure whether they experienced same or not.

(3) Personnel selection

Clarification of the relationship between carbon dioxide level and oxygen tolerance, and association of specific symptoms with high carbon dioxide levels, will require carrying similar studies into the range where correlations will be more apparent and symptoms will be more frequent. If further studies clearly implicate carbon dioxide, it may be possible to designate a "crucial level" above which a man is definitely in danger. An arbitrary approach of this sort appears to be the main hope of making personnel selection practical.

(4) General

The high carbon dioxide levels recorded particularly during nitrogen-oxygen exposure indicate that carbon dioxide is a negligible respiratory stimulus in some men under these conditions. A man who spontaneously develops a carbon dioxide tension above 55 mm Hg would not be likely to increase his ventilation very much in response to any further increase in the level. The implications relative to apparatus dead space, absorption canister failure, and the like, may be quite serious.

### 5.6.5 Mechanisms

(1) At this point it is possible only to surmise the actual mechanism of the observed changes. The increase of carbon dioxide levels in the nitrogen-oxygen exposure during work appears to be due to a decrease in effective ventilation. It seems likely that nitrogen itself is largely responsible: neither the same oxygen pressure nor the same depth produced such a change in the absence of nitrogen. However, the breathing resistance was undoubtedly higher with nitrogen-oxygen at 99 feet than with helium at the same depth or with oxygen at 26 feet. The influence of this factor would have to be ruled out before nitrogen could be implicated definitely.

(2) The fact that the RMV was also low with helium without a corresponding increase in carbon dioxide seems paradoxical. The RMV data is not too reliable for working conditions (because of the influence of minor differences in work-rate (5.3.2) but the same type of "paradox" appears in the rest data as well. These findings may indicate the importance of some factor such as ease of diffusion of carbon dioxide in the lungs through various gases under pressure.

(3) The observation that carbon dioxide levels were relatively low at rest in the 26-foot oxygen and 99-foot helium-oxygen runs may be related to the respiratory stimulation which apparently occurs while breathing oxygen during rest at the surface. (The mechanism of this effect is a matter of controversy.) The fact that the decrease was much less marked with nitrogen-oxygen may be related to the changes noted during work with that breathing medium.

(4) It is clear that further work and more complete analysis of data will be required if the mechanisms of the observed phenomena are to be understood.

## 5.7 Respiratory Rate and Tidal Volume

The mean respiratory rates were low under all conditions of the study, and some of the individual rates recorded even during work were very surprising in view of accepted "normal" values. The tidal volumes were correspondingly large. Respiratory rate was not modified significantly by depth or breathing medium. How much the particular breathing characteristics of the system influenced the respiratory patterns is not known.

# 6. CONCLUSIONS

## 6.1 Conclusions

To date the results of this study have produced the following conclusions:

(1) Exposure to nitrogen-oxygen mixtures at depth causes a significant increase in the carbon dioxide level indicated by end-tidal gas sampling.

(1.1) The increase was observed in virtually all subjects.

(1.2) It appears to be due to a decrease in effective pulmonary ventilation with consequent retention of metabolic carbon dioxide.

(1.3) Although nitrogen itself appears to be responsible for the effect, this is not certain.

(2) Some men show exceptionally high carbon dioxide levels during nitrogen-oxygen exposure. However, neither the levels reached not the relative degree of change can define a discrete group of individuals especially subject to this effect.

(3) Some men especially with exposure to nitrogen-oxygen during exertion, have carbon dioxide levels in the range generally considered capable of causing symptoms of carbon dioxide intoxication.

(3.1) Symptoms of this type were observed only in the presence of carbon dioxide levels well above average.

(3.2) However, casual connection between these symptoms and carbon dioxide retention remains unproved.

(4) The practical relationship between oxygen tolerance and carbon dioxide levels also remains uncertain.

(5) If carbon dioxide retention does affect oxygen tolerance adversely, the majority of individuals should show a reduction of oxygen tolerance with concurrent exposure to increased partial pressures of nitrogen.

(6) Until oxygen tolerance and carbon dioxide levels can be related more closely and critical values defined, selection of personnel on the basis of tendency to retain carbon dioxide is not a promising approach to extension of nitrogen-oxygen diving limits.

(7) The mechanism of the observed elevation of carbon dioxide levels requires further elucidation.

(8) The findings of the study imply a marked loss of respiratory sensitivity to carbon dioxide under certain diving conditions. This may have serious potentialities in connection with carbon dioxide absorption failures, added respiratory dead space, and related problems.

## 6.2 Recommendations

The following recommendations cover the research most needed at present to extend diving capabilities and potentialities.

(1) Make direct studies of oxygen tolerance during exposure to nitrogen-oxygen mixtures at depth, approaching the limits of tolerance more closely than before, with appropriate instrumentation and all possible safeguards.

(2) Pursue the projected laboratory investigation (Phase 3) with at least two objectives: (a) to clarify the relationship of respiratory control mechanisms to the observed phenomena, and (b) to find a means of personnel selection.

(3) Extend the type of studies reported here, as time permits, to include other depths, a wider variety of breathing mixtures, and different work rates.

(4) Conduct appropriate experiments to determine the relationship of factors such as dead space and breathing resistance to the observed phenomena.

(5) Give prompt and vigorous consideration to other approaches than those currently under study for reduction of decompression in scuba diving.

## 7.1 Apparatus

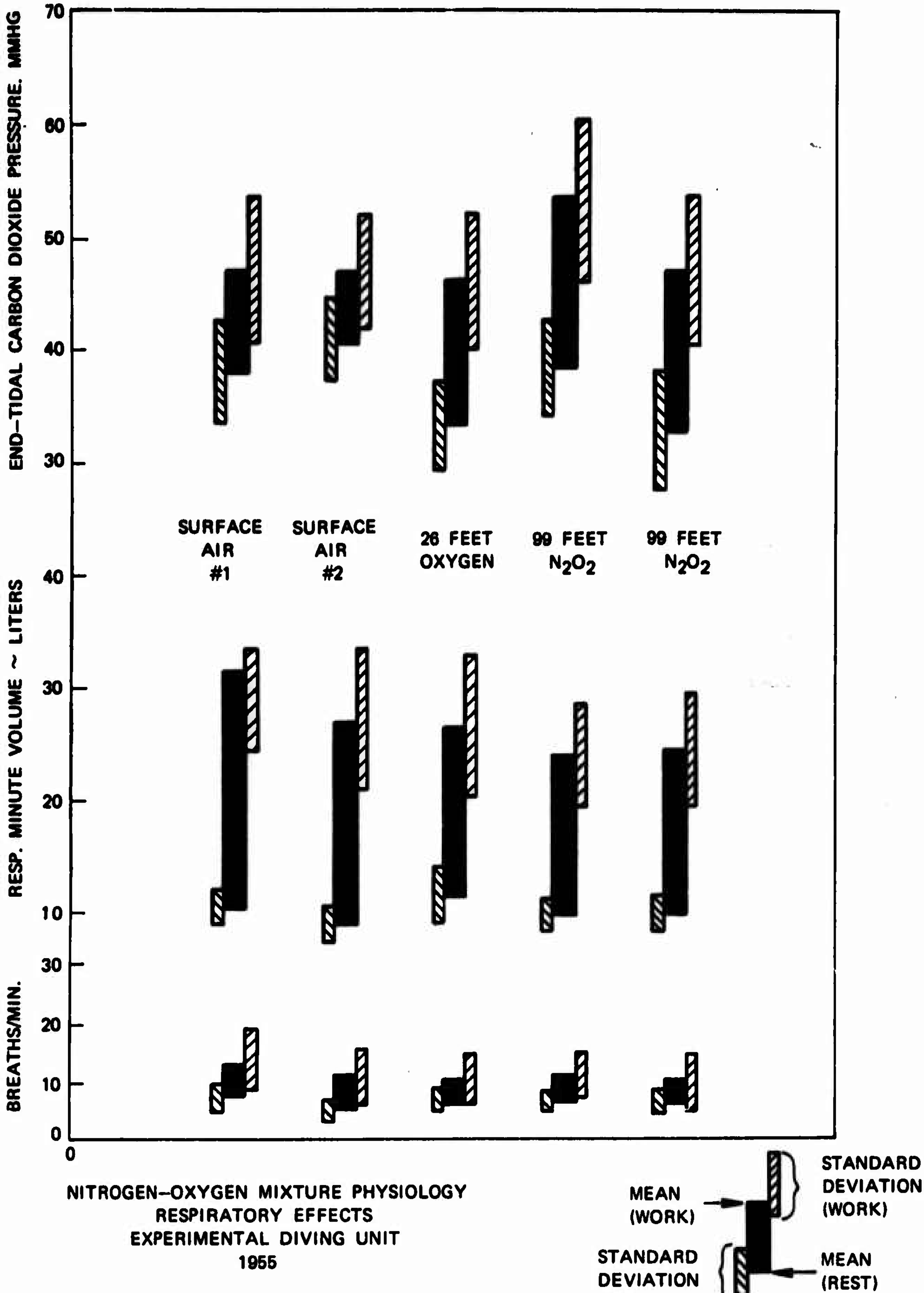
The apparatus used in Phase 2 of this study was a complexity of arrangements for establishing and investigating various physiological conditions. A complete diagram of these arrangements will appear in a later interim report.

## 7.2 Individual graphs

The graphs for each run formed a very bulky mass which could not be reproduced here because of time and cost considerations. They will appear in a later interim report.

## 7.3 Figure 1

Figure 1 is a bar-graph presentation of the mean values listed in the overall summary of Table 2 (Appendix A).




NITROGEN–OXYGEN MIXTURE PHYSIOLOGY
RESPIRATORY EFFECTS
EXPERIMENTAL DIVING UNIT
1955

FIGURE 1

APPENDIX A

SUMMARY TABLES

| TABLE | TITLE |
|---|---|
| 1 | Average respiratory ventilation during work under water |
| 2 | Group mean values for work and rest under various conditions of depth and breathing medium |
| 3 | Surface #1, air, work |
| 4 | Surface #1, air, rest |
| 5 | Surface #2, air,work |
| 6 | Surface #2, air, rest |
| 7 | 26 feet, $0_2$, work |
| 8 | 26 feet, $0_2$, rest |
| 9 | 99 feet, $N_2O_2$, work |
| 10 | 99 feet, $N_2O_2$, rest |
| 11 | 99 feet, $HeO_2$, work |
| 12 | 99 feet, $HeO_2$, rest |
| 13 | "Rank" of subjects according to end-tidal carbon dioxide tension during work under various conditions. |
| 14 | Synopsis of symptoms reported during runs |
| 15 | Oxygen consumption in "Trapeze Ergometer" swimming ($0_2$ cons. in liters per min.STPD) |
| 16 | Reproducibility and Intra-Individual variability (values obtained in comparable runs other than Surface-Air) |

"NOTES ON TABLE 1"

NOTES:

AIR-SURFACE

Actual depth - approximately 4 feet

Work - trapeze-ergometer swimming against a steady 7-pound force or during the 7-pound phase of "8-7-6" cycle.

Breathing apparatus - Scott "Hydro-Pak" mask (no mouthpiece). Dead space assumed to be 0.4 liters.

OXYGEN-MOD. DEPTH

Depths - 16 to 24 feet

Work, Br. app. (same as AIR-SURFACE)

NITROGEN-OXYGEN MIXTURES

Same as above, except

Depths - 90 to 160 feet

Breathing Media - 29.5 to 41% oxygen in nitrogen

AIR-DEPTH

Depth - 150 feet unless otherwise specified

Work - trapeze-ergometer swimming, steady 8-pound force unless otherwise noted.

Breathing app. - open circuit scuba with mouthpiece

RMV

Expired gas volume in liters per minute as measured with "bubble-catcher" - gas meter system. (Volumes are corrected for pressure difference between subject and gas meter.) Figures are estimated "steady state" values for conditions involved. Especially in the case of "oxygen" and "$N_2O_2$" figures given are averages of several runs.

NET ("Net Ventilation")

Approximate volume of dead space ventilation has beem subtracted from RMV. (Dead space ventilation is assumed to be the respiratory rate times 0.4 liters - the assumed dead space of the Hydro-Pak mask.)

Mouthpiece scuba are assumed to have negligible dead space; hence no "Net" values were computed.

TABLE I

## AVERAGE RESPIRATORY VENTILATION DURING WORK UNDERWATER

| SUBJECT | AIR SURFACE | | OXYGEN MOD. DEPTH | | $N_2O_2$ MIX. GREATER DEPTH | | AIR DEPTH |
|---|---|---|---|---|---|---|---|
| | RMV | NET | RMV | NET | RMV | NET | RMV |
| CARR | 41 | 33 | 37 | 29 | 35 | - | 30 |
| | | | | | 52 | 40 | |
| CARROLL | 28 | - | - | - | 28 | - | - |
| FUNDERBURK | 34 | 26 | 28 | - | 27 | 22 | 19 |
| GRIFFITH | 30 | - | - | - | 35 | - | - |
| HOLLINGSWORTH | 28 | 23 | 27 | 22 | 34 | 28 | 15/14 (1) |
| KELLEY | 43 | 32 | 37 | - | 37 | 29 | 48 |
| KISSEE | 33 | - | 25 | - | 34 | - | - |
| LEWIS | 25 | 20 | 17 | 15 | 21 | - | 16 |
| MANNAN | 36 | - | - | - | 41 | - | 41 |
| MILLER | 25 | 22 | 23 | - | 21 | 15 | - |
| RICKERT | 40 | 32 | 29 | 23 | 28 | 21 | 38 |
| WILLOUGHBY | 48 | 39 | 45 | - | 38 | 30 | - |
| CIRELLI | - | - | - | - | - | - | 21/19 (2) |

(1) Second value is for 200-foot depth

(2) Second value is for 12-pound force

TABLE 2 GROUP MEAN VALUES FOR WORK AND REST UNDER VARIOUS CONDITIONS OF DEPTH AND BREATHING MEDIUM.

| | COND. | MEAN RMV (liters) | MEAN END-TIDAL $pCO_2$ (mm Hg) | RESPIRATORY RATE (bpm) | MAX. END-TIDAL $pCO_2$ (mm Hg) | TIDAL VOLUME (liters) | MIXED EXPIR. % $CO_2$ | $CO_2$ OUTPUT (lit/min) | D.S. OMDEX |
|---|---|---|---|---|---|---|---|---|---|
| WORK | SURFACE AIR #1 | 31.4 | 47.2 | 13.8 | 48.4 | 2.3 | - | - | - |
| | Surface AIR #2 | 27.2 | 46.7 | 11.6 | 47.4 | 2.6 | 4.4 | 1.19 | 0.53 |
| | 26-FOOT OXYGEN | 26.7# | 46.1* | 11.1 | 47.2 | 2.3 | - | - | - |
| | 99-FOOT NITROGEN OXYGEN | 24.0# | 53.5* | 11.4 | 56,4 | 2.4 | 1.2 (4) | (4) 0.291 | 0.55 (4) |
| | 99-FOOT HELIUM OXYGEN | 24.5 | 46.9 | 10.0 | 48.9 | 2.4 | 1.16 (3) | 0.26 (3) | 0.317 (3) |
| REST | SURFACE AIR #1 | 10.5 | 38.0 | 7.4 | 39.0 | 1.6 | - | - | - |
| | SURFACE AIR #2 | 9.0 | 40.7 | 5.6 | 40.8 | 2.0 | 4.3 | 0.381 | 0.214 |
| | 26-FOOT OXYGEN | 11.6 | 33.4 | 6.8 | 34.9 | 1.9 | - | - | - |
| | 99-FOOT NITROGEN-OXYGEN | 9.9 | 38.4 | 6.7 | 40.9 | 1.6 | 0.91 (4) | 0.079 (4) | 0.280 (4) |
| | 99-FOOT HELIUM OXYGEN | 10.0 | 32.8 | 6.6 | 34.0 | 1.7 | 0.85 (3) | 0.079 (3) | 0.367 (3) |

NOTE: Numbers in parenthesis indicate number of subjects in whom the particular measurement was obtained.

# Difference between these values is not statistically significant

*Difference is significant at the 0.1% level of confidence.

## EXPLANATION OF TABLES 3-12

RMV, liters - respiratory minute volume as measured at depth. Corrected for pressure difference between submerged subject and gas meter. Not corrected to BTPS.

END-TIDAL $pCO_2$ - carbon dioxide tension in millimeters of mercury (see text, 5.2.1).

RESPIRATORY RATE - breaths per minute

END-TIDAL (max.) - highest end-tidal carbon dioxide tension (mmHg) recorded for any minute of the run. (This is given only for working phases.)

TIDAL VOLUME - volume of average breath in liters.

MIXED EXPIR. % $CO_2$ - percent carbon dioxide of mixed expired gas (measured only in certain runs).

$CO_2$ OUTPUT l/min. - carbon dioxide output in liters per minute as determined from mixed expired gas % $CO_2$ (where measured) and RMV. (Not corrected to standard conditions).

D.S. INDEX - this is an arbitrary value involved in evaluation of accuracy of end-tidal carbon dioxide measurements. It represents the dead space volume which would have to be assumed if end-tidal carbon dioxide tension as measured were identical with mean expired alveolar carbon dioxide tension where the mixed expired gas carbon dioxide percentage has also been measured. (This will be discussed in a subsequent report).

MEAN - this is simply the average of the recorded measures.

S.D. - Standard Deviation. This is a universally-employed measure of "central tendency" or variability of data. It is employed in evaluating the probable accuracy of mean values, the significance of differences, correlations how "unusual" individual values are, and the like.

NOTE: The subjects whose data is presented at the bottom of these tables are those who did not make a complete series of runs.

The ASTERISKS indicate that the values presented are the average from two runs. In most cases, the individual runs are detailed in Table 16.

Numbers in parenthesis indicate that symptoms were reported. The numbers refer to entries in Table 14.

TABLE 3

## TABULATION OF INDIVIDUAL RUNS

Depth: SURFACE #1 Breathing Medium: AIR Activity: WORK

| SUBJECT | RMV liters | End-Tidal $pCO_2$ | Resp. Rate | End-Tidal (max.) | Tidal Volume |
|---|---|---|---|---|---|
| BOURLAND | 40 | 44 | 30 | 44 | 1.3 |
| CIRELLI | 34 | 62 | 12 | 65 | 2.8 |
| COGGESHALL | 24 | 49 | 12 | 50 | 2.0 |
| des GRANGES | 36 | 47 | 14 | 49 | 2.6 |
| DWYER | 27 | 57 | 9 | 60 | 3.0 |
| FUNDERBURK | 28 | 47 | 11 | 49 | 2.5 |
| HANES | 38 | 48 | 10 | 48 | 3.8 |
| HOLLER | 33 | 37 | 22 | 38 | 1.5 |
| HOLLINGSW. | 24 | 53 | 10 | 54 | 2.4 |
| KIRK | 22 | 48 | 13 | 49 | 1.7 |
| LANPHIER | 38 | 36 | 13 | 37 | 2.9 |
| LEWIS | 21 | 53 | 5 | 55 | 4.2 |
| MANNAN | 35 | 39 | 15 | 40 | 2.6 |
| MILLER | 26 | 44 | 12 | 44 | 2.2 |
| PLOOF | 33 | 45 | 12 | 45 | 2.9 |
| RICKERT | 32 | 47 | 16 | 49 | 2.0 |
| WILLOUGHBY | 43 | 46 | 18 | 47 | 2.4 |
| MEAN | 31.4 | 47.2 | 13.8 | 48.4 | 2.3 |
| S.D. | 6.7 | 6.7 | 5.6 | 7.3 | 7.8 |
| CARR | 35 | 44 | 14 | 44 | 2.5 |
| FORD | 52 | 44 | 24 | 46 | 2.1 |
| KELLEY | 37 | 43 | 18 | 43 | 2.1 |
| SNIDER | 32 | 37 | 23 | 37 | 1.4 |

TABLE 4

## TABULATION OF INDIVIDUAL RUNS

Depth: SURFACE #1 Breathing Medium: AIR Activity: REST

| SUBJECT | RMV liters | End-Tidal $p_{CO_2}$ | Resp. Rate | Tidal Volume |
|---|---|---|---|---|
| BOURLAND | 9 | 36 | 8 | 1.1 |
| CIRELLI | 12 | 43 | 11 | 1.1 |
| COGGESHALL | 11 | 39 | 10 | 1.1 |
| des GRANGES | 8 | 45 | 5 | 1.6 |
| DWYER | 9 | 45 | 3 | 3.0 |
| FUNDERBURK | 10 | 37 | 6 | 1.7 |
| HANES | 12 | 40 | 4 | 3.0 |
| HOLLER | 12 | 31 | 8 | 1.5 |
| HOLLINGSW. | 8 | 44 | 6 | 1.3 |
| KIRK | 11 | 37 | 10 | 1.1 |
| LANPHIER | 12 | 30 | 6 | 2.0 |
| LEWIS | 11 | 40 | 4 | 2.8 |
| MANNAN | 13 | 31 | 8 | 1.6 |
| MILLER | 11 | 37 | 9 | 1.2 |
| PLOOF | 11 | 37 | 7 | 1.6 |
| RICKERT | 8 | 38 | 9 | 0.9 |
| WILLOUGHBY | 11 | 36 | 12 | 0.9 |
| MEAN | 10.5 | 38.0 | 7.4 | 1.6 |
| S.D. | 1.6 | 4.6 | 2.6 | 0.7 |
| CARR | 8 | 37 | 5 | 1.6 |
| FORD | 14 | 35 | 9 | 1.6 |
| KELLEY | 17 | 27 | 10 | 1.7 |
| SNIDER | 10 | 36 | 13 | 0.77 |

TABLE 5

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Rate (bpm) | Maximum End-tidal $pCO_2$ (mm Hg) | Tidal Volume (liters) | Mixed expir. % $CO_2$ | $CO_2$ output (lit/min) | D.S. Index |
|---|---|---|---|---|---|---|---|---|
| BOURLAND | 34 | 43 | 24 | 44 | 1.4 | 4.0 | 1.34 | 0.30 |
| CIRELLI | 21 | 55 | 10 | 56 | 2.1 | 5.5 | 1.14 | 0.34 |
| COGGESHALL | 21 | 48 | 13 | 49 | 1.6 | 4.4 | 0.92 | 0.35 |
| desGRANGES | 34 | 48 | 11 | 48 | 3.0 | 4.5 | 1.53 | 0.63 |
| DWYER | 27 | 51 | 7 | 53 | 4.5 | 4.6 | 1.24 | 0.90 |
| FUNDERBURK | 18 | 54 | 8 | 55 | 2.2 | 5.6 | 1.01 | 0.26 |
| HANES | 24 | 51 | 7 | 52 | 3.5 | 4.9 | 1.20 | 0.61 |
| HOLLER | 32 | 38 | 17 | 39 | 1.9 | 3.9 | 1.25 | 0.23 |
| HOLLINGSW. | 28 | 48 | 11 | 48 | 2.6 | 4.6 | 1.28 | 0.47 |
| KIRK | 23 | 44 | 12 | 45 | 1.9 | 4.3 | 0.99 | 0.32 |
| LANPHIER | 39 | 42 | 10 | 42 | 3.9 | 3.7 | 1.45 | 0.98 |
| LEWIS | 21 | 52 | 6 | 52 | 3.5 | 5.0 | 1.05 | 0.61 |
| MANNAN | 29 | 39 | 14 | 39 | 2.1 | 3.4 | 0.99 | 0.53 |
| MILLER | 22 | 46 | 11 | 46 | 2.0 | 4.2 | 0.92 | 0.43 |
| PLOOF | 25 | 44 | 9 | 45 | 2.8 | 4.1 | 1.01 | 0.61 |
| RICKERT | 35 | 44 | 17 | 45 | 2.1 | 4.2 | 1.49 | 0.37 |
| WILLOUGHBY | 30 | 46 | 12 | 48 | 2.5 | 4.7 | 1.41 | 0.33 |
| MEAN | 27.2 | 46.7 | 11.6 | 47.4 | 2.6 | 4.4 | 1.19 | 0.53 |
| S.D. | 6.2 | 4.9 | 4.5 | 5.1 | 0.86 | 0.59 | 0.21 | 0.024 |

TABULATION OF INDIVIDUAL RUNS

Depth: SURFACE #2 Breathing Medium: AIR Activity: WORK

TABLE 6

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Rate (bpm) | Tidal Volume (liters) | Mixed Expir. % $CO_2$ | $CO_2$ output (lit/min) | D.S. Index |
|---|---|---|---|---|---|---|---|
| BOURLAND | 12 | 38 | 12 | 0.9 | 4.3 | .490 | 0.42 |
| CIRELLI | 9 | 45 | 7 | 1.3 | 4.9 | .441 | 0.10 |
| COGGESHALL | 9 | 42 | 10 | 0.9 | 4.6 | .414 | 0.07 |
| des GRANGES | 9 | 44 | 4 | 2.2 | 4.3 | .387 | 0.38 |
| DWYER | 7 | 42 | 3 | 2.3 | 4.8 | .336 | 0.13 |
| FUNDERBURK | 7 | 50 | 2 | 3.5 | 5.4 | .374 | 0.32 |
| HANES | 9 | 42 | - | - | 4.4 | .396 | - |
| HOLLER | 10 | 36 | 7 | 1.4 | 3.8 | .380 | 0.15 |
| HOLLINGSW. | 9 | 40 | 8 | 1.1 | 3.2 | .288 | 0.36 |
| KIRK | 7 | 42 | 3 | 2.3 | 4.22 | .295 | 0.36 |
| LANPHIER | 10 | 37 | 3 | 3.3 | 3.7 | .370 | 0.50 |
| LEWIS | 11 | 40 | 4 | 2.8 | 4.2 | .463 | 0.30 |
| MANNAN | 9 | 37 | 6 | 1.3 | 4.0 | .360 | 0.10 |
| MILLER | 11 | 38 | 6 | 1.8 | 3.8 | .413 | 0.31 |
| PLOOF | 10 | 38 | 5 | 2.0 | 4.0 | .405 | 0.21 |
| RICKERT | 7 | 38 | 8 | 0.9 | 4.0 | .315 | 0.09 |
| WILLOUGHBY | 7 | 43 | 2 | 3.5 | 5.0 | .353 | 0.00 |
| <u>MEAN</u> | 9.0 | 40.7 | 5.6 | 2.0 | 4.3 | .381 | 0.214 |
| <u>S.D.</u> | 1.52 | 3.58 | 2.24 | 0.90 | 0.7 | .041 | |

TABULATION OF INDIVIDUAL RUNS

<u>Depth:</u> SURFACE #2 <u>Breathing Medium:</u> AIR <u>Activity:</u> REST

TABLE 7

## TABULATION OF INDIVIDUAL RUNS

Depth: 26-FOOT Breathing Medium: OXYGEN Activity: WORK

| SUBJECT | RMV | End-Tidal $pCO_2$ | Resp. Rate | End-Tidal (max.) | Tidal Volume |
|---|---|---|---|---|---|
| BOURLAND | 31 | 42 | 26 | 42 | 1.2 |
| CIRELLI | 21 | 56 | 8 | 59 | 2.6 |
| COGGESHALL | 30 | 48 | 12 | 48 | 2.5 |
| des GRANGES | 35 | 47 | 12 | 48 | 2.9 |
| DWYER | 26 | 53 | 8 | 54 | 3.2 |
| FUNDERBURK | 21 | 49 | 9 | 50 | 2.3 |
| HANES | 32 | 51 | 8 | 52 | 4.0 |
| HOLLER | 24 | 34 | 19 | 36 | 1.3 |
| HOLLINGSWORTH | 35 | 51 | 15 | 52 | 2.3 |
| KIRK | 22 | 46 | - | 46 | - |
| LANPHIER | 39 | 38 | 12 | 40 | 3.2 |
| LEWIS | 19 | 50 | 7 | 52 | 2.7 |
| MANNAN | 26 | 40 | 10 | 42 | 2.6 |
| MILLER | 18 | 47 | 9 | 47 | 2.0 |
| PLOOF | 21 | 39 | 9 | 41 | 2.3 |
| RICKERT | 28 | 45 | 15 | 46 | 1.9 |
| WILLOUGHBY | 26 | 47 | 10 | 48 | 2.6 |
| MEAN | 26.7 | 46.1 | 11.1 | 47.2 | 2.3 |
| S.D. | 6.2 | 5.8 | 4.8 | 5.9 | 0.7 |
| | | | | | |
| CARR | 22 | 43 | 9 | 43 | 2.4 |
| FORD | 45 | 52 | 25 | 49 | 1.8 |
| KELLEY | 36 | 40 | 17 | 42 | 2.1 |
| SNIDER | 29 | 36 | 18 | - | 1.6 |

TABLE 8

## TABULATION OF INDIVIDUAL RUNS

**Depth:** 26-FOOT **Breathing Medium:** OXYGEN **Activity:** REST

| SUBJECT | RMV liters | End-Tidal $p_{CO_2}$ | Resp-Rate | Tidal Volume |
|---|---|---|---|---|
| BOURLAND | 12 | 33 | 11 | 1.1 |
| CIRELLI | 10 | 39 | 6 | 1.7 |
| COGGESHALL | 12 | 30 | 8 | 1.5 |
| des GRANGES | 9 | 36 | 5 | 1.8 |
| DWYER | 12 | 35 | 6 | 2.0 |
| FUNDERBURK | 13 | 35 | 6 | 2.1 |
| HANES | 11 | 34 | 6 | 1.8 |
| HOLLER | 13 | 27 | 12 | 1.1 |
| HOLLINGSWORTH | 11 | 36 | 6 | 1.8 |
| KIRK | 9 | 33 | 7 | 1.3 |
| LANPHIER | 18 | 25 | 6 | 3.0 |
| LEWIS | 10 | 39 | 4 | 2.5 |
| MANNAN | 12 | 31 | 6 | 2.0 |
| MILLER | 11 | 35 | 8 | 1.4 |
| PLOOF | 14 | 32 | 5 | 2.8 |
| RICKERT | 10 | 32 | 10 | 1.0 |
| WILLOUGHBY | 11 | 35 | 4 | 2.7 |
| MEAN | 11.6 | 33.4 | 6.8 | 1.9 |
| S.D. | 2.4 | 3.7 | 2.3 | 0.6 |
| CARR | 10 | 32 | 6 | 1.7 |
| KELLEY | 17 | 26 | 10 | 1.7 |
| SNIDER | 12 | 32 | 11 | 1.1 |

TABLE 9

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Rate (bpm) | Maximum End-tidal $pCO_2$ (mm Hg) | Tidal Volume (liters) | Mixed expir. % $CO_2$ | $CO_2$ output (lit/min) | D. S. Index |
|---|---|---|---|---|---|---|---|---|
| BOURLAND | 30 | 51 | 24 | 53 | 1.2 | - | - | - |
| CIRELLI*#(1) | 22 | 60 | 11 | 67 | 2.0 | 1.47 | .324 | 0.51 |
| COGGESHALL | 24 | 56 | 11 | 56 | 2.1 | - | - | - |
| des GRANGES | 26 | 54 | 10 | 54 | 2.6 | - | - | - |
| DWYER*(3) | 20 | 63 | 6 | 72 | 3.3 | - | - | - |
| FUNDERBURK | 19 | 61 | 9 | 68 | 2.1 | - | - | - |
| HANES | 30 | 61 | 9 | 62 | 3.3 | - | - | - |
| HOLLER* | 26 | 40 | 17 | 43 | 1.5 | 0.97 | .252 | 0.40 |
| HOLLINGSW.* | 21 | 58 | 10 | 65 | 2.1 | - | - | - |
| KIRK* | 21 | 50 | 11 | 51 | 1.9 | 1.28 | .269 | 0.43 |
| LANPHIER* | 32 | 40 | 10 | 44 | 3.0 | 0.92 | .298 | 0.91 |
| LEWIS | 17 | 59 | 4 | 60 | 4.3 | - | - | - |
| MANNAN | 31 | 48 | 11 | 50 | 2.9 | - | - | - |
| MILLER | 20 | 56 | 13 | 57 | 1.5 | - | - | - |
| PLOOF | 25 | 47 | 11 | 49 | 2.3 | - | - | - |
| RICKERT* | 27 | 52 | 16 | 54 | 1.7 | - | - | - |
| WILLOUGHBY* | 23 | 53 | 10 | 54 | 2.3 | 1.36 | .313 | 0.50 |
| MEAN | 24.0 | 53.5 | 11.4 | 56.4 | 2.4 | 1.2 | 0.291 | 0.55 |
| S. D. | 4.6 | 6.8 | 4.4 | 8.3 | .79 | .24 | .06 | - |
| KELLEY | 34 | 49 | 18 | 51 | 1.9 | - | - | - |

*Average of 2 runs. # One run at 89 feet and one at 99 feet.

TABULATION OF INDIVIDUAL RUNS

Depth: 99-FOOT Breathing Medium: NITROGEN-OXYGEN Activity: WORK

TABLE 10

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Rate (bpm) | Tidal Volume (liters) | Mixed Expir. % $CO_2$ | $CO_2$ output (lit/min) | D.S. Index |
|---|---|---|---|---|---|---|---|
| BOURLAND | 8 | 39 | 9 | 0.9 | - | - | - |
| CIRELLI*#(1) | 12 | 44 | 9 | 1.3 | - | - | - |
| COGGESHALL | 10 | 38 | 8 | 1.2 | - | - | - |
| des GRANGES | 11 | 40 | 7 | 1.6 | - | - | - |
| DWYER* | 10 | 45 | 3 | 3.3 | - | - | - |
| FUNDERBURK | 10 | 39 | 5 | 2.0 | - | - | - |
| HANES | 12 | 36 | 6 | 2.0 | - | - | - |
| HOLLER* | 8 | 33 | 8 | 1.0 | 1.87 | .070 | 0.20 |
| HOLLINGSW.* | 10 | 39 | 7 | 1.4 | - | - | - |
| KIRK* | 8 | 37 | 6 | 1.2 | 0.99 | .079 | 0.22 |
| LANPHIER* | 10 | 29 | 7 | 1.5 | 0.90 | .086 | 0.11 |
| LEWIS | 9 | 47 | 4 | 2.2 | - | - | - |
| MANNAN | 9 | 37 | 4 | 2.3 | - | - | - |
| MILLER | 12 | 38 | 10 | 1.2 | - | - | - |
| PLOOF | 11 | 36 | 6 | 1.8 | - | - | - |
| RICKERT* | 10 | 36 | 10 | 1.0 | - | - | - |
| WILLOUGHBY* | 9 | 38 | 4.5 | 2.0 | 0.88 | .079 | 0.59 |
| MEAN | 9.9 | 38.4 | 6.7 | 1.6 | .91 | .079 | 0.280 |
| S. D. | 1.3 | 4.2 | 2.1 | 0.62 | - | - | - |
| KELLEY | 13 | 33 | 10 | 1.3 | - | - | - |

*Average of 2 runs. #One run at 89 feet and one at 99 feet.

TABULATION OF INDIVIDUAL RUNS

Depth: 99-Foot Breathing Medium: NITROGEN-OXYGEN Activity: REST

TABLE 11

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Rate (bpm) | Maximum End-tidal $pCO_2$ (mm Hg) | Tidal Volume (liters) | Mixed Expir. % $CO_2$ | $CO_2$ output (lit/min) | D.S. Index |
|---|---|---|---|---|---|---|---|---|
| BOURLAND | 26 | 45 | 21 | 45 | 1.2 | 1.0 | .26 | .40 |
| CIRELLI# (2) | 23 | 57 | 9 | 58 | 2.6 | - | - | - |
| COGGESHALL | 28 | 49 | 11 | 49 | 2.5 | - | - | - |
| des GRANGES | 21 | 51 | 18 | 52 | 1.2 | 1.2 | .25 | .13 |
| DWYER | 26 | 54 | 7 | 72 | 3.7 | - | - | - |
| FUNDERBURK (4) | 20 | 49 | 9 | 49 | 2.2 | - | - | - |
| HANES | 27 | 55 | 11 | 57 | 2.5 | - | - | - |
| HOLLER | 31 | 32 | 19 | 33 | 1.6 | - | - | - |
| HOLLINGSW. | 20 | 50 | 10 | 51 | 2.0 | 1.3 | .26 | .42 |
| KIRK | 24 | 41 | 11 | 42 | 2.1 | - | - | - |
| LANPHIER | 34 | 39 | 10 | 39 | 3.4 | - | - | - |
| LEWIS | 15 | 54 | 5 | 54 | 3.0 | - | - | - |
| MANNAN | 28 | 43 | 8 | 45 | 3.5 | - | - | - |
| MILLER | 18 | 44 | 11 | 46 | 1.6 | - | - | - |
| PLOOF | 23 | 43 | 9 | 43 | 2.5 | - | - | - |
| RICKERT | 27 | 43 | 15 | 45 | 1.8 | - | - | - |
| WILLOUGHBY* | 26 | 49 | 10 | 51 | 2.6 | - | - | - |
| MEAN | 24.5 | 46.9 | 10.0 | 48.9 | 2.4 | 1.17 | .26 | .317 |
| S. D. | 4.8 | 6.5 | 4.6 | 8.6 | 0.75 | | | |

# One run at 89 feet. *Average of 2 runs

TABULATION OF INDIVIDUAL RUNS

Depth: 99-FOOT Breathing Medium: HELIUM-OXYGEN Activity: WORK

TABLE 12

| SUBJECT | RMV (liters) | Mean End-tidal $pCO_2$ (mm Hg) | Respiratory Ra[te] (bpm) | Tidal Volume (liters) | Mixed Expir. % $CO_2$ | $CO_2$ output (lit/min) | D.S. Index |
|---|---|---|---|---|---|---|---|
| BOURLAND | 11 | 33 | 8 | 1.4 | 0.80 | .088 | 0.363 |
| CIRELLI (2) | 11 | 36 | 8 | 1.4 | - | - | - |
| COGGESHALL | 12 | 32 | 9 | 1.3 | - | - | - |
| des GRANGES | 9 | 35 | 6 | 1.5 | 0.86 | .077 | 0.383 |
| DWYER | 10 | 38 | 3 | 3.3 | - | - | - |
| FUNDERBURK | 11 | 36 | 7 | 1.6 | - | - | - |
| HANES | 12 | 34 | 9 | 1.3 | - | - | - |
| HOLLER | 12 | 23 | 11 | 1.1 | - | - | - |
| HOLLINGSW. | 8 | 37 | 6 | 1.3 | 0.90 | .072 | 0.343 |
| KIRK* | 11 | 26 | 6 | 1.8 | - | - | - |
| LANPHIER | 11 | 27 | 5 | 2.5 | - | - | - |
| LEWIS | 8 | 43 | 4 | 2.0 | - | - | - |
| MANNAN | 6 | 36 | 2 | 3.0 | - | - | - |
| MILLER | 12 | 29 | 9 | 1.3 | - | - | - |
| PLOOF | 9 | 29 | 5 | 1.8 | - | - | - |
| RICKERT | 9 | 29 | 10 | 0.9 | - | - | - |
| WILLOUGHBY* | 9 | 36 | 4 | 2.2 | - | - | - |
| MEAN | 10.0 | 32.8 | 6.6 | 1.70 | 0.85 | .079 | 0.367 |
| S. D. | 1.8 | 5.1 | 2.5 | 0.67 | | | |

*Average of 2 runs.

TABULATION OF INDIVIDUAL RUNS

Depth: 99-FOOT Breathing Medium: HELIUM-OXYGEN Activity: REST

TABLE 14

SYNOBSIS OF SYMPTOMS REPORTED DURING RUNS

CIRELLI

(1) Because this subject had shown unusual sensitivity to nitrogen-oxygen mixtures (convulsion in 20 minutes on 47% oxygen at 100 feet), his initial depth runs were made at 89 feet rather than 99 feet.

(1.1) 89-foot nitrogen-oxygen (55/45):

Reported drowsiness after 3 minutes of swimming, and headache over left eye at about 9 minutes. Felt better, but symptoms were still present, during resting phase. Complete relief on ascent.

(Maximum $p_{CO_2}$, 67 mm Hg: average RMV, 24 liters)

(1.2) 99-foot nitrogen-oxygen (55/45):

After 10 minutes of swimming, reported "drifting away from actual consciousness of swimming in tank". Run was discontinued at 14 minutes at subject's request. Subject was shaky and slightly dizzy on coming off trapeze but felt all right after about 1 minute of breathing air.

(Maximum $p^{CO}2$, 59 mm Hg: average RMV, 20 liters)

(2) 89-foot helium-oxygen (55/45):

Experienced transient episode of marked anxiety at 23 minutes (after 3 minutes of rest following swimming)

DWYER

(3) Second run, 99-foot nitrogen-oxygen (55/45):

Reported chilly sensation and shaking (more like shivering than twitching in upper part of body just after beginning of rest phase. Breathing seemed to "jerk". Mind became slightly "dim" and "cloudy" but "nowhere near unconscious".

(Maximum $p_{CO_2}$, 72 mm Hg; average RMV, 17 liters)

FUNDERBURK

(4) 99-foot helium-oxygen (55/45): Noticed nothing unusual until last 5 minutes of run. Then became exceedingly irritable. Was annoyed "terrifically" by noise of exhalation bubbles and became apprehensive. At run-end signal, experienced local muscular spasms which seemed to move the entire right side of his face. On getting head out of water and breathing air, he felt shaky for about 1-1/2 minutes but improved considerably and felt normal by the time of reaching 40 feet on ascent. NOTE: Subject had a severe bout of gastro-intestinal upset with chills 3 days previously. Had not felt well enough previous day to make run.

TABLE 15

OXYGEN CONSUMPTION IN TRAPEZE ERGOMETER SWIMMING AGAINST 8-POUND FORCE
($O_2$ cons. in liters per minute, STPD)

| subject | $O_2$ cons. l/min STPD |
|---|---|
| BOURLAND | 1.47 |
| CIRELLI | 1.78 |
| COGGESHALL | 1.20 |
| des GRANGES | 1.56 |
| DWYER | 1.55 |
| FUNDERBURK | 1.30 |
| HANES | 1.55 |
| HOLLER | 1.12 |
| HOLLINGSWORTH | 1.39 |
| KIRK | 1.19 |
| LEWIS | 1.27 |
| MANNAN | 1.33 |
| MILLER | 1.48 |
| PLOOF | 1.28 |
| RICKERT | 1.38 |
| SNIDER | 1.39 |
| WILLOUGHBY | 1.67 |
| MEAN | 1.40 |
| RANGE | 1.12-1.78 |
| S. D. | ±0.18 |

TABLE 16

REPRODUCIBILITY AND INTRA-INDIVIDUAL VARIABILITY

(Values obtained in comparable runs other than Surface-Air)

| SUBJECT / CONDITIONS | WORK RMV liters | WORK End-tidal $pCO_2$ mmHg | WORK RATE | REST RMV liters | REST End-tidal $CO_2$ mmHg | REST Rate | Remarks |
|---|---|---|---|---|---|---|---|
| CIRELLI | | | | | | | |
| 89ft. $N_2$-$O_2$ | 24 | 62 | - | 11.6 | 44 | 9 | Sympt. (1.1) |
| 99ft, $N_2$-$O_2$ | 20 | 58 | - | - | - | - | Sympt. (1.2) |
| DWYER | | | | | | | |
| 99ft. $N_2$-$O_2$ | 24 | 55 | 7 | 11 | 41 | 3 | |
| 99ft. $N_2$-$O_2$ | 17 | 70 | 4 | 8 | 50 | 3 | Sympt(3) |
| HOLLINGSWORTH | | | | | | | |
| 99ft. $N_2$-$O_2$ | 19 | 64 | 9 | 8 | - | 5 | "Controlled" breathing |
| 99ft. $N_2$-$O_2$ | 24 | 53 | 11 | 11 | 39 | 9 | Normal breathing |
| HOLLER | | | | | | | |
| 99ft. $N_2$-$O_2$ | 28 | 42 | 19 | 10 | 33 | 12 | |
| 99ft. $N_2$-$O_2$ | 24 | 37 | 15 | 5.4 | 33 | 4 | |
| KIRK | | | | | | | |
| 99ft. $N_2$-$O_2$ | 21 | 51 | 12 | 8 | 36 | 7 | |
| 99ft. $N_2$-$O_2$ | 21 | 50 | 10 | 8 | 39 | 6 | |
| LANPHIER | | | | | | | |
| 99ft. $N_2$-$O_2$ | 34 | 42 | 11 | 11 | 29 | 4 | |
| 99ft. $N_2$-$O_2$ | 31 | 38 | 10 | 8 | 30 | 3 | |
| RICKERT | | | | | | | |
| 99ft. $N_2$-$O_2$ | 29 | 50 | 17 | 10 | 35 | 10 | |
| 99ft. $N_2$-$O_2$ | 25 | 53 | 14 | 10 | 37 | 9 | |
| WILLOUGHBY | | | | | | | |
| 99ft. $N_2$-$O_2$ | 22 | 54 | 9 | 9 | 42 | 4 | |
| 99ft. $N_2$-$O_2$ | 24 | 52 | 10 | 9 | 33 | 5 | |
| 99ft. He-$O_2$ | - | 48 | 10 | - | 37 | 4 | |
| 99ft. He-$O_2$ | 26 | 50 | 9 | 9 | 34 | 4 | |

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BM1 J. A. CIRELLI and DC1 P.L. WILLOUGHBY ably took charge of respiratory measurements both during runs and in the subsequent labor of tabulating data.

The Master Diver, BMC George MILLER did a remarkable job of respiratory measurements both during runs and in the subsequent labor of tabulating data.

A tremendous amount of graphing, not evident in the report, was contributed by DM3 H.G. HENLEY.

Summer medical student assistants Albert Loewe, Alvin Szjochst, and Andrew White devoted a large amount of time to the tiresome job of checking tabulated data against original records and to doing all of the statistical work.

YN R.W. WILTERDINK typed all of the text and tables.

The fact that specific names have been mentioned should not detract from the unnamed men who contributed many things beside performing the vital function of serving as subjects, tenders, and tank-operators jobs which were shared by nearly all.

If this project accomplished nothing else, it would stand as an impressive demonstration of the research potential of the Experimental Diving Unit and its men.