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NAVY EXPERIMENTAL DIVING UNIT
WASHINGTON NAVY YARD
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FORMAL REPORT 14-54

OXYGEN CONSUMPTION IN UNDERWATER SWIMMING

PROJECT NS186-200 SUBTASK 4
TEST 33

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22 DECEMBER 1954

Project NS186-200 Subtask 4 Test 33
OXYGEN CONSUMPTION IN UNDERWATER SWIMMING

FOREWORD

Information concerning the physiological needs to be met is a necessity in the design and evaluation of self-contained underwater breathing apparatus. Difficulties arising from the lack of such information led to BuShips authorization of a study of respiratory factors in self-contained diving. Oxygen consumption in underwater swimming was considered most urgently in need of investigation, and study of this factor was undertaken.

ABSTRACT

Oxygen consumption was determined during underwater swimming at speeds between 0.5 and 1.2 knots in 15 subjects. The method involved use of oxygen-rebreathing (closed-circuit) scuba with calibrated supply cylinders and a means of maintaining constant speed over a marked course.

The results indicate that oxygen requirements are approximately tripled by increasing speed from 0.5 to 1.2 knot. The mean values indicated a distinct and progressive loss of efficiency above 0.8 knot. The probable average normal speed of underwater swimmers using similar equipment to 0.8 to 0.9 knot. Speeds below 0.7 knot were uncomfortably slow, speeds above 1.0 knot were considered too fast for more limited periods.

The oxygen requirements at any given speed varied markedly between individuals even among proficient swimmers. Comparisons between UDT subjects and experienced swimmers from EDU showed little difference between the groups, but a group of relatively untrained men had considerably higher requirements.

Values for the probable range of individual oxygen requirements in underwater swimming are derived from the results and are presented for various ranges of activity.

Swimming is a remarkably inefficient and generally limited means of propulsion.

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I. OBJECTIVES

A. Objectives

Three basic objectives governed the design and conduct of this study:

1) To determine the oxygen consumption of a representative group of underwater swimmers at a variety of swimming speeds; to estimate the probable range of oxygen requirements.

2) To determine the probable range of swimming speeds and to investigate the relationship between speed and the efficiency of oxygen utilization.

3) To determine the relative efficiency of trained Underwater Demolition Team swimmers and Experimental Diving Unit personnel who had participated in the evaluation of self-contained underwater breathing apparatus.

B. Scope

Limitations of time and manpower restricted the objectives of the study to the above. Important but less immediately vital questions such as the endurance of swimmers and the effects of fatigue on efficiency had to be reserved for future study. Technical difficulties also restricted the number of physiological measurements which could be obtained concurrently.

II. DESCRIPTION

A. Background

1. Introduction

The primary function of self-contained underwater breathing apparatus is to fulfill the diver's respiratory needs: to supply the oxygen which he consumes, to remove the carbon dioxide produced, and to provide appropriate gas in sufficient volume for normal breathing. Proper design and meaningful evaluation of breathing apparatus demand information concerning the magnitude of these needs under various conditions of use. The relationship between the characteristics of the breathing apparatus and the diver's requirements is critical in terms of operational capability.

A man's oxygen consumption, carbon dioxide output, and ventilation are regulated primarily by his physical activity: the amount of work he is doing. A number of types and degrees of exertion have been studied extensively at the surface, and adequate information about them has been available for some time. Unfortunately, underwater work has received little attention. Among the various forms of activity related to scuba diving, underwater swimming is the most prevalent and commonly believed to be the most demanding. It has been the most controversial and least certain as to its physiological requirements and its relation to well-studied forms of surface activity. While several previous studies (refs 1-5, see also V) have devoted attention to underwater swimming, none yielded sufficient information for present purposes.

Lack of adequate information had several unfortunate consequences. One of these arose repeatedly in the evaluation of closed-circuit scuba. Evaluation of endurance relative to oxygen supply should require no more than determination of cylinder capacity and comparison of this value with the probable need. In the absence of sufficient information concerning the latter, this phase of evaluation required many manhours of working test.

At one time, forms of work other than swimming were employed for tests and yielded grossly misleading results. Even where swimming was used, the validity of results remained questionable for various reasons. For example, apparent differences between Experimental Diving Unit evaluations and field experience questioned the suitability of EDU divers as subjects for such tests. It was felt that their swimming "efficiency" might be significantly lower than that of trained Underwater Demolition personnel. If so, the demands placed upon scuba in EDU tests might be unduly large. It was this question of relative efficiency which led most directly to authorization of an appropriate study.

2. Specific aspects

a. Oxygen consumption

Oxygen consumption data is important not only of its bearing upon the endurance and performance of closed-circuit oxygen rebreathing systems and mixed gas scuba but also as a basic measure of exertion. As such, it provides a means of evaluating the relative efficiency of work under different conditions and in different individuals.

b. Carbon dioxide output

Information concerning carbon dioxide output is necessary because of its bearing on absorption canister performance. The inadequacy of canisters may be more restrictive and less readily remedied than inadequacy of gas supply in rebreathing scuba. For this reason, simultaneous measurement of both carbon dioxide output and oxygen consumption was requested when subject study was authorized.

However, there is no reliable method of determining carbon dioxide output during free swimming (surface connections and cumbersome apparatus are required). It was therefore decided to postpone carbon dioxide output studies and to concentrate on the measurement of oxygen consumption.

The relationships between oxygen consumption and carbon dioxide output have been investigated in various types and degrees of work at the surface. There was little reason to doubt the applicability to swimming of existing data on this subject. Consequently, oxygen consumption data was expected to provide a sufficient indication of carbon dioxide output for interim use (Report 6-54, Section 6.4.1).

C. Other measurements

Respiratory minute volume (RMV) in swimming is of direct concern in the design and evaluation of open circuit scuba and, together with measurements of peak respiratory flow rate, is important in the evaluation of breathing resistance in all types of self-contained apparatus. Simultaneous measurements of these variables involved the same technical problems as carbon dioxide studies and was likewise postponed. The proposed approach to these entities involved construction and calibration (in terms of oxygen consumption) of a stationary swimming arrangement (Report 6-54, Section 6.2.2. and Figure 6-4). With this system, the necessary connections and measuring equipment could be used. The "swim ergometer" was also expected to provide a satisfactory method for studying endurance and related problems whose investigation was beyond the scope of the current project.

D. Estimation of variability

Determination of average values for measures such as oxygen consumption is worthwhile but by no means sufficient. An oxygen supply designed for an "average" man would, of course, be inadequate for one whose needs were above average.

It was expected that large variations in oxygen consumption and related measures would be found in individuals swimming at the same speed. Comparable determinations in a reasonable number of individuals would, in themselves, provide an indication of variability. In addition, it was hoped that the application of statistical measures might permit reasonably accurate estimation of the probable variation among trained underwater swimmers as a whole.

E. Range of swimming speeds

At the outset of this study, surprisingly little information was available even concerning "normal" speed in underwater swimming or the range of speeds which a swimmer might use in the course of an operation. Information on this subject has important bearing on design and evaluation of scuba because of the influence of speed upon physiological needs, the length of time required for swimming a given distance, and other inter-related variables.

Time would not permit investigation of this factor by measuring the speed of subjects allowed to pace themselves at speeds which they considered "slow","good for a long pull", "uncomfortably fast", and the like. It was necessary instead to depend upon subjective reactions to various pre-determined controlled speeds; but this was expected to yield valuable information.

The question of endurance at various speeds has important bearing on this subject, but its investigation had to be left to future study.

F. Influence of speed on efficiency

It seemed more than likely that a swimmer would require more oxygen per unit of distance covered as his speed increased. Observations of the CUSP study (5) in fact suggested that there might be a point within the normal range of speeds at which a rather abrupt drop in "efficiency" occurred. This possibility was of considerable importance not only in connection with breathing apparatus but also from the standpoint of swimmer-training. The oxygen consumption vs. speed data would be amenable to analysis along these lines.

G. Relative efficiency of individuals

The importance of estimating the variability of physiological requirements among individuals has been mentioned. Individual swimming "efficiency" is simply another way of looking at the problem of variability. However, the question was given special significance by the expression of doubt concerning the suitability of EDU divers as subjects for evaluation of swimming gear. As indicated above, the necessity of answering this question influenced authorization of this study and was reflected in its specific objectives.

3. Previous studies

Previous investigations bearing on physiological factors in swimming are to be found in references 1 to 5. These are summarized in Report 6-54, Sections 6.2 and 6.3. The relationship between the findings of previous studies and those of this project is discussed in Section V of this report.

B. Statement of the problem

The immediate problem of this study was the following:

To determine the oxygen consumption of appropriate groups of subjects during free underwater swimming at a variety of controlled speeds.

This constituted an objective in itself, and work with the data obtained (together with a few concurrent observations) was expected to fulfill the other major objectives.

C. Approach

1. Subjects

The objectives required that oxygen consumption measurements be made in at least two groups of subjects: one group to represent trained underwater swimmers who use scuba extensively in the field, the other to represent EDU divers who had participated in scuba evaluations.

a. Underwater Demolition swimmers

The "field" group consisted of six men supplied by Underwater Demolition Teams Two and Four. All of the six were experienced in underwater swimming with scuba, but the teams expressed the intention of sending two excellent swimmers, two of average ability, and two of somewhat less than average proficiency. At the time of study, the investigators did not know the order in which the individuals had been rated. Subsequently, it was learned that except for two (PARRISH and PETWAY) who were selected for unusual proficiency, the group was chosen largely at random.

b. Experimental Diving Unit Divers

Among the divers attached to the Experimental Diving Unit at the time of study, swimming ability was highly variable. It ranged from almost complete inability in the case of one man to what was considered outstanding proficiency on the part of two others. One of the latter (STEVENS) had previously been in Underwater Demolition for several years; the other (SUGLIA) had done competitive swimming.

Five men, including these two, were considered reasonably proficient in underwater swimming and had been the most active participants in evaluation studies. They thus constituted a group which appeared to be suitable for comparison with the UDT swimmers.

Another group, of four men, was chosen largely at random from among the EDU divers who were considered less proficient and who had played a less active role in evaluations. Measurements on these men were expected to provide some indication of the influence of training on swimming efficiency.

None of the subjects in any of the three groups had done extensive swimming during the preceeding 6 months.

2. Swimming speed

As has been mentioned, swimming speed required investigation in itself, but it was not possible to make this a primary object of study. Previous studies indicated that the "normal" or "average" speed was somewhere in the neighborhood of 1 knot (see table of speed conversions, table 20), but the probable range of speeds was quite uncertain. The range for study thus had to be selected in a rather arbitrary manner.

Plans called for investigation of speeds between 0.5 and 1.2 knots, and the entire UDT group was studied at approximately 0.1 knot increments throughout this range. It soon became apparent that only speeds between about 0.7 and 1.0 knot were of much practical interest, so most of the "proficient" EDU group was studied only in this range. The less proficient EDU men made runs only in the neighborhood of 0.8 k.

The lack of recent swimming activity on the part of the subjects was expected to introduce a learning factor into the results. To keep this from warping the oxygen consumption vs. speed curve, it was planned to study the various speeds in a random manner. This was not entirely possible. Difficulties with the breathing apparatus at higher speeds necessitated concentraing on the low and medium ranges until alterations could be made.

3. Swimming technique

The "standard" method of underwater swimming - using "fine" and a flutter or scissor kick - was employed. Individual techniques varied in matters such as width, rate, and force of kicks, degree of knee-bending, and the like. No attempt was made to alter a man's style or to study variations, although this would be of interest and has been the subject of some previous work (6). Use of the arms except as "planes" (for depth control and turns) was discouraged although one subject (SUGLIA) used a supplementary breast-stroke much of the time.

All subjects used Voit-Churchill swim-fins (R). Most men had a favorite pair which they were allowed to use. The fins varied somewhat in stiffness but were otherwise the same except that one subject (PETWAY) used the somewhat larger "demolition" model in preference to the standard type.

4. Duration of runs

Study of swimmer-endurance and of fatigue effects was beyond the primary objectives of this study. Initial plans called for making all runs cover a distance of 0.5 nautical mile, the duration thus depending on the speed. This was expected to yield some information concerning endurance and fatigue at least at the higher speeds. In practice, a variety of factors often caused earlier termination of runs. Except when runs were of questionable validity for other reasons, time rarely permitted repeating them. Runs as short as 10 or 15 minutes were accepted for data purposes in some cases if the rate of oxygen consumption appeared to have stabilized.

5. Measurements

The technical difficulties involved in making extensive physiological measurements during runs have been discussed. Only the following factors were measured:

1. Oxygen consumption
2. Respiratory rate
3. Kick-rate

The method of measuring oxygen consumption is discussed under Procedures. The respiratory rate was counted as a rough index of ventilation and because it was of some interest in itself. The kick rate was of interest because of its possible relationship to the efficiency of a man's swimming technique and because it might indicate whether increased rate or increased width and force of kick was the most important means of increasing swimming speed.

A number of measurements were obtained in addition to those involved in the swimming runs. These included:

1. Height, weight, and age.
2. Vital capacity and residual lung volume.
3. Body specific gravity.
4. Various body measurements
5. Front and side view body photographs.
6. Basal metabolic rate.
7. Radioactive iodine uptake.

All of the above were obtained for UDT subjects. With a few exceptions, all but 3, 6, and 7 were obtained for EDU subjects as well.

III. PROCEDURES

A. Method of determining oxygen consumption

A general discussion of methods of oxygen consumption determination is presented in Report No. 15-54. The only method suitable for this study was that involving use of closed-circuit oxygen rebreathing apparatus with measurement of the volume of oxygen which was added to the system to replace that consumed. This volume was measured indirectly by noting the pressure drop in the small cylinder which supplied oxygen to each breathing apparatus. These cylinders were calibrated in terms of the volume of oxygen delivered per unit of pressure drop. By applying the calibration factor and appropriate corrections, the volume of oxygen could be calculated. This method is discussed fully in Report No. 15-54.

B. Apparatus

1. Breathing equipment

The only closed circuit oxygen rebreathing units available in sufficient number for the study were World War II models of the Lambertsen Amphibious Respiratory Unit (LARU) (Figure 1). These were in a condition appropriate to their age, required vigorous maintenance operations, and not infrequently developed serious leaks during the course of runs. The masks were particularly affected by age, and mouthpiece were substituted in some cases as the only means of eliminating leaks.

One 1952 model of the LARU was available part of the time and was used in some of the runs (figure 2).

Further comments concerning the apparatus and its performance are presented in Appendix E.

2. Oxygen supply

The regular oxygen supply cylinders were used for initial purging (nitrogen washout), then replaced by the calibrated "run cylinders" (see figure 1). Each run cylinder was equipped with a 2-1/2 inch diameter oxygen gage and a Hoke or needle valve with which to control admission of oxygen to the system. The gages were calibrated at intervals and appropriate corrections applied when indicated. Gage-reading was accomplished underwater at stated intervals during the runs without stopping the swimmers.

3. Carbon dioxide absorption

The World War II LARU is equipped with a cylindrical carbon dioxide absorption canister 4 inches in diameter and 8 inches long.

Baralyme (R), which contains an indicator (changes color when the absorbent is exhausted), was used in all runs. Like other carbon dioxide absorbents, this loses most of its effectiveness when it becomes grossly wet. Water entering the canisters directly or via the mask and breathing tubes was a problem since carbon dioxide accumulation would follow and necessitate termination of runs. Due to the condition of the apparatus, this was not an infrequent occurrence. Whenever carbon dioxide accumulation was suspected, the canister was thoroughly examined to determine the cause.

Numerous instances of apparent carbon dioxide accumulation were encountered at speeds of 1.0 k and above. The absence of an evident cause suggested that the canister was simply too small and that carbon dioxide "blow-through" was occurring. The canisters on two units were subsequently lengthened to 12 inches, and further difficulties of this sort occurred when the lengthened canisters were used. The 10-inch canister of the 1952 LARU appeared to perform aadequately. (See Appendix E).

C. Swimming course and depth

The study was conducted during winter months, and the only available heated and enclosed body of water was the swimming pool at the U.S. Naval Receiving Station, Anacostia. This pool is approximately 80 feet long and 40 feet wide. The necessity of operating in a confined space was unavoidable.

A rectangular course with well-rounded corners was laid out in the poll by means of colored weights placed on the bottom. The course-length was 200 feet. The necessity of making the rounded 90 degree turns did not present evident difficulties for the swimmers although the exact consequences could not be determined.

The depth of the pool varied from 3 to 11 feet. Swimmers were instructed to maintain constant depth to the best of their ability. In the shallow end of the pool, swimmers with wide kicks sometimes broke surface with their fins. These men, in particular, tended to increase their depth on reaching deeper water. The tendency of these depth changes to increase effective course-length was considered too small and too variable to warrant attempts at mathematical correction.

At the slower speeds, where the "planing" effect was largely lost, some subjects had difficulty in controlling their depth. In some cases, these men were allowed to swim at the surface rather than expend energy in maintenance of the desired depth.

The temperature of the water averaged about 78 F and showed relatively little variation from day to day.

D. Speed control

The following method of controlling swimming speed was adopted: Markers (distinctively colored weights) were placed at 20-foot intervals along the course. Signals audible underwater were sounded at appropriate intervals, and the swimmers were instructed to control their speed so that they passed a marker each time the signal was heard. The interval between signals thus determined the swimming speed. The swimmers were able to control their speed by this method with little difficulty.

The signal system at first consisted of a man with a stopwatch and a partially submerged gong. Later, an automatic intervalometer and a partially submerged automobile horn were substituted, making the system completely automatic except for setting the interval. In a few instances, the available intervals did not permit making runs at precisely 0.1 k increments of speed.

In these cases, oxygen consumption values for the specific increments were obtained graphically, and the averages were reported on that basis.

Noting the time of each complete lap provided a check on both the signal system and the swimmer's accuracy in following it. All calculations were based on the swimmer's actual average speed.

E. General procedure

The procedure involved in the runs is discussed fully in Appendix A. The essential details were as follows:

Each subject had a "tender" who followed him at all times by walking around the edge of the pool. This tender reported any significant incidents or abnormalities and at intervals counted the man's kicks.

Cylinder pressure was read underwater once per lap (twice at the slower speeds) without stopping the swimmer.

Respirations were counted at intervals by another swimmer who watched (or lightly palpated) the subject's breathing bag for stated periods during the run.

Each subject had a recorder to whom the counts and measurements were called when taken. The recorder also wrote down all pertinent observations and noted the time at completion of each lap.

F. Handling of data

The method of deriving oxygen consumption values from raw data is described in Report No. 15-54. Briefly, this process consisted of graphing the recorded gage pressures against time, deriving an average "slope" of pressure-drop per unit time, and applying the appropriate cylinder and correction factors to obtain the value in liters of oxygen (STPD) per minute.

The raw breath and kick counts were also converted to per minute values.

Each individual's oxygen consumption values were graphed against swimming speed. A curve was then faired through these points. Where the runs were not at exact 0.1 k increments of speed, values for such increments were dervied from these curves for averaging purposes.

IV. RESULTS

A. Oxygen consumption at various swimming speeds

The oxygen consumption data is summarized in Table 1, which presents high, low, and average values obtained at the different speeds Figure 3 presents, in graphic form, data from the UDT swimmers and the more proficient EDU group. The lighter lines above and below the mean designate the range of values obtained.

Values obtained during rest are presented in Table 5.

Oxygen consumption values for all individual subjects are tabulate together with group means in Table 3.

The various measurements and other pertinent data related to each run of every subject are presented in Tables 6 to 17. The oxygen consumption values are plotted against time for each individual in Figures 5a through 15a.

Several observations appear especially noteworthy:

1. Mean values for oxygen consumption in the proficient groups range from 0.82 lpm. at 0.5 k to 2.5 lpm at 1.2 k. Within this same range, individual values in the two proficient groups run from as little as 0.67 to as much as 3.03 lpm.

2. There is little difference between the two "proficient" groups. Not only are the oxygen consumption values very similar, but both oxygen consumption vs. speed curves show the same general shape, characterized by increasingly steep slope as speed increases beyond 0.8 k.

3. The similarity of curves for the two proficient groups not withstanding, curves for individual subjects show as much variation in shape as in level. Note also that the same individuals did not necessarily show the highest and lowest values throughout the range of speeds.

4. The mean value for the "fair" group of swimmers approximates the highest value in the proficient groups. All individual values in the "fair" group are above the mean for the others.

B. Probable range of speeds

The subjects were almost unanimous in their subjective characterization of the various speeds.

Speeds below 0.7 k were uncomfortably slow. Some subjects had considerable difficulty holding themselves down to the desired rate. All found that they had lost most of the ability to "plane" themselves up or down, and this made depth-control difficult.

Few of the subjects had real difficulty maintaining the 1.0 k speed for moderate periods once the problem of carbon dioxide accumulation had been handled (see Appendix E), but they considered it too fast for either comfort or endurance. Speeds above 1.0 k rather rapidly produced either respiratory or muscular fatigue. Most of the subjects approached their limits in less than 20 minutes and were frankly uncomfortable almost from the outset. Some blamed their respiratory fatigue on the breathing apparatus (Appendix E).

As a comfortable speed suitable for a "long pull", most agreed on 0.8 k. They felt they could maintain this speed almost indefinitely. The 0.9 k speed was also reasonably comfortable.

C. Speed and "efficiency"

Values for the "Efficiency Index" - yards of distance covered per liter of oxygen consumed - were calculated from the oxygen consumption data. High, low, and average values are presented in Table 2, and Figure 4 presents the mean values graphically. Individual values are tabulated in Table 4 and those for each subject are graphed separately in Figures 5b to 15b.

Note that the means for the UDT and EDU "good" groups differ by one-half yard or less. Both curves show only minor fluctuations up to 0.8 k, but beyond this point display a progressive drop. Within the range of speeds studied, the drop is from about 20 yards per liter to 16 - a 20% loss.

Note, however, that the individual "efficiency" curves differ considerably from each other and from the mean curves.

D. Comparison of groups

As has been pointed out, the differences between the UDT group and the "proficient" EDU swimmers were very small. The "efficiency index" indicated that the latter, on the average, covered 0.5 yards less distance per liter of oxygen consumed at 0.7 and 0.8 k. This difference amounted to about 2-1/2%. The difference was smaller at 1.0 k and was reversed in direction at 0.9 k.

The "less proficient swimmer" group of EDU subjects, studied only around 0.8 k, consumed an average of 0.28 liters of oxygen more than the proficient groups at that speed. All of these subjects consumed more than the average of either of the other groups, but the lowest oxygen consumption in the "fair" group was less than that of the "high man" in each of the other groups.

In terms of distance covered per liter of oxygen consumed, the "fair" group was 3.5 yards (more than 17%) behind the proficient groups.

E. Respiratory Rates and Kick-Rates.

(See Appendices E and C).

F. Miscellaneous Measurements

Measurements not directly related to the swimming runs are presented as follows:

Table 5.	Oxygen consumption at rest underwater
	Basal oxygen consumption
	Radioactive Iodine Uptake
Table 18a.	Age, height, weight.
	Lung volumes
	Body surface area
	Specific gravity and lean body mass
Table 18b.	Various body measurements.

G. Oxygen consumption in terms of body size; statistical procedures

In Table 19, the oxygen consumption values for 0.8 k swimming are tabulated in terms of a) total, b) liters per square meter of body surface area, and c) liters per kilogram of lean body mass.

The background of these tabulations is discussed in Appendix D.

Extensive statistical analysis of the results of this study was not considered warranted either in terms of available time or expected relevance. Standard deviations were computed in a few cases and these are noted in tables 3 and 19.

H. Endurance; fatigue effects

The individual run data tables (Tables 6 to 17) contain 2 entries which bear upon endurance and fatigue. In runs at speeds above 1.0 k, the noted duration of the run comes close to representing the subject's endurance at that speed with the apparatus used. At slower, speeds, run duration is less significant since many runs were carried to the intended duration and others were terminated for reasons other than fatigue.

Each pressure vs. time graph was inspected for evidence of a change in oxygen consumption rate in the latter part of the run. The conclusions were noted in the "trend" column. In the vast majority no change could be noted, and the sporadic appearance and variable direction of evident change argues against trying to reach any conclusions about the effects of fatigue from this study.

V. DISCUSSION

A. Oxygen consumption vs. speed

Increasing swimming speed from 0.5 to 1.2 k increases the mean oxygen consumption by an approximate factor of 3, and the high and low values are increased in approximately the same proportion. The fact that oxygen consumption is tripled while speed is multiplied only by 2.4 is explained by the progressively increasing increments of oxygen consumption required for increments of speed above 0.8 k. The increasing slope of the oxygen consumption vs. speed curve and the loss of efficiency beyond 0.8 k are other reflections of the same relationship.

The range of individual values at the various speeds in impressive. The "high" man consumed from 1.4 to 1.7 times as much oxygen as the "low" man at a given speed. Individual curves for oxygen consumption vs. speed (figures 5a to 15a) show that not only do individuals vary in oxygen consumption at a given speed but also in the additional amount of oxygen they require for a given increase in speed. The difference in this respect is demonstrated by the varied shapes of the individual curves. It suggests the necessity of studying an individual at more than one speed in order to obtain an adequate idea of his performance: an individual who has unusually high (or low) values at one speed does not necessarily do so at other speeds.

B. Probable range of speeds

The subject's characterization of the various speeds defines the probable range rather well. The lowest speed studied, 0.5 k, was slower than any of them would have used in purposeful swimming and thus may approach an absolute lower limit. The upper limit, except for momentary bursts of speed, cannot be much beyond 1.2 k since this speed was uncomfortable from the outset, produced great fatigue, and could be maintained for only 20 minutes at best usually for much shorter periods.

In actual operations, a man is unlikely to maintain any constant speed; but if he can be governed by his own comfort, he will probably not vary more than between 0.7 k and 1.0 k. A good estimate of average normal speed is 0.8 to 0.9 k. Although 0.8 k was considered most comfortable and best for a prolonged swim, 0.9 k was generally maintained without complaint.

Note that the "drag" of the swimmer's breathing apparatus and other equipment are important in considering swimming speed. If more streamlined gear were used and less effort in propulsion were thus required, the speed-range would be shifted upward, and vice-versa. The data presented apply only to equipment similar in drag to that used in the study. This was considered close to "average" in this respect, but application of this aspect of the study requires comparative "drag" data on various other types of gear. Estimates of "normal" speed obtained during CUSP (5), with Aqua-Lungs which appear to have somewhat less drag, were in the neighborhood of 1.0 k. The maximum speed and endurance at that speed would also be influenced by the breathing characteristics of the scuba used, and by its carbon absorption capacity if it is a re-reathing type.

In any event, the range of swimming speeds is certainly limited. How limited it is can be appreciated by considering the length of time required to cover even short distances and by noting that currents of not unusual magnitude could reduce the net results of a man's efforts to less than zero.

C. Speed vs. Efficiency

That a point of abruptly diminishing efficiency might exist within the feasible range of swimming speeds has been mentioned as a possibility. The mean "Speed vs. Efficiency index" values (table 4, figure 4) suggest that 0.8 k is such a point. However, none of the individual subjects showed such a change at exactly 0.8 k, and some had completely different types of "efficiency curve" (tables 5b to 15b).

In any event, pushing speed beyond a certain point tends to decrease the return from energy expenditure. The exact point is variable, but it may be related to comfort at least, the average values showed decreased efficiency beyond the speed which most of the subjects considered most comfortable.

Not only is the swimmer's speed strictly limited, but his attempts to increase it produce diminishing returns in most cases. And according to the mean values, swimming at speeds below the point of abrupt change does not increase efficiency beyond a certain maximum.

D. Comparison of groups

Although there were only minimal differences between the UDT and EDU "good" groups, the difference between these and the "fair" group was considerable. It strongly suggests that experience in underwater swimming with scuba can make a large difference in requirements certainly a reasonable concept.

Most of the questioned evaluation work had been done by the proficient EDU men, but they gained most of their experience in the course of such evaluations. There being no information about the amount of experience required for reasonable efficiency, no conclusions about the validity of these prior evaluations can be reached on that basis.

Analysis of the data of the present study for evidence of "learning effect" was inconclusive, and not enough runs were made with the inexperienced group to show progression. A study of the influence of training and experience on development of efficiency would be valuable.

E. Probable range of metabolic oxygen requirements.

Information concerning the probable oxygen consumption of swimmers is needed in two primary connections. One of these is concerned with the adequacy of oxygen supply in closed circuit oxygen scuba. Here, the probable maximum requirement is of primary concern. The other has to do with the performance of mixed gas scuba in which the oxygen content of respired gas is directly influenced by oxygen consumption in normal operation, as in systems with constant injection and pop-off (Report No. 2-54, Section 2.3, Report No. 9-54, Section 9.2.4) or where a minimum rate of oxygen supply is involved. Here, the minimum rate of oxygen consumption is also important. Mean values for oxygen consumption are of less vital importance but are useful in both connections.

In attempting to derive the necessary information from the data of this study, the interrelation of the stated objectives becomes evident. Oxygen consumption at various speeds is not very meaningful unless the probable range of speeds is known, and much depends upon the subjects from whom the data is obtained - whether they are representative of underwater swimmers as a whole or not.

1. Subjects: a representative sample?

Without at least some study of swimmers as a whole group, it is not possible to take for granted even that the UDT men were representative. The fact that they were chosen largely at random was fortunate in this connection.

Note also that the two (PARRISH and PETWAY) who were selected as most proficient actually were at opposite extremes of the range at most speeds.

The close agreement (in oxygen consumption values and range) between the UDT and proficient EDU groups is of interest, as is the relative ease of distinguishing both from an inexperienced group. These observations may indicate that both of the proficient groups are reasonably representative of experienced underwater swimmers and that predictions based especially upon the two groups taken together might have definite value.

2. Statistical considerations

In some situations, statistical methods permit fairly precise predictions to be made about a given factor in a large group from analysis of that factor in a sample of individuals drawn from the "population" concerned. The standard deviation is the usual index of variation. If the factor has a "normal" distribution, about 67% of the values will lie within 1 standard deviation from the mean, and about 95% of the values within 2 standard deviations. If the sample is truly representative of the larger group, the mean and standard deviation in the sample will be very similar to those of the larger group, and predictions can be based on them.

It is not safe to assume blindly either that oxygen consumption values have a normal distribution or that the "proficient" subjects are a sufficiently representative sample of swimmers as a whole for this purpose. But it is of interest to consider what the predictions would be if these assumptions could be made.

For example, the mean value for the proficient subjects at 0.8 knots was 1.31 lpm, and the standard deviation was 0.16 lpm. This suggests that 95% of experienced swimmers should have oxygen consumption values (at that speed) between 0.99 and 1.63 lpm. The observed range was from 1.04 to 1.58 lpm. The prediction at least appears to be reasonable.

3. Allowances for larger men

Questions could be raised especially concerning the size of the subjects. While smaller or more efficient men than PARRISH are unlikely to be found among swimmers as a whole, larger men than the subjects of this study should not be infrequent. It would be unfortunate if predictions based on the study failed to cover the larger men in a swimmer group.

If the statistical approach were to be used, defining the probable range as minus 2 standard deviations to plus 3 standard deviations would probably be safe. Plus 3 standard deviations corresponds, at most speeds, to about the same value as mean plus twice the observed deviation above the mean. At the higher speeds, the latter value is lower than +3 S.D. but appears more logical.

A rough test of the probable adequacy of "mean plus 2 observed deviations" can be based on the body size measurements of this study. A consideration is presented in Appendix F.

The calculations indicate that a man would have to be considerably below average in efficiency and considerably above average in size to exceed such a value. The borderline of size is roughly indicated by 6 feet 3 inches height and a weight of 200 pounds, assuming the lowest "efficiency".

4. Suggested range-limits

In predicting probable oxygen requirements, values ranging from the low man's oxygen consumption to twice the high man's deviation from the mean at each speed should yield a reasonable estimate covering almost all experienced swimmers. This range includes even the inexperienced swimmer group in this study and virtually all of the high values which were considered questionable (see figures 5a to 15a).

5. Previous studies

It is desirable to check the adequacy of this range of values by comparison with the results of other similar studies. Comparable data was presumably obtained by the Admiralty EDU study (1,2) and by CUSP (5). The fact that speed control was indefinite in both studies makes comparison somewhat difficult, but the means appear to be from 0.3 to 0.5 lpm higher than those of the study being reported. Of the runs reported by CUSP (8 subjects, one run each, various speeds) 4 fall just above the range-limits mentioned above. Whether these runs actually indicate that the suggested limits are too low is difficult to determine The CUSP subjects were not accustomed to free-swimming with closed circuit apparatus and may thus have had considerable trouble especially with depth-control. They were, on the whole, larger men; and the water was about 18° F colder. All of these factors may help explain the discrepancy and the effects of cold seem especially worthy of further study. Although the mean admiralty values are even father above the mean of the present study, they fall within the "+2 observed deviaion "limits except in the case of one subject who was probably swimming faster than 1.2 k.

6. Ranges of speed

The next problem in predicting oxygen consumption values for various ranges of swimming activity is that of accounting fro probable ranges of speed. These ranges have already been discussed for their own sake, and the comparable range of oxygen requirements can be approximated by taking the lowest probable oxygen consumption for the lowest probable speed and the highest consumption for the highest speed. Ranges derived in this way are presented in Table 21.

7. Total range of oxygen consumption

The final question concerns the total range of probable variation in oxygen consumption. The least oxygen consumption would be associated with minimal activity underwater, and there are circumstances in which a scuba diver might have to remain almost motionless. What his oxygen consumption may be under these circumstances is of vital concern in some mixed gas systems. This state of almost total inactivity was approached in the measurements made (table 5). Note that some of the values are within the basal range.

The Admiralty EDU study (1,2) reported a mean value of 0.25. CUSP (5) reported a mean of 0.41 with no values below 0.31. However, the subjects in that study had to hang onto a platform during the measurements and were in cold (64°F) water. The CUSP values are probably representative of inactivity underwater under the most probable conditions but do not represent the absolute minimum.

In estimating minimum possible oxygen consumption, values as low as 0.25 lpm must be considered possible.

Neither the present study nor any other offers adequate data on maximal exertion in underwater swimming. It must be assumed that for brief periods a swimmer could exert himself to the utmost limits of this ability to absorb oxygen and could accumulate a sizeable oxygen debt as well. Values in excess of 4 lpm are therefore within the possible range. These extremes are also noted in Table 21.

8. Comment

Table 21 probably represents the best available estimate of the range of metabolic oxygen requirements in various ranges of activity, but it has numerous shortcomings. For example, it refers only to metabolic requirements and includes no allowance for other forms of oxygen-use: leakage, water-dumping, the losses associated with expansion on ascent, the amount used for purging, and the like. The possible magnitude of requirements for these purposes is discussed in Appendix G.

The questions of relative "drag", fatigue and endurance, cold, restriction of movement by protective clothing, and the needs of forms of work other than swimming all remain to be studied. Better estimates of the range of variation in the swimmer-population are needed, and the effects of training and experience deserve further investigation. All of these factors can influence the estimation of requirements.

F. Efficiency of Underwater Swimming

1. Comparison with other forms of work

Work is frequently classified as light, heavy, moderate, and the like, on the basis of either endurance or subjective severity. Oxygen consumption values are variously assigned to these gradations.

According to most classification dealing with leg-work, the mean values for 0.5 to 0.9 knots fall in the "moderate" range, speeds of 1.0 and 1.1 k would be considered "heavy", and 1.2 k falls in the "severe" range. Estimates based on endurance and subjective impressions would classify swimming in about the same way. It does not appear to differ very much, in this sense, from other forms of work done mainly with the legs.

The actual efficiency of muscular work is estimated by dividing the work done (in caloric terms) by the calorimetric equivalent of the associated increase in oxygen consumption. The upper limit of efficiency is about 25%. On the bicycle ergometer (70 rpm), it averages about 22%.

Without accurate information concerning an equipped swimmer's "drag", it is not possible to derive precise measures of efficiency on this basic. Assuming a drag of 9 pounds at 0.8 k (80 ft. per minute), the swimmer would be accomplishing about 720 foot-pounds of work per minute. This is equivalent to 0.233 kilogram-calories. The mean oxygen comsumption at 0.8 k was 1.31 lpm - equivalent to 6.37 kilogram calories, assuming and R.Q. of 0.85. The efficiency is thus only 3.6% in these terms, or about one-sixth that of a man working on a bicycle erometer.

In terms of distance covered per unit of oxygen consumed, the 20 yards per liter value is about one-fifth to one-sixth that of a man walking or running on dry land.

2. Comment

Although the efficiency of an underwater swimmer using fins is greater that that of a surface swimmer without fins, it is certainly remarkably poor. The major loss is in transmission of muscular effort to the water. Although swimming can probably never be replaced as a necessary means of underwater propulsion in many situations, devices which either increase the transmission of effort or which provide additional power are clearly needed (See Report No. 10-54, Section 10.7.2).

The metabolic cost of underwater propulsion would probably be greatly reduced by such means of walking or crawling along the bottom or by pulling along a line where either would be possible. The relative speed and oxygen consumption of these methods, as opposed to swimming, deserves study.

G. Miscellaneous Measurements and Observations

1. Respiratory Rate and Kick-Rate

The observations on these variables are discussed in Appendices B and C. On the whole, they do not appear to have notable implications, but the wide range of values is noteworthy. The apparent tendency of some men to use a large portion of their vital capacity in swimming is significant in the design of rebreathing circuits.

2. Body measurements, etc.

These are discussed in Appendix D. Body size data assisted in evaluating adequacy of oxygen consumption predictions, above, and showed some correlation with oxygen requirements. Basal metabolism and thyroid activity seemed to have little bearing on swimming oxygen requirements except possibly in the case of PARRISH.

3. Endurance and fatigue

These factors were not primary objects of study, and useful information was obtained only at the high speeds. A specific study in the practical range of speeds is required.

4. Shallow-water blackout

A number of informed individuals are skeptical about the existence of this entity although it is regarded as a serious problem by British workers and, at the present time, by this activity. (See Report No. 5-54, Section 5.6 and Report No. 6-54, Section 6.6; also reference 2).

Three times during this study (one preliminary run and 2 regular runs) men lost consciousness underwater without prior awareness of any abnormality. The possibility of anoxia cannot entirely be ruled out, but the breathing apparatus was always well-purged. In each case, the carbon dioxide absorbent was either wet (hence inactive) or showed unusual evidence of exhaustion. (Blueness of the indicator). In one of these cases, one of the supervisors (E.H.L.) donned the apparatus after the subject had been pulled out. He purged properly, began swimming, and shortly developed definite signs of carbon dioxide intoxication - primarily respiratory but with a strong CNS depressant effect developing before he could get out.

These episodes strongly suggest that insidious development of depressant levels of carbon dioxide, during work while breathing high concentrations of oxygen, is a serious potential problem in diving with rebreathing scuba.

5. Carbon dioxide output respiratory minute volume

Neither of these variables could be measured during the study, but the oxygen consumption data can provide a rough indication especially concerning carbon dioxide output. (See Report No. 6-54, Section 6.4). Estimates based upon the normal relationship between RMV and oxygen consumption are useful in some connections but are likely to be misleading where either depth or increased partial pressures of oxygen are concerned. (See Report No. 6-53, Section 6.3).

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Recognizing that certain conditions of the study, such as the breathing apparatus used, may have influenced the results to some extent, the following conclusions are considered warranted. Except where otherwise specified, the conclusions apply to reasonably proficient swimmers.

1. Oxygen consumption

a. Influence of swimming speed

Increasing the swimming speed from 0.5 k to 1.2 k approximately triples the rate of oxygen consumption. The rate of increase in oxygen consumption as accelerated beyond 0.8 k.

b. Individual differences

Oxygen requirements vary widely even among proficient swimmers. One man may require over 1-1/2 times as much oxygen as another man swimming at the same speed. Differences in body size explain only part of this variation. A given man's requirements may also vary from day to day.

c. Range of requirements

The total possible range of oxygen requirements in underwater activity extends from near-basal levels to a man's maximum possible rate of oxygen uptake. More specific ranges can be predicted on the basis of the oxygen consumption values and subjective reactions obtained at various speeds in this study. (See Table 21).

2. Probable range of speeds; speed vs. "efficiency"

a. Range

With apparatus having characteristics similar to those of the apparatus used in this study, the approximate normal range of swimming speeds of 0.7 to 1.0 k. The most probable average swimming speed is 0.8 to 0.9 k. Speeds as high as 1.2 k can be maintained for 10 - 20 minutes. Speeds considerably above this can probably be achieved for brief periods.

b. "Efficiency"

In terms of distance covered per unit of oxygen consumed, average efficiency is almost constant up to 0.8 k. It decreases distinctly and progressively beyond this speed. Individuals vary considerably in the shape of their "efficiency vs. speed" curves. Up to 0.8 k, the average distance per liter of oxygen consumed is slightly more than 20 yards.

3. Comparison of UDT and EDU groups; influence of training and experience.

The EDU swimmers who were reasonably experienced in the use of scuba showed virtually no difference from the UDT group. However, the less experienced men studied required considerably more oxygen at a given speed.

Use of inexperienced men as subjects could have considerable influence on the results of apparatus evaluation.

4. Underwater swimming as a means of propulsion.

The metabolic cost of covering distance by means of underwater swimming makes this an extremely inefficient means of propulsion. The very limited range of practical speeds imposes severe limitations on the swimmer's capabilities.

5. Need for further study

Broader and more confident application of the data on this investigation requires a considerable amount of additional study particularly in the following areas:

Relative "drag" of various types of scuba and auxiliary equipment.

Endurance at various speeds

Effects of fatigue.

B. Recommendations

1. In considering oxygen metabolic requirements and related matters in the deign and evaluation of scuba, apply values derived from this study (see especially Table 21) until more complete information becomes available. Make adequate allowance for non-metabolic use of oxygen.

2. Consider observations concerning probable ranges of swimming speed together with oxygen consumption values at various speeds.

3. In phases of evaluation requiring human subjects, employ men who are experienced in scuba swimming but do not require that they be members of field activities actively engaged in underwater swimming.

4. Avoid the use of evaluation procedures such as repeated endurance runs wherever established data can be applied directly to the question at hand. Employ fully controlled mechanical methods whenever established data can be applied in this way. In these cases, employ subjective runs only to check the predictions involved.

5. Continue and extend laboratory studies concerning oxygen consumption and related matters.

    a. Investigate the drag of various types of breathing apparatus and other swimmer equipment to permit broader application of present study.

    b. Investigate maximum swimming effort and determine endurance at various swimming speeds.

    c. Study the effect of fatigue and cold on swimming efficiency.

    d. Establish the relationships (and the extent of individual variation therein) between oxygen consumption and respiratory minute volume, carbon dioxide output, peak respiratory flow, and alveolar carbon dioxide levels, in various degrees of underwater work. Study the effect of depth and breathing medium on these relationships.

    e. Study methods of underwater propulsion other than swimming from the standpoint of requirements and relative efficiency.

    f. Study forms of work not related to propulsion.

6. Institute studies in the field.

    a. Investigate significant physiological variables during actual operations.

b. Obtain basic physiological measurements in large numbers of men whose work involves the use of scuba. Determine the actual range of requirements.

c. Establish the relationship between experience and efficiency by following men through various stages of training.

d. Attempt to obtain information concerning magnitude of non-metabolic forms of oxygen - use in actual operations.

7. Promote development of propulsive aids in view of the extreme inefficiency of underwater swimming.

a. Devices which increase the efficiency of the diver's own muscular effort.

b. Devices which provide auxiliary propulsive power.

APPENDIX A

DETAILS OF PROCEDURE IN CONDUCTION RUNS

I. Simultaneous runs.

In order to conserve time, two runs at the same speed were generally conducted at the same time. When this was done, one swimmer was started 1/2 to 1-1/2 laps behind the other to forestall collisions and confusion.

II. Personnel, observations, arrangements.

A. Tenders

One "tender" was assigned to each subject. His initial responsibility was that of helping the subject don and purge his breathing apparatus, attaching the "run bottle", and assisting in the adjustment of buoyancy. During the run, he followed the swimmer by walking along the edge of the pool, observing him closely at all times for any signs of distress or abnormality. He noted and reported any occasions when the swimmer used oxygen for expelling water, failed to keep up with the speed signals, broke surface, etc. At specified intervals, the tender also counted the kick-rate. (The tender system proved its worth on occasions when swimmers lost consciousness in the water and were promptly brought to the surface without untoward consequences. This accident occurred in one trial run and in two regular runs.)

B. Gauge-reader.

One man read the gauges for both subjects. He was equipped with a face mask and would skin-dive for the purpose when a swimmer approached the gauge-reading station in the deep end of the pool. On slow speeds runs where gauges were read twice each lap, another gauge-reader was stationed at the shallow end. Swimmers were instructed to "fill bag" at a definite point on the course prior to reaching the gauge-reader.

C. Respiration-counter

One man, wearing on Aqua Lung, had the responsibility of counting breaths for both subjects. He accomplished this by swimming alongside the subject at the specified times and observing the breathing bag for expansion and contraction. In some cases where respirations were not readily visible, the counter palpated the bag lightly.

As in the case of kick-rate, the respiratory count for two consecutive horn-intervals was obtained and subsequently converted to "per minute" values.

D. Recorders

A recorder, with stopwatch and clipboard, was assigned to each subject. The gauge readings and counts were called to him by the observers when obtained. He also had the responsibility of recording lap-time as an additional check on the speed-control system and the subject's ability to follow it. All observations of any consequence were noted by the recorder.

E. Data sheets

The recorders were supplied with data sheets having spaces for all of the specific information desired and for relevant comments. They were required to fill out all applicable spaces completely during the course of each run. (A sample data sheet is shown at the end of this section).

F. Rotation of jobs

Since an individual man frequently had to serve as both subject and as observer during the same half-day's runs, and since both fatigue and cold were problems, a rotation plan was devised which permitted the subject to have relatively easy dry-land jobs in runs preceding and following his own. He generally acted as recorder prior to being the subject and as a tender afterwards.

III.. Supervision of runs

All runs were supervised either by a master diver or an officer; usually in conjunction with Mr. Thomas HECKEL, the civilian engineer assigned by BuShips, Code 524, to assist with this study.

IV. Termination of runs

Few runs of this study are invalid because reasonable indications for termination were ignored. One of the problems of supervision was keeping runs from being stopped for insufficient cause.

The following were considered valid reasons for termination:

1. Genuine distress of potentially serious nature on the part of the subject.

   (Exceptional dyspnea or central nervous system symptons were accepted as evidence of carbon dioxide accumulation and led to termination).

2. Frank flooding of apparatus
3. Water-leaks requiring repeated use of oxygen for expulsion of water.

   (The method of determining oxygen consumption - slope of cylinder pressure vs. time - generally permitted correction for isolated instances of using oxygen for water explusion. When such correction was impossible, the run was discarded)

4. Leaks involving direct loss of gas.
5. Excessive fatigue or exhaustion of the subject.
6. Miscellaneous difficulties such as muscle cramps.

V. Carbon dioxide absorption: material, observations

A. Baralyme (R) was employed for carbon dioxide absorption throughout the study. Canisters were freshly charged before each run even when exhaustion of the absorbent was considered unlikely.

B. In any run where carbon dioxide accumulation was suspected, the canister was examined carfully for gross wetness and evidence of either channeling or exhaustion.

VI. Maintenance of apparatus

Keeping the breathing units in working condition was a considerable problem aggravated by their age. A routine "preventive maintenance" schedule including thorough inspection and leak-tests was of some help in preventing breakdowns.

APPENDIX B

RESPIRATORY RATE

Respiratory rates recorded during the various runs were averaged and are presented in the individual run data tables (Tables 6 to 17).

Inspection of the data indicates the following:

1. Respiratory rate tended to increase with increasing swimming speed, but the extent to which it did so was highly variable. In a few subjects, no definite upward trend can be noted.
2. Respiratory rates vary considerably even among a given subject' runs at the same or adjacent speeds with similar oxygen consumptio values.
3. There is no obvious relationship between respiratory rate and relative efficiency.
4. As a group, EDU swimmers had lower respiratory rates that the UDT men.
5. The lowest average respiratory rate in any of the runs was 9 breaths per minute. The highest was 39. In the range of speeds between 0.7 k and 1.0 k, the majority of swimmers had respiratory rates between 10 and 25 breaths per minute. Only 3 men had rates above 25.
6. Inspection of raw data indicates that respiratory rates were generally quite consistent during a given run. (Variations of more than 2-4 breaths per minute were rare).

Respiratory rate data can be considered in conjunction with the respiratory minute volumes which could be expected to accompany the various rates of oxygen consumption. Some of the subjects appeared to achieve increase in RMV largely through increased respiratory rate while others did so almost entirely be increasing their tidal volume.

If RMV is assumed to be about 22 times the oxygen consumption, rough estimates of average tidal volume can be made. On this basis, it appears that while most subjects at most speeds had tidal volumes less than 3 liters, values over 3 were not uncommon (about 10% of the runs showed tidal volumes between 3 and 4 liters). Four subjects appear to have had average tidal volumes up to 5 liters in at least on run. As noted in Appendix E, the breathing characteristics of the apparatus may have favored smaller tidal volumes.

Respiratory rate is also important in considering the effects of added respiratory dead space. For example, a dead space of 0.5 liters is not uncommon in full-face masks used with scuba. If such a dead space is present together with a respiratory rate of 20 breaths per minute, it would subtract 0.5 x 20 = 10 lpm from the swimmer's effective lung ventilation. Compensation for the dead space would necessitate a corresponding increase in RMV or more, if the rate also increased in the process of compensation.

In this example, the increase in RMV required to compensate for the dead space is at least equivalent to that which would accompany a 0.2 k increase in swimming speed. The effects of added dead space are less serious at the lower respiratory rates, more serious at the higher ones.

APPENDIX C.

KICK RATE

Kick-rates recorded during the various runs were averaged, and these values are presented in the individual run data tables (Tables 6 to 17). (The figures given are for individual kicks of both legs. Divide by two to obtain kick-cycles).

Inspection of the data indicates that the kick-rate is highly individual matter. The average rates varied over a wide range. All subjec increased their kick-rates with increases in swimming speed, but the extent of such increases was very variable. There was no evident relationship between kick-rate and swimming efficiency. EDU men tended to have lower kick-rates than the UDT men.

The range of recorded average rates is from 27 to 115 kicks per minute.

APPENDIX D

MISCELLANEOUS MEASUREMENTS AND CORRELATIONS

A variety of miscellaneous (non-swimming) measurements were obtained largly in the hope of finding useful correlation with oxygen consumption in swimming.

The metabolic measures (Basal Metabolism and Radioactive Iodine Uptake) appeared to have no relationship to oxygen consumption in swimming except in one possible instance. PARRISH had a low radioactive iodine uptake which indicates subnormal thyroid activity and the probability of subnormal metabolic levels. Although his B.M.R. was well within the normal range, his oxygen consumption in swimming was exceptionally low. However, PARRISH was also the smallest man by a considerable margin.

If one could assume equal "swimming efficiency", variations in actual oxygen consumption between individuals would presumably be proportional to body size. The large man not only has more tissue to supply even under basal conditions and more active tissue working during exertion but probably also presents greater resistance to passage through the water.

It is customary in procedures such as the B.M.R to reduce all individual values to a "least common denominator" by expressing the oxygen consumption in terms of volume consumed per square of body surface area. In these terms, all normal individuals are expected to have about the same values regardless of size, and the standard units are based on this assumption.

Theoretically, expression of oxygen consumption values in swimming in terms of a unit which tends to eliminate the influence of body size should relect only differences inefficiency and, assuming that the group is relatively homogeneous in that respect, greatly reduce the variability of values. If true, one should then be able to estimate a trained swimmer's oxygen requirements largely on the basis of his bulk.

Translation of the 0.8 k data into "per square meter of body surface" terms (Table 19) did not reduce the variability but almost completely rearranged the "highs" and "lows". Whether a truer indication of a man's actual efficiency is thus obtained may be open to question. At least, the "fair" groups continued to have high values while PETWAY and ZIEGLER were "normalized". Attempts to correlate oxygen consumptic and body surface area revealed a positive relationship, but the actual correlation did not appear impressive.

Body surface area is a somewhat artifical measure derived from height and weight with the aid of a table or nomogram. Lean body mass, derived from specific gravity measurement, seems more likely to be meaningful in this connection since it reflects the amount of actively metabolizing tissue. Expression in terms of this measure yielded even greater variability, and the correlation between lean body mass and oxygen consumption was even less striking than that with surface area.

APPENDIX E

PERFORMANCE OF BREATHING APPARATUS

The age and condition of the Lambertsen Amphibious Respiratory Units used in most of the runs has been discussed. Aside from problems related to age and condition, which explained most of the leakage, serious difficulties were few.

Several of the men repeatedly complained of "breathing resistance". In some cases, this was mainly related to the size of the breathing bag. What with a limited capacity under any conditions, stiffness, and hydrostatic factors related to position, the bags would not accomodate a full breath. If a man characteristically used a large proportion of his vital capacity, he found this restriction quite uncomfortable. In other cases, especially at high speeds, airway resistance was thought to be a factor as well.

The inadequacy of carbon dioxide absorption was noted at speeds of 1.0 k and above. This was largely a matter of "blow-through" since exhaustion of the absorbent, except possibly down the center, was rarely involved. (See Report No. 6-54, Section 6.4.3). Lengthening the canisters from the original 8 inches to 12 inches seemed to eliminate the difficulty. The study involved no runs long enough to bring the total absorption capacity of the canisters into question.

Many of the subjects felt that the large "front" presented by the bag and canister resulted in an inordinate amount of drag.

The 1952 LARU, used in some of the runs, incorporated many modifications. A much better mask, larger breathing bag, larger canister, and a demand valve for oxygen admission were the most important. The demand valve is a highly desirable feature especially useful in oxygen consumption studies.

Unfortunatley, it was an almost constant source of trouble. The unit used was a prototype, and the demand valve difficulties and most other faults appear to have been corrected in subsequent models.

The canister did not prove inadequate in any of the runs, but its limits were not specifically tested. The breathing bag's size and arrangement was much more satisfactory than that of the older model, but its larger area may have increased drag to some extent.

APPENDIX F

POSSIBLE INFLUENCE OF BODY SIZE ON OXYGEN REQUIREMENTS

The size of the subjects used, and the possibility of encountering larger men among underwater swimmers, is important in considering the applicability of the data of this study to trained swimmers as a whole. The following consideration indicates the possible magnitude of differences related to body size.

Question: How large would a man have to be for his oxygen consumption to exceed the maximum value obtained (among experienced subjects in the study) by twice the distance of that maximum from the mean?

(Use data for 0.8 K: the mean was 1.31 lpm; maximum value was 1.58 lpm distance from mean is 0.27; (2 x 0.27) + 1.31 = 1.85 lpm).

Solution:

1. Usual measure of body size for such purposes is square meters of body surface. (Values are obtained from a standard nomogram, entered with height and weight. See Table 18a for surface areas of subjects).

2. Oxygen consumption values were calculated in terms of liter per M^2 of body surface area (See Table 19). Values:

Low - 0.63

Mean - 0.71

High - 0.85

(Theoretically, the man having the lowest value is the most efficient swimmer).

3. Dividing 1.85 lpm (total) by the oxygen consumption in liters per M^2 of body surface area yields the hypothetical man's body surface area.

Values obtained are as follows:

"Efficient" - 2.95 M^2 (body surface area)

"Average" - 2.60 M^2 (body surface area)

"Inefficient" - 2.18 M^2 (body surface area)

4. Translation of these surface areas into height-weight figures yields the following approximations:

	Surface Area			
Height	2.18	2.60	2.95	
5' 6"	246	370	-	
5' 9"	230	345	-	
6' 0"	212	315	425	Wr. in pounds
6' 3"	198	295	392	
6' 6"	188	280	370	

Note that only values for 2.18 M^2 at heights of 6' or more fall within a likely range.

5. Conclusions:

Neither an "efficient" nor an "average" swimmer is likely to be larger enough to exceed 1.85 lpm at 0.8 k. A man whose efficiency (in terms of liters per M^2 of body surface area) is as low as the lowest observed among the "proficient" swimmers may exceed this value if he is over 6 feet tall and weights around 200 pounds. Similar relationships probably exists at other speeds.

(All of these figures are based on assumptions which have not been proved, but they are believed to indicate the order of magnitude reasonably well).

APPENDIX G

NON-METABOLIC OXYGEN REQUIREMENTS

The diver's oxygen consumption is not the only form of oxygen-use which must be considered in estimating requirements for closed-circuit oxygen scuba. There are at least four other factors:

1. Use of oxygen for purging the system.
2. Maintenance of volume during descent; expansion and dumping of gas during ascent.
3. Use of oxygen in expulsion of water, as from a leaking mask.
4. Frank leakage of gas.

The magnitude of some of these can be estimated. Others depend entirely upon the situation and must remain largely uncertain.

Those which can be estimated in some degree are:

1. Purging

This is the process of "rinsing" the breathing system and lungs with oxygen to remove atmospheric nitrogen. (The necessity for this procedure is discussed in Report No. 2-54, Section 2.2.5).

One of the best methods of purging involves removing all air possible from the system by inhaling, closing the system off, exhaling completely to the outside, refilling the system with oxygen enough for one full inspiration, and repeating the process for a total of about 3 times.

This would require a volume of oxygen about 3 times the man's vital capacity, or about 15 liters. If the regular oxygen supply of the gear is marginal, initial purging can be done from a separate source, but subsequent purges would depend on the regular supply. Re-purging must be done whenever air may have entered the circuit - as when the circuit is left open while using the surface breather - and at least a partial re-purge is recommended about once per hour of use. When air is breathed ("surface breather", removing mask at surface) the lungs should be "purged" before returning to the oxygen circuit.

The approximate oxygen requirements for purging can be summarized as follows:

Certain:

Initial Purge - 15 liters
Re-purge (routine) - 10 - 15 liter (per hour)

Possible:

Re-purge (air in circuit) - 15 liters (per instance)
Re-purge (lungs only) - 5 liters (per instance)

Example: A 2-hour swimming operation with average speed 0.8 - 0.9 knots. Metabolic requirement - 1.4 lpm x 120 minutes = 168 liters ("average man").

Requirements for purging: Initial, 15 l. 1-hr., 15 l.; re-purge lungs after surface breathing (twice) - 10 liters; total, 40 liters. In this particular case, purging alone would require an amount of oxygen equivalent to 25% of the metabolic requirements. Although this is only a hypothetical example, the relationship is probably fairly typical.

2. Maintenance of volume; expansion and dumping.

As a man wearing closed circuit scuba descends, he must add enough oxygen to compensate for compression of gas in the system. This gas is not necessarily lost. If the diver ascended slowly enough, he could utilize all of it before surfacing. Usually, however, he will ascent farily rapidly and much of the re-expanding gas will either escape from the system spontaneously or have to be dumped to prevent it from causing excess positive buoyancy.

When using oxygen rebreathing scuba, a man will rarely exceed about 33 feet of depth. A direct descent to that depth would require an additional volume (surface terms) of oxygen equal to that in his lungs and breathing circuit. This will probably average around 6 liters. Average ascent would probably take a little more than a minute, and one liter consumption is a fair estimate for that period. Thus, each acsent (from around 33 feet) may involve loss of about 5 liters of gas.

The "5 liter per ascent" value is necessarily inexact, but it does indicate an order of magnitude. Gas-use of this type would be a negligible factor on a "straight" dive of fair duration. It might conceivably exceed the metabolic requirement in a dive with many "ups and downs". Where the character of a dive is known in advance, an approximate allowance can be made.

Factors related to leakage are impossible to estimate with any kind of assurance. Indeally, there should be no leaks; but this ideal is not easily achieved. There are many places on most closed circuit where gas-leaks may develop; and even a good mask may admit some water on occasion. A trained man should be able to clear water from a leaking mask adequately without using more than a liter of gas. Assuming one liter per instance, having to clear every 5 minutes during an operation would, for example, require about 15% of the average metabolic requirement. This would be tolerable, although highly undesirable, situation.

Because of the vagueness of the estimates which can be made, and the near-impossibility of estimating some factors at all, it is extremely difficult to predict the total non-metabolic requirements. The discussion above does indicate, however, that they may be large. It is instructive to consider the hypothetical dive mentioned earlier, adding the other factors.

Hypothetical swim-dive:

Av. Speed - 0.8 to 0.9 k.

Duration - 2 hours.

Surfacing during dive - 2 times.

Mask-clearing - once every 5 minutes.

Leakage of gas - small, constant leak.

Non-metabolic use of oxygen	Approx. % of Metabolic Requirement
Purging	25
Expansion - dumping	10
Clearing mask	15
Constant leak	10
Total:	60%

Note: the variability of factors involved precludes taking 60% as an overall estimate. Even remotely remotely reasonable estimates can be made only by taking each type of operation into consideration separately. Since adequacy of gas supply must be assumed, the errors of estimate should always be made on the "high" side.

APPENDIX H. REFERENCES

I. Specific references cited in Report (numbers in parenthesis in body of report - - i.e., (5).

1. Donald, K.W., and Davidson, W.M.: Oxygen Uptake of Divers, Admiralty Experimental Diving Unit report XV, Sep. 1945.
2. Donald, K.W., and Davidson, W.M.: Oxygen Uptake of 'Booted' and 'Fin Swimming' Divers, J. Appl. Physiol., 7:31, Jul 1954.
3. Frassetto, R.: Report No. 17 to Office of Naval Research, 1951 (Confidential).
4. Experimental Diving Unit Data, Evaluation of 1952 Lambertsen Amphibious Respiratory Unit (LARU), Jun 1952 (unpublished).
5. Report of the Cooperative Underwater Swimmer Project, National Research Council Committee on Amphibious Operations, Report NRC:CAO:003, Jan 1953.
6. Frassetto, R.: Report No. 24 to Office of Naval Research, 1952 (Confidential).

II. General references

Karpovich, P.V.: Physiology of Muscular Activity, Philadelphia, W.B. Saunders Company, 1953.

Lanphier, E.H. and Dwyer, J.V., Jr.: Diving with Self-Contained Apparatus, Experimental Diving Unit, Special Report Series - 1954 (Reports No. 1-54 to 11-54).

EXPERIMENTAL DIVING UNIT

REPORT NO. 14-54

OXYGEN CONSUMPTION IN UNDERWATER SWIMMING

TABLES
and
FIGURES

CONTENTS

FIGURE 1. BREATHING APPARATUS RIGGED FOR DETERMINATION OF OXYGEN CONSUMPTION IN UNDERWATER SWIMMING.

Breathing apparatus shown is World War II Lambertsen Amphibious Respiratory Unit (LARU), the type used in most runs of this study. Note small (calibrated) "run cylinder" and oxygen gauge. Hoke valve just beyond gauge controls admission of oxygen to system. (Subject: STEVENS).

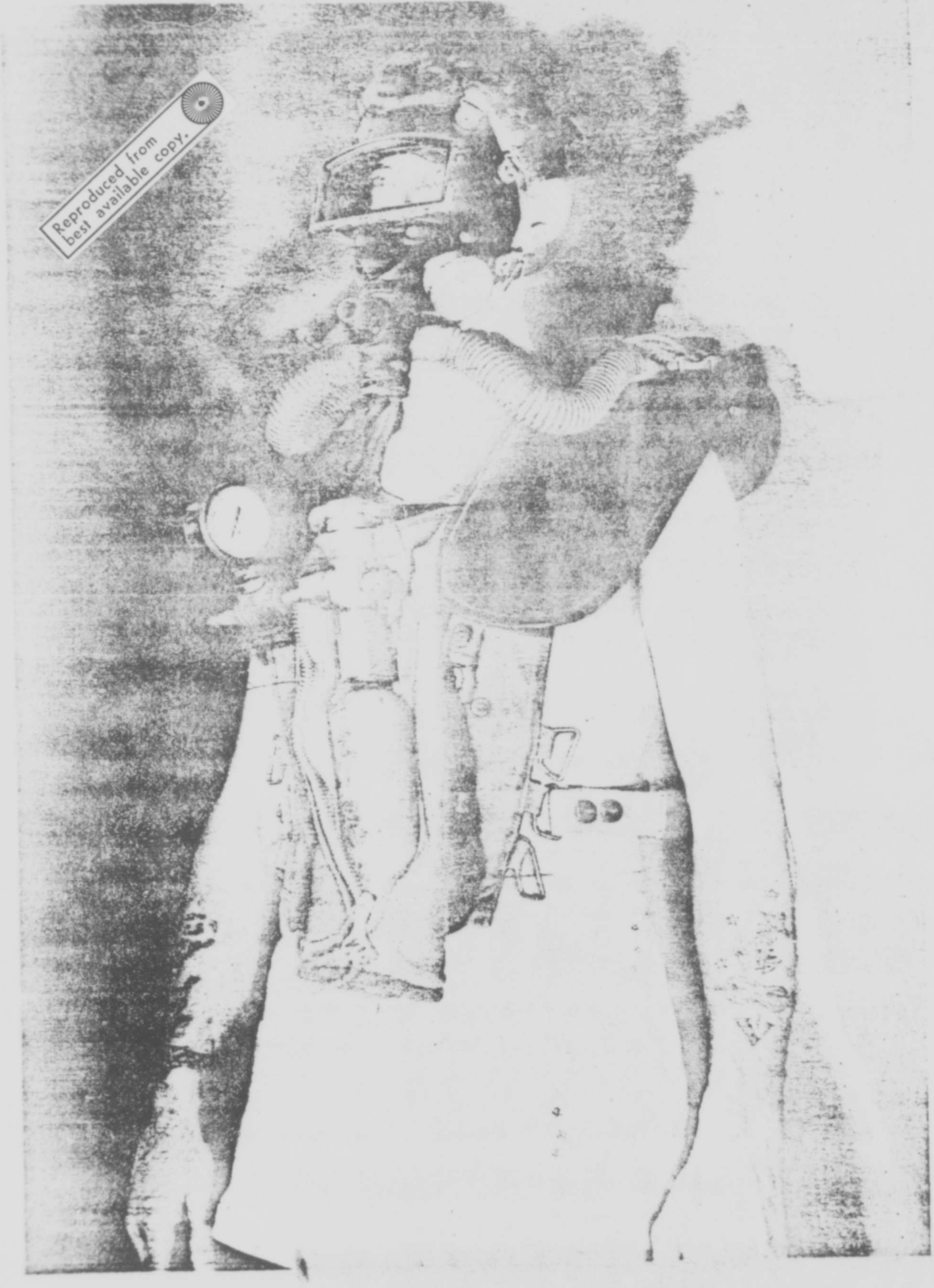

FIGURE 2. UNDERWATER PHOTOGRAPH OF SWIMMER EQUIPPED FOR MEASUREMENT OF OXYGEN CONSUMPTION

Apparatus is 1952 LARU, used in some of the runs. It is rigged essentially as is scuba shown in Figure 1, but here a demand valve admits oxygen as needed. Disc above subject's right shoulder covers diaphragm of valve. (Subject: McKenzie).

TABLE 1.

OXYGEN CONSUMPTION IN UNDERWATER SWIMMING
MEAN VALUES AND RANGE
(Liters of oxygen, STPD, per minute)

Speed (knots)	UDT Swimmers (6)			EDU Swimmers; good (5)			EDU Swimmers, fair (4)		
	mean	low	high	mean	low	high	mean	low	high
0.5	0.82	0.67	1.00						
0.6	0.96	0.83	1.14						
0.7	1.14	0.96	1.35	1.17	1.06	1.36			
0.8	1.30	1.04	1.52	1.33	1.20	1.58	1.59	1.49	1.67
0.9	1.53	1.13	1.90	1.52	1.38	1.76			
1.0	1.83	1.34	2.26	1.80	1.54	2.13			
1.1	2.10	1.56	2.64						
1.2	2.50	1.87	3.03						
Rest	0.34	0.26	0.41	0.34		0.42			

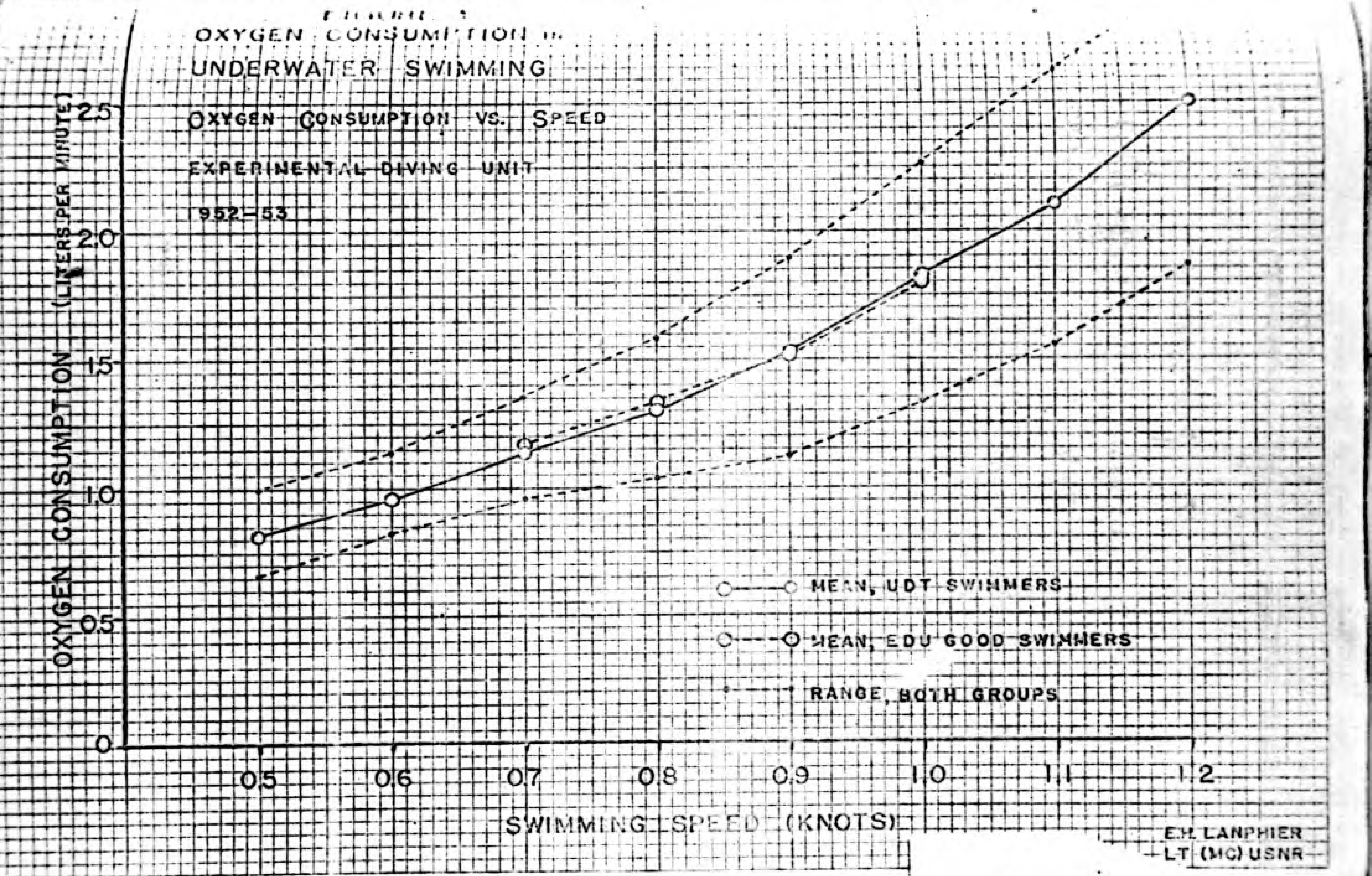

FIGURE [illegible]

OXYGEN CONSUMPTION IN UNDERWATER SWIMMING

OXYGEN CONSUMPTION VS. SPEED

EXPERIMENTAL DIVING UNIT

952–53

E.H. LANPHIER
LT (MC) USNR

TABLE 2. DISTANCE PER LITER OF OXYGEN CONSUMED IN UNDERWATER SWIMMING
MEAN VALUES AND RANGE
(Data of Table 1 converted to yards per liter)

Speed (knots)	UDT Swimmers (6)			EDU Swimmers, good (5)			EDU Swimmers, fair (4)		
	mean	high	low	mean	high	low	mean	high	low
0.5	20.3	24.9	16.7						
0.6	20.8	24.1	17.5						
0.7	20.4	24.3	17.3	19.9	22.0	17.2			
0.8	20.5	25.6	17.5	20.0	22.2	16.9	16.8	17.9	16.0
0.9	19.6	26.6	15.8	19.7	21.8	17.0			
1.0	18.2	24.8	14.7	18.5	21.6	15.7			
1.1	17.4	23.5	13.9						
1.2	16.0	21.4	13.2						

FIGURE 4

DISTANCE PER LITER OF OXYGEN CONSUMED IN UNDERWATER SWIMMING

YARDS PER LITER VS. SPEED

EXPERIMENTAL DIVING UNIT — 1952-53

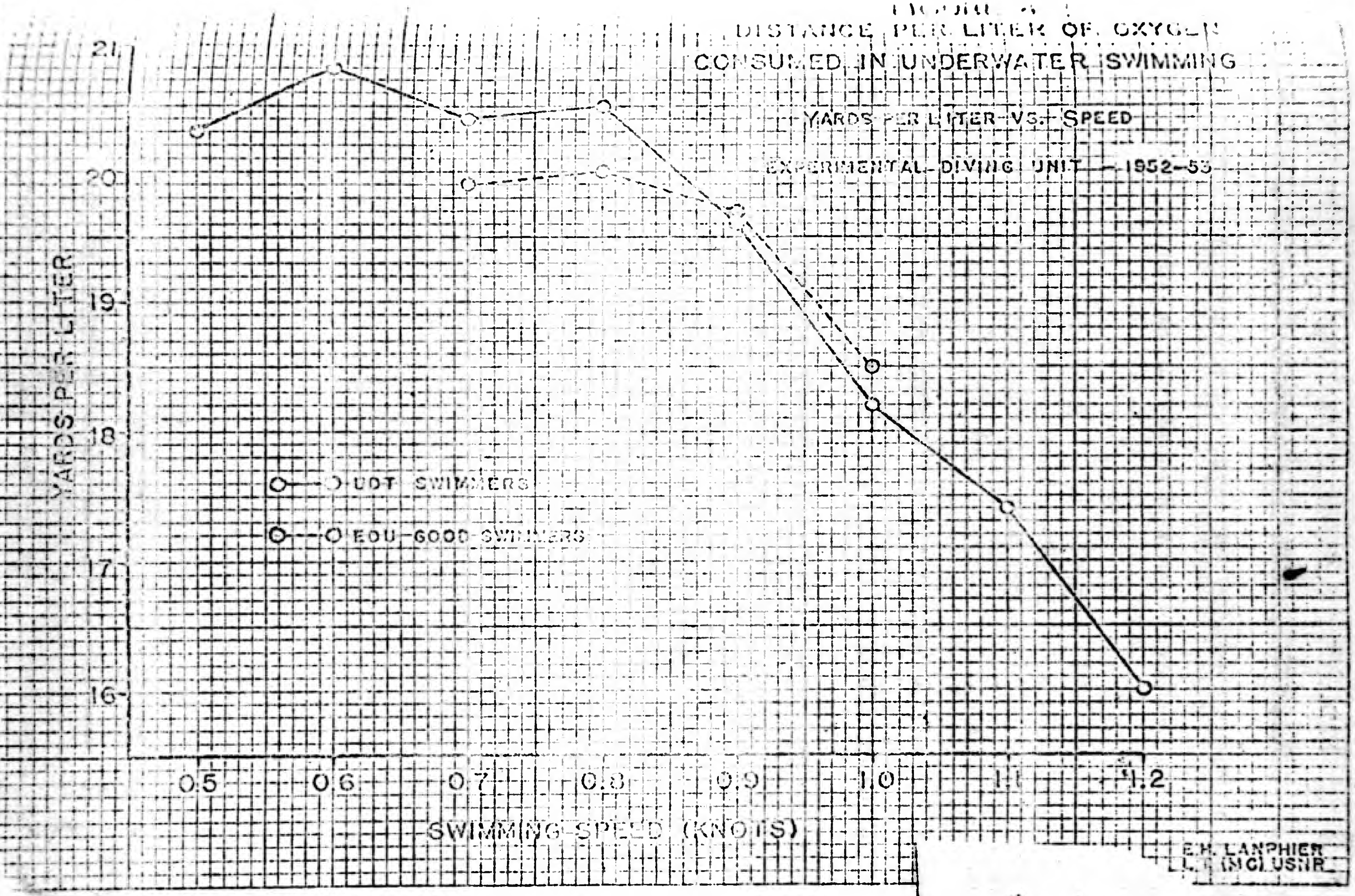

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TABLE 3. AVERAGE O2 CONSUMPTIONS AT VARIOUS SPEEDS (INDIVIDUAL VALUES FROM "BEST-FITTING LINES" ON GRAPHS):

SUBJECT	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
UDT								
ALFANO	.90	1.14+	1.35+	1.52+	1.68	1.89	2.05	2.24
BAKER	.83	.85	1.04	1.20	1.40	1.66	1.92	2.18
HENDERSON	.67-	.83-	1.06	1.26	1.42	1.67	1.79	2.76
PARRISH	.81	.88	.96-	1.04-	1.13-	1.34-	1.56-	1.87-
PETWAY	1.00+	1.12	1.25	1.48	1.90+	2.26+	2.64+	3.03+
ZIEGLER	.68	.94	1.20	1.30	1.66	2.14	2.62	2.94
Mean	.82	.96	1.14	1.30	1.53	1.83	2.10	2.50
EDU "Good"								
CARROLL			1.06-	1.30	1.43	2.13+		
KISSEE			1.10	1.22	1.38-	1.54-		
MC KENZIE			1.36+	1.58+	1.76+	1.93	1.84-	
STEVENS			1.29	1.33	1.46	1.57	1.94	
SUGLIA			1.06-	1.20-	1.56	1.84	2.20+	
Mean			1.17	1.33	1.52	1.80		
EDU "Fair"								
BOHLINE				1.67+	2.24			
GRIFFITH				1.63				
MC ARDLE				1.55				
MOERSCH				1.49-	1.69			
Mean				1.59				
Mean of UDT & EDU "Good"			1.15	1.31	1.53	1.82	2.06	
S. D.	.13	.14	.14	.16	.21	.29	.37	.47

NOTE: + designates highest value in group at each speed.
- designates lowest value.

TABLE 4 - "EFFICIENCY INDEX" - DISTANCE (YARDS) PER LITER OF OXYGEN CONSUMED:

SWIMMING SPEED (KNOTS):

JECT:	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
DT								
FANO	18.5	17.5-	17.3-	17.5-	17.9	17.6	17.9	17.8
ER	20.1	23.5	22.4	22.2	21.4	20.1	19.1	18.3
DERSON	24.9+	24.1+	22.0	21.2	21.1	20.0	20.5	14.5
RISH	20.6	22.7	24.3+	25.6+	26.6+	24.8+	23.5+	21.4+
MAY	16.7-	17.9	18.7	18.0	15.8-	14.7-	13.9-	13.2-
GLER	24.5	21.3	19.5	20.5	18.1	15.6	14.0	13.6
AN*	20.3	20.8	20.4	20.5	19.6	18.2	17.4	16.0
DU ood"								
RROLL			22.0+	20.5	21.0	15.7-		
SSEE			21.2	21.8	21.8+	21.6+		
C KENZIE			17.2-	16.9-	17.0-	17.3	20.0	
VENS			18.1	20.0	20.6	21.2	20.5+	
GLIA			22.0+	22.2+	19.2	18.1	16.7-	
AN*			19.9	20.0	19.7	18.5		
DU air"								
LINE				16.0-				
IFFITH				16.4				
C ARDLE				17.2				
ERSCH				17.9+				
AN*				16.8				
AN* of T & EDU ood"			20.2	20.3	19.6	18.3		

*"EANS" are derived from average oxygen consumption figures in Table I.

TE: + designates highest value in group at each speed.
- designates lowest value.

TABLE 5. OXYGEN CONSUMPTION AT REST AND IN BASAL STATE; THYROID ACTIVITY

	Oxygen Consumption (Liters/min.)		I^{131} Uptake (%)		
SUBJECT	Resting Underwater	"Basal"	24 hr.	48 hr.	Comment
Alfano	0.26	0.23 (-13)*	19.1	28.1	Normal
Baker	0.32	0.31 (+15)	22.4	19.7	Normal
Henderson	0.33	0.29 (+8)	11.5	17.4	Low Normal
Parrish	0.33	0.23 (-1)	18.6	12.9	Low
Potway	0.41	0.32 (+9)	12.0 7.1	14.6 20.2	Low Normal
Ziegler	0.37	0.23 (-11)	10.4	15.2	Low Normal
Carroll	0.24				
Kissee	0.37	(*B.M.R.)			
McKenzie	0.34				
Stevens	0.42				
Suglia	0.35				
Mean	0.34				

NOTES ON INDIVIDUAL RUN-DATA TABLES (TABLES 6 TO 17)

1. Speed

Figure given is derived from average of recorded lap-times. It is thus corrected for deviations from desired speed where these occurred.

2. Run number.

Runs were numbered consecutively in two series: UDT and EDU. The arrangement of these tables is in order of increasing speed. The run number indicates the sequence of the runs - of significance in considering the "training" factor.

3. Oxygen consumption

Method of deriving these values is discussed in III (Procedures) and covered in detail in Report No. 15-54. Values were rounded to 2 decimal places.

4. Cylinder number

Cylinder numbers are given since the cylinders used had different calibration factors. These factors, including the correction to STPD, were as follows:

Cylinder No.	Factor (liters/100 psi drop)
510	3.28
518	3.29
519	3.29
520	3.33
522	3.35

An asterisk by the cylinder number indicates that Gauge No. 3 was used. This was the only gauge which required application of a correction factor (pressure-drop values multiplied by 1.05).

5. psi drop/min.

The average pressure-drop per minute was derived from plot of cylinder pressure vs. time. Multiplying pressure-drop per min./100 by cylinder factor yields O2 consumption.

6. Av. Resp./min.

The respiratory rate was counted every third lap during the runs.

7. Av. kicks/min.

Kick rate, counted simultaneously with the respiratory rate, represents total number of down-strokes of *both* legs. (Divide by 2 to obtain kick cycles).

8. Duration of run

Durations were rounded to nearest minute.

9. Trend

The plots of cylinder pressure vs. time were examined for evidence of increasing or decreasing rate of pressure-drop in latter portions of runs. Symbols indicate the following:

= no evident change.

\+ apparent increase, suggesting loss of efficiency.

\- apparent decrease in rate of oxygen consumption.

10. Remarks

Comments on original data sheets were examined for information bearing on validity of runs or having general interest.

NOTES ON INDIVIDUAL OXYGEN CONSUMPTION VS. SPEED CHARTS (Figures 5a to 15a)

These graphs were plotted for two main reasons: 1) to yield values for even 0.1 knot increments of speed and 2) to permit, in some degree, the use of runs at adjacent speeds for "averaging" purposes.

In many cases, the variability of values made it difficult to fair acceptable curves through the available points. Three primary considerations governed the fairing process: 1) that points which clearly fell "out of line" from the majority of points should be given relatively little "weight" particularly if the comments recorded at the time of run shed doubt on their validity. 2) that wherever possible, the line should approximate the average of values at the same speed and, allowing for the general trend of points, of the values at the next higher and lower speeds. 3) that the method of measuring oxygen consumption is very much more likely to yield falsely high values than falsely low ones - therefore that low values should be given greater weight.

Had it been possible to run each subject a large number of times at each speed and to accept high values as having equal validity, the mean values obtained might have been higher than the values indicated by the "faired" lines in some cases. The method used may cause a subject's true variability in the direction of higher rates of consumption to be obscured to some extent. Note, however, (see V, discussion) that the suggested allowance for high requirements is sufficient to include even those individual "highs" which are of very dubious validity.

Individual graphs of Yards per Liter vs. Swimming Speed (Figures 5b to 15b) represent conversion of oxygen consumption values, derived from faired lines in graphs of oxygen consumption vs. speed, to distance covered per liter of oxygen consumed.

TABLE 6. INDIVIDUAL RUN DATA

Subject: ALFANO (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.50	25	0.90	522	27.0	12	46	32	=	Irreg. speed.
0.60	31	1.14	522	34.0	11	35	31	=	
0.70	42	1.49	520	44.7	--	32	32	-	Small constant leak.
0.70	46	1.35	519	41.0	13	27	31	=	
0.78	36	1.51	510	46.0	12	45	28	=	
0.80	8	1.38	520	41.3	23	73	19	=	Sl. leak; one stop.
0.80	13	1.50	522*	42.6	17	61	35	=	
0.92	50	1.72	520	51.6	--	54	26	=	Curve sl. irregular.
1.00	19	2.59	520*	74.0	30	92	6	-	Lost consciousness
1.00	82	1.89	519*	54.8	29	63	29	=	
1.10	73	2.05	518*	59.4	25	81	27	=	
1.20	83	2.24	520	64.0	28	106	17	=	

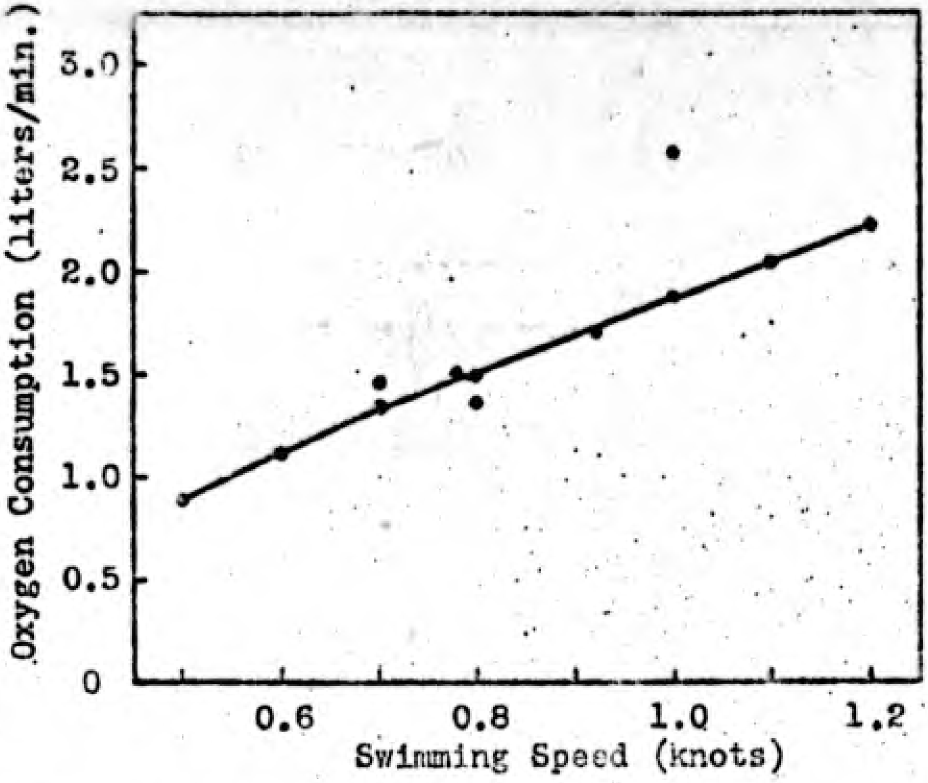


Figure 5a. Alfano. Oxygen consumption vs. speed in Underwater swimming.

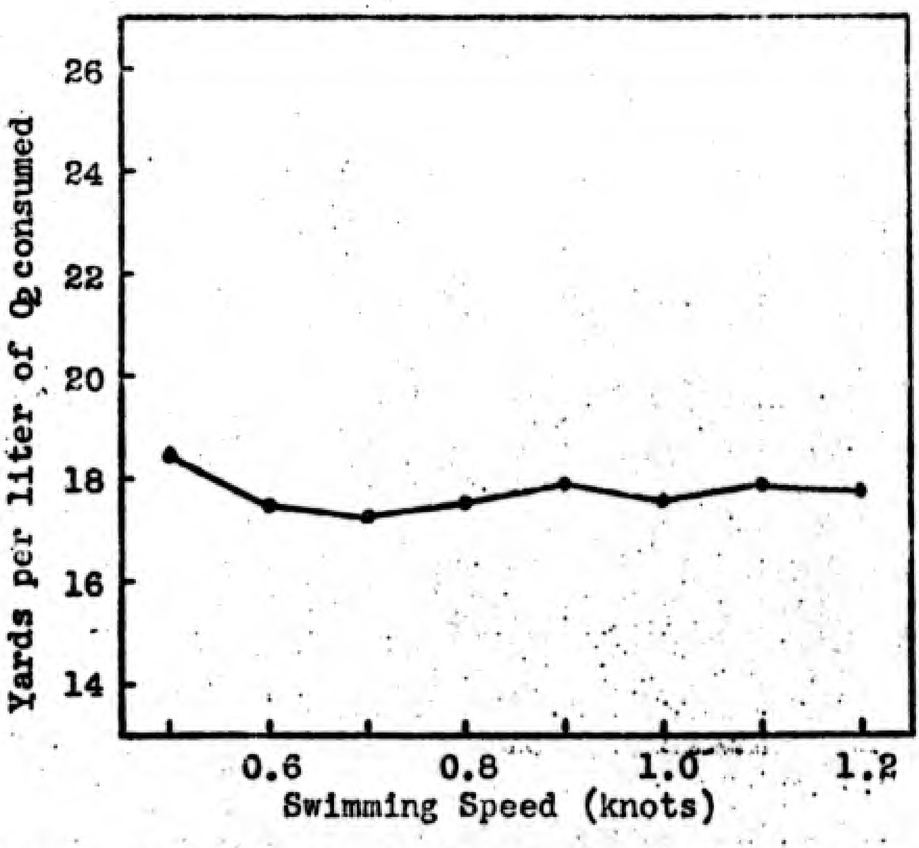


Figure 5b. Alfano. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 7. INDIVIDUAL RUN DATA

Subject: BAKER (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.50	23	0.83	520*	23.8	16	80	32	+	Irreg; probably ok.
0.60	29	0.85	522	25.3	13	70	30	-	
0.71	45	1.06	510	32.2	16	99	31	=	
0.77	35	1.13	520	33.8	18	91	31	=	
0.80	12	1.22	520	36.6	16	100	38	=	
0.93	55	1.41	520 510	48.0 43.0	20	91	34	=	Shifted cylinders.
0.91	39	1.49	520	44.8	17	100	31	=	
1.00	6	1.78	510	54.4	21	89	22	=	
1.00	17	1.66	510	50.5	23	118	20	=	
1.10	71	1.92	510	58.5	20	98	26	=	
1.20	77	2.42	510	73.9	28	130	17	=	
1.20	85	2.11	520	63.3	26	108	15	=	

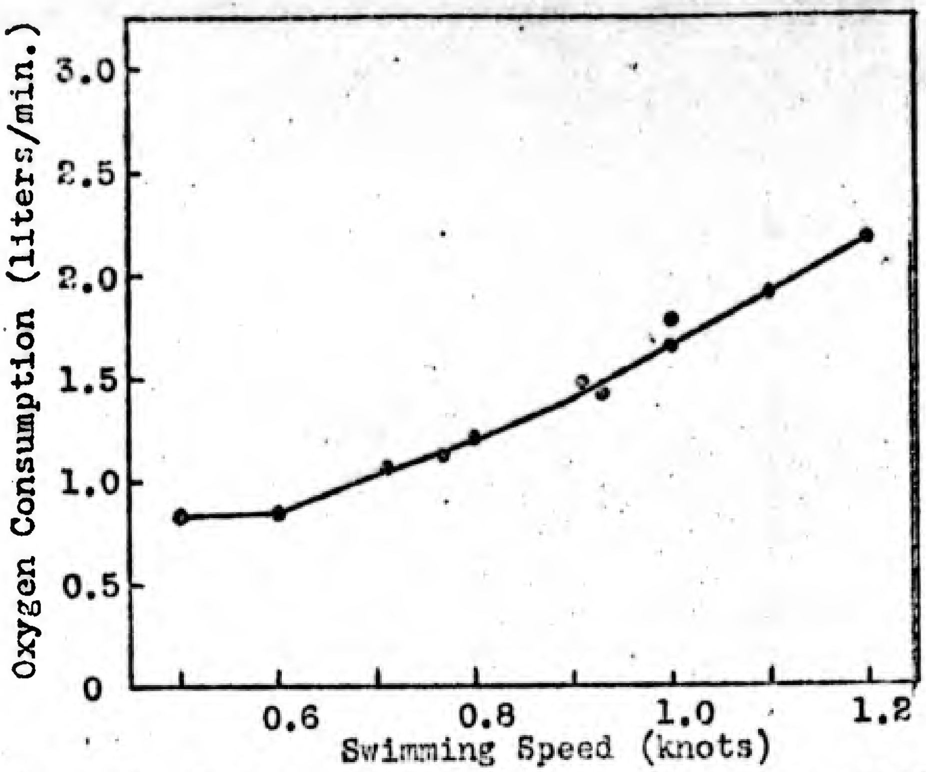


Figure 6a. Baker. Oxygen consumption vs. speed in Underwater swimming.

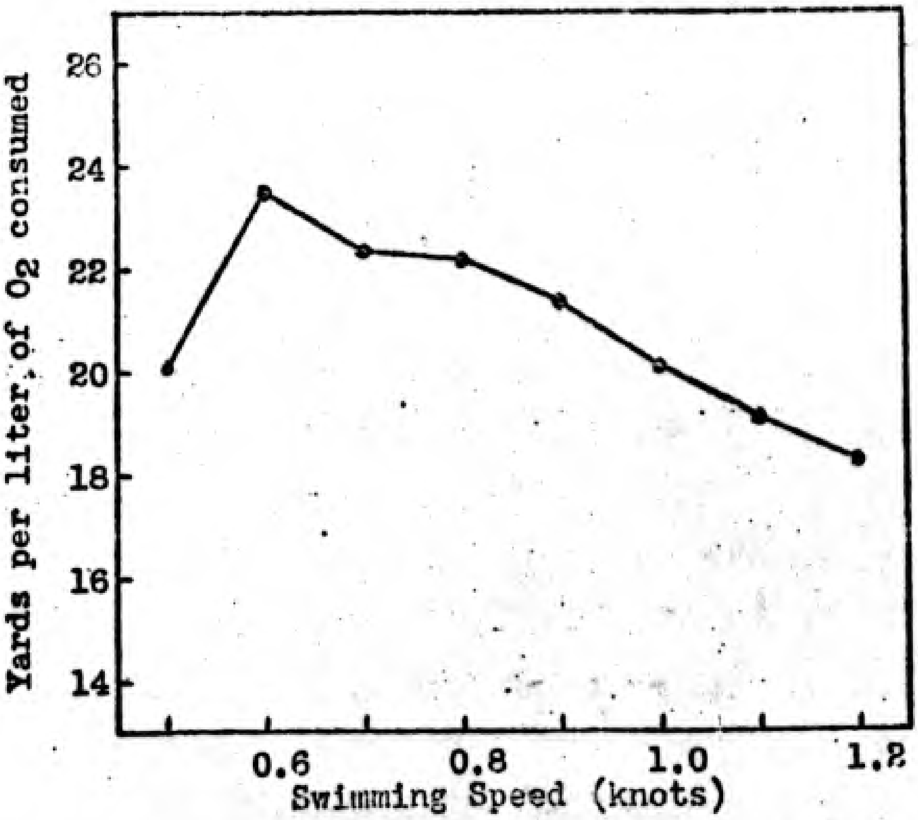
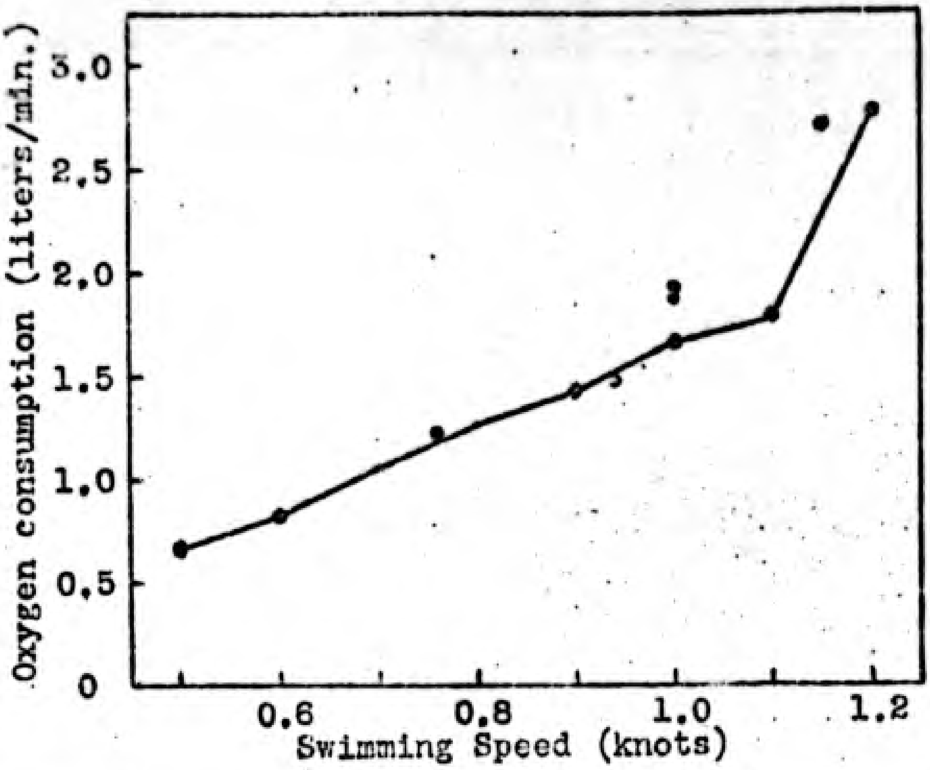


Figure 6b. Baker. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

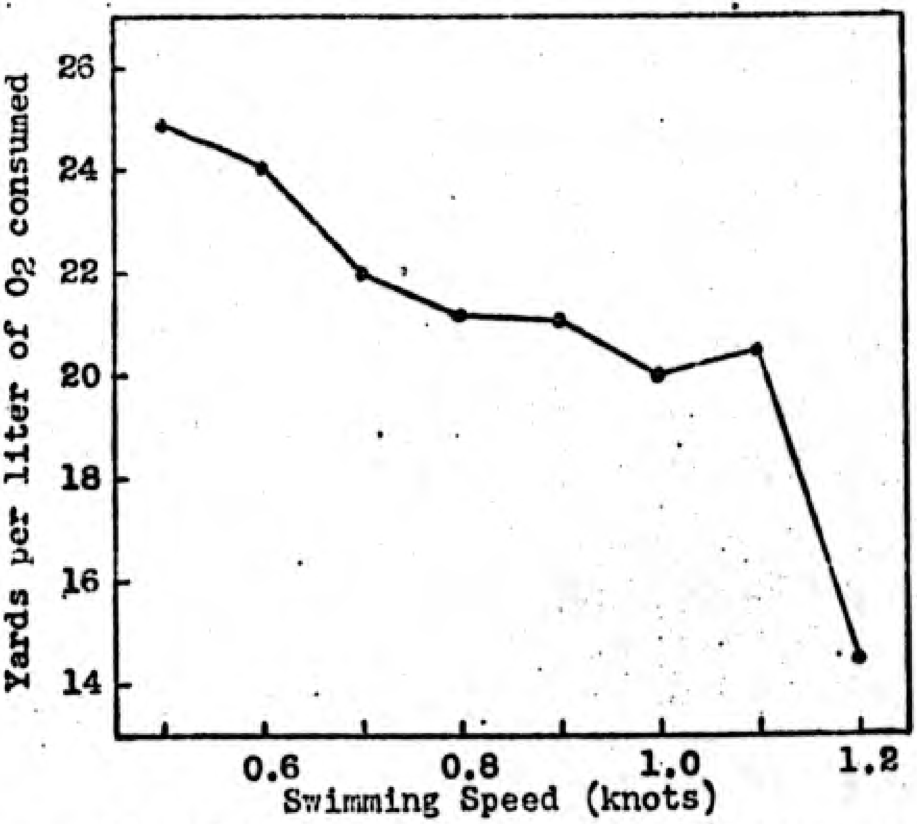
TABLE 8. INDIVIDUAL RUN DATA

Subject: HENDERSON (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.50	22	0.67	510	20.5	15	58	33	=	
0.60	28	0.83	519	25.3	13	60	30	+	
0.71	47	1.38	510	42.0	20	96	32	=	Sore foot; using 1 fin.
0.77	34	1.22	519	37.0	22	69	31	=	
0.80	11	1.43	510*	41.4	23	74	48	=	
0.94	38	1.49	510*	43.2	24	94	32	=	
1.00	5	1.94	510	59.2	33	104	21	=	
1.00	61	1.92	520	57.5	25	99	28	+	Small leak ?
1.00	64	1.67	510*	48.3	27	93	32	=	
1.10	70	1.79	522	53.3	27	--	31	=	
1.14	81	2.71	522*	77.1	--	116	7	=	
1.20	84	2.76	519*	80.0	30	116	16	+	Brief stop midway to tighten canister.



<u>Figure 7a</u>. Henderson. Oxygen consumption vs. speed in underwater swimming.



<u>Figure 7b</u>. Henderson. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter of oxygen consumed.)

TABLE 9. INDIVIDUAL RUN DATA

Subject: PARRISH (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run (min)	Trend (see note)	Remarks
0.50	21	1.27	519	38.5	13	70	33	=	Freq. mask-clearing.
0.50	53	0.81	510	24.7	14	75	36	=	Occas. clearing.
0.60	26	1.03	520	30.8	15	53	33	=	
0.71	49	0.97	510	29.7	10	74	32	-	
0.77	33	1.14	510	34.7	12	98	31	=	
0.80	10	1.11	520	33.4	16	65	50	-	
0.80	16	1.23	519	37.3	17	67	33	=	Interrupted 3 min.
0.86	56	1.21	522	36.0	22	67	33	=	
0.92	63	1.15	519*	33.3	14	82	29	=	Poor depth control.
1.00	1	1.83	520	55.0	17	68	36	=	(First run made)
1.10	69	1.56	510	47.5	25	114	29	+	Freq. clearing.
1.20	75	1.87	510*	57.0	18	130	12	=	

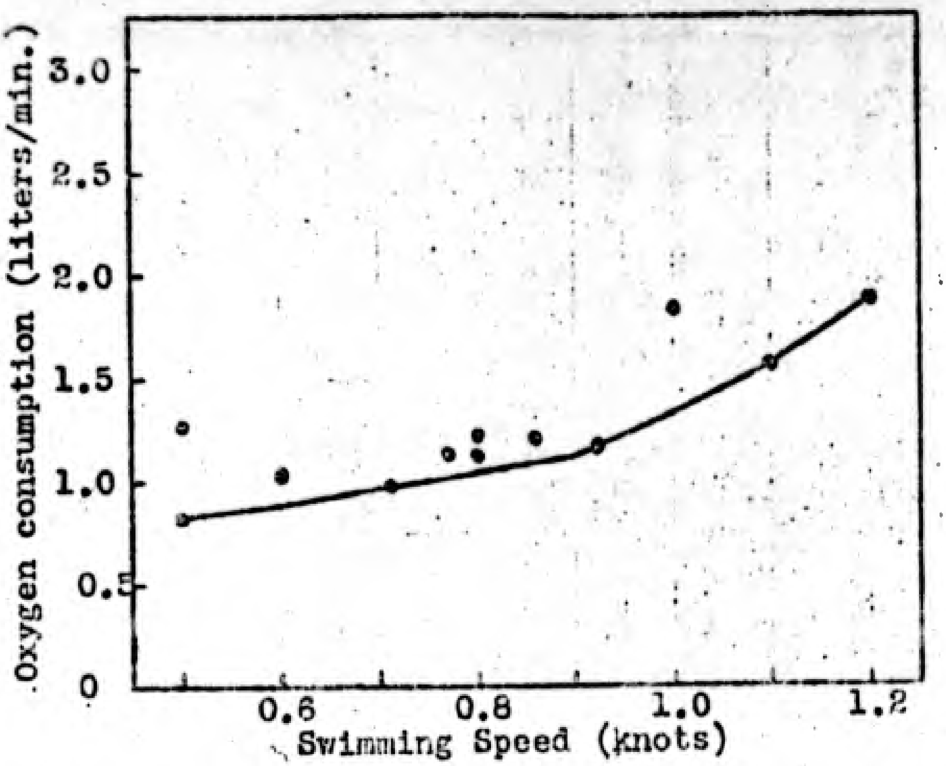


Figure 8a. Parrish. Oxygen consumption vs. speed in underwater swimming.

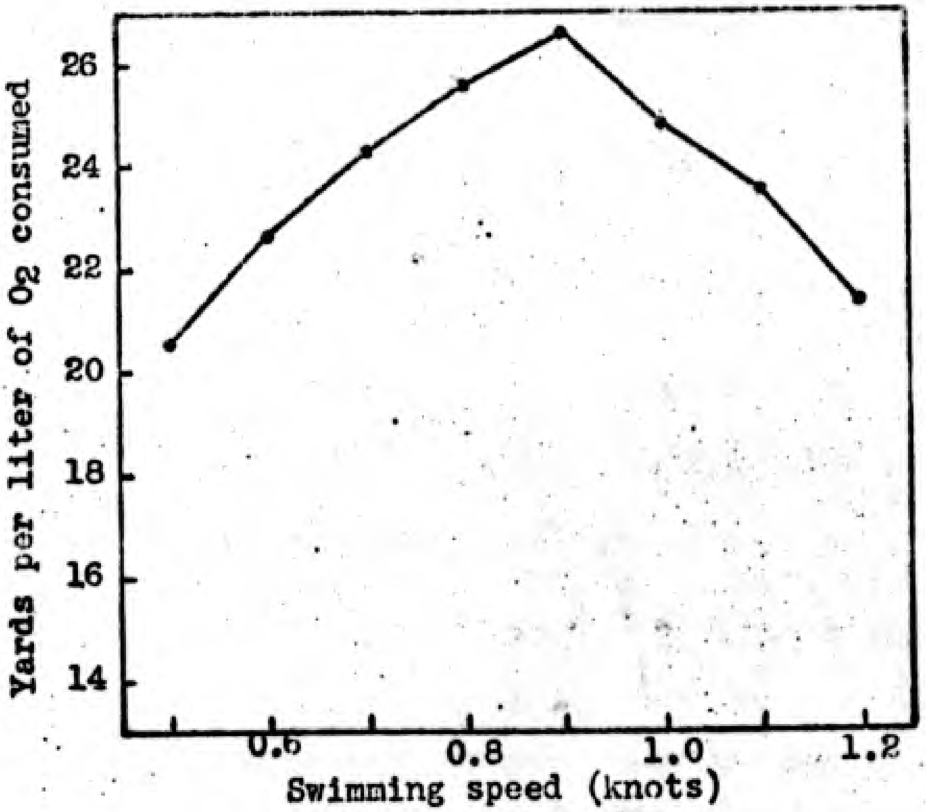


Figure 8b. Parrish. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter.)

TABLE 10. INDIVIDUAL RUN DATA

Subject: PETWAY (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.50	24	1.09	510	33.1	13	43	32	=	
0.50	54	1.00	519*	28.9	14	42	37	=	Interrupted briefly.
0.60	30	1.56	519*	45.0	14	44	30	=	Dumped water.
0.70	43	1.25	510	38.0	--	44	32	=	
0.78	14	1.44	520	43.2	20	56	30	=	
0.92	52	2.18	522*	62.0	21	54	20	=	
0.92	62	2.17	510	66.0	22	61	17	=	Leaks.
0.92	65	1.98	522	59.0	18	82	30	=	Small leak from valve.
1.00	2	2.50	522	74.5	17	65	22	=	Leaks, headache, dyspnea.
1.00	7	2.26	520	68.0	19	73	10	=	"Can't get enough air"
1.00	18	2.53	520*	72.5	21	86	15	=	Irregular speed.
1.13	72	2.30	522	68.5	--	113	7	=	Dyspnea.
1.20	78	3.03	519	92.0	26	98	17	=	

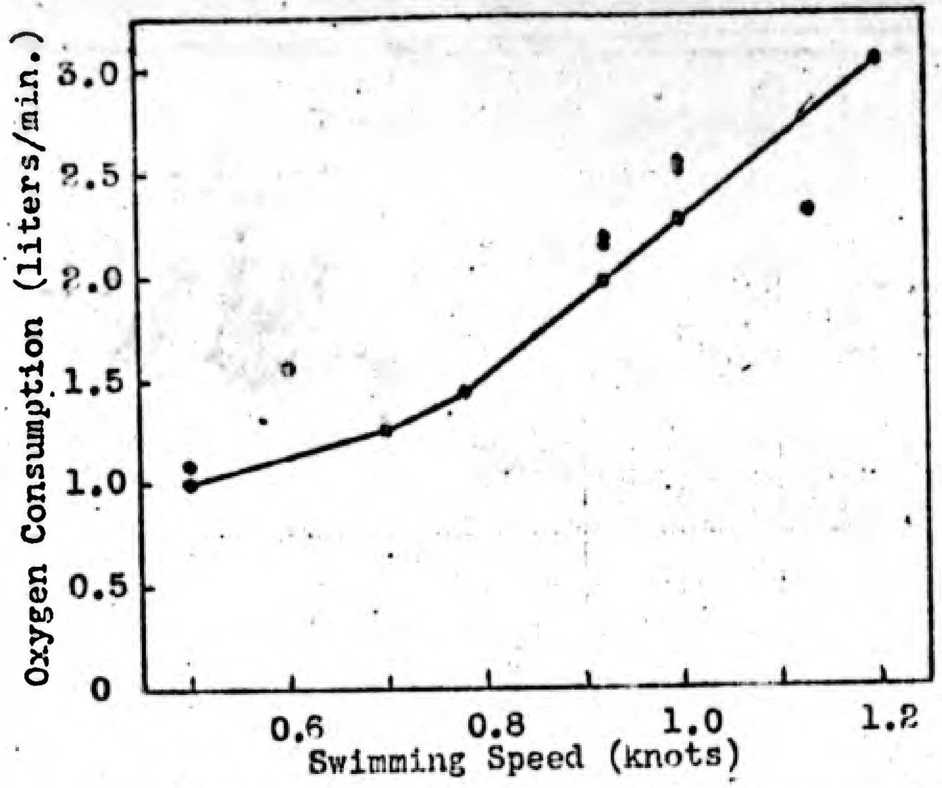


Figure 9a. Petway. Oxygen consumption vs. speed in underwater swimming.

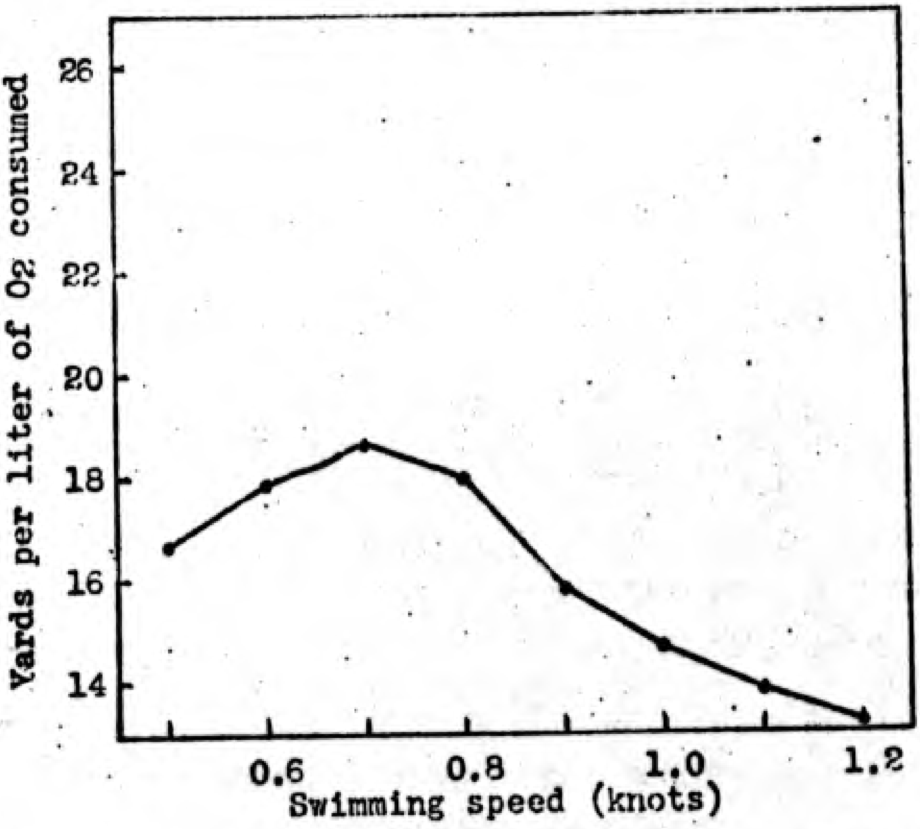


Figure 9b. Petway. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 11. INDIVIDUAL RUN DATA

Subject: ZIEGLER (UDT)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.55	41	0.81	519	24.7	--	45	32	=	
0.60	26	1.09	510*	31.7	24	--	32	=	
0.70	44	1.20	520*	34.3	21	59	31	=	Slight leakage.
0.71	48	1.24	522*	35.3	18	48	31	=	
0.77	32	1.76	522	52.5	16	68	29	=	
0.80	9	1.38	510*	40.0	27	69	25	+	
0.80	15	1.30	510	39.7	24	61	32	=	
0.93	37	1.78	520	53.3	24	79	31	=	
1.00	3	2.31	520	69.3	28	98	21	+	
1.00	20	2.44	519	74.0	27	74	16	=	
1.00	58	1.94	519	59.0	32	75	10	=	
1.00	60	2.31	522*	65.5	25	81	22	=	
1.10	67	2.17	520	65.0	27	60	8	=	Unusual fatigue
1.10	68	3.03	519*	87.8	25	84	7	=	" "
1.10	79	2.78	522	83.0	20	78	12	=	
1.20	74	2.94	522	87.8	32	103	8	=	

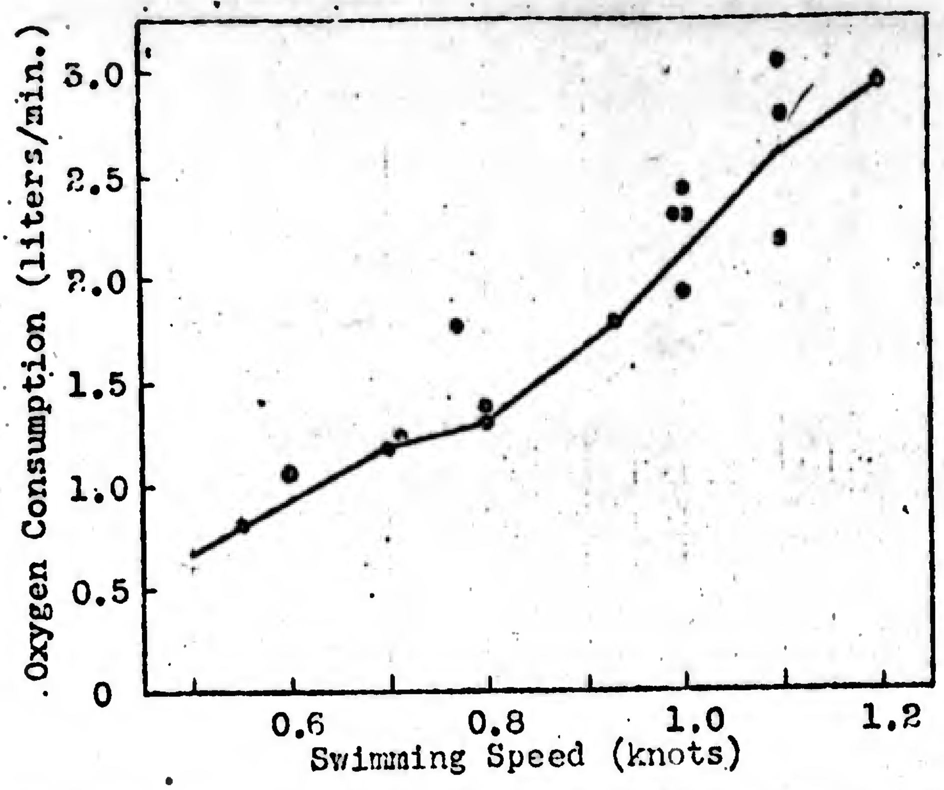


Figure 10a. Ziegler. Oxygen consumption vs. speed in underwater swimming.

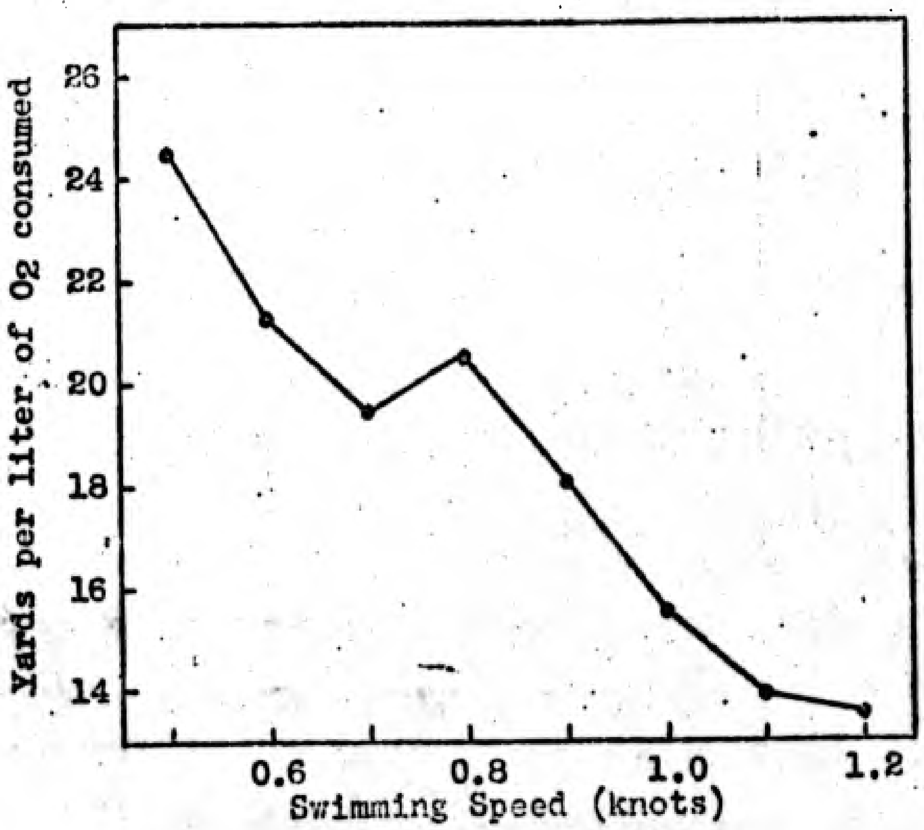


Figure 10b. Ziegler. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter of oxygen vs. swimming speed.)

TABLE 12. INDIVIDUAL RUN DATA

Subject: CARROLL (EDU)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run	Trend (see note)	Remarks
0.71	44	1.08	510*	31.3	16	45	26	=	
0.80	8	1.32	519	40.0	21	37	35	+	
0.79	48	1.27	510	38.6	17	39	28	=	
0.92	29	1.44	520	43.3	16	38	26	+	
1.00	19	2.13	510	65.0	16	43	10	=	

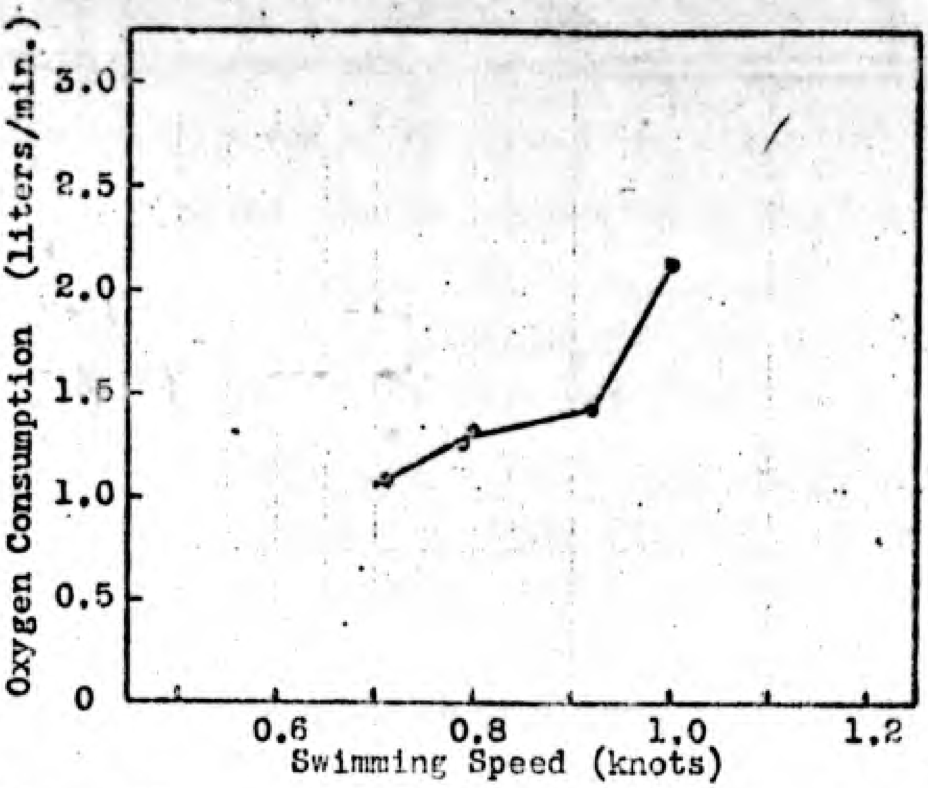


Figure 11a. Carroll. Oxygen consumption vs. speed in underwater swimming.

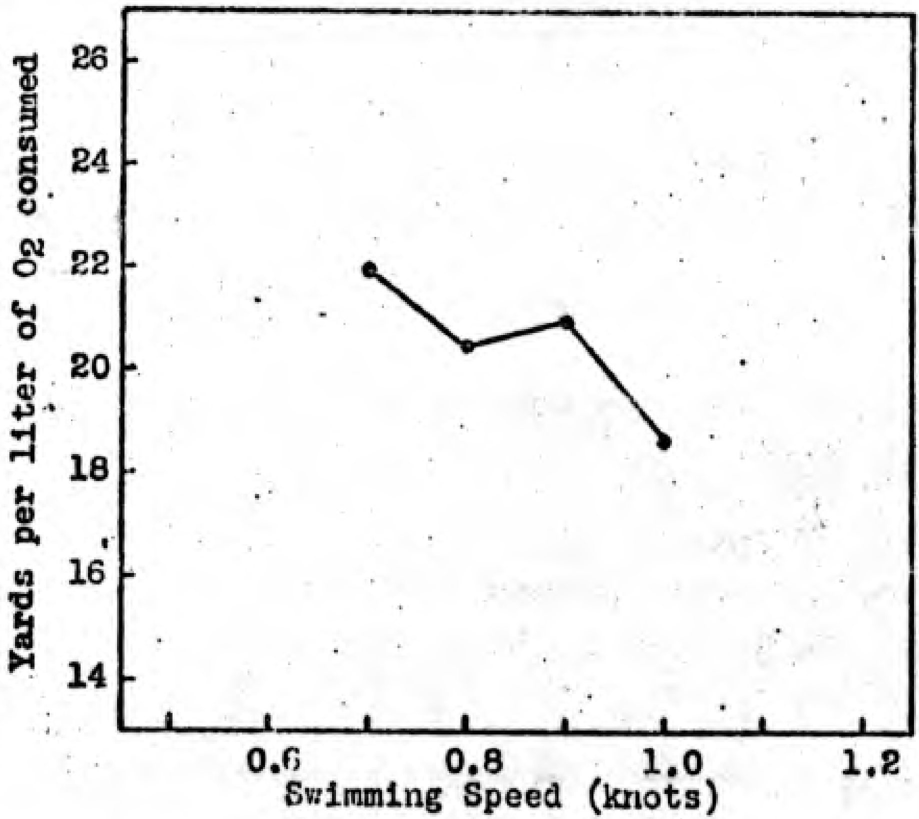


Figure 11b. Carroll. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 13. INDIVIDUAL RUN DATA

Subject: KISSEE (EDU)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of run(min.)	Trend (see note)	Remarks
0.71	31	1.16	522	34.7	16	39	35	=	Leaks (?)
0.80	35	1.22	520	36.7	22	46	33	+	
0.90	38	1.83	520	55.0	20	50	14	=	Fins chafing feet.
1.00	18	1.54	522	46.2	17	42	28	=	

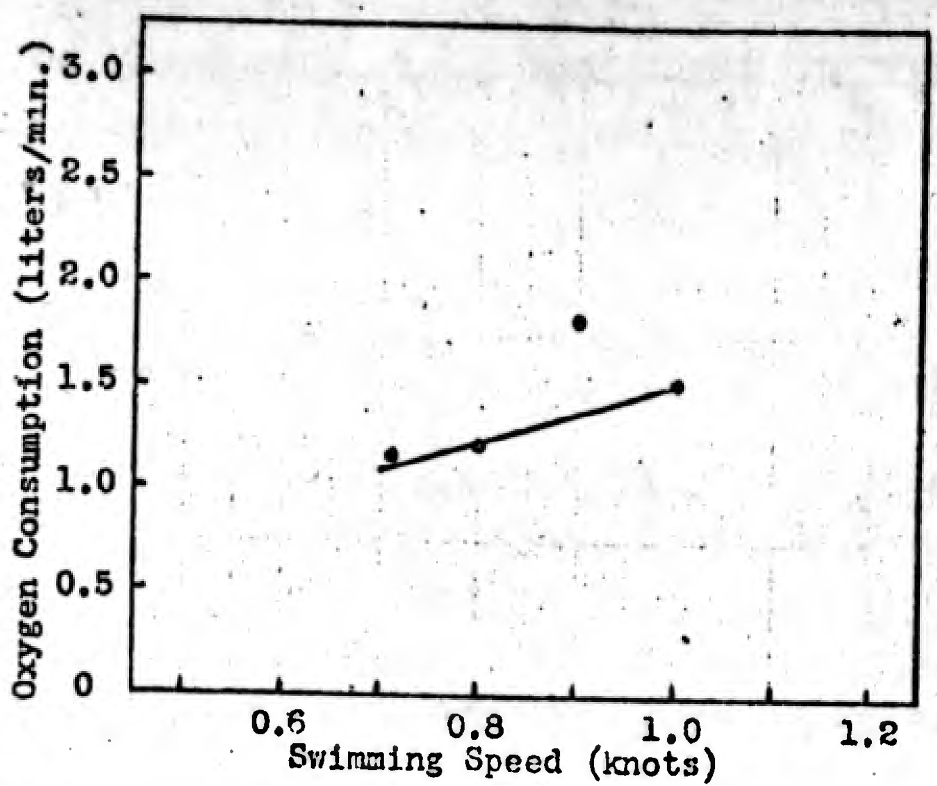


Figure 12a. Kissee. Oxygen consumption vs. speed in underwater swimming.

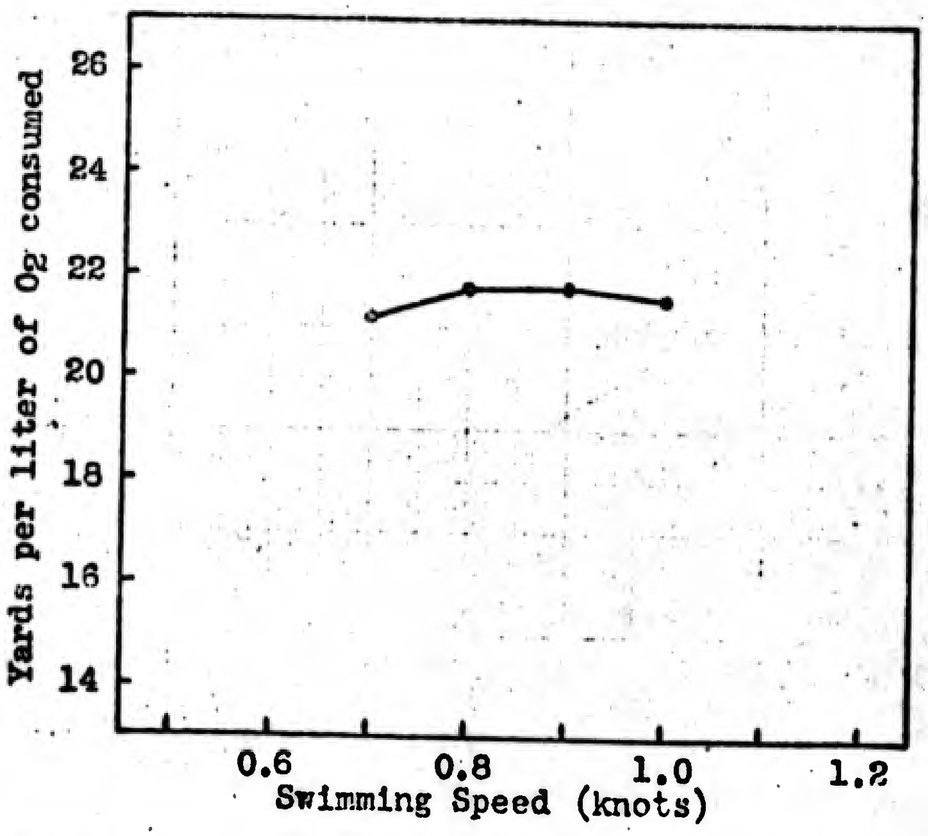


Figure 12b. Kissee. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 14. INDIVIDUAL RUN DATA

Subject: MC KENZIE (EDU)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run(min.)	Trend (see note)	Remarks
0.70	26	1.44	522	43.0	12	28	31	=	
0.77	22	1.43	522	42.7	10	28	31	=	
0.80	14	1.67	519*	48.3	16	31	32	+	Frequent clearing.
0.87	23	1.62	522	48.3	13	31	35	-	
0.90	40	1.75	510	53.3	13	28	26	=	
1.00	1a	2.04	519	62.0	14	39	21	=	Stops;water-dumping.
1.00	7	1.85	522	55.3	13	35	16	=	Baralyme dust (?)
1.00	20	2.00	522	59.7	15	30	25	+	Stop to clear.
1.10	60	1.84	522	55.0	19	32	15	=	

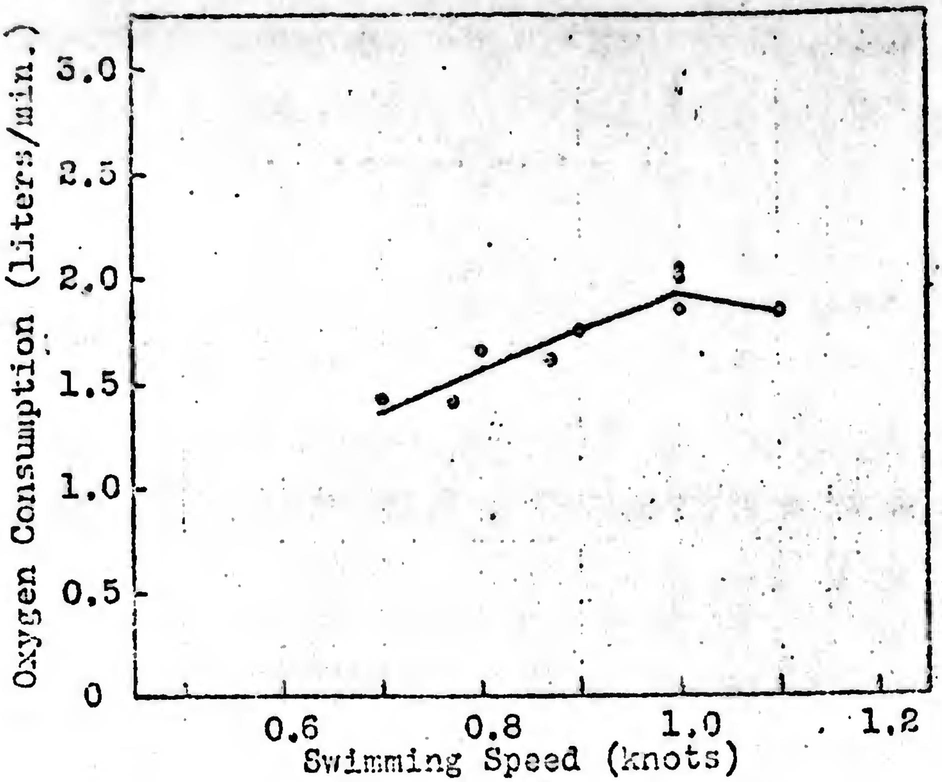


Figure 13a. McKenzie. Oxygen consumption vs. speed in underwater swimming.

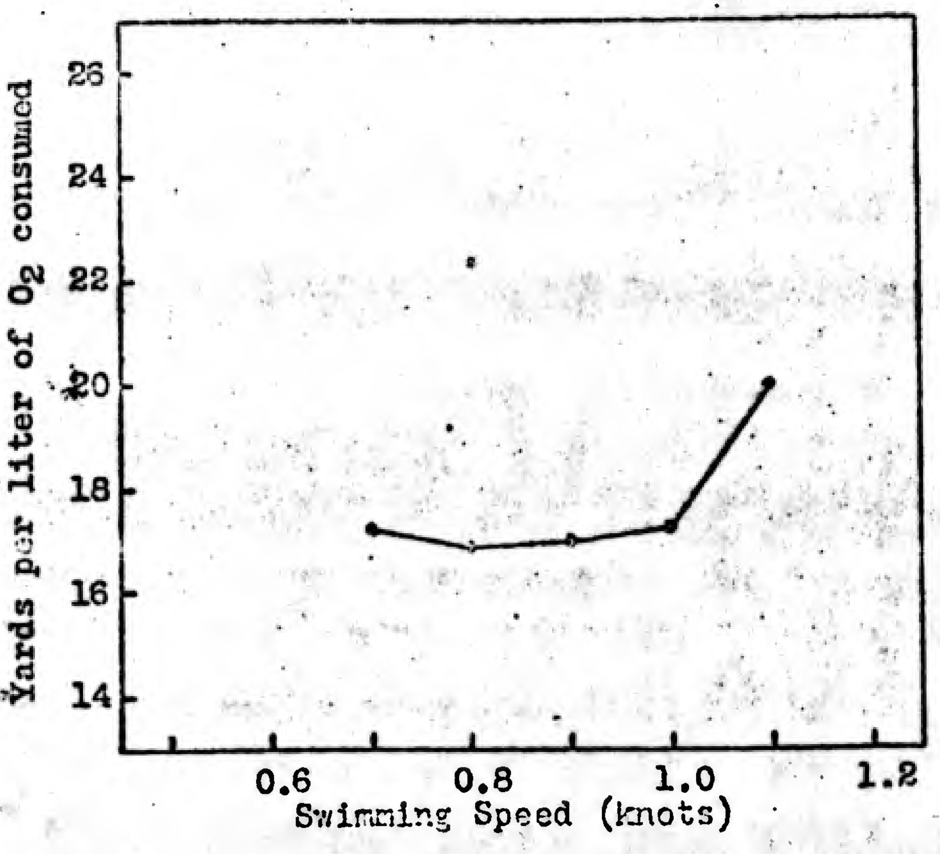


Figure 13b. McKenzie. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 15. INDIVIDUAL RUN DATA

Subject: STEVENS (EDU)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder Number	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run(min.)	Trend (see note)	Remarks
0.70	28	1.29	510	39.3	15	40	31	=	
0.80	12	1.33	510	40.8	12	35	14	=	Sl. leaks;interrupted.
0.86	27	1.42	520	42.5	14	44	26	=	
1.00	17	1.57	519	47.7	12	33	18	=	CO_2 accumulation(?).
1.00	43	1.91	519	58.0	13	53	24	=	
1.05	52	1.71	518	52.0	11	55	14	=	
1.20	58	1.94	519	59.0	10	54	7	+	Fatigue.

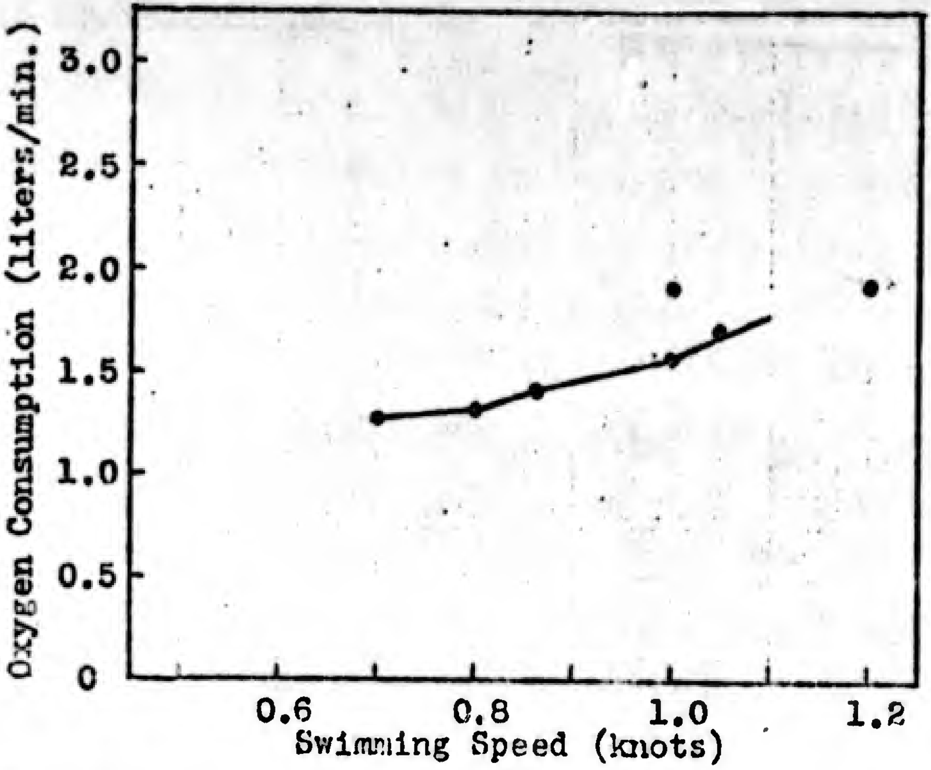


Figure 14a. Stevens. Oxygen consumption vs. speed in underwater swimming.

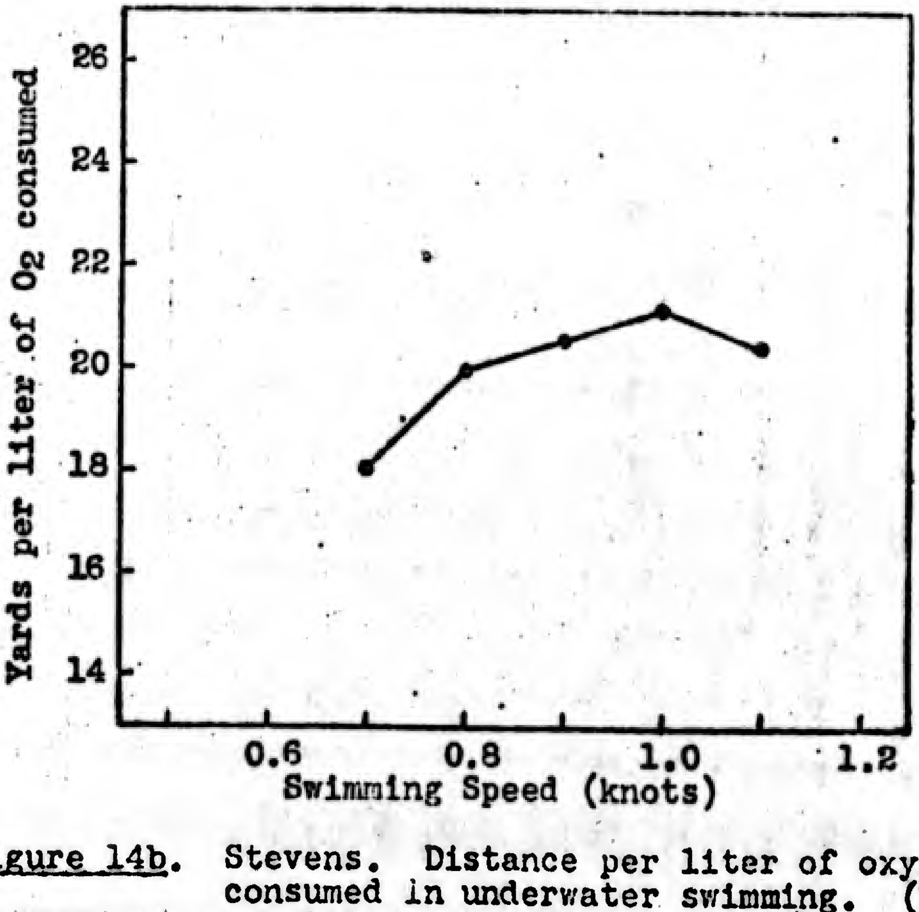


Figure 14b. Stevens. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 16. INDIVIDUAL RUN DATA

Subject: SUGLIA (EDU)

Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run(min.)	Trend (see note)	Remarks
0.70	46	1.06	520	31.7	10	26	31	=	
0.80	36	1.18	522	35.3	11	32	40	=	Stop to change valve.
0.81	54	1.24	510*	36.0	11	26	29	=	
0.92	39	1.59	519	48.2	9	30	31	=	
0.98	49	1.79	522	53.5	11	25	23	=	
1.10	45	2.01	518	61.0	12	50	3	=	Fatigue
1.10	51	2.20	520*	63.0	12	28	20	=	
1.20	59	3.26	510	99.0	13	37	12	=	

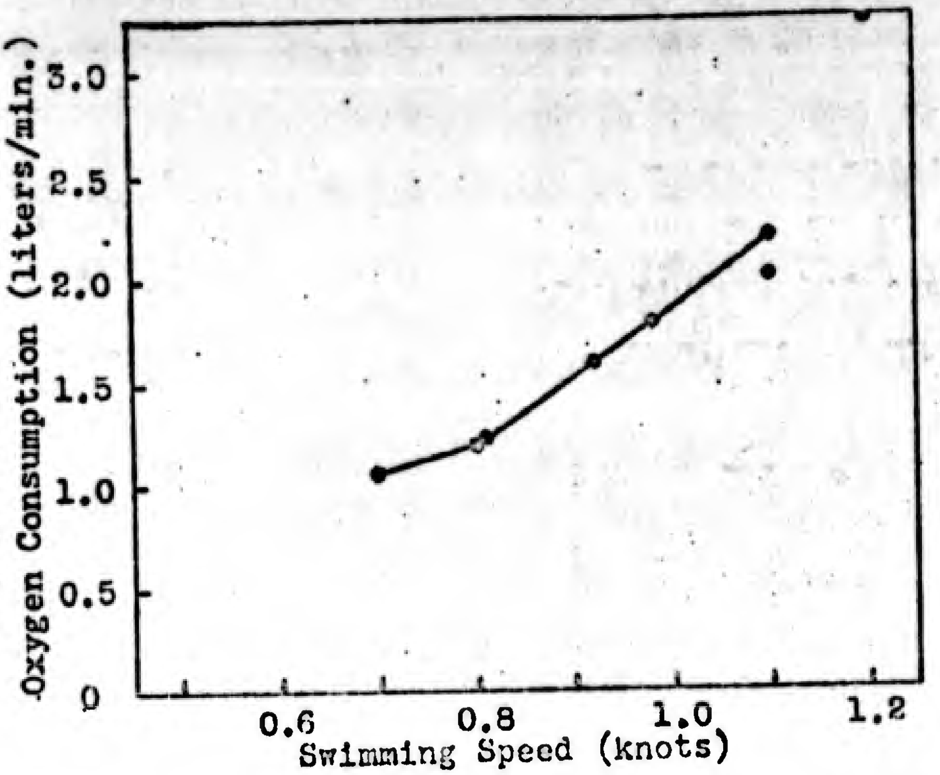


Figure 15a. Suglia. Oxygen consumption vs. speed in underwater swimming.

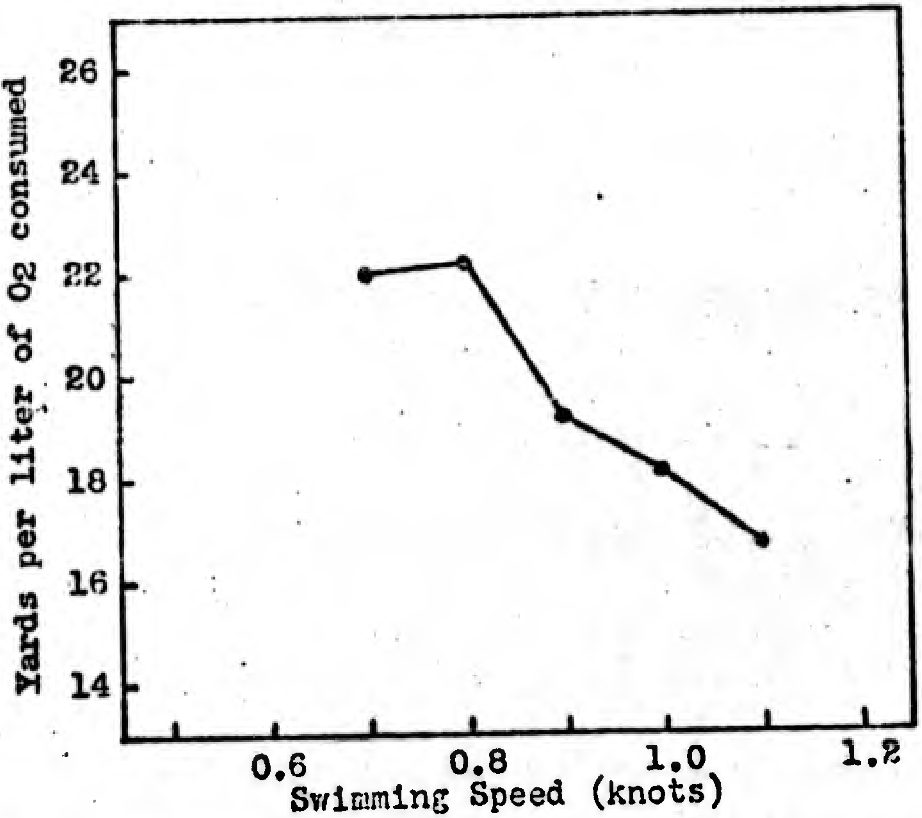


Figure 15b. Suglia. Distance per liter of oxygen consumed in underwater swimming. (Yards per liter vs. swimming speed.)

TABLE 17. INDIVIDUAL RUN DATA

Experimental Diving Unit men making limited number of runs.

Subject	Speed (knots)	Run Number	O_2 Consumption (L/min.)	Cylinder No.	psi drop /min.	Av. Resp. /min.	Av. Kicks /min.	Duration of Run(min.)	Trend (see note)	Remarks
Bohline	0.80	53	1.67	522	49.7	12	44	30	=	
"	0.96	56	2.57	522	76.7	15	51	13	=	
Griffith	0.80	15	1.63	522	46.3	20	39	33	=	Sporadic leaks.
McArdle	0.79	9	1.55	522	46.3	13	42	38	=	
Hoersch	0.80	13	1.49	519	45.3	13	32	20	=	Headache (CO_2 ?)
"	0.95	41	1.79	522	53.5	12	34	14	=	Leaks; lost consciousness.

BODY MEASUREMENTS

MISCELLANEOUS TABLES

PHYSICAL DATA

	e s.)	Height (in.)	Weight (lbs.)	Vital Cap. (L.)	Resid. Volume (L.)	Body Area (M2)	Specific Gravity	L.B. Mass (Kg.)
Alfano	22-	66.8	153	4.62	1.32	1.79	1.083	59.8
Baker	26	69.3	163	4.89	1.30	1.90	1.075	64.8
Henderson	27	67.3	162	4.16	1.24	1.84	1.060	58.5
Parrish	26	64.3-	128-	4.16	0.76-	1.61-	1.064	47.4-
Petway	26	71.4	184	5.51	0.95	2.06+	1.063	71.9+
Ziegler	32+	69.3	159	4.06	1.38	1.87	1.079	64.0
Mean	26.5	68.1	158.2	4.57	1.16	1.85	1.072	61.1
EDU (G)								
Carroll	28	68.8	154	5.49	1.21	1.86	1.080	62.7
Kisseo	30	65.0	149	3.85-	0.92	1.74	1.058-	54.0
McKenzie	24	69.3	164		- -	1.91	- -	- -
Stevens	28	72.8+	170	5.03	1.71+	2.00	1.074	70.7
Suglia	27	67.0	152	- -	- -	1.81	- -	- -
Mean	27.4	68.6	157.8			1.86		
EDU (F)								
Bohline	31	69.5	188+	6.01+	1.45	2.00	1.067	69.9
Griffith	30	70.8	161	5.20	1.02	1.91	1.070	61.9
McArdle	24	66.5	151	4.47	0.78	1.81	1.065	58.0
Moersch	30	68.8	168	- -	- -	1.92	- -	- -
Mean	28.8	68.9	167.0			1.91		

NOTES:

Age - to nearest birthday
Residual volume of lungs - Helium dilution method (EDU)
Body (surface) area - nomogram (Sandiford)
Specific gravity - water-weighing method (EDU)
Lean body mass - Calc. from wt. and S.G.

$$\text{L. B. M.} = \text{Total wt.} - \left(\frac{5.548}{\text{S.G.}} - 5044\right)$$

\+ indicates highest value in group
\- indicates lowest value in group

TABLE 18b. PHYSICAL DATA (continued)

	Length(in.)		Circumference (in.)						
Subject	Arms	Legs	Chest (norm.)	Chest (insp.)	Abdomen.	Hips	Biceps	Thigh	Calf
UDT									
Alfano	28.5	39.0	38.0	40.0	30.5	38.0	11.8	21.3	14.0
Baker	29.5	39.0	37.0	39.3	32.5	37.0	12.0	21.0	14.0
Henderson	30.0	40.0	36.8	38.5	34.0	39.5	12.0	20.5	14.3
Parrish	29.0	38.3	32.5-	35.5-	30.0-	35.0-	10.5-	20.0-	13.5
Petway	33.0	42.0	38.5	41.5	34.0	39.5	12.5	22.5	16.0
Ziegler	32.8	40.0	38.0	41.0	33.0	37.3	11.5	21.0	14.0
EDU (G)									
Carroll	31.0	40.0	37.0	39.5	31.5	37.0	11.0	21.3	13.8
Kissee	28.5-	37.0-	36.5	37.5	33.0	37.0	11.8	21.3	13.8
McKenzie	31.0	41.0	41.0+	42.5	32.0	38.0	11.8	22.0	15.3+
Stevens	33.0	43.5	39.0	43.0	32.5	38.0	11.0	21.0	14.0
Suglia	31.0	39.0	35.5	38.5	29.5	36.5	12.0	21.0	14.5
EDU (F)									
Bohline	31.0	40.5	40-5	43.3+	35.0+	40.8+	13.0+	24.0+	15.0
Griffith	33.3+	42.5+	37.0	41.0	32.5	38.3	11.0	20.0-	12.5-
McArdle	30.0	39.0	36.8	40-3	32.5	37.5	11.5	20.5	13.5
Moersch	32.5	41.5	38.0	39.0	34.5	39.0	12.0	21.5	14.0

NOTES:

Arm length - acromion process to fingertip.
Leg length - anterior superior iliac spine to heel.
Chest circumferences - level of nipples
("normal" - end normal expiration)
("insp" - at maximal inspiration)
Abdominal circumference - level of umbilicus
Hip circumference - level of greater trochanters
Biceps, thigh, calf - level of greatest circumference.

\+ indicates highest value in group
\- indicates lowest value in group.

CONSUMPTION (AT 0.8k) IN TERMS OF BODY SURFACE AREA AND LEAN BODY MASS

	ters/min. (total)	Per M² of Body Surface Area	Per Kilo. of Lean Body Mass
	1.52	0.85	.025
	1.20	0.63	.019
Henderson	1.26	0.69	.022
Parrish	1.04	0.65	.022
Petway	1.48	0.72	.021
Ziegler	1.30	0.70	.020
C[illegible]ll.	1.30	0.70	.021
Kiss[illegible]e	1.22	0.70	.023
McKenzie	1.58	0.83	- -
Stevens	1.33	0.67	.019
Suglia	1.20	0.66	- -
Bohline	1.67	0.84	.024
Griffith	1.63	0.85	.026
McArdle	1.55	0.86	.027
Moersch	1.49	0.78	- -
MEAN OF UDT & EDU "Good"	1.31	0.71	
S. D.	0.16	0.07	

TABLE 20. CONVERSION OF KNOTS* TO VARIOUS UNITS OF SPEED

Knots *	Mph	Yards /hr.	Yards /min.	Feet /hr.	Feet /min.	Feet /sec.	Meters /hr.	Meters /min.	Meters /sec.
0.6	0.68	1200	20.0	3600	60	1.00	1097	18.3	0.31
0.7	0.80	1400	23.3	4200	70	1.17	1280	21.3	0.36
0.8	0.91	1600	26.7	4800	80	1.33	1463	24.4	0.41
0.9	1.02	1800	30.0	5400	90	1.50	1646	27.4	0.46
1.0	1.14	2000	33.3	6000	100	1.67	1829	30.5	0.51
1.1	1.25	2200	36.7	6600	110	1.83	2012	33.5	0.56
1.2	1.36	2400	40.0	7200	120	2.00	2195	36.6	0.61

*NOTE:

One Knot is defined as a speed of one nautical mile per hour.
One nautical mile equals 6080 feet. For the sake of convenience in this study, however, this figure was rounded to 6000.
To convert to true knots, subtract 1.3% from the stated speed.
(The figures presented above are based on the rounded value of 6000 ft. per hour.)

TABLE 21. PROBABLE MINIMUM AND MAXIMUM VALUES FOR OXYGEN CONSUMPTION IN VARIOUS RANGES OF UNDERWATER ACTIVITY.

Range of Activity	O2 Cons. Liters/min. (1) (STPD) minimum	 maximum
Swimming, probable average speed (0.8 - 0.9 knots)	1.0	2.3 (2)
Swimming, "comfortable" range (0.7 - 1.0 knots)	0.9	2.7
Swimming, maximum probable range (0.5 - 1.2 knots) (3)	0.6	3.6
Maximum possible range (rest - maximal exertion)	0.25	4.0+ (4)

NOTES:

(1) Values derived from study as indicated in V (Discussion).

Note that they are corrected to standard conditions (STPD). In order to apply values to cylinder volumes and pressures at temperatures other than 0° C, must apply temperature correction.

(2) Mean value in this range is approximately 1.4 lpm.

(3) Speed of 1.2 knots can be sustained for 20 minutes or less. Higher speeds possible but only for brief periods; considered unlikely.

(4) Maximum value depends on individual's absolute maximum rate of oxygen uptake. In well-trained athletes, this may exceed 4.0 lpm.

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

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13. ABSTRACT

Oxygen consumption was determined during underwater swimming at speeds between 0.5 and 1.2 knots in 15 subjects. The method involved use of oxygen-rebreathing (closed-circuit) scuba with calibrated supply cylinders and a means of maintaining constant speed over a marked course.

The results indicate that oxygen requirements are approximately tripled by increasing speed from 0.5 to 1.2 knot. The mean values indicated a distinct and progressive loss of efficiency above 0.8 knot. The probable average normal speed of underwater swimmers using similar equipment to 0.8 to 0.9 knot. Speeds below 0.7 knot were uncomfortably slow, speeds above 1.0 knot were considered to fast for more limited periods.

The oxygen requirements at any given speed varied markedly between individuals even among proficient swimmers. Comparisons between UDT subjects and experienced swimmers from EDU showed little difference between the groups, but a group of relatively untrained men had considerably higher requirements.

Values for the probable range of individual oxygen requirements in underwater swimming are derived from the results and are presented for various ranges of activity.

Swimming is a remarkably inefficient and generally limited means of propulsion.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
EDU						
Oxygen Consumption						
Exercise Physiology						
Respiratory Physiology						

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