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MEDICAL RESEARCH DEPARTMENT



U. S. Submarine Base New London

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OBSERVATIONS ON EFFICIENCY OF
SUBMARINE PERSONNEL DURING
PROLONGED SUBMERGENCE WITH
THE ATMOSPHERIC OXYGEN BALANCE
AT 17% AND THE CARBON DIOXIDE
AT 3%

CONFIDENTIAL

(Final Report)

Bureau of Medicine and Surgery
Research Division - Project X-516
(Sub. N. 105) (Paragraph 6)

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NOTE

This project deals with one phase (paragraph 6) of the Bureau of Medicine and Surgery Research Project X-516 (Sub. No. 105), entitled: "Evaluation of Comparable Efficiency of Certain Methods for Production of Oxygen and Absorption of Carbon Dioxide for Air Purification in Submarines".

It is a joint study under the Naval Research Laboratory and the Medical Research Department, U. S. Submarine Base, New London, Connecticut.

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**OBSERVATIONS ON EFFICIENCY OF
SUBMARINE PERSONNEL DURING
PROLONGED SUBMERGENCE WHEN
THE ATMOSPHERIC OXYGEN IS MAINTAINED
AT 17% AND THE CARBON DIOXIDE
AT 3%**

**(Final Report)
Bureau of Medicine and Surgery
Research Division - Project X-516
(Sub. No. 105) Paragraph 6**

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It need hardly be mentioned that this report would not have been possible without the efforts of the representatives from the Naval Research Laboratory. In addition to providing us with the relevant data on the gas conditions during submergence, they cooperated wholeheartedly in coordinating their procedures with those relating to observations on efficiency.

We are therefore indebted to Dr. Parry Borgstrom and his assistants, Dr. R. R. Miller and Dr. White; and to Comdr. R. I. Olsen, USN and his assistants.

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SUMMARY AND CONCLUSIONS

1. The purpose of this investigation was to determine whether the operating efficiency of submarine personnel deteriorated during submergence when the atmospheric oxygen was maintained at 17% and the carbon dioxide at 3% for extended periods.

2. Observation of submarine duties and discussions with submarine officers helped us construct a series of job operations which simulated the actual submarine jobs themselves.

3. The crew of the U.S.S. SAILFISH were made familiar with the job operations prior to the submergence. On the boat, the men performed the job operations before the boat submerged; this represented their level of efficiency in normal air.

4. The air in the submarine reached 3% carbon dioxide after 18 hours submergence. The gas was held at this level for a further 68 hours.

5. After the air had reached 17% oxygen and 3% carbon dioxide as many men as possible were run through on the job operations. Observations on these men were, for the most part, repeated at four different stages during submergence. The average of these four observations represented the level of efficiency for the conditions of submergence.

6. The difference in levels of efficiency obtained in normal air and increased carbon dioxide conditions represents the effect of the conditions of submergence.

7. The results of the observations show:

(a) Very definitely decreased capacity for physical work for all hands.

(b) Very definite decrease in efficiency of night vision for about one third of the ship's company.

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- c) Indications of marked decrement in mental efficiency for all hands.
- d) Very probable decrease in efficiency of interior voice communications.
- e) Noticeable, but unproven, tendency towards general decrease in efficiency of radar watch and watch on the bow and stern planes.
- f) No indication of deterioration in straight-forward listening performance for sonar signals.
- g) No reliable evidence either on efficiency in watching the "Christmas Tree" or memory for numbers.

8. The following opinions were submitted by observers aboard for the entire submergence:

- a) Commanding Officer:# Definite decrease in general efficiency of the boat's complement; would be unfavorably disposed towards permitting gas conditions to become any worse than 17-3 as a general practice; men temporarily motivated by considerations of life and death would probably be able to overcome the drop in efficiency encountered during this submergence.
- b) Medical Officers: General discomfort owing to respiratory distress; general lowering in physiological reserve; prevalent headaches, in some cases approaching incapacitating severity.
- c) Psychologists: The decrement in efficiency of performance is, in general, probably

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greater and more extensive than appeared during this submergence. More refined tests in some cases, and more elaborate tests in others would, if more preparation time had been available, have constituted more critical measures of efficiency. It was clear during the submergence that prolonged attentiveness and connected thinking were adversely affected even in routine and habitual duties.

9. Factors other than the percentages of oxygen and carbon dioxide were undoubtedly influencing performance during the submergence; such factors are temperature, humidity, lack of exercise and boredom. It is our feeling, however, that the stress caused by these factors is slight compared with that directly attributable to the oxygen want and excess carbon dioxide.

10. To summarize, it is indicated by this experiment, that no relaxation in the present Navy standards of 17% oxygen and 3% carbon dioxide should be permitted, and, further, that Submarine Commanders be informed of the insidious effects of even these percentages over prolonged periods of time. Careful observations of carbon dioxide percentages should be made, and, as it approaches 3%, immediate preparations be made for its absorption and the release of oxygen. It must be remembered that, particularly under some combat conditions, any decrement in efficiency, however slight, may be disastrous.

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STATEMENT OF THE PROBLEM

1. During submergence of a submarine, the atmospheric oxygen gradually decreases from about 21%, and the carbon dioxide increases from almost 0%.

2. Navy procedures stipulate that the air in submarines, during submergence, shall provide for a concentration of oxygen of not less than 17%, and of carbon dioxide of not more than 3%. Experience has indicated that these are the limits of safe operation, particularly for prolonged submergence; less favorable percentages are thought to produce serious decrement in the efficiency of submarine personnel.

3. Informal reports of some commanding officers of submarines returned from patrol have often indicated that even the 17% oxygen and 3% carbon dioxide limits do not allow their men to carry out their jobs with the efficiency they consider optimal for battle conditions.

4. The present investigation was undertaken to provide opportunity for systematic observation of the efficiency of submarine personnel exposed for long periods to 17% oxygen and 3% carbon dioxide under operating conditions.

5. It seemed to us that these observations would be most useful if:

a) They were made on tests of efficiency which simulated as closely as possible the actual jobs performed on submarines, and

b) They were made under conditions which simulated as closely as possible those encountered during patrols.

6. The nature of the tests used was determined by:

a) Discussion with submarine commanders of the specific submarine jobs which seemed particularly to be affected during lengthy submergence,

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b) Knowledge of how other relevant tests of psychological and physical efficiency had turned out in previous experiments on deficient oxygen and excess carbon dioxide.

7. Both these sources of information led us to conclude that:

a) For submarine jobs of a simple character, serious drop in efficiency would result only if the job called for lengthy and sustained attentiveness, required, for example, in radar watches.

b) As the job became more complicated, the drop in efficiency would tend to show up even in short-term tasks, as, for example, in reading and memorizing dial settings, and performing computations on the information.

c) The jobs worth observing were:

1. Efficiency for physical work.
2. Night Vision.
3. Ability to think clearly.
4. Interior Voice Communications.
5. Watch on Bow and Stern Planes.
6. Radar Watch.
7. Sonar Listening
8. Ability to notice changes in the colored lights of the "Xmas Tree" out of the corner of the eye, when attention is directed primarily on some other job.
9. Memory for numbers.

d) The submarine men would not willingly do their best unless any tests they took were enough like their normal jobs so that "they could see some sense to it", and could feel that the results would really be of service to them in their future duties.

e) The observations be made on submarine men with patrol experience, rather than on trainees.

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8. It was decided, therefore, that the observations be made as follows:

a) The experienced crew of the U.S.S. SAILFISH, Lieut. Comdr. L. Marcy, Commanding Officer, be used;

b) The SAILFISH be submerged until the atmospheric oxygen decreased to 17% and the carbon dioxide increased to 3%, and that these conditions be maintained for a further 48 hours;

c) During the 48 hours, the submarine pursue a course of action previously mapped out by the Commanding Officer as being as close as possible to conditions which might prevail on patrol;

d) Observations be made on the men before submergence to establish their "normal" level of efficiency and that this level be compared with that established during the 48 hours of submergence.

e) Prior to submergence the men should be well practiced in the various simulated jobs to be observed, so that any drop in efficiency during submergence would not be obscured by men continuing to learn more efficient ways of performing their tasks;

f) Since the ideal situation of observing men at their jobs on actual operations is not practicable, the men be observed instead while using equipment built to simulate that on the submarine.

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1. The crew of the SAILFISH were available for training for a total of nine hours. This short time was due to pressure of other demands on the boat. Nine hours is considerably less than the amount of training necessary to learn adequately the jobs involved; so it was expected that any possible decrease in efficiency during the 48 hours would not show up as much as it might with more training. This is because continued learning during the 48 hours would counteract decrease in level of performance. For some jobs, the training consisted merely in explaining the nature of the job, with only token practical experience.

2. Every possible effort was made throughout every procedure to simulate patrol conditions. The usual cooked meals were served, smoking was permitted (during the latter portion of the experiment combustion was so poor that most smokers ceased), and other routine procedures were encouraged.

3. The schedule of operations was as follows:

- 24 May - 0900: Underway from Pier #13.
- 1400: Anchored in Gardiner's Bay. Equipment for job observation set up.
- 1600: Observations made on men performing various simulated jobs. Conning tower hatch open. Air normal. Information collected during this period serves to indicate efficiency in normal air.
- 2400: Observations complete. Men asleep.
- 25 May - 0600: Buttoned up the boat, submerged and trimmed down; underway with decks awash; normal cruising watch stationed.
- 0800: Exercised the crew at general quarters.
- 1000: Evasive status. Commenced silent running. Crew standing two hour watches. Bow and stern planes in hand; hand steering. Simulated depth charge attack by Sub-Chaser with hand grenades.

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- 1600: Secured from silent running. Normal cruising watch stationed. Crew standing four hour watches.
- 2400: The carbon dioxide was now up to 3%. Boat trimmed down until lying on the bottom. Bridge superstructure above water. Four hour watches set to simulate normal cruising, but no way on. During each watch men were required to carry out their jobs on the equipment installed for simulated job performance. Observations were made continuously for twenty four hours. Thus each man was observed on two watches. The observers worked in relays.
- 27 May - 0000: Return to normal cruising status. Underway; all equipment in operation.
- 0200: Conducted general drills -- fire, chlorine.
- 0400: Evasive status. Rig for silent running. Rig for depth charge. Attacked by Sub-Chaser with hand grenades.
- 0600: Boat trimmed down; lying on the bottom. Normal four hour cruising watch simulated, but no way on. Observations on simulated job performance made continuously for eighteen hours. Observers worked in relays.
- 2400: Normal cruising watch stationed. Underway. Drills.
- 28 May - 0200: Boat surfaced. Crew exercised at battle stations surface. This concluded a continuous period of sixty-eight hours during which the boat was buttoned up. Crew now standing two hour watches. Observations on job efficiency relating to return to normal air.
- 0800: Underway from Gardiner's Bay.
- 1100: Moored at Pier #13.

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3. The observations on efficiency thus fell into three categories:

- a) Normal air prior to submergence; eight hours.
- b) During submergence when the oxygen was kept at 17% and the carbon dioxide at 3%; sixty-eight hours.
- c) Normal air after surfacing; six hours.

4. We believe, that the best estimate of efficiency for the conditions of period 3b is given by the average of the four or so observations made during that period. This is because a man's performance on any one simulated job will be affected by such factors as amount of previous sleep, time after last meal, nature of watch duties just before the observations, and temporary fluctuations in the oxygen and carbon dioxide concentrations.

5. The equipment for the simulated job performance was set up in whatever space was available in the submarine. Since the forward torpedo room was given over to the apparatus for controlling the gas percentages, the job equipment was rigged up as best possible in the more cramped spaces, such as the pump room, fore and aft engine rooms, and radio shack. Job performance was, therefore, carried out under difficult and uncomfortable conditions. This type of disadvantage will generally make job performance more erratic. Any systematic decline in efficiency which shows itself in period 3b, as compared with 3a, is therefore, all the more significant.

6. The personnel aboard the submarine at any one time was comprised of:

- a) Five officers,
- b) Sixty-nine enlisted men,
- c) Sixteen observers.

The observers were given rest periods at least once every two hours. After twelve hours of observing, the observers were exchanged with a fresh set of observers from the Sub-Chaser in attendance. The exchange was affected via the conning tower; it did not affect the prevailing oxygen and carbon dioxide concentrations.

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7. Four observers, two medical doctors and two psychologists, remained aboard the full sixty-eight hours. It was felt that they could help interpret the results of the observations more meaningfully if they underwent the same experience as the men performing the jobs.

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DESCRIPTION AND RESULTS OF OBSERVATIONS

It seems to us that observations on the efficiency with which submarine men perform their jobs during lengthy submergence, are most meaningful, if, among other points, they take into account the following:

- a) The jobs observed should duplicate as closely as possible the submarine jobs themselves.
- b) If the job is easy, it should be lengthy and require continuous concentration; otherwise decreased efficiency can be counteracted by short bursts of abnormal energy.
- c) If the job is short, it should be difficult and tax effort to the utmost; this for the reason given just above.
- d) Since the period of practice, prior to submergence, was so short, it is to be expected that the men will continue to learn more efficient ways of performing their simulated jobs during the period of submergence; this will work against the appearance of any decrease in efficiency.
- e) The arduous conditions under which the jobs were carried out will likewise cut down the amount of decrement in efficiency during submergence; this is because the performance will tend to become more erratic and make it harder to show up systematic trends.
- f) The conditions under which the observations are to be made should approach regular patrol as much as possible. The men should stand normal watches, perform normal duties, undergo the strain of silent running and the stress of depth charges. The maintenance of these conditions would, in addition, sustain the interest and motivation of the crew.

Every effort was made to take into account the factors above, either in setting up the simulated job situation, or in evaluating the results of job performance.

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I. Observations on Physical Efficiency

a) Introduction:

Expressed very simply, human muscle performs work by, in addition to other requirements, consuming oxygen carried to it from the atmosphere by the blood stream, and producing carbon dioxide, which is, in turn, returned to the atmosphere by the blood stream. If the blood oxygen is less than normal, there is danger that the muscle will not operate at maximal efficiency. However, if, at the same time, the atmospheric carbon dioxide is greater than normal, various complex compensatory mechanisms will automatically come into play, in the attempt to maintain the blood oxygen at a level adequate for the needs of the muscle.

It is obvious that when muscles are worked to exhaustion, these compensatory mechanisms have become inadequate. Therefore, it seemed sensible to us to test physical efficiency by working the men to a point approaching exhaustion; for lesser tasks, decrement in efficiency might be obscured by the action of the compensatory mechanisms.

The test chosen to measure physical efficiency was a "step-up" test devised by the Fatigue Laboratory, Harvard University, Cambridge, Massachusetts.* The man being tested is required to step up on a platform twenty inches high. He starts with the right leg, brings up the left, straightens both, steps down with the right, then down with the left; the total task being accomplished in two seconds. Our preference for this test was based mainly on the following considerations:

1. No skill is required.
 2. The muscular work is proportional to the
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* See appendix, page 40

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man's weight.

3. The test has been shown to relate well to other criteria of physical efficiency used by various branches of the Services.

b) Procedure:

Since the test demands that the man exercise to the point of exhaustion, it was decided to call for volunteers, rather than endanger morale by making the test compulsory. Thirteen men volunteered. The spirit of competition and excusal from the rest of the tests, were the incentives used. The men all exercised to exhaustion; this state was reached in five minutes or less.

Immediately after exhaustion, the man is seated, resting, and his pulse rate is counted during the period one minute to one and a half minutes after exercise. The efficiency index is a function of the ratio:
duration of exercise (in seconds)
pulse rate (per minute)

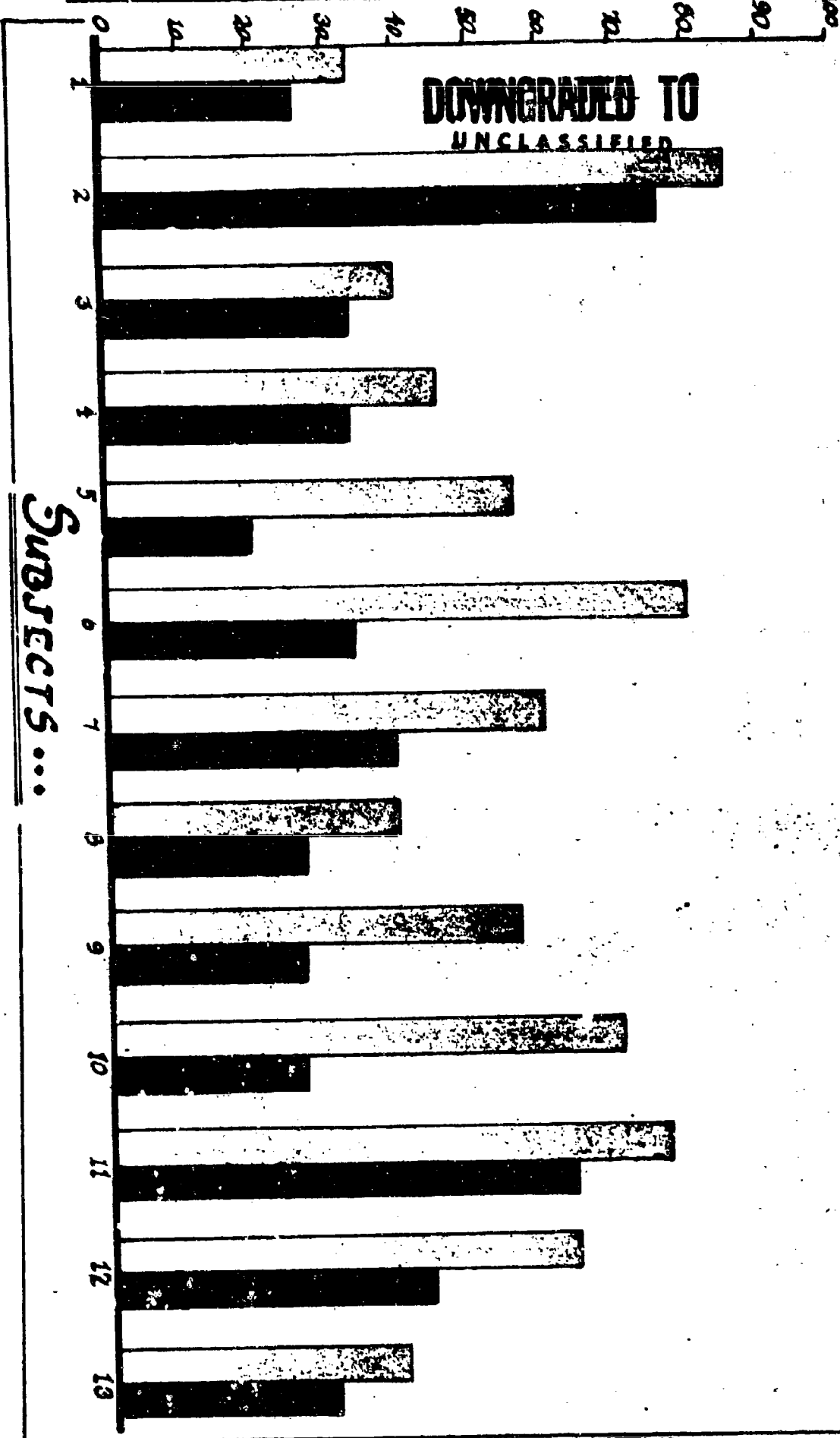
The test was carried out both in normal air and midway through the submergence. The difference between the two sets of results represents the decrement in physical efficiency. The worse the physical state of a man, the more rapid will be his pulse rate after strenuous exercise.

c) Results:

The statistics of the test are given on page 40 of the Appendix. They serve to show that there was a very definite decrement in physical efficiency during the submergence. Fig. 1 illustrates this loss pictorially. In every single one of the thirteen cases there was a considerable drop in efficiency. The average drop was 17 points; to evaluate the significance of this drop, it might be mentioned that drops of this size occur typically:

1. After a respiratory illness of two or more days.
2. In a working man after two days on a diet which is deficient by one thousand calories a day.

PHYSICAL FITNESS SCORE



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PHYSICAL FITNESS INDEX

NORMAL ATMOSPHERE ...

SUBMERGENCE



SUBJECTS ...

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3. In a trained athlete after two to three weeks break in training.

2. Observations on Efficiency of Night Lookout

a) Introduction:

To observe night vision, we were able to use a test previously developed at this activity. This test set up a job of visual performance at low levels of illumination, which simulated the task of searching a periscope field. The visual field presented to the man tested approximated in area, brightness, and sky-sea brightness contrast the appearance of the sea on a clear starlit night (5.05 log uvl), when viewed through a periscope. A target appearing on the "horizon" duplicated in retinal area an aircraft carrier viewed head-on at approximately 13,000 yards.*

b) Procedure:

Thirty-one men who had received a minimum amount of prior training, took the test. The men were dark-adapted at least 30 minutes in red goggles in other compartments prior to taking the test, and received their final adaptation period in the testing compartment. Three men were run, one at a time, taking successive turns at the "periscope". For each trial, the man positioned his head to the eyepiece, located the horizon, and then attempted to identify the target in one of five positions across the periscope field. When an incorrect report was made, the man continued to scan until a correct report was given. Each trial was scored in terms of the time taken (log seconds) to identify the position of the target correctly, after the horizon had been located. After 20 trials the man was rested; after 60 trials the session was ended. Men took part of one session in normal air before submergence, either three or four sessions during submergence, and part of one session in normal air after surfacing. The curtailment of the sessions in normal air was due to pressure of time. The two curtailed

* See Appendix page 41

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sessions were combined to give a more reliable efficiency level in normal air.

c) Results:

1. Two measures of efficiency were obtained:

a) Average time to report target correctly (log seconds); time was measured after location of the horizon. These times averaged 3-5 seconds.

b) Variability of these times.

2. The test statistics are presented on page of the Appendix.

3. Of 31 men observed:

a) None showed improvement during submergence.

b) Ten showed definite decrement.

c) Twenty-one did not show any change.

4. The decrement for the ten men ranged from an increase of 20% to an increase of 80% in the time taken to report the target position correctly.

5. These results indicate that the night vision of about one third of a submarine crew would be adversely affected by similar conditions during submergence.

3. Observations on Efficiency of Complex Mental Function

a) Introduction:

It seemed reasonable to us to suppose that the cumulative discomfort and stress which the body undergoes when subjected to 3% carbon dioxide for long periods, would inevitably have an effect on a man's mental efficiency. Among the more important of the mental activities aboard a submarine are:

1. Reading dial settings on various meters, correct to the smallest unit on the meter.

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2. Memorizing these readings, and relaying them to other parts of the boat.
3. Observing changes in the readings, and determining the size and direction of the change.
4. Performing computations on the basis of the information above.

Because of the importance of errors made in any one of these four mental operations during critical battle situations, we endeavored to set up a simulated job situation which would enable us to measure possible decrease of efficiency during the submergence. This job was called "Meter Reading and Computing Test".

b) Procedure:

Three dials found typically on submarines were used in the test -- Depth Gauge, DC Voltmeter, and Air Injector Pressure. The three dials are presented simultaneously. In each case the man is required to read the dial correctly to the smallest unit on the dial. All dial settings were photographed on microfilm and projected on a screen. The Depth Dial was always on the left, the Pressure on the right, and the Voltmeter in the center. The men were grouped around the screen in groups of ten; the dial settings were clearly visible to all men.

A typical item of the test was as follows:

1. The first frame would appear on the screen. The readings might be:

68 140 2000

Ten seconds are allowed for the men to read and memorize these settings. The frame is then removed.

2. The second frame then appears. The readings might be:

72 110 1900

As soon as this frame appears the man is required to compare analagous settings of the two frames. For the dial on the left,

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the second frame became larger, so the answer written down would be plus four; for the center dial, the second frame became smaller, so the answer would be minus thirty; for the dial on the right, the answer would be minus one hundred. Fifteen seconds are allowed for performing the computations and writing down the answers. The frame is then removed. Item number one is then complete.

Each test was composed of fifty such items, making a total of one hundred and fifty answers to be written down. One point is given for each correct answer. An answer was scored correct only if both the size and direction of the change were correct. Six equivalent forms of the test were prepared. The men were given two forms of the test for practice prior to the observational period; this was to prevent learning during submergence counteracting any decrement in mental efficiency. During the observational period the men took one form of the test in normal air; this score was taken as representative of the efficiency in normal air; and four forms at various stages of submergence; these scores were to be compared with those in normal air for decrement. On the average, about thirty men took the tests.

c) Results:

1. The four tests during submergence showed small but consistent improvement over the test in normal air, though this was not of a degree consistent with greater practice. This is shown by Curve I in Figure 2; the score obtained in normal air is taken as zero, so that the other points on the curve show the relative improvement.

2. This finding of an improvement was very surprising to us, for two reasons:

a) There does not seem to be any reason why the discomfort of excess carbon dioxide should improve mental efficiency; on the other hand, the mental job was complicated, fatiguing, and long enough (involving continuous thinking under pressure for half an hour for each test) so that we would certainly have expected decrement under the conditions of the submergence.

ALL POINTS ARE BASED ON AVERAGE OF 30 MEN... THE CURVE OF DECREMENT IS THE DIFFERENCE BETWEEN THE TWO LEARNING CURVES...

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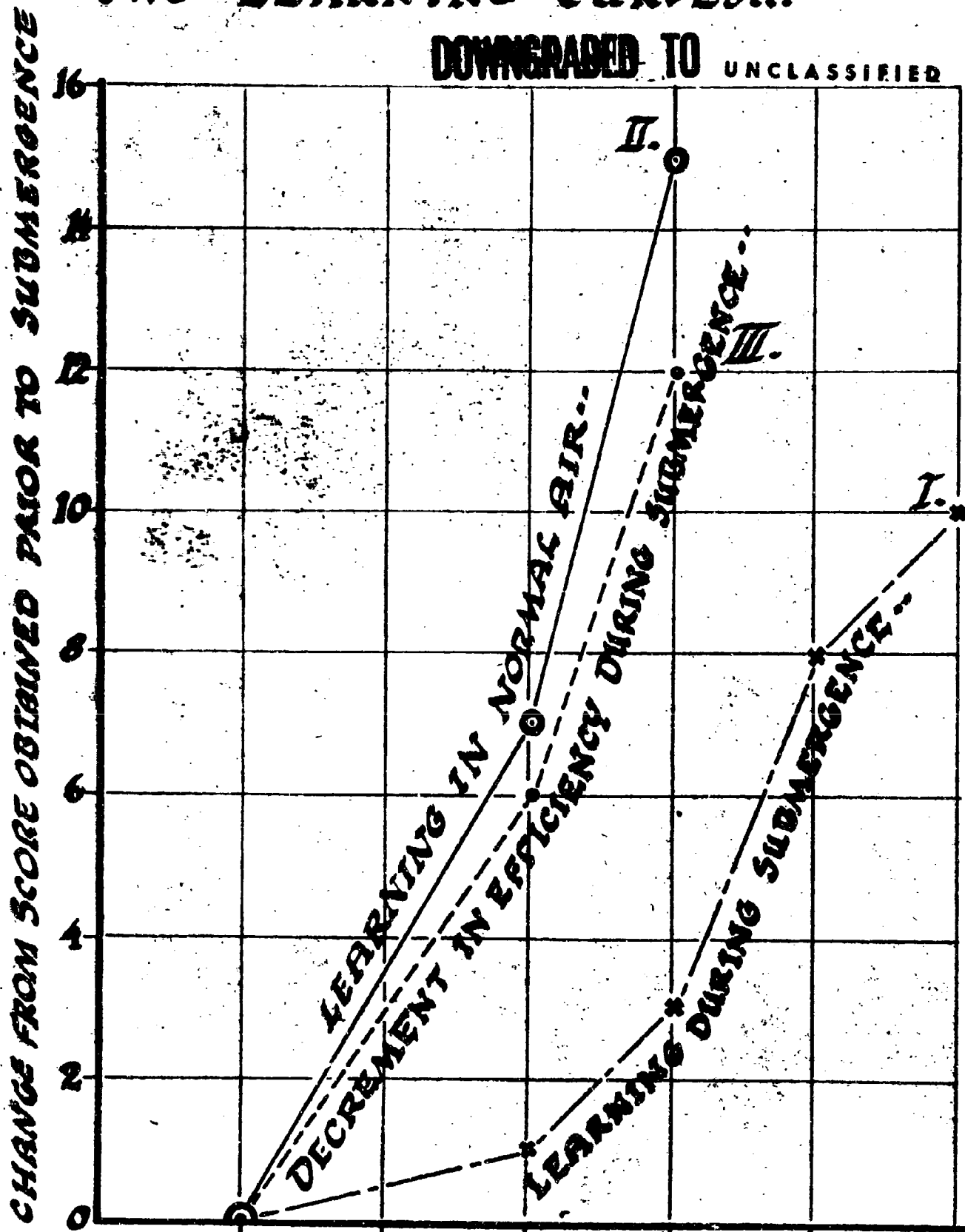


Fig.

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b) Apart from the tests, it was generally observed during submergence that normal thinking tended to become confused at times.

3. It could only seem to us that the two practice runs on the test were insufficient, and that the men continued to learn more efficient ways of performing the mental job all through the submergence. This improvement could have been great enough to overcome any decrement which might be occurring.

4. To check this hypothesis, we took a similar group of thirty men on the Base, and gave them the same tests in the same order, but all in normal air. If these men showed greater improvement than the men did during the submergence, then the difference in amount of improvement might reasonably be attributed to the decrease in mental efficiency brought on by the conditions of the submergence.

5. For practical reasons the group on the Base could only take five forms of the test, one each on successive days. Forms one and two, as with the Submarine Group, were considered as practice. The score on Form three was taken to correspond to the normal air score for the Submarine Group, and is plotted as zero on Curve II in Figure 2. This score is very close to the score obtained by the Submarine Group. The scores on the last two forms may be considered comparable to the first two tests taken during submergence. These two points complete Curve II.

6. It seems clear from Curves I and II in Figure 2, that:

- a) The mental job was difficult enough so that learning goes on for all six successive forms of the test.
- b) More learning takes place under normal air than under the conditions of submergence.
- c) The difference between the two rates of learning, shown as Curve III in Figure 2 might well be the decrement in mental ef-

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iciency during submergence. In other words, the conditions of submergence slowed up mental acuteness and tended to prevent the men from learning more efficient ways of performing the mental job.

7. We do not feel as confident of this conclusion as we would have, if the submarine men could have been much better practiced before submergence and had themselves shown a decreased efficiency during submergence unhampered by learning effects. However, we do feel that the additional results of the Base group supports the feeling we had during the submergence that mental efficiency is visibly impaired. Page 33 below cites further supporting observational evidence on less efficient mental function which was noted during submergence.

4. Observations on Efficiency of Interior Voice Communications

a) Introduction:

Most of the observations during the submergence were on single men carrying out relatively specific operations such as radar watch or watch on the bow and stern planes. There are also other types of activity which are more general and involve participation by almost the entire boat's company, in which co-ordination and co-operation are as important as the efficiency of single men. Such activities as drill at general quarters are of this type.

Because of the importance of these overall functions of boat efficiency we attempted two such measures:

1. Staging drills at general quarters; this proved impractical because of lack of time prior to submergence in which to establish a norm of performance and efficiency in normal air.
2. Staging communication drills; these drills involved all men on a watch and could be observed satisfactorily, since all men had taken the regular IVC course in the two weeks preceding the submergence.

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b) Procedure:

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Two talker drills, Drills Able and Charley, were given. Section II took Drill Able in normal air, midway through the submergence, and just before surfacing; the same section took Drill Charley in normal air and just before surfacing. Section III took Drill Charley in normal air and about two-thirds of the way through submergence.

Drill Able closely simulated the drills given to the crew in the classroom prior to submergence. It consisted of a series of orders and messages presented to the talkers in mimeographed form immediately before each performance of the drill. The talker at the sending station designated on the sheet, read off the message as written. The talker at the station called was responsible for following standard voice communication procedure by giving acknowledgment, report of execution, etc., as called for by the boat's doctrine.

Drill Charley was designed to simulate closely actual shipboard voice communications. In this drill, the talker sending the message was presented with a typewritten order couched in very general terms. The order required that the talker formulate a brief standard message from the information presented, and transmit the message to a designated compartment. The talker at the station called was again responsible for the use of standard procedures in giving his acknowledgments and formulating necessary reports of execution, but did not have a copy of the message he was receiving. This drill provided more realism and greater difficulty than Drill Able where both the originator and receiver of the message had the exact written message before them. Formulation was required for 21 messages of routine nature, and 12 messages containing difficult numeral series.

Samples of both drills are reproduced on pp. ~~44~~-45-46 of the Appendix. All the drills were recorded in their entirety on a "Commando" Model A Recordograph, Amortype Recordgraph Corporation. Each drill was observed and graded by qualified instructors from the Communication School, both at the time the drills were given and later from the recordings.

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The frequency of errors was tabulated under two general headings:

1. Errors Affecting Intelligibility

- a. Repeats Required.
- b. Corrections Made.
- c. Garbled Messages.
- d. Inaudible Messages.
- e. Critically Poor Enunciation.

2. Errors of Procedure

- a. Failure to Acknowledge.
- b. Failure to Report Execution.
- c. Failure to Correct Error.
- d. Failure to Use "Wait".
- e. Incorrect Use of "Wait".
- f. Non-standard Pronunciation of Ciphers.
- g. Unnecessary Acknowledgment.
- h. Pause after Station Call.
- i. Failure to Respond Promptly.

c) Results:

Compared with normal air, communications during submergence showed the following observable changes:

1. Slowness of speech.
2. Labored breathing.
3. Gasps resulting from the increased effort required for talking.

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4. Considerable difficulty in carrying on a conversation for longer than two or three short sentences, owing to shortness of breath.

The tabulation of errors is shown in Figure 3, in which there appears a consistent decrease in efficiency of communications for all three drills. The only indication of the reliability of this decrement is the fact that it occurred in all drills staged. Practical considerations of time and personnel made it impossible to stage repeat drills for any gas condition. If there is any learning present in these drills, it would tend to improve the efficiency of communications during submergence, since that always came after the drill in normal air. Hence the decrement in efficiency of communications may be greater than that indicated by the results.

These errors are approximately equally distributed between intelligibility and procedure.

5. Observations on the Efficiency of Watch on the Planes

a) Introduction:

Often a decrease in efficiency of submarine personnel is temporarily obscured by short bursts of energy during some particular operation. In Watch on the Bow and Stern Planes and in Radar Watch, the monotony and strain of continuous attention, and the length of the watch make it less likely that any such decrease in efficiency will be obscured.

b) Procedure:

Portable apparatus was set up to simulate the job of watch on the bow or stern planes. The man on watch was required to maintain a "zero bubble" over a period of half an hour. During this period the bubble was occasionally set off zero by the irregular movements of a rotating wheel, invisible to the man on watch. The man on watch restored the zero bubble by turning a hand crank. The movement of the bubble was not restricted to any pattern that the man could learn to anticipate. The movement was slow and gradual, with intervals between movements when the bubble remained stationary. The monotony of the job produced a strong tendency towards lapses in

CURVES SHOWING INCREASE IN NUMBER OF ERRORS MADE AT VARIOUS STAGES OF SUBMERGENCE..... DOWNGRADED TO UNCLASSIFIED

ERRORS

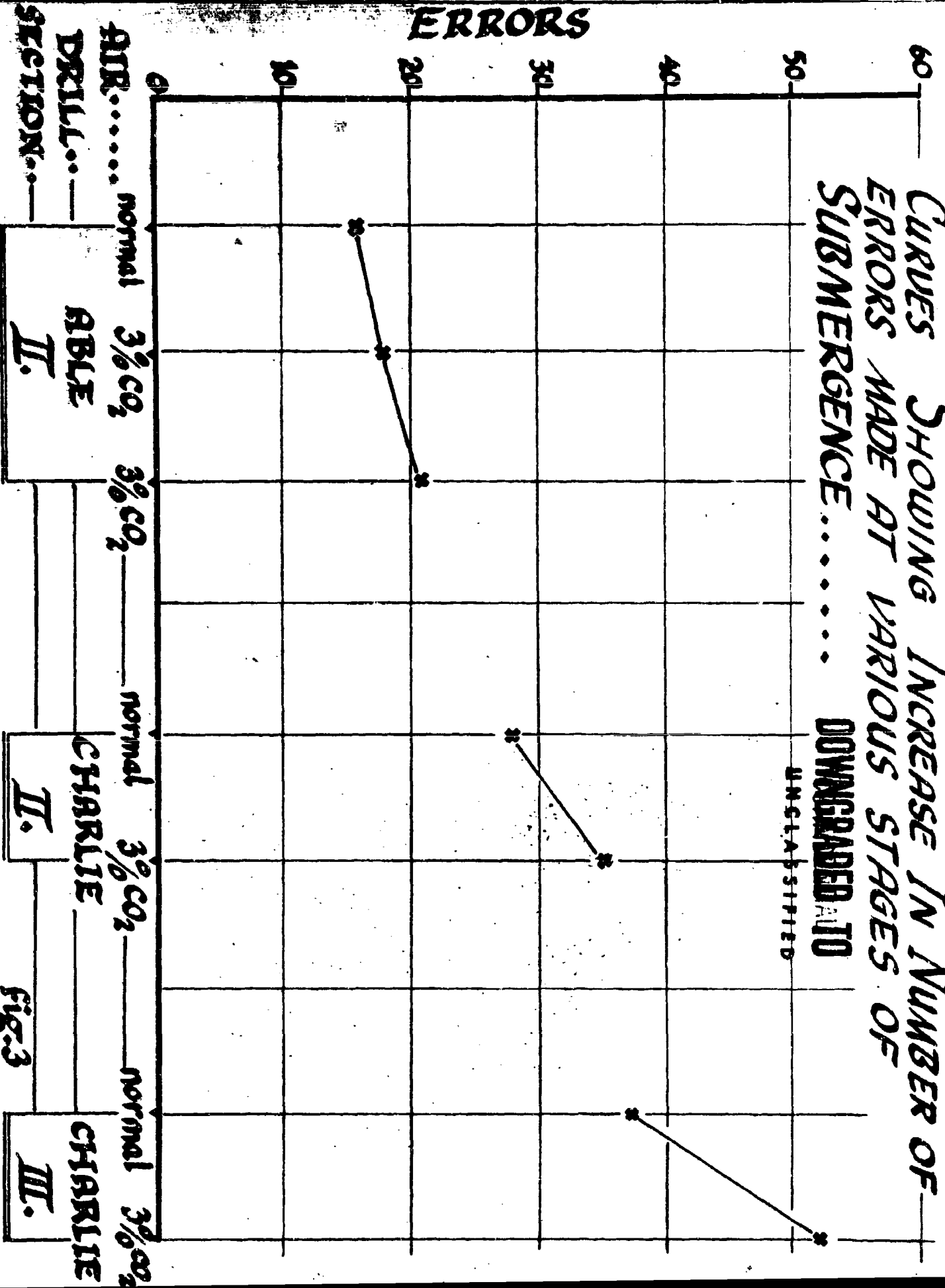


Fig. 3

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attention. The position of the bubble was recorded on a continuously moving tape. The tape was divided into 68 intervals of twenty seconds each; the number of errors made by a man on watch was the number of intervals in which the bubble deviated noticeably from zero. An error was a deviation which was large enough to indicate an obvious lapse in attention.

c) Results:

Practical difficulties of apparatus break-down and unavailability of men at appropriate moments, limited the number of men adequately tested to six. Each man stood watch once in normal air and twice during submergence. The average of the two watches during submergence was taken as the score for submergence.

The test statistics are shown on page 43 of the Appendix.

Two men showed a small amount of improvement; four showed a substantial decrement in efficiency.

On the average, the watch on the Planes had sixteen more errors per man during submergence than in normal air.

The number of men tested is too small to permit any very general conclusions. All that can be said is that the results indicate a strong likelihood that watch on the planes was adversely affected by the conditions of the submergence.

6. Observations on Efficiency of Radar Watch

a) Introduction:

Like watch on the planes, radar watch involves continuous attention to a lengthy, monotonous job. The job itself may be easy, but inefficiency is apt to result from the wavering of attention.

b) Procedure:

The man on watch was seated four feet from the screen of an oscilloscope, and was required to identify

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a "pip" as being in one of five positions on the screen. The pip stood about a quarter of an inch above the "grass", and remained in view for about one second. The job was easy enough so that it was impossible to miss the pip because of visual difficulties alone, if the man on watch was concentrating. Any decrease in efficiency, measured by missing a pip, could only be caused by a slacking off in attention.

Each watch lasted about half an hour. During that time sixty pips were artificially injected at irregular intervals and in randomized position on the screen. The man's score was the number of incorrect positions reported plus the number of failures to report anything.

Only six men took the test often enough to provide useful information for a comparison of efficiency between watch in normal air and during submergence. The test was taken once in normal air, and four times at various stages during submergence. The average of the four scores was taken as the best estimate of efficiency during submergence.

c) Results:

1. The test statistics are reported on page 43 of the Appendix.

2. Of the six men on watch, one showed a small amount of improvement, and five showed greater decrease of efficiency during submergence.

3. The number of men observed is small, and the decrease in efficiency is slight but consistent; general conclusions should therefore be made with caution. About all that can be said here is that the results do tend towards the conclusions that efficiency on radar watch suffered during the submergence.

4. If the job had been made somewhat more difficult by shortening the height and duration of the pips, the decrease in efficiency would probably have been marked.

Note: The apparatus for part of this test was provided by Lieut. Dean Farnsworth of this activity.

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During submergence, men often wavered in attention, and caught the pip out of the corner of the eye just before it left the screen. With shorter pips there would not have been time for attention to be focused back on the screen, and the number of errors would have been substantially greater. It was also noted that subjects on this test, during submergence, were irritable and found it necessary to "work harder" at the job than they did in normal air.

7. Observations on Sonar Efficiency

a) Introduction:

Previous work had indicated clearly that hearing is much less impaired by deficient oxygen or excess carbon dioxide than vision. This finding refers to hearing acuity, rather than to the more complex job of operation of sonar gear; this complexity lies in such factors as the co-ordination of different activities of the two hands, dividing attention between auditory signals, visual signals, and manual tasks, and resisting fatigue and monotony on lengthy watches. For this particular submergence, we were not able to devise means of observing men on simulated sonar watch. Instead, we observed only the effect of the submergence on hearing acuity as such. For this purpose we used two tests used to select Sound Men. Pitch Memory* and Loudness Discrimination for Bands of Noise.** Our results will not tell anything about possible decrement in manual dexterity and co-ordination of movements, or wavering of attention during the monotony of lengthy sonar watches.

b) Procedures:

Both tests were given over loudspeakers to groups of ten men. About forty men took the tests. The tests were given once in normal air and four times during various stages of submergence. Both tests were played from phonograph discs. The pitch test has 100 items of varying difficulty; in each item the man has to decide whether the simulated "return echo" of a "ping" has gone up or down in pitch. The loudness test has 110 items of

* BuPers Sonar Pitch Memory Test.

** Psycho-Acoustic Laboratory, Harvard University,
Cambridge, Mass.

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varying difficulty; in each item the man has to decide whether the second of two bands of noise, typical of noises picked up by a hydrophone, is louder or softer than the first.

c) Results:

1. There is no indication of any change in these types of hearing acuity during submergence,

2. These results do not say anything about the efficiency of men on regular sonar watch during submergence; factors such as fatigue, inattention due to monotony, manual dexterity and co-ordination in handling sonar equipment could not be observed.

8. Observations on Efficiency in Watching the "Christmas Tree"

a) Introduction:

Men who are busy on other jobs; in addition, often have to watch the "Christmas Tree" out of the corner of their eyes. It has been suspected that under some conditions, such as fatigue or lack of oxygen, the ability to notice color changes out of the corner of the eye is decreased. Failure to notice a color change could, to say the least, be highly undesirable.

b) Procedure:

The man being observed was seated directly in front of a small screen. Letters of the alphabet were flashed on the screen. On his right side was a bank of colored lights, consisting of two rows of three lights each, one row above the other. Lights in the top row were all green, and in the bottom red. The four outside lights were illuminated throughout the test; the middle green and middle red lights could be turned on separately. Normally the middle green and middle red lights are turned off.

A dual exposure system was arranged, whereby, simultaneously, a letter flashed on the screen and one of three things happened to the bank of lights:

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1. The middle red light went on and the middle green stayed off.
2. The middle green light went on and the middle red stayed off.
3. Neither middle light went on.

The man being tested was required, for each exposure, to name the letter in front of him, and indicate what had happened to the middle column of lights by saying "red", "green", or "neither". The exposures were controlled by a Telechron motor and were short enough so that the man was forced to use the center of his vision to identify the letter and the side of his vision to observe the color changes; the exposure time did not permit the man to shift his center vision to the colored lights.

The fixation letter was about twenty inches from the eye; the bank of lights formed angles of 60, 75, 90 and 105 degrees with the line of sight. The lights were in the horizontal meridian. In each testing session, four series of successive discriminations were given, going from the 60 degree position to the 105. Exposures were presented at five second intervals. The score was taken as the number of errors in naming colors during the 40 trials of each session.

It should be mentioned that the test was given under very unfavorable conditions. The only space available was in the pump room; both the man taking the test and the man giving it, were perched precariously on machinery adjuncts. Incautious movement was detrimental to life and limb.

c) Results:

1. The unfavorable conditions under which the observations were made produced results which are not meaningful in efficiency.
2. No change could be attributed to the effects of submergence.

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3. A fair test of indirect color vision would require better apparatus and testing conditions than were available during this particular submergence.

9. Observations on Efficiency of Memory for Numbers

A test of memory for numbers typical of target bearings was tried, and later rejected because of uncontrollable errors which crept into the administration and observing of the test. These errors made the results meaningless.

10. Medical Observations on General Efficiency

Two of the observers were Submarine Medical Officers, and were aboard for the entire submergence. They made the following observations relating to general efficiency during submergence:

1. Respiration, pulse and blood pressure:

Perhaps the most noticeable effect was breathing difficulty. Respiration was quite labored during submergence after carbon dioxide reached its greatest concentration. All hands quickly learned to limit any particular conversation to no more than a couple of short sentences, so as to avoid the resulting shortness of breath. Likewise, men soon realized that during submergence ascent of ladders into the pump room or conning tower at a rate comfortable in normal air produced both shortness of breath and dizziness for several minutes afterwards. Measurements made by the medical officers on 14 men indicated that the basal respiratory rate per minute went up on the average from 16.1 to 20.5. Readings of basal pulse rate (counted for thirty seconds) averaged 61.4 per minute before and 63.0 per minute during submergence. Blood pressure change was from 103.1/67.3 to 95.3/63.3 on the same fourteen men at the same time. (Diastolic blood pressure was taken at the point of disappearance of sound.)

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It was felt that physiological efficiency was decreased; especially where any kind of exertion was involved. For example, one man, who had to help open a torpedo tube during a drill, found himself exhausted, had to lie down in his bunk, and was incapacitated for about 15 minutes.

2. Headache:

The opinion of the observers, corroborated by the Commanding Officer of the submarine, was that almost everyone aboard suffered from headache at some point during submergence. Fourteen men and six officers had headaches so severe that they requested treatment from the Medical Officers or the Pharmacist's Mates. These headaches were unusual in that they were chiefly occipital. Also, one officer, an ex-enlisted man with considerable experience aboard submarines, became nauseated and vomited several times towards the end of the submergence. There was no explanation for this, except the increase in carbon dioxide and decrease in oxygen.

3. Clarity of Mental Activity:

The conditions of the submergence exerted an insidious but noticeable effect on the thinking process. It was generally observed that, during the submergence, and especially towards the latter part of the submergence, one's thoughts had a tendency to wander, and it sometimes became rather difficult to carry through a train of thought to its logical conclusion. A few incidents will illustrate this point:

- a. The Skipper during final surfacing, was using a stop watch to time the Battle Surface; he complained that the figures on the watch appeared to be rotating around the face.
- b. The Chief of the Boat, during the final surfacing, found himself attempting to blow a tank with the vents open, "Something I never did before in all my life."

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- c. The ship's cook, on the second night of the submergence, forgot to put yeast in his bread — "I had a heck of a time trying to concentrate."
- d. Several of the ship's company, found, to their surprise, that they had difficulty in remembering "points" in crap games.
- e. Several men taking the radar test found not only that the pips were often seen in duplicate, but that often a pip would be seen and not reported for several seconds because of a vagueness in remembering the purpose of the job in hand.

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REACTION OF SHIP'S OFFICERS TO EFFICIENCY DURING SUBMER-
GENCE

On the day following surfacing, a list of questions was submitted in writing to the officers of the submarine inviting their evaluation of the efficiency of the boat's crew during submergence. After consulting among themselves, the officers returned appropriate answers. Both questions and answers are reproduced below in their original form.

- I. Q. Would you regard the activities of the men during the submergence as fairly typical of actual operations?
- A. The activity of the ship's company during the 72 hour test was as typical of operating conditions as safety permitted. It would be fairer to say that the operations of the ship simulated operating conditions but never actually approached them nor were they typical inasmuch as such elements as depth control, evasion, etc., were lacking. It is believed, however, that the spirit of competition made up for at least part of the lack of tension.
- II. Q. Did you or your officers note a decrement in the operating efficiency of the submarine at any time during the 72 hour period? If so, at what times?
- A. There was a decided decrease in operating efficiency due to two causes. The first can be attributed to excessive carbon dioxide and lack of oxygen. The second was due to lack of tension. This occurred at about 20 hours. The lack of tension was, however, minimized by the spirit of competition that prevailed amongst the men taking the various tests.
- III. Q. On the basis of this submergence, would you feel that any submarine commander would be justified in tolerating the percentage of oxygen to become less than 17, or the percentage of carbon dioxide to rise higher than 3? If so, for what length of time, or under what circumstances?

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- A. Not as a general principle is so essential that each member of the team do his job perfectly that it would be desirable to keep the air as pure as possible. Naturally there are so many different situations that could arise which would necessitate accepting greater than 3% carbon dioxide and less than 17% oxygen that to enumerate them all and pass judgement on them would be foolhardy.
- IV. Q. What percentage of oxygen and carbon dioxide do you feel is consistent with efficient operating conditions?
- A. The ship's opinion is 2.7% carbon dioxide and 18-19% oxygen. We sent people with headaches to the forward torpedo room for cure. It was there that gas control was being exercised, hence; less carbon dioxide and more oxygen.
- V. Q. Would you feel that, whether or not observable decrement in overt action appeared, the physical efficiency of the crew deteriorated? If so, can this deterioration be overcome under emergency conditions, as when the men are highly motivated?
- A. Yes. Men motivated by the necessity of saving their lives can do remarkable things.

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**OBSERVATIONS ON EFFICIENCY IMMEDIATELY FOLLOWING RETURN
TO NORMAL AIR AFTER SUBMERGENCE**

1. A limited number of hours was available for observing efficiency of performance on the job operations following surfacing and opening of the main induction and the hatches.
2. A battle surface was staged to end the submergence. No definite effects on efficiency were noticed with the sudden return to normal air. No symptoms of dizziness or sickness were shown by any of the hands. The Commanding Officer reported that the battle surface was as good as average.
3. Observations on the simulated job operations, while curtailed in extent, showed clearly that the men were in no way incapacitated by sudden return to normal air.
4. These observations were too sketchy to indicate anything about the course of progress back to normal. Our impression is that efficiency is rapidly restored to normal.

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CRITICAL EVALUATION OF THE EXPERIMENT

1. We feel that the experiment would have been more valuable if:

a) More time had been available for training the men in the various jobs to be observed during submergence. Continued learning during submergence was a decided hindrance in interpreting the results.

b) More time had been available for setting up equipment in the submarine and rehearsing the jobs before observation proper began. Unforeseen difficulty in obtaining suitable testing space adversely affected the reliability of our data.

2. It is our opinion that the decrement which did show up is, because of the unfavorable testing conditions, all the more significant, in that it had to overcome the errors introduced by these conditions. It is our strong impression that, given more time to refine some of the tests and elaborate on others, we would have found that the decrement in efficiency was both more marked and more extensive than that discovered during this submergence.

3. Theoretically, we cannot be sure that the decrement in efficiency which did appear was due to the oxygen lack and excess carbon dioxide rather than to a number of other factors present, such as lack of exercise, boredom, unusualness of the prolonged submergence, and so on. Theoretically, the entire submergence should be repeated with the one difference that the air be kept normal throughout. If, in these circumstances, decrement in efficiency did not appear, the presumption would be very good that it was the oxygen want and excess carbon dioxide which were responsible for the present decrement. However, practical considerations of availability of submarines and personnel make this repeat submergence unfeasible for the time being. In addition, there is such widespread agreement among all the men undergoing the submergence, including officers, observers, and crew, that the effects of the oxygen want and excess carbon dioxide far outweighed those due to other causes, that we would not, even if we could, feel justified in requesting such a repeat. Other problems seem to us more urgent of solution than checking on this somewhat remote possibility.

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RELATION OF THE FINDINGS OF THIS REPORT TO THOSE OF THE
CONFIDENTIAL REPORT OF BUMED RESEARCH PROJECT X-349, NMRI,
23rd SEPTEMBER 1944.

1. BUMED Research Project X-349 presents an exhaustive study of the effects of carbon dioxide increase and oxygen decrease. It is precisely because of its exhaustiveness that we were able to make our report very specific; we felt that the reader could turn to the previous report for the large fund of excellent data contained there, and that, for the most part, there was no point in our repeating any of the studies described therein, particularly the relationships of atmospheric, alveolar and physiological blood gas contents.

2. Our experiment, however, does not agree with the general findings on efficiency of operating personnel during prolonged submergence. Our results indicate clearly to us that decrease in efficiency does result. This discrepancy may possibly arise:

- a) Because our procedure more nearly approximated patrol conditions,
- b) Because our tests would appear to simulate somewhat more closely the actual jobs on submarines,
- c) Because in the cases where, in the previous report, statistically significant decrement did occur, the decrement was deemed practically unimportant.

3. We believe that the previous report performed a great service in showing us that even 12% oxygen and 5% carbon dioxide can be reached, in an emergency, without drastic incapacitation. This finding was certainly also true in our experience with 17% oxygen and 3% carbon dioxide. But that is not to say that operating efficiency was not impaired.

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APPENDIX

1. Step-up Test

(a) Half the men took the test in normal air before submergence and then the test in 3% carbon dioxide; the other half took the test in 3% carbon dioxide first, and the test in normal air six days after surfacing. This arrangement provides a check on the possibility that decrement in efficiency during submergence was due to fatigue carried over from prior exercising in normal air.

(b) The index of physical fitness during exposure to 3% carbon dioxide deteriorated for all 13 subjects.

Mean drop - 17.3 points.

Standard error of the difference of the two means
= 3.44.

"t" = 5.03

"p" = 0.0002

(c) The correlation between physical index and resting pulse beat either in normal air or in 3% carbon dioxide is zero.

(d) For further information about the step-up test see:

1. The problem of measuring physical fitness for hard work. Report #7 to OSRD, from the Fatigue Laboratory, Harvard University, Cambridge, Mass., 21 May 1942.
2. Rev. Canad. Biol., Vol. 1, No. 5, June 1942.
3. Report from School of Aviation Medicine, Randolph Field, Texas, by Peter V. Karpovich, M.D.
4. Manual of Instructions for Step-Up Test of Physical Fitness, Harvard Fatigue Laboratory.

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2. Night Vision Test

(a) Description of test

The test of visual performance at low levels of illuminations was designed to simulate the task of searching a periscope field. The visual field presented to the subject in this test approximated in area, brightness, and sky-sea brightness contrast the appearance of the sea on a clear starlit night (5.05 log uul), when viewed through a periscope. A target appearing on the "horizon" duplicated in retinal area an aircraft carrier viewed head-on at approximately 13,000 yards.

This test was selected inasmuch as it was desired to include a night visual performance which depended not only on retinal physiology, but also on general psychological and physiological factors. Extensive experience with this test in another experiment indicated that it met these requirements.*

The apparatus consisted in a modification of the NDRC Model III adaptometer. The stimulus patch of this instrument, from which the rotating T had been removed, was viewed through one barrel of a 7 x 50 binocular. The whole optical pathway, and the front end of the adaptometer was housed in a black box. Spatial relations were such that the 7 degree field of the binocular just included the illuminated field of the adaptometer.

Across the face of the adaptometer field, and bisecting it horizontally, moved a slide consisting of a .40 log density neutral gelatin filter cemented between two sheets of clear glass. This slide provided the "sea" foreground to the subject's field of view. Attached to the upper edge of this slide was the small gelatin tab of density .30 log units which served as target.

Movement of the slide enabled the target to appear in any of five positions, "far right", "far left", "right", "left", and "center".

* "Red Illumination of the Conning Tower", to be issued shortly.

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(b) Test statistics

The following is the distribution of "t" and "p" values for the 31 subjects:

(1) Decrement:

t	7.1	5.6	5.9	5.3	3.7	2.5	3.2	2.5	3.1	1.3
p	.0001	.0001	.0001	.0001	.0001	.006	.0007	.006	.001	.097

t	1.5	2.2	1.2	1.2	1.3	0.9	1.2	1.1	0.7	1.2	4.1
p	.067	.004	.115	.115	.097	.184	.115	.136	.242	.115	.0001

(2) Improvement:

t	.05	.101	.10	.105	.171	.206	0.16	1.27
p	.309	.460	.460	.460	.430	.421	.44	.11

Two subjects showed no change.

All changes significant beyond the 1% level were decrements.

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3. Watch on Bow and Stern Planes

Average increase in errors during submergence = 16.0

Standard error of mean = 8.66

$$t = 1.847$$

$$\text{For } t = 1.85$$

$$\text{and } n' = 6$$

$$p = .066$$

4. Radar Watch

(1) For $n = \del{10} 9$

Mean increase in errors during submergence = 1.05

Standard error of mean = 1.04

$$t = 1.0$$

$$p = .178$$

(2) Omitting subject "Bar" whose performance is suspect:

$$n = \del{6} 5$$

Mean increase = 1.723

Standard error of mean = 0.94

$$t = 1.8$$

$$p = .066$$

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5. Dry Bulb Temperature (°F) and Percent Relative Humidity
During the Period of 17% Oxygen and 3% Carbon Dioxide.

<u>Compartment</u>	<u>Mean</u>	<u>Standard Deviation</u>
Forward Torpedo	72	2.6
Forward Battery	73	1.5
COC	73	2.6
Pump Room	73	3.0
After Battery	77	1.6
Forward Engine	72	3.8
After Engine	75	2.2
After Torpedo	70	5.2
Forward Torpedo	64	2.8
Forward Battery	65	4.3
COC	62	4.0
Pump Room	61	5.1
After Battery	60	8.1
Forward Engine	64	5.3
After Engine	58	5.1
After Torpedo	64	9.2

These conditions are considered comfortable compared to the respiration distress produced by 3% carbon dioxide. Higher temperatures and humidities, such as those encountered in Pacific waters, would no doubt cause more marked decrement in efficiency than appeared during this submergence.

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6. Sample Interior Voice Communications Drills

U.S.S. SAILFISH (SS192), DRILL ABLE

INC: MAN THE PHONES FOR A TALKER DRILL.

CONTROL All stations, Control testing.

CONN Forward Battery, Captain to Conn.

CONTROL After Machinery, tell Mr. Friedman to come forward and take the dive.

CONN Maneuvering, are you making 50 turns?

CONTROL After Machinery, secure the evaporators and take salinity reading.

FWD. MACHINERY Conn, request permission to secure port lube oil purifier.

TUBES FORWARD Tubes Aft, is Chief Gray in Tubes Aft?

AFTER BATTERY Conn, request permission to dump trash and garbage.

DRILL CHARLEY

Messages

MANEUVERING Tell Forward Battery that you want them to check on the position of the battery blower damper

FWD. MACHINERY Find out if After Machinery has placed its bilges on the drain line.

AFTER BATTERY Tell Tubes Aft to send the Pharmacist's Mate back to After Battery in a hurry.

~~CONFIDENTIAL~~
UNCLASSIFIED

CONNING TOWER

Ask JP to give you a turn count on a target that he reported on bearing 008.

DRILL CHARLEY

Numerals

MANEUVERING

Send this message to Control.
"Bearing 060, range 9000, speed 10."

CONNING TOWER

Pass the word to the Captain in Battery Forward that ship has been sighted bearing 269, looks like enemy cruiser.

FWD. MACHINERY

Send this message to After Battery.
"Aircraft bearing 135, position angle 15."

AFTER BATTERY

Send this message to Conning Tower.
"Target is on 055, speed 65. Must be blimp."

CONNING TOWER

Call Forward Machinery and get the amount of fuel consumed from 0100 to 0400.
