



DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32401

IN REPLY REFER TO

with the... of underwater... for a portable device to be carried... by the diver... An ORN... is... a theoretical design of a... computer... presented by the... and presented... The... that the... is... but the computer as... extensive... to ensure consistency... accuracy... standard... (assessments)...

EVALUATION REPORT 7-57
PROJECT NS 185-005 SUBTASK 4 Test 31

FOXBORO DECOMPUTER MARK I

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ORIGINAL

ABSTRACT

With the increased military use and civilian popularity of underwater swimming and untended diving in recent years has come a pressing need for a portable device to be carried by the diver by which he may gage his decompression during ascent. An ONR research project at Scripps Institute of Oceanography in 1953 sponsored a theoretical design of a decompression analog computer a prototype of which was subsequently manufactured by the Foxboro Company and presented to NEDU for evaluation. The evaluation indicates that the method of approach is practicable but that the computer as submitted requires extensive refinement to ensure consistency and to extend the range of accuracy (as compared to standard decompression tables and to theoretical calculations). Though the computer's applicability to use in repeated dives and variable depth dives is discussed, none of this type run was made.

SUMMARY

PROBLEM

To evaluate a decompression analog computer (Foxboro "Decomputer Mark I") for use by divers, particularly for free swimmers and for multiple dives, towards a determination of its accuracy and practicability.

FINDINGS

- (1) The prototype computer was found to be inconsistent in readings for identical dives.
- (2) The prototype computer was found to be within standard decompression ranges for some dives and outside the ranges on other dives, to the point where, without improvement, it could not be relied upon for decompression.
- (3) The size and bulk of the apparatus, though not beyond use, borders upon being too large.
- (4) The concept of the prototype gage is considered acceptable once its range of accuracy is improved and proven.

RECOMMENDATIONS

- (1) Improve the operating characteristics to ensure consistency by improvement of basic construction.
- (2) Reset the built-in constants of the gage to extend the range of accuracy of the decompression readings.

ADMINISTRATIVE INFORMATION

- Ref: (a) Groves and Munk, "A Decompression Gage For Divers", University of California, Scripps Institution of Oceanography report sponsored by Office of Naval Research, S10 References 53-64, 10 December 1953.
- (b) Dwyer, "Calculation of Air Decompression Tables", U.S. Navy Experimental Diving Unit Research Report 4-56; BuShips Project NS185-005, Subtask 5, Test 3, November 29, 1955.

With the ever widening fields of both civilian and military free-swimming and diving using self-contained breathing apparatus, and particularly when such diving is untended from the surface, there arises a very pressing need for a small portable indicating apparatus to be used to indicate proper decompression in ascent. As stated in part 1 of reference (a), "for a diver using self-contained equipment, three possibilities present themselves:

- (a) the diver keeps a log of depth and time and then computes the decompression requirement while under water (this involves a depth gauge, watch and wits);
- (b) the diver follows a prearranged schedule
- (c) by guess and by God".

Reference (a), intitled "A Decompression Gauge For Divers", is the result of an Office of Naval Research project at the University of California, Scripps Institution of Oceanography for the theoretical development of a gauge designed to overcome the above tasks and thus prevent "decompression sickness" or "bends".

As a consequence of reference (a), Mr. Mead Bradner of Foxboro Company, Foxboro, Massachusetts, without specific contract by the Navy designed several decompression gauges, the prototype of which was submitted to the Navy Experimental Diving Unit on 3 October 1955.

The gauge was tested in the early part of 1956 but was damaged in handling and returned to the manufacturer in approximately May. To date, the gauge has not been returned the the Navy Experimental Diving Unit. Since sufficient data was obtained prior to damage to warrant an evaluation, this report is submitted as a final report in order that the recommendations may be included in the repaired gauge. The project should be re-opened if and when the gauge is improved and returned.

The prototype gauge is identified as Foxboro "Decomputer Mark I" and conforms to the following two Foxboro plans: Number 12001-DC2 dated 9/9/54 and number 12001-DC2, Sheet 1 of 2 dated 9/6/55.

The project number was requested verbally from the Bureau of Ships on 14 October 1955 and was assigned that date by telephone.

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1. OBJECT

1.1 Objective

The objective of the evaluation reported herein was to pressure test under set conditions an analog decompression computer manufactured by the Foxboro Company and identified as "Decomputer Mark I" to ascertain whether or not the computer was sufficiently accurate and consistent to warrant use in the field (particularly by SCUBA divers) for regulating decompression of human divers. An additional objective was to ascertain areas of non-acceptability and to, if possible, make recommendations for correction or improvement.

1.2 Scope

The scope of the evaluation covered testing the computer in a dry chamber for comparison with theoretical decompression times and with Navy Standard Decompression times. The scope did not include subjective tests or multiple (repeat) dives. The scope also did not include ascertaining continuous-rate ascents with the decomputer but rather was limited to dives wherein decompression stops were used, all ascents being at the standard 25 feet per minute between stops.

2. DESCRIPTION

2.1 Background

As mentioned under Administrative Information, the Office of Naval Research sponsored a research project at the University of California, Scripps Institution of Oceanography for the theoretical design of "A Decompression Gauge for Divers". Reference (a) is the resultant project report. The approach was theoretically based on the classical Haldane decompression theory of tissues. The authors concluded that it would be possible to design a two-tissue analog decompression computer based upon linear decompression curves with constant tissue rates, thus simplifying the selection of time constants in an analog computer.

Reference (a), figure 5 presented decompression curves, based on two tissues each with tissue ratio of 1.75, giving time of decompression as time of exposure for given depth of dive. The analog decompression computer evolved from this treatment and it is to these curves that part of the data of this evaluation are compared. See section 4.1 for formulas representing figure 5 of reference (a).

Subsequent to completion of reference (a), the Foxboro Company developed a series of prototype gauges one of which was presented to the Navy Experimental Diving Unit as "Decomputer Mark I".

2.2 Review of decompression theory

Decompression is necessary for dives on air beyond 30 feet. The need arises when body tissue saturation with inert gas reaches the point that the particular tissue in question can no longer surface directly without bubble formation. Theoretically, there are an infinite number of body tissues with different saturation characteristics.

Haldane's theory of exponential saturation yields a basis for calculation of tissue pressures throughout the course of a dive. The entire theory of exponential tissue saturation can be expressed by the equation

where

$$A = P + [1 - 2 - \left(\frac{t}{n}\right)] (N - P)$$

N = inert gas partial pressure (feet)

P = initial tissue pressure (feet)

Q = final tissue pressure (feet)

t = time interval

h = tissue half time

For a more complete treatment of the above formula, see reference (b).

A tissue can hold some amount of dissolved inert gas in supersaturation. The amount depends on the absolute pressure around the tissue. If a tissue is at the point of supersaturation and the absolute pressure falls (as during ascent), the tissue releases inert gas as bubbles. The tissue continues to form bubbles until it reaches a new state of supersaturation in balance with the lower absolute pressure.

A tissue gains inert gas during a dive. At the end of the dive, the tissue can safely ascend a certain distance. It then reaches supersaturation and cannot ascend farther until it loses some of the inert gas. Haldane's theory of tissue ratio furnished a tool for determining:

- (1) The depth at which the first decompression stop must be made.
- (2) The length of time for the first and all subsequent "stops".

The theory and a consideration of natural phenomena wherein effects are generally not discontinuous (as ascending, stopping to wait and then ascending again) leads to the belief that there may exist a rate or series of rates at which a tissue could ascend and be continuously at the threshold of supersaturation.

From their investigations, Haldane and his associates inferred that the human body could withstand a tissue-to-absolute pressure ratio of two-to-one without risking decompression sickness. Because of the tissue ratio, at the end of bottom time each tissue has a different value of depth above which it cannot ascend without bubble formation. The controlling tissue for ascent is the tissue which must stop earliest (at the greatest depth) to avoid bubble formation.

At a given decompression stop, some initial tissue pressures (P) will be greater than the corresponding maximum tissue pressures (M) at the next stop. Each final tissue pressure (Q) must be equal to or less than the maximum tissue pressure (M) for the next stop before the tissue can ascend to that stop. The controlling tissue for the given stop is the tissue which requires the longest time to desaturate to the maximum tissue pressure at the next stop.

In the discussion of reference (a), considerable thought was devoted to the number of tissues which the analog would endeavor to represent. For purposes of size and simplicity, the ultimate computer described therein and evaluated by this report was limited to two tissues. In addition, the assumption was made that the tissue ratio would remain constant for a given tissue whereas in practice it has been found necessary to consider the tissue ratio as varying with depth in some cases.

The above two assumptions, namely (a) two tissues only, and (b) constant tissue ratio for a given tissue, constitute a basic compromise in the design of the analog computer. If the assumptions are not too radical, it may be possible to limit the use of the computer to certain ranges of dives (depth and duration) or introduce a constant factor to ensure satisfactory (but not excessive) decompression on a sufficiently large percentage of dives to warrant use.

The Foxboro Decomputer has two analog elements representing two tissues of the decompression problem. In addition, the decomputer is a depth (pressure) gauge giving depth reading and operating in conjunction with the tissue elements in the solution of the problem. Each analog consists of an external bellows and an internal bellows connected by a capillary of known value. The case is filled with silicone oil and there is a slack diaphragm between the

silicone oil and the external sea water permitting sea water pressure to act on the bellows through the oil. The internal bellows are enclosed in an evacuated chamber so that change in depth (pressure) at the external bellows forces oil through the capillary into the internal bellows. The flow of oil through the capillaries is designed to approximate, in the analog, the equation of section 2.2 above.

2.3 Physical characteristics

The decomputer is enclosed in a stainless steel jacket 5 1/2 inches long, 3 inches wide and 1 7/16 inches thick. One end is rounded to conform to the decomputer indicator. The face is covered with plexi-glass through which can be seen the depth gauge and the decomputer indicator. The depth gauge is graduated in two foot intervals to 60 feet and in 5-foot intervals from 60 to 200 feet.

The decomputer indicator has both red (danger) and green (safe) markings to be used as a guide for decompression. The decomputer indicator is a disc, only half of which shows through the plexi-glass cover, one-half of the disc is white and the remaining half is divided into two quarters, one colored red and the other colored green. When the decomputer is on the surface and has not been used, its normal indication is about 10 degrees of the green segment showing on the right hand side. During pressurization, the amount of green increases. During decompression, the amount of green decreases until the full white semi-circle is showing. Theoretically, at this point the diver must stop his ascent, or slow it down to keep all the white segment showing or a portion of the green showing. If he exceeds the safe depth for decompression, some of the red segment comes into view on the left side.

The visible springs are steel and brass. The housing of the two analog chambers is brass, along with the mounting for the depth gauge.

The weight of the decomputer is 1.87 pounds in air. Buoyancy cannot be checked at this time because the jacket is not watertight and the proper amount of silicone oil for filling the jacket is not available.

Figures 1, 2 and 3 are photographs of the Foxboro Decomputer Mark I.

3. PROCEDURE

3.1 General

The test evaluation procedure was directed towards an evaluation of the accuracy and consistency of the readings of the Foxboro Decomputer Mark I in regulating a diver's ascent to preclude decompression sickness or "bends".

In as much as the decomputer evolved from the theoretical design presented in reference (a) and was based upon the assumptions mentioned in 2.2 above, the operation of the apparatus was compared to the predicted total decompression time shown on the curves of figure 5 of reference (a) or more specifically to the equations for the curves as recorded in 4.1 below.

Since the current Navy Standard Decompression Tables (1943) are held to be generally safe for decompression, the operation of the decomputer was also compared to these tables.

A series of fixed dives was selected in order to test the decomputer over a wide range of depths, exposure times and decompression combinations. The decomputer is designed for depths to 200 feet only and all test conditions were limited accordingly. Test dives selected were as follows: (depth of dive/exposure time to time of ascent): 50/78; 50/120; 100/25; 100/40; 100/60; 150/15; 150/30; 150/38; 200/15; 200/23.

Though reference (a) points out the possible use of the decompression analog computer in repeated dives wherein the decomputer carries residual readings from an initial dive into a second dive, no attempts were made at such an evaluation.

3.2 Preparation of equipment

In order to be able to quantitatively measure the relative condition of safe (green) or unsafe (red) on the decompression dial, the red and green quarter circles were marked at five degree intervals working away from the white semi-circle.

The decomputer was placed in a decompression chamber in a horizontal (flat) position and mirrors were arranged to permit accurate dial (decompression and depth) readings through a chamber port. Care was taken not to block the equalizing holes in the back of the instrument.

The chamber depth gauge readings were taken as standard and also for comparison with the decomputer's depth gauge.

3.3 Depth runs, decomputer controlling

A series of depth runs in conformance with the fixed dives enumerated in 3.1 above was run with the decomputer controlling.

The instrument was brought to the required depth at the standard rate of 60 feet per minute. Readings were taken upon reaching the bottom and every five minutes thereafter until beginning of ascent. Readings taken were as follows:

- (a) time of dive
- (b) depth by chamber gauge
- (c) depth by decomputer gauge
- (d) decompression indicator reading as number of units green (plus) or minus (red) or in safe zone.

At the end of bottom time, the chamber was brought up at the standard rate of 25 feet per minute. The green marker (which was in the positive zone upon starting ascent) was watched carefully. At the instant the green mark totally disappeared (entire white semi-circle showing) the chamber was stopped and readings taken. This decompression stop was held until five units (plus 5) of the green marker were again visible (five units were selected arbitrarily), whereupon readings were taken and ascent resumed repeating decompression stops as necessary, with the green dial controlling, until the instrument was returned to the surface and final readings taken. Several runs were duplicated.

In order to check the consistency of the instrument, a second series of runs, with the decomputer controlling, were run after an interval of several days.

3.4 Depth runs, Navy Standard Decompression Tables Controlling

A series of depth runs in conformance with the fixed dives enumerated in 3.1 above was run with decompression being accomplished in accordance with the Navy Standard Decompression Tables.

The instrument was brought to the required depth at the standard rate of 25 feet per minute to the first stop (as applicable) as required by the tables. If during the ascent the green mark disappeared, the depth and time was noted. At the decompression stop, readings were taken as enumerated in 3.3 for both beginning and end of decompression. This procedure was repeated to the second stop and then to the surface. When, during ascent, the decomputer decompression gauge went unsafe or negative (red), the time and reading was recorded, no attempt being made to stop the ascent.

Depth runs conducted in accordance with the above are tabulated in 4.4. No repeat runs were made with the tables controlling.

4. RESULTS

4.1 Foxboro Decomputer controlling ascent

Data Sheet #1 is a compilation of results for the initial set of runs wherein the Foxboro "Decomputer" was considered controlling. Readings are tabulated at the start of descent, upon reaching bottom, at intervals on the bottom if the decomputer gage reading changed, upon commencing ascent, at each decompression stop (zero gage reading), at commencement of re-ascent (gage reading at plus 5) and at the surface. For runs not requiring decompression stops and for those wherein the gage did not vary while on the bottom, the corresponding readings do not apply.

Based upon the linear theoretical decompression curves developed and shown in figure 5, reference (a), and described in 2.1 above, the linear equation, and the decompression times for the fixed dives listed in 3.1 follow:

- (1) Depth 50 feet. Formula $t_d = 0.284 t_e + 5$

<u>Exposure time</u>	<u>Decompression time</u>
78 min.	26 min.
120 min.	39 min.

- (2) Depth 100 feet. Formula $t_d = 1.172 t_e + 4$

<u>Exposure time</u>	<u>Decompression time</u>
25 min.	33 min.
40 min.	51 min.
60 min.	74 min.

- (3) Depth 150 feet. Formula $t_d = 2.308 t_e - 6$

<u>Exposure time</u>	<u>Decompression time</u>
15 min.	29 min.
30 min.	63 min.
38 min.	82 min.

- (4) Depth 200 feet. Formula $t_d = 3.25 t_e + 3$

15 min.	52 min.
23 min.	78 min.

4.1.3 Data Sheet #1

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHNG. degrs.
F-1 (50/78)	0	0	2	+10	---
	2	50	52	+25	+15
	78	50	52	+25	0
	81	0	2	+3	-22
F-2 (50/78)	0	0	3	+10	---
	1	50	56	+23	+13
	78	50	56	+23	0
	81	0	2	+3	-20
F-3 (50/120)	0	0	2	+10	---
	2	50	54	+25	+15
	120	50	55	+25	+15
	123	0	0	0	-25
F-4 (50/120)	0	0	3	+10	---
	1	50	56	+23	+13
	120	50	56	+23	0
	123	0	2	+1	-22
F-5 (100/25)	0	0	2	+10	---
	3	100	110	++++	+++
	25	100	110	+++	0
	30	0	3	+2	---
F-6 (100/25)	0	0	3	+10	---
	2	100	110	+++	+++
	25	100	110	+++	0
	30	0	3	+3	---
F-7 (100/40)	0	0	2	+7	---
	2	100	110	+35	+28
	40	100	110	+35	0
	45	0	11	+5	-30
F-8 (100/40)	0	0	3	+10	---
	2	100	110	+30	+20
	40	100	110	+30	0
	47	0	2	-1	-31
F-9 (100/60)	0	0	0	+12	---
	2	100	110	(+35)	(+23)
	60	100	110	(+35)	(0)
	64	12	12	0	(-35)
	85	12	13	+5	+5
	105	6	6	0	-5
	106	6	3	+5	+5
	106	0	3	0	-5

4.1.3 Data Sheet #1 (Continued)

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHNG. degrs.
F-10 (150/15)	0	0	2	+12	---
	3	150	158	(+45)	(+33)
	15	150	158	(+45)	(0)
	22	0	3	+4	(-41)
F-11 (150/30)	0	0	1	+5	---
	3	150	160	+23	+18
	30	150	160	+14	-9
	36	12	13	0	-14
	75	12	13	+5	+5
	76	4	6	0	-5
	106	4	6	+5	+5
	107	0	4	+2	-3
F-12 (150/30)	0	0	0	+12	---
	3	150	158	+23	+11
	30	150	158	+19	-4
	36	10	10	0	-19
	64	10	10	+5	+5
	65	4	5	0	-5
	88	4	5	+5	+5
	89	0	3	+1	-4
F-13 (150/38)	0	0	0	+7	---
	3	150	160	+23	+16
	15	150	158	+23	0
	20	150	158	+20	-3
	30	150	158	+15	-5
	38	150	158	+15	0
	44	16	17	0	-15
	82	16	17	+5	+5
	83	8	9	0	-5
	103	8	9	+5	+5
	104	0	-	0	-5
F-14 (200/15)	0	0	1	+10	---
	4	200	195	(+50)	(+40)
	15	200	195	(+50)	0
	21	50	56	+17	(-33)
	24	5	6	0	-17
	58	5	6	+5	+5
	59	0	4	+2	-3
F-15 (200/23)	0	0	2	+10	---
	4	200	195	(+45)	(+35)
	23	200	195	(+45)	0
	27	100	109	+25	(-20)
	31	12	14	0	-25
	66	12	14	+5	+5
	66	5	6	0	-5
	78	5	6	+2	+2
	79	0	---	-3	-5

4.1.3 Data Sheet #1 (Continued)

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
F-16 (200/23)	0	0	3	+10	--
	4	200	198	(+45)	(+35)
	23	200	198	(+45)	0
	31	12	14	0	(-45)
	61	12	13	+5	+5
	62	6	7	0	-5
	92	6	7	+5	+5
	93	0	3	+1	-4

4.2 Navy Standard Decompression Tables, controlling ascent

4.2.1 Data Sheet #2 is a compilation of results for the runs wherein decompression was accomplished in accordance with Navy Standard Decompression Tables, listing correspondence readings on the decompression dial of the computer. For a given standard decompression stop, plus readings on the decomputer indicate (in so far as the decomputer is concerned) too liberal decompression; minus readings, insufficient decompression; and zero readings indicate agreement. Decompression stops conform to the values indicated in paragraph 4.1.3.

4.2.2 Based upon the U.S. Navy Standard Decompression Tables the decompression times for the dives listed in 3.1.4 are as follows:

- (1) Depth 50 feet.
 - (a) Exposure time 78 minutes. No decompression stop required. Total decompression two minutes during standard ascent rate of 25 feet per minute.
 - (b) Exposure time 120 minutes. Stop -2 minutes at 10 feet. Total decompression time - 4 minutes.
- (2) Depth 100 feet.
 - (a) Exposure time 25 minutes. No stops. Total decompression time - 4 minutes.
 - (b) Exposure time 40 minutes. Stop - 12 minutes at 10 feet. Total decompression time - 16 minutes.
 - (c) Exposure time 60 minutes. First stop - 18 minutes at 20 ft. Second stop - 16 minutes at 10 feet. Total decompression time - 38 minutes.

4.2.2 (Continued)

- (3) Depth 150 feet.
 - (a) Exposure time - 15 minutes. Stop - 7 minutes at 10 feet. Total decompression time - 13 minutes.
 - (b) Exposure time - 30 minutes. First stop - 13 minutes at 20 ft. Second stop - 21 minutes at 10 ft. Total decompression time - 40 minutes.
 - (c) Exposure time - 38 minutes. First stop - 28 minutes at 20 ft. Second stop - 30 minutes at 10 feet. Total decompression time - 64 minutes.
- (4) Depth 200 feet.
 - (a) Exposure time - 15 minutes. Stop - 32 minutes at 10 feet. Total decompression time - 40 minutes.
 - (b) Exposure time - 23 minutes. First stop - 23 minutes at 20 ft. Second stop - 37 minutes at 10 feet. Total decompression time - 68 minutes.

4.2.3 Data Sheet #2

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
N-1 (50/78)	0	0	2	+10	--
	1	50	56	+23	+13
	70	50	56	+22	-1
	78	50	56	+22	0
	81	0	3	+2	-20
N-2 (50/120)	0	0	3	+10	--
	1	50	56	+23	+13
	70	50	56	+22	-1
	120	50	56	+22	0
	122	10	10	+6	-16
	124	10	11	+7	+1
125	0	3	0	-7	
N-3 (100/25)	0	0	3	+10	--
	2	100	110	(+35)	(+25)
	20	100	110	+30	(-5)
	25	100	110	+30	0
	31	0	3	+1	-29

4.2.3 Data Sheet #2 (Continued)

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
N-4 (100/40)	0	0	2	+10	--
	2	100	110	(+35)	(+25)
	30	100	110	+30	(-5)
	40	100	110	+30	0
	45	10	10	+4	-26
	57	10	10	+6	+2
	58	0	3	-1	-7
N-5 (100/60)	0	0	2	+10	--
	2	100	110	(+35)	(+25)
	35	100	110	+30	(-5)
	60	100	110	+25	(-5)
	64	20	22	+8	-17
	82	20	22	+9	+1
	83	10	10	+1	-8
	99	10	10	+5	+4
	100	0	3	-3	-8
N-6 (150/15)	0	0	2	+12	--
	3	150	158	(+45)	(-33)
	15	150	158	(+45)	(0)
	21	10	10	+8	(-37)
	28	10	10	+8	0
	29	0	3	+2	-6
N-7 (150/30)	0	0	2	+10	--
	3	150	160	(+45)	(+35)
	30	150	160	(+45)	(0)
	36	20	21	+8	(-37)
	49	20	22	+10	+2
	50	10	10	+1	-9
	71	10	10	+6	+5
	72	0	3	-1	-7
N-8 (150/38)	0	0	0	+10	--
	3	150	158	(+40)	(+30)
	38	150	158	(+40)	(0)
	44	20	23	+6	(-34)
	72	20	22	+9	+3
	73	10	11	+1	-8
	103	10	10	+7	+6
	104	0	2	0	(-7)

4.2.3 Data Sheet #2 (Continued)

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
N-9 (200/15)	0	0	2	+10	--
	4	200	198	(+50)	(+40)
	15	200	198	(+50)	(0)
	23	10	12	+5	(-45)
	55	10	10	+7	+2
	56	0	3	+1	-6
N-10 (200/23)	0	0	2	+10	--
	4	200	198	(+50)	(+40)
	23	200	198	(+45)	(-5)
	31	20	21	+7	(-38)
	54	20	21	+9	+2
	55	10	11	+2	-7
	92	10	11	+7	-5
	93	0	3	+1	-6

4.3 Repeated runs, decomputer controlling

4.3.1 In order to ascertain the consistency and consequently the reliability of the decomputer, various depth runs with the decomputer controlling were duplicated. These repeat runs are compiled on Data Sheet #3.

4.3.2 In addition to the repeat runs tabulated on Data Sheet #3, there were six runs shown on Data Sheet #1 which were repeated. For comparison purposes, all repeated runs are indicated below.

DEPTH	EXPOSURE Time	TOTAL DECOMPRESSION		TIME DECOMPUTER			
		RUN #	TIME	RUN #	TIME		
50	78	F-1	3	F-2	3		
50	120	F-3	3	F-4	3		
100	25	F-5	5	F-6	5		
100	40	F-7	5	F-8	7	R-1	5
100	60	F-9	46			R-2	61
150	15	F-10	7			R-3	7
150	30	F-11	77	F-12	59	R-4	37
150	38	F-13	62			R-5	62
200	15	F-14	44			R-6	39
200	23	F-15	46	F-16	69	R-7	68

4.3.3 Data Sheet #3

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
R-1 (100/40)	0	0	0	+13	--
	2	100	155	(+35)	(+22)
	40	100	155	(+35)	(0)
	45	100	155	+4	(+31)
R-2 (100/60)	0	0	3	+12	--
	2	100	106	(+35)	(+23)
	40	100	106	+30	(-5)
	60	100	106	+30	0
	64	11	10	0	-30
	94	11	10	+5	+5
	95	4	4	0	-5
	120	4	4	+5	+5
	121	0	3	+2	-3
R-3 (150/15)	0	0	3	+12	--
	3	150	160	(+45)	(+33)
	15	150	160	(+45)	(0)
	22	0	3	+2	(-43)
R-4 (150/30)	0	0	3	+12	--
	3	150	160	(+45)	(+33)
	30	150	160	(+45)	(0)
	36	9	8	0	(-45)
	66	9	8	+5	+5
	67	0	3	-1	-6
R-5 (150/38)	0	0	3	+10	--
	3	150	160	(+40)	(+30)
	38	150	160	(+40)	(0)
	44	15	14	0	(-40)
	63	15	16	+5	+5
	64	10	9	0	-5
	89	10	9	+5	+5
	90	0	3	-1	-6
	100	0	3	0	+1
R-6 (200/15)	0	0	3	+12	--
	4	200	192	(+50)	(+38)
	15	200	192	(+50)	(0)
	24	5	5	0	(-50)
	52	5	5	+5	+5
	53	0	3	+1	-4

4.3.3 Data Sheet #3 (Continued)

RUN (DEPTH/TIME)	RUN TIME min.	ACTUAL DEPTH feet.	GAGE DEPTH feet	INDICATOR degrs.	CHANGE degrs.
R-7 (200/23)	0	0	3	+12	--
	4	200	192	(+50)	(+38)
	23	200	192	(+50)	(0)
	31	12	12	0	(-50)
	54	12	12	+5	+5
	55	6	6	0	-5
	90	6	6	+5	+5
	91	0	2	+1	-4

4.4 Navy Standard Decompression Stops vs Decomputer Stops

4.4.1 Based on the theory of reference (a) it should be possible to approach an optimum rate or rate of ascent by using the decomputer to always keep the dial at zero (neither red nor green) and proceed to the surface without stops. The tests were however conducted using the standard rate of ascent of approximately 25 feet per second. With the decomputer controlling (Section 4.1) ascent was stopped when the readings became zero from the positive side and the decompression stop was held until the reading again became +5.

4.4.2 The following tabulation indicates the decompression stops for the various dives. The columns at the extreme right indicate the readings for the decomputer at the start and end of each decompression stop required by the Navy Standard Decompression Tables. The column labeled "Decomputer Reading at the Surface" indicates for all runs the status of the decomputer at the end of the dive.

DECOMPUTER READING @ SURFACE	FOI TAI 3 DIVES		DECOMPUTER READ		EXPOSURE DEPTH TIME	RUN #	TOTAL DECOMP	FIRST STOP DEPTH	STOP TIME	SEC. DEPTH	STOP TIME
	Start	Stop	Start	Stop							
-3	-	-	-	-	200	F-15*	46	12	35	5	12
+1	-	-	-	-		F-16	69	12	30	6	30
+1	+7	+9	+2	+7		R-7	68	12	23	6	35
+1	-	-	-	-		N-10	68	20	23	10	37
+2	-	-	-	-	200	F-14	44	5	34	-	-
+1	-	-	-	-		R-6	38	5	28	-	-
+1	+5	+7	-	-		N-9	40	10	32	-	-
0	-	-	-	-	150	F-13	66	16	38	8	20
0	-	-	-	-		R-5	62	15	19	10	25
0	+6	+9	+1	+7		N-8	66	20	28	10	30
+2	-	-	-	-	150	F-11*	77	12	39	4	30
+1	-	-	-	-		F-12	59	10	28	4	23
+1	-	-	-	-		R-4	37	9	30	-	-
-1	+8	+10	+1	+6		N-7	40	20	13	10	21
+4	-	-	-	-	150	F-10	7	-	-	-	-
+2	-	-	-	-		R-3	7	-	-	-	-
+2	+8	+8	-	-		N-6	13	10	7	-	-
0	-	-	-	-	100	F-9	46	12	21	6	20
+2	-	-	-	-		R-2	61	11	30	4	25
-3	-	-	-	-		N-5	38	20	18	10	16
+5	-	-	-	-	100	F-7	5	-	-	-	-
-1	-	-	-	-		F-8	7	-	-	-	-
+4	-	-	-	-		R-1	5	-	-	-	-
-1	+4	+6	-	-		N-4	18	10	12	-	-
0	-	-	-	-	50	F-3	3	-	-	-	-
+1	-	-	-	-		F-4	3	-	-	-	-
0	+6	+7	-	-		N-2	4	10	2	-	-

*Disregarded in tabulation 5.1

4.5 Comparison of Decompression Times

4.5.1 The foregoing gives for the dives (3.1.4) three sets of decompression times, namely;

- (a) Theoretical total decompression time for a two stage analog with stated assumptions (4.1.2).
- (b) Total decompression time required by decomputer using 25 feet per minute rate of ascent between stops (4.1.3 and 4.3.3).
- (c) Total decompression time required by Standard Navy Decompression Tables (4.2.2).

For purposes of comparison the above data is tabulated as follows:

DEPTH	EXPOSURE TIME	TOTAL DECOMPRESSION TIME (minutes)		
		Decomputer*	Theo. Curves	Tables
50	78	3	26	2
	120	3	39	4
100	25	5	33	4
	40	6	51	16
	60	46	74	38
150	15	7	29	13
	30	59	63	40
	38	74	82	64
200	15	44	52	40
	23	69	78	68

*Averaged for repeated runs. Runs F-11 and F-15 discounted.

5. DISCUSSION

5.1 Theoretical performance

5.1.1 As noted previously, the authors of reference (a) present in Figure 5 a series of curves showing total decompression times for a two-tissue analog after specific exposure times at various depths. The tissue analog half-times are 40 and 75 minutes and the "total pressure" tissue ratio is 1.75 for each and is considered constant throughout decompression. Reference (a)

5.1.1 (Continued)

unfortunately does not give a tabulation of basic data or sample calculations. For the purposes of comparison and discussion of the decomputer, the curves were accepted at face value, and since the original figure did not have an adequate grid, the straight line formulas of 4.1.2 above were developed.

5.1.2 The amount of total decompression time required by the curves as compared to that called for by the gage may be seen in the tabulation of paragraph 4.5.1. The tabulation also indicates the total decompression time required by the proven Navy Standard Decompression Tables.

5.1.3 A study of the tabulation of 4.5.1 would indicate that for dives of greater depth and exposure time, the theoretical values for decompression time approach more closely the Navy Standard Times and the decomputer times. In all cases the theoretical values are higher than either the standard or decomputer values.

5.1.4 The theoretical curves of reference (a) are undoubtedly very rough. The assumption of constant tissue ratio is reflected in the great disparity of values at shallower and shorter dives. Since reference (a) gives insufficient basic data to reconstruct the process by which the curves were generated, no attempt will be made here to analyze their shortcomings other than to state that the assumptions upon which they were based were not entirely adequate. The curves may be looked upon as a vehicle through which the gauge was designed.

5.1.5 Section 2.2.6 indicates the theoretical possibility of a rate or series of rates of ascent for which the instrument (or diver) should be continuously at the threshold of supersaturation all the way to the surface but without decompression stops. In such a case the decomputer would be entirely controlling where as in the runs described above the computer controls within the initial assumption of rate of ascent of 25 feet per minute.

5.2 Decomputer total decompression time

5.2.1 If it may be momentarily assumed that the current Navy Standard Decompression Tables are generally safe, it would then follow that an analog decompression gage which gave total decompression time in very close agreement with the tables was satisfactory for use in the field. This of course assumes that the decompression stops required by the analog gauge were adequate for tissue decompression. Based upon this, the degree to which the gauge requires total decompression time as compared to the table is very pertinent.

5.2.2 From the tabulation in paragraph 4.5.1 above (3rd and 5th columns) it may be seen that there is a spread in the comparison of decomputer total time with table time. Both the 50 foot dives are within one minute of the tables; in only three cases (50/120, 100/40, and 150/15) are the decomputer times less than the tables (and thereby likely to be in error on the dangerous side); in all other cases the decomputer time is greater than total time, showing surprising agreement at the 200 foot dives. It is generally felt that the data would have been better (and more positive conclusions reached) had a larger number of dives been conducted at each set dive. This was however not possible due to damage of the decomputer. Runs number F-11 and F-15 were felt to be random bad examples and were discounted. A greater quantity of runs would have helped to determine positively which runs were in the normal pattern.

5.3 Decompression stops

5.3.1 It should be recalled that in the classical Haldane computation of decompression, the stops are fixed at set depths (namely 10 feet, 20 feet, etc.) and that if the calculation shows a stop at an inbetween depth, the next deeper set depth is used (i.e., if computation requires five minute stop at 7 feet, the stop is recomputed for 10 feet). Therefore, the fact that the analog stops are at random depths hold little or no significance.

5.3.2 Since in the ultimate it would be possible to design an analog which would exactly duplicate the reaction of the body tissues and which, with varying rates of ascent, could be brought to the surface without complete decompression stops, a comparison of the number of stops holds no theoretical importance. However, since the rate of ascent for the tests of the decomputer is the same as that by which the tables were computed, it would follow that if the analog as built is a close approximation to the Haldane method of computation, there should be a general agreement in number and depth of stops (the decomputer stops should be within ± 10 of the table stops).

5.3.3 Using the tabulation of 4.4.2, for the 200/23 dive, the above is borne out by the fact that the three dives on which the decomputer controlled had stops at 12 and 6 feet and the table dive called for 20 and 10 feet. The same is borne out in all dives at 200/15, 150/38 and 100/60 and in all dives at 150/30 with the exception of run R-4.

5.3.4 At the 100/40 dive none of the three decomputer controlling dives required stops whereas the table called for a 12 minute

5.3.4 (Continued)

stop at 10 feet. The discrepancy here is consistent with the discrepancy in total decompression time. It appears that this dive represents the area of the greatest discrepancy between decomputer and the tables. Though no firm explanation is possible, it may be either that the tables are too safe in this area or that the dive may represent an area wherein there is an insipient change in controlling tissue and the errors in the analog assumptions are cumulative. A requirement for additional dives in this area is definitely indicated. A similar but less exaggerated condition exists at the 150/15 and 50/120 dives though in the latter the importance is questionable due to the very short total decompression time involved.

5.3.5 An interesting observation is the reading on the decompression gauge at the beginning and end of each stop for table-controlled dives. Based upon the method of table computation discussed in 5.3.1 wherein stops are made at the next deeper 10 foot increment stop, it could be predicted that the decomputer should always be safe when the table stop begins. This condition is borne out in every dive as may be seen in the four right hand columns of tabulation 4.4.2. It should also be noted that the decompression gage increased in value during each stop. No attempt will be made at this time to analyze the variance in the amount of change.

5.4 Decomputer reading upon reaching surface

5.4.1 The ninth column of tabulation 4.4.2 indicates the positive ("safe") or negative ("unsafe") reading of the decomputer's decompression gauge upon surfacing from the dives. With the exception of runs F-15 and N-5 there is a generally safe (considering minus one as statistically safe) readings.

5.4.2 Run F-15 has been discounted in both tabulations 4.4.2 and 4.5.1 as a random bad run.

5.4.3 Run N-5 bears further discussion. This is the only table run in which there was a major unsafe condition indicated by the decomputer. This is consistent with the fact that the total decompression times required by the decomputer were generally greater than the total decompression time required by the tables. Both these facts would indicate that the decomputer was over-safe in the 100/60 area.

5.5 Depth gage accuracy

5.5.1 For all readings taken the decomputer's depth reading was taken and recorded for comparison with the chamber depth gage, the latter being considered as the standard and therefore controlling the dive. As may be seen in the tabulations of Data Sheets 1, 2, and 3 the decomputer depth gage read consistently high as compared to the actual depth (chamber gage) except at the end of the scale where at 200 feet it read consistently low.

5.6 Decompression Gage consistency

5.6.1 The number of duplicate runs at the various diving conditions was unfortunately cut short because of damage to the decomputer. As may be seen from the tabulation of 4.4.2 above wherein two and in some cases three dives were made under identical conditions and with the decomputer controlling (for example at 100/40 runs F-7, F-8 and R-1) there is good consistency in some cases (as 200/23, 150/15, 100/40 and 50/120) and great inconsistency in others (as 150/30 and 100/60). Multiple runs under identical conditions are required in order to obtain good average readings (excluding random bad runs) and to determine more positively the consistency of the gauge.

6. CONCLUSIONS

6.1 Conclusions

On the basis of the foregoing results and discussion it is concluded that:

- (a) The idea of an analog computer to control divers' decompression is entirely feasible and that satisfactory results may be predicted from a two tissue analog.
- (b) The Foxboro Decomputer Mark I in its present state of development is not sufficiently accurate or consistent over the range of test dives to permit approval.
- (c) The Foxboro Decomputer Mark I shows definite promise of being an acceptable decompression guide subsequent to further refinement and study.
- (d) The physical size of the apparatus is not overly large though it does border on being cumbersome.

6.1 Conclusions (Continued)

(e) The arrangement and readability of the gages are satisfactory.

(f) Due to damage to the decomputer, insufficient data has been obtained in this project in order to permit definite conclusions to be reached.

6.2 Recommendations

Based on the above, the following recommendations are made:

(a) The decomputer should be repaired and returned for additional evaluation in order to more accurately determine ranges of agreement and disagreement with the Standard Tables.

(b) Multiple runs should be made at each diving condition to average out erroneous runs.

(c) The depth gage should be improved or calibrated.

(d) Subsequent to additional test runs and subject to the more conclusive results obtained therefrom, it may be found necessary to change various analog constants to improve operation over the zero to 200 foot diving range. It is not felt that results so far obtained warrant a recommendation for changes at this time.

(e) Subsequent to the development of a satisfactory decompression gage for single dives, the gage should then be tested for use in repeat diving.

PROJECT NS 185-005

SUBTASK 4 TEST 3I

FOXBORO DECOMPUTER

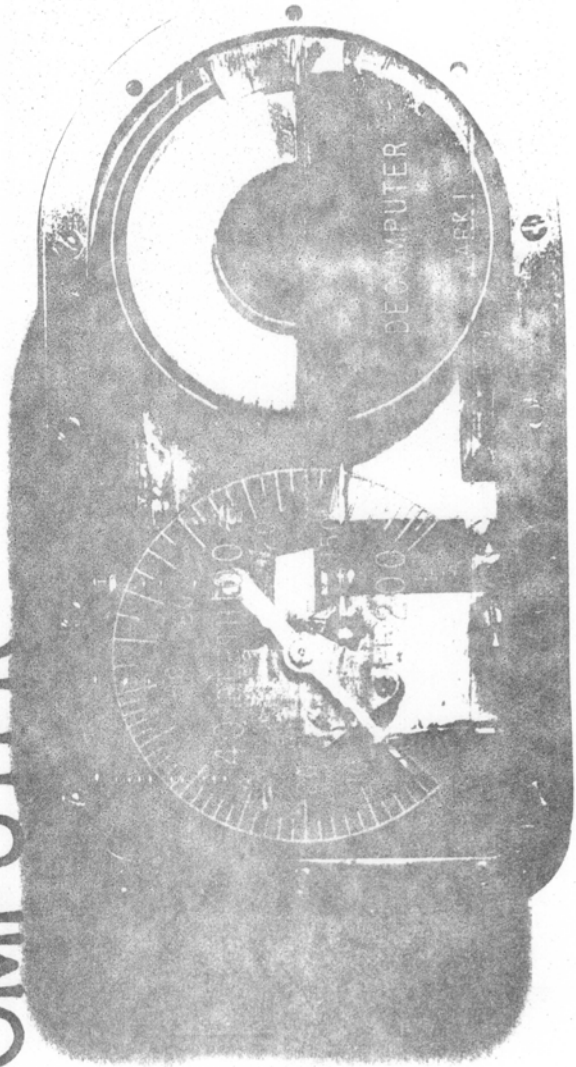


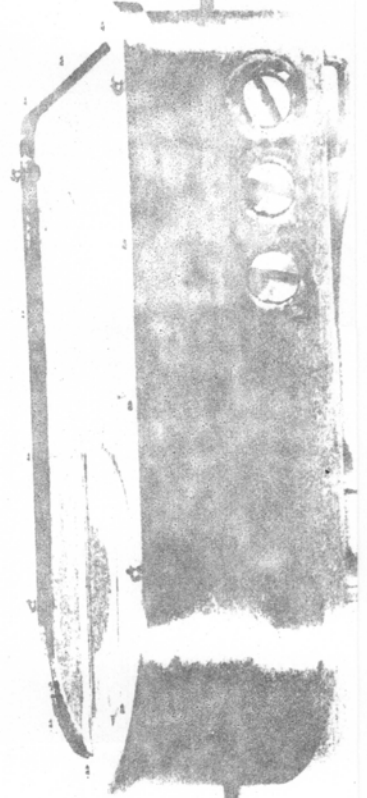
FIGURE NO. 1

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SUBTASK 4 TEST 31

FOXBORO DECOMPUTER

FIGURE NO. 2



PROJECT NS 185-005

SUBTASK 4 TEST 3I

FOXBORO DECOMPUTER

FIGURE NO. 3

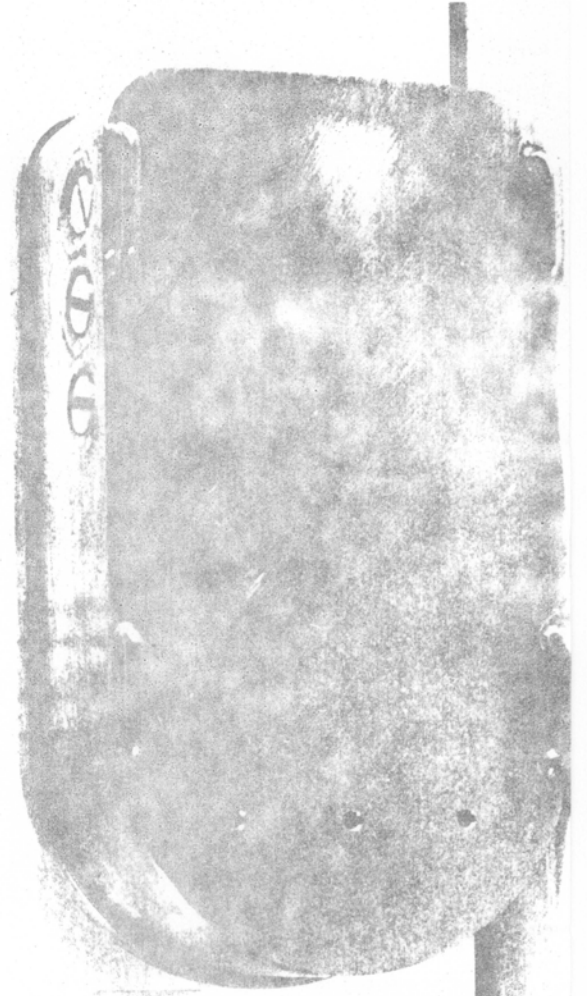
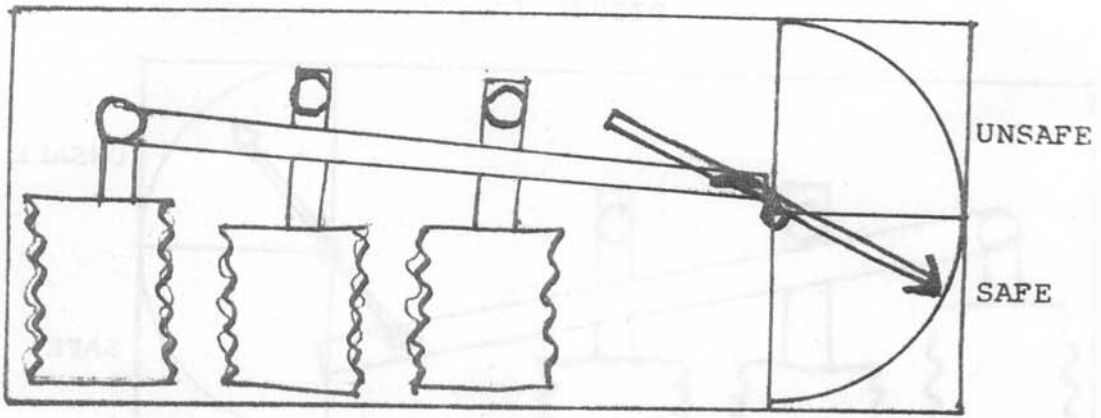
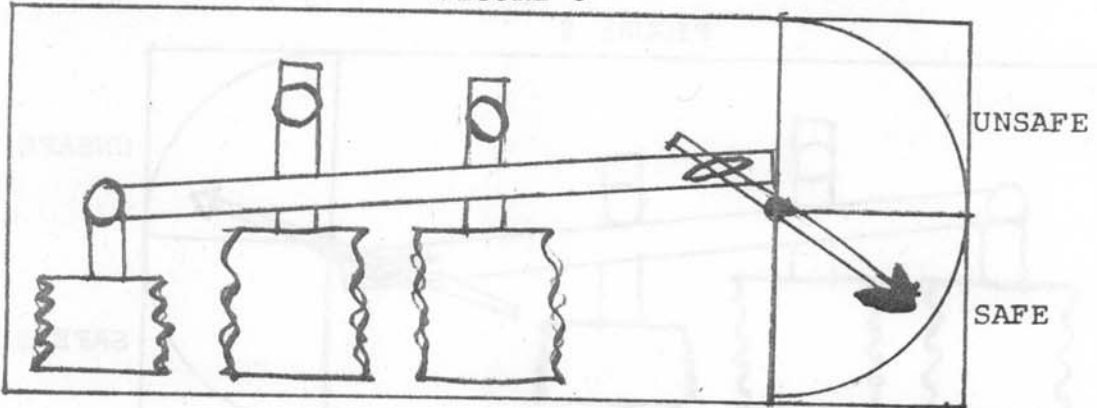


FIGURE 4



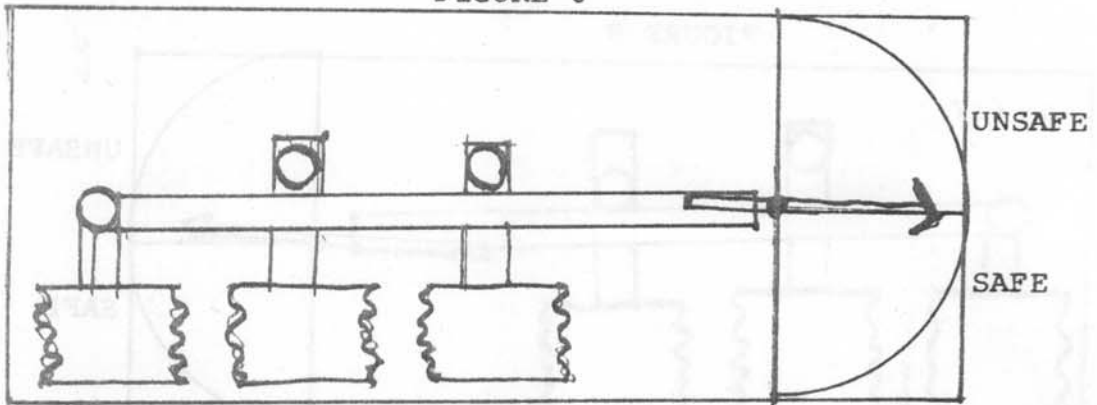
SURFACE (NORMAL)

FIGURE 5



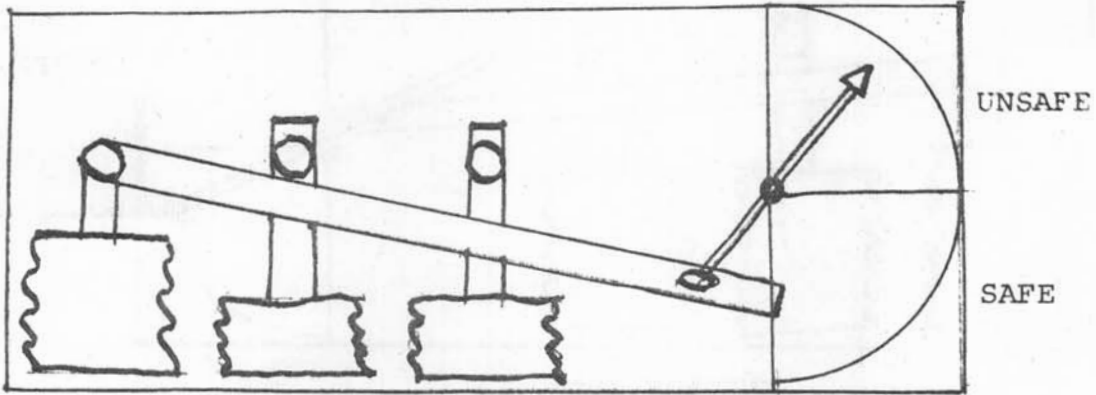
PRESSURIZED (200 FEET)

FIGURE 6



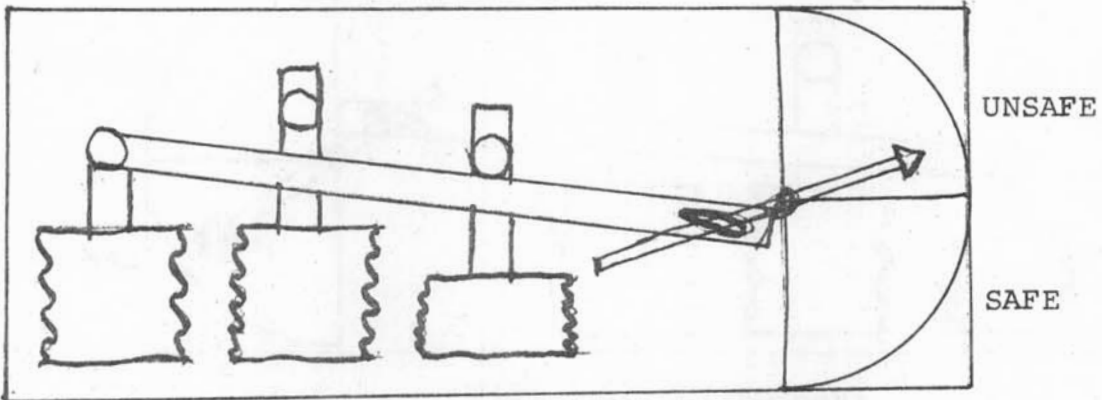
SATURATED (200 FEET)

FIGURE 7



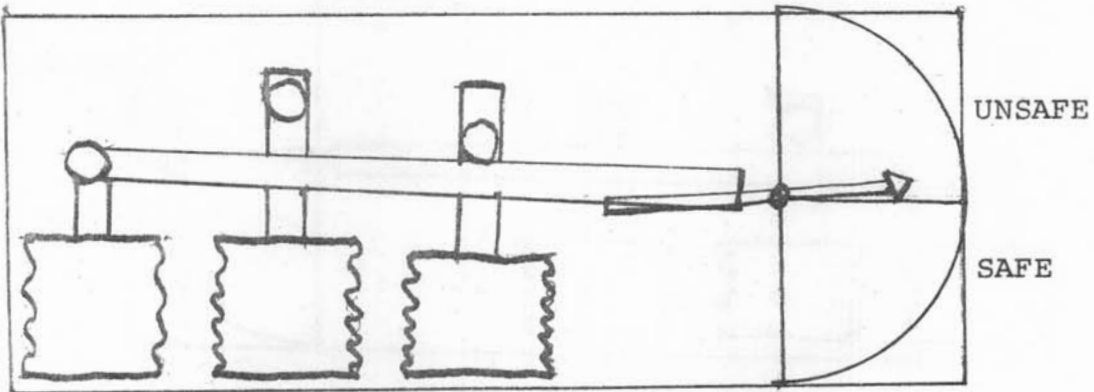
PROCESS OF DECOMPRESSION

FIGURE 8



PROCESS OF DECOMPRESSION

FIGURE 9



PROCESS OF DECOMPRESSION
(approaching end of stop)