NRL Report 4430

ATMOSPHERIC CONTROL ON TWO EXTENDED DIVES ON THE USS TROUT (SS566)

W. E. McConnaughey and W. N. Crofford
Physical and Inorganic Branch

F. S. Thomas and A. J. Andreatch
Electrochemistry Branch

Chemistry Division

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NAVAL RESEARCH LABORATORY
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ABSTRACT

During two dives which lasted 39-1/2 and 82-1/2 hours in deep, moderately warm waters, pelletized lithium hydroxide (LiOH) and 8-16 mesh soda-lime were used in a hopper system to maintain the atmospheric CO_2 concentration at 1.5% on the USS TROUT (SS566), a Fast-Attack-Type submarine. Results showed the system to be workable, and the amount of LiOH which can be carried readily (2000 lb) would be adequate for a total submerged time of at least 10 days, the period becoming longer as the dives become shorter. Battery exhaustion terminated both dives of this cruise after two performance records had apparently been set. Soda-lime was found to offer advantages over LiOH in operating convenience and in being much less expensive, but it required 25% more volume and 140% more weight for stowage.

In addition to studying hopper operating variables the concentrations of O_2, CO, CO_2, H_2, and hydrocarbons were measured throughout both dives. The CO concentration reached 150 parts per million on the first dive; however, on the second dive, probably because of limited smoking and use of the hydrogen eliminator, it reached only 75 parts per million. The O_2 was consumed and CO_2 was evolved at about 0.82 and 0.70 cu ft (STP) per man-hour respectively. Leaks from the air banks were found to be a major source of O_2 only when the boat pressure was allowed to rise steadily.

Stibine (SbH_3) concentrations were essentially zero at the start and finish of the second dive but averaged 0.63 part per million in the engine room over a 1-3/4 hour period of charging batteries at the finishing rate.

Freon 12 (dichlorodifluoromethane) was found in the ship's atmosphere during both dives at a concentration of approximately 2000 parts per million each.

PROBLEM STATUS

This is a final report on this phase of the problem; work is continuing on the project.

AUTHORIZATION

NRL Problem No. C08-05
Project NR 608-050
Bureau SW 01401

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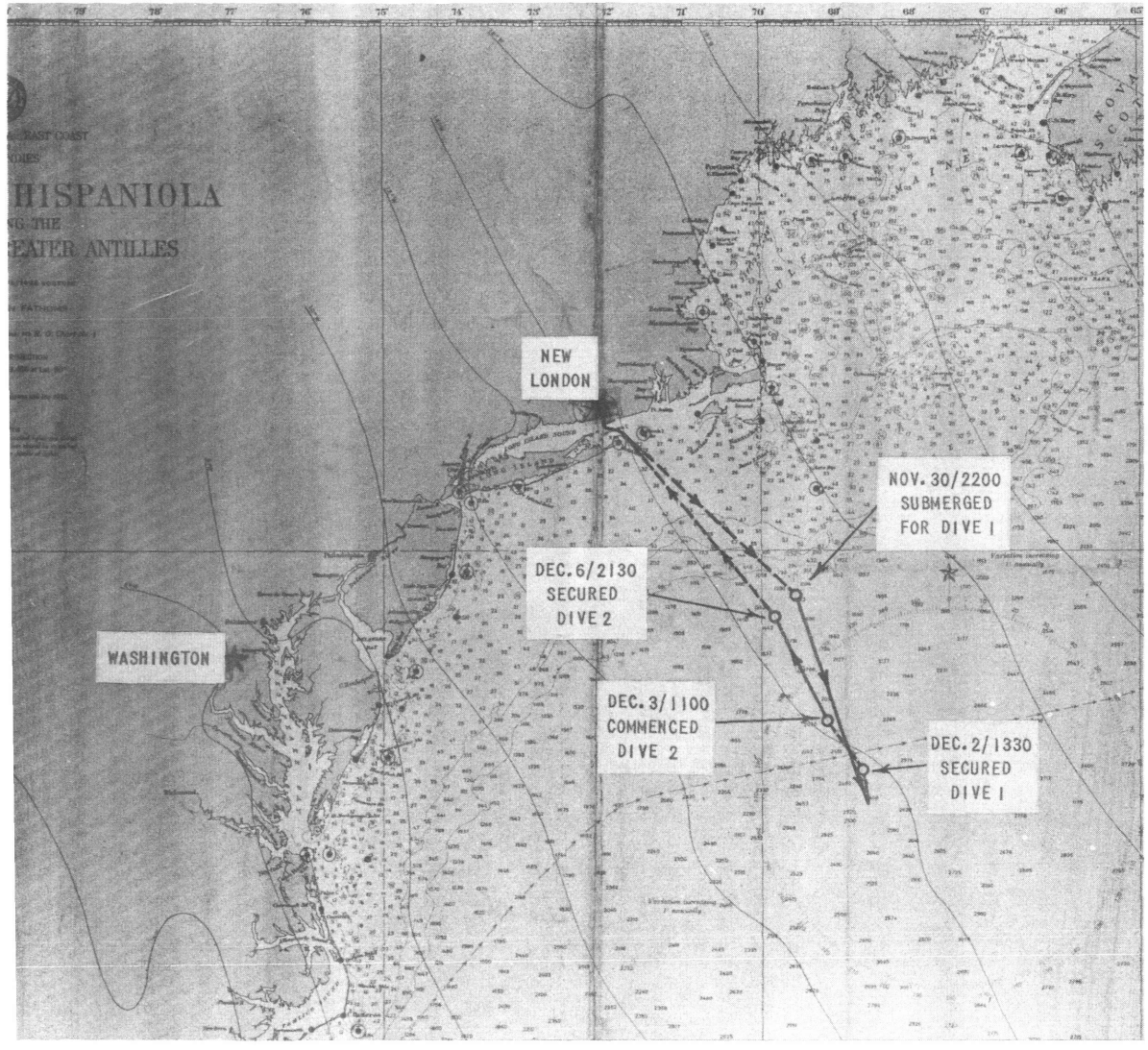

Fig. 1 - Chart of course

ATMOSPHERIC CONTROL ON TWO EXTENDED DIVES
ON THE USS TROUT (SS566)

INTRODUCTION

The Fast-Attack-Type submarines (563 Class) were designed to be able to remain submerged a total of about 10 days based on the amount of breathing oxygen carried in outboard high pressure banks. Since it is necessary to control the CO_2 concentration during this period a cruise was made at the request of the Bureau of Ships (Code 549) to evaluate jointly the submergence capabilities of this class submarine and to evaluate a hopper system of CO_2 removal using pelletized lithium hydroxide (LiOH) and 8-16 mesh high-moisture soda-lime. The USS TROUT (SS566) under the command of LCdr T. Turner, USN, was assigned to this cruise and the Naval Research Laboratory handled the technical details for BuShips.

Several preliminary meetings in Washington and New London (1) resulted in an operational schedule calling for a cruise from New London in a southeasterly direction into relatively warm water. Two extended dives (Fig. 1) were to be made to the limit of battery capacity with the operational objective of the first being to cover the maximum distance and of the second to remain submerged but off the bottom for as long as possible. Appendix A lists the auxiliary load and Appendix B indicates the battery performance during both dives.

A proposed agenda for hopper operation and instrumentation (2) was submitted to the Bureau of Ships and was incorporated in an official cruise agenda. This agenda was modified during the cruise as was felt desirable.

The cruise ended with the first dive (3) lasting 39-1/2 hours and covering 177 miles and the second dive lasting 82-1/2 hours. These are believed to be records for distance traveled while submerged and total time continuously submerged. Sea water temperatures varied between 62° and 75°F during the first dive and between 58° and 66°F during the second dive.

The personnel on board for the cruise totaled 75 including seven not regularly assigned to the ship. These seven were:

NAME	ORGANIZATION	DUTIES
Cdr Joseph Vogel, MC, USN	Staff, Cdr Sub. Squad. 10	Observer to assure safety of personnel
A. S. Gates, Jr.	Code 549, BuShips	Observers
J. M. Davidson	Code 588, BuShips	

F. S. Thomas	Code 6160, NRL	Instrument maintenance and calibration
A. J. Andreatch	Code 6160, NRL	
W. N. Crofford	Code 6130, NRL	Air purification
W. E. McConnaughey*	Code 6130, NRL	

Routine activities which were compatible with normal watch standing or which would be required to operate the hoppers and supply oxygen during any extended dive were conducted by the ship's personnel during both dives. Civilian activities included the establishment of hopper operating schedules, instrument calibration and maintenance, absorbent mixing and sampling, and the carrying out of several nonroutine tests and determinations.

APPARATUS AND INSTRUMENTATION

Hoppers

The four hoppers (Fig. 2) are based on a unit developed at NRL (4) and were built under BuShips contract according to Specification Mil -F-17150(Ships) dated 30 April 1952. These units hold 3/4 cu ft of granular absorbent material and have a self-contained fan and motor to draw air through the absorbent bed. Fresh absorbent is poured in through a filling chute (A) at the top and after use is emptied through a door (B) in the bottom. A filter (C) is provided on the air outlet to catch absorbent fines during the filling operation but a by-pass (D) is provided for normal running. Thermometers are provided to measure inlet and outlet air temperatures. The fan is powered by a 1/3-hp 115-volt ac motor which draws about 175 watts in operation.

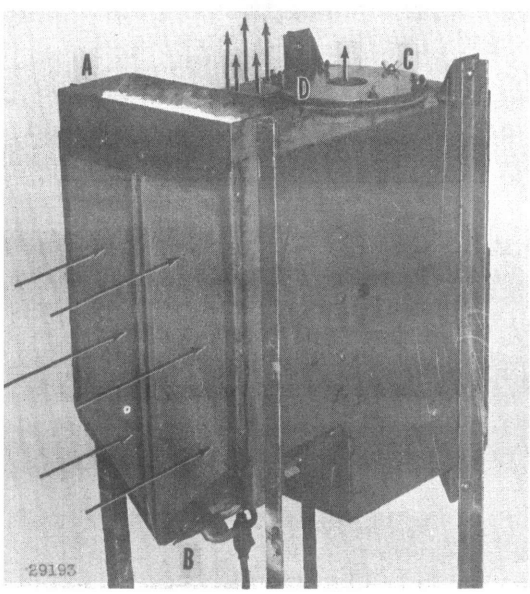

Fig. 2 - Hopper

*Principal author of this report

Absorbents

LiOH -- The lithium hydroxide used was made for the Bureau of Ships under contract with the Maywood Chemical Company, Maywood, New Jersey. This material is a pelletized form (4-14 mesh, U. S.) of the powdered material currently carried for emergency use on submarines. It conforms to military specification Mil-L-20213A(Ships) dated 17 April 1952 as amended by speedletter NObs-61655(549A), ser 549-8345 dated 20 October 1953, and speedletter NObs-61655(549A), ser 549-9557 dated 17 December 1953. The material was packed in cans containing an average of 7.5 lb of LiOH. A total of 2000 lb of LiOH was carried on the cruise and 454 lb were used.

The reaction between LiOH and CO_2 is as follows:

$$2\ LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O\ .$$

From this it can be calculated that 0.41 pound of water is produced for every pound of CO_2 absorbed with less than 0.5% water being present in the original material.

Soda-lime -- The soda-lime used was Wilson Soda-Lime, 8-16 mesh (U.S.), high moisture, indicator-type sold in 5-gallon buckets as "Sodasorb" by the Dewy and Almy Chemical Company, Cambridge, Massachusetts. This material consists of 1 part sodium hydroxide to 21 parts calcium hydroxide and has a water content of 14 to 19%. The reactions with CO_2 are as follows:

$$2\ NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O.$$

As with LiOH, 0.41 pound of water is produced per pound of CO_2 absorbed. Work at NRL (5,6) has shown the 8-16 mesh material to have a much higher absorption rate in hoppers than 4-8 mesh. The total 1252 lb of soda-lime carried on the cruise was completely expended.

Instruments

Physiological and absorptive effects are related to partial pressures of gases and not to their percentage concentrations at boat pressures other than one atmosphere (29.9 in. Hg). Thus gas concentrations in this report are given in terms of partial pressure or percent effective except for hydrogen where true percentage concentration is the factor involved in flammable limits. The term "percent effective" is sometimes used in deep sea diving work and is the true percent concentration at any pressure corrected to one atmosphere. On this cruise the Dwyer CO_2 Analyzers were the only gas analysis instruments other than the hydrogen analyzers that read true percentages so only their readings needed pressure corrections. For example, if a Dwyer reading of 1.5% was obtained at a boat pressure of 36.0 in. Hg the effective concentration is

$$\frac{36.0}{29.9} \times 1.5 = 1.8\%\ \text{effective}.$$

The gas analyses and pressure measurements made in each compartment during both dives are indicated in Fig. 3.

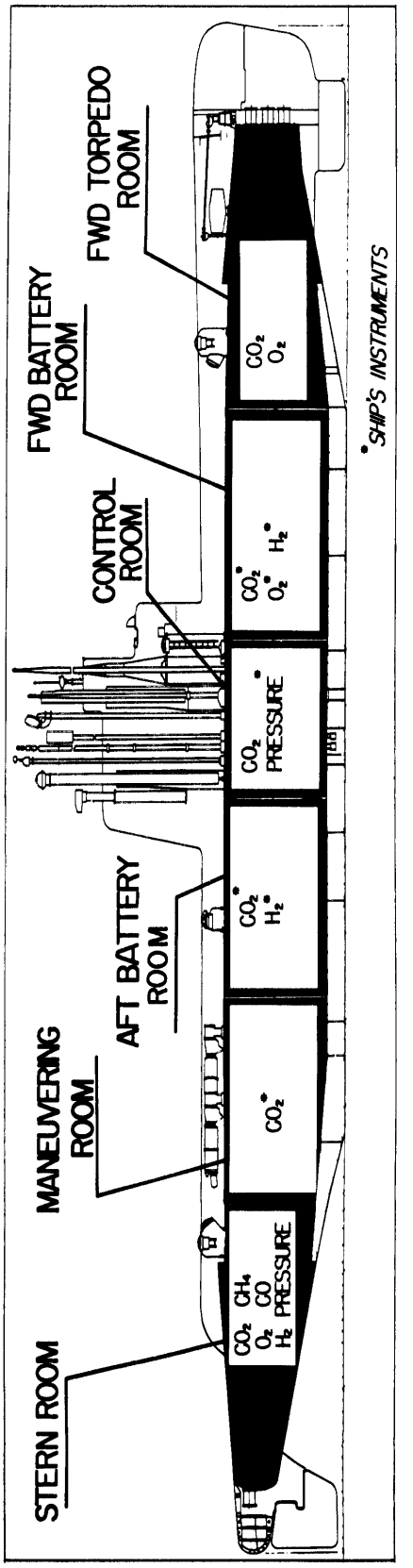

Fig. 3 - Locations of instruments used to make gas measurements during both dives

CO_2 Analyzers — The instruments used in the forward torpedo room and the control room were the infrared absorption type developed for use on the troop carrying submarines PERCH and SEA LION (ASSP313 and ASSP315). They are continuously indicating instruments made by the Liston-Becker Instrument Company, Stamford, Connecticut as model No. 23.

The instruments used in the forward and after battery rooms and the maneuvering room are regular submarine issue reading from 0 to 5% true. They are manufactured by the F. W. Dwyer Manufacturing Company, Chicago, Illinois stock no. 57-1-432; order no. N140s-70841A. The operating principle is one of volumetric change similar to the Orsat analyzer and analyses are batchwise.

O_2 Analyzer — The instruments used in the forward torpedo room and the forward battery room are standard Navy issue, the latter instrument belonging to the ship. They are made by Arnold O. Beckman, Pasadena, California and may be identified as model N-1 (contract NObs 23193). The principle of operation is one of paramagnetism and the instruments are continuously indicating.

NRL Composite Gas Analyzer — Concentrations of CO_2, oxygen, hydrogen, carbon monoxide, and mathane as well as boat pressure were measured in the stern room by Model 1 Serial 1 of the NRL Composite Gas Analyzer, which was developed by NRL for use on the USS NAUTILUS (SSN571). The principles of operation are infrared absorption for CO, CO_2, and methane measurements, thermal conductivity for hydrogen, and paramagnetism for oxygen. Pressure measurements are based on the aneroid principle but for this cruise had a maximum reading of 32 in. Hg. All gas and pressure measurements are automatically recorded on a Brown recording potentiometer in addition to being continuously indicated on panel meters.

Hydrogen Eliminator — This unit is standard Navy issue and was ac powered. The operating principle is one of catalytically oxidizing hydrogen to water.

DETERMINATION OF SHIP'S FLOODABLE VOLUME

Calculations on CO_2 evolution and O_2 consumption require that the volume of air in the boat (floodable volume) be known. Although a figure of 35,850 cu ft is available from the ship's moment diagram its accuracy is open to question for the conditions of these tests. With the ship alongside the tender after returning to New London but still in approximately the same condition as in both dives an attempt was made to measure this volume. A water manometer was connected between the inside of the boat and the open atmosphere by means of a drain connection from the torpedo room escape trunk. The outer hatch was left open; on closing the inner hatch and sealing the boat, the steady pressure rise due to leaks was measured by means of the manometer exactly 5 minutes. Then the boat pressure was equalized with atmospheric pressure by opening the inner hatch. After again sealing the boat, two weighed 200 cu ft cylinders of nitrogen were released into the inside atmosphere and manometer readings were taken after 3, 4, and 5 minutes. The following data was obtained:

Initial combined weight of N_2 cylinders = 288-1/2 lb

Final combined weight of N_2 cylinders = 261-3/4 lb

Pressure rise due to leaks in 5 minutes = 8 mm H_2O

Pressure rise after 3 minutes of N_2 release period = 104 mm H_2O

Pressure rise after 4 minutes of N_2 release period = 106 mm H_2O

Pressure rise after 5 minutes of N_2 release period = 108 mm H_2O.

With the above data and by assuming the Gas Law and Dalton's Law to hold and the system to be isothermal, the volume of the boat can be calculated as follows:

$$V_2 = \frac{\text{atmospheric pressure} \times \text{vol. of } N_2 \text{ released at 760 mm Hg and } 70^0\text{F}}{\text{boat pressure produced by released } N_2}$$

$$= \frac{760 \times 369}{7.28} = 38{,}500 \text{ cu ft of floodable volume.}$$

The pressure correction due to leaks was obtained by averaging the result of the first 5-minute period with that resulting from an extrapolation of the straight portion of the pressure curve for the second 5-minute period.

Another basis for calculating this volume is the change in average CO_2 concentration produced at the beginning of the second dive (from 1200 to 1415 on 12/3) by releasing CO_2 from a cylinder. In this case 42 lb of CO_2 were released in 2-1/4 hr, and combined with the evolved respiratory CO_2 produced a change in effective concentration of 1.2%. This permits the following calculation:

Total CO_2 released = CO_2 from cylinder + CO_2 from respiration

$$= \frac{42 + 2.25 \times 0.085 \times 75}{0.1147} = \frac{42 + 14}{0.1147} = 490 \text{ cu ft}$$

$$\text{boat volume} = \frac{490}{0.012} = 41{,}000 \text{ cu ft.}$$

CARBON DIOXIDE REMOVAL

Hoppers were used during both dives to control the CO_2 concentration and the rate of clearing the boat was determined after surfacing (Table 1).

Hopper Operation

General — Hoppers were operated to maintain the average effective CO_2 concentration at about 1.5% during both dives except near the end of the second dive when the object was to lower the concentration as rapidly as possible. Performance of the absorbents was determined by chemically analyzing representative samples (Appendix C) in addition to weighing the hopper contents before and after use on spring scales located by each hopper.

Operating Procedures — For the first dive (Fig. 4), after a normal CO_2 buildup period of about 10 hours, three hoppers were operated with soda-lime chargings staggered at intervals of about 6 hours between rechargings for each hopper (procedure A). The hoppers were spread over the ship with number 1 being in the forward torpedo room, number 2 in the control room, and number 3 in the stern room. For the second dive (Fig. 5) all

hoppers were operated in the torpedo room with numbers 1 and 2 being near the torpedo tubes, number 3 by the crew's washstand, and number 4 in the crew's shower with the door open and a bracket fan providing ventilation. The initial delay required for the CO_2 concentration to reach 1.5% was reduced to 3-1/4 hours by releasing CO_2 from a cylinder.

During the second dive (from 1415 on 12/3 to 1120 on 12/4) two hoppers were recharged alternately with LiOH at intervals of about 5 hours for each hopper (procedure B). From 1120 on 12/4 to 1200 on 12/5 four hoppers were recharged alternately in pairs with soda-lime at intervals of about 8 hours for each pair (procedure C). All hopper fans were off for 45 minutes of this period (1900 to 1945 on 12/4) due to a power failure. From 1200 to 2400 on 12/5 two hoppers were recharged alternately with soda-lime at intervals of 4 hours for each hopper (procedure D). From 2400 on 12/5 to 1000 on 12/6 three hoppers were recharged in sequence with LiOH at intervals of 9 hours for each hopper (procedure E). However, only one hopper, number 1, operated for the full period. From 0900 to 1530 on 12/6 three hoppers were recharged in sequence with LiOH at intervals of about 1-1/2 hours for each hopper (procedure F). There was some overlap initially with the previous procedure.

TABLE 1
Summary of CO_2 Removal Procedure

Dive	Time Submerged (hr)	Procedure
1	0 - 10	Allow CO_2 concentration to build up at normal rate to 1.5%
	10 - 39.5	Operate 3 hoppers with soda-lime at 1.5% CO_2. Spread 1 can (about 7.5 lb) of LiOH for 3 hours. Determine how rapidly boat can be cleared after surfacing.
2	0 - 3	Release bottled CO_2 to accelerate build-up of CO_2
	3 - 24	Operate 2 hoppers with LiOH at 1.5% CO_2
	24 - 49	Operate 4 hoppers with soda-lime at 1.5% CO_2
	49 - 61	Operate 2 hoppers with soda-lime at 1.5% CO_2. Spread 1 can (about 7.5 lb) of LiOH for 4 hours.
	61 - 70	Operate 3 hoppers with LiOH at 1.5% CO_2
	70 - 77	Operate 3 hoppers with LiOH to reduce CO_2 concentration
	77 - 82.5	Stand by for surfacing. Determine how rapidly boat can be cleared after surfacing.

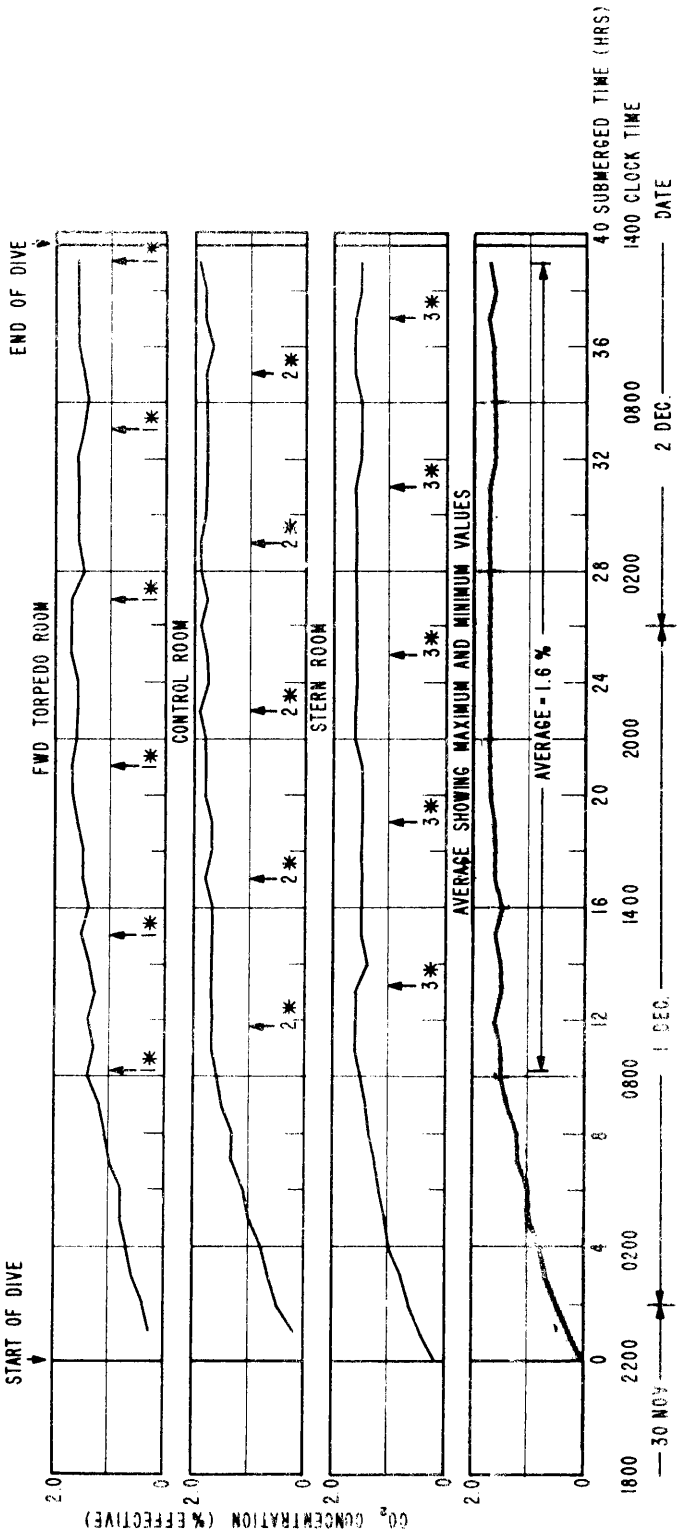

Fig. 4 - CO_2 concentrations and hopper operation on first dive

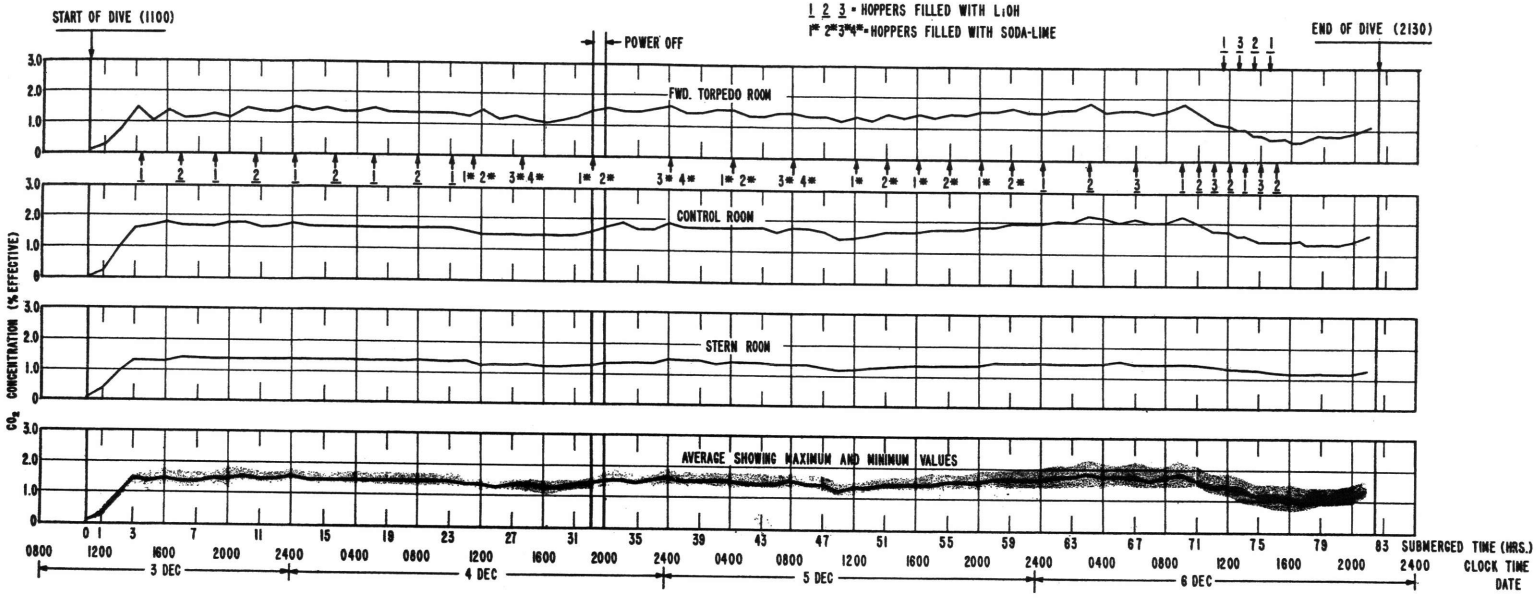

Fig. 5 - CO_2 concentrations and hopper operation on second dive

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The absorbent performances as determined from subsequent chemical analyses are given in Table 2. The saturations are based on the theoretical capacity of 0.92 pound of CO_2 per pound of LiOH and the experimentally determined value of 0.38 pound of CO_2 per pound of soda-lime. The values in excess of 100% for soda-lime are not significant except as an indication of the over-all accuracy of the data. Figure 6, based on Table 2, shows the relation between exposure time and saturation for soda-lime and LiOH in hoppers operating in an atmosphere containing between 1.1 and 1.9% CO_2 effective. Table 3, also based on Table 2, gives the results in terms of pounds and cubic feet of absorbent required per man-hour protection at approximately 1.5% CO_2 effective. The man-hour equivalent of CO_2 involved in this method of calculation is discussed on page 17.

While operating under the final procedure where the object was to reduce the effective CO_2 concentration as rapidly as possible, 216 lb of LiOH were used to lower the average concentration in the boat from 1.9 to 0.7%. This required 7 hours and the average saturation of the spent LiOH was 38%.

Only one hopper filter, which had been used during 12 fillings with soda-lime and five with LiOH, was changed during both dives. Although the replacement had lower flow resistance, no significant operating advantage was noted. To investigate the feasibility of cleaning used filters, the used unit was returned to NRL and installed in a similar hopper filled with soda-lime. The flow and resistance data in Table 4 was obtained using various cleaning techniques; in all cases the by-pass was closed.

Spread LiOH

During each dive one can (approximately 7.5 lb)of LiOH was spread on a bunk in the torpedo room. The method of spreading was to put a sheet directly on the springs of a bunk and carefully pour the LiOH to a uniform depth of about 1/2 inch. The material was located on the lower, aft, portside bunk and no special ventilation was used. The exposure time was 3 hours (from 0955 to 1300 on 12/2) on the first dive and 4 hours (from 1335 to 1735 on 12/5) on the second dive but, as shown in Table 2, the saturations obtained were essentially the same, 22 and 23%. The small amount of CO_2 removed by the spread material had no effect on hopper operation.

Clearing the Boat on Surfacing

To determine the rate at which CO_2 could be cleared from the ship's atmosphere after switching to outboard ventilation, readings of effective CO_2 concentration were made in the torpedo room and control room at short intervals during and after surfacing from both dives using infrared analyzers. These data plus that automatically recorded in the stern room permit determination of the time required to clear the boat under two different ventilation conditions. Air intake (Fig. 7) after surfacing from the first dive was through the snorkel head valve and after the second dive it was through the bridge access trunk. Figures 8 and 9 show the CO_2 concentrations at various intervals after the first and second dives respectively. Figures 10 and 11 show the concentrations of O_2,H_2, and CO, as well as CO_2 during these periods.

TABLE 2
Absorbent Performance

Procedure	Absorbent	Length of Exposure (hr)	Initial Weight (lb)	Final Weight (lb)	CO_2 Takeup (lb CO_2 per lb Absorbent)	Total CO_2 Absorbed (lb)	Absorbent Saturation (%)	Batch No.	Dive No.	Hopper No.	Time	Date
A	Soda-lime	4.8	37	39.5	0.306	11.3	81		1	1	0810	12/1
		5.2	37	38	0.286	10.6	75		1	2	0950	12/1
		5.8	38	40	0.321	12.2	84		1	3	1112	12/1
		6.0	34	37	0.337	11.5	89		1	1	1300	12/1
		6.0	36	38	0.298	10.7	78		1	2	1500	12/1
		6.0	37.5	39	0.319	12.0	84		1	3	1700	12/1
		6.0	36	39	0.369	13.3	97		1	1	1900	12/1
		6.0	36	39	0.311	11.2	82		1	2	2100	12/1
		6.0	37	40	0.310	11.5	82		1	3	2300	12/1
		6.0	35	39	0.356	12.5	94		1	1	0100	12/2
		6.0	38	41	0.314	11.9	83		1	2	0300	12/2
		6.0	38.5	40	0.311	12.0	82		1	3	0500	12/2
		6.0	34	38	0.332	11.3	87		1	1	0700	12/2
		4.5	37	39	0.295	10.9	78		1	2	0900	12/2
		2.0	38	38	0.238	9.0	63		1	3	1100	12/2
		0.5	36	-	-	-	-		1	1	1300	12/2
	LiOH (spread)	3.0	1 can (≈7.5)		0.199	≈1.5	22				0955	12/2
B	LiOH	4.8	19.5	29.5	0.753	14.7	82	1	2	1	1415	12/3
		4.8	20	31	0.690	13.8	75	1	2	2	1645	12/3
		5.0	19.5?	30	0.744	14.6	81	2	2	1	1900	12/3
		4.8	20	31	0.794	15.9	86	1	2	2	2145	12/3
		4.8	20	30	0.750	15.0	82		2	1	2400	12/3
		5.0	20	30	0.744	14.9	81	2	2	2	0230	12/4
		5.0	20	30	0.768	15.4	83		2	1	0500	12/4
		3.2	20	30	0.729	14.6	79	1	2	2	0745	12/4
		1.3	19	24	0.398	7.6	43	1	2	1	1000	12/4
C	Soda-lime	7.7	36	40	0.372	13.4	98		2	1	1120	12/4
		7.7	37	42	0.372	13.8	98		2	2	1120	12/4
		8.8*	38	41	0.348	13.2	92		2	3	1425	12/4
		8.8*	38	41	0.342	13.0	90		2	4	1425	12/4
		8.2*	35.5	39.5	0.379	13.5	100		2	1	1900	12/4
		8.2*	37	41	0.391	13.7	98		2	2	1900	12/4
		8.0	38	41	0.354	13.5	93		2	3	2400	12/4
		8.0	38	41	0.342	13.0	90		2	4	2400	12/4
		8.0	35.5	40	0.383	13.6	101		2	1	0400	12/5
		8.0	36.5	41.5	0.387	14.1	102		2	2	0400	12/5
		4.0	38	40	0.293	11.1	77		2	3	0800	12/5
		4.0	37.5	39	0.231	8.7	61		2	4	0800	12/5
D	Soda-lime	4.0	36	36	0.267	9.6	70		2	1	1200	12/5
		4.0	39.5	41	0.296	11.7	78		2	2	1400	12/5
		4.0	35.5	39	0.307	10.9	81		2	1	1600	12/5
		4.0	38	39	0.319	12.1	84		2	2	1800	12/5
		4.0	36	39	0.302	10.9	80		2	1	2000	12/5
		2.0	37	40	0.210	7.8	55		2	2	2200	12/5
	LiOH (spread)	4.0	1 can ≈7.5		0.211	≈1.6	23		2	-	1335	12/5
E	LiOH	9.0	19	31	0.892	16.9	97	1	2	1†	2400	12/5
		7.0	21	33	0.817	17.2	89	1	2	2	0300	12/6
		5.0	20	32	0.818	16.4	89	2	2	3	0600	12/6
F	LiOH	2.5	19	27	0.543	10.3	59	2	2	1	0900	12/6
		2.0	20	27	0.452	9.0	49	2	2	2	1000	12/6
		1.5	20	26	0.369	7.4	40	1	2	3	1100	12/6
		1.5	18.5	24	0.345	6.4	38	2	2	1	1130	12/6
		1.5	20	23.5	0.220	4.4	24	2	2	2	1200	12/6
		1.5	21	26	0.294	6.2	32	2	2	3	1230	12/6
		1.5	17	20.5	0.295	5.0	32	2	2	1	1300	12/6
		1.5	19	23	0.297	5.6	32		2	2	1330	12/6
		6.0	21.5	32	0.686	14.7	75	1	2	3	1400	12/6
		5.5	19	28	0.664	12.6	72	1	2	1	1430	12/6
		5.0	21	30	0.582	12.2	63	2	2	2	1500	12/6

*Exclusive of 45 minutes when power was off.
†New filter installed.

TABLE 3
Man-Hour Requirements for Soda-Lime and LiOH

Procedure	Dive	Absorbent	Hopper No.	No. of Completely Exposed Charges	Total Weight Absorbent Used (lb)	Total Exposure Time (hr)	CO_2 Absorbed		Average CO_2 Concentration** (% effective)	Absorbent Use Factors	
							(lb)	man-hr Equivalent*		Weight† (lb/man-hr)	Volume†‡ (cu ft/man-hr)
A	1	soda-lime	1	4	139	24	48.6	580	1.6	0.240	0.0052
			2	3	110	18	33.8	402	1.6	0.274	0.0056
			3	4	151	23.8	47.7	570	1.6	0.265	0.0053
										0.26 avg	0.0054 avg
B	2	LiOH	1	4	79	19.5	59.6	702	1.4	0.113	0.0043
			2	3	60	14.5	44.6	526	1.4	0.114	0.0043
										0.11 avg	0.0043 avg
C	2	soda-lime	1, 2	3	217.5	24.7	82.1	967	1.4	0.225	0.0046
			3, 4	2	152	17.5	52.7	620	1.4	0.245	0.0048
										0.24 avg	0.0047 avg
D	2	soda-lime	1	3	107.5	12	31.4	370	1.5	0.290	0.0061
			2	2	77.5	8	23.8	280	1.5	0.277	0.0054
										0.28 avg	0.0058 avg
E	2	LiOH	1	1	19	9	16.9	199	1.7	0.10	0.0038

*Based on 0.084 and 0.085 pound of CO_2 per man-hour for the first and second dives, respectively.

**Based on entire boat for first dive and on torpedo room only for second dive.

†Calculated on the basis of hopper charges receiving complete exposure.

‡Calculated on the basis of hoppers holding 0.75 cu ft of absorbent.

TABLE 4
Hopper Filter Flow Resistances

Filter	Airflow Through Filter (cfm)	Pressure Drop Across Filter (in. H_2O)	Method of Cleaning
None	48	0.48	No filter
New	42	0.61	None
Used	20	1.37	None
Used	25	0.97	Knock on cement floor
Used	30	0.88	Air blast (100 psig)
Used	25	0.95	Soak in dilute acetic acid, rinse in water, dry with air blast, and dry overnight.

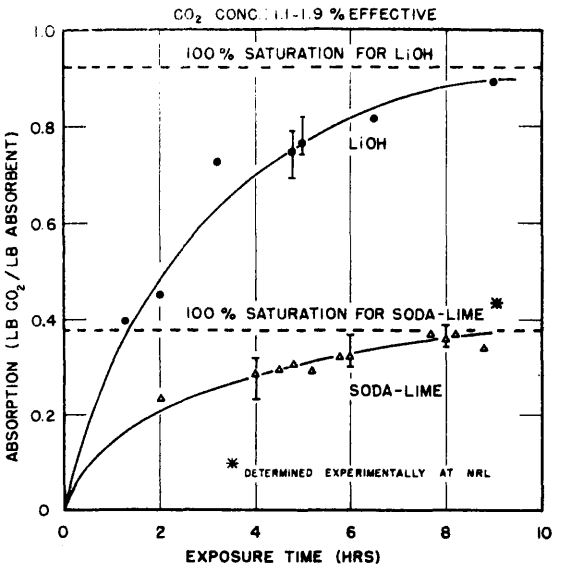

Fig. 6 - Effect of exposure time on saturation of soda-lime and LiOH in hoppers

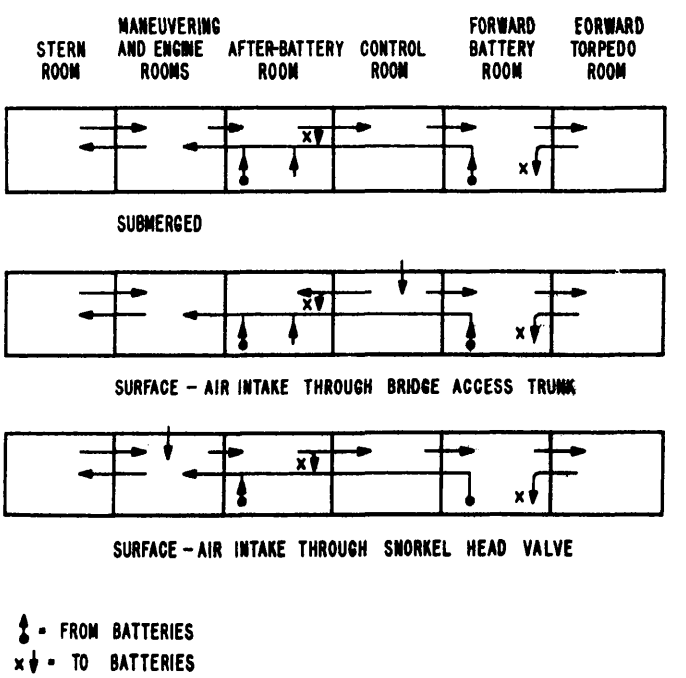

Fig. 7 - Diagram of ship's ventilation under various conditions

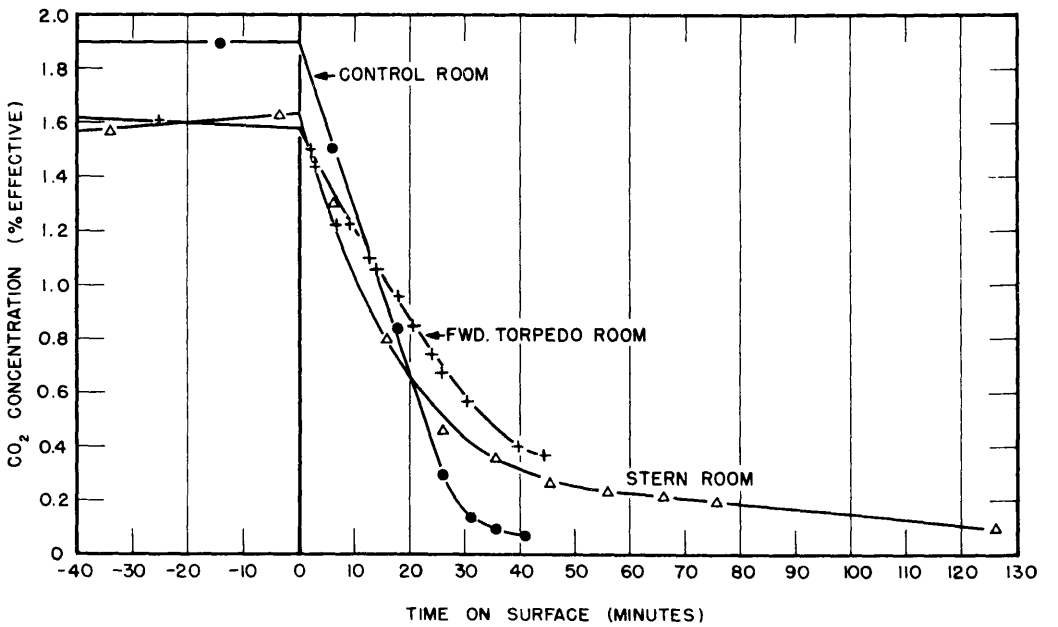

Fig. 8 - Rate of elimination of CO_2 after surfacing from first dive

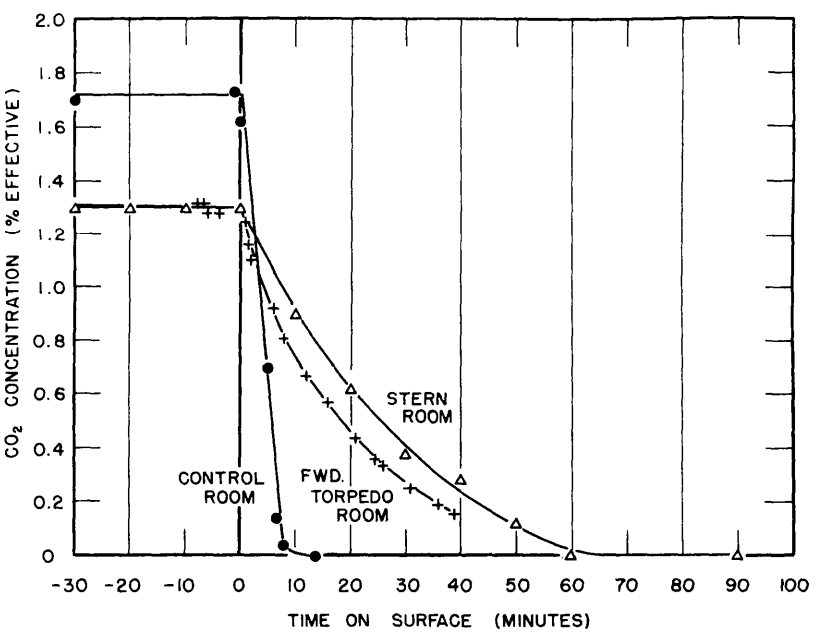

Fig. 9 - Rate of elimination of CO_2 after surfacing from second dive

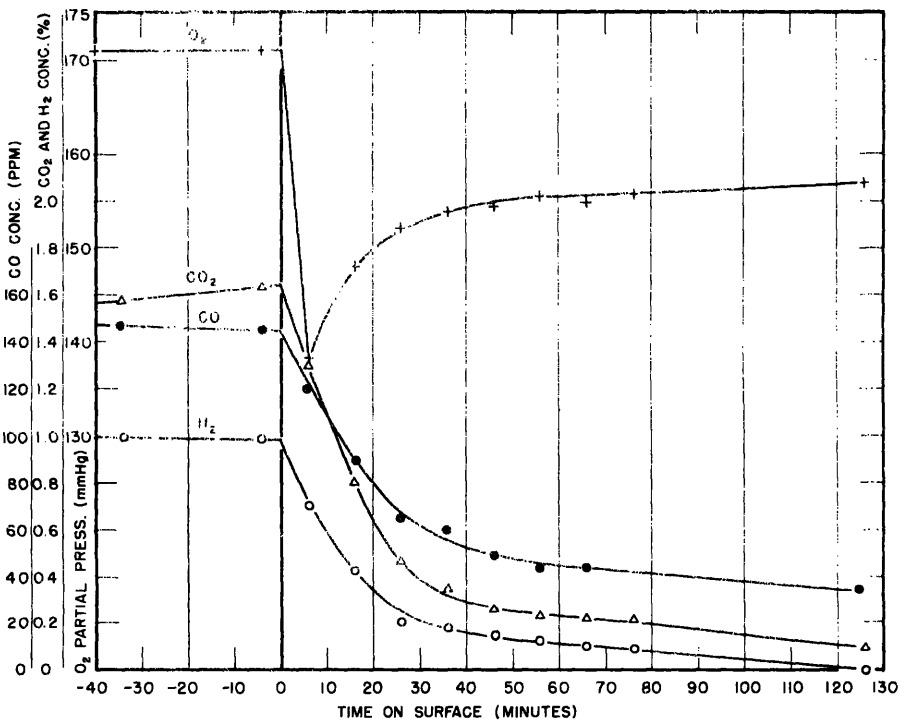

Fig. 10 - Effect of surfacing on stern room gas concentrations after first dive

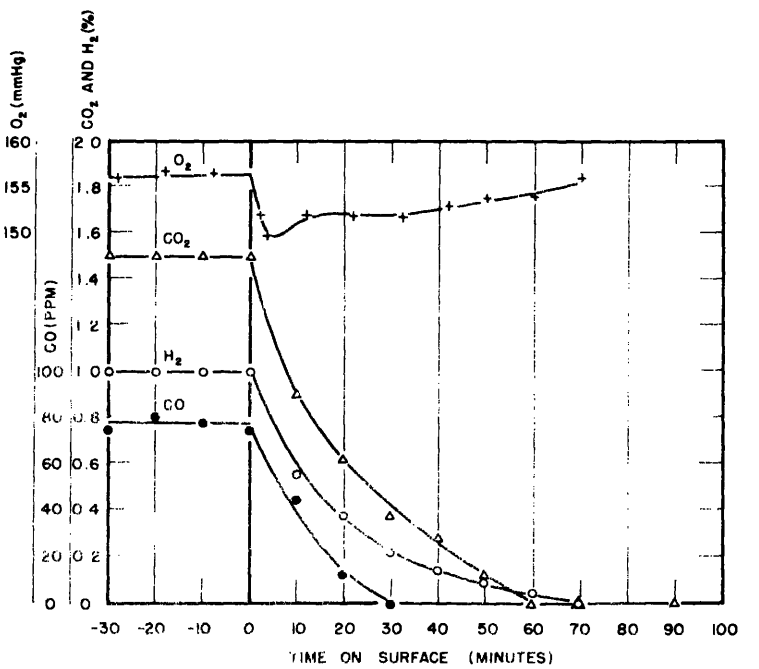

Fig. 11 - Effect of surfacing on stern room gas concentrations after second dive

CO_2 Evolution

The total amount of CO_2 produced during each dive is equal to the amount taken up by the absorbents plus the amount added to the atmosphere by respiration. The amounts absorbed during each dive are listed in Table 2 and the initial and final concentrations in the atmosphere can be obtained from Figs. 4 and 5. In the following calculations a floodable volume of 38,500 cu ft and a temperature of 70°F are used.

For the first dive the calculation is as follows:

$$\text{total } CO_2 \text{ evolved} = \text{total } CO_2 \text{ absorbed} + \Delta\ CO_2 \text{ conc.} \times \text{boat vol.} \times CO_2 \text{ density at } 70^\circ F$$

$$= 175 + (0.017-0.000) \times 38{,}500 \times 0.1147$$

$$= 175 + 75 = 250 \text{ lb}/39.5 \text{ hr}$$

$$CO_2 \text{ evolution rate} = \frac{\text{total CO}}{\text{no. of men} \times \text{time}} = \frac{250}{75 \times 39.5}$$

$$= 0.084 \text{ lb } CO_2/\text{man-hr } (0.68 \text{ cu ft (STP)/man-hr}).$$

For the second dive the calculation is as follows:

$$\text{total } CO_2 \text{ evolved} = \text{total } CO_2 \text{ absorbed} + \Delta CO_2 \text{ conc.} \times \text{boat vol.} \times CO_2 \text{ density at } 70^\circ F - CO_2 \text{ from cylinder} + CO_2 \text{ removed by pumpdowns}$$

$$= 488 + \left[(0.014-0.001) \times 38{,}500 \times 0.1147\right] - 42 + 21$$

$$= 488 + 57 - 42 + 21 = 524 \text{ lb}/82.5 \text{ hr}$$

$$CO_2 \text{ evolution rate} = \frac{524}{75 \times 82.5} = 0.085 \text{ lb } CO_2/\text{man-hr } (0.69 \text{ cu ft (STP)/man-hr}).$$

Another determination was made at the start of the first dive when the concentration was allowed to build up at a normal rate with no removal by absorption or pumpdowns. The calculation for this is as follows:

$$CO_2 \text{ evolution rate} = \frac{\Delta CO_2 \text{ conc.} \times \text{boat vol.} \times \text{density of } CO_2}{\text{no. of men} \times \text{time}}$$

$$= \frac{(0.015-0.000) \times 38{,}500 \times 0.1147}{75 \times 10}$$

$$= 0.088 \text{ lb } CO_2/\text{man-hr } (0.71 \text{ cu ft (STP)/man-hr}).$$

OXYGEN SUPPLY

Oxygen Concentrations

A plot of oxygen partial pressure throughout the first and second dives is shown in Figs. 12 and 13. Although this represents readings from only one instrument the average for the three instruments is not appreciably different (Appendix D). The intention in both

dives was to maintain the oxygen partial pressure around the normal atmospheric level of 160 mm Hg but this was complicated by air leakage and pumpdowns.

Oxygen Consumption

All oxygen bled into the ship's atmosphere from the outboard high pressure banks was metered through a dry-test gas meter under conditions of known pressure and temperature. A laboratory-type flowrator was connected in series with the gas meter to facilitate setting the bleed-in rate as determined by the average O_2 partial pressure. Hourly readings of the gas meter and the flowing gas temperature plus the barometric pressure permit calculation of the mass flow of oxygen throughout both dives. These data and calculations are summarized in Appendix E.

For the first dive oxygen consumption calculations are complicated by the normal leakage of high pressure air into the boat and the change in the average O_2 partial pressure existing at the end of the dive (Appendix D). By assuming the Gas Law and Dalton's Law to hold, the temperature and water vapor pressure to be constant (the former at 70°F), all leakage to be air containing 21% oxygen, and a negligible effect from the small pumpdown (at 0500 on 12/2) it is possible to calculate the oxygen consumption rate for the first dive as follows:

$$\text{total } O_2 \text{ consumed} = O_2 \text{ from leakage} + O_2 \text{ bled in} + \Delta O_2 \text{ content of atmosphere}$$

$$= 148 + 125 + \frac{(160-171)}{760} \times 38{,}500 \times 0.0829$$

$$= 148 + 125 - 46.1 = 227 \text{ lb/39 hr}$$

$$O_2 \text{ consumption rate} = \frac{227}{75 \times 39} = 0.078 \text{ lb } O_2\text{/man-hr (0.87 cu ft (STP)/man-hr)}.$$

For the second dive there are some additional complications in that O_2 is removed during pumpdowns and is consumed by the hydrogen eliminator. If the same assumptions are made as for the first dive except that pumpdown effects are not negligible but that leakage rate and gas concentrations (% true) are constant during pumpdowns, it is possible to calculate the O_2 consumption rate for the second dive as follows (refer to Fig. 13 and Appendixes D and E):

$$\text{total } O_2 \text{ consumed} = O_2 \text{ from leakage} + O_2 \text{ bled in} - \Delta O_2 \text{ content of atmosphere} - O_2 \text{ removed by pumpdowns} - O_2 \text{ used by the burner}$$

$$= 245 + 418 - 8.4 - 230 - 26.4 = 398 \text{ lb/82 hr}$$

$$O_2 \text{ consumption rate} = \frac{398}{75 \times 82} = 0.065 \text{ lb } O_2\text{/man-hr (0.73 cu ft (STP)/man-hr)}.$$

The after main oxygen bank having a nominal internal volume of 50 cu ft was used for both dives. A rough check on its volume was made using data from the first dive. Hourly bank pressure and sea water temperature readings (Appendix E) were taken and for the first dive the initial values were 2725 psig and 62°F. The final values were 2340 psig and 73°F at which time 1400 cu ft (STP) of oxygen (as measured with the gas meter) had been removed. From this information the bank volume can be calculated as 50.7 cu ft.

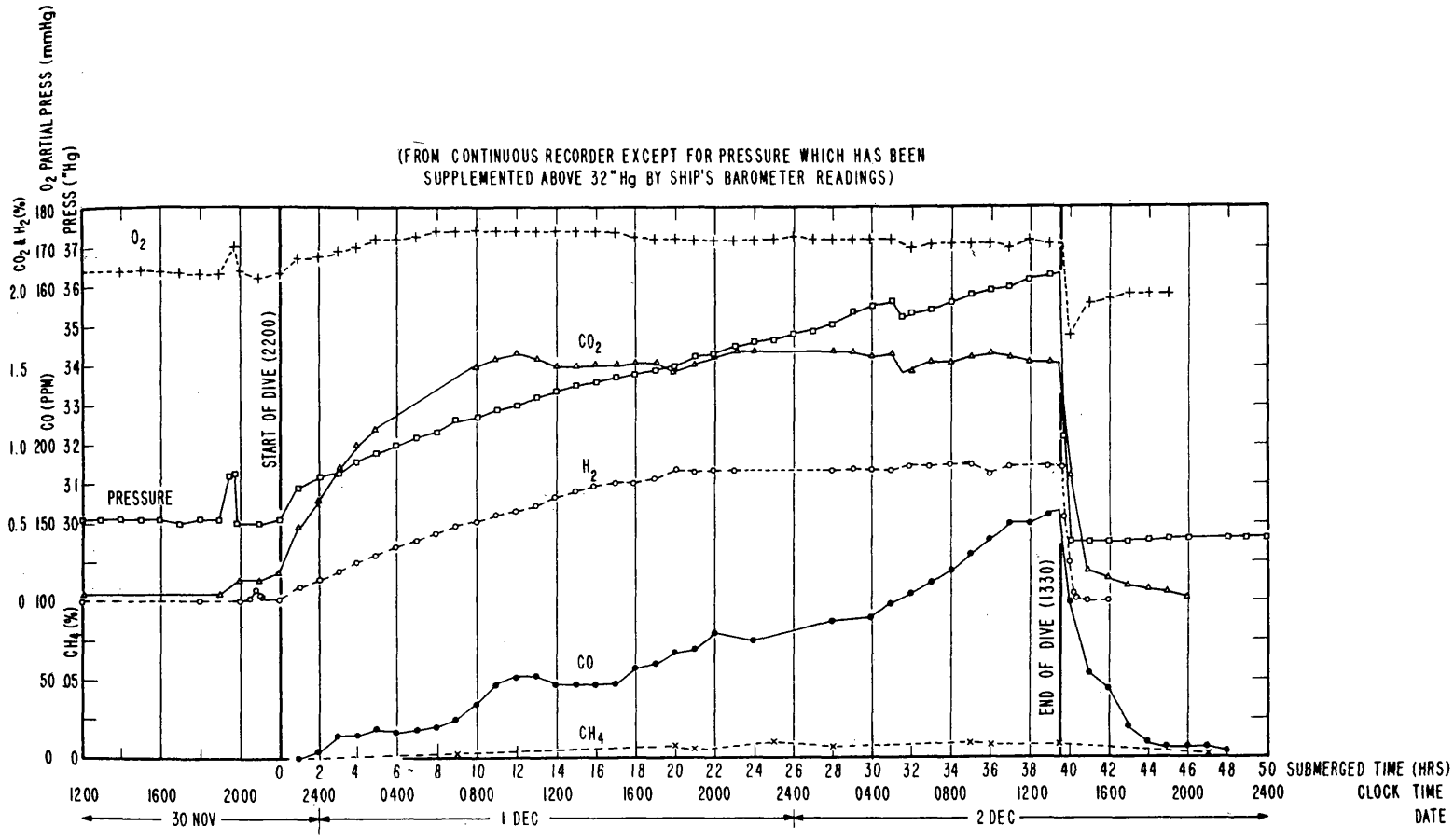

Fig. 12 - Stern room gas concentrations and pressure during first dive

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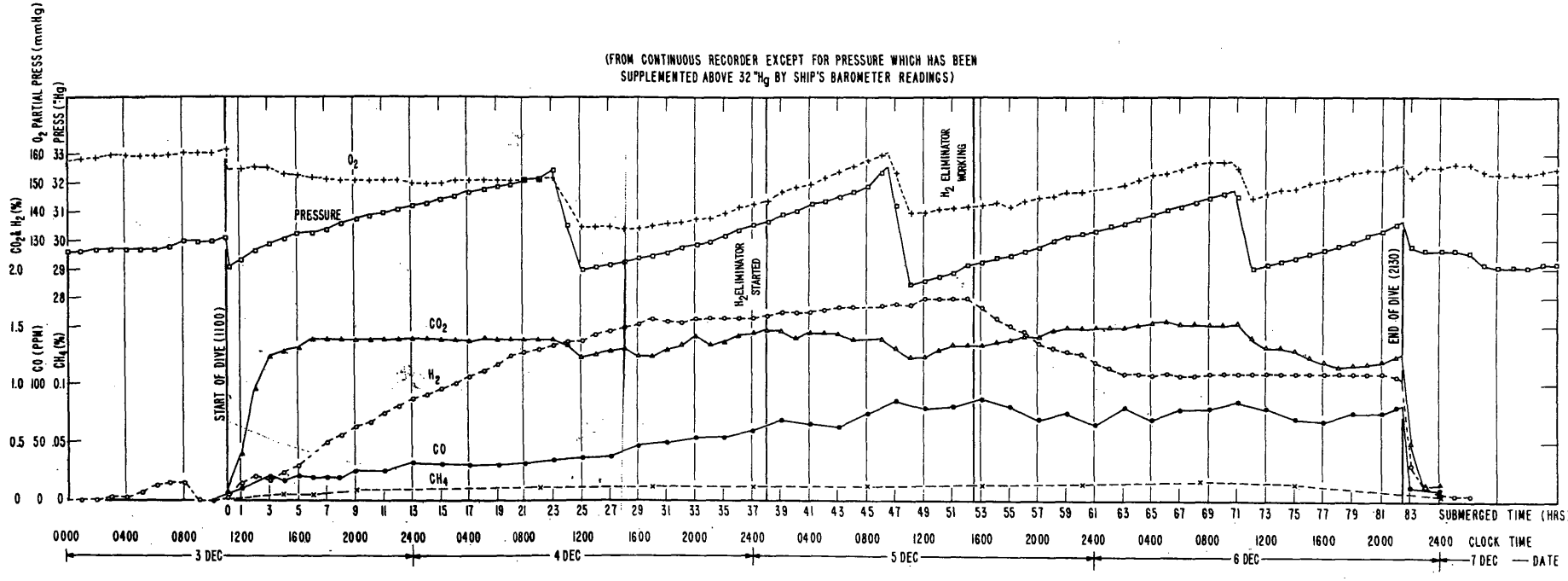

Fig. 13 - Stern room gas concentrations and pressure during second dive

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HYDROGEN EVOLUTION

The hydrogen concentration (Figs. 12 and 13) throughout the first and second dives was measured by the NRL Composite Gas Analyzer. There was a normal buildup of hydrogen during the first dive with the concentration at this battery discharge rate leveling off at about 0.9%. During the second dive there was a normal buildup until the hydrogen eliminator started operating at about 1500 on 12/5. The concentration had leveled off to approximately 1.75% at this point which is higher than the previous dive because of the lower battery discharge rate. Operation of the eliminator reduced the concentration to 1.1% where the eliminator operated at reduced efficiency due to the low concentration of hydrogen resulting from decreased gassing of the batteries.

CARBON MONOXIDE EVOLUTION

During the first dive there was a steady increase in the effective CO concentration, reaching a maximum of about 150 parts per million (0.015%) at the end (Fig. 12). Unrestricted smoking was permitted during this dive and no known CO removal system was operating.

There was a slower buildup of the CO concentration during the second dive (Fig. 13) and after the hydrogen eliminator was started it remained essentially constant at 75 parts per million (0.0075%).

During this dive smoking was nominally restricted to one cigarette every 2 hours or its equivalent in cigars or pipes. There were frequent violations of this restriction but it is quite certain that the amount of smoking on the second dive was considerably less than on the first dive.

The first dive was characterized by a high incidence of headaches near the end of the dive which varied from mild to severe. A possibly related fact was that high incidence of seasickness was experienced on surfacing in a rough sea. Headaches were fewer and milder on the second dive and seasickness was not evident on surfacing in a somewhat less rough sea.

STIBINE EVOLUTION

The stibine (SbH_3) concentration was determined in the stern room near the start of the second dive (2030 on 12/3) and again near the end (1242 on 12/6) by drawing a known quantity of air through silver nitrate impregnated silica gel and subsequently analyzing it at NRL by the rhodamine B method. Then again at New London additional determinations were made in the engine room while the batteries were being charged at the finishing rate. The results (Table 5) show that essentially no stibine was present during the second dive but significant amounts were present near the end of battery charging after the second dive.

FREON GAS

Samples of the ship's atmosphere were collected in evacuated bottles near the end of both dives (1015 on 12/2 and 0915 on 12/6) and were subsequently analyzed by an infrared spectrophotometer at NRL. The only different atmospheric ingredient revealed by these analyses was Freon 12 (dichlorodifluoromethane) gas in concentrations of approximately 2000 parts per million (0.2%).

TABLE 5
Stibine (SbH_3) Concentrations

Time	Place	SbH_3 Concentration (parts per million)
2030 on 12/3	Stern room--2nd dive	0.00
1242 on 12/6	Stern room--2nd dive	0.00
2312 on 12/7 to 0055 on 12/8	Engine room--batteries on finishing rate	0.62, 0.57, 0.76, 0.55, 0.66 } = 0.63 avg

TABLE 6
Summary of Absorbent Performances

Location of Test	Absorbent	No. of Hoppers	Absorbent Use Factors		
			Weight lb/man-hr	Volume cu ft/man-hr	Cost $/man-hr
NRL*	LiOH	2	0.11	0.0042	0.53
	Soda-lime	3	0.27	0.0056	0.10
	Soda-lime/LiOH	-	2.5	1.33	0.19
USS TROUT	LiOH	2	0.11	0.0043	-
	LiOH	3	0.10	0.0038	-
	Soda-lime	2	0.28	0.0058	-
	Soda-lime	3	0.26	0.0054	-
	Soda-lime	4	0.24	0.0047	-

*Reference 2

DISCUSSION

Hopper Operation

The hoppers performed very much as expected although it was not anticipated that the CO_2 concentration would remain as constant as it did. A comparison (Table 6) of the results obtained from the two dives with the anticipated performances based on Laboratory experiments (2) shows that the results obtained with LiOH used in two hoppers are in good

agreement. The performances of soda-lime used in three hoppers also compare favorably. The effect of the amount of material exposed at one time on the efficiency of absorbent utilization can be seen by comparing the three shipboard tests for soda-lime and the two shipboard tests for LiOH. From Table 6 it is evident that only 86% as much soda-lime is required if four hoppers are used, instead of two. For LiOH, 91% as much absorbent is required when three hoppers are used instead of two.

As to the relative merits of soda-lime and LiOH the ratios given in Table 6 remain essentially unchanged by data from the two dives which are slightly more favorable for soda-lime. Thus, if in the interest of economy soda-lime is used instead of LiOH the weight requirements will be 140% greater while the volume requirements will be only 25% greater. Two factors in favor of soda-lime are: (1) it does not have the highly irritating dust that LiOH does and (2) it may be discarded after use unlike LiOH which must be saved because of its high recovery value. A disadvantage (7) is that soda-lime is ineffective at low temperatures, i.e., of the order of 45 to 50°F; therefore, LiOH would still be necessary for salvage conditions.

Filter performance appeared to be satisfactory although some irritating dust was evident when the by-pass was opened on a hopper freshly filled with LiOH. A possible solution may be to leave the by-pass closed until the small particles of LiOH remaining in the bed have converted to the much less irritating Li_2CO_3. Most of the discomfort in using LiOH resulted from emptying hoppers containing a high percentage of unused material as during the period of the second dive when the object was to reduce the CO_2 concentration as rapidly as possible. The mixing and sampling produced considerable dust but this is normal operating procedure. Filter cleanings by tapping, air blasting, and soaking in dilute acid all proved ineffective. However, the filter used was clogged largely with soda-lime and previous experience has indicated that tapping and/or air blasting is effective on a filter which has been used with LiOH.

The location of the hoppers on the ship appeared to have no significant effect on their performance or the CO_2 concentrations in various compartments. Thus, the control room concentration was consistently higher than the forward torpedo and stern rooms whether a hopper was located in each of these compartments as in the first dive or whether all hoppers were in the forward torpedo room as in the second dive.

The data obtained from reading hopper thermometers, and hopper inlet and outlet CO_2 concentrations during the two dives are not adequate to decide on the practicability of determining absorbent saturation by temperature difference. This apparently is due primarily to the inaccuracy of the thermometers. However, since the CO_2 concentration remained fairly constant at 1.5%, laboratory data of the type shown in Fig. 14 will give the desired information if the airflow rate and inlet CO_2 concentration are specified.

Although the original intention was to operate at 3% for part of the time, the effect of CO_2 concentration was not investigated during either dive because after finding that the concentration remained essentially constant it was felt that the time could be better spent investigating other operating variables which are not so readily studied in the laboratory. For a given absorbent and hopper model a family of curves relating saturation with exposure time in various CO_2 concentrations (Fig. 6) would permit selection of a hopper system for any given situation.

As with any other type of shipboard CO_2 removal system, a rapid decrease in concentration is not easy to achieve. From the standpoint of making escapes from a sunken submarine this ability is highly desirable since in any flooding-up type escape the CO_2 would rapidly become dangerous if it started at 1-1/2% at one atmosphere. Thus, if it is

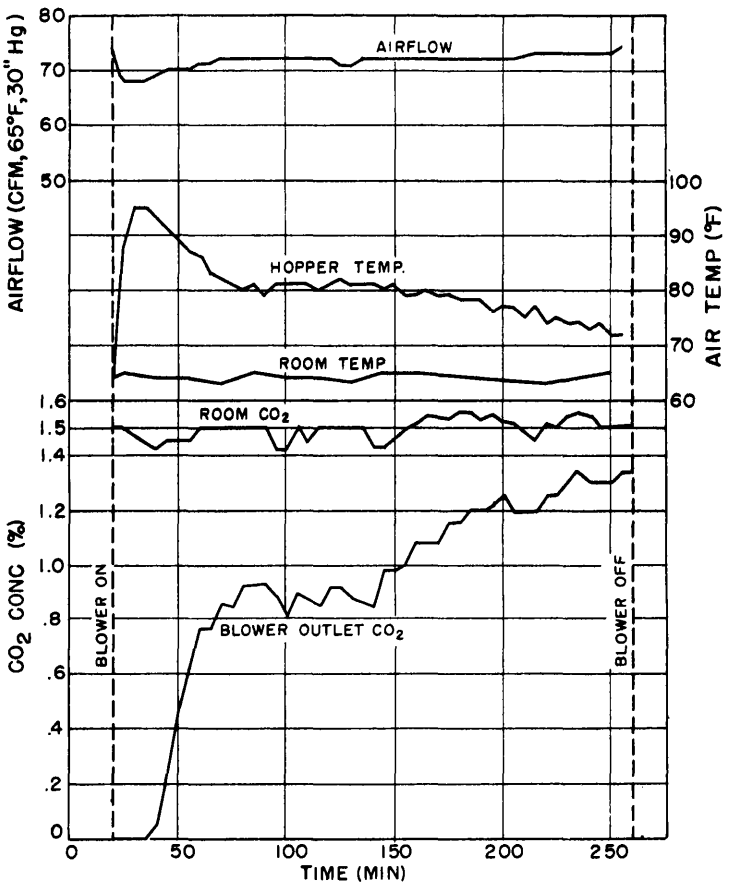

Fig. 14 - NRL hopper test of 8-16 mesh soda-lime

necessary to equalize the submarine's atmosphere with sea pressure at 100 feet under these conditions, the resulting effective concentration will be 6.0% and at 200 feet it will be 10.5%. The fact that 7 hours was required at the end of the second dive to reduce the concentration from 1.9 to 0.7% is undesirable but this was for the entire submarine where the total quantity of CO_2 in the atmosphere at 1.9% is considerable (about 73 lb). It would thus be more desirable — and more likely — for activities to be confined to a single compartment. It should be noted that equalizing pressure in a compartment is not normal escape procedure on this ship but it is on others and the possibility of unavoidable pressure buildup should not be neglected. Two other factors should be noted in this use of LiOH: (1) frequent hopper chargings where only slightly used material is removed is a rather dusty, unpleasant job, and (2) no spread material was used to augment the hoppers in this test.

Spread LiOH

The 22 and 23% saturation rate for CO_2, obtained when pelletized LiOH was spread on bunks for 3- and 4-hour exposures, is considerably below the 80 to 85% saturation reported(7) for fine granular LiOH which is still carried on submarines for emergency use. However,

the exposure was much shorter for the pelletized material and it is reasonable to assume equivalent saturation in a comparable time. A higher CO_2 concentration would also result in a greater saturation rate. As to the relative merits of pelletized and granular LiOH as absorbents when spread, Reference 8 showed them to be equivalent.

Gas Purging on Surfacing

The results as shown in Figs. 8, 9, 10, and 11 show only a short time on the surface was required to clear the air sufficiently for another dive. Thus, after surfacing for 30 minutes with air intake through the bridge access trunk the average CO_2 concentration was down to 0.2% (Fig. 8) which at the rate of buildup obtained during the first dive would have allowed another 8-hour submergence before reaching 1.5%. Figure 10 shows that the CO and H_2 concentrations were sufficiently lowered to prevent their being the limiting factors.

CO_2 Evolution

The results of three calculations of the CO_2 evolution rate agree quite well and their average of 0.086 lb/man-hr (0.70 cu ft (STP)/man-hr) may be compared with the following: 0.74 cu ft from the SAILFISH test (9), 0.72 cu ft from a comparable period in Operation Hideout (10), 0.70 to 0.82 from scrubber tests on the PERCH (11), 0.66 cu ft from an R boat dive in 1932 (7). The differences are easily accounted for by variations in crew activity; the level of activity during the experimental dives was no doubt lower than during a war patrol.

Ship's Volume Determinations

The figure of 38,500 cu ft which was obtained by releasing a known amount of bottled nitrogen into the sealed boat is believed to be the most accurate value and was used in all calculations. The floodable volume given on the ship's moment diagram is somewhat lower at 35,850 cu ft and, while given to four places, is not believed to be as accurate for the purposes of this report as the above value. The calculated volume of 41,000 cu ft obtained from the change in CO_2 concentration produced by releasing a known amount of CO_2 in a known time is believed to be the least accurate of the three figures because of its dependence on extreme accuracy in determining the average CO_2 concentration and the CO_2 evolution rate over a short period of time.

Oxygen Supply and Consumption

It is of interest to note that when the boat pressure was allowed to build up with no large pumpdowns during the first dive over half (54%) of the oxygen supplied came from the air leaks into the boat. On the other hand, when there were regular pumpdowns to prevent a steady pressure buildup during the second dive essentially all of the oxygen for breathing, smoking, etc., came from the oxygen banks. Thus, from the standpoint of oxygen stowage, it is better not to pumpdown during an extended dive. However, it is disadvantageous because the excess pressure complicates the surfacing operation and, if the O_2 partial pressure is maintained at a normal level of about 160 mm Hg, the pressure drop on surfacing may be dangerous. Therefore, if the pressure were allowed to reach 42 in. Hg (36.3 in. was reached in 39-1/2 hours during the first dive) the oxygen concentration would be down to 15% at 160 mm Hg partial pressure which is below the normal limit of safety when the total pressure drops to atmospheric.

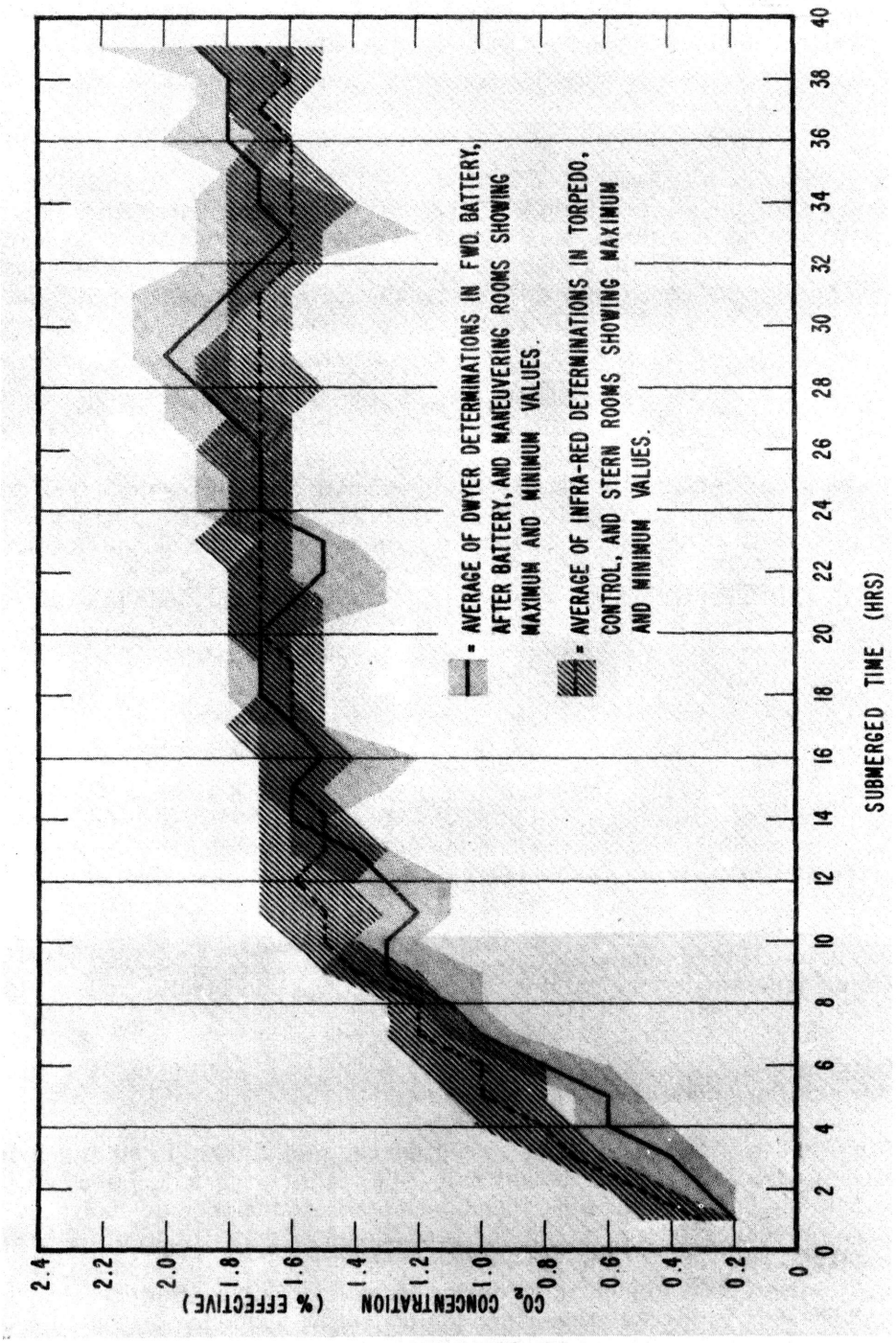

Fig. 15 - Comparison of Dwyer and infrared CO_2 determinations for first dive

Thus the estimate of 20 to 30 days oxygen supply for the TROUT given in Reference 3 must be accepted with reservation as it is true only when the boat pressure is allowed to steadily increase; the maximum allowable pressure would then limit the duration of the dive, e. g., about 76 hours, with a pressure increase rate equivalent to that of the first dive of this cruise.

Hydrogen Eliminator Operation

The hydrogen eliminator performed two functions on the second dive. The first was to lower the H_2 concentration in the boat from 1.75% to 1.1% although use of the eliminator for this purpose was probably not essential since the concentration had practically leveled off by the starting time due to the decreased gassing rate of the batteries. The second function, which was unintentional, was to remove CO and cause its concentration to level off.

The eliminator did not function when it was first started because the catalyst had not been heated to a sufficiently high temperature. After this had been remedied the unit operated effectively as a hydrogen eliminator considering that its performance improves as the hydrogen concentration increases. Since it was determined that the eliminator outlet concentration was about half that of the inlet this may provide a means of controlling CO on a submarine. However, it is not an ideal solution as the eliminator consumes from 1-1/2 to 2 kw of electrical power.

Performance of Ship's Instruments

CO_2 concentrations determined with Dwyer analyzers are compared in Figs. 15 and 16 and Appendix F with those obtained with infrared analyzers. The Dwyer readings have been corrected for pressure to read percent effective as the infrared analyzers do and all values have been rounded off to the nearest 0.1%. As shown in Fig. 3 each type instrument was used in three different compartments with no compartment having both types. The average of the infrared values is believed to represent best the average CO_2 concentration in the boat but it can be seen that there is generally good agreement between the averages obtained throughout both dives with both instruments. Thus the Dwyer analyzer appears to be satisfactory for its intended use under the following conditions: (1) several instruments should be used and readings should be taken in several compartments, and (2) the instruments should be properly operated and maintained. The need for the first condition is shown by the series of low readings obtained with one instrument between the 28th and 32nd hours of the second dive.

The hydrogen concentration as automatically recorded by the NRL Composite Gas Analyzer has been taken as the best value for the ship's atmosphere. However, for comparative purposes Appendix G tabulates the readings taken routinely on the ship's hydrogen indicators as well as the corresponding values from the Composite Analyzer. From these data it can be seen that the after battery indicator became highly inaccurate during both dives. The forward battery indicator agreed very well with the Composite Analyzer during the first dive but read considerably lower during most of the second dive. This appears to indicate that neither of the ship's hydrogen indicators is reliable.

Hourly oxygen partial pressure readings for both dives are tabulated in Appendix D. The ship's instrument appears to be at least the equal of the test instruments in accuracy of calibration because the initial readings (at 2300 on 11/30) of 165 and 166 mm Hg during the first dive apparently indicate a high calibration for the test instruments since this is above normal atmospheric pressure and the oxygen bleed-in had not yet started. It was

quite difficult to read the type instrument supplied to the ship due to poor illumination with or without a flashlight.

The ship's barometer, located on the port side in the control room, was calibrated at NRL after the experimental dives and was found to be accurate to ±0.05 in. Hg over the range of 30.0 to 37.0 in. Hg. This should be highly satisfactory for its normal use and the practice of reading to the nearest 0.01 in. Hg appears to be unnecessary.

CONCLUSIONS AND RECOMMENDATIONS

CO_2 Removal System

The hopper system of using LiOH or soda-lime appears to be practical for medium submergence submarines such as the 563 class. The maximum amount of LiOH that the TROUT can conveniently carry is 2000 lb (3) which with a 2-hopper system would permit a 10-day continuous submergence for 75 to 80 men at a CO_2 concentration of 1.5%. Battery capacity would prevent a single dive of this length and the total submerged time for a series of shorter dives would be greater because of the 8 to 10 hours available before the CO_2 reaches 1.5% at the start of each dive. Another means of extending the total submerged time is to purge the boat whenever possible by surfacing or snorkeling for short periods, i. e., 30 minutes or less.

The use of soda-lime in place of LiOH is of interest because of its relatively low cost, ease of handling, and expendibility. However, if three hoppers are used, it would require 25% more volume and 140% more weight for stowage than LiOH with the same method of packing and would not be satisfactory for emergency use.

It appears from these tests that hoppers are somewhat inconvenient to install and operate and it is recommended that work be done to improve the system. A manifold system having a self-contained blower and motor with a filter and using inexpensive expendable cannisters (possibly fiber) with screens at both ends and filled with 8-16 mesh high-moisture soda-lime appears worthy of investigation. According to Reference 3 use of non-metallic containers would greatly increase the available stowage space.

The use of LiOH in three hoppers does not appear satisfactory as a means of rapidly lowering the CO_2 concentration although it is considerably more efficient than spreading the same amount of material for the same time. The saturation of spread pelletized LiOH is relatively slow but is equivalent to the fine granular material now carried.

Oxygen Supply

The normal air leaks inside the ship are an important source of oxygen under certain conditions. For dives not exceeding 76 hours where a final boat pressure of 42 in. Hg is acceptable, less than half of the oxygen consumed will need to be bled from the oxygen banks. However, where the pressure is pumped down periodically, essentially all of the oxygen consumed will be drawn from the oxygen banks. In both cases it is assumed that the oxygen partial pressure will be maintained at about 160 mm Hg (normal atmospheric pressure).

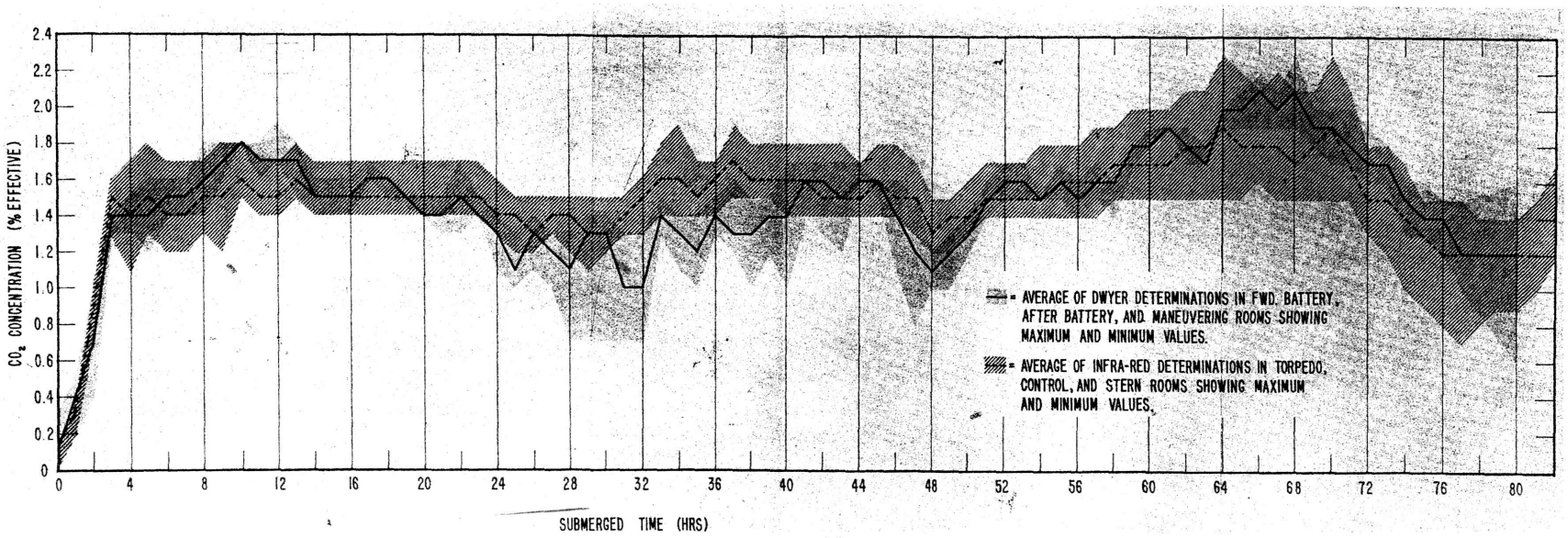

Fig. 16 - Comparison of Dwyer and infrared CO_2 determinations for second dive

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The average O_2 consumption rate for the two dives was about 0.82 cu ft (STP)/man-hour which considering the average CO_2 evolution rate of about 0.70 cu ft (STP)/man-hour gives a respiratory quotient of about 0.87. The design value of 1.0 cu ft (STP) of O_2/man-hour still appears to be correct as the level of activity was probably lower than normal on these dives.

CO Evolution

The problem of CO in the ship's atmosphere during extended dives will probably become increasingly important since it appears to be related directly to smoking. The second dive suggests two methods of control — restricted smoking and operation of the hydrogen eliminator. The former is undesirable psychologically and the latter from the standpoint of power consumption. No ideal solution can be suggested at the present time.

Hydrogen Evolution

The hydrogen eliminator performed satisfactorily after an initial mechanical fault was remedied. The decreasing gassing rate characteristic of batteries should be well understood to eliminate over emphasis of the need for hydrogen eliminators.

Performance of Ship's Instruments

The ship's CO_2 analyzers, oxygen analyzer, and barometer appear to be quite satisfactory for their intended use. The ship's hydrogen indicators did not perform satisfactorily during these tests.

ACKNOWLEDGMENTS

The authors wish to acknowledge the wholehearted cooperation of the officers and men of the USS TROUT in making these tests. In addition, the advice and help of Mr. A. S. Gates, Jr.(BuShips Code 549) in all phases of the work contributed greatly to the success of the cruise and is much appreciated. Also, the authors are grateful for the assistance of Mr. J. M. Davidson (BuShips Code 588) in conducting tests related to submarine escape techniques.

* * *

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* * *

APPENDIX A

Auxiliary Equipment Operated During the First and Second Dives*

FORWARD TORPEDO ROOM

1 air blower
1 hot water heater
lighting

FORWARD BATTERY ROOM

1 air blower
4 battery-well circulating fans
1 battery exhaust blower
1 agitation blower
1 TBL transmitter
1 LM oscillator heater
1 AN/BQR-3 Sonar Receiving Set
forward gyro compass
lighting

CONTROL ROOM

No. 1 and No. 2 75-kva generators
No. 2 400-cycle generator
No. 1 IMO pump
2 air blowers
No. 2 air conditioning unit
1 hot water pump
2 circulating water pumps
2 gyro compass synchro amplifiers
1 dead reckoning computer
miscellaneous IC circuits
lighting

AFTER BATTERY ROOM

1 exhaust blower
1 agitation blower
1 battery exhaust blower
1 hot water heater
1 hot water heater booster
1 galley range and oven
1 coffee urn
1 refrigeration unit
1 circulating water pump
1 circulating blower
lighting

ENGINE AND MANEUVERING ROOMS

1 circulating pump
1 circulating blower
after gyro compass
1 air booster blower
1 precipitron blower
1 precipitron booster blower
1 lub oil pump
miscellaneous IC circuits

STERN ROOM

1 circulating blower
1 hot water heater
1 IMO pump (steering)
lighting

*On the second dive, steering was by hand and the pit log and dead reckoning computer were secured.

* * *

APPENDIX B
Summary of Electrical and Battery Logs

The electrical and battery logs for the first and second dives may be summarized as follows:

1. Average armature current for each of the 4 motors was 153 amp during the first dive, and 25 amp for 25 hours and 225 amp for 1 hour during the second dive.

2. Average range of field current for each of the 4 motors ranged from 14 to 9.5 amp during the first dive, and was 36 amp for 25 hours and 17 amp for 1 hour during the second dive.

3. Average auxiliary load was 101 amp for the first dive and 78.5 amp for the second dive.

4. Batteries were operated in parallel and ranged from 530 to 475 volts for the first dive and 530 to 485 volts for the second dive. Table B1 gives itemized information for both the forward and after batteries.

TABLE B1
Summary of Battery Log

Dive	Battery	Pilot Cell			Average Ventilation (cfm)	Total Charge Used (amp-hr)
		Avg Temp (°F)		Avg Specific Gravity at Start		
		Start	End			
1	Forward	101	91	1.261	700	6650
	After	96	86	1.258	1450	6750
2	Forward	98	79	1.263	1250	6900
	After	98	77	1.266	1200	7100

APPENDIX C
Analytical Procedures for Determining Absorbent Peformance *

ANALYSIS OF LiOH

1. Unused LiOH was assumed to contain no carbonate.

2. Samples of spent LiOH were obtained during the cruise by mixing the entire hopper charge in a commercial-type tumbler mixer and drawing a 4-ounce sample.

3. The samples were returned to NRL where a portion of each was powdered with a mortar and pestle. To determine the total LiOH and Li_2CO_3 content approximately 1-gram samples were weighed, dissolved in water, and titrated with 1 N HC1 to a methyl orange endpoint. To determine the LiOH content alone, approximately 1-gram samples were again weighed and dissolved in water, 30 ml of 1 N $BaCl_2$ solution was added to each sample to precipitate the carbonate, and the mixture was titrated with 1 N HC1 to a phenolphthalein endpoint. From these two determinations the carbonate content can be obtained by difference.

4. Weights of hopper charges before and after use were determined during the cruise. From the above analyses the CO_2 absorption in terms of used material is obtained. Multiplying this value by the ratio of final to initial weights of absorbent gives the desired result of pounds of CO_2 absorbed per pound of unused LiOH.

ANALYSIS OF SODA-LIME

1. Approximately one third of the unused soda-lime was sampled during hopper fillings by taking 4-ounce samples. Used soda-lime was sampled during the cruise by mixing the entire hopper charge in a commercial-type tumbler mixer and taking 4-ounce samples.

2. These samples were ground at NRL in the same manner as was the LiOH samples. Then approximately 4-gram samples were weighed and analyzed gasometrically by adding the minimum amount of 6 N HC1 required to dissolve the material.

3. Initial and final hopper charge weights were determined during the cruise as for LiOH. The results obtained for used soda-lime by the above analysis were put in terms of weight of CO_2 per pound of initial material which was then corrected for initial CO_2 content by subtracting the average of the initial soda-lime analysis results.

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*Performed by C. H. Blachly of the Analytical Section, Chemistry Division

* * *

APPENDIX D
Oxygen Concentrations

Oxygen Concentrations* on First Dive

Date	Time	Fwd. Torp. Rm.	Fwd. Bat. Rm.	Stern Rm.†	Avg
11/30	2200	-	-	-	160‡
	2300	165	158	166	163
	2400	165	161	168	164
12/1	0100	167	161	168	165
	0200	168	161	170	166
	0300	169	164	172	171
	0400	169	165	172	168
	0500	170	165	172	169
	0600	170	167	172	169
	0700	171	167	172	170
	0800	172	167	172	170
	0900	173	168	173	171
	1000	173	168	173	171
	1100	173	168	172	171
	1200	173	168	174	171
	1300	173	168	174	171
	1400	173	168	172	171
	1500	173	168	172	171
	1600	171	168	170	169
	1700	171	169	170	170

Date	Time	Fwd. Torp. Rm.	Fwd. Bat. Rm.	Stern Rm.†	Avg
12/1	1800	171	169	170	170
	1900	172	169	170	170
	2000	173	169	170	170
	2100	173	169	171	171
	2200	173	169	172	171
	2300	173	169	170	171
	2400	174	169	172	171
12/2	0100	174	169	170	171
	0200	174	169	170	171
	0300	174	169	170	171
	0400	173	170	170	171
	0500	174	170	170	171
	0600	172	169	168	169
	0700	172	169	170	170
	0800	173	169	169	170
	0900	174	170	169	171
	1000	173	170	169	170
	1100	173	170	168	170
	1200	174	170	170	171
	1300	175	170	170	171

*Partial pressure in mm Hg
†From hourly panel meter readings
‡Estimated from shape of stern room record

Oxygen Concentrations on Second Dive*

Date	Time	Fwd. Torp. Rm.	Fwd. Bat. Rm.	Stern Rm.†	Avg
12/3	1100	158	153	154	155
	1200	157	152	154	154
	1300	157	152	154	154
	1400	158	152	152	154
	1500	156	152	152	154
	1600	154	152	150	152
	1700	154	152	150	152
	1800	154	152	150	152
	1900	154	152	150	150
	2000	156	152	150	152
	2100	156	152	150	152
	2200	156	150	150	151
	2300	156	150	148	152
	2400	154	152	150	152
12/4	0100	156	152	148	152
	0200	156	152	150	153
	0300	156	152	150	153
	0400	157	152	150	153
	0500	154	152	150	152
	0600	155	152	150	152
	0700	156	152	150	153
	0800	156	152	151	153
	0900	157	153	150	153
	1000	158	154	152	155
	1100	144	144	142	143
	1200	141	136	134	137
	1300	141	136	134	137
	1400	140	137	134	137
	1500	141	137	134	137
	1600	140	137	134	137
	1700	140	137	136	137
	1800	140	138	136	138
	1900	140	138	136	138
	2000	143	139	136	139
	2100	143	139	138	140
	2200	145	141	140	142
	2300	147	141	142	143
	2400	148	143	142	144
12/5	0100	150	146	144	147
	0200	152	147	146	148
	0300	154	149	148	150
12/5	0400	154	150	150	151
	0500	156	152	150	153
	0600	158	155	154	156
	0700	160	156	156	157
	0800	162	154	156	157
	0900	164	157	160	160
	1000	159	154	152	155
	1100	145	141	142	143
	1200	145	142	140	142
	1300	146	142	140	142
	1400	147	142	142	144
	1500	149	143	142	145
	1600	146	143	142	144
	1700	147	143	142	144
	1800	148	145	142	145
	1900	149	145	144	146
	2000	152	145	144	147
	2100	152	147	144	148
	2200	153	148	146	149
	2300	153	148	146	149
	2400	154	149	148	150
12/6	0100	155	149	148	151
	0200	155	151	150	152
	0300	157	151	150	153
	0400	156	153	150	153
	0500	157	153	152	154
	0600	158	155	152	155
	0700	160	155	154	156
	0800	153	156	155	155
	0900	163	156	158	159
	1000	162	156	155	157
	1100	150	147	144	147
	1200	153	147	146	149
	1300	154	147	146	149
	1400	154	149	148	150
	1500	156	150	148	151
	1600	154	150	150	151
	1700	157	152	150	153
	1800	157	153	150	153
	1900	158	153	152	154
	2000	159	154	153	155
	2100	161	156	154	157

*Partial pressure in mm Hg
†From hourly panel meter readings

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APPENDIX E
Oxygen Bleed-In

Oxygen Bleed-In During First Dive

Date	Time	Gasmeter Reading (liters)	Gas Temp (°F)	Barometer Reading (in. Hg)	Sea Water Temp (°F)	O_2 Bank Pressure (psig)	O_2 Added in 1 hr (liters, ambient)	Temp Corr*	Pres Corr	O_2 Added in 1 hr, Corrected (liters, STP)
11/30	2300	0650	78	30.8	-	2725	650		1.032	613
	2400	2541	80	31.1	62	2710	1891		1.040	1795
12/1	0100	4309	80	31.3	62	2700	1768		1.045	1685
	0200	6191	80	31.6	62	2700	1882		1.055	1790
	0300	7786	79	31.8	62	2680	1595		1.062	1545
	0400	9339	79	32.0	62	2650	1553		1.070	1515
	0500	0811	79	32.2	62	2640	1472		1.075	1452
	0600	2173	79	32.4	62	2625	1362		1.082	1345
	0700	3407	79	32.6	62	2600	1234		1.090	1228
	0800	4583	79	32.7	62	2575	1176		1.092	1170
	0900	5515	78	32.9	63	2550	932		1.098	932
	1000	6477	78	33.0	63	2540	962		1.105	970
	1100	7495	77	33.2	64	2540	1018		1.112	1032
	1200	8417	77	33.4	65	2550	922		1.120	938
	1300	9225	77	33.5	65	2540	808		-	823
	1400	0113	76	33.6	65	2525	888	0.907	-	905
	1500	0980	76	33.7	64	2510	867	(min)	-	883
	1600	1867	78	33.8	64	2500	887		1.130	914
	1700	2634	78	33.9	64	2490	767		-	791
	1800	3524	78	34.0	64	2475	890		1.135	920
	1900	4614	78	34.2	64	2460	1090		1.144	1140
	2000	5364	76	34.3	64	2450	750		1.147	784
	2100	6105	76	34.5	71	2440	741		1.154	780
	2200	6933	77	34.6	74	2440	828		-	872
	2300	7804	77	34.7	75	2440	871		1.159	916
	2400	8705	79	34.8	75	2460	901		-	950
12/2	0100	9576	78	34.9	75	2480	871		1.167	930
	0200	0284	78	35.1	74	2475	708		1.174	756
	0300	1087	79	35.3	75	2470	803		-	857
	0400	1870	80	35.5	74	2425	783		1.188	850
	0500	2649	80	35.6	74	2410	779		1.191	845
	0600	3468	79	35.2	74	2400	819		1.178	880
	0700	4256	79	35.4	74	2390	788		1.188	854
	0800	5015	80	35.6	74	2375	759		1.191	822
	0900	5708	80	35.8	74	2365	693		1.198	756
	1000	6504	82	35.9	74	2360	796	0.916	1.120	870
	1100	7293	82	36.0	74	2350	789	(max)	1.203	868
	1200	8056	81	36.2	74	2350	763		1.210	834
	1300	8808	81	36.3	73	2340	752		1.214	834
										39,644 total

*Average used was 0.912

Oxygen Bleed-In During Second Dive

Date	Time	Gasmeter Reading (liters x10)	Gas Temp (°F)	Barometer Reading (in. Hg)	Sea Water Temp (°F)	O_2 Bank Pressure (psig)	O_2 Added in 1 hr (liters x10, ambient)	Temp Corr*	Pres Corr	O_2 Added in 1 hr, Corrected (liters, STP)
12/3	1100	14505	80	29.1	63	2225	-		-	-
	1200	18635	80	29.3	63	2225	4130		0.98	3720
	1300	25875	81	29.7	63	2200	7240	0.910	0.99	6590
	1400	33406	80	29.9	63	2200	7531	(min)	1.00	6920
	1500	40932	80	30.1	63	2200	7526		1.01	6990
	1600	48475	79	30.2	63	2200	7543		1.01	7000
	1700	56428	79	30.3	64	2200	7953		1.01	7390
	1800	63089	79	30.4	64	2175	6661		1.02	6250
	1900	71625	80	30.6	65	2160	8536		1.02	8000
	2000	79222	79	30.8	65	2150	7597		1.03	7190
	2100	86481	78	30.9	66	2150	7259		1.03	6880
	2200	95449	79	31.0	65	2125	8968		1.04	8580
	2300	04498	79	31.1	66	2110	9049		1.04	8650
	2400	13569	79	31.2	63	2110	9071		1.04	8680
12/4	0100	22520	78	31.3	63	2100	8951		1.05	8660
	0200	31369	79	31.4	63	2100	8849		1.05	8560
	0300	40180	78	31.6	64	2075	8811		1.06	8600
	0400	48910	78	31.7	63	2075	8730		1.06	8510
	0500	58278	78	31.8	62	2050	9368		1.06	9140
	0600	66606	76	31.9	61	2025	8228		1.07	8200
	0700	75674	76	32.0	60	2010	9068		1.07	8940
	0800	84465	76	32.1	60	2000	8791		1.07	8650
	0900	93427	76	32.2	60	1975	9062		1.08	9000
	1000	02472	77	32.5	60	1960	9045		1.09	9055
	1100	11935	76	30.6	60	1950	9463		1.09	9490
	1200	22373	76	29.0	60	1950	10438		0.97	9320
	1300	31729	74	29.1	60	1940	9356		0.97	8350
	1400	41303	74	29.2	58	1940	9574		0.98	8640
	1500	51963	74	29.3	61	1925	10660		0.98	9610
	1600	66650	73	29.4	61	1910	14687		0.98	13220
	1700	81467	73	29.5	61	1900	14817		0.99	13500
	1800	97361	72	29.6	61	1880	15894		0.99	14480
	1900	15700	72	29.8	62	1760	18339		1.00	16890
	2000	31919	71	29.9	62	1825	16219		1.00	14930
	2100	45458	74	30.0	62	1800	13539		1.00	12480
	2200	87524	74	30.2	62	1760	42066		1.01	39100
	2300	20340	74	30.4	62	1720	32816		1.02	30800
	2400	51670	74	30.6	62	1700	31330		1.02	29400
12/5	0100	84824	72	30.7	62	1675	33154		1.03	31400
	0200	13243	72	30.9	62	1650	28419		1.03	26920
	0300	43012	71	31.0	62	1600	29769		1.04	28430
	0400	72060	71	31.3	61	1550	29048		1.05	28100

*Average used was 0.920

Oxygen Bleed-In During Second Dive (cont'd)

Date	Time	Gasmeter Reading (liters x10)	Gas Temp (°F)	Barometer Reading (in. Hg)	Sea Water Temp (°F)	O_2 Bank Pressure (psig)	O_2 Added in 1 hr (liters x10, ambient)	Temp Corr*	Pres Corr	O_2 Added in 1 hr Corrected (liters, STP)
12/5	0500	00475	71	31.4	62	1550	28415		1.05	27500
	0600	28223	71	31.6	62	1510	27748		1.06	27050
	0700	56305	71	31.7	62	1480	28182		1.06	27450
	0800	81173	71	31.9	62	1425	24868		1.07	24500
	0900	97252	70	32.4	61	1410	16079	0.930	1.08	15980
	1000	14502	71	31.9	62	1400	17250	(max)	1.07	16990
	1100	33129	71	28.5	61	1360	18627		0.95	16290
	1200	50591	72	28.6	61	1375	17462		0.96	15400
	1300	67320	74	28.8	61	1350	16729		0.96	14780
	1400	83655	74	28.9	61	1325	16335		0.97	14590
	1500	01050	74	29.2	62	1300	17395		0.98	15690
	1600	17462	76	29.3	62	1300	16412		0.98	14800
	1700	38075	75	29.4	62	1275	20613		0.98	18600
	1800	58140	72	29.5	62	1250	20065		0.99	18250
	1900	78780	74	29.7	62	1225	20640		0.99	18800
	2000	98658	72	29.8	62	1200	19878		1.00	18280
	2100	19505	72	30.0	62	1160	20847		1.00	19200
	2200	40205	73	30.2	62	1140	20700		1.01	19220
	2300	60594	73	30.2	61	1120	20389		1.01	18920
	2400	81258	72	30.4	62	1100	20664		1.02	19400
12/6	0100	01700	71	30.5	62	1060	20442		1.02	19200
	0200	22187	71	30.6	61	1050	20487		1.02	19220
	0300	41920	73	30.8	62	1030	19733		1.03	18700
	0400	63450	75	31.0	62	1010	21530		1.04	20600
	0500	84200	75	31.1	62	975	20750		1.04	19850
	0600	02041	75	31.2	62	960	17841		1.04	17080
	0700	22264	75	31.4	62	950	20223		1.05	19580
	0800	42782	75	31.5	62	900	20518		1.05	19850
	0900	64825	75	31.7	62	875	22043		1.06	21500
	1000	81071	76	31.6	61	850	16246		1.06	15850
	1100	06432	75	29.1	62	840	25361		0.97	22620
	1200	28660	76	29.2	62	825	22428		0.98	20250
	1300	51917	76	29.3	62	800	23257		0.98	21000
	1400	75753	76	29.5	61	775	23836		0.99	21700
	1500	97641	75	29.6	61	750	21888		0.99	19930
	1600	20552	75	29.7	62	710	22911		0.99	20850
	1700	42372	75	29.9	62	700	21820		1.00	20500
	1800	65100	74	30.1	61	650	22728		1.00	20950
	1900	89575	75	30.2	61	630	24475		1.01	22750
	2000	97150	74	30.4	61	620	7575		1.02	7110
	2100	30455	75	30.6	61	575	33305		1.02	31250
										1,327,245 total

*Average used was 0.920

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APPENDIX F
CO_2 Concentrations

CO_2 Concentrations During First Dive

Date	Time	Infrared Analyzer				Dwyer Analyzer						
		Fwd. Torp. Rm.	Control Rm.	Stern Rm.	Avg	Fwd. Bat. Rm.		Aft. Bat. Rm.		Man. Rm.		Avg
						% True	% Eff.	% True	% Eff.	% True	% Eff.	
11/30	2200	-	-	0.2	0.0?	-	-	-	-	-	-	-
	2300	0.3	0.2	0.5	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.2
	2400	0.4	0.5	0.6	0.5	0.3	0.3	0.2	0.2	0.4	0.4	0.3
12/1	0100	0.6	0.6	0.8	0.7	0.4	0.4	0.3	0.3	0.6	0.6	0.4
	0200	0.7	0.8	1.0	0.8	0.7	0.7	0.4	0.4	0.6	0.6	0.6
	0300	0.8	1.0	1.1	1.0	0.7	0.7	0.5	0.5	0.6	0.6	0.6
	0400	0.8	1.1	1.2	1.0	0.8	0.9	0.6	0.6	0.8	0.9	0.8
	0500	1.0	1.3	-	1.2?	0.9	1.0	0.8	0.9	1.0	1.1	1.0
	0600	1.1	1.3	-	1.2?	1.0	1.1	0.9	1.0	1.1	1.2	1.1
	0700	1.2	1.5	-	1.4?	1.2	1.3	0.9	1.0	1.4	1.5	1.3
	0800	1.4	1.6	1.5	1.5	1.3	1.4	1.1	1.2	1.2	1.3	1.3
	0900	1.3	1.7	1.6	1.5	1.2	1.3	1.0	1.1	1.2	1.3	1.2
	1000	1.4	1.7	1.6	1.6	1.3	1.4	1.0	1.1	1.2	1.3	1.3
	1100	1.3	1.7	1.6	1.5	1.3	1.4	1.2	1.3	1.4	1.6	1.4
	1200	1.4	1.7	1.4	1.5	1.4	1.6	1.3	1.5	1.4	1.6	1.6
	1300	1.5	1.7	1.5	1.6	1.5	1.7	1.2	1.3	1.5	1.7	1.6
	1400	1.4	1.7	1.5	1.5	1.5	1.7	1.1	1.2	1.5	1.7	1.5
	1500	1.5	1.8	1.5	1.6	1.5	1.7	1.3	1.5	1.5	1.7	1.6
	1600	1.5	1.7	1.5	1.6	1.4	1.6	1.4	1.6	1.6	1.8	1.7
	1700	1.6	1.7	1.5	1.6	1.4	1.6	1.4	1.6	1.6	1.8	1.7
	1800	1.7	1.8	1.5	1.7	1.6	1.8	1.5	1.7	1.4	1.6	1.7
	1900	1.7	1.8	1.5	1.7	1.5	1.7	1.1	1.3	1.6	1.8	1.6
	2000	1.6	1.8	1.6	1.7	1.6	1.8	1.3	1.5	1.3	1.5	1.6
	2100	1.6	1.9	1.6	1.7	1.2	1.4	1.3	1.5	1.5	1.7	1.5
	2200	1.6	1.8	1.6	1.7	1.4	1.6	1.4	1.6	1.6	1.9	1.7
	2300	1.7	1.8	1.6	1.7	1.4	1.6	1.4	1.6	1.6	1.9	1.7
	2400	1.7	1.9	1.6	1.7	1.6	1.9	1.4	1.6	1.4	1.6	1.7
12/2	0100	1.7	1.8	1.6	1.7	1.7	2.0	1.4	1.6	1.6	1.9	1.8
	0200	1.5	1.9	1.6	1.7	1.7	2.0	1.5	1.8	1.7	2.0	1.9
	0300	1.6	1.9	1.6	1.7	1.7	2.0	1.5	1.8	1.8	2.1	2.0
	0400	1.6	1.8	1.6	1.7	1.5	1.8	1.5	1.8	1.8	2.1	1.9
	0500	1.6	1.8	1.6	1.7	1.4	1.7	1.4	1.7	1.8	2.1	1.8
	0600	1.6	1.8	1.5	1.6	1.4	1.7	1.4	1.7	1.6	1.9	1.8
	0700	1.5	1.8	1.5	1.6	1.5	1.8	1.0	1.2	1.6	1.9	1.6
	0800	1.4	1.8	1.5	1.6	1.4	1.7	1.2	1.4	1.6	1.9	1.7
	0900	1.5	1.8	1.6	1.6	1.4	1.7	1.4	1.7	1.5	1.8	1.7
	1000	1.6	1.7	1.6	1.6	1.5	1.8	1.3	1.6	1.7	2.0	1.8
	1100	1.6	1.8	1.6	1.7	1.4	1.7	1.4	1.7	1.6	1.9	1.8
	1200	1.6	1.8	1.5	1.6	1.5	1.8	1.3	1.6	1.6	1.9	1.8
	1300	1.6	1.9	1.5	1.7	1.5	1.8	1.3	1.6	1.8	2.2	1.9

CO_2 Concentrations on Second Dive

		Infrared Analyzer				Dwyer Analyzer						
						Fwd. Bat. Rm.		Aft. Bat. Rm.		Man. Rm.		
Date	Time	Fwd. Torp. Rm.	Control Rm.	Stern Rm.	Avg	% True	% Eff.	% True	% Eff.	% True	% Eff.	Avg
12/3	1100	0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.3	0.3	0.1
	1200	0.3	0.2	0.4	0.3	0.2	0.2	0.4	0.4	0.5	0.5	0.4
	1300	0.8	1.0	1.0	0.9	0.4	0.4	0.6	0.6	1.0	1.0	0.7
	1400	1.5	1.6	1.3	1.5	1.4	1.4	1.4	1.4	1.3	1.3	1.4
	1500	1.1	1.7	1.3	1.4	1.5	1.5	1.4	1.4	1.2	1.3	1.4
	1600	1.4	1.8	1.3	1.5	1.5	1.5	1.6	1.6	1.2	1.2	1.4
	1700	1.2	1.7	1.4	1.4	1.6	1.6	1.6	1.6	1.4	1.4	1.5
	1800	1.2	1.7	1.4	1.4	1.6	1.6	1.5	1.5	1.4	1.4	1.5
	1900	1.3	1.7	1.4	1.5	1.8	1.8	1.6	1.6	1.4	1.4	1.6
	2000	1.2	1.8	1.4	1.5	1.7	1.8	1.6	1.6	1.6	1.6	1.7
	2100	1.5	1.8	1.4	1.6	1.7	1.8	1.7	1.8	1.7	1.8	1.8
	2200	1.4	1.7	1.4	1.5	1.7	1.8	1.7	1.8	1.5	1.6	1.7
	2300	1.4	1.7	1.4	1.5	1.5	1.6	1.4	1.5	1.8	1.9	1.7
	2400	1.5	1.8	1.4	1.6	1.7	1.8	1.6	1.7	1.4	1.5	1.7
12/4	0100	1.4	1.7	1.4	1.5	1.3	1.4	1.3	1.4	1.5	1.6	1.5
	0200	1.5	1.7	1.4	1.5	1.5	1.6	1.3	1.4	1.5	1.6	1.5
	0300	1.4	1.7	1.4	1.5	1.5	1.6	1.3	1.4	1.4	1.5	1.5
	0400	1.4	1.7	1.4	1.5	1.5	1.6	1.6	1.7	1.5	1.6	1.6
	0500	1.5	1.7	1.4	1.5	1.5	1.6	1.5	1.6	1.4	1.5	1.6
	0600	1.4	1.7	1.4	1.5	1.4	1.5	1.4	1.5	1.4	1.5	1.5
	0700	1.4	1.7	1.4	1.5	1.4	1.5	1.3	1.4	1.3	1.4	1.4
	0800	1.4	1.7	1.4	1.5	1.4	1.5	1.2	1.3	1.3	1.4	1.4
	0900	1.4	1.7	1.4	1.5	1.5	1.6	1.2	1.3	1.6	1.7	1.5
	1000	1.4	1.7	1.4	1.5	1.3	1.4	1.3	1.4	1.4	1.5	1.4
	1100	1.3	1.6	1.4	1.4	1.3	1.4	1.0	1.1	1.3	1.4	1.3
	1200	1.5	1.5	1.2	1.4	1.3	1.3	1.0	1.0	1.0	1.0	1.1
	1300	1.2	1.5	1.3	1.3	1.3	1.3	1.4	1.4	1.1	1.1	1.3
	1400	1.3	1.5	1.3	1.4	1.3	1.3	1.2	1.2	1.0	1.0	1.2
	1500	1.2	1.5	1.3	1.4	1.3	1.3	1.3	1.3	0.7	0.7	1.1
	1600	1.1	1.5	1.2	1.3	1.4	1.4	1.4	1.4	0.7	0.7	1.3
	1700	1.2	1.5	1.2	1.3	1.3	1.3	1.4	1.4	0.7	0.7	1.3
	1800	1.3	1.5	1.3	1.4	1.3	1.3	1.0	1.0	0.7	0.7	1.0
	1900	1.5	1.6	1.3	1.5	1.3	1.3	1.0	1.0	0.9	0.7	1.0
	2000	1.6	1.8	1.4	1.6	1.5	1.5	1.5	1.5	1.3	1.3	1.4
	2100	1.5	1.9	1.4	1.6	1.4	1.4	1.4	1.4	1.1	1.1	1.3
	2200	1.5	1.7	1.4	1.5	1.2	1.2	1.4	1.4	1.0	1.0	1.2
	2300	1.6	1.7	1.4	1.6	1.5	1.5	1.5	1.5	1.3	1.3	1.4
	2400	1.7	1.9	1.5	1.7	1.2	1.2	1.2	1.2	1.6	1.6	1.3
12/5	0100	1.5	1.8	1.5	1.6	1.5	1.5	1.0	1.0	1.5	1.5	1.3
	0200	1.5	1.8	1.5	1.6	1.4	1.4	1.2	1.2	1.5	1.5	1.4
	0300	1.6	1.8	1.4	1.6	1.5	1.6	1.0	1.0	1.6	1.7	1.4

CO_2 Concentrations on Second Dive (cont'd)

Date	Time	Infrared Analyzer				Dwyer Analyzer						
		Fwd. Torp. Rm.	Control Rm.	Stern Rm.	Avg	Fwd. Bat. Rm.		Aft. Bat. Rm.		Man. Rm.		Avg
						% True	% Eff.	% True	% Eff.	% True	% Eff.	
12/5	0400	1.6	1.8	1.4	1.6	1.6	1.7	1.5	1.6	1.3	1.4	1.6
	0500	1.4	1.8	1.4	1.5	1.6	1.7	1.6	1.7	1.2	1.3	1.6
	0600	1.4	1.8	1.4	1.5	1.5	1.6	1.6	1.7	1.1	1.2	1.5
	0700	1.5	1.7	1.4	1.5	1.6	1.7	1.5	1.6	1.5	1.6	1.6
	0800	1.5	1.8	1.4	1.6	1.4	1.5	1.5	1.6	1.5	1.6	1.6
	0900	1.4	1.8	1.4	1.5	1.3	1.4	1.5	1.6	1.0	1.1	1.4
	1000	1.4	1.7	1.3	1.5	1.3	1.4	1.4	1.5	0.8	0.8	1.2
	1100	1.2	1.5	1.2	1.3	1.2	1.1	1.3	1.2	1.0	1.0	1.1
	1200	1.4	1.5	1.2	1.4	1.0	1.0	1.5	1.3	1.4	1.3	1.2
	1300	1.3	1.6	1.3	1.4	1.5	1.4	1.2	1.2	1.5	1.4	1.3
	1400	1.5	1.7	1.4	1.5	1.5	1.4	1.4	1.4	1.7	1.6	1.5
	1500	1.4	1.7	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.6
	1600	1.5	1.7	1.4	1.5	1.6	1.6	1.5	1.5	1.7	1.7	1.6
	1700	1.4	1.8	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	1800	1.5	1.8	1.4	1.6	1.7	1.7	1.7	1.7	1.5	1.5	1.6
	1900	1.5	1.8	1.4	1.6	1.6	1.6	1.4	1.4	1.6	1.6	1.5
	2000	1.6	1.9	1.4	1.6	1.6	1.6	1.7	1.7	1.5	1.5	1.6
	2100	1.6	1.9	1.5	1.7	1.6	1.6	1.7	1.7	1.4	1.4	1.6
	2200	1.7	2.0	1.5	1.7	1.8	1.8	1.8	1.8	1.7	1.7	1.8
	2300	1.6	2.0	1.5	1.7	1.8	1.8	1.8	1.8	1.9	1.9	1.8
	2400	1.6	2.0	1.5	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9
12/6	0100	1.7	2.1	1.5	1.8	1.7	1.7	1.7	1.7	1.9	1.9	1.8
	0200	1.7	2.1	1.5	1.8	1.7	1.7	1.7	1.7	1.8	1.8	1.7
	0300	1.9	2.3	1.5	1.9	1.8	1.9	1.9	2.0	1.9	2.0	2.0
	0400	1.6	2.2	1.5	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.0
	0500	1.7	2.1	1.6	1.8	1.8	1.9	2.0	2.1	2.1	2.2	2.1
	0600	1.7	2.2	1.5	1.8	1.8	1.9	2.0	2.1	2.0	2.1	2.0
	0700	1.6	2.1	1.5	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.1
	0800	1.7	2.1	1.5	1.8	1.9	2.0	1.9	2.0	1.7	1.8	1.9
	0900	1.9	2.3	1.5	1.9	1.8	1.9	1.9	2.0	1.6	1.7	1.9
	1000	1.6	2.1	1.5	1.7	1.6	1.7	1.9	2.0	1.7	1.8	1.8
	1100	1.3	1.8	1.4	1.5	1.6	1.6	1.7	1.7	2.0	1.9	1.7
	1200	1.2	1.8	1.4	1.5	1.6	1.6	1.8	1.8	1.7	1.7	1.7
	1300	1.0	1.7	1.4	1.3	1.3	1.3	1.6	1.6	1.5	1.5	1.5
	1400	0.9	1.5	1.3	1.2	1.3	1.3	1.6	1.6	1.3	1.3	1.4
	1500	0.8	1.5	1.2	1.2	1.2	1.2	1.4	1.4	1.5	1.5	1.4
	1600	0.7	1.5	1.2	1.1	1.2	1.2	1.0	1.0	1.5	1.5	1.2
	1700	0.8	1.4	1.2	1.1	-	-	-	-	-	-	-
	1800	0.9	1.4	1.2	1.2	-	-	-	-	0.6	0.6	0.6?
	1900	0.9	1.4	1.2	1.2	1.6	1.6	1.5	1.5	0.6	0.6	1.2
	2000	1.0	1.5	1.2	1.2	1.6	1.6	1.5	1.5	0.5	0.5	1.2
	2100	1.2	1.7	1.3	1.4	-	-	-	-	0.7	0.7	0.7?

APPENDIX G
Hydrogen Readings

Hydrogen Readings During First Dive

Date	Time	Hydrogen Concentration (% true)		
		Forward Battery Room*	After Battery Room*	Stern Room†
11/30	2200	0	0	0
	2300	0	0	0.2
12/1	0300	0.3	0.1	0.3
	0700	0.42	0.15	0.5
	1100	0.6	0.175	0.6
	1545	0.7	0.5	0.75
	1900	0.75	0.48	0.8
	2300	0.8	0.4	0.8
12/2	0400	0.81	0.3	0.8
	0700	0.81	0.2	0.9
	1200	0.83	0.05	0.9

*From ship's hydrogen indicators
†From NRL Composite Gas Analyzer

Hydrogen Readings During Second Dive

Date	Time	Hydrogen Concentration (% true)		
		Forward Battery Room*	After Battery Room*	Stern Room†
12/3	1100	0.2	0.2	0.0
	1500	0.4	0.3	0.25
	1900	0.7	0.6	0.6
	2400	0.85	0.75	0.9
12/4	0330	1.0	0.8	1.0
	0700	1.1	0.6	1.25
	1100	1.2	0.5	1.4
	1530	-	-	1.5
	1700	1.2	0.25	1.6
	2300	1.3	0.05	1.6
12/5	0330	1.2	0.05	1.6
	0700	1.1	0	1.7
	1200	1.1	0.2	1.75
	1600	1.1	0.6	1.7
	1900	0.9	1.0	1.5
	2300	0.8	2.0	1.3
12/6	0400	0.7	1.4‡	1.1
	0700	0.8	-	1.1
	1100	0.8	-	1.1
	1600	0.8	-	1.1

*From ship's hydrogen indicators
†From NRL Composite Gas Analyzer
‡From ship's portable meter