Naval Submarine Medical Research Laboratory

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STORAGE STABILITY OF LITHIUM HYDROXIDE USED IN THE SUBMARINE FORCE

P. L. Perrotta
Naval Submarine Medical Research Laboratory

A. Davis and A. McCarrick
Carderock Division - Naval Surface Warfare Center

Released by
P. K. WEATHERSBY, CAPT, MSC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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Naval Medical Research and Development Command
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Approved and Released by

P. K. Weathersby, CAPT, MSC, USN
Commanding Officer
NAVSUBMEDRSCHLAB

SUMMARY PAGE

PROBLEM

Lithium hydroxide is the only non-regenerative carbon dioxide absorbent available aboard United States submarines for use during emergency scenarios. Several questions have arisen concerning the use of this material under actual operational conditions. The canisters have no documented shelf-life and relative change in effectiveness of carbon dioxide removal with storage is unknown. It is also uncertain whether extremes in temperatures occurring in various boat compartments affects absorptive capacity.

FINDINGS

We found that canisters 10 years old (from the date displayed on the canister) were significantly less effective than new canisters. Canisters 4 to 9 years old were not statistically different than new canisters although performance slightly decreased. Although lithium hydroxide stored in warmer compartments (e.g. engine room) appeared to be slightly less effective that those stored in other areas, again, this difference was not significant. Absorbent effectiveness was independent of air velocity through the canister and amount of external damage to the container. Canisters which were rejected because they exceeded 10% of their initial labeled gross weight sometimes performed well and sometimes were inadequate for use.

APPLICATION

From these results we recommend that canisters greater than 10 years of age be replaced. Canisters should be distributed throughout the boat as much as possible with a smaller number stored in areas expected to be exposed to higher temperatures. Severely damaged canisters should be replaced because of potential difficulties when inserting them into the hoppers and because of questions concerning the integrity of the container. The procedure of discarding canisters exceeding 10% of their initial weight should be continued because it is not possible on the boat to distinguish whether the weight increase is due to water or carbon dioxide absorption.

ADMINISTRATIVE INFORMATION

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Abstract

We examined several issues concerning the use of lithium hydroxide as a non-regenerative carbon dioxide absorbent on operational submarines. Specific questions concerning the storage of the compound and stability under various storage conditions were addressed. We found that canisters over 10 years old were significantly less effective than new canisters for our measures of effectiveness which included total carbon dioxide absorptive capacity and rate of carbon dioxide absorptive capacity at 4 and 8 hours. Canisters stored in warmer areas such as the engine room appeared to be slightly less effective than those stored in other areas although this difference did not reach statistical significance. Amount of damage to the canister and air velocity through the canister did not appear to decrease performance. It was not possible to predict effectiveness of canisters rejected because they exceeded 10% of their initial weight. We conclude that the shelf-life of operational lithium hydroxide canisters is approximately 10 years and canisters older than this should be replaced. Canisters should be stored throughout the boat with a smaller number kept in warmer compartments. Severely damaged canisters should be replaced because of potential difficulties when inserting these into the hoppers and possible breach in absorbent integrity. The procedure of discarding canisters exceeding 10% of their initial weight should be continued because it is not possible to easily determine on board if this weight change is attributed to water or carbon dioxide absorption.

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Storage Stability of Lithium Hydroxide Used in the Submarine Force

Lithium hydroxide (LiOH) continues to be the only non-regenerative carbon dioxide (CO_2) absorbent used aboard United States (U.S.) submarines. In the event of loss of the regenerative monoethanolamine (MEA) CO_2 scrubber, LiOH would be utilized in a portable canister receptacle blower assembly, or if power was not available to this unit, would be spread out in thin beds[1]. The electrically powered canister receptacles are designed to hold five individual canisters each containing 6.3 pounds of LiOH.

The supply of LiOH is typically divided and stored in forward and aft compartments although this is not always the case. Storage conditions vary in terms of temperature, with aft spaces generally being warmer than those forward, with temperatures reaching 120°F in some areas. There is currently no standard expiration date for canisters of LiOH, so canisters may be older than 10 to 15 years. The canisters are reported to be "air-tight" (Personal communication with Cyprus Foote Mineral, 1993) but are not drawn to vacuum when sealed. Canisters are required[2] to be weighed and if they exceed 110% of their initial weight, are discarded.

The primary objective of this study was to test the CO_2 absorbent performance of a variety of canisters of LiOH obtained from operational boats stored under normal conditions of humidity, temperature, and carbon dioxide concentration, and determine the effects of factors such as age and storage conditions. Results will be used to make specific recommendations to the submarine force.

Background

Reaction of LiOH with CO_2 typically requires water (H_2O) in an amount sufficient to produce $LiOH \cdot H_2O$ by the reaction:

$$LiOH(s) + H_2O(g) \rightarrow LiOH \cdot H_2O(s) \qquad (1)$$

where (s) and (g) denote solid and gaseous phases respectively. The monohydrate and non-hydrated compounds both react with CO_2 to produce the carbonate and water in exothermic reactions:

$$2LiOH \cdot H_2O(s) + CO_2(g) \rightarrow Li_2CO_3(s) + 3H_2O(g) + heat \qquad (2)$$

$$2LiOH(s) + CO_2(g) \rightarrow Li_2CO_3(s) + H_2O(g) + heat \qquad (3)$$

The kinetic factors which drive equations (1) through (3) to the right include higher gas partial pressure of CO_2, high vapor pressure of water,[3] and removal of heat.[4] Bed dynamics, including absorbent bed length and linear gas velocity, also have significant effects on rates of LiOH consumption.[5] Residence time, defined as the time CO_2 is exposed to LiOH, is a convenient means of expressing bed dynamics and has been studied for several CO_2 absorbents.[6] Particle characteristics such as granule porosity alter the surface area and subsequently affect the reaction rate significantly. Optimal reaction bed temperatures and water vapor pressure ranges for absorption of CO_2 have been examined for LiOH.[7] The effect of changes in temperature and humidity in a disabled submarine (DISUB) on absorptive capacity is expected to be small because changes in these parameters is usually small in the normal submarine environment.

Methods

<u>Setup</u>

Approximately 80 LiOH canisters were obtained from Atlantic and Pacific fleet submarines. These canisters were of various ages, weights and conditions of external damage. The canisters were stored in different compartments prior to being collected for testing. New canisters were also obtained. The canisters tested were selected by taking a cross-section from the various grouping characteristics.

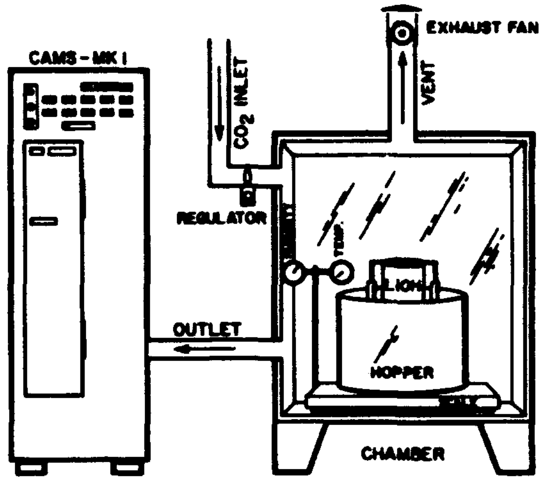

Figure 1. Experimental setup.

The overall experimental design is to measure the gain in canister weight as the LiOH is converted to the heavier Li_2CO_3. The experimental setup was similar to that in a previous study.[8] Two aluminum enclosures were used to contain the hoppers and the test canisters. Figure 1 illustrates the setup of one enclosure during testing. These enclosures were approximately 64 ft^3 with an external supply of CO_2 and an exhaust fan. A Central Atmosphere Monitoring Unit (CAMS MK1) was used to measure the partial pressure of CO_2 in each of the enclosures. The percentage of CO_2 was maintained at 2% by manual regulation for the duration of all individual canister testing. Preliminary tests showed that a 2% level of CO_2 coupled with the air flow from the exhaust fan allowed reaction of the LiOH over an 8-hour shift without creating excessive heat and moisture. Temperature and humidity inside the enclosures were recorded but were not used in the final analysis. The goal was to maintain chamber temperature less than 100°F and relative humidity less than 90%.

Since a hopper is designed to expend 5 canisters simultaneously, it was necessary to block air flow to all but one of the slots. One canister was inserted into the remaining slot and reacted for 8 hours in an atmosphere containing 2% CO_2.

<u>Test Procedure</u>

Canister age, weight, damage and original storage location were recorded at the beginning of each test run. The canister was inserted into the test slot of the hopper, and the Plexiglas cover of the enclosure bolted in place. The flow of CO_2 was then introduced into the hopper enclosure, and regulated until 2% concentration was achieved. Typically, it took less than 2 minutes to stabilize the pressure of CO_2 in the chamber. The hopper and exhaust fan were energized when the chamber CO_2 concentration reached 2%. Weight change, humidity, temperature and partial pressure of CO_2 were measured for eight hours. After this eight hour period, the CO_2 concentration was increased by approximately 20% until there was no change in weight for approximately 1 hour. Final weight of the canisters was then recorded.

Several of the canisters obtained from the boats were identified as "heavy". Heavy canisters were those whose weights exceeded 110% of the manufacturer's labeled gross weight. Small samples (< 20g) were extracted from each of the heavy canisters prior to testing; these samples were weighed and carefully heated (temperature not controlled) to determine if the excess weight could be attributed to water or CO_2. The remainder of these samples were tested in the experimental chambers as previously described.

Data Analysis

Weight change over time data was first examined for each canister test run. Several mathematical equations were evaluated with pilot data to model the test data. The final equation which appeared to give excellent fit through the data had smooth limits at both short and long times and subsequently used for data analysis was:

$$mass(increase)_m = A_1 e^{\frac{-A_2}{t}} + B_1 e^{\frac{-B_2}{t}} \quad (4)$$

The constants A_1, A_2, B_1, and B_2 were estimated for this non-linear equation using least squares to minimize deviations in the estimated mass. The Quasi-Newton estimation method which uses numeric estimates of the first and second derivatives of the least squares function was used . Initial parameters were estimated from inspection of the raw time/mass data. Multiple runs with different starting parameters were performed to assure that the coefficients obtained were optimal. Goodness-of-fit was determined by calculating the squared multiple R (R^2) which denotes the proportion of variance in mass attributed to the time functions.

Three measures of LiOH effectiveness were defined to compare differences between individuals canisters and groupings. Total capacity per canister was defined as the final weight change after expending the canister in a high CO_2 atmosphere multiplied by a factor of 1.69 (1 molecule of CO_2 is gained for each molecule of H_2O lost by equation (3))

$$total\ capacity = (mass_{expended} - mass_{initial})\ 1.69 \quad (5)$$

Average absorption rates in lbm/hr were calculated at 240 minutes ($rate_{240}$) and 480 minutes ($rate_{480}$). The total mass increase over 4 and 8 hours was calculated from the fitted exponential curve and then divided by time to obtain average absorption rates:

$$rate_{240} = \frac{A_1 e^{\frac{-A_2}{240}} + B_1 e^{\frac{-B_2}{240}}}{240} \quad (6)$$

$$rate_{480} = \frac{A_1 e^{\frac{-A_2}{480}} + B_1 e^{\frac{-B_2}{480}}}{480} \quad (7)$$

Differences in effectiveness for various groupings of canisters (e.g. age, storage conditions, damage) were measured by paired samples t-test with SYSTAT statistical software. All reported p-values are two-sided and significant differences are reported when $p < 0.05$.

Results

A total of 45 canisters were tested over 5 weeks. Each canister was exposed to 2% CO_2 for 8 hours. Seven canisters were excluded because of equipment difficulties, leaving 38 canister data sets available for analysis. Temperature of the chamber ranged from 60-100°F and generally was maintained from 85-90°F throughout the majority of the test. Humidity ranged from 25-90%, usually between 30-40%. The weight change test data for each canister is available in Appendix A.

New Canisters

Five new canisters were tested to be used as standards for comparison between the other groups. Each set of mass(time) data was fitted individually to equation (4) and constants obtained (Table 1). Overall fit to the equation was excellent ($R^2 >= 0.999$) and is shown graphically for a single new canister (canister 1) in Figure 2. The initial and final masses and the calculated coefficients showed little variation among the new canisters (Table 1). Total capacity, $rate_{240}$ and $rate_{480}$ are listed in Table 2. The sum of the constants A_1 and B_1 was significantly greater than the total capacity ($p < 0.0001$).

Individual coefficients were averaged to obtain the mass(time) equation that is used to compare other groups:

$$mass_{lb} = 2.77e^{\frac{-0.386}{t}} + 4.88e^{\frac{-3.58}{t}} \quad (8)$$

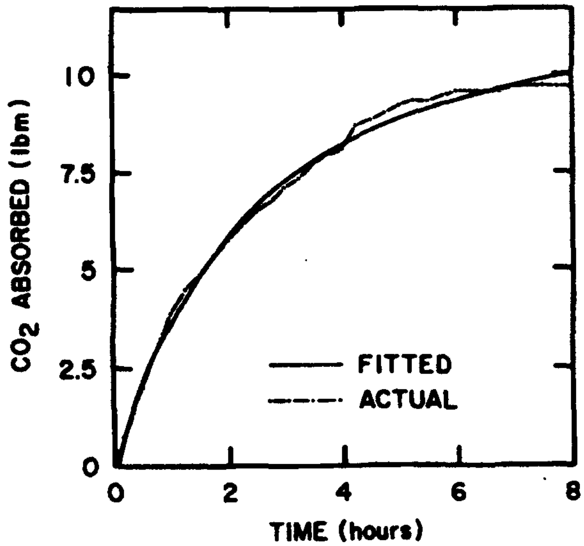

Figure 2. Comparison of test data and fitted equation for a single new canister.

TABLE 1
Summary of New Canisters

Can	Initial Mass (lbm)	Final Mass (lbm)	A1 (lbm)	A2 (hr)	B1 (lbm)	B2 (hr)
1	7.50	10.94	2.38	0.32	5.06	2.46
2	7.54	11.07	2.46	0.31	5.11	3.08
3	7.28	11.02	3.23	0.40	4.49	4.46
4	7.45	10.94	2.99	0.50	4.30	2.94
5	7.50	10.98	2.79	0.37	5.34	4.93

TABLE 2
New Canister Effectiveness

Canister	Total Capacity (lbm)	Rate240 (lbm/hr)	Rate480 (lbm/hr)	Avg. Vel. (ft/min)
1	5.81	1.23	0.75	200
2	5.96	1.16	0.73	230
3	6.33	1.09	0.70	522
4	5.88	1.17	0.72	317
5	5.88	1.02	0.69	397

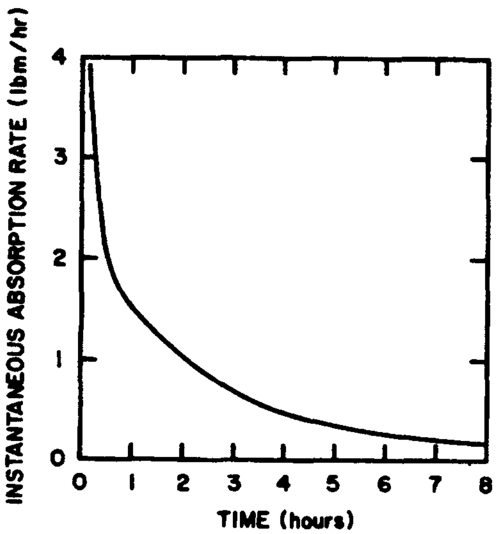

Figure 3. Instantaneous absorption rate over time for a single new canister (canister 1).

Coefficients of variations for A_1, A_2, B_1, and B_2 were 0.128, 0.197, 0.091, and 0.297 respectively.

Instantaneous absorption rate for a single canister can be calculated by taking the derivative of equation (4):

$$rate_{\frac{lb}{hr}} = \frac{\Delta\, mass_{lb}}{\Delta\, t_{hr}} = \frac{-A_1 A_2}{t^2} e^{\frac{-A_2}{t}} + \frac{-B_1 B_2}{t^2} e^{\frac{-B_2}{t}} \qquad (9)$$

Figure 3 shows the instantaneous CO_2 absorption rate (lbm/hr) curve for a representative new cannister. This curve does not represent average absorption rates. These are calculated by equation (6) and (7).

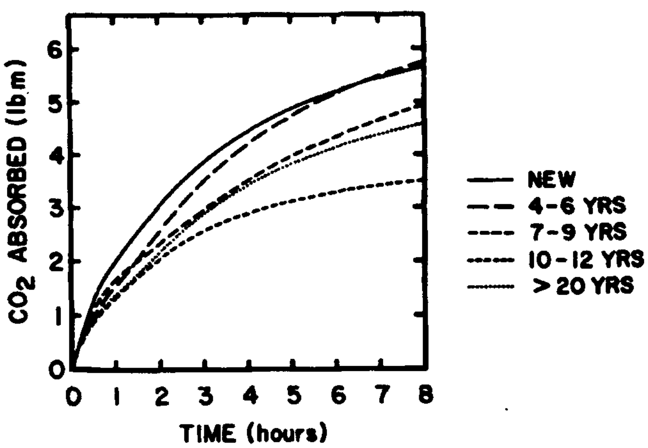

Figure 4. Mass change over time for canisters grouped by age.

TABLE 3
Relative Effectiveness (Standard Deviation) by Age

Age (yr.)	Number of Canisters	Capacity (1bm)		Rate240 (1bm/hr)		Rate480 (1bm/hr)	
New	5	5.98	(0.20)	1.13	(0.07)	0.72	(0.02)
4-6	7	5.77	(0.12)	1.09	(0.16)	0.73	(0.07)
7-9	10	5.62	(0.50)	0.94	(0.20)	0.62	(0.11)
10-12	9	4.07	(0.22)	0.75	(0.13)	0.45	(0.06)
> 20	3	5.44	(0.32)	0.88	(0.19)	0.58	(0.07)

Old Canisters

Twenty-nine canisters ranging from 4 to 23 years old were tested and relative effectiveness compared against new canisters (Table 3). Mass versus time curves are shown in Figure 4 for canisters grouped into various ranges of age. Measures of effectiveness were averaged within age groups for comparison. Canisters 10 to 12 years old were significantly less effective than new canisters in terms of total capacity ($p < 0.001$), average absorption rate at 240 minutes ($p < 0.001$) and average rate at 480 minutes ($p < 0.001$). The three canisters greater than 20 years old appear more effective than those 10 to 12 years old but are still significantly less effective than new canisters for total capacity ($p = 0.027$), $rate_{240}$ ($p = 0.037$), and $rate_{480}$ ($p = 0.008$). Canisters 4 to 6 years old were not different than new canisters for $rate_{240}$, $rate_{480}$, or total capacity. Similarly, canisters 7 to 9 years old showed no significant difference in any of the measures of effectiveness

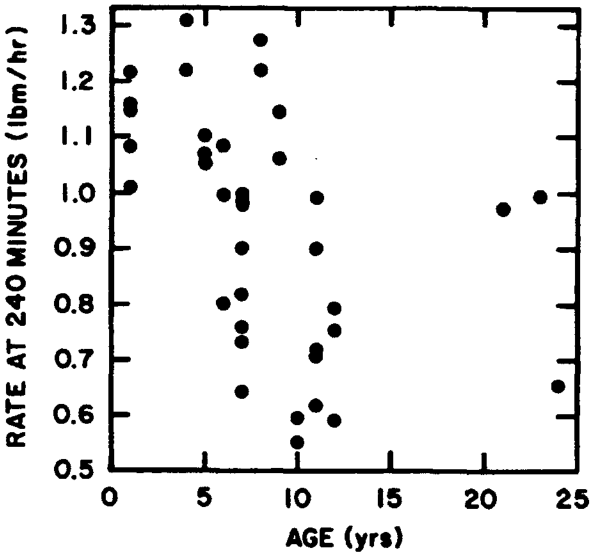

Figure 6. Average $rate_{240}$ of individual canisters and age.

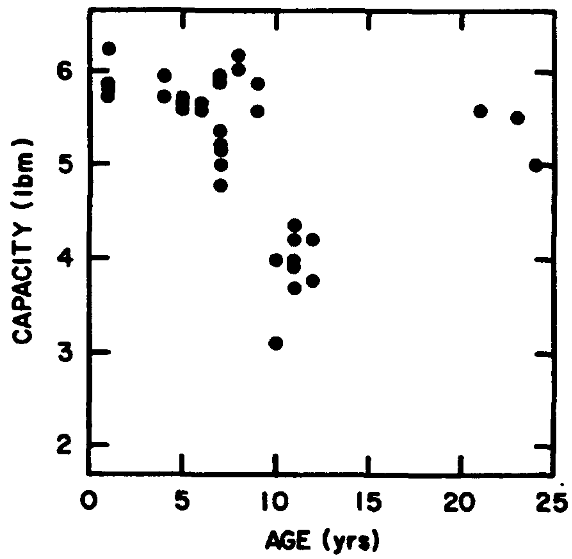

Figure 5. Capacity of individual canisters and age.

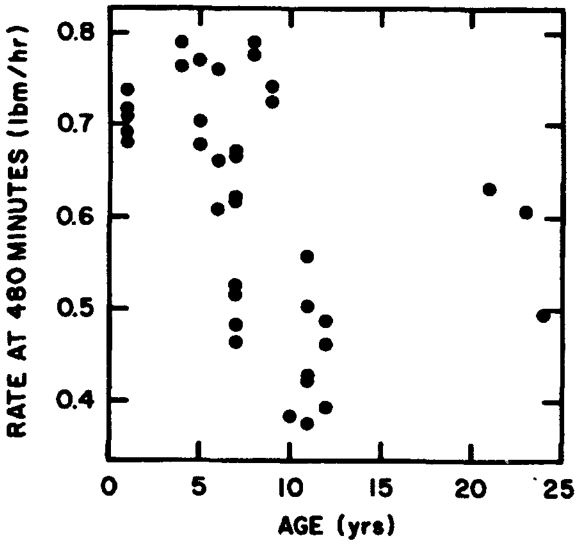

Figure 7. Average $rate_{480}$ of individual canisters and age.

TABLE 4
Relative Effectiveness (Standard Deviation) by Storage Conditions

Storage Location	Capacity (lbm)	$Rate_{240}$ (1bm/hr)	$Rate_{480}$ (1bm/hr)
Engine Room	5.39 (0.46)	0.79 (0.10)	0.50 (0.02)
Torpedo/OPS	5.81 (0.17)	0.93 (0.14)	0.67 (0.06)

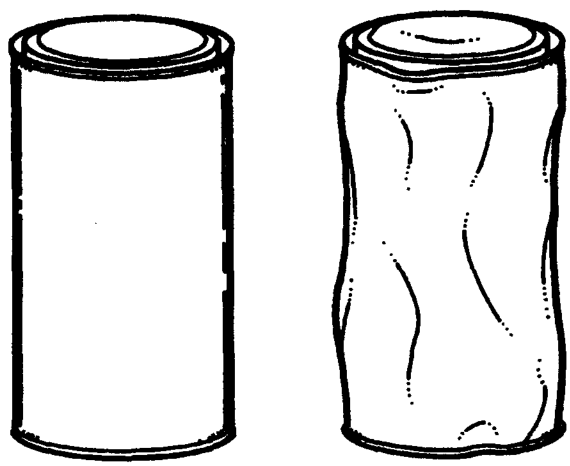

Figure 8. Representative samples of canister damage.

although there was greater variability within the group. Plots of capacity, $rate_{240}$ and $rate_{480}$ versus age for individual canisters is shown in Figures 5-7.

Storage Location
Four canisters stored in the engine room of a 640 class boat were compared with 5 canisters stored in the torpedo room or operations of the same boat (Table 4). All canisters were from 4 to 8 years old. Several of these canisters were also used in the age comparisons. No significant difference was found in total capacity and $rate_{240}$, although the relative effectiveness of those stored in the engine room was decreased at 8 hours ($p=0.002$). When the mean values for constants (A_1, A_2, B_1, B_2) derived for these groups are obtained, no significant difference is demonstrated.

Effects of External Damage
Seventeen canisters from 4 to 8 years old were subjectively divided into 2 groups based on external damage (none/mild, moderate/severe). Figure 8 shows representative samples from each group. Several of these canisters were used in the age comparisons. No significant difference was found between these two groups for total capacity, $rate_{240}$ or $rate_{480}$ (Table 5). It was subjectively noted that the severely damaged canisters were more difficult to insert in the hopper. It is uncertain how this would impact actual submarine use.

Air Velocity Effects
To study the effects of air velocity on effectiveness, seventeen canisters matched for age

TABLE 5
Relative Effectiveness (Standard Deviation) and Canister Damage

Amount of Damage	Capacity (lbm)	$Rate_{240}$ (1bm/hr)	$Rate_{480}$ (1bm/hr)
None/Mild	5.84 (0.27)	0.95 (0.19)	0.66 (0.11)
Moderate/Severe	5.54 (0.43)	1.05 (0.20)	0.67 (0.11)

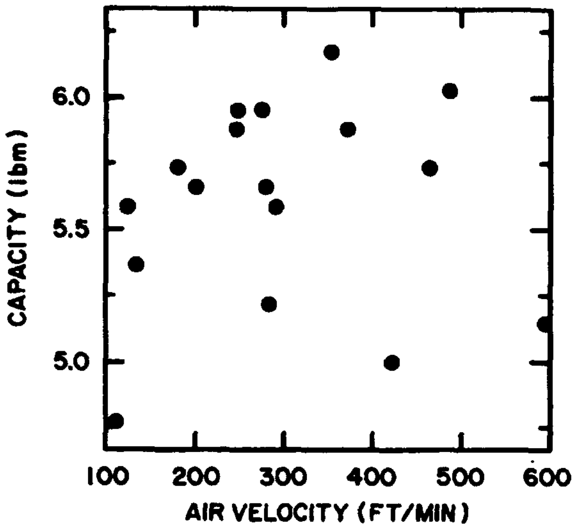

Figure 9. Air velocity and total capacity.

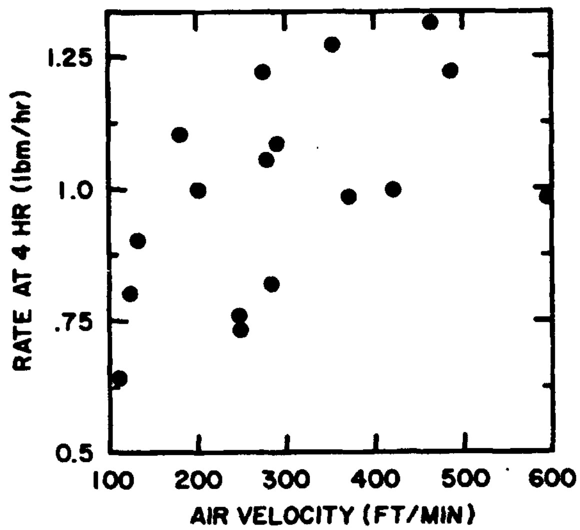

Figure 10. Air velocity and average $rate_{240}$.

were compared. No correlation was found between air velocity and total capacity, $rate_{240}$, or $rate_{480}$ as demonstrated in the scatter plots (Figures 9 and 10) and suggested by regression analysis (slope of regression analysis = 0.001 and $R^2 > 0.30$ for each correlation).

<u>Heavy Canisters</u>

Four canisters rejected from operational units because of an increase in weight during storage were tested. Samples from all of the canisters decreased in weight from 5% to 23% when gently heated over approximately 2 hours (Table 6). No correlation could be found between the weight loss during heating and our various measures of effectiveness. No significant differences were found when the averages for this group were compared to the group of new canisters although canister 35 performed extremely poorly.

TABLE 6
Heavy Canister Effectiveness

Canister	Capacity (lbm)	$Rate_{240}$ (1bm/hr)	$Rate_{480}$ (1bm/hr)	Weight Loss (%)
35	3.13	0.56	0.34	22
36	5.96	1.07	0.75	23
37	5.66	1.16	0.73	15
38	5.66	1.08	0.71	5

Discussion

The most important aspect of this study was considered the determination of a shelf-life for canisters of lithium hydroxide. We have shown that there appeared to be a significant decrease in absorptive capacity for canisters that have been stored on boats for more than 10 years. Although there is a mild drop in effectiveness for canisters over 5 years of age (mean decrease in capacity for those 7 to 9 years old was only 0.21 lbm), these changes were not statistically significant and are not expected to dramatically effect actual use scenarios.

There are several possible explanations for this drop in effectiveness of older canisters. It was observed that the LiOH of the oldest canisters was less granular than new canisters, and was slightly "caked". This could certainly effect absorptive area and decrease flow through the material. The safety implications of contacting the older material are unknown, but include the same caustic effects on skin and respiratory mucosa.

Although canisters that were stored in warmer areas (e.g. engine room), appeared to be slightly less effective than those stored in other areas, the differences were not statistically significant. It was expected that LiOH would remain stable at the temperatures expected in the worst conditions, but there may be mild degradation. From an operational standpoint, it appears logical to store canisters throughout the boat, forward and aft. Our results suggest that it may be reasonable to store smaller amounts in the warmest compartments.

A surprising result was that canister effectiveness was independent of measured air velocity. It was originally thought that absorptive capacity would be highly dependent on air flow and a large amount of time was spent attempting, unsuccessfully, to standardize air flow. The hoppers may be generating more than sufficient flow of air though the canisters, thereby limiting the effects that may be seen if smaller air velocities were examined. Although only a single canister was tested at a time instead of 5, we expect the results were not affected, because of the tight control of CO2 concentration.

We also found that the amount of external damage did not negatively impact canister performance. This would be expected as long as there was no breach in the canister's integrity with subsequent exposure to ambient carbon dioxide. From a usage standpoint though, it would be reasonable to discard severely damaged canisters because they may not be able to be inserted into the hopper if both ends are damaged. Evidence of oxidative damage (rust) may also suggest a higher risk of loss of canister integrity although quantitative data is not available for confirmation.

Interpretation of the results of heavy canisters must be done with great caution. The decrease in weight of the LiOH on heating is assumed to be due to loss of water since the hydroxide and carbonate compounds should be stable at the temperatures used. No chemical analysis of the compound was performed. Hydration of LiOH should not degrade effectiveness since the hydrate is formed prior to reaction with CO_2 by equation (1). The amount of water in $LiOH \cdot H_2O$ is approximately 43%. Therefore, the decrease in weight found probably indicates the presence of partially hydrated material which does not decrease the material's CO_2 absorbant capacity. Effectiveness of three of the four canisters were quite good although the number of canisters may have been too small for a good analysis. Since it is not possible to unambiguously determine whether the increase in weight is due to absorption of CO_2, water or other contaminants without chemical analysis, it appears reasonable to continue the practice of replacing canisters that are over 10% of their initial labeled weight.

There were several assumptions made which could be interpreted as weaknesses in our experimental design. It was assumed that the beds of lithium hydroxide were hot enough to evaporate all of the liberated water. If this were not true, then water condensing within the bed or on the wall of the canister would cause a greater increase in weight. The chamber temperature, not the bed temperature, was measured during the runs.

The weight gain measured was assumed to be a function only of carbon dioxide uptake by equation (3). Water vapor formed when CO_2 reacts with LIOH should be immediately expelled from the chamber by the high air flow, therefore making the contributions of equation (2) insignificant. Relative humidities were recorded as high as 90% during the runs despite attempts to keep this humidity down by using a muffin fan and running the tests at a reasonable CO_2 concentration (2%). No control runs of 0% CO_2 in a humid environment were run to further examine these aspects.

Our series of exponential terms equation (4) that we used to model the change in weight of the canisters for each run consistently overestimated the total capacity of each canister. The sum of Al and Bl should be equal to the weight of the expended canister. This is probably a combination of both weaknesses in the experimental design and the model. Each canister was run for only 8 hours which may not have been long enough for the model to estimate the asymptote. The process may not truly reach a smooth asymptote, and instead may more quickly reach an endpoint. As mentioned previously, the effects of water vapor on lithium hydroxide were not accounted for. If water reacted with lithium hydroxide by equation (2) in a significant amount, there would be a small weight loss associated with the formation of carbonate.

We did not feel that the asymptote was the most critical aspect of this model because lithium hydroxide canisters would not be used until they were totally expended under normal use. For example, if one person produces 0.10 lbm/hr of CO_2, 10 men would produce 1.0 lbm/hr. To keep up with this production, LIOH would need to remove this 1.0 lb/hr. When the C02 absorbency rate drops below this value, C02 would start to accumulate in the atmosphere. This change will occur long before the asymptotic value is approached.

We do not feel that these weaknesses impact our final recommendations concerning the relative effectiveness of the canisters tested. All conditions were controlled as well as possible and operating conditions were the same for each canister. Previous studies in the Navy examining lithium hydroxide have generally used the weight gain method and should therefore also be looked at critically. Lithium hydroxide scrubbing efficiency could be examined by smaller bench studies, but this was not our intent from the beginning. Rather, we were more interested in larger scale studies using lithium hydroxide as it is used in the submarine force in hopes of providing information that could help add to current standard operating procedures.

Recommendations

1. Discard all canisters of lithium hydroxide 10 years after the date stamped on the canister by the manufactures.

2. Store lithium hydroxide in both forward and aft compartments, with a smaller proportion of canisters being stored in engine rooms or areas expected to have higher temperatures.

3. Discard canisters that appear severely damaged.

4. Continue replacing canisters that exceed 10% of their initial weight.

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APPENDIX A

LITHIUM HYDROXIDE TEST DATA

This appendix shows all canister test data analyzed. Time is in minutes and weight is in lb-m.

TIME (minutes)	CAN 1	CAN 2	CAN 3	CAN 4	CAN 5	CAN 6	CAN 7	CAN 8
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.13	0.18	0.15	0.11	0.11	0.09	0.13	0.18
10	0.26	0.31	0.20	0.20	0.20	0.18	0.22	0.26
15	0.35	0.40	0.42	0.29	0.37	0.22	0.31	0.35
20	0.49	0.53	0.53	0.37	0.51	0.26	0.35	0.44
25	0.62	0.62	0.71	0.49	0.64	0.31	0.44	0.53
30	0.71	0.75	0.79	0.62	0.77	0.31	0.53	0.62
40	0.93	0.93	1.04	0.79	0.95	0.40	0.71	0.79
50	1.15	1.10	1.21	1.01	1.08	0.49	0.84	0.97
60	1.37	1.28	1.34	1.19	1.17	0.53	0.97	1.10
75	1.59	1.46	1.46	1.48	1.30	0.62	1.19	1.28
90	1.72	1.59	1.59	1.70	1.43	0.75	1.32	1.41
105	1.90	1.76	1.74	1.90	1.52	0.84	1.50	1.54
120	2.03	1.90	1.90	2.05	1.65	0.93	1.63	1.63
135	2.16	2.03	2.01	2.16	1.76	1.01	1.76	1.76
150	2.29	2.12	2.09	2.25	1.87	1.06	1.85	1.85
165	2.38	2.25	2.14	2.29	1.96	1.15	1.98	1.94
180	2.51	2.34	2.18	2.38	2.01	1.23	2.07	2.03
195	2.60	2.47	2.29	2.43	2.09	1.30	2.16	2.12
210	2.73	2.56	2.36	2.49	2.20	1.39	2.25	2.20
225	2.82	2.65	2.49	2.58	2.20	1.41	2.34	2.25
240	2.87	2.73	2.54	2.65	2.29	1.46	2.38	2.34
255	3.09	2.87	2.67	2.80	2.54	1.59	2.51	2.38
270	3.13	2.91	2.76	2.89	2.62	1.68	2.51	2.43
285	3.20	2.98	2.82	3.00	2.77	1.76	2.56	2.47
300	3.26	3.04	2.89	3.06	2.87	1.85	2.60	2.51
315	3.31	3.09	2.98	3.13	2.91	1.90	2.65	2.56
330	3.31	3.13	3.02	3.17	2.95	1.98	2.69	2.60
345	3.35	3.17	3.06	3.24	2.98	2.03	2.73	2.65
360	3.40	3.17	3.11	3.28	2.98	2.12	2.73	2.69
375	3.40	3.26	3.15	3.31	2.98	2.16	2.78	2.91
390	3.40	3.31	3.20	3.33	2.98	2.20	2.78	2.91
405	3.40	3.31	3.20	3.33	2.98	2.20	2.82	2.91
420	3.44	3.35	3.20	3.33	2.98	2.25	2.82	2.95
435	3.44	3.35	3.20	3.33		2.25	2.82	3.00
450	3.44	3.40	3.24	3.33		2.29	2.87	3.00
465	3.44	3.40	3.24	3.33		2.29	2.87	3.04
480	3.44	3.44	3.24	3.33		2.29	2.91	3.04

TIME (minutes)	CAN 9	CAN 10	CAN 11	CAN 12	CAN 13	CAN 14	CAN 15	CAN 16
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.09	0.13	0.13	0.13	0.15	0.13	0.22	0.18
10	0.13	0.22	0.22	0.22	0.24	0.22	0.40	0.33
15	0.22	0.31	0.26	0.26	0.40	0.31	0.46	0.46
20	0.26	0.35	0.31	0.35	0.49	0.35	0.57	0.62
25	0.31	0.40	0.40	0.44	0.60	0.40	0.66	0.71
30	0.35	0.49	0.44	0.49	0.68	0.49	0.75	0.82
40	0.44	0.57	0.53	0.62	0.79	0.57	0.90	1.01
50	0.53	0.71	0.62	0.71	0.90	0.62	1.06	1.23
60	0.66	0.84	0.66	0.79	0.99	0.71	1.19	1.37
75	0.79	0.97	0.75	0.93	1.12	0.79	1.37	1.52
90	0.97	1.10	0.84	1.01	1.21	0.93	1.52	1.65
105	1.10	1.23	0.93	1.10	1.32	1.01	1.61	1.81
120	1.23	1.28	0.97	1.19	1.37	1.06	1.72	1.90
135	1.37	1.37	1.06	1.28	1.41	1.15	1.83	1.98
150	1.50	1.46	1.10	1.37	1.48	1.19	1.92	2.07
165	1.59	1.50	1.15	1.46	1.52	1.23	1.98	2.14
180	1.68	1.59	1.19	1.50	1.54	1.28	2.03	2.23
195	1.76	1.63	1.28	1.54	1.59	1.37	2.12	2.23
210	1.85	1.68	1.32	1.59	1.65	1.41	2.14	2.29
225	1.90	1.72	1.37	1.68	1.68	1.41	2.14	2.31
240	1.94	1.76	1.41	1.72	1.70	1.50	2.20	2.36
255	2.03	1.81	1.46	1.72	1.74	1.50	2.20	2.40
270	2.07	1.85	1.50	1.76	1.76	1.54	2.23	2.40
285	2.07	1.90	1.50	1.81	1.76	1.54	2.25	2.45
300	2.12	1.94	1.54	1.85	1.81	1.59	2.25	2.45
315	2.12	1.94	1.59	1.85	1.83	1.63	2.27	2.47
330	2.16	1.98	1.63	1.90	1.85	1.63	2.29	2.49
345	2.16	2.03	1.68	1.90	1.87	1.68	2.31	2.51
360	2.16	2.03	1.68	1.90	1.90	1.68	2.31	2.56
375	2.20	2.07	1.72	1.94	1.94	1.72	2.34	2.58
390	2.20	2.16	1.76	1.98	1.96	1.72	2.34	2.60
405	2.20	2.16	1.76	1.98	2.03	1.72	2.34	2.65
420	2.25	2.20	1.81	1.98	2.05	1.76	2.34	2.65
435	2.25	2.20	1.85	1.98	2.03	1.76	2.38	2.71
450	2.25	2.20	1.85	2.03	2.01	1.76	2.38	2.69
465	2.25	2.25	1.90	2.03	2.01	1.81	2.38	2.71
480	2.29	2.25	1.90	2.07	2.03	1.81	2.40	2.76

TIME (minutes)	CAN 17	CAN 18	CAN 19	CAN 20	CAN 21	CAN 22	CAN 23	CAN 24
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.13	0.22	0.22	0.18	0.04	0.18		0.18
10	0.18	0.31	0.33	0.26	0.15	0.26	0.26	0.26
15	0.22	0.44	0.49	0.31	0.22	0.33	0.35	0.31
20	0.26	0.60	0.64	0.40	0.33	0.42	0.44	0.40
25	0.31	0.71	0.75	0.49	0.46	0.51	0.49	0.49
30	0.35	0.79	0.88	0.53	0.55	0.60	0.57	0.53
40	0.40	1.06	1.12	0.66	0.73	0.75	0.71	0.71
50	0.49	1.32	1.34	0.79	0.93	0.90	0.84	0.88
60	0.53	1.52	1.50	0.93	1.10	1.06	1.01	1.01
75	0.66	1.74	1.70	1.10	1.34	1.28	1.19	1.23
90	0.75	1.96	1.92	1.23	1.50	1.52	1.32	1.41
105	0.84	2.09	2.12	1.37	1.63	1.68	1.50	1.63
120	0.93	2.18	2.23	1.50	1.76	1.85	1.63	1.85
135	1.06	2.27	2.34	1.63	1.87	1.96	1.76	2.03
150	1.10	2.36	2.43	1.76	1.96	2.07	1.94	2.20
165	1.19	2.43	2.51	1.90	2.05	2.18	2.07	2.38
180	1.23	2.51	2.62	1.98	2.14	2.29	2.16	2.51
195	1.28	2.58	2.73	2.12	2.23	2.38	2.29	2.65
210	1.32	2.69	2.84	2.20	2.29	2.43	2.38	2.78
225	1.37	2.82	2.95	2.29	2.36	2.51	2.47	2.87
240	1.41	2.91	3.06	2.38	2.43	2.60	2.51	3.00
255	1.46	3.00	3.17	2.43	2.47	2.69	2.60	3.09
270	1.46	3.06	3.22	2.51	2.49	2.78	2.65	3.13
285	1.50	3.15	3.28	2.56	2.56	2.89	2.69	3.22
300	1.54	3.22	3.33	2.60	2.60	2.95	2.78	3.26
315	1.59	3.31	3.42	2.65	2.65	3.02	2.82	3.31
330	1.59	3.37	3.44	2.69	2.69	3.06	2.82	3.35
345	1.63	3.42	3.48	2.73	2.71	3.09	2.87	3.40
360	1.63	3.46	3.51	2.78	2.76	3.13	2.91	3.44
375	1.72	3.62	3.59	2.82	2.93	3.37	3.04	3.53
390	1.76	3.66	3.62	2.82	2.98	3.42	3.09	3.53
405	1.76	3.68	3.64	2.87	3.04	3.53	3.13	3.53
420	1.81	3.70	3.66	2.87	3.06	3.59	3.17	3.53
435	1.81	3.66	3.66	2.91	3.13	3.64	3.22	3.53
450	1.85	3.70	3.66	2.91	3.17	3.70	3.26	3.57
465	1.85	3.73	3.66	2.95	3.17	3.70	3.31	3.57
480	1.85	3.73	3.68	2.95		3.73	3.31	3.57

TIME (minutes)	CAN 25	CAN 26	CAN 27	CAN 28	CAN 29	CAN 30	CAN 31	CAN 32
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.20	0.09	0.20	0.20	0.15	0.15	0.13	0.15
10	0.29	0.13	0.35	0.37	0.24	0.18	0.22	0.24
15	0.37	0.18	0.44	0.44	0.33	0.22	0.26	0.31
20	0.49	0.20	0.53	0.51	0.44	0.31	0.31	0.35
25	0.57	0.26	0.60	0.55	0.51	0.40	0.35	0.44
30	0.68	0.31	0.68	0.64	0.62	0.46	0.44	0.53
40	0.90	0.42	0.86	0.79	0.82	0.62	0.53	0.66
50	1.10	0.51	1.01	1.01	0.93	0.73	0.62	0.79
60	1.32	0.57	1.19	1.15	1.10	0.86	0.71	0.88
75	1.59	0.73	1.39	1.34	1.28	0.95	0.84	1.04
90	1.85	0.86	1.46	1.48	1.41	1.06	0.97	1.17
105	2.05	0.93	1.50	1.54	1.52	1.12	1.10	1.32
120	2.23	0.99	1.57	1.61	1.65	1.19	1.23	1.34
135	2.36	1.10	1.59	1.68	1.79	1.28	1.37	1.41
150	2.45	1.15	1.65	1.74	1.85	1.30	1.46	1.48
165	2.56	1.19	1.68	1.83	1.94	1.41	1.59	1.57
180	2.69	1.30	1.68	1.94	1.98	1.48	1.68	1.74
195	2.80	1.34	1.70	2.03	2.05	1.52	1.76	1.90
210	2.91	1.39	1.72	2.20	2.09	1.63	1.85	2.03
225	3.00	1.43	1.76	2.31	2.12	1.72	1.85	2.20
240	3.13	1.52	1.81	2.40	2.16	1.76	1.94	2.36
255	3.26	1.57	1.87	2.47	2.18	1.85	2.03	2.51
270	3.28	1.63	1.92	2.47	2.20	1.94	2.12	2.67
285	3.40	1.70	1.96	2.58	2.23	2.01	2.16	2.84
300	3.46	1.74	1.98	2.67	2.25	2.09	2.20	3.00
315	3.53	1.81	1.98	2.67	2.29	2.18	2.20	3.09
330	3.55	1.87	2.01	2.71	2.38	2.29	2.25	3.15
345	3.59	1.92	2.05	2.76	2.36	2.38	2.29	3.22
360	3.62	1.96	2.07	2.80	2.34	2.47	2.34	3.28
375	3.66	2.01	2.09	2.82	2.40	2.56	2.34	3.31
390	3.68	2.05	2.12	2.84	2.43	2.67	2.38	3.33
405	3.68	2.07	2.16	2.87	2.40	2.82	2.43	3.37
420	3.70	2.09	2.18	2.84	2.43	2.91	2.43	3.40
435	3.73	2.14	2.20	2.87	2.45	3.00	2.43	3.42
450	3.75	2.16	2.27	2.89	2.45	3.11	2.47	3.44
465	3.75	2.20	2.31	2.89	2.47	3.15	2.47	3.48
480	3.73	2.20	2.36	2.89	2.47	3.20	2.51	3.51

TIME (minutes)	CAN 33	CAN 34	CAN 35	CAN 36	CAN 37	CAN 38
0	0.00	0.00	0.00	0.00	0.00	0.00
5	0.13	0.18	0.11	0.13	0.20	0.18
10	0.18	0.24	0.18	0.26	0.31	0.26
15	0.26	0.37	0.24	0.35	0.42	0.31
20	0.31	0.46	0.29	0.40	0.53	0.40
25	0.35	0.55	0.33	0.49	0.64	0.44
30	0.40	0.64	0.37	0.57	0.68	0.53
40	0.49	0.82	0.49	0.75	0.82	0.62
50	0.57	0.93	0.57	0.88	0.97	0.75
60	0.66	1.10	0.66	1.01	1.15	0.84
75	0.79	1.30	0.77	1.23	1.30	1.01
90	0.97	1.48	0.86	1.41	1.59	1.19
105	1.06	1.65	0.88	1.59	1.76	1.37
120	1.19	1.81	0.95	1.72	1.87	1.50
135	1.28	1.92	1.01	1.85	1.98	1.68
150	1.37	2.05	1.06	1.94	2.12	1.81
165	1.46	2.18	1.10	2.03	2.23	1.98
180	1.54	2.27	1.17	2.12	2.34	2.12
195	1.63	2.36	1.21	2.20	2.43	2.29
210	1.72	2.43	1.26	2.29	2.45	2.43
225	1.76	2.54	1.28	2.38	2.60	2.51
240	1.85	2.60	1.32	2.47	2.67	2.60
255	1.94	2.69	1.34	2.56	2.73	2.69
270	2.07	2.73	1.37	2.65	2.87	2.78
285	2.16	2.80	1.39	2.78	2.98	2.82
300	2.20	2.84	1.41	2.87	3.06	2.91
315	2.29	2.89	1.43	2.95	3.11	2.95
330	2.38	2.93	1.46	3.04	3.17	3.00
345	2.47	2.98	1.48	3.13	3.17	3.09
360	2.56	3.00	1.52	3.22	3.28	3.13
375	2.60	3.00	1.52	3.31	3.33	3.17
390	2.65	3.04	1.54	3.35	3.35	3.17
405	2.73	3.04	1.54	3.40	3.37	3.22
420	2.78	3.09	1.57	3.44	3.40	3.22
435	2.82	3.11	1.59	3.44	3.42	3.26
450	2.82	3.13	1.61	3.48	3.44	3.26
465	2.87	3.15	1.63	3.48	3.44	3.31
480	2.91	3.15	1.63	3.53	3.44	3.31

APPENDIX B

LITHIUM HYDROXIDE RESULTS

Coding of columns is as follows:

CAN:	# of canister
AGE:	Age of canisters in yrs
DAMAGE:	0: No damage 1: Mild damage 2: Moderate damage 3: Severe damage
STORED:	0: Unknown 1: Engine room of 640 class 2: Torpedo room or OPS of 640 class
HEAVY:	0: Normal 1: Exceeded 10% of initial weight

CAN	AGE (yrs)	DAMAGE	STORED	HEAVY	VELOCITY (ft/min)	INITIAL WT (lb-m)	EXPENDED WT (lb-m)
1	1	0	0	0	200	7.50	10.94
2	1	0	0	0	230	7.54	11.07
3	1	0	0	0	522	7.28	11.02
4	1	0	0	0	317	7.45	10.94
5	1	0	0	0	397	7.50	10.98
6	24	3	0	0	59	8.16	11.16
7	23	3	0	0	171	7.72	11.02
8	21	1	0	0	306	7.76	11.11
9	12	2	0	0	179	7.50	10.01
10	12	3	0	0	125	7.89	10.41
11	12	1	0	0	217	7.72	9.97
12	11	2	0	0	222	6.79	9.30
13	11	1	0	0	353	7.72	10.10
14	11	3	0	0	220	7.85	10.05
15	11	1	0	0	412	7.50	9.83
16	11	1	0	0	743	7.58	10.19
17	10	2	0	0	109	8.29	10.67
18	8	0	0	0	488	7.89	11.51
19	8	2	0	0	354	7.80	11.51
20	7	2	0	0	595	7.63	10.72
21	7	2	0	0	422	7.58	10.58
22	5	2	0	0	181	7.89	11.33
23	5	2	0	0	280	7.89	11.29
24	4	1	0	0	275	7.94	11.51
25	4	2	0	0	465	7.89	11.33
26	7	2	1	0	112	7.85	10.72
27	7	0	1	0	247	7.72	11.24
28	7	1	2	0	372	7.72	11.24
29	7	2	1	0	134	7.72	10.94
30	7	1	2	0	248	7.80	11.38
31	7	1	1	0	284	7.85	10.98
32	6	1	2	0	202	7.85	11.24
33	6	1	2	0	125	7.98	11.33
34	6	3	2	0	291	7.76	11.11
35	10	3	0	1	154	8.73	10.58
36	9	2	0	1	671	7.76	11.29
37	9	2	0	1	366	7.94	11.29
38	5	2	0	1	129	8.07	11.42

CAN	A_1 (lb-m)	A_2 (hour)	B_1 (lb-m)	B_2 (hour)	RESIDUAL	R^2	CORR R^2
1	2.38	0.32	5.06	2.46	0.169	0.999	0.997
2	2.46	0.31	5.11	3.08	0.07	1.000	0.998
3	3.23	0.40	4.49	4.46	0.105	0.999	0.997
4	2.99	0.50	4.30	2.94	0.206	0.999	0.996
5	2.79	0.37	5.34	4.93	0.185	0.999	0.994
6	1.19	0.31	5.29	4.93	0.08	0.999	0.996
7	1.24	0.20	4.85	2.13	0.033	1.000	0.999
8	2.77	0.43	4.32	4.36	0.126	0.999	0.996
9	0.58	0.11	4.31	1.95	0.059	0.999	0.997
10	1.32	0.23	3.35	2.48	0.052	0.999	0.997
11	1.41	0.28	3.02	4.11	0.033	0.999	0.997
12	1.24	0.21	3.02	2.33	0.021	1.000	0.999
13	2.07	0.28	2.06	2.96	0.041	1.000	0.997
14	1.11	0.17	2.64	2.43	0.016	1.000	0.999
15	1.11	0.08	3.46	1.21	0.019	1.000	0.999
16	1.73	0.18	3.39	1.46	0.038	1.000	0.998
17	0.79	0.15	3.26	2.72	0.031	1.000	0.998
18	4.25	0.50	5.05	5.75	0.214	0.999	0.996
19	3.01	0.32	4.95	2.91	0.122	1.000	0.998
20	1.29	0.18	5.25	2.60	0.041	1.000	0.999
21	4.22	0.76	4.50	8.41	0.102	0.999	0.997
22	3.61	0.61	6.32	6.13	0.262	0.999	0.995
23	1.78	0.28	5.54	3.01	0.054	1.000	0.999
24	1.05	0.13	6.88	2.24	0.106	1.000	0.998
25	1.60	0.20	6.30	2.03	0.115	1.000	0.998
26	1.93	0.61	4.11	5.91	0.048	0.999	0.998
27	3.21	0.44	3.81	11.76	0.158	0.999	0.99
28	1.94	0.23	4.55	3.00	0.212	0.999	0.993
29	1.02	0.13	3.77	1.40	0.018	1.000	0.999
30	2.65	0.58	13.33	11.95	0.075	0.999	0.998
31	0.94	0.15	4.62	2.61	0.024	1.000	0.999
32	1.91	0.33	8.40	5.21	0.422	0.998	0.992
33	1.82	0.43	6.41	5.51	0.096	0.999	0.997
34	1.52	0.20	5.14	2.23	0.029	1.000	0.999
35	1.13	0.25	2.23	2.58	0.024	1.000	0.997
36	2.93	0.49	6.32	5.23	0.171	0.999	0.996
37	1.92	0.23	5.78	2.86	0.112	1.000	0.998
38	1.11	0.14	6.58	2.81	0.071	1.000	0.999

CAN	CAPACTIY (lb-m)	$RATE_{240}$ (lb-m/hr)	$RATE_{480}$ (lb-m/hr)
1	5.81	1.23	0.75
2	5.96	1.16	0.73
3	6.33	1.09	0.70
4	5.88	1.17	0.72
5	5.88	1.02	0.69
6	5.06	0.66	0.50
7	5.58	1.00	0.61
8	5.66	0.98	0.64
9	4.24	0.80	0.49
10	4.24	0.76	0.46
11	3.80	0.60	0.39
12	4.24	0.71	0.43
13	4.02	0.72	0.42
14	3.72	0.62	0.38
15	3.94	0.91	0.51
16	4.39	1.00	0.56
17	4.02	0.60	0.38
18	6.11	1.23	0.80
19	6.25	1.29	0.79
20	5.21	0.99	0.63
21	5.06	1.01	0.67
22	5.81	1.11	0.78
23	5.73	1.06	0.69
24	6.03	1.23	0.78
25	5.81	1.32	0.80
26	4.84	0.65	0.47
27	5.96	0.76	0.49
28	5.96	0.99	0.62
29	5.44	0.91	0.52
30	6.03	0.74	0.68
31	5.29	0.82	0.53
32	5.73	1.01	0.77
33	5.66	0.81	0.61
34	5.66	1.09	0.67
35	3.13	0.56	0.34
36	5.96	1.07	0.75
37	5.66	1.16	0.73
38	5.66	1.08	0.71

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We examined several issues concerning the use of lithium hydroxide as a non-regenerative carbon dioxide absorbent on operational submarines. Specific questions concerning the storage of the compound and stability under various storage conditions were addressed. We found that canisters over 10 years old were significantly less effective than new canisters for oueasures of effectiveness which included total carbon dioxide absorptive capacity and rate of carbon dioxide absorptive capacity at 4 and 8 hours. Canisters stored in warmer areas such as the engine room appeared to be slightly less effective than those stored in other areas although this difference did not reach statistical significance. Amount of damage to the canister and air velocity through the canister did not appear to decrease performance. It was not possible to predict effectiveness of canisters rejected because they exceeded 10% of their initial weight. We conclude that the shelf-life of operational lithium hydroxide canisters is approximately 10 years and canisters older than this should be replaced. Canisters should be stored throughout the boat with a smaller number kept in warmer compartments. Severely damaged canisters should be replaced because of potential difficulties when inserting these into the hoppers and possible breach in absorbent integrity. The procedure of discarding canisters exceeding 10% of their initial weight should be continued because it is not possible to easily determine on board if this weight change is attributed to water or carbon dixoide absorption.

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