

# Naval Submarine Medical Research Laboratory

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Recalculation of Carbon Dioxide Scrubbing Capacity of Battelle Curtains: Implications for  
Distressed Submarine Survivability Lithium Hydroxide Load Out Requirements

-AND-

Addendum to NSMRL Technical Reports No. 1228 of 27 August 2003 No. TR--2009-1270  
of 12 August 2009

by:

Anthony Quatroche  
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<p>This document is a response to Naval Surface Warfare Center Philadelphia Detachment (NSWCPD) Code 416 Comments on Naval Sea Systems Command (PMS-390) Proposed Alteration and Improvement (A&amp;I), "Partial Replacement of Granular lithium hydroxide (LiOH) Canisters and LiOH Curtain Kits with ExtendAir Canisters and ExtendAir Deployment Kits in the Forward Compartment of SSN 688 Class Submarines." This document will also serve as an addendum to Naval Submarine Medical Research Laboratory (NSMRL) technical reports TR1228 and TR--2009-1270. The A&amp;I is proposed to correct the inconsistency in the published carbon dioxide (CO2) absorption effectiveness of granular LiOH as used in Battelle Curtains. For only the forward compartment of the Los Angeles Class the value used was 0.85 lbs. of CO2 absorbed per 1.0 lb. of LiOH. For all other classes of submarines and all other compartments the value used was 0.75 lbs. of CO2 absorbed per 1.0 lb. of LiOH. This report reviews the methodologies and calculations used to determine the effectiveness of granular LiOH in order to elucidate the source of the inconsistent published values. The original 0.75 lbs. of CO2 absorbed per 1.0 lb. of LiOH capacity calculations in the NSMRL Technical Reports was found to be correct; however, additional data analysis steps were required to complete the analysis and reach values that are consistent with the 0.85 lbs. of CO2 absorbed per 1.0 lb. of LiOH reported by NSWCPD and used in the original determination of LiOH required for the Los Angeles Class. NSMRL believes the subject A&amp;I is not necessary for Los Angeles Class Submarines to meet the seven-day passive survivability.</p>					
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## Abstract

This document is a response to Naval Surface Warfare Center Philadelphia Detachment (NSWCPD) Code 416 Comments on Naval Sea Systems Command (PMS-390) Proposed Alteration and Improvement (A&I), “Partial Replacement of Granular lithium hydroxide (LiOH) Canisters and LiOH Curtain Kits with ExtendAir Canisters and ExtendAir Deployment Kits in the Forward Compartment of SSN 688 Class Submarines.” This document is also intended to serve as an addendum to Naval Submarine Medical Research Laboratory (NSMRL) technical reports TR1228 and TR--2009-1270. The A&I is proposed to correct the inconsistency in the published carbon dioxide (CO<sub>2</sub>) absorption effectiveness of granular LiOH as used in Battelle Curtains. For only the forward compartment of the Los Angeles Class the value used was 0.85 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH. For all other classes of submarines and all other compartments the value used was 0.75 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH. This report reviews the methodologies and calculations used to derive the effectiveness of granular LiOH in order to elucidate the source of the inconsistent published values. The original 0.75 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH capacity calculations in the NSMRL Technical Reports was found to be correct; however, additional data analysis steps were required to complete the analysis and reach values that are consistent with the 0.85 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH reported by NSWCPD and used in the original determination of LiOH required for the Los Angeles Class. Based upon our reanalysis, NSMRL believes the subject A&I is not necessary for Los Angeles Class Submarines to meet the seven-day passive survivability.

## Executive Summary

This document is a response to Naval Surface Warfare Center Philadelphia Detachment (NSWCPD) Code 416 A. McCormick (personal communication March 26, 2021) Appendix (A) and A. McCormick (personal communication April 16, 2021) Appendix (B) comments on Naval Sea Systems Command (PMS-390) Proposed Alteration and Improvement (A&I), “Partial Replacement of Granular lithium hydroxide (LiOH) Canisters and LiOH Curtain Kits with ExtendAir Canisters and ExtendAir Deployment Kits in the Forward Compartment of SSN 688 Class Submarines,” and is also intended to serve as an addendum to Naval Submarine Medical Research Laboratory (NSMRL) technical reports: TR1228 (Norfleet and Horn; 2003) and TR--2009-1270 (Horn, et al.; 2009). The proposed A&I recommends a partial replacement of granular lithium hydroxide (LiOH) canisters and LiOH curtain kits (Battelle Curtains) with Micropore ExtendAir canisters and deployment kits in the forward compartment of Los Angeles Class submarines. The Subject A & I was developed to correct an inconsistency in the published carbon dioxide (CO<sub>2</sub>) absorption effectiveness of granular LiOH as used in Battelle Curtains and applied only to the forward compartment of Los Angeles class submarines and then to ensure that the remaining Los Angeles Class submarines have sufficient passive Carbon Dioxide removal capability to reach the required seven days of survivability in a Distressed Submarine (DISSUB) condition. The comments from NSWCPD argue that the LiOH capacity values derived from the experiments in NSMRL Technical Reports 1228 and 2009-1270 underestimated the actual effectiveness of granular LiOH when used in Battelle Curtains to absorb CO<sub>2</sub>, and that the original effectiveness value used by NAVSEA (0.85 lbs. CO<sub>2</sub> absorbed per 1.0 lb. of LiOH) was accurate and does not require modification. This addendum serves to clarify items raised as

concerns by the NSWCPD comments. NSMRL agrees with NSWCPD that TR1228 did underestimate the absorption effectiveness of LiOH used in Battelle Curtains and that a comparable absorption effectiveness calculation could have been completed using data from TR—2009-1270. Based on the clarifications provided in this response, we feel the A&I is not required, and that there is sufficient LiOH available in the Forward compartment of Los Angeles Class submarine to meet the seven day passive survivability requirement. Additionally, all concerns raised by NSWCPD are fully addressed here concerning the original research from 2003 and 2009. Furthermore, we recommend the following be added as addenda to NSMRL tech reports TR- 1228 and TR--2009-1270:

In TR1228:

1. Change abstract SF290 Form and (page iv) from “The total scrubbing capacity (mass of CO<sub>2</sub> scrubbed per unit mass of agent) of the BC was  $0.756 \pm 0.012$  (mean  $\pm$  SD), and the comparable value for the RPC was  $0.808 \pm 0.007$ ”. To: “The total scrubbing capacity (mass of CO<sub>2</sub> scrubbed per unit mass of agent) of the BC was  $0.810 \pm 0.012$  (mean  $\pm$  SD), and the comparable value for the RPC was  $0.808 \pm 0.007$ .”
2. Change section titled “Scrubbing Capacity” (page 10). From: “The total capacity of four Hangings of RPC ( $0.808 \pm 0.007$ ; mean  $\pm$  SD) is larger than that of four Hangings of BC( $0.756 \pm 0.012$ ), but this difference is small. To: “The total capacity of four Hangings of RPC ( $0.808 \pm 0.007$ ; mean  $\pm$  SD) is similar to that of four Hangings of BC ( $0.810 \pm 0.012$ ).”
3. Discussion page 17, paragraph 1, 3<sup>rd</sup> sentence. Change from “The total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four Hangings of BC was  $0.756 \pm 0.012$ , and the comparable value for the RPC was  $0.808 \pm 0.007$ .” To: “The total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four Hangings of BC was  $0.810 \pm 0.012$ , and the comparable value for the RPC was  $0.808 \pm 0.007$ .”

4. Change Table 2 page 17 to:

“Table 2. Capacity Estimate for the RPC (Micropore ExtendAir Sheets) and the BC (Battelle Curtains) in a Multi-Day Scenario.

Product	Capacity
RPC	0.794
BC	0.786

Data are means - 2SD.”

5. Change the first sentence of the final paragraph on page 21. From “In summary, the total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four Hangings of BC was  $0.756 + 0.012$  (mean + SD), and the comparable value for the RPC was  $0.808 + 0.007$ .” To: “In summary, the total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four hangings of BC was  $0.810 \pm 0.012$  (mean  $\pm$  SD), and the comparable value for the RPC was  $0.808 \pm 0.007$ .”

In TR2009-1270:

1. Change the following sentences in paragraph 3 (page 7). From “To do this, a compartment size of 283 m<sup>3</sup> and a volume of three cu ft per person were assumed, leaving 275.35 cu m of free volume. The Ideal Gas Law can be used to convert to mass:” To: “To do this, a compartment size of 1438.5 m<sup>3</sup> and a volume of three cu ft per person (0.08495 m<sup>3</sup> is considered a conservative value for a male body volume) were assumed, leaving 1430.9 m<sup>3</sup> of free volume. The Ideal Gas Law can be used to convert to mass:

$$lb\ CO_2 = \frac{\left(\frac{44lb}{1lb-mol}\right)(1\ atm)\left(\frac{\%SEV}{100}\right)(1430.9\ m^3)}{(8.20575 \times 10^{-5})(294.26\ K)} \quad (1)''$$

2. Additionally on page 42 (Lessons Learned 1. CO<sub>2</sub> Removal) after paragraph 3 and before the start of the next section (Lessons Learned 1. O<sub>2</sub> Removal) add the following paragraph and table:

An approximation of the scrubbing capacity of the Battelle Curtains using data from both SURVIVEX 2003 and SURVIVEX 2004 can be found from the following table

Submarine	Dallas	Salt Lake City
“Survivors”	94	90
Number of LiOH cans	98	101
Lb LiOH	617.4 lb	636.3 lb
Initial CO <sub>2</sub>	0.32%	0.15%
Final CO <sub>2</sub>	1.97%	1.75%
Hours	72	72
Human CO <sub>2</sub> generation	0.1 lb/hour	0.1 lb/hour
Total CO <sub>2</sub> generated	676.8 lb	648.0 lb
Excess CO <sub>2</sub> in 50,800 ft <sup>3</sup>	95.5 lb	92.7 lb
Net CO <sub>2</sub> absorbed on LiOH	581.3 lb	555.3 lb
<b>Capacity, lb CO<sub>2</sub>/lb LiOH</b>	<b>0.94</b>	<b>0.87</b>

Using the average of the two experiments the scrubbing capacity of Battelle Curtains would be approximately 0.90 lb CO<sub>2</sub>/lb LiOH.

In conclusion, we found that the original LiOH capacity calculations in NSMRL tech reports 1228 and 2009-1270 were correct; however, additional calculation steps were required to reach values that are consistent with those reported by NSWCPD. Based upon our reanalysis reported here NSMRL believes the A&I is not required for Los Angeles Class Submarines to meet the seven-day passive survivability requirement.

The purposes of this Technical Memo are to:

1. Address comments by Naval Surface Warfare Center Philadelphia Detachment (NSWCPD) Code 416, References (b) and (c), to a proposed Alteration and Improvement (A&I), reference (a), to the remaining Los Angeles (SSN 688) Class submarines that removes a portion of the granular lithium hydroxide (LiOH) stored onboard and replaces it with Micropore ExtendAir cartridges in order to meet the requirements for seven days

of passive survivability with the maximum number of expected survivors in a Distressed Submarine (DISSUB) situation as specified by references (g) and (h).

2. Serve as an addendum to Naval Submarine Medical Research Laboratory (NSMRL) technical reports: TR1228 (Norfleet and Horn; 2003) and TR—2009-1270 (Horn, et al; 2009).

## Background

The goal of the Alteration and Improvement (A&I) TS-9090-210D “Partial Replacement of Granular LiOH Canisters and LiOH Curtain Kits with ExtendAir Canisters and ExtendAir Deployment Kits in the Forward Compartment of SSN-688 Class Submarines” is to replace the previously assumed scrubbing capacity of lithium hydroxide (LiOH) Battelle Curtains used solely for the Forward Compartment of Los Angeles Class submarines of 0.85 lbs. of Carbon Dioxide (CO<sub>2</sub>) absorbed per 1.0 lb. of LiOH with the more conservative 0.75 lbs. of CO<sub>2</sub> per 1.0 lb. of LiOH (as suggested by NSMRL reference (2) results). Paragraph 2 of reference (5) states “NAVSEA (Naval Sea Systems Command) and the TYCOMs (Type Commanders) have re-evaluated the validity of this less conservative assumption on 688 Class submarines and determined that there is insufficient technical justification for its use.” The problem the A&I is attempting to remedy is if the less conservative CO<sub>2</sub> scrubbing capacity of 0.85 lbs. of CO<sub>2</sub> per 1.0 lb. of LiOH is used instead of the more conservative value of 0.75 lbs. of CO<sub>2</sub> per 1.0 lb. of LiOH, it is possible the required seven days of passive survivability may not be achieved. If the more conservative value of 0.75 lbs. of CO<sub>2</sub> per 1.0 lb. of LiOH is used then additional LiOH is required to reach the required seven-day passive survivability requirement. The proposed A&I would remove 102 granular LiOH Canisters and replace them with 102 Micropore ExtendAir Canisters.

### Granular LiOH canisters versus Micropore ExtendAir canisters

In a DISSUB, CO<sub>2</sub> is passively removed from the atmosphere through the use of LiOH in one of two forms. The Battelle Curtain, a sleeve of KimGuard<sup>TM</sup> microscopically porous material placed over an open canister of LiOH and then the contents of the canister are poured into the sleeve where it is prevented from dusting into the compartment atmosphere but can still easily interact with the atmosphere. Or the Micropore ExtendAir Sheets, a commercial product with LiOH embedded into a porous plastic matrix that allows CO<sub>2</sub> access to the embedded LiOH almost as easily as CO<sub>2</sub> accesses the granular LiOH. The Micropore ExtendAir Sheets have the advantage that they are produced in a continuous roll of the same height dimension as the LiOH Granular Canisters but each Micropore ExtendAir canister contains a third more LiOH than the granular canisters. Also, the ExtendAir Sheets are easy to handle and require no Personal Protective Equipment to deploy. The ExtendAir sheets are simply rolled out, cut to desired length, and hung from the overhead of the surviving compartments. The ExtendAir sheets begin absorbing CO<sub>2</sub> as soon as the protective covering is removed from the roll. The one disadvantage of the Micropore ExtendAir Sheets is the significantly greater cost. The Navy Stock System price for a single canister of granular LiOH is \$418.98 while the Navy Stock System price for a single Micropore ExtendAir canister is \$2,012.58. The Micropore product is almost five times more expensive than the standard granular LiOH canister.

The Micropore ExtendAir canisters Supplied to the United States Navy are the same size as the granular LiOH canisters but contain 9.8 lbs. of LiOH as compared to the canisters of granular LiOH that only contain 6.3 lbs. of LiOH. The reasoning used in the development of the A & I is that the additional LiOH available from the Micropore ExtendAir Sheets would increase the passive survivability time to the required 7 days or beyond.

The comments provided by Appendices (A) and (B), A. McCarrick (Personal communications March 2, 2021 and April 6, 2021), argue that based on reanalysis of NSMRL test results from references (2) and (3), the 0.85 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH is accurate and does not need to be changed. In the reanalysis, the author of Appendices (A) and (B) makes the following arguments supporting the assertion of the accuracy of 0.85 lbs. of CO<sub>2</sub> absorbed per 1.0 lb. of LiOH (summarized): (each will be addressed in further paragraphs)

- a. The testing conducted by NSMRL in reference (2) is not representative of actual use of Battelle Curtains and ExtendAir sheets in the DISSUB situation.
- b. The maximum capacity of LiOH supplied by the Navy Supply System as tested by NSMRL in reference (2) was not replicated by the author of Appendices (A) and (B) and does not match the expected theoretical stoichiometric capacity of 0.92 lb. CO<sub>2</sub>/lb. LiOH. NSWCPD Code 416 argues that the maximum capacity of LiOH granules reported by NSMRL ref (d) could be interpreted as a capacity of 0.865 lb. CO<sub>2</sub> absorbed/lb. LiOH.
- c. NSMRL reference (2) did not offer an explanation for the reason the time to exhaustion of the first hanging of Battelle Curtains in each of the four test runs was significantly shorter (3 hr. vs. 12 hr.) than all other hangings of Battelle Curtains. In Appendix (A) NSWCPD Code 416 states the cause could be low relative humidity in the test chamber which could thus limit the reaction of the LiOH in the Battelle Curtains.
- d. NSMRL reference (2) improperly included the data from the third and fourth Battelle Curtain hangings in the final calculation of curtain scrubbing capacity and did not take into account a significant amount of unreacted LiOH remaining in the curtains of hangings 3 and 4 of each trial run.
- e. NSMRL reference (3) used an incorrect value for the volume of the Forward Compartment of a Los Angeles (SSN-688) Class submarine.
- f. NSMRL reference (3) did not calculate a Battelle Curtain scrubbing capacity based on the results of the two SURVIVEX experiments. If the calculation had been completed it would have determined the scrubbing capacity of the Battelle Curtains was greater than 0.87 lb CO<sub>2</sub> absorbed/lb LiOH.

## NSMRL Responses

NSMRL responses to Appendices (A) and (B) assertions (from paragraph 1 above):

- a. In Appendix (A), NSWCPD Code 416 argues that the testing mode used by NSMRL in comparing the effectiveness of Battelle Curtains and Micropore ExtendAir sheets was not representative of actual DISSUB usage. At the time the testing was

conducted in 2003, the guidance to DISSUB survivors was to hang half of the available Battelle Curtains, monitor CO<sub>2</sub> levels and, when the concentration of CO<sub>2</sub> began to increase, signaling the exhaustion of the LiOH in the curtains, hang the remaining available Battelle Curtains. In reference (2), additional sets of Battelle Curtains or Micropore ExtendAir sheets were hung when CO<sub>2</sub> levels in the test chamber returned to 3% Surface Equivalent Value (SEV) CO<sub>2</sub>. The test chamber atmosphere was set to a level of 3% SEV CO<sub>2</sub> at the start of each test run and a hanging of Battelle Curtains was assumed to have reached exhaustion when the chamber atmosphere returned to 3% SEV CO<sub>2</sub>. During that period CO<sub>2</sub> was added to the test chamber at a rate to simulate the addition of CO<sub>2</sub> equal to that of seven crewmembers at rest. An argument could be made that the starting CO<sub>2</sub> concentration of 3% SEV was higher than might be expected in a DISSUB situation. In reference (e), the starting CO<sub>2</sub> concentration for both SURVIVEX 2003 and SURVIVEX 2004 was less than 0.5% SEV. We believe that based on the information and DISSUB experience available in 2003, the reference (2) experiment, comparing the performance of Battelle Curtains and Micropore ExtendAir Sheets was conducted as close to actual DISSUB conditions as possible. The decision to direct survivors to hang all available Battelle Curtains or Micropore ExtendAir sheets at the start of a DISSUB casualty was not made and promulgated until 2010. We therefore recommend no changes to NSMRL Technical Report T-1228, reference (2), be made in response to that specific criticism.

- b. Appendices (A) and (B), and reference (2) conducted tests to determine if the LiOH supplied by the Navy Stock System would reach the theoretical Stoichiometric capacity of 0.92 lbs of CO<sub>2</sub> absorbed per lb of LiOH when exposed to pure CO<sub>2</sub> until reaction completion. The study in Appendix (A) used the following quoted method to determine the CO<sub>2</sub> absorption capacity of supplied LiOH:

“NSWCPD Code 416 performed a simple experiment to evaluate whether the granular material provided to the stock system was LiOH or partially hydrated LiOH•H<sub>2</sub>O by exposing a known mass of fresh unground granular material to a steady stream of pure CO<sub>2</sub> for approximately 16-20 hours. The weight change of the material indicated that the original material was pure anhydrous and the theoretical mass change was observed.” (Appendix (A) page 21)

Reference (2) used an adaption of the Military Specification Mil-L-20213E(SH) test for LiOH content. Small samples of the granular LiOH were exposed to 100% CO<sub>2</sub> for 24 hours in a sealed Erlenmeyer flask. Assay results from those tests indicated that 5.9% of the original LiOH was remaining and unreacted after the exposure to CO<sub>2</sub>. That implies that 94.1% of the available LiOH was able to react and thus could have achieved 94.1% of the theoretically possible 0.92 lbs CO<sub>2</sub>/Lb LiOH capacity or 0.865 lbs CO<sub>2</sub>/ lb LiOH. Reference (2) notes that there was a difference in final LiOH content of LiOH samples that were finely ground prior to testing as compared to the raw granules taken directly from the canisters. After exposure to the 100% CO<sub>2</sub> atmosphere for 24 hours, the finely ground samples had no detectable remaining

unreacted LiOH. That result matched the results of Appendix (A) with the exception that Appendix (A) testing reached the theoretical value with the granular LiOH (samples did not need to be ground to powder). We believe the differences in results were due to differences in testing methods and that both sets of testing resulted in values near the theoretically possible values. Thus, the comment from NSWCPD Code 416 Appendix (A) is deemed incorrect: The weight change of the material indicated that the original material was pure anhydrous and the theoretical mass change was observed. This is contrary to reference (2) which reported that exposure to pure CO<sub>2</sub> still had 5.9 ±2.7 % of the original LiOH unreacted. (page 15)

Paragraph 4 of NSWCPD comments, Appendix (A) observes that the first hanging of Battelle Curtains in each of the four test runs of the NSMRL test of Battelle Curtains and Micropore ExtendAir Sheets, reference (d), appeared to reach “exhaustion” in only three hours. Figure 3 from reference (d) is copied below. The three other hangings of Battelle Curtains did not reach “exhaustion” for approximately 12 hours. NSMRL reference (d) noted the short duration of the first hanging in the Results section (page 9) but did not comment on the possible cause, despite the fact that the short time to exhaustion was observed during each of the four trials in the experiment. Reference (2) stated:

“These graphs also demonstrate that Hanging 1 of the BC became exhausted more quickly than Hanging 1 of the RPC, but that, over the course of four Hangings, the total endurance times of the two products were nearly identical.” [BC = Battelle Curtain; RPC = Reactive Plastic Curtain = Micropore ExtendAir Sheets]

NSWCPD Appendix (A) speculates that the cause may have been low relative humidity in the test chamber at the start of each experiment trial. Based on reference (2) that speculation is probably not correct as the NSMRL reference (2) report states, “The mean minimum RH (Relative Humidity) observed with the BC was 98.5%, with a range of 96% -100%.” (page 13)

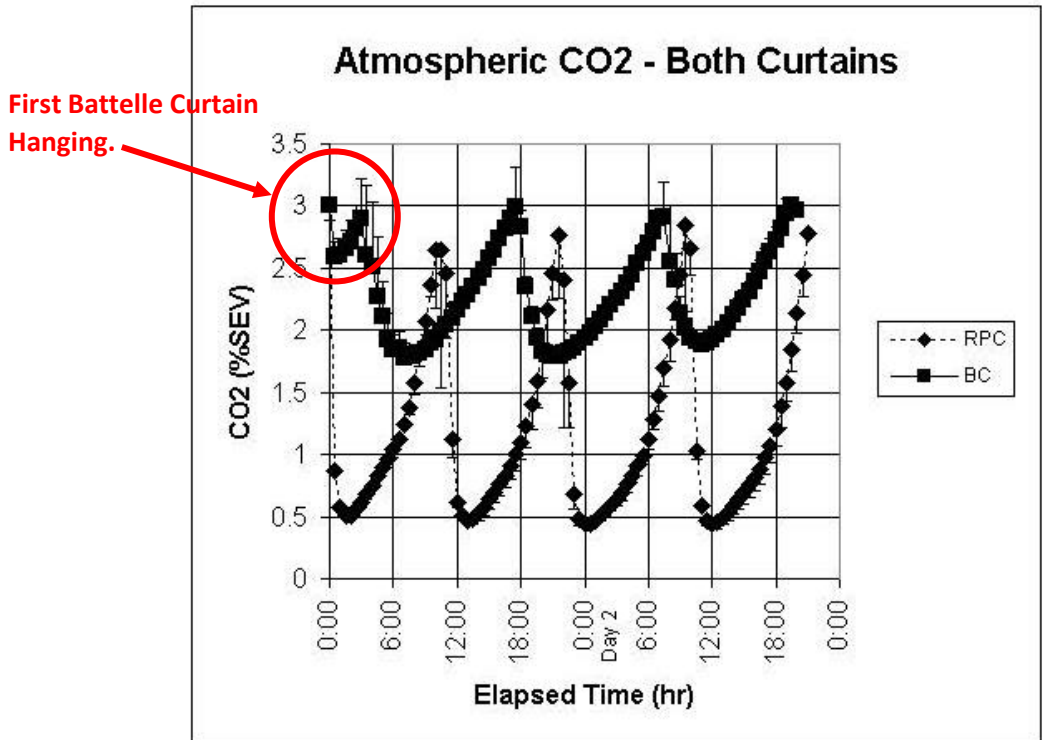


Figure 3. Chamber atmospheric CO<sub>2</sub> content throughout the course of experiments with the BC and the RPC. Each point depicts the mean of the data from four experiments. Error bars depict 1SD.

**Figure 1.** Copy of Figure 3 from reference (2). RPC = Reactive Plastic Curtain (Micropore ExtendAir Sheets); BC = Battelle Curtains.

Navy Research Laboratory (NRL) testing in reference (6) confirms that CO<sub>2</sub> absorption performance by LiOH relies on the presence of water vapor and at relative humidity below 20% CO<sub>2</sub> absorption efficiency drops to below 50% of theoretical capacity. The Results section of reference (h) also indicates that at very high relative humidity (>85%), the efficiency of LiOH absorption of CO<sub>2</sub> drops. Reference (6) reported CO<sub>2</sub> absorption efficiency (% of theoretical capacity) as 16% at >95 % relative humidity. Below is Table 2 from reference (6) and a graph (Fig 3) constructed from those data. Reference (2) reported that in all hangings of all experiments, the relative humidity at the conclusion of each hanging was 100%. The high relative humidity may have slowed the reaction rate and reduced the effectiveness of the curtains in the first hanging and hastened the end of the trial run by allowing CO<sub>2</sub> to return to the 3% level sooner than would have occurred if relative humidity had stayed below 95%. The Lock-in and Lock-out of the divers to hang the next set of Battelle curtains may have introduced enough dry air so that the curtains could resume reacting and then assisted the second hanging in scrubbing CO<sub>2</sub>. We believe the comment from NSWCPD Appendix (A) concerning the lack of sufficient relative humidity as the cause for the short time to “exhaustion” of the first hangings is incorrect. In fact, it is more likely that the exact opposite occurred and the initially

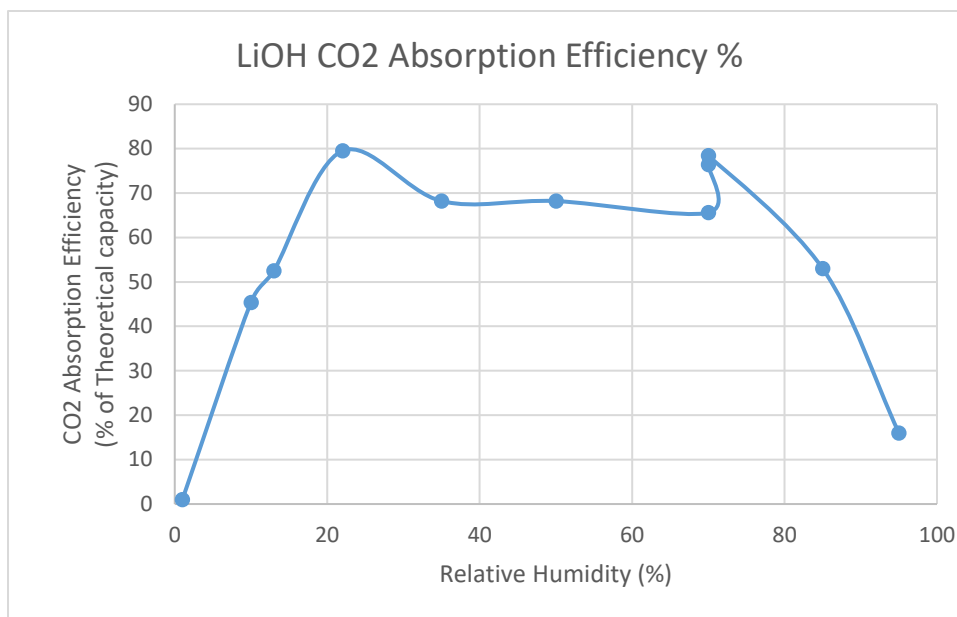
high, and then increasing, relative humidity may have caused a slowing of the absorption reaction and allowed CO<sub>2</sub> to build up to the 3% level faster than expected.

**Table 2**  
**Post-Run Analyses**

Run Parameters			Analysis					LiOH/ H <sub>2</sub> O (mole ratio)	CO <sub>2</sub> Absorp- tion Efficiency (% of theoretical capacity)*	Remarks
Material	Weight (g)	RH (% at 25°C)	Weight (g)	Components (wt-%)						
					LiOH	Li <sub>2</sub> CO <sub>3</sub>	H <sub>2</sub> O			
LiOH	3.1248	< 1	Total	3.1270	98.0	2.0	0.0	∞	< 1	
LiOH	2.9801	10	Inlet	1.5628	41.5	58.5	0.0	∞		
			Outlet	2.1525	45.6	54.3	0.1	342		
			Total	3.7153	43.9	56.05	0.05	657	45.4	
LiOH	3.4876	13	Inlet	2.2067	27.6	70.9	1.5	13.8		
			Outlet	2.2920	44.0	54.9	1.1	30.0		
			Total	4.4987	36.0	62.8	1.2	22.5	52.5	
LiOH	3.3065	22	Inlet	2.6871	8.1	85.5	6.4	0.323		
			Outlet	2.4767	17.4	71.0	11.6	1.12		
			Total	5.1638	12.5	78.5	9.0	1.045	79.5	
LiOH	3.1470	35	Total	4.9989	22.0	61.8	16.2	1.02	68.2	
LiOH	3.1400	50	Total	5.0543	21.0	63.6	15.4	1.02	66.4	
LiOH	3.1250	70	Total	5.1310	21.9	61.6	16.5	0.996	65.6	
LiOH	3.1035	70	Inlet	2.4202	3.8	83.1	7.1	1.03		270 cc/min
			Outlet	2.5155	20.1	65.4	14.5	1.04		
			Total	4.9357	15.0	74.1	10.9	1.03	76.4	
LiOH	3.1589	70	Inlet	2.3391	4.8	91.2	4.0	0.9		200-400 cc/min
			Outlet	2.6770	20.9	62.9	16.2	0.97		
			Total	5.0161	13.3	76.1	10.6	0.94	78.4	
LiOH	3.0134	85	Inlet	2.4000	31.35	45.1	23.55	0.996		
			Outlet	2.5470	25.8	54.6	19.6	0.996		
			Total	4.9470	28.55	50.0	21.45	0.997	53	More CO <sub>2</sub> in outlet
LiOH	3.1700	> 95	Total	-6.9	37.7	11.3	51.0	0.55	16	Soaking wet, pellets destroyed
LiOH·H <sub>2</sub> O (Pellets)	5.2330	< 1	Inlet	1.8324	35.0	63.6	1.4	18.7		
			Outlet	2.1266	32.0	66.7	1.3	18.5		
			Total	3.9590	33.4	65.3	1.3	19.3	56	
LiOH·H <sub>2</sub> O (Pellets)	5.4711	70	Total	5.2764	39.4	31.4	29.2	1.01	34	

\*0.917 grams of CO<sub>2</sub> per gram of LiOH or equivalent.

Figure 2. Copy of Table 2 from reference (6).



**Figure 3.** Graph of LiOH CO<sub>2</sub> Absorption Efficiency (%) as function of Relative Humidity in test chamber based on reference (6) Table 2 (Results)

- c. NSMRL reference (2) improperly included the data from the first Battelle Curtain hangings in the final calculation of curtain scrubbing capacity and also did not take into account the unreacted LiOH remaining in the curtains of hangings three and four of each trial run. Figure 3 of reference (2) indicates that in all four trials the second hanging had the longest endurance, which was most probably due to the assistance of the unreacted LiOH in hanging one continuing to absorb CO<sub>2</sub> during the second hanging. At the conclusion of the experiment, samples of all Battelle Curtain contents were analyzed to determine the amount of unreacted LiOH that remained. Figure 9 of reference (2) is copied below (see Fig 4) and indicates that hangings one and two had less than 12% of the initial weight of LiOH remaining in them. From NSMRL's reference (d) small experiment to determine highest achievable absorption capacity of the Navy Supplied Granular LiOH cited in paragraph b above, it was determined that approximately 6% of the weight of unreacted LiOH would remain after granular LiOH was exposed to 100% CO<sub>2</sub> for 24 hours. That analysis indicates there would have been more LiOH available to react had a fifth and sixth hanging of Battelle Curtains been included in the experiment. Had two more hangings been conducted during the experiment, the Battelle Curtain LiOH content for hangings

three and four, remaining at the end of the experiment, would have approached the much smaller amounts found remaining in hangings one and two. The more complete use of LiOH would then convert to a larger value for the amount of CO<sub>2</sub> absorbed per pound of LiOH. That value would have been approximately 0.8096 lb. CO<sub>2</sub> / lb. LiOH

The author of NSWCPD Appendix (A) questioned the calculations performed in NSMRL reference (2) that combined the average of the remaining unreacted LiOH from all four hangings (which included hangings three and four that had significant unreacted LiOH at the termination of the experiment) to determine the “scrubbing

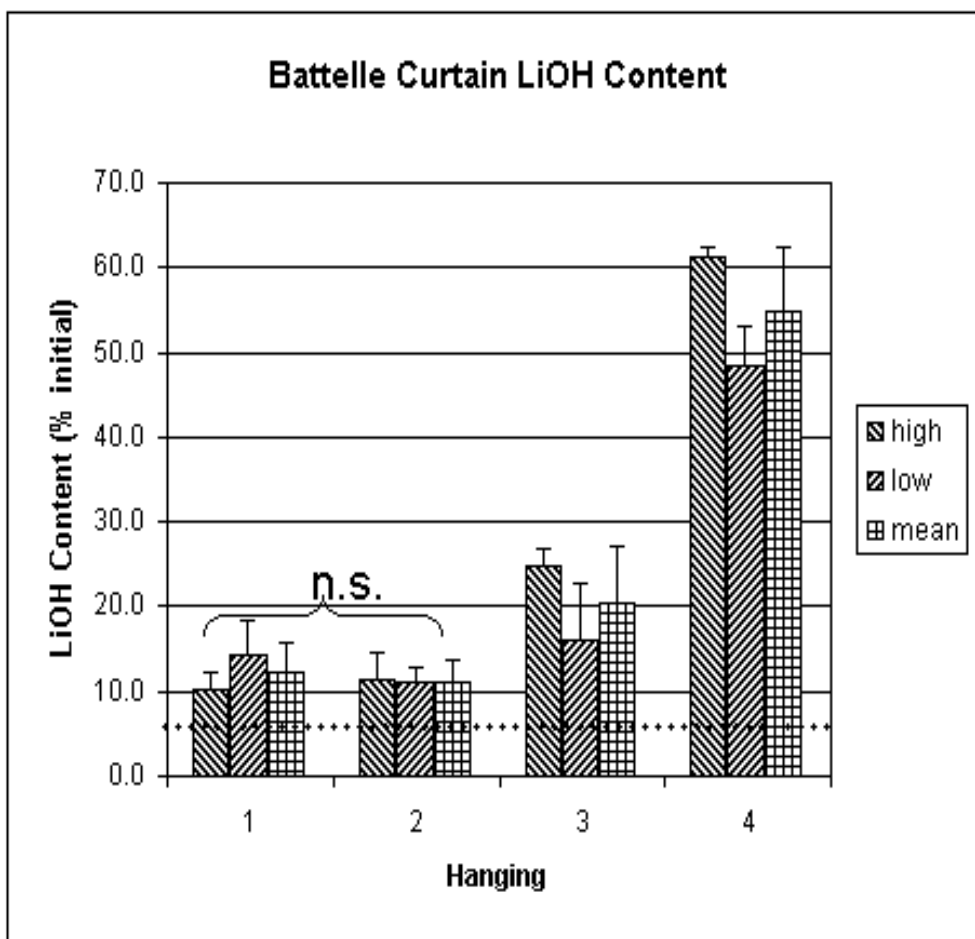


Figure 9. LiOH content, expressed as percent by weight of the LiOH initially present when the curtains were hung, of samples taken at the end of the experiments from four Hangings of BCs. Data are means + 1 SD; n.s. = differences not statistically significant. The LiOH contents of Hangings 1 and 2 were the same, while the content of Hanging 3 was greater than those of Hangings 1 and 2, and the content of Hanging 4 was greater than that of Hanging 3. Content at high locations was higher than at low locations. The dotted line is at 6%, the content that was observed after granular LiOH was subjected to 100% CO<sub>2</sub> for 24 h.

Figure 4. Copy of Figure 9 from NSMRL reference (2).

capacity” of the Battelle Curtains. If only hangings one and two are considered to have reached total exhaustion, then the author of NSWCPD Appendix (A) calculates that the “scrubbing capacity” of the Battelle Curtains is approximately 0.83 lbs CO<sub>2</sub> / lbs LiOH as opposed to the NSMRL reported 0.756 lbs CO<sub>2</sub> / lbs LiOH. The 0.83 lbs CO<sub>2</sub> / lbs LiOH value is very close to the original 0.85 lbs CO<sub>2</sub> / lbs LiOH implemented by the NAVSEA 05Z Technical Warrant Holder (TWH) in 2010 and reflected in the text of reference (4) and the number of LiOH Canisters loaded onboard Los Angeles Class (SSN 688) submarines. Based on this reevaluation of results, we believe that the original value of 0.85 lbs CO<sub>2</sub> absorbed per pound of LiOH value is sufficiently accurate and that the cost and effort involved in approving and issuing the subject A&I (Partial Replacement of Granular LiOH with Micropore ExtendAir sheets), reference (a), is not warranted. Additionally, if approved, the change in load out of LiOH on the Los Angeles Class would immediately generate the need for an additional revision to the Guard Book to account for the two types of CO<sub>2</sub> absorption products onboard. This document is to be considered a change to final results of NSMRL Technical Report 1288, reference (2). The work of Appendices (A) and (B) indicate that additional testing should be conducted to validate the value for CO<sub>2</sub> absorption by LiOH supplied by the U.S. Navy Supply System. It is suggested that NSMRL conduct an additional set of tests using both the Battelle Curtains and Micropore ExtendAir sheets in a larger test facility (e.g. the Navy Experimental Dive Unit Ocean Simulation Facility “Wet pot.” At approximately 7,100 ft<sup>3</sup> (201.0 m<sup>3</sup>) as compared to the 700 ft<sup>3</sup> (19.8 m<sup>3</sup>) for the inner lock plus 510 ft<sup>3</sup> (14.4 m<sup>3</sup>) for the outer lock available in the NSMRL Genesis Chamber) to more closely approximate the volume of the forward compartment of a Los Angeles Class SSN and extend the test duration to seven days. That test would also provide data on the shape of the compartment CO<sub>2</sub> content curves as the curtains become exhausted. At present, survivors are directed to linearly extend the compartment CO<sub>2</sub> content curve to determine time to start escapes. Based on the results shown in reference (2) and the fact that reference (3) testing did not exceed 96 hours, current Guard book guidance may be insufficient to ensure that all survivors have escaped prior to compartment CO<sub>2</sub> content reaching 6% SEV.

- d. In reference (3), the fourth paragraph of the CO<sub>2</sub> Removal section (page 7) states an incorrect value for the volume of the forward compartment of a Los Angeles Class SSN. Reference (3) uses the value of 283 m<sup>3</sup> (~10,000 ft<sup>3</sup>). That is the same volume value that was used for the volume of the test chamber in reference (2). It appears the author of reference (3) may have made a transcription error that was not found during the review process. The value was not used again in the technical report and did not affect any calculations made in the report. To rectify this error we recommend changing this value to 1,438 m<sup>3</sup> (50,800 ft<sup>3</sup>).
- e. Despite having data available from the USS Dallas (SSN-700) and USS Salt Lake City (SSN-716) SURVIVEX exercises, NSMRL reference (3) did not calculate a Battelle Curtain scrubbing capacity based on the recorded results. In retrospect, there were sufficient data to complete that calculation and verify the work done in Appendix (B). NSWCPD Appendix (B) did calculate an approximate value for

Battelle Curtain scrubbing capacity based on the NSMRL reference (3) data. The Appendix (B) calculation table is copied below in Figure 5 (three rows were eliminated as they were related to a capacity calculation using the incorrect compartment volume noted above). We have checked the calculations and confirmed their accuracy. Total CO<sub>2</sub> generated is found by: 0.1 lbs/hr/survivor x number of survivors x 72 hours. Excess CO<sub>2</sub> in 50,800 ft<sup>3</sup> (i.e., in the forward compartment volume of a LA Class submarine) is found by taking the difference of CO<sub>2</sub> present in the compartment at the start of the experiment and the amount found in the compartment atmosphere at the end of the experiment, converting the difference to the cubic feet of CO<sub>2</sub> in the compartment and then converting to lbs of CO<sub>2</sub>. For the USS Dallas, the excess CO<sub>2</sub> is found by: (1.97 – 0.32)/100 x 50800 ft<sup>3</sup> = 838.2 ft<sup>3</sup> of excess CO<sub>2</sub>. Converting to lbs CO<sub>2</sub> using the conversion factor that 1 lb of CO<sub>2</sub> occupies 8.741 SCF at 1 Atmosphere. Then 838.2 ft<sup>3</sup>/ 8.741 ft<sup>3</sup>/pound = 95.89 lbs CO<sub>2</sub>. Net CO<sub>2</sub> absorbed = 676.8 lbs – 95.89 lbs = 580.9. Scrubbing capacity equals: Net CO<sub>2</sub> absorbed divided by lbs LiOH deployed = 580.9 lbs CO<sub>2</sub>/ 617.4 lbs LiOH = 0.94 lbs CO<sub>2</sub>/lbs LiOH. For the USS Salt Lake City the equivalent calculation yields a capacity of 0.87 lbsCO<sub>2</sub>/lbs LiOH.

Both values exceed the 0.85 lbs CO<sub>2</sub>/ lbs LiOH value used to determine the amount of LiOH required to achieve the Seven-Day survivability requirement. Based on this reanalysis, this document should be taken as a formal change to NSMRL reference (3) with the calculation table added to page 41 Lessons Learned and Recommendations, Section 1 CO<sub>2</sub> Removal. This also contributes to the recommendation that A&I TS-9090-210D (ref a) is not required.

### 3. Additional Rationale

- a. We also believe that the high relative humidity conditions established during reference (2) testing resulted in shorter times to exhaustion than could have been achieved in a more moderate relative humidity environment. By comparison, during SURVIVEX 2003, the relative humidity levels began at approximately 51% and the exercise terminated at 72 hours with relative humidity at 65% (the

Submarine	Dallas	Salt Lake City
“Survivors”	94	90
Number of LiOH cans	98	101
Lb LiOH	617.4 lb	636.3 lb
Initial CO <sub>2</sub>	0.32%	0.15%
Final CO <sub>2</sub>	1.97%	1.75%
Hours	72	72
Human CO <sub>2</sub> generation	0.1 lb/hour	0.1 lb/hour
Total CO <sub>2</sub> generated	676.8 lb	648.0 lb
Excess CO <sub>2</sub> in 50,800 ft <sup>3</sup>	95.5 lb	92.7 lb
Net CO <sub>2</sub> absorbed on LiOH	581.3 lb	555.3 lb
Capacity, lb CO <sub>2</sub> /lb LiOH	0.94	0.87

**Figure 5.** Modified copy of Unlabeled calculation table from Appendix (B). Highlighting from Appendix (B) author.

highest relative humidity reached was 70% at 64 hours.). The Battelle Curtains appeared to function as desired as CO<sub>2</sub> was maintained below 2% for the 72 hours of the experiment using 98 Battelle Curtains with 94 “Survivors” in the forward compartment. On the USS Salt Lake City in SURVIVEX 2004 the relative humidity varied from 58% at the start of the experiment and increased to 85% which, when combined with the increased temperature in the compartment, resulted in termination of the experiment due to concerns with heat stress injuries to the “Survivors” at 96 hours. Figures 7, 9, and 24 of reference (3) are copied below to illustrate the CO<sub>2</sub> levels and relative humidity during the experiments.

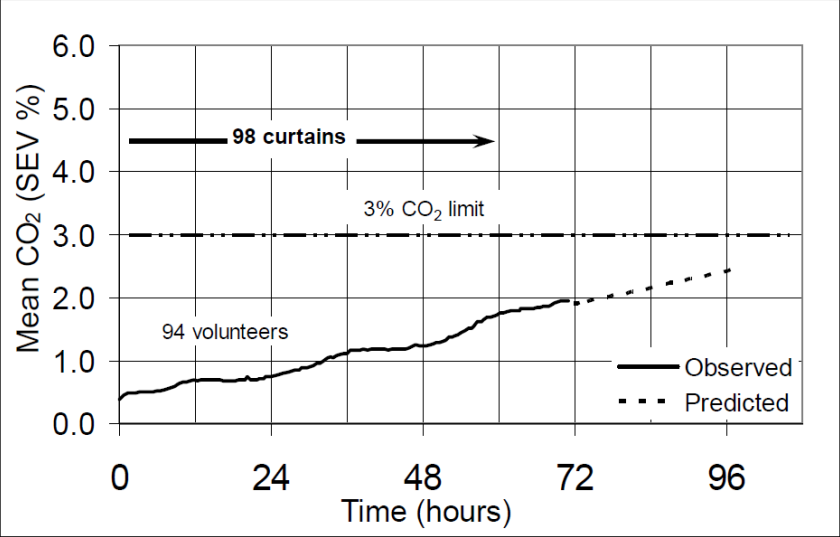


Figure 7. Mean carbon dioxide levels on DALLAS during SURVIVEX 2003. The solid line represents the mean boat observed measurements using the Analox analyzer. Using linear least squares regression estimates, the dotted line shows the predicted levels from 72-96 hours derived from the prior observed levels.

Figure 6. Copy of Figure 7 from NSMRL reference (3)

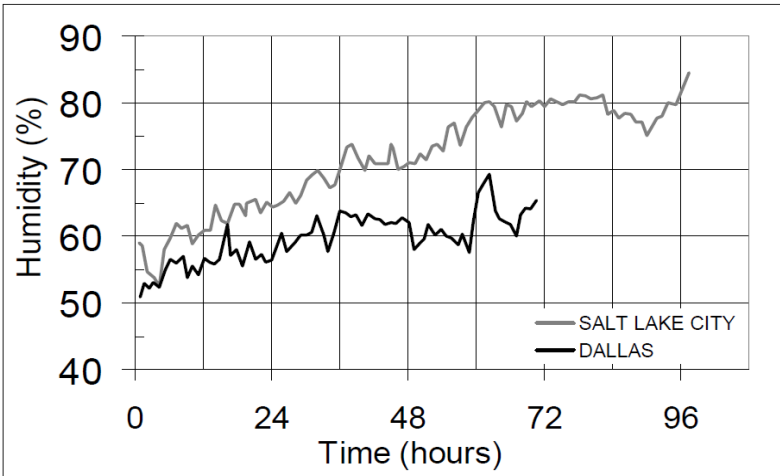


Figure 24. Comparison of boat humidity levels averaged across compartment spaces on SALT LAKE CITY and DALLAS.

Figure 7. Copy of Figure 24 from NSMRL reference (3)

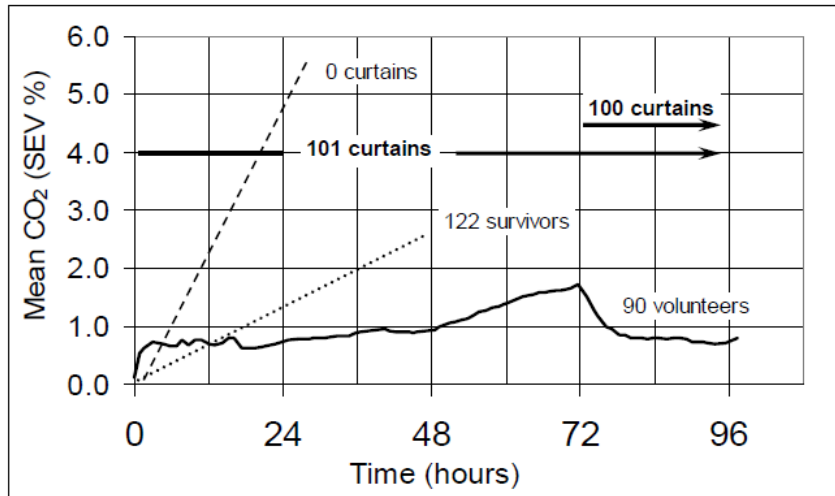


Figure 9. Mean Analox carbon dioxide levels on SALT LAKE CITY during two deployments of curtains. The initial deployment began at 0 hours and the second, with 100 additional curtains, at 72 hours. The dotted line predicts compartment CO<sub>2</sub> generated by 122 survivors with curtains hung as in this study. The dashed line predicts CO<sub>2</sub> level generated by 122 survivors if no curtains are used. Due to malfunctioning monitoring equipment, identified from hour 26 to 32, these CO<sub>2</sub> readings were deemed invalid, and were replaced using linear interpolation.

Figure 9. Copy of Figure 9 from NSMRL reference (3)

As in SURIVEX 2003, the Battelle Curtains in SURIVEX 2004 maintained CO<sub>2</sub> below 2% for the entire experiment. We believe the curtains functioned better than in the initial experiment of NSMRL reference (d) due to the lower relative humidity. If the NSMRL reference (d) experiment were repeated today, we recommend starting with relative humidity at 50% and allowing it to increase “naturally” through the reaction of the LiOH. Additionally, all curtains to be tested in a further experiment should be hung at the start of the trial to match the current guidance to DISSUB survivors to hang all available LiOH curtains at the start of the DISSUB casualty period to minimize generation of CO<sub>2</sub> during a second filling and hanging process (and to utilize the available strength and energy of the survivors at the start of the DISSUB period. Both are expected to decrease over the DISSUB period while awaiting rescue). We would also change the initial starting CO<sub>2</sub> level to 0.5% and then add CO<sub>2</sub> to the test chamber based on the expected metabolic production rate for the simulated number of survivors. The real missing information at this point that would be gained from another test of Battelle Curtains is the shape of the atmospheric CO<sub>2</sub> concentration curve as the LiOH is exhausted. At present, DISSUB survivors are directed to linearly extend the CO<sub>2</sub> concentration curve and estimate when it will reach 6% and then to subtract the time it will take to escape all Fit Survivors (at eight personnel escaping per hour) to determine the actual time to begin escapes. If the curve is not as linear as depicted in figures 6 and 8 above, then the guidance to survivors must be adjusted to account for a non-linear increase in CO<sub>2</sub> level.

## Conclusions

Based on the above responses to the specific comments from NSWCPD Code 416 (Appendix A. and Appendix B.), we offer counter arguments and alternative explanations for his comments a, b, and c. In response to his comments d, e, and f, we recommend the following changes be made to NSMRL tech reports 1228 (reference (d)) and 2009-1270 (reference (e)).

In TR1228:

1. Change abstract SF290 Form and (page iv) 8<sup>th</sup> sentence to: “The total scrubbing capacity (mass of CO<sub>2</sub> scrubbed per unit mass of agent) of the BC was  $0.810 + 0.012$  (mean + SD), and the comparable value for the RPC was  $0.808 + 0.007$ .”
2. Change section titled “Scrubbing Capacity” (page 10) to: “The total capacity of four Hangings of RPC ( $0.808 + 0.007$ ; mean + SD) is similar to that of four Hangings of BC ( $0.810 + 0.012$ ).”
3. Discussion page 17 paragraph 1, 3<sup>rd</sup> sentence change to: “The total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four Hangings of BC was  $0.810 + 0.012$ , and the comparable value for the RPC was  $0.808 + 0.007$ .”
4. Change Table 2 page 17 to: Capacity Estimate for the RPC (Micropore ExtendAir Sheets) and the BC (Battelle Curtains) in a Multi-Day Scenario. Data are means - 2SD.

Product	Capacity
RPC	0.794
BC	0.786

5. Change the first sentence of the final paragraph on page 21 to: “In summary, the total scrubbing capacity (i.e., mass of CO<sub>2</sub> scrubbed per unit mass of product) of four Hangings of BC was  $0.810 \pm 0.012$  (mean  $\pm$  SD), and the comparable value for the RPC was  $0.808 \pm 0.007$ .”

In TR2009-1270:

1. Change the following sentences in paragraph 3 (page 7): “To do this, a compartment size of 1438.5 m<sup>3</sup> and a volume of three ft<sup>3</sup> per person (0.08495 m<sup>3</sup> is considered a conservative value for a male body volume) were assumed, leaving 1430.9 m<sup>3</sup> of free volume. The volume used in equation (1) would then also change to 1430.9 m<sup>3</sup>.”
2. Add to page 42 (Lessons Learned 1. CO<sub>2</sub> Removal) the following paragraph and table:  
  
An approximation of the scrubbing capacity of the Battelle Curtains using data from both SURVIVEX 2003 and SURVIVEX 2004 can be found from the following table.

Submarine	Dallas	Salt Lake City
“Survivors”	94	90
Number of LiOH cans	98	101
Lb LiOH	617.4 lb	636.3 lb
Initial CO2	0.32%	0.15%
Final CO2	1.97%	1.75%
Hours	72	72
Human CO2 generation	0.1 lb/hour	0.1 lb/hour
Total CO2 generated	676.8 lb	648.0 lb
Excess CO2 in 50,800 ft <sup>3</sup>	95.5 lb	92.7 lb
Net CO2 absorbed on LiOH	581.3 lb	555.3 lb
Capacity, lb CO2/lb LiOH	0.94	0.87

Using the average of the two experiments the scrubbing capacity of Battelle Curtains would be approximately 0.90 lb CO<sub>2</sub>/lb LiOH. Highlighting shows most significant results. Provided by original reference (c) author.

In conclusion, we found that the original LiOH capacity calculations in NSMRL tech reports 1228 and 2009-1270 were correct, however additional steps were required to reach values that are consistent with those reported by NSWCPD. Based upon our reanalysis reported here, NSMRL believes, the A&I is not required for SSN-688 Class Submarines to meet the Seven-day Passive Survivability requirement of reference (g).

## References

1. Commander Portsmouth Naval Shipyard 2021 “Updated Alteration and Improvement Draft Package for 688 Class ExtendAir Partial Replacement” 4700 Ser 205/011 of 5 Feb 2021.
2. Norfleet W, Horn WG, Carbon Dioxide Scrubbing Capabilities of Two New Non-powered Technologies. Naval Submarine Medical Research Laboratory Tech Report TR1228. 2003.
3. Horn WG, Benton, P, Hughes L, Jankosky, C, Woodson P, Lunney T, Wagner S, Quatroche A, Burnside D. SURVIVEX 2003 and SURVIVES 2004: Simulated Disabled Submarine Exercises. Naval Submarine Medical Research Laboratory Tech Report NSMRL/TR--2009-1270. 2009.
4. Naval Sea Systems Command (PMS 39) 2015 “Seven Day Distressed Submarine (DISSUB) Survivability Life Support Stores Requirements” 4700 Ser 391/0348 of 4 Dec 2015.
5. Naval Sea Systems Command (PMS 391) 2021 2015 PMS 391 “Updated Seven Day Distressed Submarine (DISSUB) Survivability Life Support Stores Requirements” 4700 Ser 391/0205 of 21 Dec 2020.
6. Williams D, Miller R. The effect of Water Vapor on the LiOH-CO<sub>2</sub> Reaction Part 1 – Dynamic Isothermal System Naval Research Laboratory Interim Report 6937. 1969.

## Appendix A: A. McCarrick (Personal Communication March 26, 2021)

Comments (Draft) on ShipAlt TS-9090-210D: Partial Replacement of Granular LiOH...

- Ref:
- (a) Mandatory Safety shipalt TS-9090210D
  - (b) PMS 391 ltr 4700 Ser 391 / 0348 of 4 Dec 2015
  - (c) NSMRL Report No TR1228, of 27 Aug 2003
  - (d) NRL Interim Report AD698118 of problem C08-05, of 29 Oct 1969

1. The text of the proposed ShipAlt Safety document, reference (a) implied incorrectly that NAVSEA 05 erred in assuming 0.85 lb CO<sub>2</sub> / lb LiOH as a working capacity for the granular LiOH used aboard 688 class submarines. The exact word used in reference (a) section 9 was “a deficiency.” Enclosure (1) to reference (b) states that the unique assumption for 688 class granular LiOH capacity was made solely for the purpose of minimizing the storage dilemma on 688 class boats. The rationale was given in paragraph j of the enclosure to reference (b) as copied below:

“j. Carbon dioxide is removed passively by lithium hydroxide(LiOH) filled curtains or ExtendAir sheets. Power is not available to operate hoppers, nor are hoppers as efficient as passive methods. It is assumed that the capacity of passive methods for CO<sub>2</sub> removal is 0.75 lbs of CO<sub>2</sub> / lb of LiOH. It should be noted that a less conservative assumption of 0.85 lbs of CO<sub>2</sub> / lb of LiOH was utilized to determine the load out for the SSN 688 SHIPALT to provide seven day capability. This assumption was used to minimize weight and volume impact of the alteration...”

2. The text of the proposed ShipAlt, reference (a), claims that NSMRL testing, reference (c), reported the maximum capacity of granular LiOH to be 0.756 ±0.012 lb CO<sub>2</sub> / lb LiOH. This is the reported capacity given in the abstract and text of reference (c). However, that capacity is for the specific mode of testing that NSMRL did claim to replicate actual DISSUB usage. NSWCPD Code 416 wishes to make the case that as well intended the NSMRL testing was, it does not represent the true use of LiOH in Battelle curtains required during DISSUB and that the actual capacity may be as high as high as 0.86 lb CO<sub>2</sub> / lb LiOH using NSMRL’s own test data or higher based on NSWCPD Code 416 prior testing of pure granular LiOH.

3. The theoretical stoichiometric capacity of anhydrous LiOH for CO<sub>2</sub> is approximately 0.92 lb CO<sub>2</sub> / lb LiOH as stated in the introductory paragraph of reference (c). When the assumed capacities were selected by the former TWH for Submarine ventilation and life support in cooperation with NSWCPD Code 416 ISEA, the full capacity was not used. NSWCPD Code

416 performed a simple experiment to evaluate whether the granular material provided to the stock system was LiOH or partially hydrated LiOH•H<sub>2</sub>O by exposing a known mass of fresh ungrown granular material to a steady stream of pure CO<sub>2</sub> for approximately 16-20 hours. The weight change of the material indicated that the original material was pure anhydrous and the theoretical mass change was observed. This is contrary to reference (c) which reported that exposure to pure CO<sub>2</sub> still had 5.9 ±2.7 % of the original LiOH unreacted. This can be interpreted as a maximum workable capacity for the granules of 94.1 % or 86.5 lb CO<sub>2</sub> / lb LiOH

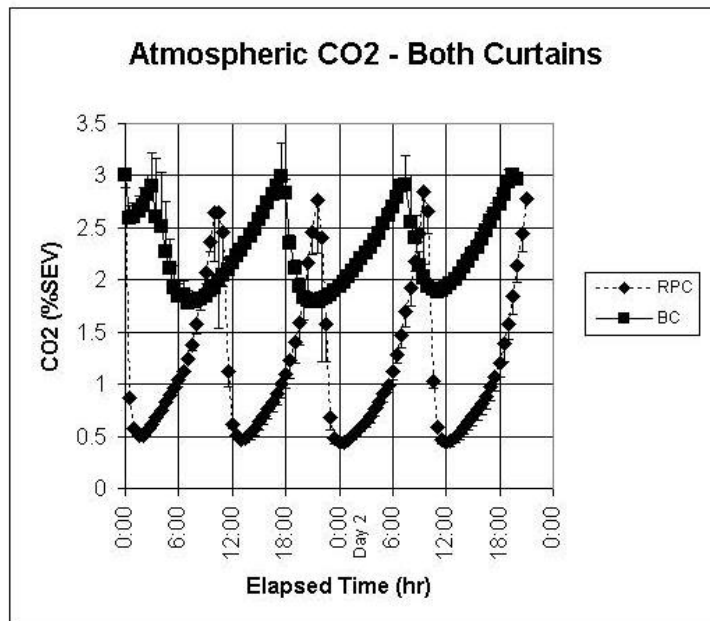


Figure 3. Chamber atmospheric CO<sub>2</sub> content throughout the course of experiments with the BC and the RPC. Each point depicts the mean of the data from four experiments. Error bars depict 1SD.

4. The NSMRL tests of reference (c) were well controlled and replicated 4 times to insure reliability of the data. Granular LiOH as deployed in pairs of Battelle curtains estimated to provide for approximately 12 hours of CO<sub>2</sub> removal at the rate CO<sub>2</sub> was fed into the chamber. The chamber was initialized to 3% CO<sub>2</sub> prior to deploying the LiOH and curtains were considered expended when 3% was again reached. Each test consisted of four curtain hangings conducted in series with the “expended” curtains left in place to further, if slowly, react. The process of starting and stopping at the same CO<sub>2</sub> concentration allowed easy computation of CO<sub>2</sub> absorption since the input of CO<sub>2</sub> was known. The results of their tests were shown as Figure 3 in reference (c) is reproduced below. (The Battelle Curtain granular LiOH experiments are designated as “BC” and ExtendAir sheets, also tested, were designated “RPC” for “Reactive Plastic Curtains.”) It is difficult to make use of the error bars, but the overall impression is that the results were consistent from run to run.

5. The results for the first hanging was peculiar as the time for the chamber CO<sub>2</sub> to return to 3% was only a little over 3 hours. This occurred in each of the four trials. Although reference

(c) noted the unusually short time, no further discussion of it appeared. It may be possible that the lower humidity in the chamber at the beginning of each test may have limited the reaction rate of the first hanging. The availability of water vapor plays an important function in the actual reaction of the LiOH capturing the CO<sub>2</sub>, reference (d). The chamber was initially started at 85% RH and 26.1°C, and subsequently rose in both temperature and RH (~98%RH on average) with each hanging. At the higher temperatures, the increased RH represents significantly more available water vapor. It is not certain that this available water vapor can explain the unusually slow rate of CO<sub>2</sub> absorption by hanging 1. Reference (d) reports that humidities above 80%RH should be adequate for LiOH absorption. (The data for that comes from reference (d) only for 25°C while the NSMRL tests, reference (c) reached 31°C by the fourth hanging.)

6. The calculated capacity of each set of curtains was computed as the “exhaustion time” multiplied by the flow of CO<sub>2</sub>. The “capacity” of the Battelle curtain / granular LiOH results were presented in reference (c) as Figure 5 shown below. (The Battelle curtains / granular LiOH are the open columns in the figure below.) The average of these hanging capacities is indeed 0.756 lb CO<sub>2</sub> / lb LiOH.

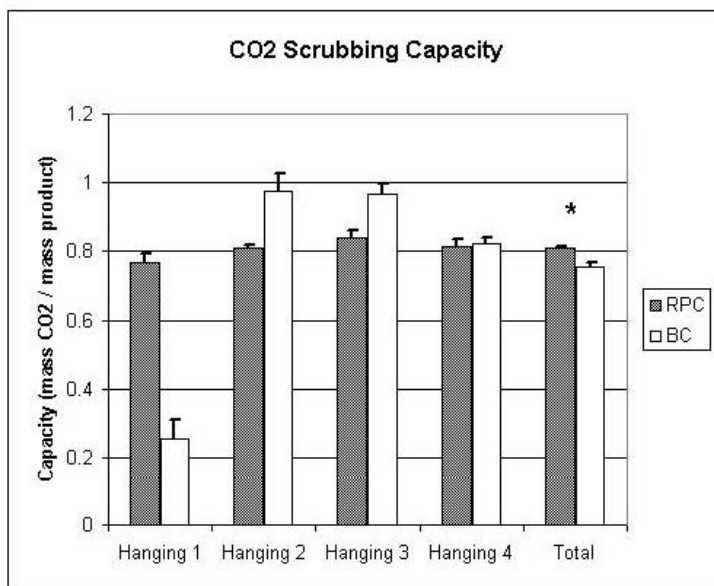


Figure 5. Capacities of the BC and the RPC for CO<sub>2</sub> scrubbing. Data are means + 1SD. Statistical analyses indicate that, for the BC, Hangings 2 and 3 have the same capacity, but that all other comparisons of the Hangings of that product are different. For the RPC, Hanging 1 is different from all other Hangings, and all other Hangings are the same. For Total capacity over the course of the complete experiments, the capacities of the BC and RPC are different.

7. However, at the end of the four hangings in a row of each test, the LiOH material was assayed for unreacted LiOH. That data gives the final unreacted capacity of each of the four hangings which had been exposed for different lengths of time. The final unreacted LiOH in each set of Battelle curtains was presented as Figure 9, shown below. That figure clearly shows that although the first hanging performed dismally based on initial exposure time it reached approximately 90% of its theoretical capacity or 0.83 lb. CO<sub>2</sub> / lb. LiOH in the approximately 44 total hours of exposure. Reference (c) Figure 9 also shows that the second hanging also reached approximately the same final usage in approximately 34 hours. The “scrubbing capacity” given by reference (c) included both the poor performance of the first hanging and the less than fully consumed third and fourth hangings which clearly have additional absorbing capacity.

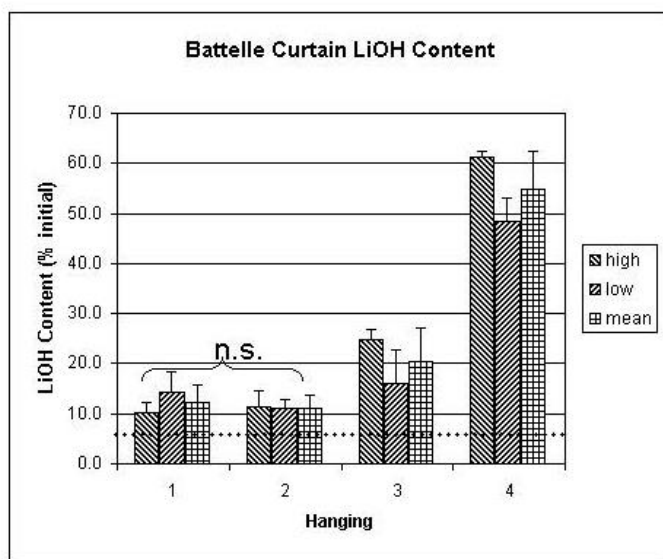


Figure 9. LiOH content, expressed as percent by weight of the LiOH initially present when the curtains were hung, of samples taken at the end of the experiments from four Hangings of BCs. Data are means + 1 SD; n.s. = differences not statistically significant. The LiOH contents of Hangings 1 and 2 were the same, while the content of Hanging 3 was greater than those of Hangings 1 and 2, and the content of Hanging 4 was greater than that of Hanging 3. Content at high locations was higher than at low locations. The dotted line is at 6%, the content that was observed after granular LiOH was subjected to 100% CO<sub>2</sub> for 24 h.

8. Current instructions for DISSUB require that after addressing injuries and immediate concerns such as fires, all the available LiOH is to be deployment. This is radically different than the NSMRL testing. All the available sheets would therefore react for the full 7 days and be fully expended (unlike hangings 3 and 4 of the NSMRL tests). If we take the results for hangings 1 and 2 to be exhaustion, then the working capacity of granular LiOH in Battelle curtains would be 0.83 lb. CO<sub>2</sub> / lb. LiOH. However, if we accept NSMRL’s extreme test of some LiOH granules which achieved 94% of theoretical capacity we would expect 0.86 lb. CO<sub>2</sub> / lb. LiOH. The significant extension of time from 44 hours to 168 hours gives confidence that the existing assumption of 0.85 lb. CO<sub>2</sub> / lb. LiOH is safe.

## Appendix B: A. McCarrick (Personal Communication April 6, 2021)

Second Comments (Draft) on ShipAlt TS-9090-210D: Partial Replacement of Granular LiOH...

Ref: (a) Mandatory Safety shipalt TS-9090210D  
(b) NSMRL Report No TR1228, of 27 Aug 2003  
(c) NSMRL/TR-2009-1270, Survivex 2003 and Survivex 2004: Simulated Disabled Submarine Exercises, 12 Aug 2009

1. The text of the proposed ShipAlt, reference (a), claims that NSMRL testing, reference (b), reported the maximum capacity of granular LiOH to be  $0.756 \pm 0.012$  lb CO<sub>2</sub> / lb LiOH. This is the reported capacity given in the abstract and text of reference (b). However, that capacity is for the specific mode of testing that NSMRL did claiming to replicate actual DISSUB usage.

2. This short document argues a second defense of the 0.85 lb CO<sub>2</sub> / lb LiOH working capacity for the granular LiOH used aboard 688 class submarines. Using the NSMRL report of two SURVIVEX experiments conducted on the Salt Lake City and the Dallas (688 submarines), reference (c) a reasonably accurate capacity of the LiOH can be obtained under conditions much more appropriate to a DISSUB situation.

3. The theoretical stoichiometric capacity of anhydrous LiOH for CO<sub>2</sub> is approximately 0.92 lb CO<sub>2</sub> / lb LiOH as stated in the introductory paragraph of reference (b).

4. The NSMRL tests of reference (c) were conducted with 90 or more volunteer “survivors” comprised of submariner volunteers and medical personnel. CO<sub>2</sub> control was accomplished using a large number of LiOH filled Battelle Curtains hung up at the beginning of the simulated DISSUB with no further curtains hung until after 72 hours as the CO<sub>2</sub> rose. The prior NSMRL tests, reference (b) were conducted as 4 separate hangings over a total of only 44 hours. Unlike the tests in reference (b), the atmosphere started at low levels rather than being preset to 3% CO<sub>2</sub>.

5. The important data from the two Survivex tests were reported as figures 7 and 9 of reference (c) reproduced below. Knowing the volume of the compartment, number of survivors, CO<sub>2</sub> productions rate, starting and final CO<sub>2</sub> concentration and time, the mass of CO<sub>2</sub> absorbed by the LiOH. With the additional knowledge of the mass of LiOH deployed, the capacity per pound can be calculated.

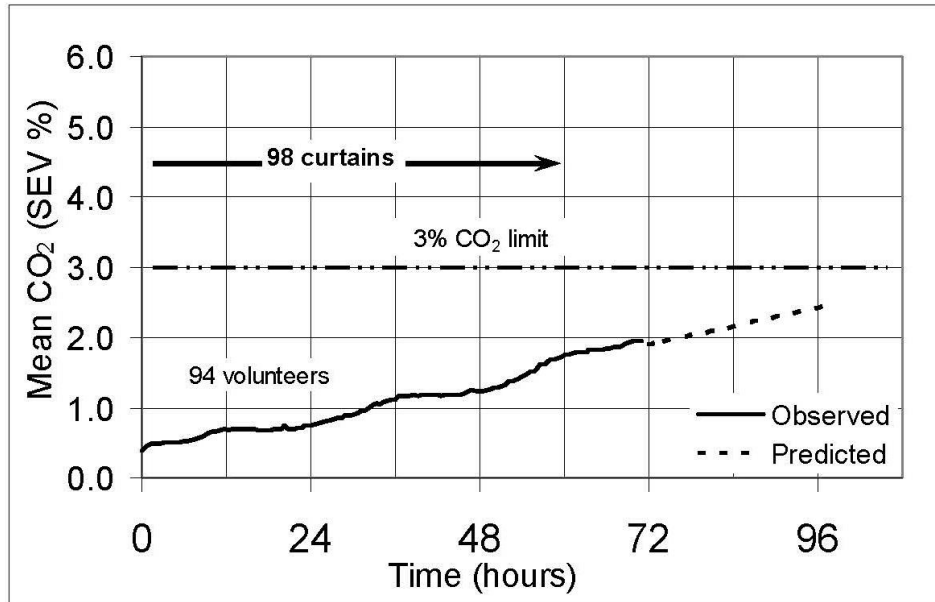


Figure 7. Mean carbon dioxide levels on DALLAS during SURVIVEX 2003. The solid line represents the mean boat observed measurements using the Analox analyzer. Using linear least squares regression estimates, the dotted line shows the predicted levels from 72-96 hours derived from the prior observed levels.

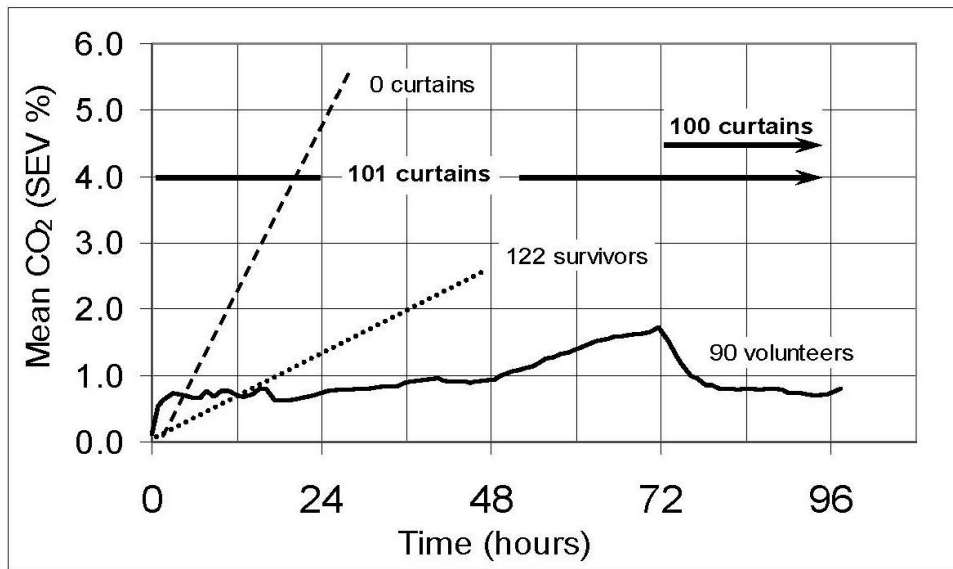


Figure 9. Mean Analox carbon dioxide levels on SALT LAKE CITY during two deployments of curtains. The initial deployment began at 0 hours and the second, with 100 additional curtains, at 72 hours. The dotted line predicts compartment CO<sub>2</sub> generated by 122 survivors with curtains hung as in this study. The dashed line predicts CO<sub>2</sub> level generated by 122 survivors if no curtains are used. Due to malfunctioning monitoring equipment, identified from hour 26 to 32, these CO<sub>2</sub> readings were deemed invalid, and were replaced using linear interpolation.

6. The important data for the calculation and the capacity estimates are provided by reference (c) and summarized in the following table. (Reference (c) stated that the open volume of the forward compartment was given as 275 cubic meters. This converts to 9,710 cubic feet. The full volume of 688 boats is 50,800 cubic feet. This source of this discrepancy is not known and contacts with NSMRL staff are being initiated.)

TABLE 1. Data from SURVIVEX tests and Computed LiOH Capacities

Submarine	Dallas	Salt Lake City
“Survivors”	94	90
Number of LiOH cans	98	101
Lb LiOH	617.4 lb	636.3 lb
Initial CO2	0.32%	0.15%
Final CO2	1.97%	1.75%
Hours	72	72
Human CO2 generation	0.1 lb/hour	0.1 lb/hour
Total CO2 generated	676.8 lb	648.0 lb
Excess CO2 in 9,710 ft <sup>3</sup>	18.3 lb	17.7 lb
Net CO2 absorbed on LiOH	658.5 lb	630.3 lb
Capacity, lb CO2/lb LiOH	1.07	0.99
Excess CO2 in 50,800 ft <sup>3</sup>	95.5 lb	92.7 lb
Net CO2 absorbed on LiOH	581.3 lb	555.3 lb
Capacity, lb CO2/lb LiOH	0.94	0.87

7. The estimated capacity of the granular LiOH used in the Survivex tests are shown in yellow in Table 1. The 275 m<sup>3</sup> volume given in reference (c) corresponds to capacities higher than theoretically possible. The capacities based on the normal volume of the forward compartment (50,800 ft<sup>3</sup>) are realistic. Both Survivex tests lead to apparent capacities higher than the troublesome assumption of 0.85 lb CO2 / lb LiOH. The curtains were hung for only 72 hours and probably had some small capacity remaining.