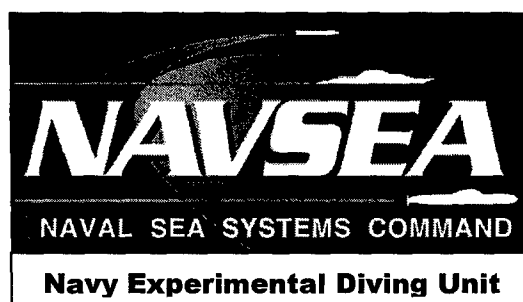


Navy Experimental Diving Unit
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TA 04-17
NEDU TR 05-07
April 2005

**LIMITED UNMANNED EVALUATION OF THE DIVEX SLS MK IV
BACKPACK AT SEA LEVEL AND 1000 FSW**



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INTRODUCTION

The Secondary Life Support System, SLS MK IV (Divex, Ltd.; Aberdeen, Scotland) is an emergency breathing apparatus intended for use with the Divex Gasmizer primary gas supply system used by saturation divers operating from a diving bell. The SLS MK IV operates on the semiclosed principle with complete independence from the diver's primary breathing system.¹ According to the manufacturer, this system meets Norwegian Petroleum Directorate standards that require 10 minutes of breathing gas at a respiratory minute volume (RMV) of 62.5 liters per minute (L/min).^{1,2}

The Navy Experimental Diving Unit (NEDU) tested an earlier generation of this life support system to assess its operational limits. The results indicated that the backpack provides life support for 15 to 18 minutes at 1000 feet of seawater (fsw) and at a temperature of 29 ± 2 °F. The limiting factor was the canister's capacity to absorb carbon dioxide (CO₂).³

Subsequent design modifications by the manufacturer resulted in the SLS MK IV backpack. Unmanned and manned tests were recently conducted at NEDU to assess SLS MK IV performance at 100 (unmanned), 108 (manned), 727 (unmanned), and 723 (manned) fsw. Unmanned results indicated that the SLS MK IV did not consistently perform at the level of manufacturer expectations or the Norwegian Petroleum Directorate standards.⁴ Manned results indicated that the SLS MK IV provided adequate breathable gas for at least 19 ± 7 min. Carbon dioxide canister durations fell below these standards (11 ± 2 min) only at the 0.5% surface equivalent value (SEV).⁵

The objective of this task was to conduct unmanned evaluations of the SLS MK IV backpack attached to an SLS diving helmet, a Divex Ultrajewel 601 Reclaim Diving Helmet with interface hardware for the SLS backpack. The basic helmet structure is an extensively modified Kirby Morgan (Santa Barbara, CA) DSI SuperLite 17C.⁶ Per COMNAVSEASYS COM Task Assignment 04-17,⁷ SLS CO₂ canister performance, respiratory effort (resistive effort), bottle gas supply duration, and inspired temperature were characterized. Testing was conducted at sea level (0 fsw) and at 1000 fsw.

METHODS

GENERAL

The performances of two SLS MK IV backpacks (serial #477-030 and #477-029) with an extensively modified Kirby Morgan DSI SuperLite 17C (Serial #C0315) were assessed in three phases: (1) resistive effort at normobaric pressure (0 fsw), (2) CO₂ canister performance and resistive effort during simulated dives to 1000 fsw, and (3) bottle duration and resistive effort during simulated dives to 1000 fsw. Each backpack was identified by color — RED (#477-030) and GREEN (#477-029). Testing was conducted in the NEDU Building 398 hyperbaric facility (CHARLIE Chamber). In accordance with the Divex manual,¹ a 94/6 helium-oxygen gas mixture was used — a range that allows

higher partial pressure levels of oxygen than are indicated in the *U.S. Navy Diving Manual*.⁸ Respiratory minute volume was set at 62.5 L/min (tidal volume = 2.5 L, frequency = 25 breaths/min).⁹

EXPERIMENTAL DESIGN

Phase 1: Resistive Effort at 0 fsw

Ten pressure-volume (P-V) loops⁹ from each rig were recorded at three backpack orientations — 0° (upright), 45°, and 90° (prone) — while it was immersed in an ark filled with fresh water at ambient chamber temperature.

Phase 2: CO₂ Canister Duration and Resistive Effort at 1000 fsw

Each rig was instrumented at a 45° orientation, immersed in an ark (29 ± 2 °F water; salinity = 34 ± 2 parts per thousand of sodium chloride), and compressed to 1000 fsw. Carbon dioxide was injected into the exhalation hose at a rate of 2.5 standard liters per minute (SLPM)⁹ while the canister duration was recorded. Each rig was tested at depth. Carbon dioxide canister duration was measured until a 5.0% CO₂ SEV was attained. After CO₂ canister duration data had been collected, ten consecutive P-V loops were recorded when bottle pressure was 1600 psi.

Phase 3: Bottle Duration and Resistive Effort at 1000 fsw

Bottle duration for each rig was recorded at depth after Phase 2 data had been collected. Bottle duration was recorded from the time the SLS was activated until bottle pressure was equal to ambient chamber pressure (445 psi). Ten consecutive P-V loops were recorded twice at different bottle pressures (4500 and 2500 psi) during this phase.

EQUIPMENT AND INSTRUMENTATION

Diagrams of test configurations are provided in Appendix A1 (Phase 1), Appendix B1 (Phase 2), and Appendix C1 (Phase 3). Selected images of an instrumented SLS MK IV backpack are shown in Appendix E.

PROCEDURES

Test parameters, recorded data, and stepwise procedures are listed in Appendix A2 (Phase 1), Appendix B2 (Phase 2), and Appendix C2 (Phase 3). Breathing cycles were recorded after the breathing loop was purged of air used to maintain the breathing hoses, demand regulator, and helmet during compression (Phase 1). These cycles were recorded in succession following data collection from CO₂ canisters (Phase 2) and bottles (Phase 3).

RESULTS

GENERAL

Data collection to assess the duration of the SLS MK IV backpack bottle yielded substantially different results for the two backpacks. The GREEN backpack's duration was approximately 9 minutes less than that of the previously tested RED backpack; therefore, the regulator pressure and injection flow rate were checked on both backpacks with the Divex SLS Tool Test Kit.¹ The GREEN regulator pressure (14 psig) and flow rate (~5 SLPM) were within acceptable limits. The RED regulator pressure (14 psig) was also within acceptable limits; however, its flow meter registered an injection flow rate (~4 SLPM) below the manufacturer's "acceptance" zone. The RED gas supply injection orifice (part #D277) was removed after testing, ultrasonically cleaned, and reinstalled¹ for manned testing. Since the GREEN backpack was fully instrumented at the time, bottle duration was measured again with this rig at 1000 fsw. The results from these tests are reported in **PHASE 3: BOTTLE DURATION AND WORK OF BREATHING AT 1000 FSW**.

During preparations for the CO₂ canister duration testing, the CO₂ log rate was inadvertently set at an unacceptably low resolution. Since the project was ahead of schedule and no additional costs would be incurred, it was deemed appropriate to repeat CO₂ canister duration tests. The RED backpack was included to assess how a reduction in supply gas flow affects CO₂ canister duration. The results from these tests are reported in **PHASE 2: CO₂ CANISTER DURATION AND WORK OF BREATHING AT 1000 FSW**.

Monitored throughout testing, the ark water temperature occasionally exceeded the desired test range (29 ± 2 °F). Ark water temperatures were collected along with canister duration data during Phase 2 and bottle duration data during Phase 3. Mean ark temperatures were within parameters. Summary statistics are listed in Table A.

Table A. Ark Water Temperatures (°F) During Phases 2 and 3.

| | Phase 2 | | | | Phase 3 | | |
|----------------|------------------|------------------|--------------------|--------------------|---------|--------------------|--------------------|
| | RED _A | RED _B | GREEN _A | GREEN _B | RED | GREEN _A | GREEN _B |
| Minimum | 29.01 | 28.96 | 29.10 | 28.96 | * | 29.05 | 30.28 |
| Maximum | 31.74 | 31.17 | 31.77 | 31.17 | * | 32.33 | 31.42 |
| Mean | 30.34 | 30.12 | 30.28 | 30.12 | * | 30.09 | 30.87 |
| STD | 0.51 | 0.44 | 0.42 | 0.44 | * | 0.55 | 0.20 |

Note: Subscript letters indicate each test conducted with the backpack.

Oral gas temperature was also monitored throughout testing and collected during Phases 2 and 3. Summary statistics are listed in Table B. Mean oral gas temperature was 69.5 °F.

Table B. Oral Gas Temperatures (°F) During Phases 2 and 3.

| | Phase 2 | | | | Phase 3 | | |
|----------------|------------------|------------------|--------------------|--------------------|---------|--------------------|--------------------|
| | RED _A | RED _B | GREEN _A | GREEN _B | RED | GREEN _A | GREEN _B |
| Minimum | 67.29 | 66.03 | 55.87 | 66.03 | * | 64.37 | 66.13 |
| Maximum | 74.38 | 76.45 | 71.64 | 76.45 | * | 68.91 | 68.08 |
| Mean | 72.27 | 70.89 | 69.73 | 70.89 | * | 65.82 | 67.20 |
| STD | 1.16 | 1.25 | 2.24 | 1.25 | * | 1.03 | 0.39 |

Note: Subscript letters designate each test conducted with the backpack.

DATA REDUCTION AND ANALYSIS

Breathing cycles were characterized as pressure-volume (P-V) loops. The volume-averaged pressure of each breathing cycle was calculated in joules per liter (J/L) and compared for each rig across experimental conditions. Minimum (inhalation) and maximum (exhalation) values (kPa) were identified in each loop to indicate peak values within a simulated breathing cycle.

Carbon dioxide measurements were converted to SEVs. Canister duration for each rig was measured to the nearest 0.1 minute and was defined as the elapsed time (min) to arrive at target percentages for CO₂ SEVs — 0.5, 1.0, 1.5, 2.0, 2.5, and 5.0 min.

Bottle duration was also measured to the nearest 0.1 minute and was defined as the elapsed time (min) to arrive at the ambient chamber pressure of 445 psi.

Alpha level was set at .01 for all inferential tests.

PHASE 1: RESISTIVE EFFORT AT 0 FSW

Appendix A3 summarizes resistive effort results at 0 fsw. Sample breathing cycles at each orientation are illustrated in Figures 1a-1c. Resistive effort is characterized in J/L for each breathing cycle. Differences in breathing resistance between the tested orientations were small. As expected, the 90° orientation produced greater breathing resistance than the 0° [RED: $t(9) = -16.46$, $p < .01$; GREEN: $t(9) = -35.82$, $p < .01$] and 45° orientations [RED: $t(9) = -22.59$, $p < .01$; GREEN: $t(9) = -28.92$, $p < .01$] produced. The 45° orientation produced greater breathing resistance than the 0° orientation produced in the GREEN backpack [$t(9) = -37.50$, $p < .01$], a result that was not replicated in the RED backpack [$t(9) = -1.93$, n.s.].

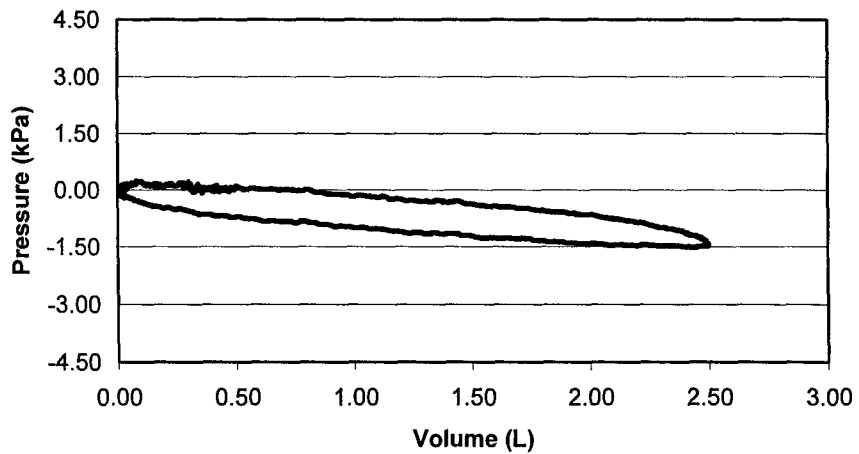


Figure 1a. Breathing loop #1 for the RED backpack oriented at 0°. The “noise” at the end of exhalation is attributed to the overpressure relief valve.

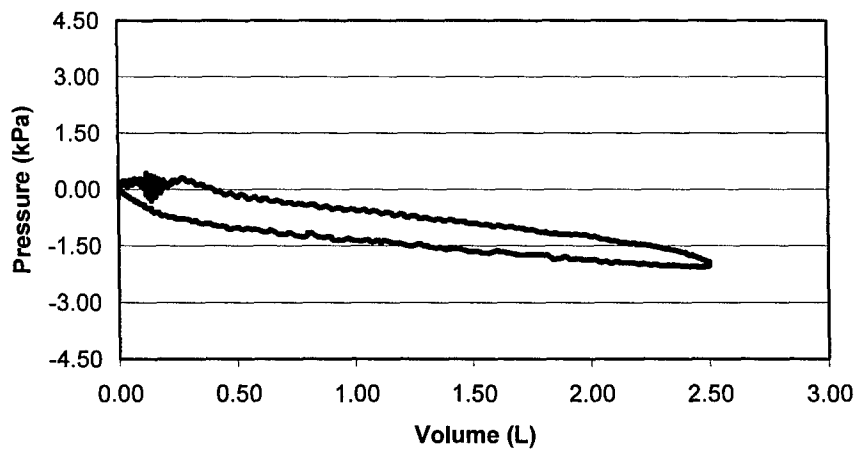


Figure 1b. Breathing loop #5 for the GREEN backpack oriented at 45°. The “noise” at the end of exhalation is attributed to the overpressure relief valve.

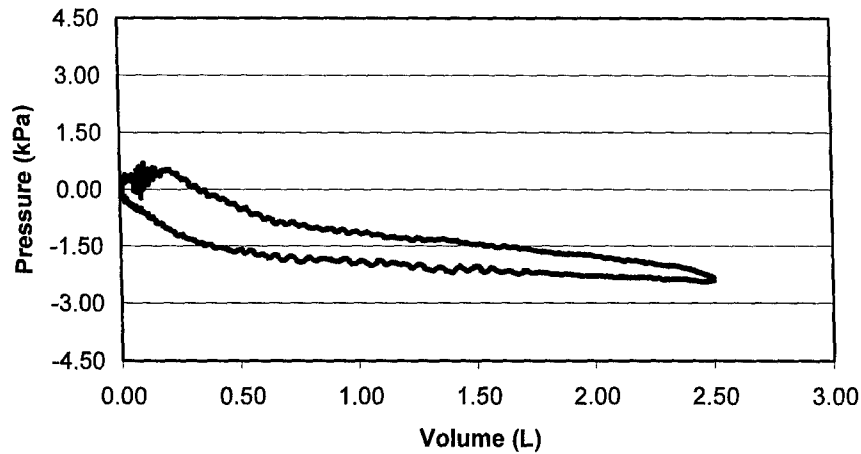


Figure 1c. Breathing loop #8 for the GREEN backpack oriented at 90°. The “noise” at the end of exhalation is attributed to the overpressure relief valve.

PHASE 2: CO₂ CANISTER DURATION AND RESISTIVE EFFORT AT 1000 FSW

Carbon dioxide canister durations for targeted surface equivalent CO₂ values are listed in Table C and illustrated in Figures 2a and 2b. Carbon dioxide canister weights are listed in Appendix D. The shortest recorded CO₂ canister duration (RED_A) to attain a 0.5% surface equivalent CO₂ value was 12.7 minutes. The shortest recorded CO₂ canister duration (RED_A and RED_B) to attain a 5.0% surface equivalent CO₂ value was 22.3 minutes. All recorded times to attain surface equivalent percentages of CO₂ exceeded 10 minutes.

Table C. Elapsed Time in Minutes to Attain Surface Equivalent Percentages of CO₂.

| Test | Percent CO ₂ (SEV) | | | | | |
|--------------------|-------------------------------|------|------|------|------|------|
| | 0.50 | 1.00 | 1.50 | 2.00 | 2.50 | 5.00 |
| RED _A | 12.7 | 13.5 | 14.6 | 16.1 | 17.6 | 22.3 |
| RED _B | 13.3 | 16.0 | 17.1 | 18.0 | 18.7 | 22.3 |
| GREEN _A | 13.7 | 16.1 | 18.0 | 19.5 | 20.8 | 25.4 |
| GREEN _B | 14.3 | 15.1 | 16.4 | 17.7 | 19.1 | 24.1 |

Note: Elapsed time to attain percent CO₂ (SEV) was rounded down to the nearest 0.1 minute when the elapsed time did not result in a match with target CO₂ SEV.

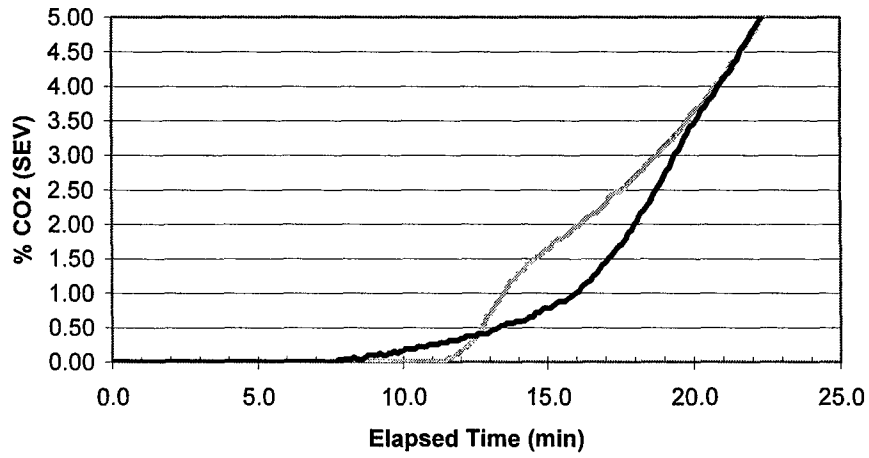


Figure 2a. Canister duration profiles for the RED backpack.

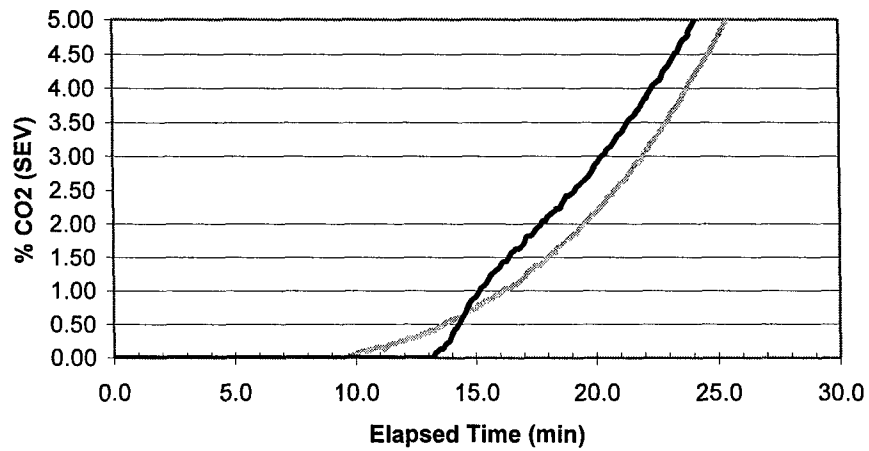


Figure 2b. Canister duration profiles for the GREEN backpack.

Appendix B3 summarizes resistive effort results at 1000 fsw, with a starting bottle pressure of 1600 psi. Sample breathing cycles are illustrated in Figures 2c and 2d. These results are compared to breathing cycles recorded during Phase 3 in that subsection.

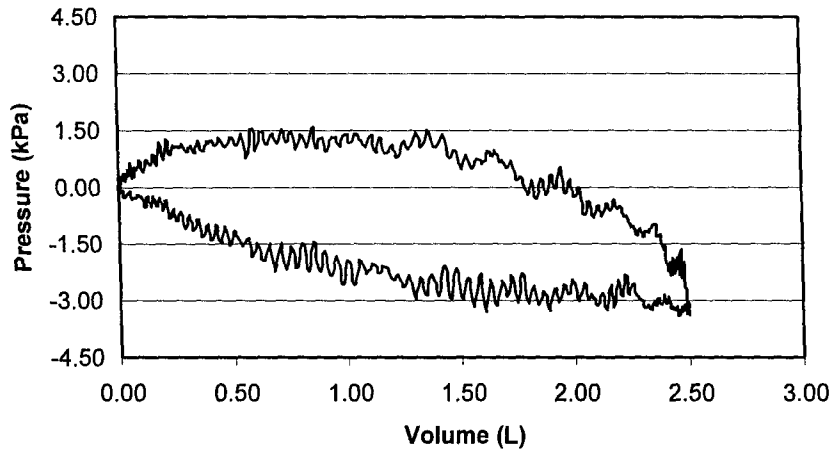


Figure 2c. Breathing loop #1_B for the RED backpack when starting bottle pressure was 1600 psi.

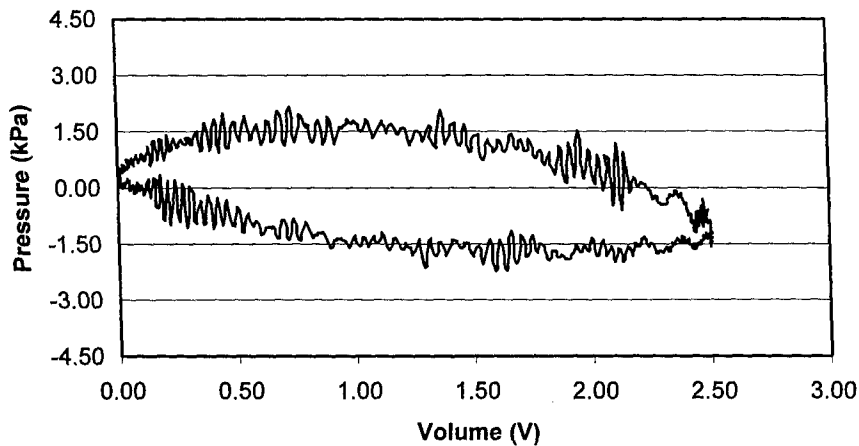


Figure 2d. Breathing loop #10_B for the GREEN backpack when starting bottle pressure was 1600 psi.

PHASE 3: BOTTLE DURATION AND RESISTIVE EFFORT AT 1000 FSW

Two hours into RED Phase 3 testing, the P-V loop recorded kPa values exceeding 4.0 (bottle pressure ~1000 psi), an indication that the breathing bags were not filling properly and that the SLS was supplying gas via the demand regulator. This method of gas supply produced a more rapid depletion of bottle gas than was expected. After testing concluded, the RED backpack was examined. The source of the gas loss from the breathing bag was a malfunctioning overpressure valve (part #DM3305) inside the helmet interface valve. The overpressure valve normally relieves at 19–21 cm H₂O at

the end of each expiration, and then it reseats. The valve seats were cocked in the cartridge sleeve and permitted gas to escape from the breathing bags. The relief valve was replaced with a spare assembly, and the system was returned to normal service.

Bottle durations for GREEN_A and GREEN_B are illustrated in Figure 3a. Bottle durations for the two measurements were 22.4 and 22.8 minutes, respectively.

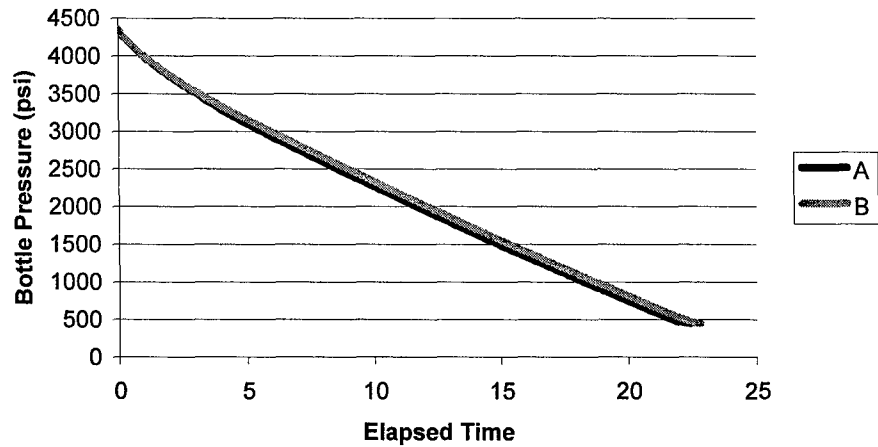


Figure 3a. GREEN backpack bottle duration functions.

Appendix C3 provides a summary of P-V loops at 1000 fsw with starting bottle pressures of 4350 and 2500 psi. Breathing cycles for each bottle pressure are illustrated in Figures 3b and 3c.

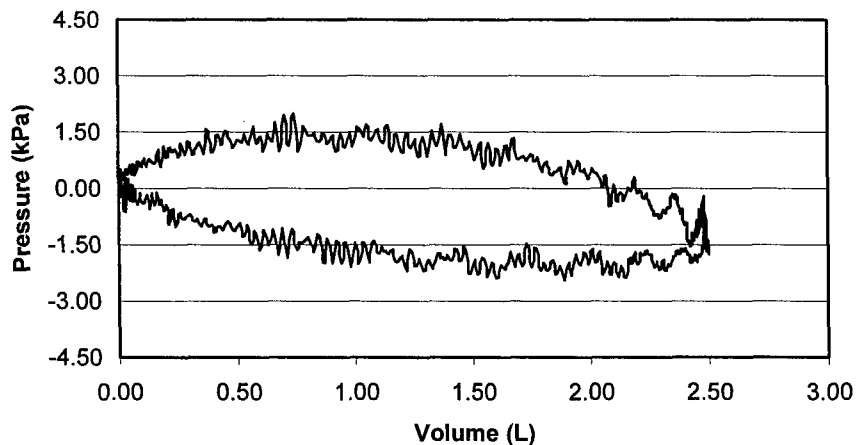


Figure 3b. Breathing loop #7_A for the GREEN backpack when starting bottle pressure was 4350 psi.

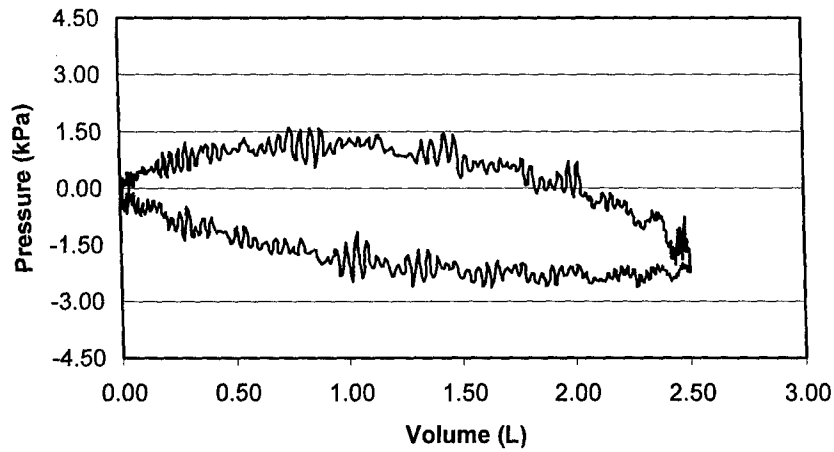


Figure 3c. Breathing loop #2 for the RED backpack when starting bottle pressure was 2500 psi.

Phase 2 and Phase 3 P-V loops were compared to Phase 1 P-V loops at the same orientation (45°). Differences in breathing resistance were observed in both backpacks as a function of ambient pressure. As anticipated, 1000 fsw resulted in greater breathing resistance than 0 fsw.

Pressure-volume loops from Phase 3 were assessed with results from Phase 2 (Appendix B3; 1600 psi). Table D lists mean differences in P-V loops for each backpack test as a function of starting bottle pressure. None of the differences in P-V loops as a function of starting bottle pressure for the GREEN backpack exceeded tolerance limits (± 0.13 J/L) for orifice calibration.

Table D. Mean Differences in Resistive Effort (J/L) for Each Backpack as a Function of Starting Bottle Pressure.

| | RED _A | | GREEN _A | | GREEN _B | |
|------|-----------------------|--------|--------------------|-------|--------------------|-------|
| | Bottle Pressure (psi) | | | | | |
| | 4350 | 2500 | 4350 | 2500 | 4350 | 2500 |
| 2500 | 0.052 | | -0.008 | | -0.041 | |
| 1600 | -0.228 | -0.280 | 0.061 | 0.069 | -0.002 | 0.038 |

Note: Mean differences (column - row) were calculated with mean J/L scores from Appendix B3 and Appendix C3.

Table E lists mean differences in resistive effort across starting bottle pressures as a function of backpack injection flow rate. The RED backpack, which had an injection flow rate below the acceptance zone for the manufacturer's flow meter, produced greater breathing resistance than did the GREEN backpack when the starting bottle pressure was at the lowest tested starting point (1600 psi); RED_A vs. GREEN_A $t(9) = 15.91$, $p < .01$; RED_A vs. GREEN_B $t(9) = -16.08$, $p < .01$; RED_B vs. GREEN_A $t(9) = 28.18$, $p < .01$; RED_B vs. GREEN_B $t(9) = 20.18$, $p < .01$. The relevance of this difference for human applications at 1000 fsw is unknown.

Table E. Differences in Resistive Effort (J/L) at Tested Bottle Pressures as a Function of Backpack Injection Flow Rate.

| | RED Bottle Pressure (psi) | | | |
|--------------------|---------------------------|--------|-------------------|-------------------|
| | 4350 | 2500 | 1600 _A | 1600 _B |
| GREEN _A | 0.007 | -0.045 | 0.296 | 0.350 |
| GREEN _B | 0.059 | -0.034 | 0.284 | 0.338 |

Note: Mean breathing differences between backpacks are calculated from Appendices B3 and C3. All calculations refer to the RED backpack. Positive means indicate an increase in breathing resistance compared to the GREEN backpack; negative means indicate a decrease in breathing resistance compared to the GREEN backpack.

DISCUSSION

The SLS MK IV system performed in accordance with manufacturer expectations throughout unmanned simulations. Small increases in breathing resistance were observed as backpack orientation was manipulated from the upright to the prone position, and as expected, breathing resistance was greater when the backpack was tested at 1000 fsw than at 0 fsw. Resistive effort at 1000 fsw (range: 2.29–2.64 J/L) was comparable to an earlier version of the SLS backpack at 1000 fsw³ and recently reported unmanned evaluations of the same SLS backpack at 723 fsw (2.51 J/L).⁴ Work of breathing at 1000 fsw in the emergency mode is approximately 1.5 times greater than resistive effort at the same depth in the normal mode.³ Carbon dioxide canister and bottle durations indicate that the SLS MK IV system should provide sufficient secondary life support for a saturation diver to return to a diving bell at 1000 fsw. Controlled manned testing conducted at NEDU will attempt to confirm these assumptions.

CONCLUSIONS AND RECOMMENDATIONS

- Unmanned simulations indicate that the breathing resistance of the SLS MK IV backpack oriented at 45° should not prohibit humans from using it at 1000 fsw.
- Unmanned simulations indicate that the SLS MK IV CO₂ canister should provide sufficient secondary life support for a saturation diver to return to a diving bell at 1000 fsw.
- Unmanned simulations indicate that the SLS MK IV gas supply should provide sufficient secondary life support for a saturation diver to return to a diving bell at 1000 fsw.
- The SLS MK IV backpack is safe for controlled human testing.

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**APPENDIX A2:
PHASE 1 TEST PARAMETERS AND PROCEDURES**

Test Parameters

SLS Orientations: 0°, 45°, 90°
Normobaric Pressure
Breathing Medium: 94/6 Helium-Oxygen
Breathing Simulator: 62.5 RMV
Ark Water: Fresh
Ark Water Temperature: Ambient (approximately 70 °F)

Recorded Data [Appendix A1 reference] (range/type)

SLS Serial Number [manual]
Helmet Serial Number [manual]
SLS Helmet ID [manual] (R/G)
Gas Storage Bottle Pressure [P2] (0–5000 psi)
SLS Inlet Hot Water temperature [T3] (°F)
RMV [manual] (L/min)
Date and Time [automatic]
Resistive Effort [computer system record] (J/L)

Procedures

- a. Identify and record the SLS MK IV serial number(s).
- b. Assign and record the ID number (R or G): clearly indicate the ID on the system exterior.
- c. Instrument the SLS MK IV system (see Appendix A1): set the
 - i. backpack orientation,
 - ii. pressure transducers, and
 - iii. breathing simulator.
- d. Record the ambient temperature.
- e. Activate the backpack by energizing the pressurized pneumatic cylinder attached to the actuation valve.
- f. Start the breathing simulator.
- g. Collect and save data for 10 simulated breathing cycles.
 - i. Collect 10 respiration cycles when the bottle pressure is
 - a. 3000–4350 psi (300 bar), and
 - b. 1500–2999 psi.
 - ii. Save data for 10 respiration cycles.
 - a. filename convention: yymmdd-SLS-id-phase-orientation-cycle-psi
 - b. example: 050119-SLS-R-1-45-01-3500
- h. Stop the breathing simulator.
- i. Repeat steps (c)–(h) until all orientations have been tested.
- j. Secure the breathing machine.
- k. Backup data files to a CD.

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**APPENDIX A3:
DIVEX SLS MK IV RESISITIVE EFFORT AT 0 FSW
AS A FUNCTION OF BACKPACK ORIENTATION**

| RED BACKPACK ORIENTATION | | | | | | | | | |
|---------------------------------|------------|----------------|----------------|------------|----------------|----------------|------------|----------------|----------------|
| | 0° | | | 45° | | | 90° | | |
| Loop # | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 0.713 | -1.52 | 0.24 | 0.719 | -2.04 | 0.24 | 0.766 | -2.52 | 0.31 |
| 2 | 0.727 | -1.52 | 0.30 | 0.723 | -2.04 | 0.23 | 0.764 | -2.54 | 0.33 |
| 3 | 0.706 | -1.49 | 0.28 | 0.720 | -2.05 | 0.19 | 0.767 | -2.56 | 0.36 |
| 4 | 0.710 | -1.49 | 0.34 | 0.704 | -2.06 | 0.08 | 0.766 | -2.58 | 0.39 |
| 5 | 0.691 | -1.57 | 0.16 | 0.706 | -2.08 | 0.09 | 0.762 | -2.55 | 0.30 |
| 6 | 0.699 | -1.55 | 0.16 | 0.707 | -2.10 | 0.13 | 0.762 | -2.60 | 0.29 |
| 7 | 0.705 | -1.56 | 0.14 | 0.713 | -2.06 | 0.21 | 0.761 | -2.54 | 0.35 |
| 8 | 0.699 | -1.49 | 0.25 | 0.711 | -2.03 | 0.20 | 0.761 | -2.54 | 0.32 |
| 9 | 0.717 | -1.50 | 0.24 | 0.719 | -1.99 | 0.33 | 0.758 | -2.55 | 0.29 |
| 10 | 0.712 | -1.47 | 0.32 | 0.706 | -2.04 | 0.12 | 0.759 | -2.57 | 0.27 |
| MEAN | 0.708 | -1.516 | 0.243 | 0.713 | -2.049 | 0.182 | 0.763 | -2.555 | 0.321 |
| STD | 0.010 | 0.034 | 0.070 | 0.007 | 0.030 | 0.078 | 0.003 | 0.023 | 0.037 |

| GREEN BACKPACK ORIENTATION | | | | | | | | | |
|-----------------------------------|------------|----------------|----------------|------------|----------------|----------------|------------|----------------|----------------|
| | 0° | | | 45° | | | 90° | | |
| Loop # | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 0.607 | -1.64 | 0.14 | 0.697 | -2.10 | 0.37 | 0.768 | -2.41 | 0.56 |
| 2 | 0.625 | -1.63 | 0.26 | 0.701 | -2.08 | 0.46 | 0.760 | -2.44 | 0.58 |
| 3 | 0.621 | -1.61 | 0.32 | 0.704 | -2.10 | 0.42 | 0.759 | -2.44 | 0.61 |
| 4 | 0.617 | -1.59 | 0.23 | 0.697 | -2.11 | 0.26 | 0.748 | -2.44 | 0.52 |
| 5 | 0.627 | -1.62 | 0.27 | 0.695 | -2.07 | 0.43 | 0.746 | -2.44 | 0.48 |
| 6 | 0.623 | -1.62 | 0.31 | 0.696 | -2.07 | 0.48 | 0.748 | -2.45 | 0.52 |
| 7 | 0.625 | -1.61 | 0.29 | 0.696 | -2.07 | 0.39 | 0.749 | -2.40 | 0.59 |
| 8 | 0.626 | -1.61 | 0.30 | 0.701 | -2.07 | 0.42 | 0.760 | -2.44 | 0.68 |
| 9 | 0.622 | -1.60 | 0.29 | 0.694 | -2.06 | 0.38 | 0.747 | -2.43 | 0.50 |
| 10 | 0.624 | -1.58 | 0.40 | 0.701 | -2.10 | 0.28 | 0.761 | -2.42 | 0.42 |
| MEAN | 0.622 | -1.611 | 0.281 | 0.698 | -2.083 | 0.389 | 0.755 | -2.431 | 0.546 |
| STD | 0.006 | 0.018 | 0.067 | 0.003 | 0.018 | 0.071 | 0.008 | 0.016 | 0.074 |

Note: Overall breathing effort (J/L) per loop at each backpack orientation. Larger values indicate increases in breathing resistance. Minimum values (Min kPa) represent peak inhalations. Maximum values (Max kPa) represent peak exhalations. Mean scores and their respective standard deviations are calculated across the 10 breathing loops.

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**APPENDIX B2:
PHASE 2 TEST PARAMETERS AND PROCEDURES**

Test Parameters

SLS Orientation: 45°
Depth: 1000 ± 1 fsw
Breathing Medium: 94/6 Helium-Oxygen
Breathing Simulator: 62.5 RMV
CO₂ Injection Rate: 2.5 SLPM at 62.5 RMV
Ark Water: 34 ± 2 parts per thousand NaCl
Ark Water Temperature: 29 ± 2 °F

Recorded Data [Appendix B1 reference] (range/type)

SLS Serial Number [manual]
Helmet Serial Number [manual]
SLS Helmet ID [manual] (R/G)
Gas Storage Bottle Pressure [P2] (0–5000 psi)
SLS Inlet Hot Water temperature [T3] (°F)
Ark Water Temperature [T1] (°F)
Helmet End Tidal CO₂ [C2] (% CO₂ SEV)
CO₂ Injection [C1] (SLPM)
Depth [P1] (fsw)
CO₂ canister weight [manual] (kg)
RMV [manual] (L/min)
Date and Time [automatic]
Resistive Effort [computer system record] (J/L)

**APPENDIX B2:
PHASE 2 TEST PARAMETERS AND PROCEDURES**

Procedures

- a. Verify that the ark water temperature is within limits; verify the hot water flow.
- b. Instrument the SLS MK IV system in accordance with Appendix B1.
- c. Record the SLS MK IV serial number(s) and ID(s).
- d. Record the empty CO₂ canister weight.
- e. Pack the canister with 8-12 Sofnolime per Divex Manual¹ guidance in section 3.1.3 (p. 3.8): "CO₂ Scrubber Canister Filling."
- f. Record the full CO₂ canister weight.
- g. Verify that gas flasks are pressurized to the maximum working pressure of 4350 psi (300 bar).
- h. Calibrate the instruments:
 - i. pressure transducers,
 - ii. breathing simulator, and
 - iii. temperature sensors.
- i. Complete the chamber operating procedures (OP).
- j. Submerge the SLS MK IV in ark water.
- k. Close the chamber hatch.
- l. Pressurize the chamber to 1000 fsw (≤ 30 ft/min descent rate).
- m. Verify that the ark water temperature is within limits.
- n. Observe the system for abnormal gas leakage.
- o. Collect data:
 - i. CO₂ Canister Duration
 1. Log the data.
 2. Secure the hot water.
 3. Activate the backpack.
 4. Activate the breathing simulator.
 5. Start the CO₂ injection.
 6. Continue (1) until the canister reaches 5% SEV.
 7. Save the data.
 - a. filename convention: yymmdd-SLS-id-phase
 - b. example: 050120-SLS-G-2
 - ii. Work of Breathing
 1. Collect and save data for 10 respiration cycles.
 - a. filename convention: yymmdd-SLS-id-phase-cycle-psi
 - b. example: 050120-SLS-R-2-01-1600
- p. Decompress the chamber to normobaric pressure.
- q. Record the postdive CO₂ canister weight.
- r. Conduct postdive operations in accordance with the manufacturer's instructions.
- s. Secure the gas supplies and supporting machinery.
- t. Backup the data files to a CD.

**APPENDIX B3:
DIVEX SLS MK IV RESISTIVE EFFORT AT 1000 FSW
WITH A 1600 PSI STARTING BOTTLE PRESSURE**

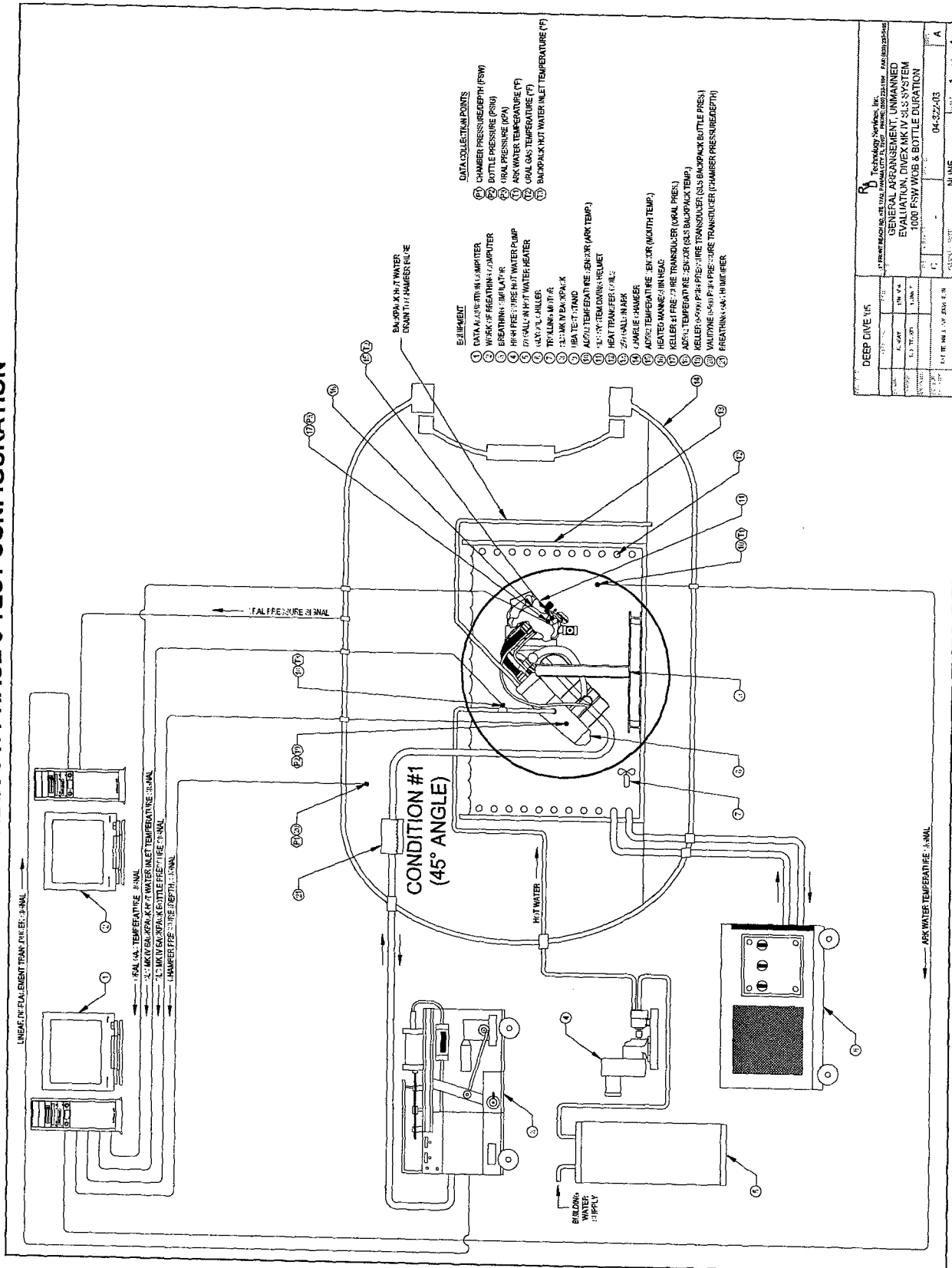
| Loop # | RED _A | | | RED _B | | |
|-------------|------------------|---------|---------|------------------|---------|---------|
| | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 2.650 | -3.400 | 1.590 | 2.676 | -5.990 | 1.640 |
| 2 | 2.653 | -3.520 | 1.510 | 2.612 | -5.970 | 1.700 |
| 3 | 2.563 | -3.420 | 1.500 | 2.651 | -5.840 | 1.640 |
| 4 | 2.532 | -3.410 | 1.370 | 2.709 | -5.950 | 1.710 |
| 5 | 2.581 | -3.330 | 1.530 | 2.624 | -5.870 | 1.560 |
| 6 | 2.612 | -3.260 | 1.540 | 2.605 | -5.810 | 1.550 |
| 7 | 2.637 | -3.630 | 1.470 | 2.621 | -5.930 | 1.530 |
| 8 | 2.655 | -3.410 | 1.580 | 2.620 | -5.960 | 1.530 |
| 9 | 2.495 | -3.370 | 1.220 | 2.610 | -5.870 | 1.500 |
| 10 | 2.502 | -3.280 | 1.460 | 2.692 | -5.970 | 1.670 |
| MEAN | 2.588 | -3.403 | 1.477 | 2.642 | -5.916 | 1.603 |
| STD | 0.059 | 0.109 | 0.103 | 0.036 | 0.058 | 0.076 |

| Loop # | GREEN _A | | | GREEN _B | | |
|-------------|--------------------|---------|---------|--------------------|---------|---------|
| | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 2.316 | -2.900 | 1.690 | 2.332 | -2.250 | 2.100 |
| 2 | 2.323 | -2.700 | 1.580 | 2.371 | -2.130 | 2.320 |
| 3 | 2.299 | -3.000 | 1.630 | 2.308 | -2.170 | 2.180 |
| 4 | 2.313 | -2.710 | 1.940 | 2.310 | -2.210 | 2.100 |
| 5 | 2.285 | -2.730 | 1.620 | 2.303 | -2.150 | 2.100 |
| 6 | 2.287 | -2.720 | 1.610 | 2.301 | -2.100 | 2.050 |
| 7 | 2.283 | -2.740 | 1.760 | 2.279 | -2.100 | 2.130 |
| 8 | 2.272 | -2.680 | 1.760 | 2.281 | -2.190 | 2.030 |
| 9 | 2.280 | -2.640 | 1.590 | 2.290 | -2.260 | 2.060 |
| 10 | 2.263 | -2.660 | 1.520 | 2.260 | -2.220 | 2.160 |
| MEAN | 2.292 | -2.748 | 1.670 | 2.304 | -2.178 | 2.123 |
| STD | 0.018 | 0.100 | 0.122 | 0.029 | 0.052 | 0.083 |

Note: Overall breathing effort (J/L) per loop at each bottle pressure. Larger values indicate increases in breathing resistance. Minimum values (Min kPa) represent peak inhalations. Maximum values (Max kPa) represent peak exhalations. Mean scores and their respective standard deviations are calculated across the 10 consecutively recorded breathing loops.

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APPENDIX C1: PHASE 3 TEST CONFIGURATION



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**APPENDIX C2:
PHASE 3 TEST PARAMETERS AND PROCEDURES**

Test Parameters

SLS Orientation: 45°
Depth: 1000 ± 1 fsw
Breathing Medium: 94/6 Helium-Oxygen
Breathing Simulator: 62.5 RMV
Ark Water: 34 ± 2 parts per thousand NaCl
Ark Water Temperature: 29 ± 2 °F

Recorded Data [Appendix C1 reference] (range/type)

SLS Serial Number [manual]
Helmet Serial Number [manual]
SLS Helmet ID [manual] (R/G)
Gas Storage Bottle Pressure [P2] (0–5000 psi)
SLS Inlet Hot Water Temperature [T3] (°F)
Ark Water Temperature [T1] (°F)
Helmet End Tidal CO₂ [C2] (% CO₂ SEV)
Depth [manual] (fsw)
RMV [manual] (L/min)
Date and Time [automatic]
Resistive Effort [computer system record] (J/L)

**APPENDIX C2:
PHASE 3 TEST PARAMETERS AND PROCEDURES**

Procedures

- a. Verify that the ark water temperature is within limits; verify the hot water flow.
- b. Instrument the SLS MK IV system in accordance with Appendixes B1, B2, and B3.
- c. Record the SLS MK IV serial number(s) and ID(s).
- d. Pack the canister with 8-12 Sofonolime.
- e. Verify that gas flasks are pressurized to the maximum working pressure.
- f. Calibrate Instruments:
 - i. pressure transducers,
 - ii. breathing simulator, and
 - iii. temperature sensors.
- g. Complete the chamber operating procedures.
- h. Submerge the SLS MK IV in ark water.
- i. Close the chamber hatch.
- j. Pressurize the chamber to 1000 fsw (≤ 30 ft/min).
- k. Verify that the ark water temperature is within limits.
- l. Observe the system for abnormal gas leakage.
- m. Collect data:
 - i. Bottle Duration
 1. Commence data collection.
 2. Activate the SLS.
 3. Start the breathing simulator.
 4. Continue collecting data until the bottle pressure is 445 psi.
 5. Save the data.
 - a. filename convention: yymmdd-SLS-id-phase
 - b. example: 050121-SLS-G-3
 - ii. Work of Breathing
 1. Collect 10 respiration cycles when the bottle pressure is
 - a. 4500 psi and then
 - b. 2500 psi.
 2. Save the data for 10 respiration cycles.
 - a. filename convention: yymmdd-SLS-id-phase-cycle-psi
 - b. example: 050121-SLS-G-3-01-4500
- n. Decompress the chamber to normobaric pressure.
- o. Conduct postdive operations in accordance with the manufacturer's instructions.
- p. Secure the gas supplies and supporting machinery.
- q. Backup the data files to a CD.

**APPENDIX C3:
DIVEX SLS MK IV RESISTIVE EFFORT AT 1000 FSW
WITH 4350 AND 2500 PSI STARTING BOTTLE PRESSURES**

| RED Bottle Pressure (psi) | | | | | | |
|---------------------------|-------|---------|---------|-------|---------|---------|
| Loop # | 4350 | | | 2500 | | |
| | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 2.366 | -2.751 | 1.679 | 2.322 | -2.764 | 1.775 |
| 2 | 2.361 | -2.633 | 1.581 | 2.307 | -2.636 | 1.600 |
| 3 | 2.354 | -2.643 | 1.758 | 2.304 | -2.608 | 1.642 |
| 4 | 2.369 | -2.636 | 1.892 | 2.304 | -2.796 | 1.877 |
| 5 | 2.359 | -3.424 | 3.621 | 2.315 | -2.749 | 2.492 |
| 6 | 2.364 | -2.611 | 1.717 | 2.262 | -2.689 | 1.618 |
| 7 | 2.362 | -2.602 | 1.976 | 2.316 | -2.633 | 1.642 |
| 8 | 2.371 | -2.793 | 1.949 | 2.322 | -2.692 | 1.574 |
| 9 | 2.349 | -2.739 | 1.797 | 2.322 | -2.957 | 1.667 |
| 10 | 2.348 | -2.582 | 1.531 | 2.308 | -2.813 | 1.729 |
| MEAN | 2.360 | -2.741 | 1.950 | 2.308 | -2.734 | 1.762 |
| STD | 0.008 | 0.250 | 0.598 | 0.017 | 0.105 | 0.272 |

| GREEN _A Bottle Pressure (psi) | | | | | | |
|--|-------|---------|---------|-------|---------|---------|
| Loop # | 4350 | | | 2500 | | |
| | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 2.352 | -2.422 | 1.974 | 2.353 | -2.908 | 1.693 |
| 2 | 2.351 | -2.349 | 1.881 | 2.365 | -3.019 | 1.638 |
| 3 | 2.356 | -2.666 | 1.939 | 2.360 | -2.879 | 1.911 |
| 4 | 2.368 | -2.597 | 1.917 | 2.368 | -2.846 | 1.648 |
| 5 | 2.370 | -2.603 | 1.809 | 2.358 | -2.921 | 1.679 |
| 6 | 2.349 | -2.550 | 1.796 | 2.356 | -2.839 | 1.421 |
| 7 | 2.353 | -2.447 | 1.977 | 2.358 | -2.987 | 1.717 |
| 8 | 2.350 | -2.623 | 1.934 | 2.369 | -2.785 | 1.711 |
| 9 | 2.354 | -2.464 | 1.910 | 2.366 | -2.970 | 1.667 |
| 10 | 2.332 | -2.561 | 1.955 | 2.358 | -2.866 | 1.607 |
| MEAN | 2.354 | -2.528 | 1.909 | 2.361 | -2.902 | 1.669 |
| STD | 0.010 | 0.095 | 0.059 | 0.005 | 0.073 | 0.120 |

Note: Overall breathing effort (J/L) per loop at each bottle pressure. Larger values indicate increases in breathing resistance. Minimum values (Min kPa) represent peak inhalations. Maximum values (Max kPa) represent peak exhalations. Mean scores and their respective standard deviations are calculated across the 10 consecutively recorded breathing loops.

**APPENDIX C3:
DIVEX SLS MK IV RESISTIVE EFFORT AT 1000 FSW
WITH 4350 AND 2500 PSI STARTING BOTTLE PRESSURES**

| Loop # | GREEN _B Bottle Pressure (psi) | | | | | |
|-------------|--|---------|---------|-------|---------|---------|
| | 4350 | | | 2500 | | |
| | J/L | Min kPa | Max kPa | J/L | Min kPa | Max kPa |
| 1 | 2.314 | -2.428 | 1.903 | 2.356 | -2.955 | 1.584 |
| 2 | 2.314 | -2.541 | 1.724 | 2.349 | -2.776 | 2.141 |
| 3 | 2.316 | -2.616 | 2.035 | 2.346 | -2.795 | 1.848 |
| 4 | 2.308 | -2.548 | 1.701 | 2.365 | -2.640 | 1.571 |
| 5 | 2.285 | -2.477 | 1.970 | 2.344 | -2.609 | 1.926 |
| 6 | 2.281 | -2.587 | 1.876 | 2.330 | -2.639 | 1.984 |
| 7 | 2.324 | -2.727 | 1.879 | 2.342 | -2.603 | 1.782 |
| 8 | 2.296 | -2.487 | 2.221 | 2.334 | -2.711 | 1.804 |
| 9 | 2.293 | -2.684 | 1.858 | 2.337 | -2.868 | 1.788 |
| 10 | 2.281 | -2.520 | 1.918 | 2.316 | -2.769 | 1.609 |
| MEAN | 2.301 | -2.562 | 1.909 | 2.342 | -2.737 | 1.804 |
| SD | 0.015 | 0.081 | 0.149 | 0.013 | 0.090 | 0.167 |

Note: Overall breathing effort (J/L) per loop at each bottle pressure. Larger values indicate increases in breathing resistance. Minimum values (Min kPa) represent peak inhalations. Maximum values (Max kPa) represent peak exhalations. Mean scores and their respective standard deviations are calculated across the 10 consecutively recorded breathing loops.

**APPENDIX D:
CANISTER WEIGHTS DURING TESTING**

CO₂ Absorbent: Sofnolime Nonindicating

Grade: D

Lot #217121

Granule Size: 812

Expiration Date: Dec 2006

| RED (#50386-055) Weight (lb) | | | | | | |
|-------------------------------------|--------------|------|--------------|--------------|--------------|--------------|
| Fill/Use Date | 1/13 | 1/14 | 1/18 | 1/19 | 1/26 | 1/26 |
| Empty | 2.315 | * | 2.315 | 2.315 | 2.315 | 2.315 |
| Packed | 5.100 | * | 5.160 | 5.155 | 5.155 | 5.160 |
| Net Weight of Absorbent | 2.785 | * | 2.845 | 2.840 | 2.840 | 2.845 |
| Postdive | NA | * | 5.440 | 5.355 | 5.340 | 5.355 |
| Test Phase | 1 | 1 | 2 | 2 | 2 | 2 |

| GREEN (#50384-049) Weight (lb) | | | | | |
|---------------------------------------|--------------|--------------|--------------|--------------|--------------|
| Fill/Use Date | 1/21 | 1/21 | 1/24 | 1/25 | 1/25 |
| Empty | 2.350 | 2.350 | 2.350 | 2.350 | 2.350 |
| Packed | 5.155 | 5.155 | 5.150 | 5.155 | 5.155 |
| Net Weight of Absorbent | 2.805 | 2.805 | 2.800 | 2.805 | 2.805 |
| Postdive | 5.350 | 5.355 | NA | 5.355 | 5.355 |
| Test Phase | 2 | 2 | 1 | 2 | 2 |

Note: Asterisks indicate a methodological trial in which the canister was empty.

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APPENDIX E

SELECTED IMAGES OF SLS MK IV INSTRUMENTATION



Figure E1a. Calibration orifice in the heated manikin head.



Figure E1b. Orifice connected to the SLS.

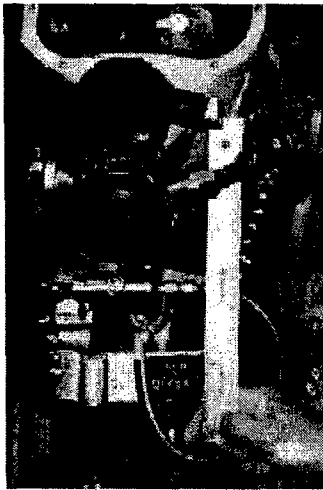


Figure E2. Suprasternal notch (90°).

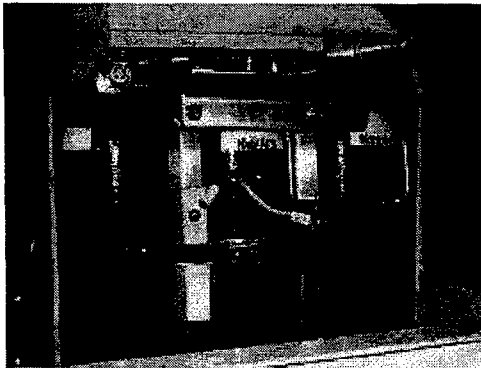


Figure E3. Spool valve pneumatic actuator.



Figure E4. Data collection point P2 (bottle pressure); see submerged black line at right.

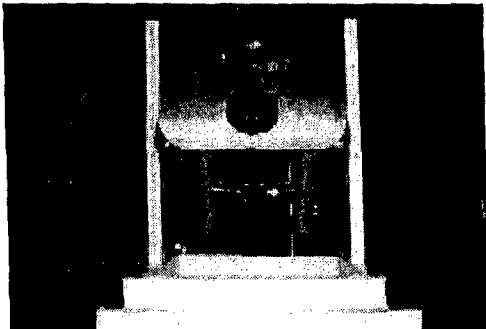


Figure E5. Data collection point P3 (oral pressure).



Figure E6a. Close-up view of data collection point T3 (backpack hot water inlet temperature).



Figure E6b. Data collection point T3 (backpack hot water inlet temperature).

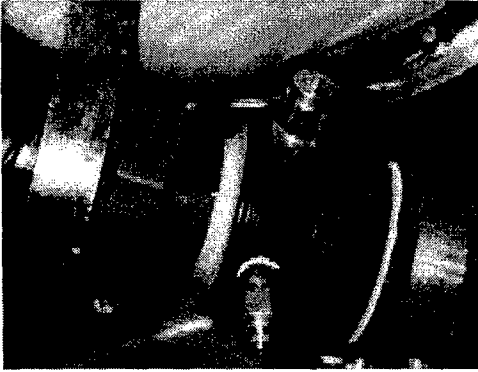


Figure E7a. Close-up view of data collection point C1 (CO₂ injection rate [SLPM]).



Figure E7b. Data collection point C1 (CO₂ injection rate [SLPM]).

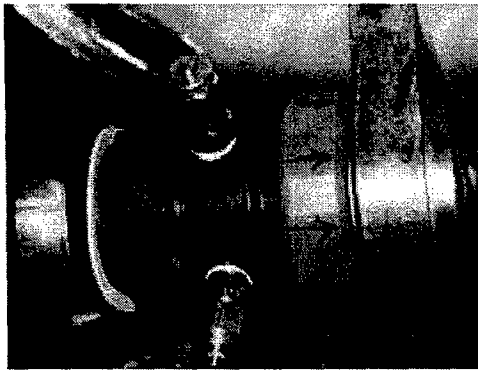


Figure E8a. Close-up view of data collection point C2 (canister outlet CO₂ sample).

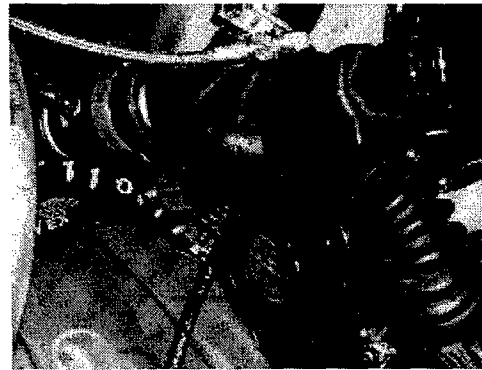


Figure E8b. Data collection point C2 (canister outlet CO₂ sample).

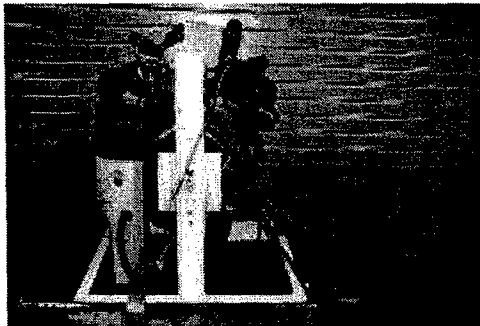


Figure E9. Right side view of a fully instrumented SLS MK IV at 0°.

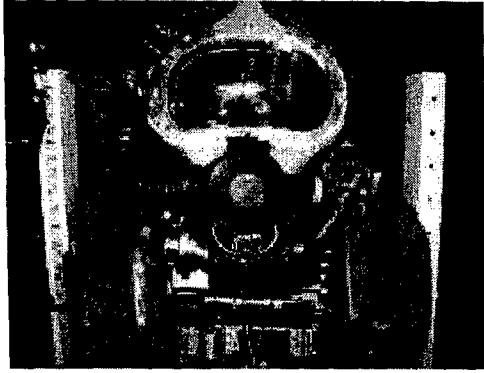


Figure E10a. Close-up view of an instrumented SLS MK IV in the chamber.

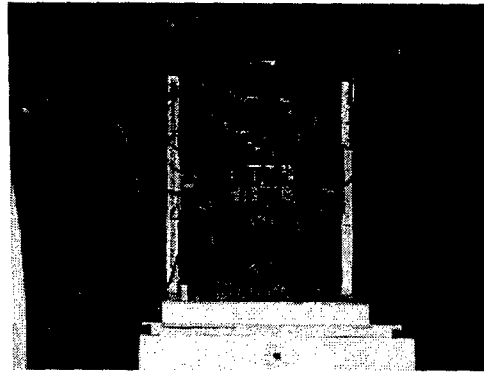


Figure E10b. View of an instrumented SLS MK IV in the chamber.



Figure E11a. SLS MK IV submerged in the chamber ark at 0°.



Figure E11b. Overhead view of the SLS MK IV submerged in the chamber ark at 0°.