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MANNED TESTING OF STANDARD MK 25 MOD 2 PURGE PROCEDURES WITH KMS 48 FULL FACE MASK

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The volume of oxygen used and resulting oxygen partial pressure (P_IO_2) were determined when current predive/surface and underwater purge procedures for the U.S. Navy MK 25 MOD 2 underwater breathing apparatus were performed with the KMS 48 face mask (Kirby Morgan Dive Systems; Santa Barbara, CA). A secondary purpose was to determine maximum pulmonary pressure (max P_{mask}) during ascent. Regardless of mouthpiece (T-bit or oral cup) used, purges performed at surface and 15 fsw yielded mean P_IO_2 exceeding 0.65 ATA. Purges at the surface and 15 fsw averaged less than 4.7 and 8.5 liters of oxygen, respectively. Regardless of mouthpiece the proportion of purges resulting in $P_IO_2 \geq 0.45$ ATA exceeded 94.0% and 91.8% at the surface and 15 fsw, respectively. Average max P_{mask} during ascent was less than 21 cm H_2O with the T-bit and 20 H_2O with the oral cup. The proportion of ascents in which max P_{mask} is less than 80 cm H_2O was greater than 91.7% regardless of mouthpiece. Average max P_{mask} during ascent from 50 fsw was less than 39 cm H_2O with the T-bit and 22 H_2O with the oral cup. The proportion of ascents where max P_{mask} is less than 80 cm H_2O was between 69.9% and 100% with either mouthpiece. Current purge procedures performed with the KMS 48 mask provide acceptable initial breathing gas P_IO_2. However, regardless of mouthpiece, it is recommended that divers always start ascent with a mostly empty breathing bag to decrease risk of pulmonary overpressurization as gas expands.

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INTRODUCTION

This technical report presents the surface/shallow and deep water testing of a two-phase project[1] to determine whether current purge procedures (Appendices A and B) for the U.S. Navy MK 25 MOD 2 (LAR V) closed-circuit underwater breathing apparatus (UBA) produce and maintain acceptable oxygen concentrations when such procedures are used with the KMS 48 face mask (Kirby Morgan Dive Systems; Santa Barbara, CA). The MK 25 MOD 2 is a closed-circuit UBA used in SEAL Delivery Vehicle (SDV) and other special operations forces diving. The approved configuration employs a T-bit mouthpiece — that is, one that the diver holds in place by clenching it between his teeth. As opposed to most full face masks, the KMS 48 would make it easy to switch from the MK 25 UBA to SDV "boat air" open circuit demand regulator.

To minimize exposing the diver's face to water and to permit diving for extended periods without jaw discomfort,[2] the SEAL community is pursuing adoption of the KMS 48 (Figure 1) — a lightweight, full face mask consisting of two rigid frames with joint face seal. With its seal, the upper frame holds the faceplate and creates an air cavity for the eyes and nose. The seal of the lower frame enables various mouth "pods" to be attached and creates a cavity for the mouth. During a dive the pod is easily removed and replaced without breaking the seal surrounding the eyes and nose. The removable pod enables the diver to buddy-breathe; use a snorkel, surface supply, or octopus; or switch the MK 25 MOD 2 UBA from open to closed circuit without removing the entire mask.

Although the MK 25 MOD 2 is considered a pure oxygen (O_2) UBA, the actual breathing gas provided to the diver is not pure O_2. To eliminate most of the nitrogen (N_2) in the diver's lungs and the UBA dead space, a diver uses a purge procedure before breathing the UBA on the surface and before switching from air supplied by the SDV to the UBA at depth. Nitrogen that is not removed from the breathing loop is mixed with the supply O_2; a nitrogen-oxygen mix therefore results in the breathing loop. For a surface purge procedure to be acceptable, it must be able to establish an O_2 concentration sufficiently high to avoid breathedown hypoxia. Forty-five percent is the accepted minimum O_2 concentration.[3] The two currently approved MK 25 MOD 2 purge procedures [the Predive/Surface Purge (PD/S)[4] and the Purge under Pressure (PUP)[5]] were developed and are used with a T-bit mouthpiece. A PD/S procedure provides an average O_2 fraction of 74%, with a range of 50% to 89%.[3] A PUP provides an average O_2 fraction of 84%, with a range of 62% to 99%.[5]

The purpose of this manned test series was to determine breathing gas O_2 concentrations when currently approved purge procedures were performed with a KMS 48 face mask fitted with a switchover block pod. This mouth pod allowed the diver to breathe from an oral cup or a T-bit within the oral cup whether he was breathing from the UBA or an open circuit demand regulator. Specifically, this study was to determine how PD/S and PUP procedures performed at the level of 20 feet of seawater (fsw) affect inspired gas composition. A secondary purpose was to evaluate the potential for pulmonary overpressurization in divers ascending from 50 fsw. Benefits from this study included providing SDV operators and combat swimmers with a full face mask that integrates open circuit air with a safe crossover to the MK 25 UBA. If approved, use of the KMS 48 face mask in training and tactical situations provides a means of switching from open to closed circuit and back, a means safer than that currently available.

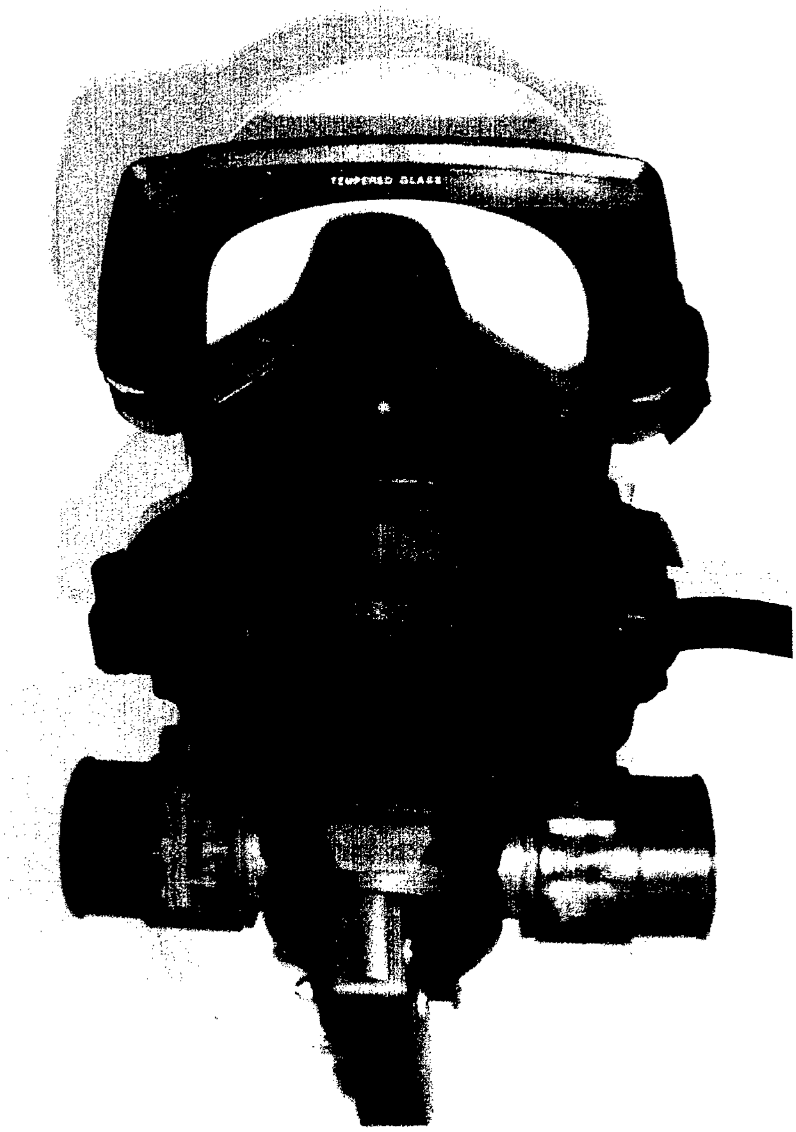

Figure 1. The KMS 48 Full Face Mask.

METHODS

GENERAL

The risks normally associated with no-decompression, closed-circuit UBA dives applied to personnel participating in this protocol. These risks were minimized by reviews from the NEDU Institutional Review Board (IRB) and by conducting all dives in accordance with the *U.S. Navy Diving Manual*,[6] monitoring the UBA O_2 concentration, instructing divers to report any unusual sensations, and maintaining protocol parameters. The direct supervision of divers by a qualified Diving Supervisor, the relatively short duration of the dives, the immediate proximity of a standby diver, the provision of diver training on the MK 25 MOD 2 as well as general diver training also minimized such risks. The IRB reviewed and approved this study before any manned trials commenced. Except where noted, procedures followed those required by the *U.S. Navy Diving Manual*.[6]

The test goals were to determine:

(1) the volume of O_2 used in performing each purge procedure,

(2) the percentage of O_2 delivered to the diver after he performed PD/S and PUP procedures,

(3) the effectiveness of the purge procedures (since breathing gas is not monitored during operational use, it is imperative to determine the incidence of ineffective purges, not simply to discern unacceptable mean gas concentrations), and

(4) the pressure differential between the breathing gas of the upright-seated diver and that of the water at the level of the diver's sternal notch (P_{mask}) during ascent.

EXPERIMENTAL DESIGN AND ANALYSIS

Test Pool

From Marineau's finding that the standard purge procedure results in inspired oxygen partial pressure (P_IO_2) > 0.45 ATA more than 95% of the time[7] (a finding that allows for an error of ±5% in predicting the proportion of purges meeting the criteria for acceptability), 70 purges were required for each of the four conditions: PD/S with T-bit, PD/S with oral cup, PUP with T-bit, and PUP with oral cup.[8] Since both the PD/S and PUP could be performed on a single dive, a minimum of 70 man-dives per configuration were required. Each diver performed at least two dives: one performing purges with the T-bit and one performing purges with the oral cup.

Descriptive statistics (mean ± 95% confidence interval (95%CI), and range) of $V_{purge}O_2$, P_IO_2, maximum P_{mask}, and F_IO_2 were calculated for both purge procedures (PD/S, PUP) and pod configurations (T-bit, oral cup only). A purge was deemed acceptable if it resulted in $P_IO_2 \geq 0.45$ ATA. An ascent was deemed acceptable if the maximum P_{mask} during ascent was less than 80 cm H_2O (centimeters of water). If breathing gas pressure attained 80 cm H_2O relative to the water pressure at the level of the diver's sternal notch[9], the diver was instructed to vent breathing gas from the UBA. To estimate the actual proportion of acceptable purge procedures and ascents, a 95% confidence interval was calculated.[8]

Ocean Simulation Facility (OSF)

Limited availability of the OSF and funding restricted data collection to 12 purges for each of the four conditions (PD/S with T-bit, PD/S with oral cup, PUP with T-bit, and PUP with oral cup). Since both PD/S and PUP can be performed on a single man-dive, 24 man-dives were conducted.

Descriptive statistics (mean ± 95% CI, and range) for $V_{purge}O_2$, P_IO_2, maximum P_{mask}, and F_IO_2 were calculated for both purge procedures (PD/S, PUP) and pod configurations (T-bit, oral cup only).

EQUIPMENT AND INSTRUMENTATION

Six MK 25 MOD 2 UBAs were prepared each day.[4] According to manufacturer specifications, each was configured with a KMS 48 face mask with switchover pod. The O_2 bottle was charged to approximately, but no more than, 3000 psi and thereby contained approximately 390 liters (L) of O_2. When not breathing on closed circuit, the diver breathed compressed air provided by a whip to the switchover pod demand regulator (open circuit). Between dives, the switchover pod was washed in Sanicide Plus® (Safetec of America; Buffalo, NY) germicidal solution and then given a freshwater rinse.

Each UBA was fitted with a model R-10DS O_2 sensor (Teledyne; City of Industry, CA) to analyze breathing gas at the inhalation hose–breathing bag junction. Sensor accuracy of at least ±5% had been demonstrated up to a partial pressure of oxygen (PO_2) level of 2.1 atmospheres absolute (ATA; see Appendix C). Calibration curves for PO_2 versus sensor output voltage for levels of PO_2 from 0 to 2.5 ATA were generated for each sensor before and after the series of dives. By exposing sensors to 0 and 100% O_2 at the surface and comparing the results to the calibration curves, we checked sensor calibration at the beginning and end of each dive day.

We estimated the volume of O_2 used to perform each purge procedure ($V_{purge}O_2$) by the change in MK 25 MOD 2 O_2 bottle pressure. Calibrated with a digital pressure gauge (model 2101, Mensor Corp.; San Marcos, TX) traceable to the National Institute of Standards Technology (NIST) before and after each dive, a model PTX-160 pressure transducer (Druck, Inc.; New Fairfield, CT) with a maximum scale of 5000 psi was used to measure bottle pressure immediately before and after each purge procedure was performed. To ensure that gas pressure reflected volume change rather than temperature change, bottle pressure was logged until it was stable before and after each purge and corrected for any temperature change. Ambient air and water temperatures were measured using, respectively, model 705 and 703 thermistors (Yellow Springs Instruments; Yellow Springs, OH) with model 1441 signal conditioners (Deban Enterprises Inc.; Beavercreek, OH).

Also calibrated with a digital pressure gauge (model 2101, Mensor Corp.; San Marcos, TX) traceable to the NIST before and after each dive, a differential pressure transducer (model DP-9, Validyne Engineering; Northridge, CA) referenced to ambient pressure at the level of the suprasternal notch was used to measure P_{mask}. Pressure inside the inhalation hose was measured, since that was the breathing gas pressure whether the diver was breathing from the T-bit or the oral cup.

Data were collected and logged with the LabVIEW® version 6.1 (National Instruments Corp.; Austin, TX) computer data acquisition system.

SUBJECTS

Participants were U.S. Navy and U.S. Marine Corps (USMC) divers who read and signed a consent form documenting that they understood the risks involved in the study and that their participation was voluntary. All subjects met the U.S. Navy physical qualification standards for diving. Subjects were given training that included a familiarization dive with the MK 25 MOD 2 and KMS 48, and were required to undergo training in the purge procedures before participating in data collection dives. The number of participants and their unit affiliations are presented in Table 1.

Table 1.
Study Participants.

Unit	Navy	USMC
NEDU	20	—
NDSTC	3	—
1st Recon Batt, 1st Marine Div FMF	3	3
2nd Force Recon Co, 2nd MEF	2	1
2nd Recon Batt, 2nd Marine Div FMF	—	1
Marine Corps System Command	1	1
1st Marine Exped. Force HQ Grp, 1st MEF FMF	—	1
TOTAL	29	7

PROCEDURES

Test Pool

Data collections were performed in the NEDU test pool, with water temperature maintained at approximately 85–90 °F (29–32 °C). Maximum test pool depth was 15 ft. Each diver wore a dive skin or shorts and shirt, and an emergency recovery harness. For each pod configuration (T-bit and oral cup only), the experimental procedure (Figure 2) was as follows:

1. The MK 25 MOD 2 was checked to ensure that its inspired oxygen concentration (F_IO_2) was 16–22%. If it was not, the UBA was flushed with air until the F_IO_2 was within that range.

2. Divers donned their MK 25 MOD 2 UBAs and sat on the bench at the surface.

3. The technician started logging UBA O_2 bottle pressure and P_{mask} on the data acquisition computer.

4. Divers performed PD/S and then breathed from their MK 25 MOD 2 UBAs (closed-circuit) for five minutes.

5. Divers entered the test pool, descended to the bottom, and positioned themselves on their knees. Their descent rate was no greater than 60 $fsw \cdot min^{-1}$.

6. Divers breathed from their MK 25 MOD 2 UBAs (closed-circuit) for five minutes.

7. Divers then switched from MK 25 MOD 2 UBAs to open circuit demand regulator, which they breathed for five minutes.

8. While divers were on their knees, they performed PUP breathing.

9. Divers breathed from their MK 25 MOD 2 UBAs (closed-circuit) for five minutes. The technician increased the data sampling rate to 80 Hz on the data acquisition computer.

10. Divers ascended to the surface at a rate no greater than 30 $fsw \cdot min^{-1}$.

11. The technician stopped logging UBA O_2 bottle pressure and P_{mask} on the data acquisition computer.

12. The dive ended.

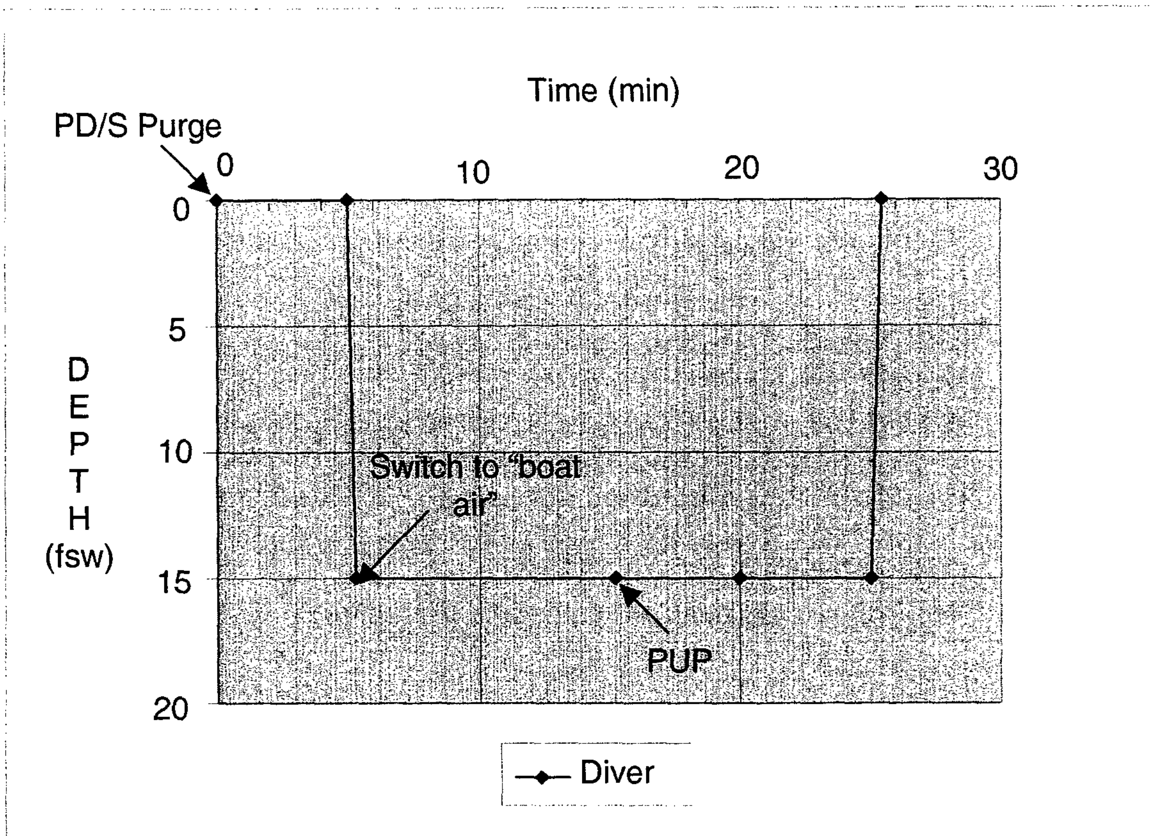

Figure 2. The dive profile and time events for dives in the test pool.

<u>Ocean Simulation Facility (OSF)</u>

Data collections were performed in NEDU's OSF, with water temperature maintained at approximately 85–90 °F (29–32 °C). Each diver wore a dive skin or shorts and shirt. For each pod configuration (i.e., T-bit and oral cup), the experimental procedure (Figure 3) was as follows:

1. A total of four divers were pressed on each run. Divers entered the OSF, donned their MK 25 UBAs, and were instrumented in the trunk (chamber connecting Charlie Chamber to OSF wetpot). The Dive Watch Supervisor (DWS) verified that trunk tenders performed predive checks.

2. Instrumentation checks with the Medical Deck Supervisor (MDS) were conducted to verify that each MK 25 UBA was registering between 16% and 22% F_IO_2. If a UBA was not, trunk tenders directed the diver to flush it with air until the F_IO_2 was within that range.

3. After all checks were completed, each diver was deployed: he descended to and stood on the stage while he breathed chamber atmosphere. (The stage

was positioned so that middle of a diver's chest was approximately three feet below the water surface when he was positioned on his knees.)

4. After all four divers were deployed, the DWS directed the trunk tenders to exit the trunk.

5. The MDS started logging UBA O_2 bottle pressures and P_{mask} on the data acquisition computer; then the DWS directed the divers to simultaneously perform a PD/S procedure.

6. After the divers had performed the PD/S procedure, they breathed from their MK 25 MOD 2 UBAs (closed-circuit) for five minutes on the surface.

7. The DWS directed divers to submerge and position themselves on their knees on the stage.

8. The wet pot was pressed to 17 fsw (a level read from the OSF Charlie Chamber digigage) at a rate no greater than 60 $fsw \cdot min^{-1}$.

9. The DWS directed the divers, upon reaching 17 fsw, to switch to open circuit breathing for five minutes.

10. Divers performed a PUP and then breathed from their MK 25 MOD 2 UBAs (closed circuit) for five minutes.

11. After divers had completed five minutes of closed-circuit breathing from their MK 25 MOD 2 UBAs, the OSF was pressed to 47 fsw (a level read from the Charlie Chamber digigage) to simulate excursion. The descent rate was no greater than 60 $fsw \cdot min^{-1}$.

12. After divers had completed four minutes of closed-circuit breathing from their MK 25 MOD 2 UBAs at 47 fsw, the DWS directed them to sit on the stage (away from the edge) in a head-up posture.

13. The technician increased the data sampling rate to 80 Hz on the data acquisition computer.

14. The wet pot left the bottom at an ascent rate no greater than 30 $fsw \cdot min^{-1}$. Note: The time at a depth greater than 20 fsw did not exceed five minutes.

15. When the OSF reached the surface (as read from the Charlie Chamber digigage), the DWS directed the divers to stand with their heads above the surface of the water and switch to open circuit.

16. The technician stopped logging UBA O_2 bottle pressures and P_{mask} on the data acquisition computer.

17. Trunk tenders recovered the divers, who doffed their UBAs and exited the OSF.

18. Divers remained near the OSF Alpha Chamber until their "clean time" had elapsed.

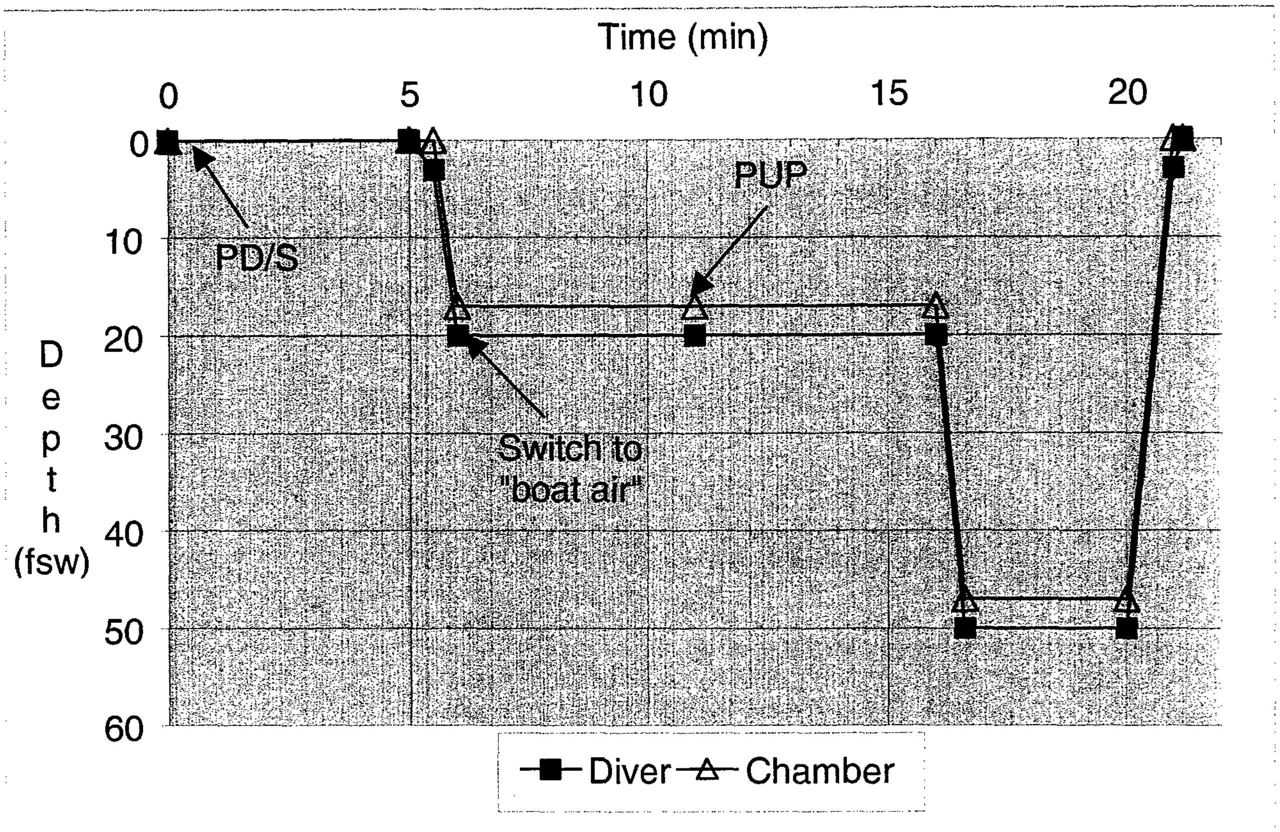

Figure 3. The dive profile and time events for dives in the OSF.

RESULTS

SUBJECTS

Test Pool

Thirty-one male divers made a total of 155 dives. Eighteen Navy divers were from NEDU and Naval Diving and Salvage Training Center, Panama City, FL; 13 (seven Navy corpsmen and six Marines) were attached to USMC units. Seventy-six dives were performed with the T-bit and 79 with the oral cup. Characteristics of divers are presented in Table 2.

OSF

Twenty-two male divers made a single dive, and one male diver made two dives for a total of 24 dives. Fourteen Navy divers were from NEDU and Naval Diving and Salvage Training Center, Panama City, FL; nine divers (six Navy corpsmen and three from the USMC) were attached to USMC units. Twelve dives were performed with the T-bit and 12 with the oral cup. Characteristics of divers are presented in Table 2.

Table 2.
Characteristics of Test Subjects.

		Age (years)	Height (inches)	Weight (pounds)
Test Pool	Mean	34.3	70.0	189.9
	sd	6.8	2.2	18.5
OSF	Mean	34.2	70.1	190.4
	sd	6.9	2.4	17.2

PURGE PROCEDURES AND ASCENTS

Test Pool

Oxygen partial pressures of inspired gas from 76 PD/S and 74 PUPs with the T-bit and from 79 PD/S and 76 PUPs with the oral cup are presented in Table 3. When the T-bit was used, a PD/S resulted in an average P_IO_2 of 0.67 ± 0.02 ATA (mean ± 95% CI; range: 0.47 to 0.79) and a PUP in an average of 1.19 ± 0.02 ATA (range: 0.89 to 1.35). When the oral cup was used, a PD/S purge resulted in an average P_IO_2 of 0.65 ± 0.02 ATA (mean ± 95% CI; range: 0.45 to 0.78) and a PUP in an average of 1.18 ± 0.02 ATA (mean ± 95% CI; range: 0.71 to 1.30). Marineau[7] reported that from the PD/S purge procedure, the average starting oxygen level with the MK 25/LAR V with T-bit was 0.72 ATA (range: 0.53 to 0.94).

The volumes of oxygen used during 75 PD/S and 74 PUPs with the T-bit and during 79 PD/S and 76 PUPs with the oral cup are presented in Table 3. When the T-bit was used, PD/S used an average of 4.7 ± 0.4 liters (mean ± 95% CI; range: 1.5 to 8.6), and PUP used an average of 8.5 ± 0.6 liters (mean ± 95% CI; range: 1.3 to 20.1). When the oral cup was used, PD/S used 4.4 ± 0.4 liters (mean ± 95% CI; range: 1.4 to 8.6), and PUP used an average of 8.4 ± 0.5 liters (mean ± 95% CI; range: 2.5 to 15.1).

The proportion of PD/S and PUPs in which $P_IO_2 \geq 0.45$ ATA was estimated from 76 PD/S and 75 PUPs with the T-bit and from 79 PD/S and 76 PUPs with the oral cup (Table 3). There was a probability of 0.95 that the actual proportion of PD/S resulting in $P_IO_2 \geq 0.45$ ATA performed with the T-bit was within the interval of 94.0% to 100%. The actual proportion of PD/S with the oral cup was within the interval of 94.2% to 100%. The actual proportion of PUP performed with the T-bit was within the interval of 91.8% to 99.9%. The actual proportion of PD/S with the oral cup was within the interval of 94.0% to 100%.

Maximum P_{mask} during ascent from 15 fsw was measured 74 times using the T-bit and 74 times using the oral cup (Table 3). The maximum P_{mask} during ascent with T-bit equaled 21 ± 1 cm H_2O (mean ± 95% CI) and ranged from 11 to 45 cm H_2O. The maximum P_{mask} during ascent with the oral cup was 20 ± 2 cm H_2O (mean ± 95% CI) and ranged from −1 to 80 cm H_2O. There is a probability of 0.95 that the proportion of ascents in which pulmonary pressure does not exceed 80 cm H_2O is between 93.9% and 100% with the T-bit and between 91.7% and 99.9% with the oral cup.

OSF

As determined from 12 PD/S and 12 PUPs with the T-bit and from 12 PD/S and 12 PUPs with the oral cup, oxygen partial pressures of inspired gas are presented in Table 4. When the T-bit was used, PD/S resulted in an average P_IO_2 of 0.76 ± 0.04 ATA (mean ± 95% CI; range: 0.64 to 0.84) and PUP in an average of 1.38 ± 0.05 ATA (range: 1.21 to 1.49). When the oral cup was used, PD/S resulted in an average P_IO_2 of 0.77 ± 0.05 ATA (mean ± 95% CI; range: 0.66 to 0.90) and PUP in an average of 1.39 ± 0.04 ATA (mean ± 95% CI; range: 1.28 to 1.46).

The volumes of oxygen used during 12 PD/S and 12 PUPs with the T-bit and during 12 PD/S and 12 PUPs with the oral cup are presented in Table 4. When the T-bit was used, PD/S used an average of 5.0 ± 0.8 liters (mean ± 95% CI; range: 3.2 to 6.9), and PUP used an average of 8.7 ± 1.3 liters (range: 5.2 to 12.1). When the oral cup was used, PD/S used 7.5 ± 2.8 liters (mean ± 95% CI; range: 3.6 to 19.5), and PUP used an average of 9.7 ± 1.6 liters (mean ± 95% CI; range: 7.0 to 13.7).

All 12 purges performed for each of the four conditions (PD/S and PUPs with the T-bit; PD/S and PUPs with the oral cup) resulted in acceptable P_IO_2 (Table 4).

Maximum P_{mask} during ascent from 50 fsw was determined 12 times using the T-bit and 12 times using the oral cup (Table 4). The maximum P_{mask} during ascent with the T-bit equaled 39 ± 13 cm H_2O (mean ± 95% CI) and ranged from 8 to 77 cm H_2O. The maximum P_{mask} during ascent with the oral cup was 22 ± 7 cm H_2O (mean ± 95% CI) and ranged from 8 to 47 cm H_2O.

Table 3.
Results of Test Pool Dives.

		$V_{purge}O_2$ (liters)		P_IO_2 (ATA)		Maximum P_{mask} during Ascent (cm H_2O)[a]		P_IO_2 resulting from Purge Procedure		Maximum P_{mask} during Ascent
		PD/S	PUP	PD/S	PUP			PD/S	PUP	
T-bit in	N[b]	75	74	76	74	74	N[b]	76	75	74
	Mean	4.7	8.5	0.67	1.19	21	# acceptable[c]	76	74	74
	95% CI of Mean	±0.4	±0.6	±0.02	±0.02	±1	% acceptable[c]	100	98.7	100
	Maximum	8.6	20.1	0.79	1.35	45	95% CI of % acceptable[d]	94.0-100	91.8-99.9	93.9-100
	Minimum	1.5	1.3	0.47	0.89	11				
Oral cup	N[b]	79	76	79	76	74	N[b]	79	76	74
	Mean	4.4	8.4	0.65	1.18	20	# acceptable[c]	79	76	73
	95% CI of Mean	±0.4	±0.5	±0.02	±0.02	±2	% acceptable[c]	100	100	98.7
	Maximum	8.6	15.1	0.78	1.30	80	95% CI of % acceptable[d]	94.2-100	94.0-100	91.7-99.9
	Minimum	1.4	2.5	0.45	0.71	-1				

a: Pressure of gas in the MK 25 MOD 2 breathing bag relative to water pressure at the level of the sternal notch
b: Sample size
c: Acceptable purge = $P_IO_2 \geq 0.45$ ATA. Acceptable ascent = maximum P_{mask} during ascent was less than 80 cm H_2O (centimeters of water).
d: 95% CI of % acceptable = 95% confidence interval of the proportion of acceptable purges and ascents (with a continuity correction) [8]

Table 4.
Results of OSF Dives.

		$V_{purge}O_2$ (liters)		P_IO_2 (ATA)		Maximum P_{mask} during Ascent (cm H_2O)[a]
		PD/S	PUP	PD/S	PUP	
T-bit in	N[b]	12	12	12	12	12
	Mean	5.0	8.7	0.76	1.38	39
	95% CI of Mean	±0.8	±1.3	±0.04	±0.05	±13
	Maximum	6.9	12.1	0.84	1.49	77
	Minimum	3.2	5.2	0.64	1.21	8
Oral cup	N[b]	12	12	12.00	12.00	12
	Mean	7.5	9.7	0.77	1.39	22
	95% CI of Mean	±2.8	±1.6	±0.05	±0.04	±7
	Maximum	19.5	13.7	0.90	1.46	47
	Minimum	3.6	7.0	0.66	1.28	8

		P_IO_2 resulting from Purge Procedure		Maximum P_{mask} during Ascent
		PD/S	PUP	
T-bit in	N[b]	12	12	12
	# acceptable[c]	12	12	12
	% acceptable[c]	100	100	100
Oral cup	N[b]	12	12	12
	# acceptable[c]	12	12	12
	% acceptable[c]	100	100	100

a: Pressure of gas in the MK 25 MOD 2 breathing bag relative to water pressure at the level of the sternal notch
b: Sample size
c: Acceptable purge = $P_IO_2 \geq 0.45$ ATA. Acceptable ascent = maximum P_{mask} during ascent was less than 80 cm H_2O (centimeters of water).

DISCUSSION

There were three instances of high mask pressure (> 70 cmH_2O) during ascent; two during the ascents from 50 fsw (73 and 77 cm H_2O) and one during the test pool dives (80 cm H_2O). The incidence of high mask pressure during the deeper dives was 8%, compared to less than 1% incidence during the 15 fsw pool dives. While both of the high mask pressures in the OSF occurred with the T-bit in, and none occurred with the T-bit out, there were too few data points to say that the incidences were statistically different: that is, that ascending with the T-bit in was riskier than with the T-bit out of the diver's mouth. During the test pool ascents, the highest P_{mask} of the study (80 cm H_2O) occurred when the mouthpiece was supposedly out of the diver's mouth.

Although it is generally believed that mouth and intrathoracic pressures of less than 80 cm H_2O rarely result in pulmonary barotrauma[9,10], those conclusions are based on limited experimental data in lightly anesthetized dogs and in human cadavers. In studies of experimental barotrauma produced during mechanical ventilation of animals, over half the study population with air in the coronary arteries showed evidence of lung rupture at mean pressures of 65 cm H_2O[11].

Three incidents of high mask pressure, more than two standard deviations above the mean, should be cause for concern. However, the most likely explanation for these aberrant results is improper management of the UBA prior to ascent. In the absence of a pressure relief valve in the MK 25, gas expanding upon ascent must escape around the diver's lips or the mask seal. If the ascent is started with a full or nearly full breathing bag, and if lips are sealed tightly around a T-bit, or if the mask is secured tightly on the face to prevent leaks, then mask pressure can rise towards potentially dangerous levels. Divers must always start an ascent with a mostly empty breathing bag to minimize the volume of gas that will expand upon ascent.

CONCLUSIONS

1. When the KMS 48 full face mask is used with either the T-bit or the oral cup, both PD/S and PUP provide acceptable initial breathing gas oxygen concentrations.

2. While infrequent, excessive pulmonary overinflation pressures can occur during ascents using KMS 48 full face mask with either the T-bit or the oral cup. Divers are warned to always start an ascent with a mostly empty breathing bag to minimize the volume of gas that will expand upon ascent.

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APPENDIX A

PREDIVE/SURFACE PURGE PROCEDURES

(Commander, U.S. Naval Sea Systems Command, 1998)

STEP	PROCEDURE
CAUTIONS	
Before proceeding, read and understand the purpose and precautions of the purge procedures, paragraph 2.3.4 and subparagraphs 2.3.4.1 through 2.3.4.5.	
If the purge procedure is interrupted at any point, the procedure should be repeated, starting with step 2. It should also be repeated any time the mouthpiece is removed and air is breathed. Additional purging during the dive is not necessary and *should not* be performed unless mouthpiece has been removed and air has been breathed.	
1. Don apparatus.	a. Don apparatus by attaching neck and waist harnesses. The breathing bag should fit in the same relative position as the lungs. b. Don face mask and ensure it creates an airtight seal to face to prevent nitrogen from entering the breathing loop.
NOTE	
The waist harness should fit loosely to permit complete filling of the breathing bag.	
2. Insert mouthpiece.	a. Ensure that oxygen cylinder valve is shut. Exhale completely and insert mouthpiece. b. Open mouthpiece rotary valve (DIVE position). The rotary valve is left open for the remainder of the procedure.
NOTE	
Should the breathing bag be partially filled, empty bag by inhaling through the mouthpiece and exhaling through the nose until bag is completely empty.	

STEP	PROCEDURE
3. Fill breathing bag completely.	a. Open oxygen cylinder valve. **Demand valve will activate.** b. Fill breathing bag completely by depressing bypass knob for approximately 6 seconds, or until bag begins to press against diver's chest.

NOTE

Do not* exhale into the mouthpiece during the emptying process in *step 4.

STEP	PROCEDURE
4. Empty breathing bag.	a. Empty the breathing bag by inhaling from mouthpiece and exhaling to the atmosphere (through the nose). b. Continue until bag is completely empty **and demand valve activates.**
5. Refill breathing bag to comfortable volume.	Fill breathing bag to a comfortable volume for swimming by depressing bypass knob completely for approximately 4 seconds. Begin normal breathing on UBA.

NOTES

If performing underwater transit using another UBA, shut oxygen cylinder valve at this time.

For surface purge, continue with step 6.

STEP	PROCEDURE
6. Discontinue breathing from MK 25 Mod 2 UBA.	After completing predive purge, discontinue breathing from MK 25 Mod 2 UBA and close mouthpiece rotary valve to SURFACE setting. The UBA should remain in this configuration (breathing bag one-half full, rotary valve on SURFACE) until breathing on MK 25 Mod 2 UBA begins. If air has been breathed, ensure predive purge procedures are accomplished prior to breathing the MK 25 Mod 2 UBA.

APPENDIX B

PURGING UNDER PRESSURE (PUP) PROCEDURES

(Commander, U.S. Naval Sea Systems Command, 1998)

The diver will be breathing from a MK 25 MOD 2 that has been purged the PD/S purge procedure on the surface.

STEP	PROCEDURE
	WARNING **Use care when subjecting the MK 25 MOD 2 to changes in ambient pressure when it is not being used for breathing. If the UBA is subject to an ambient pressure that is too high while oxygen supply valve is closed, the UBA pressure differential may result in rig floodout or canister cracking. For this reason, the MK 25 MOD 2 breathing bag is partially inflated after the surface portion of the purge procedure. If the diver discontinues breathing from the UBA at an increased ambient pressure and the rig is left in a closed status during surfacing, the breathing bag may rupture.** **NOTE** The pressurized phase of this purge procedure may be performed at any depth of 30 fsw or shallower. It is not approved for use at depths greater than 30 fsw.
1. Open oxygen supply valve.	a. Open oxygen supply valve. Valve is left open for remainder of procedure. **NOTE** Ensure that oxygen valve is open before discontinuing air/mixed-gas breathing. b. Inhale and hold breath.

STEP	PROCEDURE
2. Remove initial UBA.	a. Remove UBA used on initial portion of dive. b. Don standard face mask, if necessary.
3. Place mouthpiece in mouth.	a. Place MK 25 Mod 2 mouthpiece in mouth. b. With mouthpiece rotary valve still set on SURFACE, exhale briefly into mouthpiece to clear water from mouthpiece through vent hole. c. Switch mouthpiece rotary valve to DIVE setting.
4. Exhale.	Exhale into mouthpiece.
5. Breathe-down breathing bag.	a. Inhale from mouthpiece and exhale through nose. Continue until oxygen demand valve begins to add gas. b. Clear standard face mask if necessary.
6. Fill breathing bag.	Completely fill breathing bag by depressing bypass knob completely for approximately 9 seconds or until it begins to press against the chest.
7. Breathe-down breathing bag.	Breathe-down breathing bag as in step 5.
8. Fill breathing bag.	Fill breathing bag to comfortable volume for diving by depressing bypass knob until bag contains enough gas for diver to take a full breath. Begin normal breathing.

APPENDIX C

EQUIPMENT AND INSTRUMENTATION METHODS: TASK TA 03-10

PROTOCOL NUMBER: 03-14/32126
MANNED TESTING OF STANDARD MK 25 MOD 2 PURGE PROCEDURES TO 15 FSW WITH KMS 48 FACE MASK

PROTOCOL NUMBER: 03-24/32131
MANNED TESTING OF STANDARD MK 25 MOD 2 PURGE PROCEDURES TO 50 FSW WITH KMS 48 FACE MASK

PRINCIPAL INVESTIGATOR: N. A. CARLSON, LCDR, MSC, USN
SPONSOR: USSOCOM

TEST GOALS AND REQUIRED MEASUREMENTS

A. The volume of oxygen used in accomplishing the purge procedure
B. The percentage of oxygen (PO_2) delivered to the diver performing the PD/S and PUP procedures
C. The pressure differential between the breathing gas of the upright, seated diver and the water at the level of the diver's sternal notch (Pmask) at depth and during ascent

EQUIPMENT AND INSTRUMENTATION

A Druck PTX 160 pressure transducer was used to measure the volume of MK 25 UBA oxygen pressure by removing the bottle from the MK 25 and attaching the NEDU Biomedical MK 25 bottle pressure manifold (Figure A-1). The manifold provided an attachment point for the Druck PTX-160 to obtain bottle pressure readings during purge procedures (Figures A–2–A-4).

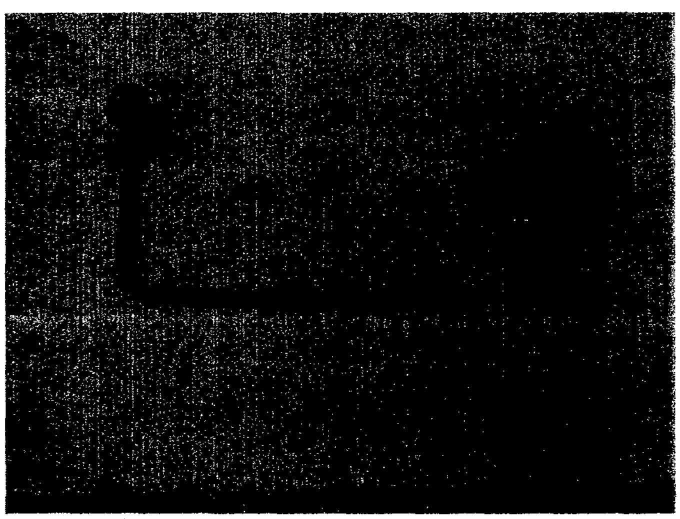


Figure A-1. The MK 25 oxygen bottle manifold.

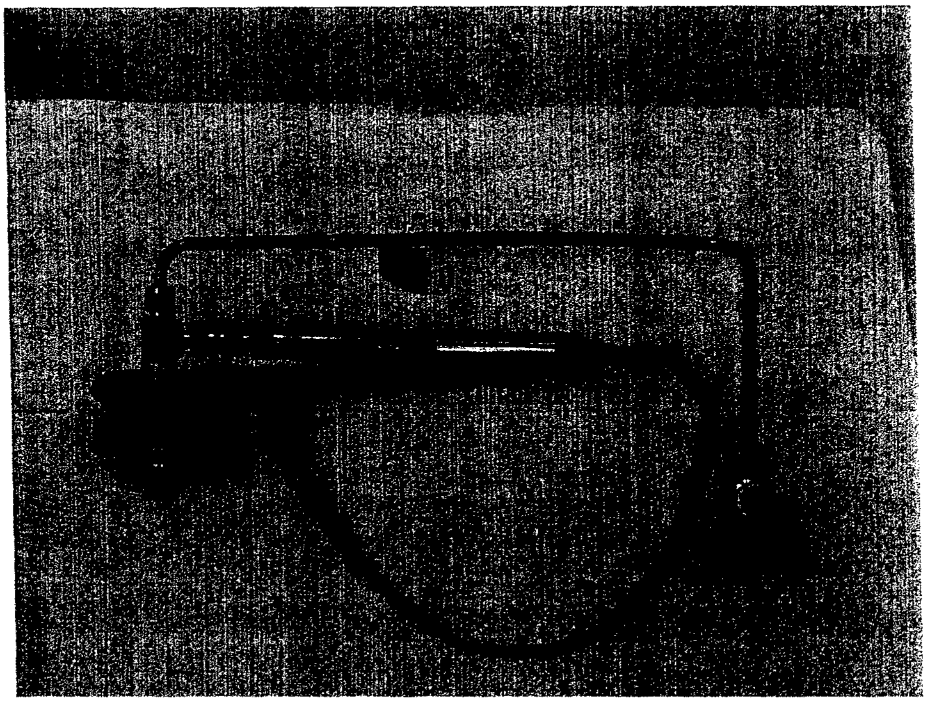


Figure A-2. The Druck PTX 160 attached to the manifold.

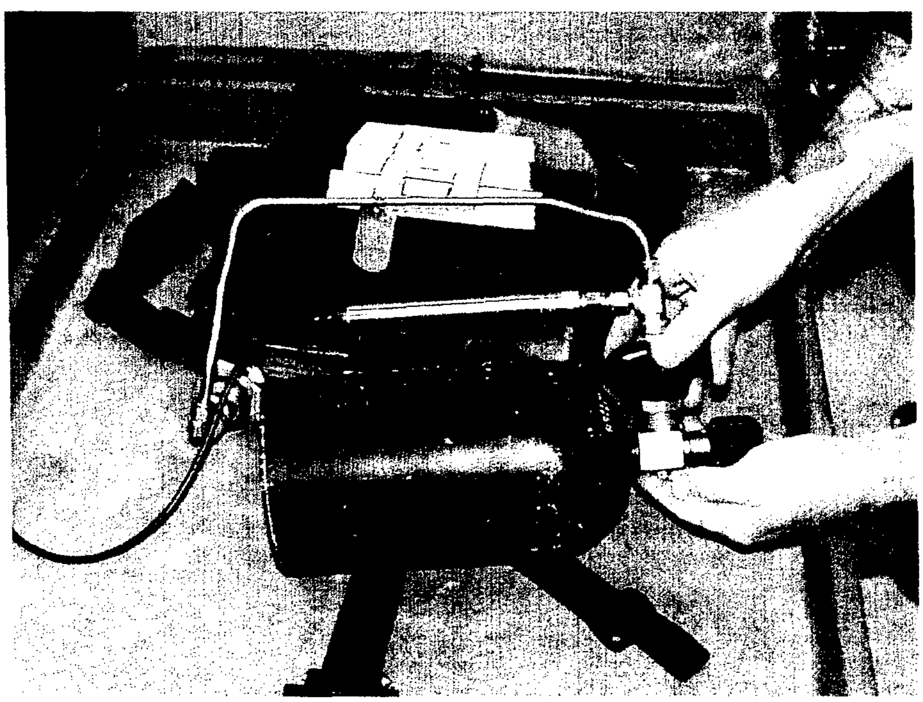


Figure A-3. The attachment of the manifold to the MK 25 oxygen bottle.

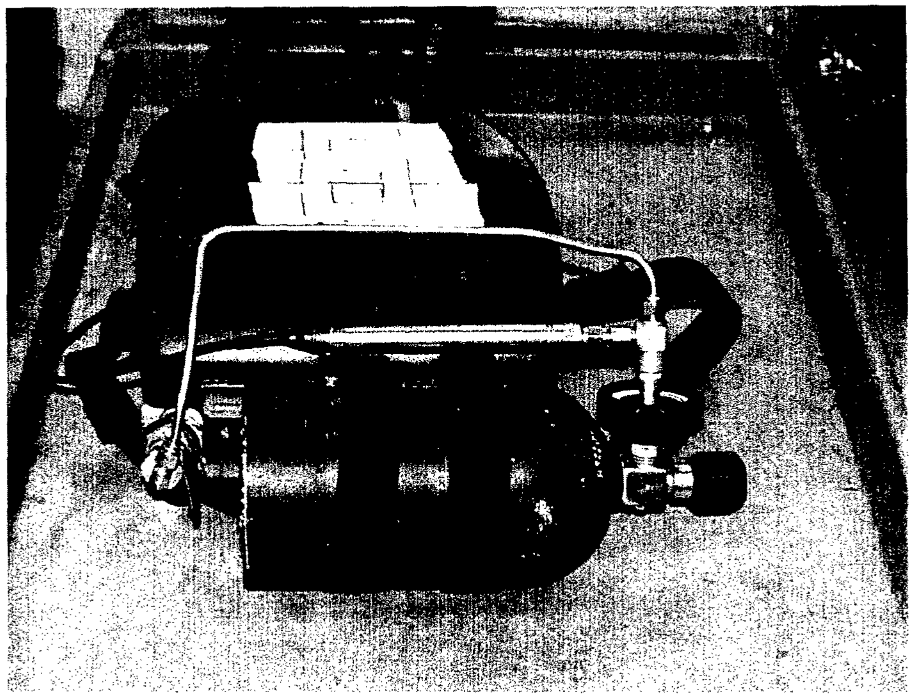


Figure A-4. The MK 25 oxygen bottle remounted to the MK 25. Note the reverse orientation of the oxygen bottle to the MK 25.

The percentage of oxygen that the diver breathed during the purge procedures was measured by a sensor placed within the MK 25 UBA inhalation hose-breathing bag junction. An R-10DS Teledyne Micro Fuel Cell was set inside a fuel cell housing built at NEDU (Figures A-5 and A-6) so that, as the breathing gas flows by the R-10DS, a portion of the oxygen concentration was consumed in the fuel cell reaction and sensed as a mVDC (V_{out}) output signal. This V_{out} signal was approximately 24 mVDC in room air oxygen and required amplification. A signal amplification circuit using an AD620 instrumentation amplifier provided a gain of 26 for the V_{out} oxygen signal.

Before the test, the response and linearity in high concentrations of oxygen was checked in the fuel cells. The procedure established for this linearity check involves placing the R-10DS fuel cells inside a hyperbaric test chamber. Information collected from the fuel cell linearity check was analyzed among the PO_2 data collected during the purge procedure.

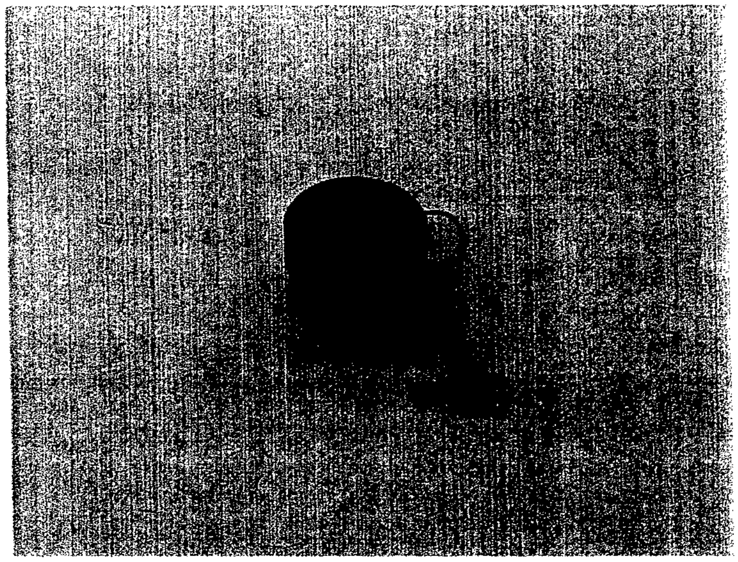


Figure A-5. An oxygen fuel cell sensor.

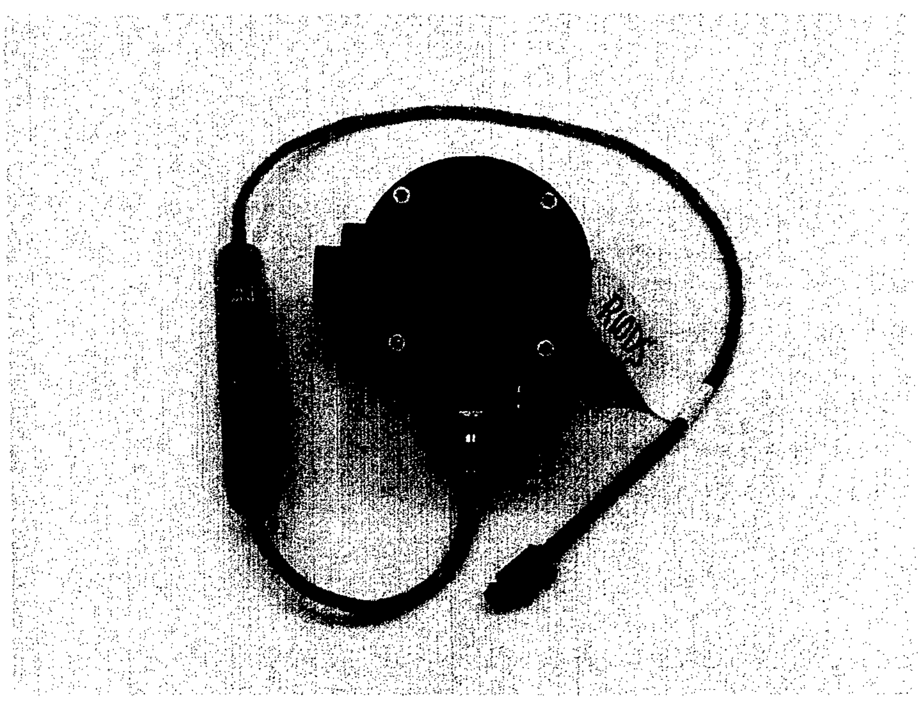


Figure A-6. An oxygen fuel cell sensor housing with the fuel cell amplifier attached.

MEMO

Linearity and temperature tests of R-10DS oxygen sensors
in support of LAR V dives

To: Mr. H. Boone, HMC A. Sanchez, and LCDR N. Carlson

From: Dr. Dan E. Warkander

Date: 14 Aug 2003

Summary

Oxygen sensors of type Teledyne Analytical Instruments R-10DS were tested for sensitivity to temperature (30 to 45 °C, 86 to 113 °F) and for linearity for oxygen partial pressures up to 2.1 atm. Sensors were ranked for preferred order of use based on least sensitivity to temperature. Any deviation from linearity can be corrected for with the data obtained. The preferred order of use is (by serial number):

1: 165727
2: 165729
3: 165730
4: 165725
5: 165726
6: 165728

Methods and Materials

For the linearity tests, sensors were placed in a hyperbaric chamber pressurized with air in steps of 33 fsw (1 atm), to provide oxygen pressures in the range 0.21 to 2.10 atm. This chamber could also be controlled for temperature: the range chosen was the expected water temperature and higher.

The voltage produced by each sensor was recorded by a laptop computer running LabVIEW 6i. The 16-bit a/d converter was a computer board DAS16/16AO set for a full scale of 1.25 V; thus, the maximum resolution was 0.02 mV. With a sampling frequency of 5 Hz, readings were taken for at least one minute and then averaged.

The tested sensors were delivered directly from the factory in mylar bags. The mylar bags were opened the day before the tests.

The reading closest to 1 atm of O_2 was chosen as the one-point calibration setting (a practice similar to that for calibrating the MK 16 underwater breathing apparatus). For each sensor, a straight line was calculated from an assumed reading of 0 in the absence of O_2. Deviations from this linear response were calculated for pressures greater than 1 atm.

For each sensor, errors due to temperature sensitivity were calculated as the maximum difference between any two readings divided by the mean reading of all temperatures.

Results

Linearity test

The results are shown in Table A-1.

Table A-1.
Results from the linearity test.

	Serial Number						
	165725	165726	165727	165728	165729	165730	Mean
Reduction at 1.26 ATA	0.2%	0.7%	0.5%	0.7%	0.6%	0.5%	0.5%
Reduction at 1.47 ATA	0.4%	1.4%	1.0%	1.5%	1.2%	1.2%	1.1%
Reduction at 1.68 ATA	0.7%	2.1%	1.5%	2.3%	2.0%	1.9%	1.8%
Reduction at 1.89 ATA	1.2%	3.2%	2.3%	3.4%	3.0%	3.0%	2.7%
Reduction at 2.1 ATA	1.8%	4.4%	3.3%	4.7%	4.3%	4.4%	3.8%
Sensitivity (mV/ATA at 1 ATA)	91.7	93.4	95.8	92.8	95.7	95.1	

Note: Deviation from a linear response is tabulated for each sensor and pressure.

Temperature sensitivity

The results are presented in Table A-2.

Table A-2.
Results from the temperature sensitivity test.

	Serial Number						
	165725	165726	165727	165728	165729	165730	Mean
Deviation from mean	0.3%	0.5%	0.5%	1.3%	0.2%	0.3%	0.5%
Ranking (best=1)	2	4	4	5	1	2	

Note: The relative change in signal is shown for each sensor.

MEMO

Linearity and temperature tests of R-10DS oxygen sensors
in support of LAR V dives

To: Mr. H. Boone, HMC A. Sanchez, and LCDR N. Carlson

From: Dr. Dan E. Warkander

Date: 22 Aug 2003

Summary

Oxygen sensors of type Teledyne Analytical Instruments R-10DS were tested for sensitivity to temperature (30 to 45 °C, 86 to 113 °F) and for linearity for oxygen partial pressures up to 2.1 atm. Sensors were ranked for preferred order of use based on least sensitivity to temperature. Any deviation from linearity can be corrected for with the data obtained. The preferred order of use is (by serial number):

1: 176204
2: 176202
3: 176206
4: 176205
5: 176200
6: 176201
7: 176207
8: 176203

Methods and Materials

For linearity tests, sensors were placed in a hyperbaric chamber pressurized with air in steps of 33 fsw (1 atm), to provide oxygen pressures in the range 0.21 to 2.1 atm. This chamber could also be controlled for temperature, at a range chosen to be at the expected water temperature and greater.

The voltage produced by each sensor was recorded by a laptop computer running LabVIEW 6i. The 16-bit a/d converter was a computer boards DAS16/16AO set for a full scale of 1.25 V; thus, the maximum resolution was 0.02 mV. With a sampling frequency of 5 Hz, readings were taken for at least one minute and then averaged.

The tested sensors were delivered directly from the factory in mylar bags. The mylar bags were opened the day before the tests.

The reading closest to 1 atm of O_2 was chosen as the one-point calibration setting (a practice similar to that for calibrating the MK 16 underwater breathing apparatus). For each sensor, a straight line was calculated from an assumed reading of 0 in the absence of O_2. Deviations from this linear response were calculated for pressures greater than 1 atm.

For each sensor, errors due to temperature sensitivity were calculated as the maximum difference between any two readings divided by the mean reading of all temperatures.

Results

Linearity test
The results are shown in Table A-3.

Table A-3.
Results from the linearity test.

	Serial Number								
	176200	176201	176202	176203	176204	176205	176206	176207	Mean
Reduction at 1.26 ATA	0.4%	0.3%	0.3%	0.2%	0.2%	0.3%	0.3%	0.1%	0.3%
Reduction at 1.47 ATA	0.9%	0.6%	0.7%	0.6%	0.5%	0.7%	0.6%	0.3%	0.6%
Reduction at 1.68 ATA	1.5%	1.0%	1.2%	1.0%	0.7%	1.2%	1.0%	0.8%	1.1%
Reduction at 1.89 ATA	2.3%	1.5%	1.9%	1.7%	1.2%	1.9%	1.7%	1.3%	1.7%
Reduction at 2.1 ATA	3.2%	2.2%	2.6%	2.3%	1.7%	2.6%	2.4%	2.0%	2.4%
Sensitivity (mV/ATA at 1 ATA)	93.8	92.6	95.7	94.9	93.3	94.1	92.3	93.8	93.8

Note: The deviation from a linear response is tabulated for each sensor and pressure.

Temperature sensitivity

The results are presented in Table A-4.

Table A-4.
Results from the temperature sensitivity test.

	Serial Number								
	176200	176201	176202	176203	176204	176205	176206	176207	Mean
Deviation from mean	0.9%	1.3%	0.6%	2.4%	0.3%	0.7%	0.7%	1.8%	1.1%
Ranking (best=1)	5	6	2	8	1	3	3	7	

Note: The relative change in signal is tabulated for each sensor.

THE DIVER'S INSPIRED PO_2 MONITORING WITH AN OXYGEN FUEL CELL

A diver's inspired O_2 partial pressures delivered by a closed-circuit UBA was monitored with a Teledyne R-10DS O_2 fuel cell positioned in a gas sample block at the base of the UBA inhalation hose.

In a real-time record, data from each diver's O_2 fuel cell was recorded as PO_2 in atmospheres and obtained by converting measured fuel cell voltage output. The conversion from measured voltage, *V*, to recorded PO_2, $P^R_{O_2}$, was performed in real time and based on a linear operational calibration line for each fuel cell:

$$V = \beta_0 + \beta_1 P^R_{O_2} . \qquad (1)$$

The slope β_1 and intercept β_0 of this line were determined from measured voltage outputs of the fuel cell flushed at sea level with air (PO_2 = 0.21 atm) and 100% O_2 (PO_2 = 1.00 atm) during setup on the morning of each dive day:

$$\beta_1 = \frac{V_{100\% O_2} - V_{\text{Air}}}{1.00 - 0.21}, \qquad (2)$$

and

$$\beta_0 = V_{\text{Air}} - (\beta_1 * 0.21), \qquad (3)$$

where $V_{100\% O_2}$ is the output of the cell flushed with 100% O_2, and V_{Air} is the output of the air-flushed cell.

A postrun correction of recorded fuel cell PO_2 values for nonlinearities in fuel cell output versus PO_2 then improved the accuracy of a diver's inspired PO_2 recorded from each fuel cell.

Recorded fuel cell PO_2 values were corrected with fuel cell voltage outputs measured in the laboratory before and after the dive series. These measurements were made at a series of actual PO_2 values from 0.21 to 2.1 atm, as each cell was compressed in air. If only small degradations in fuel cell performance (degradations graphically manifested as slight increases in voltage output curvature versus the PO_2 curve for each cell) occurred throughout the dive series, the preseries and postseries data for each cell were combined. The combined data for each cell were then fitted by a quadratic equation in actual PO_2 ($P_{O_2}^A$):

$$V = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2, \tag{4}$$

in which linear least-squares regression was used to obtain a laboratory calibration curve for each cell. For example, preseries, postseries, and fitted laboratory calibration lines for each of four fuel cells used in another NEDU study (Figures A.8-A.11), along with the values of the coefficients of Eq. (4) fitted to the combined data for each cell.

The corrected fuel cell PO_2, $P_{O_2}^A$, for each recorded value in the real-time record is obtained by finding the root of Eq. (4) at the V for the recorded $P_{O_2}^R$ determined from Eq. (1):

$$P_{O_2}^A = \frac{-\beta_1^L + \sqrt{\left(\beta_1^L\right)^2 - 4\beta_2^L\left(\beta_0^L - V\right)}}{2 \cdot \beta_2^L}. \tag{5}$$

The slope β_1 and intercept β_0 for solving Eq. (1) are determined from Eqs. (2) and (3), with $V_{100\%O_2}$ and V_{Air} determined from Eq. (4) and with $P_{O_2}^A = 1.0$ and $P_{O_2}^A = 0.21$, respectively. The process is schematized in Figure A-7.

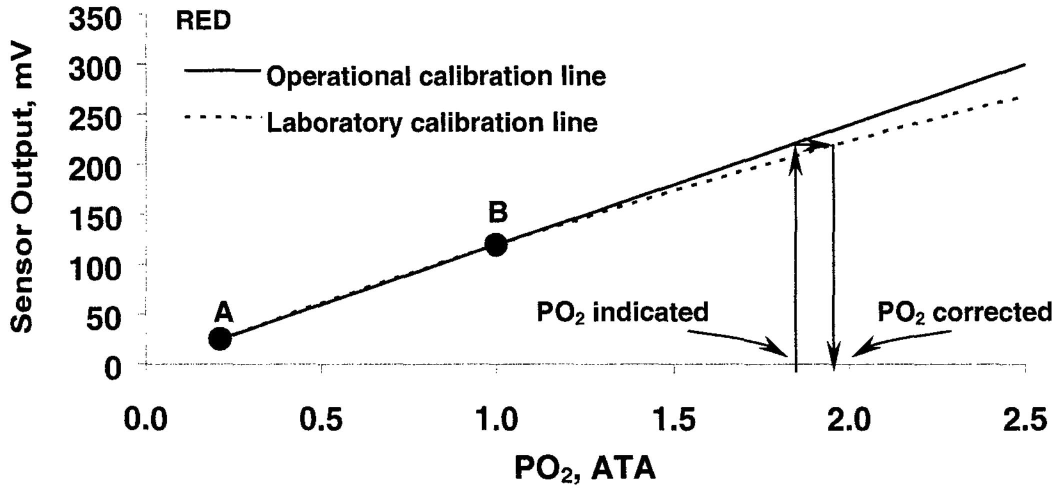
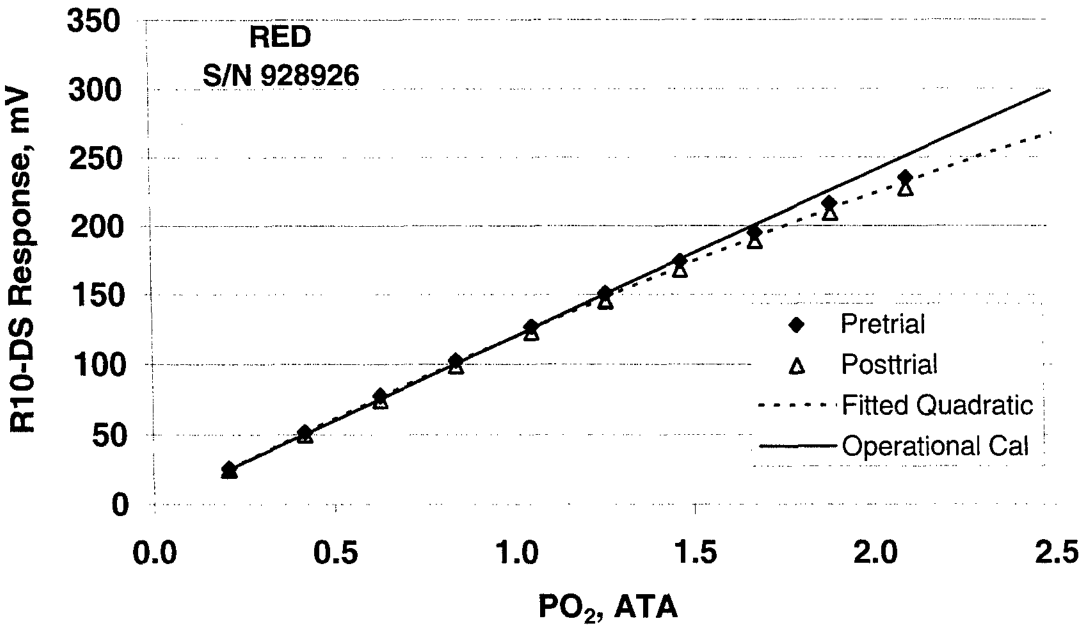
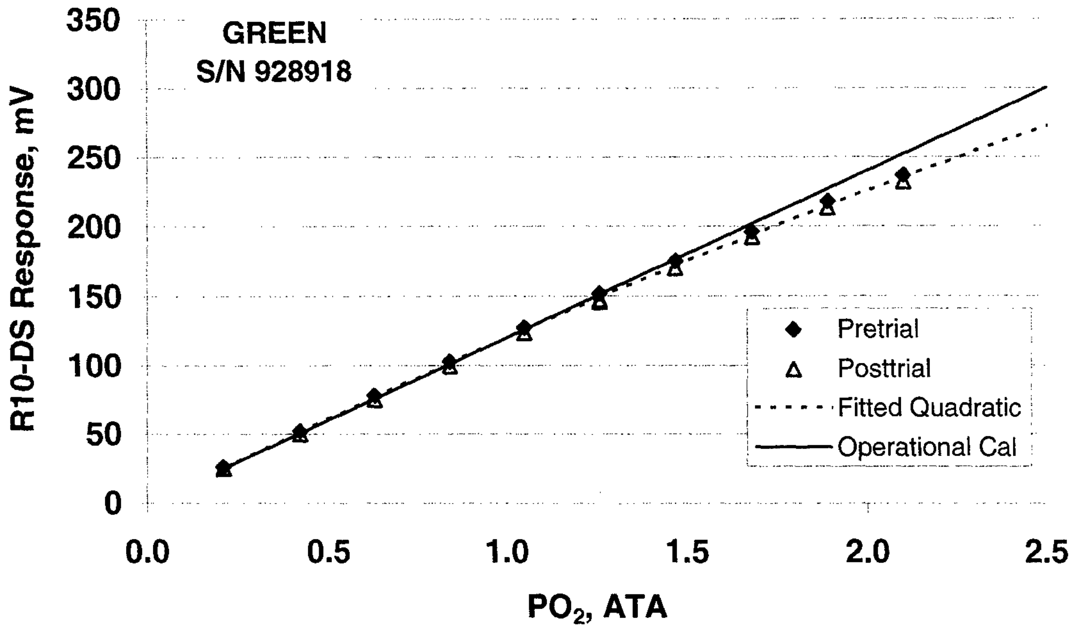


Figure A-7. Correction of R-10DS oxygen fuel cell PO_2 readings for nonlinearity in response versus PO_2. The laboratory calibration line is obtained from a quadratic equation fitted by least squares regression to measured fuel cell output at PO_2 from 0.21 to 2.1 ATA. The operational calibration line is drawn through the sea level air (PO_2 = 0.21 ATA) and 100% O_2 (PO_2 = 1.0 ATA) points on the laboratory calibration line at points A and B, respectively: i.e., the response of each fuel cell is assumed to be linear for operational purposes. Indicated PO_2 in raw fuel cell data is inverted through the operational calibration line to the laboratory calibration line to obtain the corrected PO_2. Note that corrected PO_2 values are greater than indicated values at $PO_2 > 1.0$ ATA, and less than indicated values at PO_2 levels between 0.21 and 1.0 ATA.



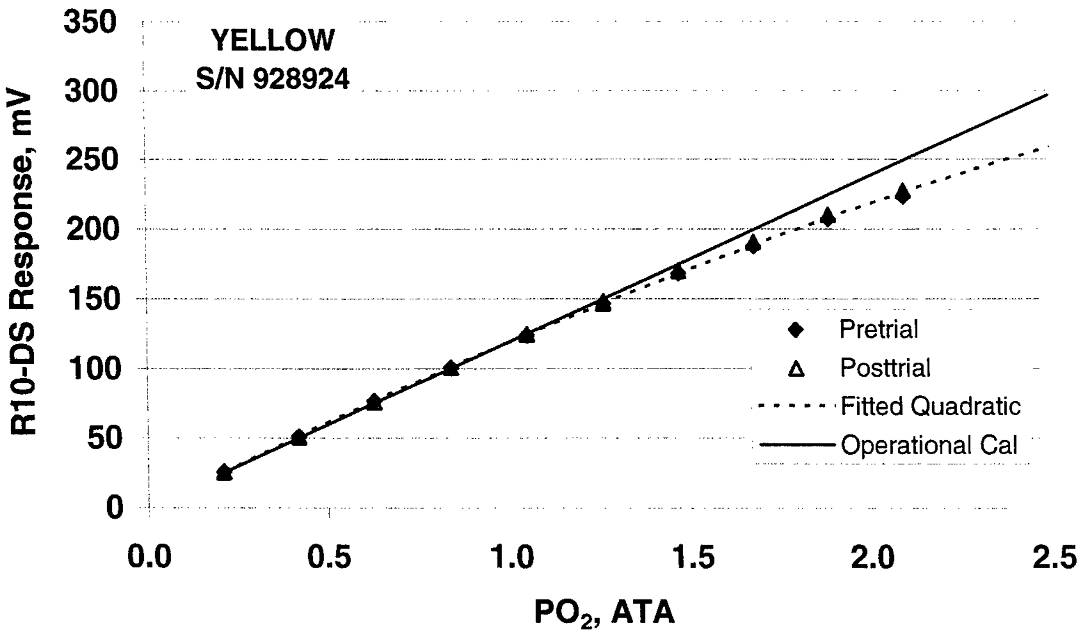
Fitted Quadratic Coefficients (S/N 928926) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	−1.75909
β_1^L	130.21065
β_2^L	−8.99660

Figure A-8. R-10DS (S/N 928926) OXYGEN FUEL CELL CALIBRATION CURVE



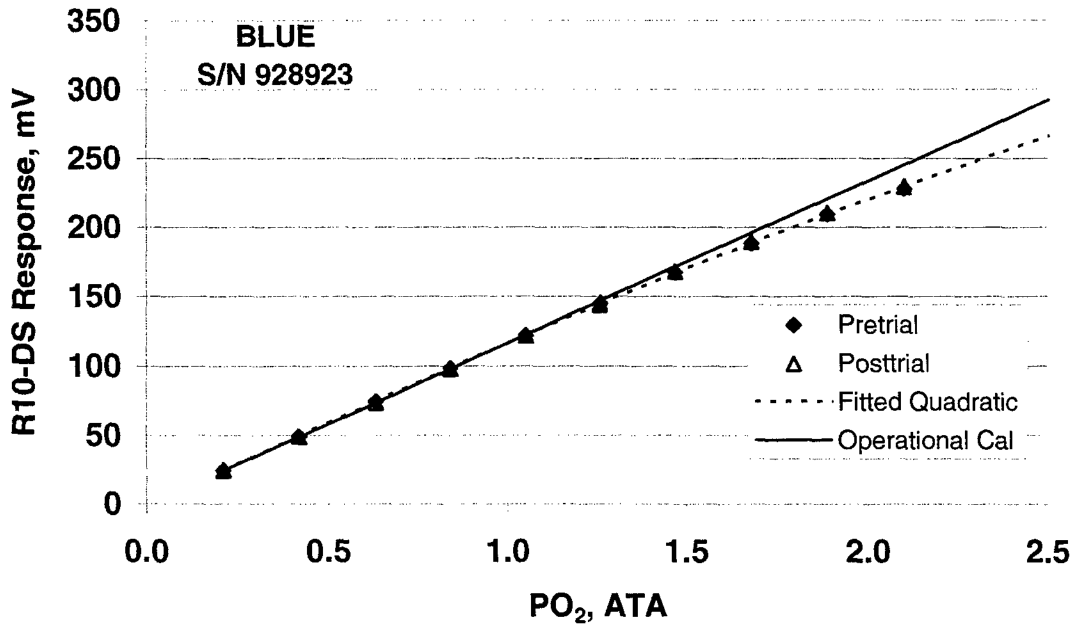
Fitted Quadratic Coefficients (S/N 928918) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	−1.75233
β_1^L	129.75983
β_2^L	−8.02167

Figure A-9. R-10DS (S/N 928918) OXYGEN FUEL CELL CALIBRATION CURVES



Fitted Quadratic Coefficients (S/N 928924) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	−1.95344
β_1^L	131.70995
β_2^L	−10.93015

Figure A-10. R-10DS (S/N 928924) OXYGEN FUEL CELL CALIBRATION CURVE



Fitted Quadratic Coefficients (S/N 928923) $V(mV) = \beta_0^L + \beta_1^L P_{O_2}^A + \beta_2^L \left(P_{O_2}^A\right)^2$	
β_0^L	−1.59136
β_1^L	125.18584
β_2^L	−7.19140

Figure A-11. R-10DS (S/N 928923) OXYGEN FUEL CELL CALIBRATION CURVE