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321 Bullfinch Rd.  
Panama City, FL 32407-7015**

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**MANNED CERTIFICATION TESTS OF THE  
MODERNIZED MK 16 MOD 1**



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# REPORT DOCUMENTATION PAGE

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<b>14. ABSTRACT</b> The MK 16 MOD 1 closed-circuit underwater breathing apparatus (UBA) has received modernized oxygen control electronics. As part of the certification process for these electronics, manned dives were performed during which PO <sub>2</sub> was monitored with an independent oxygen sensor placed in the UBA inspiratory hose. Twenty-four divers using six modernized MK 16 MOD 1 UBAs performed 63 dives: 20 each at 130 feet of sea water (fsw) for 30 minutes and 150 fsw for 35 minutes, and 23 at 300 fsw for 20 minutes (40, 45 and 91 msw). Decompression was according U.S. Navy Diving Manual. Recordings of steady-state oxygen control around the nominal 1.3 atm PO <sub>2</sub> set point, oxygen overshoot (PO <sub>2</sub> above 1.45 atm due to descent), and oxygen undershoot (PO <sub>2</sub> below 1.15 atm due to ascent) from the present dives were compared to specified oxygen control performance criteria and to data from previous manned dives with the legacy MK 16 MOD 1. The modernized MK 16 MOD 1 passed the predefined performance criteria and was comparable to the legacy UBA. Compared to the legacy MK 16 MOD1, the modernized MK 16 MOD 1 had less oxygen overshoot and a lower steady-state PO <sub>2</sub> on the bottom, although the latter was above the nominal 1.3 atm set point. These PO <sub>2</sub> s did not result in a significantly increased estimated risk of decompression sickness in the modernized compared to the legacy MK 16 MOD 1 for the schedules tested, but a significantly increased risk might result from longer dives (>four hours). Modernized MK 16 MOD 1 steady-state PO <sub>2</sub> drifted down during the course of a dive. The downward drift in PO <sub>2</sub> decompression was explained by poor temperature compensation in the UBA oxygen control sensors available at the time.					
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## INTRODUCTION

The MK 16 MOD 1 is a closed-circuit, mixed-gas underwater breathing apparatus (UBA). In a UBA of this type, the diver's expired gas is rebreathed through a counterlung and a CO<sub>2</sub> absorbent canister. Onboard electronics monitor the output of three oxygen sensors in the breathing loop and add oxygen via a piezo-electric valve if oxygen partial pressure (PO<sub>2</sub>) drops below a designated oxygen set point. Diluent gas, either nitrogen-oxygen (e.g. air) or helium-oxygen (He-O<sub>2</sub>), is added mechanically to maintain the volume of the breathing loop.

Components of the MK 16 MOD 1 Primary Electronics Assembly (PEA) are no longer available, and to extend its service life, the MK 16 MOD 1 has received modernized electronics. The new version (modernized MK 16 MOD 1) has undergone unmanned tests.<sup>1</sup> Task Assignment TA 10-08 tasked NEDU to perform the next step of the certification process by monitoring oxygen set point control during manned dives up to the maximum depths to which the apparatus is to be certified with each of the two diluent gases (air and He-O<sub>2</sub>).

## METHODS

Six modernized MK 16 MOD 1s were tested in the course of manned-diving. Each one was outfitted with a KMS 48 full face mask. Each modernized MK 16 MOD 1 was assembled with oxygen sensors from an approved manufacturer (Analytical Instruments, model PSR-11-33-NM). All sensors were well within their expected life span. The only modification to the MK 16 MOD 1 was the addition of a small sensor block between the absorbent canister and the inhalation hose to house external instrumentation (see Oxygen Monitoring section below). The sensor block had an unobstructed straight flow path about 15 cm in length and the same inner diameter as the MK 16 hoses.

## MANNED DIVING

NEDU test plan 12-08/40043 was approved by the NEDU Institutional Review Board for manned diving and assigned BUMED number NEDU 2012.0004. Test divers were military-trained divers who had undertaken familiarization training with modernized MK 16 MOD 1 in NEDU's test pool (maximum depth 15 fsw, 4.5 msw).

Test dives of the modernized MK 16 MOD 1 were conducted in the wet pot of NEDU's Ocean Simulation Facility (OSF). A maximum of four test divers took part in the OSF dives at a time. To facilitate comparison of the performance of the modernized MK 16 MOD 1 with the legacy MK 16 MOD 1, the dives were conducted in a similar fashion to previously reported legacy MK 16 MOD 1 dives in which oxygen control was monitored.<sup>2,3</sup> Test divers were dressed for thermal comfort and wore clothing ranging from swimsuits and t-shirts to wet suits. Water temperature was maintained at 80±5 °F (29±3 °C). Hot water hoses with which divers could flood their wet suits were available

during decompression and surface intervals. The divers were instructed to refrain from manually adding oxygen or diluent unless instructed to do so. No breathe-down procedure was undertaken. The OSF was compressed at a target rate of 60 fsw/min. Upon reaching bottom, test divers began intermittent cycle ergometer work. The ergometers were oriented so that the divers were approximately 30° inclined (head up) from a prone position. Divers pedaled at 60 rpm and the ergometer hysteresis brake controller was set at 50 W. This dry setting resulted in approximately a 120 W work rate and a whole body oxygen consumption of 2.1 L/min for submerged divers in the diving dress used in these dives.<sup>4</sup> The intermittent work (5 minutes of exercise and 5 minutes of rest) resulted in approximately a 1.3 L/min whole body oxygen consumption. Divers stopped work two minutes prior to the end of the bottom time and rested throughout decompression. Decompression to and between stops was at a target rate of 30 fsw/min.

## **DIVE PROFILES**

Two dive profiles were tested with an air diluent: 130 fsw (39 msw, 500 kPa) for 30 minutes, 150 fsw (45 msw, 562 kPa) for 35 minutes. 150 fsw is the maximum normal exposure depth for the MK 16 MOD 1 using air diluent. The 130 fsw for 30 minute profile was chosen because it includes an uninterrupted ascent from 130 fsw to a 20 fsw stop, which stresses the UBA oxygen control system, and comparable oxygen control data on this profile exists for the legacy MK 16 MOD 1. One dive profile was tested with 88% helium – 12% oxygen diluent to 300 fsw (91 msw, 1022 kPa) for 20 minutes. 300 fsw is the maximum certification depth of the MK 16 MOD 1. Decompression followed standard decompression tables as per U.S. Navy Diving Manual, revision 6<sup>5</sup>, chapter 18, tables 11 and 14.

## **MONITORING OF INSPIRED OXYGEN**

The sensor block on the inhalation hose housed a temperature probe and an oxygen sensor (R10-DS, Teledyne Analytical) with the sensing face in contact with and perpendicular to but not obstructing the gas path. Gas passing the sensor block location was considered to represent inspired gas.

The stated response time of the oxygen sensor is less than 6 s. In separate tests, the linearity of the R10-DS oxygen sensors was determined by exposing them to PO<sub>2</sub>s ranging from 0.21 atm to 2.1 atm in steps of 0.21 atm. Additionally, the temperature sensitivity of each sensor was determined by recording its output voltage when the sensor was exposed to temperatures of 20 and 40 °C (68 and 104 °F), covering a temperature span that the sensors would be exposed to in the course of the test dives. Before the first dive of the day each of the sensors was calibrated using 100% N<sub>2</sub> and 100% O<sub>2</sub>. After the final dive of the day their readings were checked with the same gases. The initial calibration was used to convert the sensor voltage output to PO<sub>2</sub> in atmospheres for real time display.

## DATA COLLECTION

The following signals were displayed and recorded at 2 Hz by a data acquisition system running National Instruments Labview software: OSF wet pot depth and water temperature; and for each diver, inhalation hose oxygen sensor voltage output, voltage signal converted to PO<sub>2</sub>, inhaled gas temperature, as well as cycle ergometer hysteresis brake setting and pedaling rpm.

## ANALYSIS OF INSPIRED PO<sub>2</sub>

The MK 16 MOD 1 has a PO<sub>2</sub> set point of 0.75 atm in shallow water and 1.3 atm at depth and provides warnings if the PO<sub>2</sub> deviates by more than 0.15 atm from these set points (control band).

The following metrics were calculated from each UBA inspired PO<sub>2</sub>–time recording (see Figure 1 for some of these metrics). During descent, breathing loop PO<sub>2</sub> increased and could overshoot the 1.3 atm PO<sub>2</sub> set point. The overshoot was defined as the period during which PO<sub>2</sub> exceeded 1.45 atm. The overshoot was defined by its duration, maximum PO<sub>2</sub> obtained at any time, and the integral CNS Toxic Dose Excess (CNSTDE), calculated as per reference 6 (page 5). The instantaneous dose at time point *i* defined as

$CNSTDE_i = (PO_{2,i} - 1)^{3.4} - 0.0167$ , if the PO<sub>2,*i*</sub> is greater than 1.45 atm (the upper limit of the control band). The total (integral) dose is

$$\text{integral CNSTDE} = \sum (CNSTDE_i \times \Delta t),$$

where  $\Delta t$  is the time difference between two measurements. The limit for the integral CNSTDE is 6.0 (atmosphere minutes).

General control of the PO<sub>2</sub> set point was embodied in the time-weighted average PO<sub>2</sub> calculated for several time periods: for the entire bottom time, the entire dive, the portion of bottom time after the overshoot ended, and the duration of the last decompression stop. These later two periods represent a relatively “steady-state” when oxygen control is not being influenced by changes in depth.

During ascent, breathing loop PO<sub>2</sub> decreases and can drop below the set point (undershoot). The undershoot is greatest after a long, uninterrupted ascent, and was therefore evaluated only upon arrival at the first decompression stop. The undershoot period was defined as the time from reaching the first decompression stop until PO<sub>2</sub> became  $\geq 1.15$  atm. The minimum PO<sub>2</sub> obtained during the ascent was also recorded.

A UBA was considered to “pass” or “fail” each man-dive. Failures in oxygen control were considered to occur if:<sup>6</sup>

- 1) the integrated CNSTDE was greater than 6 atm minutes;

- 2) post-overshoot time-weighted average PO<sub>2</sub> was greater than 1.45 atm or less than 1.15 atm
- 3) the PO<sub>2</sub> dropped below 0.4 atm during ascent to the first decompression stop; and
- 4) the undershoot lasted longer than four minutes.

A failure rate of 15% or less across the entire dive series, a rate consistent with the legacy MK 16 MOD 1, was considered to be acceptable.

## **COMPARISON WITH LEGACY MK 16 MOD 1**

For comparison, oxygen control data for the legacy MK 16 MOD 1 was obtained from previous dives conducted at NEDU during development of the MK 16 MOD 1 decompression tables (references 1 and 2). Nineteen data files containing 34 dives for the same 130 fsw, N<sub>2</sub>-O<sub>2</sub> schedule used in the present study were recovered and analyzed. In these legacy N<sub>2</sub>-O<sub>2</sub> dives, inspired gas was drawn continuously from the breathing loop for paramagnetic oxygen analysis, and gas transit time from the UBA to the analyzer is unknown. Therefore, short duration oxygen control events, particularly undershoot, must be interpreted cautiously. Eight data files, each containing a single He-O<sub>2</sub> dive to 300 fsw for 20 minutes bottom time were identified and analyzed. In these dives, inspired PO<sub>2</sub> was continuously analyzed using fuel cells, in the same manner as in the present report. In the present study, the 300 fsw / 20-minute bottom time dive was conducted in accordance with the schedule in the U.S. Navy Diving Manual, Revision 6, which differs slightly from that originally tested in NEDU TR 02-10.

The same oxygen control metrics were calculated for the legacy and for the modernized MK 16 MOD 1, and the resulting values compared using an ANOVA test. To provide a practical evaluation of any differences in the oxygen control between the modernized and legacy UBAs, the risk of decompression sickness (DCS) of the 300 fsw dive profiles was estimated using the LEM-he8n25 probabilistic decompression model. Probabilistic decompression models are generalized expressions of the experience embodied in large data sets comprising dive profiles with known DCS outcomes from carefully monitored dive trials. The LEM-he8n25 decompression model underlies the MK 16 MOD 1 He-O<sub>2</sub> decompression tables.<sup>3</sup> The risk of DCS was calculated from the time-course of ambient pressure and breathing gas. The same methodology was applied to existing modernized and legacy UBA's data. For each point in time, the ambient pressure was the OSF wet pot depth and the breathing gas was presumed to have the PO<sub>2</sub> indicated by the fuel cell and the balance helium. Only the 300 fsw dives were compared because oxygen control was measured in the same manner and these were the longest dives, and therefore were considered to provide the most reliable comparison of DCS risk.

## **VERIFICATION OF RESISTIVE LOAD**

A manufacturer (Teledyne Analytical Instruments) of oxygen sensors approved for use in the MK 16 requires that a 6 kΩ resistor be present (no tolerance given) for best

function of the sensor's temperature compensation circuit. The MK 16 MOD 0 and MOD 1 have this 6 k $\Omega$  load. To empirically verify that this 6 k $\Omega$  load was present in the modernized MK 16 MOD 1, an oxygen sensor was simulated by applying a voltage to the sensor connector. The voltage was adjusted to make the secondary display show 1.00. An external 6.0 k $\Omega$  resistor was then inserted between the voltage source and the sensor connector and the secondary reading was noted.

## RESULTS

A total of 24 test divers took part and completed 63 data producing dives: 20 at each of 120 and 150 fsw, and 23 at 300 fsw. Only results that were affected by the oxygen control system are reported on in the present report. Not included in these data is the one UBA-dive that was aborted due to failure of the PEA battery and the one UBA-dive during which the diver was directed to manually add oxygen while the UBA was maintaining PO<sub>2</sub> within the control band.

**Table 1.** Number of dives per modernized MK 16 MOD 1.

Depth (fsw)	Rig serial number					
	CO161	CO320	CO327	CO356	CO407	1017
130	5	0	5	5	3	2
150	3	3	4	2	4	4
300	4	0	6	5	7	1

Figure 1 illustrates how the PO<sub>2</sub> can vary during a dive. Before the compression started, the PO<sub>2</sub> was controlled around 0.75 atm. During compression the PO<sub>2</sub> climbs for two principal reasons: the existing gas in the breathing loop is being compressed and the oxygen-add valve may be briefly activated when the PO<sub>2</sub> set point changes to 1.3 atm on descending past 33 fsw. Diluent gas, which contains oxygen, is added to maintain loop volume during descent. As the maximum depth was reached, the PO<sub>2</sub> reached its highest value, typically above the control band. In the next few minutes the diver consumed oxygen and the PO<sub>2</sub> dropped until the control system activated. In this dive, the PO<sub>2</sub> remained in the middle of the control band (1.15–1.45 atm). The small PO<sub>2</sub> spikes during this period result from opening of the oxygen-add valve each time the PO<sub>2</sub> drops below the set point (nominally 1.3 atm). During the decompressions to 30 and 20 fsw, the PO<sub>2</sub> dropped along with the absolute pressure and remained low until the control system could add enough oxygen to bring the PO<sub>2</sub> back into the control band. The oxygen-add spikes in PO<sub>2</sub> are less pronounced during the decompression stops than on the bottom because the diver is at rest and consuming oxygen at a lower rate than while working.

Poor UBA PO<sub>2</sub> control (i.e., large swings in PO<sub>2</sub>) was often associated with divers who could be seen to be “skip-breathing”. It is the diver's breathing which circulates the gas within the breathing loop and past the control system oxygen sensors. Low ventilation,

as with skip-breathing, can increase the response time of the oxygen control system. Put differently, large variations in  $PO_2$  cannot necessarily be ascribed only to the electronics of the control system.

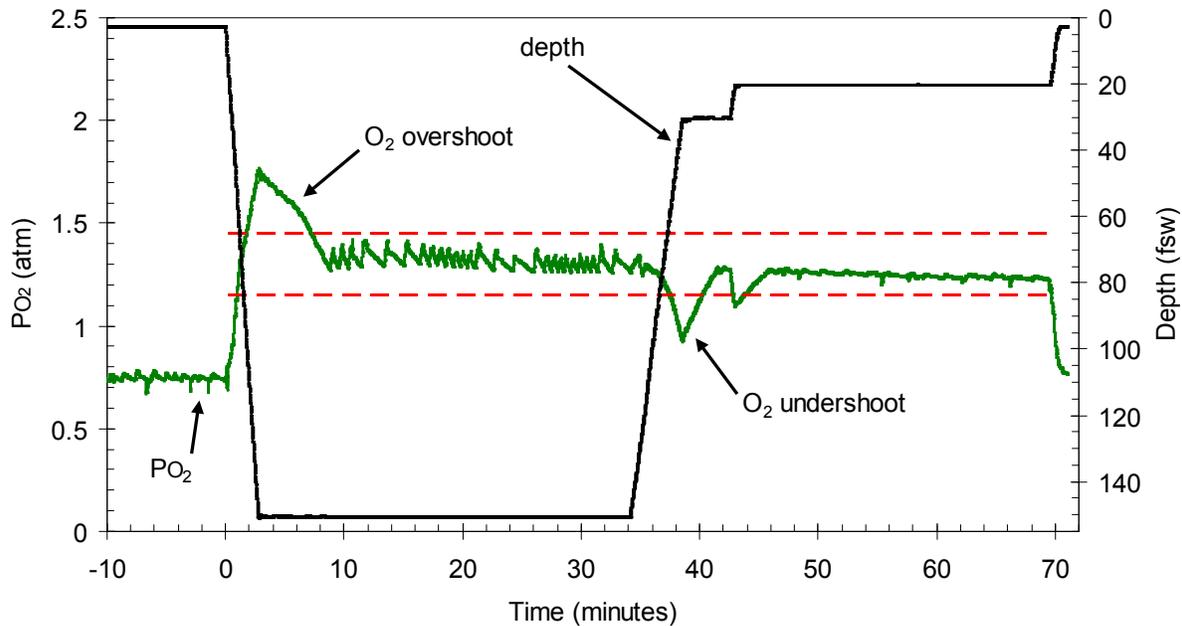


Figure 1. Illustration of variations in  $PO_2$  during a dive to 150 fsw (45 msw). The dive started at time zero and lasted for just over 70 minutes with stops at 30 and 20 fsw (9 and 6 msw). The two horizontal, interrupted lines show the desired control band for  $PO_2$ .

## OXYGEN CONTROL FAILURE RATE

Tables A1, A2 and A3 (Appendix A) give the calculated metrics for the oxygen control system for each UBA-dive. There were three instances in the 63 dives in which oxygen control was not maintained as required, for a failure rate of 4.8% (95% binomial confidence limits 1% to 13%). The observed failure rate was less than the specified maximum rate of 15%.

## OVERSHOOTS

There were three failures as a result of integrated CNSTDE above 6.0 atm minute, all occurring on 300 fsw dives. The highest  $PO_2$  overshoot reached 2.16 atm and it lasted 7.3 minutes.

## UNDERSHOOTS

No failures occurred due to undershoots. The lowest PO<sub>2</sub> undershoot was recorded during a decompression from a 130 fsw dive. The PO<sub>2</sub> reached 0.82 and it was above 1.15 atm again at four minutes.

## **OXYGEN CONTROL COMPARISON WITH LEGACY MK 16 MOD 1**

Both the modernized and legacy MK 16 MOD 1 maintain PO<sub>2</sub> oxygen above the 1.3 atm set point. However, the modernized MK 16 MOD 1 controls slightly closer to the 1.3 atm set point, and this is embodied in several statistically significant differences in oxygen control metrics between the two UBAs.

### DIVES TO 130 FSW

There was less PO<sub>2</sub> overshoot with descent in modernized MK 16 MOD 1 than with the legacy MK 16 MOD 1. This was evident in a lower maximum PO<sub>2</sub> during overshoot (1.72 atm vs. 2.00 atm,  $p < 0.001$ ) and shorter duration of overshoot (3.8 minutes vs. 6.4 minutes,  $p < 0.01$ ) with the modernized than the legacy MK 16 MOD 1. The steady-state PO<sub>2</sub> maintained on the bottom after the overshoot had ended was lower for the modernized than the legacy MK 16 MOD 1 (1.34 atm vs. 1.40 atm,  $p < 0.001$ ). The average PO<sub>2</sub> during the bottom time of the dive (leaving surface until leaving bottom and including the overshoot) was lower for the modernized than the legacy MK 16 MOD 1 (1.36 atm vs. 1.47 atm,  $p < 0.001$ ). Similarly, the average PO<sub>2</sub> for the entire dive was lower for the modernized than the legacy MK 16 MOD 1 (1.31 atm vs. 1.41 atm,  $p < 0.001$ ). There was no statistical difference in undershoot or the steady-state PO<sub>2</sub> during the 20 fsw decompression stop between the modern and the legacy UBAs.

### DIVES TO 300 FSW

The same pattern of differences in oxygen control was noted for the 300 fsw as the 130 fsw dives. The maximum PO<sub>2</sub> during overshoot was lower (1.98 atm vs. 2.20 atm,  $p < 0.0001$ ) and the time that the PO<sub>2</sub> was above 1.45 atm was shorter (5.4 minutes vs. 13.0 minutes,  $p < 0.0001$ ) with the modernized than the legacy MK 16 MOD 1. However, there was no statistical difference in CNSTDE between the two UBAs ( $p > 0.12$ ). The steady-state PO<sub>2</sub> maintained on the bottom after the overshoot had ended was lower for the modernized than the legacy MK 16 MOD 1 (1.37 atm vs. 1.40 atm,  $p < 0.05$ ). The average PO<sub>2</sub> during the bottom time of the dive (including overshoot) was lower for the modernized than the legacy MK 16 MOD 1 (1.51 atm vs. 1.65 atm,  $p < 0.001$ ). The average PO<sub>2</sub> for the entire dive was lower for the modernized than the legacy MK 16 MOD 1 (1.30 atm vs. 1.38 atm,  $p < 0.001$ ). There was no statistical difference in steady-state PO<sub>2</sub> during the 20 fsw decompression stop. The legacy 300 fsw / 20-minute bottom time decompression schedule dive originally tested in NEDU TR 02-10 has a one-minute first stop at 130 fsw, so undershoot could not be evaluated in the legacy UBA.

## ESTIMATED RISK OF DECOMPRESSION SICKNESS

The mean estimated risk of DCS for the modernized MK 16 MOD 1 300 fsw dives was 2.15% (0.41 S.D.) in comparison to 2.05% (0.27 S.D.,  $p=0.403$ , t-test) for the legacy 300 fsw dives. In all of the modernized 300 fsw dives, the wet pot left bottom shortly after 19 minutes bottom time had elapsed, instead of the full 20-minute bottom time scheduled. This slight abbreviation of bottom time reduces the estimated risk by approximately 0.2% compared to the full 20-minute bottom time. Four of the legacy dives had a bottom time just in excess of 19 minutes and four had a full 20-minute bottom time.

## VERIFICATION OF A REQUIRED RESISTIVE LOAD

The secondary display read 0.50 which indicates that the 6 k $\Omega$  load was present. However, it was noted that the primary electronics has to be turned on for this test, otherwise the display read 1.00 indicating that the 6 k $\Omega$  load was not present.

## **DISCUSSION**

### **OXYGEN CONTROL**

#### OXYGEN OVERSHOOTS

The highest PO<sub>2</sub> overshoot and resulting large CNSTDE originated from a test diver who had long pauses between breaths during descent (e.g. due to skip-breathing or ear clearing pauses). The resulting lack of gas movement in the breathing loop can contribute to PO<sub>2</sub> overshoot. Extra delays in the circulation of added oxygen from the oxygen add valve to the oxygen control sensors will cause larger spikes in the inspired PO<sub>2</sub>. Any delays in closing off the oxygen add valve after its activation in response to the PO<sub>2</sub> set point change from 0.75 atm to 1.3 atm on descent past 33 fsw, will cause larger amounts of oxygen to be added. Such breathing would have affected the PO<sub>2</sub> control the same way in the legacy MK 16 MOD 1. As indicated by similar or lower overshoot metrics, overshoot was better controlled in the modernized than legacy MK 16 MOD 1.

#### STEADY-STATE PO<sub>2</sub>

In some UBAs, the steady-state PO<sub>2</sub> decreased slowly over the course of the dives, although remained well within the required control band (1.15-1.45 atm). This was most notable during the long 20 fsw decompression stops following the 300 fsw dives where the mean steady-state PO<sub>2</sub> was 1.25 atm (Table A.3) but the effect can be seen in the shorter dive illustrated in Figure 1. There was no obvious decline in PO<sub>2</sub> in the legacy MK 16 MOD 1 data reanalyzed for this report, data which was collected using the same Teledyne R10-DS oxygen sensor used in the present report, suggesting that the presently reported decline was not a measurement artifact. Since the PO<sub>2</sub> control depends on the performance of the combination of the oxygen sensors and the electronics, either could be the source. It is known that the temperature of the gas

passing by the oxygen sensors increases as the exothermic CO<sub>2</sub> absorbent reaction proceeds and that it can take an hour or two for the temperature to stabilize (Appendix B). It is also known that the MK 16 oxygen control sensors are sensitive to temperature.<sup>7</sup> Therefore the temperature sensitivity of the Analytical Instruments PSR-11-33-NM oxygen sensors used in the MK 16 MOD 1 during the present dives was investigated further, and these were found to have poor temperature compensation, with substantial increase in sensor voltage signal with increasing temperature.<sup>8</sup>

If sensor voltage signal is increased compared to the time of calibration, this will cause the UBA to control at a proportionally lower PO<sub>2</sub> since the electronics control to sensor voltage set point, not PO<sub>2</sub> per se. This behavior could result in a UBA controlling at an actual PO<sub>2</sub> below that indicated by the primary and secondary displays. In the present dive series the MK 16 MOD 1s were stored and calibrated in an air conditioned room so that the UBA (including the CO<sub>2</sub> absorbent) started out at about 20 °C (68 °F). Figure B1 in Appendix B shows gas temperatures in the vicinity of MK 16 MOD 1 oxygen control sensors during un-manned dives in the same water temperature as the present modernized MK 16 MOD 1 manned dives. During a 300 fsw dive, the temperature around the sensors starts to climb after about 10 to 15 minutes. The first diver entering the water may have been breathing on the MK 16 for 20 minutes before the compression started, and the last diver about 5 minutes. Thus, at the end of a 20 minute bottom time, the MK 16 MOD 1s would have been in use for some 25 to 40 minutes and the temperature around the sensors would likely have been in the range 25 to 35 °C (77 to 95 °F). At this time, decompression commenced, and Figure B1 in Appendix B indicates that after about an hour of dive time, temperatures of around 45 °C (about 110 °F) could be expected at 100 fsw (the closest tested depth to the present decompression stops). This temperature is about 25 °C (45 °F) higher than the calibration temperature. The report from previous testing of the Analytical Industries PSR-11-33-NM indicate that the oxygen sensor voltage output could have increased by about 14% when the temperature increased by 25 °C (0.55% per °C).<sup>7</sup> This would result in a reduction of 14% from a PO<sub>2</sub> set point of 1.3 atm to 1.11 atm, even though the secondary display would read 1.30. This worst case would only occur if the UBA was set up with at least two sensors with the poorest temperature compensation, since the MK 16 MOD 1 controls to the middle voltage from three sensors. The worst case was not realized during the testing, where steady-state PO<sub>2</sub>s for all UBAs and all dives were always within the 1.15–1.45 atm control.

If a UBA controls at a lower than indicated PO<sub>2</sub>, this results in a higher risk of DCS than expected. NEDU TL 12-20 showed a substantial increase in risk of DCS for the worst case of a UBA controlling at a PO<sub>2</sub> of 1.11 atm during a four-hour dive (to the exceptional exposure limit line).<sup>8</sup> For dives in excess of four hours duration, the worst case increase in risk of DCS would be unacceptable. However, the present data indicate that in the modernized MK 16 MOD 1 using oxygen control sensors with relatively poor temperature compensations, the worst case was not realized, and the actual increase in risk of DCS was trivial compared to earlier dives conducted using the legacy MK 16 MOD 1.

Nevertheless, NEDU TR 04-28 concluded with the recommendation “The PSR-11-33-NM are recommended for use with MK 16 MOD 0 and MOD 1 UBAs that are calibrated at temperatures close to those of the anticipated water.”<sup>7</sup> At that time the actual gas temperatures at the MK 16 MOD 1 oxygen sensors were not known. With this new information it is clear that, for best performance of the MK 16, the oxygen sensor calibration must take place at a temperature substantially above expected water temperature. For cold water diving this would essentially be room temperature, but for relatively warm water diving, calibration would be more effective if accomplished above room temperature. If sensors with minimal temperature sensitivity are used, the calibration temperature would be of much less concern. The effort to obtain oxygen sensors with less sensitivity to temperature is in progress but is beyond the scope of this report.

## **COMPARISON TO LEGACY MK 16 MOD 1**

Compared to the legacy MK 16 MOD 1, the modernized MK 16 MOD 1 has less PO<sub>2</sub> overshoot and steady-state PO<sub>2</sub> on the bottom closer to the specified 1.3 atm set point, both of which are desirable because they reduce the diver’s exposure to high oxygen partial pressures which can be toxic to the central nervous system and the lungs. However, this behavior contributes to the slightly lower average PO<sub>2</sub> for the dive, and a resulting increase estimated risk of DCS with the modernized compared to legacy MK 16 MOD 1. However, the mean increased risk of DCS is small and is substantially less than differences arising from dive-to-dive PO<sub>2</sub> variability caused by interaction of the diver and the UBA. The estimated risk of DCS following the 300 fsw dives does not exceed the target 2.3% risk for which the MK 16 MOD 1 He-O<sub>2</sub> decompression tables were calculated.<sup>3</sup> The 300 fsw dives had a total duration of 174 minutes, and only a slightly greater increase in risk would result from dives to the four-hour exceptional exposure limit.

## **CONCLUSIONS**

The modernized MK 16 MOD 1 passed the predefined oxygen control criteria.

Modernized MK 16 MOD 1 oxygen control was comparable to legacy MK 16 MOD 1.

If dive times are to exceed four hours, the MK 16 MOD 1 should be set up with oxygen sensors that have been screened for adequate temperature compensation or the calibration of the oxygen control sensors should be conducted at temperatures substantially above the expected water temperature.

The primary electronics must be turned on when calibrating the secondary display.

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## APPENDIX A. OXYGEN CONTROL DATA

**Table A1.** PO<sub>2</sub> control results at a depth of 130 fsw.

Date	rig number	highest PO <sub>2</sub> on bottom (atm)	time above 1.45 atm (minutes)	steady state PO <sub>2</sub>			Undershoot duration (minutes)	CNSTDE	time weighted average		
				at max depth, post OS (atm)	at last stop (atm)	lowest after ascent (atm)			bottom time (atm)	reaching bottom to leaving bottom (atm)	entire dive
02-May	CO327	1.82	5.70	1.37	1.31	0.87	2.67	1.40	1.41	1.41	1.35
02-May	CO161	1.65	4.48	1.34	1.27	0.90	2.43	0.62	1.36	1.36	1.31
02-May	CO356	1.78	4.90	1.35	1.31	0.87	2.98	1.25	1.39	1.39	1.33
02-May	CO407	1.80	4.30	1.38	1.32	0.86	3.12	1.20	1.42	1.42	1.35
03-May	CO407	1.82	4.65	1.40	1.33	0.84	3.50	1.01	1.42	1.42	1.34
03-May	CO327	1.75	4.85	1.34	1.31	0.88	3.02	1.00	1.38	1.38	1.32
03-May	CO356	1.64	3.35	1.35	1.29	0.84	3.37	0.44	1.37	1.37	1.30
03-May	CO161	1.74	4.40	1.34	1.27	0.92	2.20	0.78	1.37	1.37	1.32
09-May	CO356	1.73	3.77	1.37	1.34	0.88	2.50	0.65	1.39	1.39	1.34
09-May	CO407	1.73	4.55	1.39	1.32	0.86	3.00	1.00	1.41	1.41	1.34
09-May	CO161	1.72	4.09	1.33	1.23	0.86	3.00	0.78	1.37	1.36	1.30
09-May	CO327	1.82	4.35	1.43	1.38	0.93	1.55	1.42	1.46	1.46	1.40
10-May	CO356	1.68	2.09	1.30	1.31	0.85	3.20	0.55	1.32	1.39	1.32
10-May	CO161	1.76	4.19	1.26	1.24	0.88	2.67	1.05	1.30	1.37	1.30
10-May	1017	1.66	3.34	1.25	1.29	0.82	4.00	0.43	1.27	1.35	1.27
10-May	CO327	1.77	3.55	1.29	1.31	0.87	2.85	1.02	1.32	1.39	1.32
14-May	CO356	1.68	3.85	1.38	1.30	0.93	2.68	0.57	1.39	1.39	1.32
14-May	CO161	1.67	2.03	1.27	1.20	0.87	2.83	0.35	1.30	1.3	1.24
14-May	1017	1.47	0.47	1.29	1.24	0.84	4.00	0.01	1.27	1.27	1.21
14-May	CO327	1.66	3.80	1.33	1.27	0.85	3.48	0.59	1.35	1.35	1.28
	average	1.72	3.8	1.34	1.29	0.87	2.9	0.81	1.36	1.38	1.31
	SD	0.08	1.2	0.05	0.04	0.03	0.7	0.37	0.05	0.04	0.04

**Table A2.** PO<sub>2</sub> control results at a depth of 150 fsw.

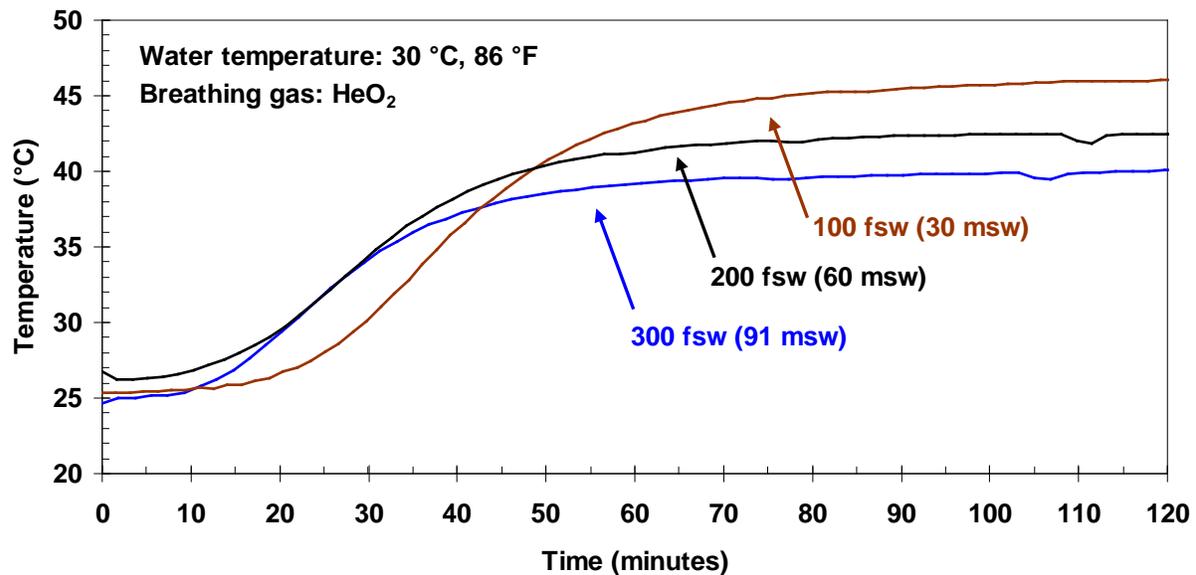
Date	rig serial number	highest PO <sub>2</sub> on bottom (atm)	time above 1.45 atm (minutes)	steady state PO <sub>2</sub>		lowest after ascent (atm)	Undershoot duration (minutes)	CNSTDE	time-weighted average PO <sub>2</sub>		
				at max depth, post OS (atm)	at last stop (atm)				bottom time (atm)	reaching bottom to leaving bottom (atm)	entire dive (atm)
16-May	CO161	1.76	4.48	1.31	1.27	1.04	0.80	1.15	1.33	1.40	1.33
16-May	CO407	1.92	5.37	1.36	1.35	1.03	0.87	2.38	1.39	1.47	1.39
16-May	CO327	1.55	0.60	1.31	1.29	0.98	1.15	0.04	1.31	1.37	1.31
16-May	CO356	1.85	4.88	1.33	1.32	0.99	1.25	1.66	1.35	1.42	1.35
23-May	1017	1.80	4.38	1.41	1.44	0.95	1.43	1.15	1.43	1.56	1.29
23-May	CO327	1.77	4.37	1.32	1.24	0.92	1.72	1.04	1.37	1.57	1.36
23-May	CO407	1.93	6.50	1.41	1.35	0.92	1.98	2.55	1.48	1.40	1.28
23-May	CO161	1.77	5.05	1.35	1.29	0.97	1.38	1.23	1.39	1.55	1.29
24-May	CO327	1.75	4.98	1.36	1.29	0.97	1.25	1.11	1.39	1.39	1.32
24-May	CO407	1.88	5.63	1.39	1.34	0.93	1.70	1.95	1.44	1.44	1.36
24-May	CO320	1.83	5.28	1.36	1.26	0.94	1.55	1.35	1.40	1.40	1.31
24-May	1017	1.81	5.22	1.39	1.40	0.96	1.15	1.51	1.43	1.43	1.38
24-May	CO327	1.67	2.14	1.20	1.15	0.89	2.35	0.44	1.25	1.24	1.18
24-May	CO407	1.91	5.72	1.37	1.30	0.94	1.73	2.39	1.43	1.43	1.34
24-May	CO320	1.89	6.29	1.40	1.34	1.00	1.05	2.30	1.45	1.45	1.37
24-May	1017	1.76	4.35	1.38	1.32	0.94	1.80	1.01	1.40	1.40	1.33
30-May	1017	1.81	4.09	1.37	1.37	0.97	1.33	1.29	1.39	1.44	1.39
30-May	CO161	1.76	5.01	1.30	1.28	1.00	1.25	1.25	1.32	1.38	1.32
30-May	CO320	1.89	5.66	1.30	1.26	0.95	1.60	2.01	1.33	1.42	1.33
30-May	CO407	2.10	6.69	1.34	1.34	0.94	1.77	5.48	1.40	1.51	1.40
	average	1.82	4.8	1.35	1.31	0.96	1.4	1.66	1.38	1.43	1.33
	SD	0.11	1.4	0.05	0.06	0.04	0.4	1.11	0.06	0.07	0.05

**Table A3.** PO<sub>2</sub> control results at a depth of 300 fsw.

Date	rig serial number	highest PO <sub>2</sub> on bottom (atm)	time above 1.45 atm (minutes)	steady state PO <sub>2</sub>		lowest PO <sub>2</sub> after ascent (atm)	Undershoot duration (minutes)	CNSTDE	Time weighted average PO <sub>2</sub>		
				post OS (atm)	at last stop (atm)				bottom time (atm)	reaching bottom to leaving bottom (atm)	entire dive (atm)
31-May	CO407	1.89	4.92	1.23	1.28	1.11	<1	2.30	1.34	1.34	1.28
31-May	1017	1.95	4.85	1.22	1.23	1.17	-	2.77	1.34	1.34	1.23
04-Jun	CO327	1.98	5.70	1.39	1.27	1.28	-	3.86	1.41	1.53	1.31
04-Jun	CO407	2.11	6.57	1.45	1.33	1.34	-	5.93	1.42	1.61	1.37
05-Jun	CO356	2.14	6.04	1.28	1.25	1.30	-	5.90	1.56	1.56	1.29
05-Jun	CO407	2.09	5.91	1.41	1.32	1.24	-	4.96	1.57	1.57	1.36
05-Jun	CO327	1.80	3.29	1.31	1.28	1.21	-	1.34	1.40	1.40	1.28
15-Jun	CO161	2.01	5.33	1.44	1.22	1.28	-	3.64	1.55	1.55	1.29
15-Jun	CO356	2.08	6.45	1.37	1.24	1.36	-	6.30	1.59	1.59	1.31
15-Jun	CO407	1.89	5.90	1.38	1.20	1.20	-	3.27	1.51	1.51	1.26
15-Jun	CO327	1.89	4.68	1.41	1.25	1.27	-	2.46	1.49	1.49	1.29
18-Jun	CO327	2.05	5.67	1.44	1.29	1.13	<1	3.67	1.34	1.53	1.34
18-Jun	CO356	2.07	4.82	1.34	1.25	1.31	-	4.74	1.31	1.53	1.31
18-Jun	CO161	2.02	6.27	1.39	1.24	1.29	-	4.31	1.30	1.54	1.30
18-Jun	CO407	2.08	5.49	1.40	1.24	1.34	-	4.57	1.30	1.55	1.30
19-Jun	CO327	1.81	3.92	1.35	1.23	1.25	-	1.44	1.28	1.40	1.28
19-Jun	CO161	1.85	5.60	1.39	1.23	1.33	-	2.49	1.28	1.47	1.28
19-Jun	CO356	2.16	7.32	1.35	1.22	1.35	-	8.49	1.30	1.64	1.30
19-Jun	CO407	2.03	5.73	1.37	1.27	1.37	-	4.87	1.33	1.54	1.33
20-Jun	CO327	2.02	5.72	1.40	1.28	1.17	-	4.31	1.33	1.54	1.33
20-Jun	CO356	2.06	6.35	1.42	1.27	1.40	-	6.30	1.34	1.60	1.34
20-Jun	CO161	1.96	5.05	1.41	1.22	1.31	-	3.28	1.28	1.51	1.28
20-Jun	CO407	1.66	2.82	1.31	1.22	1.23	-	0.64	1.26	1.33	1.26
	average	1.98	5.4	1.37	1.25	1.27		3.99	1.38	1.51	1.30
	SD	0.12	1.0	0.06	0.03	0.08		1.86	0.11	0.09	0.03

## APPENDIX B: TEMPERATURE AT THE OXYGEN SENSORS IN A MK 16 MOD 1

The temperature in the gas surrounding the oxygen sensors in a MK 16 varies drastically throughout a dive. Empirical data were retrieved from an ONR (Ocean Engineering) project that resulted in designing and building a gauge that shows the remaining capacity of the absorbent in real time. While recording temperatures inside in the absorbent, a temperature sensor had also been placed in the gas space around the oxygen sensors. Figure B1 illustrates the temperature varied during dives with heliox to three different depths.



**Figure B1.** Illustration of the temperature surrounding the oxygen sensors in the MK16. Measurements from unmanned dives where the breathing simulator was set for a minute ventilation of 22.5 L/min and a CO<sub>2</sub> injection of 0.9 L/min.

Tables A1 and A2 summarize temperatures recorded during unmanned dives at three water temperatures, three workloads, three depths with each of the two diluents.

In general, four influences on the temperature can be noted:

1. the higher the minute ventilation (diver workload) the higher temperature,
2. the greater the depth the lower the temperature,
3. the warmer the water the higher the temperature, but not quite in proportion,
4. the greater the minute ventilation, the faster the temperatures will stabilize (not shown).

**Table B1.** Temperatures (°C) recorded in the area of the oxygen sensors in a MK 16 during dives with air as diluent.

Depth (fsw)	Water temperature								
	2°C (36°F)			15°C (59°F)			30°C (86°F)		
	Minute ventilation (L/min)			Minute ventilation (L/min)			Minute ventilation (L/min)		
	22.5	40	62.5	22.5	40	62.5	22.5	40	62.5
20	32	37	36	44	44	51	48	52	51
70	29	30	37	40	42	49	47	49	49
150	25	32	31	36	39	48	44	47	48
Mean	32 (90°F)			44 (111°F)			48 (119°F)		

**Table B2.** Temperatures (°C) recorded in the area of the oxygen sensors in a MK 16 during dives with HeO<sub>2</sub> as diluent.

Depth (fsw)	Water temperature								
	2°C (36°F)			15°C (59°F)			30°C (86°F)		
	Minute ventilation (L/min)			Minute ventilation (L/min)			Minute ventilation (L/min)		
	22.5	40	62.5	22.5	40	62.5	22.5	40	62.5
20	22	28	35	37	41	41	46	47	49
70	23	28	33	33	36	39	43	46	46
150	21	24	30	32	35	35	41	42	45
Mean	27 (81°F)			37 (98°F)			45 (113°F)		