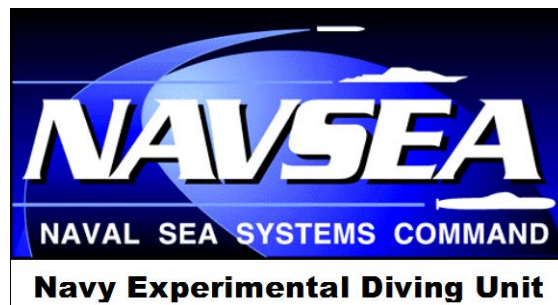


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## **NITROX SATURATION DIVE WITH 1.3 ATM CONSTANT PO<sub>2</sub>-IN-HELIUM NO-STOP DOWNWARD EXCURSIONS**



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<b>14. ABSTRACT</b> Six divers participated in an eight-day nitrox saturation dive in the Navy Experimental Diving Unit (NEDU) Ocean Simulation Facility (OSF). During five days at 100 fsw storage depth (0.33 atm PO <sub>2</sub> -in-nitrogen), 25 1.3 atm PO <sub>2</sub> -in-helium no stop downward excursions were conducted in the OSF wet pot using MK 28 closed-circuit underwater breathing apparatus. Six excursions to 120 fsw for 24 minutes bottom time and 10 excursions to 230 fsw for 28 minutes bottom time were completed without incident. Nine excursions to 200 fsw for 35 minutes bottom time resulted in one case of Type I decompression sickness (DCS) manifest as mild shoulder pain. The DCS was successfully treated with recompression from storage depth to 115 fsw and breathing 50% oxygen / 50% nitrogen. No symptoms or signs characteristic of inert gas counterdiffusion disease (e.g. pruritis, urticaria, inner ear dysfunction) occurred during the saturation-excursion operations. Saturation decompression from 100 fsw, accomplished breathing air during 77 hr 6 min of decompression stops, resulted in no DCS.					
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## INTRODUCTION

Saturation diving is a technique in which divers live for days or weeks inside a dry chamber at a pressure near to that of an underwater work site, and periodically enter the water to perform work. The living chamber may be a seafloor habitat, or more commonly may be aboard a vessel from where the divers commute to the work site in a pressurized personnel transfer capsule (diving bell). The divers may make vertical excursions in the water column to pressures above or below the pressure inside the living chamber (storage depth). Typically, the depth and duration of downward excursions are limited so that the divers could spend unlimited time and return to storage depth without decompression stops. Divers are decompressed from storage depth to the surface (saturation decompression) at the end of the mission. This saturation-excursion diving is commonly used for deep diving and is conducted with chamber atmosphere and diver's breathing gas composed primarily of helium and oxygen<sup>a</sup> (heliox). Less commonly, relatively shallow saturation–excursion diving may be conducted with chamber atmosphere and diver's breathing gas composed of nitrogen and oxygen (nitrox). Much of the development of nitrox saturation–excursion diving has been for seafloor habitats.<sup>1</sup>

The new U.S. Navy Nitrox Saturation Excursion Diving Procedures provides nitrox saturation decompression schedules for storage depths down to 104 feet sea water (fsw).<sup>2,3</sup> From this storage depth, these procedures allow unlimited-duration downward excursions breathing air, and deeper, limited duration, no-stop downward excursions breathing 1.3 atm PO<sub>2</sub>-in-nitrogen. Storage and excursion depths using nitrox breathing mixtures are limited because high inspired nitrogen partial pressures are narcotic and dense, which results in mental impairment and increased work of breathing, respectively. The U.S. Navy has an interest in conducting nitrox saturation dives with downward excursions to depths that would best be accomplished breathing heliox.

However, few excursions have ever been conducted using a different inert gas diluent in the excursion breathing mixture than in the saturation living chamber atmosphere. The concern is that switching between helium and nitrogen in the divers breathing gas or in the atmosphere may cause counterdiffusion disease (see reference 4 for a review). Counterdiffusion disease occurs if faster uptake of helium than washout of nitrogen in some body tissues causes gas supersaturation and bubble formation, resulting in manifestations like decompression sickness (DCS). Pruritus and urticaria resembling skin bends can occur if the skin is exposed to helium either while breathing nitrogen-rich gas at hyperbaric pressure, or if the helium exposure follows nitrox saturation.<sup>5-7</sup> Vertigo and nausea resembling inner ear DCS can follow a switch from breathing a high partial pressure of helium to a high partial pressure of nitrogen.<sup>5</sup> Such counterdiffusion disease can occur without change in ambient pressure. The few relevant saturation-excursion

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<sup>a</sup> “Nitrogen” and “oxygen” are used throughout this report to mean the gases N<sub>2</sub> and O<sub>2</sub>, respectively. Standard chemical notations (e.g. N<sub>2</sub>, O<sub>2</sub>, and He) will be used only where these are more readable than the corresponding words.

experiments have used a trimix (helium-nitrogen-oxygen) breathing gas for excursions from nitrox saturation, such that there were not large variations in the inspired nitrogen partial pressure between the excursion breathing mixture and the saturation atmosphere.<sup>6,7</sup> Theoretical analysis of counterdiffusion phenomena, and observations of the latency of onset and severity of manifestations, indicates that the magnitude of counterdiffusion problems are proportional to the increase in inspired nitrogen partial pressure.<sup>5,8-10</sup> We are not aware of any heliox excursions conducted from nitrox saturation, which necessarily involve large changes in inspired nitrogen and helium partial pressures.

We previously evaluated the safety of helium-to-nitrogen breathing gas switch at 70 or 100 fsw.<sup>11</sup> Wet, working heliox bounce dives to 150 to 220 fsw were followed by no-stop ascent to 70 or 100 fsw and a switch to air breathing gas and atmosphere. Although these were bounce dives, the holds at maximum depth and at the air switch depth were for one hour, a period estimated to allow 99% equilibration of the inner ear with the breathing gas<sup>10,11</sup>, thus the inner ear was exposed to similar counterdiffusion of helium and nitrogen as would occur on return to nitrox saturation after a heliox downward excursion. One hundred and four dives were conducted without inner ear DCS or other manifestations attributable to counterdiffusion phenomena. The present protocol is an extension of that earlier work and is proof of concept of heliox no-stop downward excursions from shallow nitrox saturation.

## **METHODS**

### **EQUIPMENT AND INSTRUMENTATION**

The nitrox saturation dive and downward heliox excursions were conducted in the NEDU Ocean Simulation Facility (OSF) at the Navy Experimental Diving Unit (NEDU). A high stand was positioned under the wet pot trunk on which divers could stand with mid-chest at the water surface. Three work stations were positioned on the OSF wet pot deck. Station 1 was a treadmill on which divers walked while carrying two 50-lb dumbbells. Station 2 was a set of foot restraints on the deck and pull-down bar connected by a rope and pulley to a 100-lb weight with which divers performed approximately 10 pull-downs per minute. Station 3 was a 70-lb kettle bell which the divers repeatedly lifted from the deck to a tabletop at waist level and back down. Standing at these stations, a diver's mid-chest was approximately seven feet below the water surface. Depth was measured in fsw as the gauge pressure above the wet pot plus the depth of the water column to diver mid-chest level. Depth and water temperature were digitized and recorded with a microcomputer-based data acquisition system every two seconds throughout each dive. Wet pot water temperature was actively controlled to a target of 80 °F (27 °C) and mean recorded water temperature during the excursions ranged from 79 to 82 °F (26–28 °C).

Divers' breathing gas was supplied by the MK 28 underwater breathing apparatus (UBA). Four MK 28 UBAs were used during these excursions. This closed-circuit mixed-gas UBA has a breathing circuit in which the diver's expired gas passes through an

expiration counterlung, a carbon dioxide absorbent canister, and an inhalation counterlung, and is rebreathed. Three oxygen sensors in the breathing circuit are monitored by onboard electronics which trigger the addition of oxygen via a solenoid if  $PO_2$  drops below a user-selectable set point. For these excursions the set point was 1.3 atm. The volume of the breathing circuit is maintained by mechanical addition of diluent gas. For these dives the diluent was 88% He / 12%  $O_2$  (heliox). Each UBA was fitted with a MK 24 full face mask that included a switchover assembly allowing gas to be breathed from the MK 28 or from an open-circuit emergency gas supply available via a quick disconnect umbilical. For each day of diving, the MK 28 UBAs were cleaned, the absorbent canisters packed, and the UBAs energized and calibrated outside the OSF at one atm abs, and then locked in to the OSF storage depth. The MK 28 UBAs were commonly used on two excursions each day. The UBA oxygen and diluent cylinders were refilled and locked into the OSF before each excursion.

Each MK 28 UBA was instrumented with a gas sampling block located in line between the inspiration counterlung and the hose to the mouthpiece. Although 13 inches (33 cm) upstream from the mouth, this location was assumed to be representative of inspired gas. The sampling block housed a thermistor and a K-1D micro-fuel cell oxygen sensor (Teledyne Electronics Technologies) with the sensing surfaces in contact with but not obstructing the gas flow path. The K-1D voltage signal was amplified approximately fiftyfold with an amplifier integrated into the sensor housing. Before each day of diving, the K-1D oxygen sensors were calibrated with 100% nitrogen and 100% oxygen at one atm abs, then the sensor blocks were fitted to the UBAs before they were locked into the OSF. Before each excursion, the oxygen sensor and thermistor were connected to an umbilical that penetrated the OSF hull.  $PO_2$  calculated from the daily two-point calibration and temperature of the gas in the sampling block were recorded to a microcomputer-based data acquisition system every two seconds throughout each dive. To characterize UBA  $PO_2$  control for each excursion, the following metrics were extracted from the recorded signal: the minimum, maximum, and mean  $PO_2$  from leaving storage depth to returning to storage depth (excursion), the duration of the period during which the  $PO_2$  first exceeded 1.45 atm during descent until it finally returned below 1.45 atm (overshoot), the mean  $PO_2$  from the end of the overshoot until returning to storage depth (post-overshoot), and the mean  $PO_2$  during ascent.

Prior to the dive trial, the K-1D oxygen sensors were tested for a linear response to  $PO_2$  from 0.21 to 2.1 atm. The oxygen sensor mV output was recorded over at least one minute at air pressures from 0 to 297 fsw in steps of 33 fsw (1 atm) and at an air temperature of  $25 \pm 0.5$  °C. These data were fit by a straight line with  $r^2 > 0.9998$  for all fuel cells. Additional characterization of the K-1D micro-fuel cell is given in Appendix A.

## **DIVING**

Six qualified U.S. Navy divers gave informed consent under NEDU Institutional Review Board approved protocol number 12-24/40045.<sup>12</sup> All divers were male. Individual diver characteristics are given in Table 1. A Diving Medical Officer (DMO) judged all divers to be physically qualified for diving on the basis of review of medical records and a

physical examination. Divers refrained from any hyperbaric or hypobaric exposure for 48 hours prior to the saturation dive.

Table 1. Diver-subject characteristics

DiverID	Age	Height (inch)	Height (m)	Weigh (lb)	Weight (kg)	Waist (inch)	Waist (m)	Neck (inch)	Neck (m)	BMI	Body Fat (%)*
1	29	68	1.73	175	79.4	37	0.94	16.25	0.41	27	22
2	20	72	1.83	188	85.3	35.5	0.90	15	0.38	25	19
3	30	71	1.80	185	83.9	34.5	0.88	16	0.41	26	16
4	29	67	1.70	158	71.7	33	0.84	15	0.38	25	17
5	30	70	1.78	198	89.8	38	0.97	15.5	0.39	28	24
6	30	69	1.75	230	104.3	38	0.97	17.5	0.44	34	21

\*calculated from height, waist circumference, and neck circumference according to U.S. Navy method<sup>13</sup>

### Saturation dive

The nitrox saturation dive was conducted in accordance with the U.S. Navy Nitrox Saturation Excursion Diving Procedures and NEDU Protocol Number 12-24/4005.<sup>2,3</sup> Briefly, the OSF was compressed on air to approximately 19 fsw to establish an oxygen partial pressure (PO<sub>2</sub>) of 0.33 atm, and then compressed to the 100 fsw storage depth on 100% nitrogen. Throughout the hold at 100 fsw the PO<sub>2</sub> was maintained between 0.3 and 0.35 atm (target 0.33 atm). After five days, 20 hours and 18 minutes at 100 fsw, saturation decompression commenced by exchanging the OSF atmosphere to air. This was achieved by isolating the divers in “A” and “B” chambers while unoccupied “C”–“E” chambers, the trunk, and wet pot were brought to the surface, ventilated with air, and then returned to 100 fsw. Divers then moved into “C”–“E” chambers and began breathing air while “A” and “B” chambers were similarly ventilated, a process that took 30 minutes. Decompression time started once an air atmosphere was established throughout the entire OSF complex, at which point the divers had been breathing air for 30 minutes, and approximately 16 hours had elapsed since the end of the final in-water excursion. After an additional one hour on air at the 100 fsw storage depth, decompression to the surface proceeded with stops every 5 fsw for a total decompression time of 77 hours and 6 minutes (including the one hour stop at 100 fsw). Throughout saturation decompression the OSF atmosphere was maintained at 21% oxygen fraction by volume.

### Excursions

During the hold at 100 fsw storage depth, divers conducted excursions in the OSF wet pot. Each morning during the saturation dive sick call, the duty DMO cleared or disqualified each diver for participating in excursions. Two teams of three divers (designated Red, Green, and Yellow) each performed one excursion per day.

Divers dressed in full neoprene wet suits (including hoods, booties, and gloves) and emergency safety harnesses. With the aid of a tender from the other dive team, divers entered the trunk, donned their MK 28 UBAs and connected their sample block umbilicals. To purge excess nitrogen from the lungs and UBA the divers performed

three open-circuit breaths as follows. Divers donned their full face mask with the switchover handle in the open circuit mode and exhaled fully before switching to closed-circuit mode and inhaling a full breath from the MK 28. Divers repeated this procedure for the next two consecutive breaths and after the third consecutive inhalation, divers remained in closed-circuit mode breathing from the MK 28, at which time the divers were considered on gas. Under direction from the OSF Control Room the divers and tender then completed checks of the MK 28. The divers then entered the wet pot, conducted a bubble check on the UBA, and then stood with head out of water. Owing to space limitation in the trunk, Green and Yellow divers donned their UBAs and went on gas simultaneously. Red diver donned his UBA and went on gas after Green and Yellow divers had entered the wet pot. As a result, Red diver went on gas about 10 minutes after Green and Yellow divers.

Once all divers were standing on the high stand and ready to dive, generally about two minutes after Red diver went on gas, they simultaneously descended to the wet pot deck. Upon the divers reaching the deck, the wet pot gas space, trunk, and "C" chamber were compressed at 15 fsw/min until the pressure at diver mid-chest level (chamber pressure plus seven fsw hydrostatic pressure) was at the target excursion depth. The compression was achieved by introducing air and then nitrogen so that the oxygen fraction in the wet pot gas space, trunk, and "C" chamber was maintained at approximately 8.2% by volume, equivalent to the oxygen fraction in the storage atmosphere at 100 fsw. In this manner, when depressurized back to storage depth, the wet pot, trunk, and "C" chamber atmospheres were approximately 0.33 atm PO<sub>2</sub>. Approximately one minute after reaching bottom, the divers began work at separate stations. Work periods were six minutes separated by one minute while divers moved to a different station. Divers performed three work periods, one at each station. At the end of the bottom time, the wet pot was decompressed to 100 fsw at 30 fsw/min and divers climbed on to the high stand. One at a time (in order Red, Green, Yellow) the divers removed their full face masks and climbed out of the wet pot. In this manner, Red diver was off gas approximately one minute after reaching storage depth and Yellow diver was off gas approximately five minutes after reaching storage depth.

The duty Diving Medical Officer interviewed all divers at 10 minutes and two hours after reaching storage depth, and again the following morning during the normal saturation dive morning sick call (18–22 hours after the excursion). The interview was partly unstructured, but also included specific questions to elicit complaints indicative of possible counterdiffusion disease affecting the inner ear or skin (visual changes, sensation of motion, problems with visual tracking, vertigo, tinnitus, erythema, and pruritus). The principal purpose of these interviews was to establish standard times at which divers were definitely free of symptoms and signs of DCS; this information is required for incorporating these data into the U.S. Navy decompression database. Divers were instructed to immediately report any unusual symptoms and signs that occurred outside of these interview times.

## **EXCURSION SCHEDULE SELECTION**

Although there are existing methods for calculating saturation-excursion decompression schedules, none of these are validated for calculating heliox excursions from nitrox saturation. Some of these previous methods are outlined in Appendix B. In principal, the LEM-h8n25 probabilistic decompression model could be used to calculate heliox excursions from nitrox saturation because it tracks both helium and nitrogen. LEM-h8n25 was developed to calculate 1.3 atm constant PO<sub>2</sub> heliox decompression tables, and has been tested extensively at NEDU, but this model has not been calibrated for saturation-excursion diving.

LEM-h8n25 was used to calculate decompression schedules for 104 bounce dives conducted in earlier phases of this work which comprised 60-minute bottom time heliox excursions, to a maximum depth of 220 fsw, followed by direct ascent to 70 or 100 fsw where divers breathed air for a further 60 minutes before decompression to the surface.<sup>11</sup> In the course of 27 man-dives to 220 fsw there was one incident of marginal DCS symptoms (transient shoulder pain) with onset during or shortly after leaving the 100 fsw air-breathing hold. This result suggest that divers saturated on nitrox (0.33 atm PO<sub>2</sub>) at 100 fsw storage depth would not be able to conduct no-stop heliox excursions to 220 fsw for 60 minutes, because the saturation divers would commence their excursion with more dissolved gas in their tissues than divers commencing a bounce dive from the surface (air saturation at 1 atm abs). The result also suggest that Type I DCS, rather than inner ear DCS, would limit the duration of the excursions. The previously conducted 220 fsw bounce dives accumulated 3.4% LEM-h8n25 estimated DCS risk at end of the 100 fsw air-breathing hold and a total of 4.7% LEM-h8n25 estimated DCS risk after surfacing. The present no-stop excursions from saturation were therefore selected to have LEM-h8n25-estimated DCS risk in the range 3.4–4.7%. The two test excursions were 200 fsw for 35 minutes bottom time (15 fsw/min descent plus 28.3 minutes on the bottom) with LEM-h8n25-estimated DCS risk of 3.5% and 230 fsw for 28 minutes (15 fsw/min descent plus 19.3 minutes on the bottom) with LEM-h8n25-estimated DCS risk of 4.6%

## **RESULTS**

### **EXCURSION DIVING**

Table 2 shows the excursions conducted by each diver and the interval at storage depth (SI), to the nearest hour, following excursions. Team membership remained the same throughout the saturation dives, but the order in which the teams conducted excursions (morning and afternoon) did not. On day one of the saturation dive, soon after reaching storage depth, each team conducted a work-up excursion to 120 fsw for 24 minutes bottom time; the deeper excursions were conducted on subsequent days. There were no signs or symptoms consistent with counterdiffusion disease reported following any of the excursions. On day 3, following a 200 fsw / 35 minute excursion, Diver 3 was diagnosed with Type I DCS, and did not participate in further excursions. To

accommodate treatment of Diver 3, Team 2 did not conduct an excursion that afternoon. The final entry in Table 2 indicates the interval at storage depth after the last excursion before commencing saturation decompression.

Table 2. Excursions (fsw/minutes) and subsequent interval at storage depth (SI, hours) for each diver

Diver	Team 1			Team 2		
	2	3	5	1	4	6
Day 1	120/24	120/24	120/24	120/24	120/24	120/24
SI	25	25	25	26	26	26
Day 2	200/35	200/35	200/35	200/35	200/35	200/35
SI	20	20	20	42	42	42
Day 3	200/35	200/35	200/35	-	-	-
SI	27		27			
Day 4	230/28	-	230/28	230/28	230/28	230/28
SI	24		24	23	23	23
Day 5	230/28	-	230/28	230/28	230/28	230/28
SI*	16		16	21	21	21

\*interval at storage depth before commencing saturation decompression

The one DCS in nine excursions to 200 fsw results in an observed cumulative incidence (95% exact binomial confidence limits) of 11.1% (0.3, 48.2%). No DCS in 10 excursions to 230 fsw results in an observed cumulative incidence of 0% (0, 25.9%). Neither of these observed incidences are different from the respective LEM-he8n25-estimated DCS risks (exact binomial test  $p > 0.05$ ).

## TREATMENT OF EXCURSION DECOMPRESSION SICKNESS

On the third day at storage depth, Diver 3 completed a 200 fsw / 35 minute heliox excursion, returning to the 100 fsw storage depth at 9:56 and began breathing chamber atmosphere at 10:00. At 10:25 Diver 3 complained of 1 out of 10 left elbow pain. A DMO who was a member of the saturation diving team inside the OSF examined Diver 3 in consultation with the duty DMO outside the OSF. The examination confirmed non-reproducible left elbow pain. A neurological examination was normal. At 10:51 Diver 3 began breathing 50% oxygen / 50% nitrogen treatment gas by built-in-breathing system (BIBS) mask while preparation was made for treatment in accord with U.S. Navy Nitrox Saturation Excursion Diving procedures.<sup>2,3</sup> "D" and "E" chambers were brought to the surface and ventilated with air and recompressed on air to 100 fsw with an inside tender who was not part of the saturation team (Tender 1). At 11:16, Diver 3 was transferred into "D" chamber where he continued breathing treatment gas via BIBS. At 11:18, "D" and "E" chambers were compressed on air in 5 fsw increments, with 1 minute stops to evaluate the patient, until depth of significant relief. To facilitate these evaluations, Diver 3 was taken off treatment gas shortly after leaving 100 fsw. At 115 fsw (at 11:29) Diver 3 reported 75-80% reduction of the pain. At 115 fsw, Diver 3 resumed breathing 50% oxygen / 50% nitrogen treatment gas via BIBS at 11:33, and reported complete relief of pain at 11:45. Diver 3 completed two 60-minute oxygen periods, each followed by a 15-minute air break. After the second air break at 115 fsw, Diver 3 and Tender 1 were decompressed to 100 fsw with 50 minute stops at 110 and 105 fsw. Diver 3 was given

two additional 40-minute oxygen periods followed by 10-minute air breaks during the decompression. Diver 3 remained at storage depth and symptom-free for the remainder of the saturation dive but did not participate in any further downward excursions.

### Tender Decompression

After Diver 3 was transferred back to storage depth, Tender 1 was decompressed to 60 fsw in D chamber and met by Tender 2, who had been locked in via “E” chamber. Tender 1 was decompressed to the surface on a schedule calculated with the Thalmann Algorithm Navy Dive Planner with VVal-18 parameter set. The schedule was calculated for air decompression stops (fsw / minutes) of 60 / 32, 50 / 92, and 40 / 130, but Tender 1 breathed 50% oxygen / 50% nitrogen at these stops. The schedule had calculated oxygen decompression stops (30-minute oxygen periods / 5-minute air breaks) of 30 / 52, 20 / 98, and 10 / 145 (fsw / minutes). Tender 2 breathed oxygen beginning at the third oxygen period at 20 fsw.

### **OXYGEN CONTROL IN THE MK 28 UBA**

Complete PO<sub>2</sub> data from five UBA-excursions was not recorded — on two occasions the umbilical connection to the sensor block was damaged and on one occasion the data acquisition system file containing three UBA-excursions was lost. In the latter case, some data was reconstructed from a screen capture of the data acquisition system display, and appeared consistent with the recorded data from other excursions using these UBAs. Figure 1 shows oxygen control in a MK 28 during a 230 fsw downward excursion. There is an increase in PO<sub>2</sub> above the set point as the gas in the breathing loop is compressed during the descent to 230 fsw (overshoot). Several dips in the PO<sub>2</sub> during the overshoot indicate activation of the diluent add valve. Although divers were allowed to manually override the automatic diluent add valve to maintain loop volume, they were instructed not to flush the breathing loop with diluent to restore set point. Once on the bottom the diver metabolized the excess oxygen in the breathing loop. After the overshoot the spikes in PO<sub>2</sub> indicate activation of the oxygen add valve to maintain set point.

Table 3 gives oxygen control statistics for the 22 UBA-excursions for which PO<sub>2</sub> was recorded. The highest PO<sub>2</sub> and longest overshoot occurred in the excursion illustrated in Figure 1. As a result of this relatively long overshoot the excursion illustrated in Figure 1 also had the highest mean excursion PO<sub>2</sub> (1.47 atm). In seven excursions the PO<sub>2</sub> never exceeded 1.45 atm and therefore by definition there was no overshoot, indicated by NA's in Table 3. Once divers had metabolized the excess oxygen in the breathing loop, and the MK 28 began actively controlling oxygen to set point, the post-overshoot mean PO<sub>2</sub> was close to the 1.3 atm set point (1.27–1.37). The minimum PO<sub>2</sub> occurred during ascent, transiently falling as low as 1.17 atm, but the mean PO<sub>2</sub> during the ascents was close to set point.

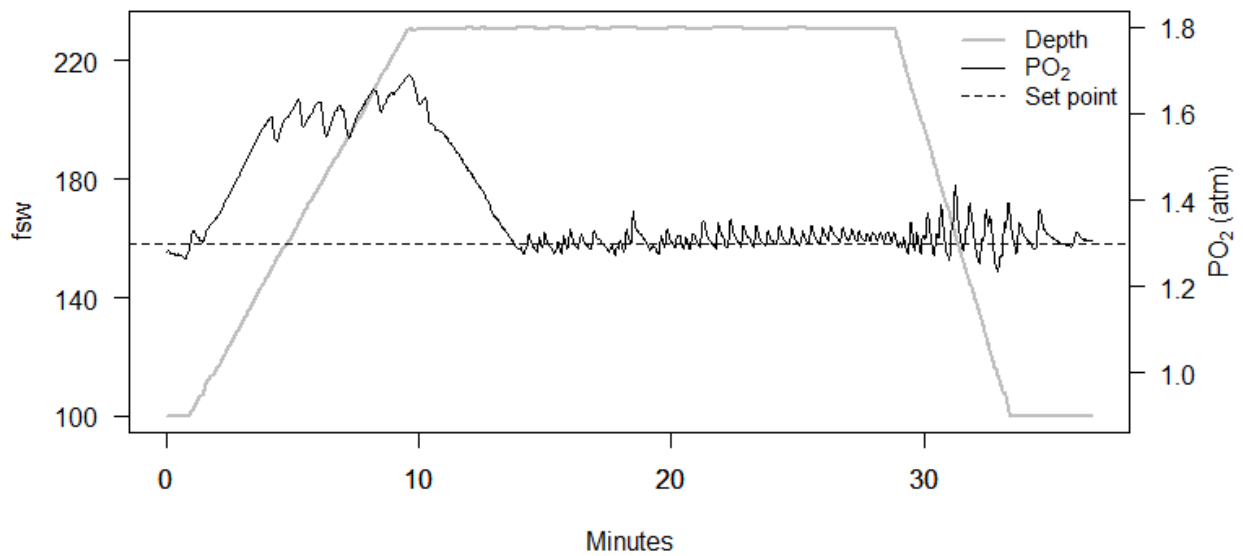


Figure 1. Oxygen control in a MK 28 UBA during downward excursion from 100 fsw storage depth.

Table 3. MK 28 oxygen control during excursions

Depth (fsw)	Excursion PO <sub>2</sub> (atm)			Overshoot Duration (mins)	Post-OS Mean PO <sub>2</sub> (atm)	Ascent Mean PO <sub>2</sub> (atm)
	Mean	Min	Max			
120	1.33	1.21	1.43	NA	NA	1.31
120	1.32	1.23	1.37	NA	NA	1.31
120	1.32	1.21	1.43	NA	NA	1.36
120	1.35	1.28	1.47	0.13	1.35	1.35
120	1.31	1.24	1.37	NA	NA	1.32
120	1.34	1.30	1.41	NA	NA	1.35
200	1.37	1.25	1.53	5.80	1.35	1.35
200	1.30	1.21	1.43	NA	NA	1.27
200	1.36	1.24	1.54	4.60	1.34	1.34
200	1.38	1.28	1.54	6.77	1.36	1.37
200	1.31	1.17	1.53	5.40	1.27	1.27
200	1.39	1.28	1.61	7.43	1.36	1.38
230	1.42	1.30	1.64	9.93	1.37	1.40
230	1.41	1.25	1.61	10.83	1.35	1.36
230	1.38	1.21	1.67	9.23	1.30	1.31
230	1.35	1.26	1.45	NA	NA	1.35
230	1.38	1.24	1.61	9.10	1.31	1.32
230	1.36	1.22	1.61	8.27	1.30	1.31
230	1.47	1.29	1.78	11.17	1.36	1.40
230	1.40	1.23	1.69	9.37	1.31	1.32
230	1.35	1.24	1.56	7.73	1.31	1.32
230	1.36	1.26	1.48	6.47	1.33	1.35

## SATURATION DECOMPRESSION

The saturation decompression was not uneventful. During the 30 fsw decompression stop, at 5:06 am, the divers were rudely awakened by accidental activation of the automatic fire deluge system in “A”–“E” chambers. There was no fire. After the deluge, the OSF complex was split so that unoccupied chambers could, in turn, be brought to the surface, cleaned and dried, and returned to depth. Despite dampened enthusiasm, the divers completed the remaining 28 hours of decompression without incident. No DCS occurred as a result of the saturation decompression.

## DISCUSSION

In an earlier phase of this work, heliox bounce dives to 220 fsw with direct ascent to 100 fsw for a one-hour air-breathing hold resulted in one marginal DCS symptom (transient shoulder pain) during this hold.<sup>11</sup> On the basis of that observation, Type I DCS, rather than counterdiffusion disease, was expected to limit the present downward excursions. The one Type I DCS following the present excursions was in accord with that expectation. Although the tested 200 fsw and 230 fsw excursion no-stop schedules had LEM-estimated DCS risks of 3.5% and 4.6%, these schedules were substantially shorter than corresponding no-stop limits prescribed by other available methods (see Appendix B). The observed DCS following the 19 excursions (200 fsw and 230 fsw) — 5.3% cumulative incidence (95% exact binomial confidence limits; 0.1, 26.0%) — indicates that the tested no-stop limits were not inordinately conservative. Indeed, the present results suggest that LEM is the preferred tool of any presently available to the U.S. Navy, for planning heliox excursion from nitrox saturation. A LEM-estimated target DCS risk no higher than 4.6% might be suitable for calculation of future heliox saturation-excursion decompression schedules, but the 95% confidence limits around the present observed incidence of DCS are too wide to allow a definitive recommendation.

No signs or symptoms consistent with counterdiffusion disease occurred in association with any of these gas switching excursions. Counterdiffusion disease can occur where uptake of helium by diffusion is faster than washout of nitrogen from the same tissue. This can result in gas supersaturation even without decompression (isobaric counterdiffusion) or potentiate gas supersaturation from a preceding decompression. The counterdiffusion may therefore cause or potentiate bubble formation and result in manifestations of DCS, but this only occurs in a few anatomical sites where the exchange of inert gas is diffusion-limited, principally the inner ear and the skin.<sup>4</sup>

Inner ear manifestations of counterdiffusion disease were not expected based on the absence of such symptoms or signs following bounce dives designed to expose the inner ear to similar counterdiffusion of helium and nitrogen as would occur following heliox excursions from 100 fsw nitrox saturation depth.<sup>11</sup> That previous study tested a substantially longer bottom time (60 minutes) than in the present study, a bottom time estimated to allow 99% equilibration of the inner ear with the breathing gas, but to a maximum depth of 220 fsw.<sup>11</sup> That same report argued that longer or deeper heliox

excursions from 100 fsw nitrox saturation would likely not result in inner ear injury if the inner ear gas supersaturation did not exceed that achieved by direct ascent to 100 fsw following 60 minutes at 220 fsw.<sup>11</sup> The present relatively brief bottom time (28 and 35 minutes) excursions to 200 and 230 fsw resulted in substantially lower estimated inner ear gas supersaturation than the 220 fsw bounce dives. Since the present excursions resulted in a Type I DCS, to conduct heliox excursion for longer bottom times or to deeper depths than tested in the present study would require decompression stops to return to 100 fsw storage depth to prevent Type I DCS. Such decompression stops would result in relatively low supersaturation in the inner ear (which has relatively fast gas exchange) on arrival at 100 fsw storage depth, and such excursions should be able to be conducted without undue risk of inner ear injury.

No skin manifestations of counterdiffusion disease occurred. Skin manifestations of counterdiffusion disease have occurred where the skin is exposed to helium in association with nitrox saturation, and at shallower depths than in the present study.<sup>9</sup> In the present excursions, skin manifestations would only have been possible where the skin was exposed to helium under the full face mask. Skin manifestations were not expected because the divers were compressed deeper than storage depth soon after their skin was exposed to helium inside the MK 24 full face mask. As a result of this compression, the ambient pressure would be substantially higher than the dissolved tissue gas pressures, such that counterdiffusion of helium and nitrogen would not result in gas supersaturation.<sup>4</sup>

The successful treatment of the DCS following an excursion is noteworthy. In normal U.S. Navy saturation diving, treatment of DCS that occurs soon after an upward excursion is considered a medical emergency and treated by recompression to the depth from which the excursion originated.<sup>3,14</sup> Such a procedure was impractical in the context of the present protocol because recompression to 200 fsw or 230 fsw in a nitrox atmosphere would result in severe mental impairment due to nitrogen narcosis in the patient and tender. Instead, the protocol provided treatment guidelines similar to the procedure specified in the U.S. Navy Nitrox Saturation Excursion Diving Procedures for DCS at storage depth occurring more than 10 minutes after an excursion.<sup>3</sup> The treatment was carried out in accord with the latter procedures and resulted in rapid and complete resolution of symptoms. The diver received treatment gas during decompression back to storage depth, which is not specified in the procedures.<sup>3</sup>

The MK 28 UBA maintained oxygen set point well during these saturation-excursions. There was no procedure for calibrating of the MK 28 UBA oxygen control system at an ambient pressure above one atm abs, so the UBAs were calibrated outside the OSF. Thus, this calibration was done in the same manner as for the surface-based, bounce dives conducted for manned certification of the MK 28 UBA.<sup>15</sup> Principal differences between the certification dives and the present excursions is that in the certification dives the set point was generally switched from 0.7 to 1.3 atm PO<sub>2</sub> at 33 fsw during a 60 fsw/min descent, whereas the excursions began with the MK 28 UBA already at the higher 1.3 atm PO<sub>2</sub> before a 15 fsw/min descent. Despite these differences, the maximum PO<sub>2</sub> during overshoot in the present excursions from 100 fsw to 230 fsw was

similar to that measured in bounce dives from the surface to 130 fsw (same vertical distance) in MK 28 UBA with air diluent (range 1.45–1.78 atm, n=24).<sup>15</sup>

In contemporary heliox saturation diving, downward excursions are usually conducted within unlimited-duration excursion depth limits, that allow relatively small vertical travel from storage depth, but allow the diver to return to storage depth without decompression stops irrespective of the duration of the excursion. In addition to being the first documented heliox excursions from nitrox saturation, the present dives differ from typical saturation-excursion diving by having excursions of relatively large vertical distance (230-100=130 fsw), and of limited-duration. In comparing saturation-excursion dives it is relevant that the evidence from laboratory trials indicates the vertical distance and the duration of an excursion that can be accomplished without decompression stops increases with increasing storage depth. For present U.S. Navy heliox saturation-excursion diving, the unlimited-duration downward excursion depth limit from 100 fsw storage depth is 158 fsw (58 fsw vertical distance), and 34 laboratory excursions (one DCS) have been conducted to the corresponding vertical distance limits from storage depths of 100 fsw or shallower.<sup>16</sup> Prior to the development of unlimited duration excursions, the U.S. Navy developed limited-duration heliox excursions.<sup>17</sup> The shallowest storage depth from which excursions were tested was 150 fsw, and 46 no-stop excursions (including repetitive excursions within a 12-hour period) to 250 fsw (100 fsw vertical distance) for up to 60 minutes bottom time were conducted without DCS.<sup>18</sup> Deeper excursions than those in the present study have been achieved from shallow nitrox saturation (storage depths 50–120 fsw). A few air-breathing excursion to depths between 235 fsw and 300 fsw (vertical distances up to 185 fsw) were accomplished with some incidents of DCS and central nervous system oxygen toxicity (air excursions deeper than 171 fsw have PO<sub>2</sub> higher than 1.3 atm).<sup>1</sup> Thirty-two trimix excursions (no DCS) to 197 or 262 fsw were conducted from 82 fsw nitrox saturation, although these excursions were conducted with decompression stops beginning at 112 fsw and 141 fsw, respectively.<sup>7</sup> Four no-stop trimix excursions (no DCS) to 262 fsw were conducted, but the nitrox storage depth was 197 fsw.<sup>6</sup>

Successful completion of the present saturation-excursion dives proves the concept that heliox downward excursions can be safely conducted from shallow nitrox saturation. Although the present no-stop excursions do not provide usefully longer bottom times than can be achieved with surface-based bounce diving, calculation of excursions with decompression stops to return to storage depth could provide greater capability.

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## APPENDIX A K-1D MICROFUEL CELL OXYGEN SENSOR EVALUATION

During manned certification testing of the MK 28 UBA, diver inspired  $PO_2$  was measured using Teledyne K-1D micro-fuel cell oxygen sensors in the same manner as in the present report.<sup>15</sup> At that time, the fidelity of the K-1D oxygen sensors was questioned in response to their indication that the inspired  $PO_2$  delivered by the MK 28 drifted higher over the course of longer dives and plateaued higher than the oxygen set point. As part of that earlier study, bench testing of K-1D oxygen sensors and the R-22 oxygen sensors used in the MK 28 oxygen control system indicated that the elevated inspired  $PO_2$  principally resulted from inadequate temperature compensation in the R-22 oxygen sensor, not from faulty performance of the K-1D oxygen sensors.<sup>15</sup> In addition to their intrinsic limitations, the R-22 placement in the MK 28 UBA has the sensing face exposed to warm gas exiting the carbon dioxide absorbent canister and the body of the sensor, which contains the temperature compensating thermistor, exposed to cooler gas returning from the exhalation counter lung. Nevertheless, an additional functional validation of the K-1D oxygen sensors was performed prior to the present study.

### METHODS

The evaluation was undertaken during four MK 28 man-dives in the NEDU test pool. Two MK 28 UBA were instrumented in a similar fashion as in the body of this report with gas sampling blocks located in line between the inspiration counterlung and the inspiration hose. The gas sampling blocks housed a thermistor and a K-1D micro-fuel cell oxygen sensor (Teledyne Electronics Technologies). These two K-1D oxygen sensors were from the batch of five sensors used in the main study described in the body of this report. The K-1D oxygen sensors were calibrated and used to record diver inspired  $PO_2$  in the same manner as described in the body of this report. In addition, a port in the sampling block was connected via nylon tubing through which gas could flow to a magnetic sector mass spectrometer (Perkin-Elmer) tuned to detect oxygen. Gas flow to the mass spectrometer was driven by the pressure differential between the depth in the test pool and the surface. Flows were regulated with metering valves to between 129 and 140 mL/min. Inspired gas temperature, K-1D amplified voltage, K-1D  $PO_2$  calculated from the daily two-point calibration, mass spectrometer oxygen fraction signal, and  $PO_2$  calculated from the mass spectrometer signal and pressure at test pool depth were recorded at 1 Hz to a data acquisition system. On each of two days, two MK 28 UBA dives of approximately two hours duration were conducted with divers resting at the bottom of the NEDU test pool at 11–13 fsw, while the inspired  $PO_2$  was simultaneously recorded using the two methods. For these dives the MK 28  $PO_2$  set point was 0.7 atm.

In post-processing, the delay between K-1D and mass spectrometer signals was characterized. Each opening of the UBA oxygen addition valve produced spikes in both signals. The times of spikes were identified in both signals and mean of the differences between corresponding oxygen addition spikes was calculated. This mean delay was used to align the two signals.

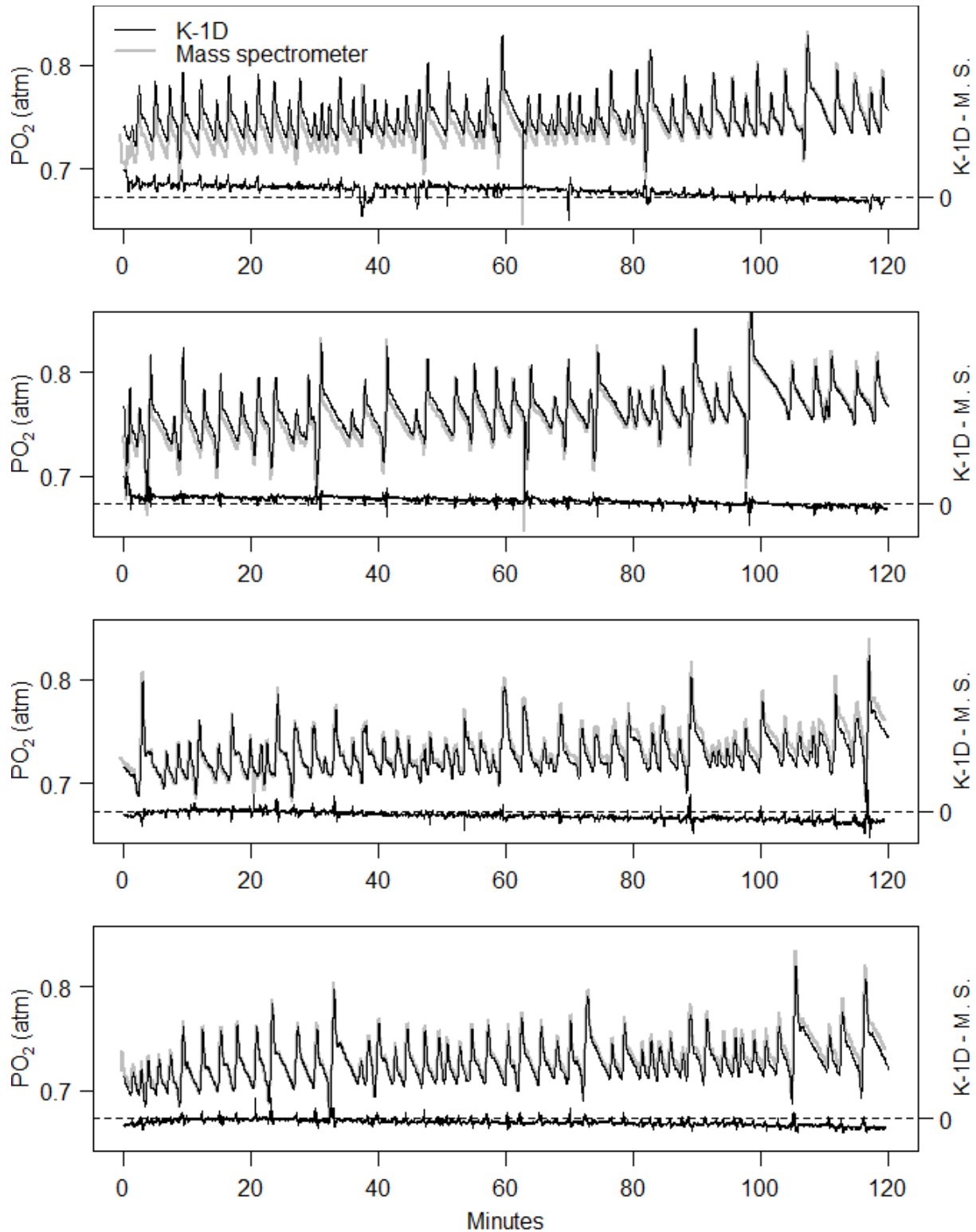


Figure A-1. PO<sub>2</sub> measured by K-1D micro-fuel cell oxygen sensor and mass spectrometer in four 120-minute MK 28 man-dives completed in the NEDU test pool. The left axis indicates the PO<sub>2</sub> and right axis indicates the difference (K-1D – mass spectrometer) in the two signals. The origin of the two y-axes are offset but the axes have the same scales.

## RESULTS AND CONCLUSIONS

Figures A-1 illustrates the inspired PO<sub>2</sub> measured by K-1D oxygen sensors and mass spectrometers aligned as described above, and the difference between the two methods of measurement for each of the UBA dives. Both the K-1D and mass spectrometer signals indicate a slight increase in inspired PO<sub>2</sub> over two hours. The difference between the measurements is small, although the K-1D signal tends to drift lower (difference less than zero) compared to the mass spectrometer over time. The slight downward drift of the signal difference is in the opposite direction than would be necessary to have caused the increase in inspired PO<sub>2</sub> seen in manned certification testing of the MK 28.

## APPENDIX B EXCURSION SCHEDULE CALCULATION

The downward excursions described in this report are, to our knowledge, the first heliox excursions from nitrox saturation ever documented. Consequently, there were no decompression algorithms available that had been validated with manned testing of similar saturation-excursions. The LEM-he8n25 probabilistic decompression model, which was developed and validated for bounce diving rather than saturation-excursion diving, was used to plan no-stop limits for these excursions. Under the LEM-he8n35 model, the 200 fsw for 35 minutes bottom time excursion had an estimated DCS risk of 3.5% and the 230 fsw for 28 minutes bottom time excursion had an estimated DCS risk of 4.6%. These risk targets were based on relevant bounce dives conducted in an earlier phase of this work.<sup>11</sup> This appendix outlines alternative methods for calculating excursions from saturation that were considered while developing the present schedules.

In contemporary saturation diving, downward excursions are usually conducted within the unlimited-duration excursion depth limits. The current U.S. Navy unlimited-duration excursion depth limits for heliox saturation-excursion diving are based on experimental upward excursions from saturation and are an empirical relationship between saturation depth and upward excursion depth.<sup>16</sup> There is no time component of this calculation, which is therefore unsuitable for calculating limited-duration excursions. In the early development of heliox saturation-excursion diving in the U.S. Navy, limited-duration heliox downward excursions deeper than accepted unlimited-duration depth limits were calculated, and a substantial number of these excursions were conducted at NEDU.<sup>17</sup> These excursions were calculated based on the maximum permissible inert gas tensions (M-values) in multiple independent compartments (Haldane method<sup>19</sup>) using the Workman helium M-value table.<sup>20</sup> The shallowest storage depth from which excursions were tested was 150 fsw, and 46 no-stop excursions (including repetitive excursions within a 12-hour period) to 250 fsw for up to 60 minutes bottom time were conducted without DCS.<sup>18</sup> More recently, the U.S. Navy nitrox saturation-excursion procedures tabulated in NEDU TR 17-07<sup>3</sup> allow for excursions deeper than accepted unlimited-duration depth limits. These procedures were provided to the U.S. Navy by Hamilton Research Ltd. and were calculated using their proprietary Decompression Computing and Analysis Program (DCAP) implementation of the Tonawanda Ila decompression algorithm<sup>21</sup> (a Haldane method algorithm) and the mf11f6 M-value table. Using these procedures, no-stop downward excursions breathing 1.3 atm PO<sub>2</sub>-in-nitrogen have been conducted from 102 fsw storage depth at NEDU.<sup>22</sup> In all these methods, the allowed vertical distance and the duration of an excursion increases with increasing storage depth. None of the U.S. Navy decompression algorithms were validated for calculating excursions to 200 fsw or deeper from 100 fsw storage depth, or for calculating heliox excursions from nitrox saturation.

The Hamilton Research Ltd. DCAP with mm11a5 M-value table (a predecessor of mf11f6) has been used to calculate trimix (helium-nitrogen-oxygen) excursions from shallow (82 fsw) nitrox saturation.<sup>7</sup> DCAP is proprietary software, but from materials

provided to NEDU with the nitrox saturation-excursion procedures, and some published reports<sup>7</sup>, it appears that DCAP accommodates the use of breathing mixtures containing both helium and nitrogen by tracking both gases in each compartment, and helium half-times are much shorter than nitrogen half-time in slower compartments. Although it is technically possible to calculate heliox excursions from nitrox saturation using this multiple inert gas feature of DCAP, Hamilton and colleagues noted that such calculations produce implausible results (excursions just exceeding the no-stop limit have hours-long decompression stops), but provided no explanation for this behavior.<sup>7</sup> However, this behavior probably arises because of the differences in helium and nitrogen half-times in the slower algorithm compartments. These slower compartments generally govern decompression stops deeper than storage depth because the mf11f6 and mm11a5 M-values for fast compartments at these depths are much higher than ambient pressure, whereas for slower compartments the M-values just exceed ambient pressure. At decompression stops close to storage depth, continued helium uptake into slow compartments can exceed nitrogen washout, and the sum of compartmental inert gas partial pressures can exceed the M-value for many hours (see Figure B-1). This behavior renders the multiple inert gas implementation of Tonawanda Ila mf11f6 inapplicable to calculating heliox excursions from nitrox saturation.

The parameter set with the mf11f6 M-value table with the nitrogen half-times has been implemented in the U.S. Navy Thalmann Algorithm Dive Planner and can be used to calculate nitrox saturation-excursion schedules.<sup>3,23</sup> The Thalmann Algorithm is a Haldane method algorithm that models the behavior of only a single inert gas, so will not manifest the behavior just described for multiple gases, but also will not accommodate any actual differences between helium and nitrogen uptake and washout, if differences exist. Nevertheless we used this implementation to calculate no-stop times for the excursions corresponding to those used in the present report, but assuming no change in inert gas background. Divers were assumed saturated at 100 fsw with 0.33 atm PO<sub>2</sub> and balance inert gas, and excursions were conducted breathing constant 1.3 atm PO<sub>2</sub>, with 15 fsw/min descent and 30 fsw/min ascent rates. The resulting no-stop excursion limits were 200 fsw for 57 minutes bottom time and 230 fsw for 26 minutes bottom time. The same assumptions were used to calculate no-stop limits with the mf11f6 M-values and the DCAP helium half-times. This resulted in no-stop excursions of 200 fsw for 46 minutes bottom time and 230 fsw for 26 minutes bottom time. For either set of half-times, the calculated 230 fsw no-stop excursion limits were similar to the bottom time dived without incident (28 minutes). However, the calculated 200 fsw no-stop excursion limits were substantially longer than the bottom time dived (35 minutes) that resulted in an incident of Type I DCS.

For comparison, a parameter set with the Workman helium M-values and helium compartment half-times was implemented in the U.S. Navy Thalmann Algorithm Dive Planner. Again, divers were assumed saturated at 100 fsw with 0.33 atm PO<sub>2</sub> and balance inert gas, and excursions were conducted breathing constant 1.3 atm PO<sub>2</sub>, with 15 fsw/min descent and 30 fsw/min ascent rates. The resulting no-stop excursion limits were 200 fsw for 137 minutes bottom time and 230 fsw for 56 minutes bottom time. Both of these limits were substantially longer than the bottom times dived.

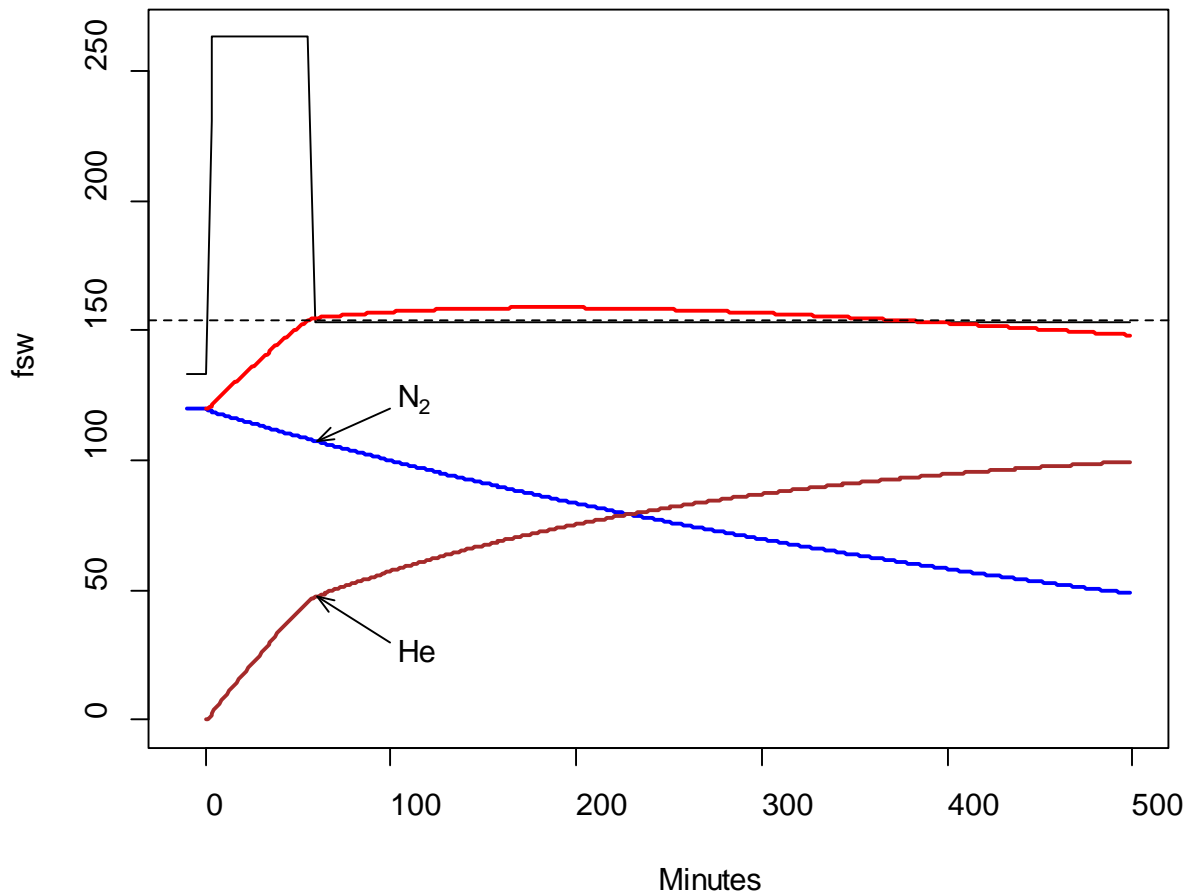


Figure B-1. Inert gas partial pressures in Tonawanda Ila mf11f6 compartment nine (nitrogen half-time 385 minutes, helium half-time 160 minutes) for a 230 fsw / 55 minute downward excursion breathing 1.3 atm PO<sub>2</sub>-in-helium from saturation at 100 fsw storage depth, 0.35 atm PO<sub>2</sub>-in-nitrogen atmosphere. The ambient pressure is illustrated in fsw absolute (fsw+33) and the compartment inert gas pressures are in equivalent units (both designated fsw abs for clarity below). The depth-time profile is indicated by the thin black line. The helium and nitrogen partial pressures are labeled and the sum of these two partial pressures given as the upper heavy (red) line. The dashed line is the compartment nine M-value for a 153 fsw abs (120 fsw) decompression stop, this M-value is 154 fsw abs. Total inert gas partial pressure exceeds this M-value during the excursion, requiring a decompression stop at 153 fsw abs (120 fsw). During this stop, continued helium uptake exceeds nitrogen washout for many hours; in effect, the decompression obligation at this stop depth increases for the first few hours at the stop depth. The result is a 319 minute required stop time before travel to a 143 fsw abs (110 fsw) stop (not shown). For comparison, according to the 1.3 atm PO<sub>2</sub> He-O<sub>2</sub> Decompression Tables in the U.S. Navy Diving Manual,<sup>14</sup> a surface-based bounce dive to 230 fsw for 55 minutes bottom time only requires 294 minutes total decompression time to return to the surface.