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XVAL-HE-4B: A MAXIMUM PERMISSIBLE TISSUE TENSION TABLE FOR REAL-TIME THALMANN ALGORITHM SUPPORT OF CONSTANT 1.3 ATM PO_2-IN-HELIUM DIVING TO 200 FSW

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The Thalmann Algorithm parameterized with the XVal-He-4 Maximum Permissible Tissue Tension (MPTT) table is a candidate real-time algorithm for use in the Navy Dive Computer (NDC) to support MK 16 MOD 1 He-O_2 diving to maximum depths of 200 fsw. However, XVal-He-4 was developed specifically to generate the U.S. Navy Diving Manual MK 16 MOD 1 He-O_2 decompression tables to 200 fsw, and not for real-time applications. The XVal-He-4-Thalmann Algorithm can prescribe infinite-duration decompression stops following bottom times of more than a few minutes at depths greater than 211 fsw. Therefore, an NDC implementation of XVal-He-4 could fail to provide decompression guidance with even a brief unplanned excursion deeper than 211 fsw. A modified MPTT table, lacking the problematic 5-minute half-time compartment, was designated XVal-He-4B. XVal-He-4 and XVal-He-4B produce identical decompression schedules at depths of 180 fsw or less and schedules with practically equal estimated risks of decompression sickness at 190 and 200 fsw. XVal-He-4B does not fail in the operational depth range of the MK 16 MOD 1 and is recommended for use in an NDC to support operations to 200 fsw.

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CONTENTS

LIST OF FIGURES

INTRODUCTION

Decompression schedules in the MK 16 MOD 1 He-O_2 Decompression Tables of the *U.S. Navy Diving Manual, Revision 6*[1] were designed to incur a near uniform 2.3% estimated risk of decompression sickness (P_{DCS}) over the tabulated ranges of dive depth and bottom time.[2] This design objective was achieved by computing the schedules with methods based on the linear-exponential multi-gas probabilistic decompression model parameterized with the nbnmx3g–he8n25 parameter set (LEM–he8n25), but the method differed depending on whether the schedules were included in the depth range over which a capability to plan for repetitive diving had to be supported. For dives to depths greater than 200 feet of seawater (fsw), dives for which no repetitive diving capability was to be supported, schedules were computed by using LEM–he8n25 directly to find the minimum decompression time required to reach but not exceed the 2.3% target P_{DCS} in each schedule.[2] For dives to depths of 200 fsw or shallower, dives for which a capability to plan for repetitive diving was required, schedules were computed with the Thalmann Algorithm parameterized with XVal-He-4, a maximum permissible tissue tension (MPTT) table derived to force the Thalmann Algorithm to calculate decompression schedules similar to those produced for the same dive by LEM–he8n25 with the 2.3% target P_{DCS}. This adoption of the Thalmann Algorithm allowed ready calculation of the surfacing repetitive groups and surface interval credit and residual gas time tables required to support repetitive diving with the familiar residual gas timetable format[3] that has been used in U.S. Navy Diving Manuals since 1959.[4]

Traditionally, MPTT tables are constructed from surfacing MPTT values (M_0-values) that are defined to just allow well accepted no-stop bottom times.[5] These surfacing values are then projected to depth, generally as linear functions of depth with slopes of one or greater[6] to ensure that the MPTTs at depth are always greater than the corresponding arterial inert gas tensions. The MPTTs in XVal-He-4 were also constrained to be linear functions of depth, but with surfacing MPTTs and slopes derived in a formal statistical process described in NEDU TR 02-10[2] with additional details in Appendix A of the present report. This process yielded slopes for several of the XVal-He-4 MPTT generating functions that are less than one (see Figure 1 and Appendix A). As a result, some XVal-He-4 MPTTs may intersect and become less than the arterial inert gas tension at depth, a circumstance which causes the XVal-He-4 Thalmann Algorithm to fail at or deeper than the intersection depths. Because these intersection depths are deeper than 200 fsw for MK 16 MOD 1 dives, this problem did not arise when XVal-He-4 Thalmann Algorithm decompression schedules were calculated for the MK 16 MOD 1 He-O_2 Decompression Tables.

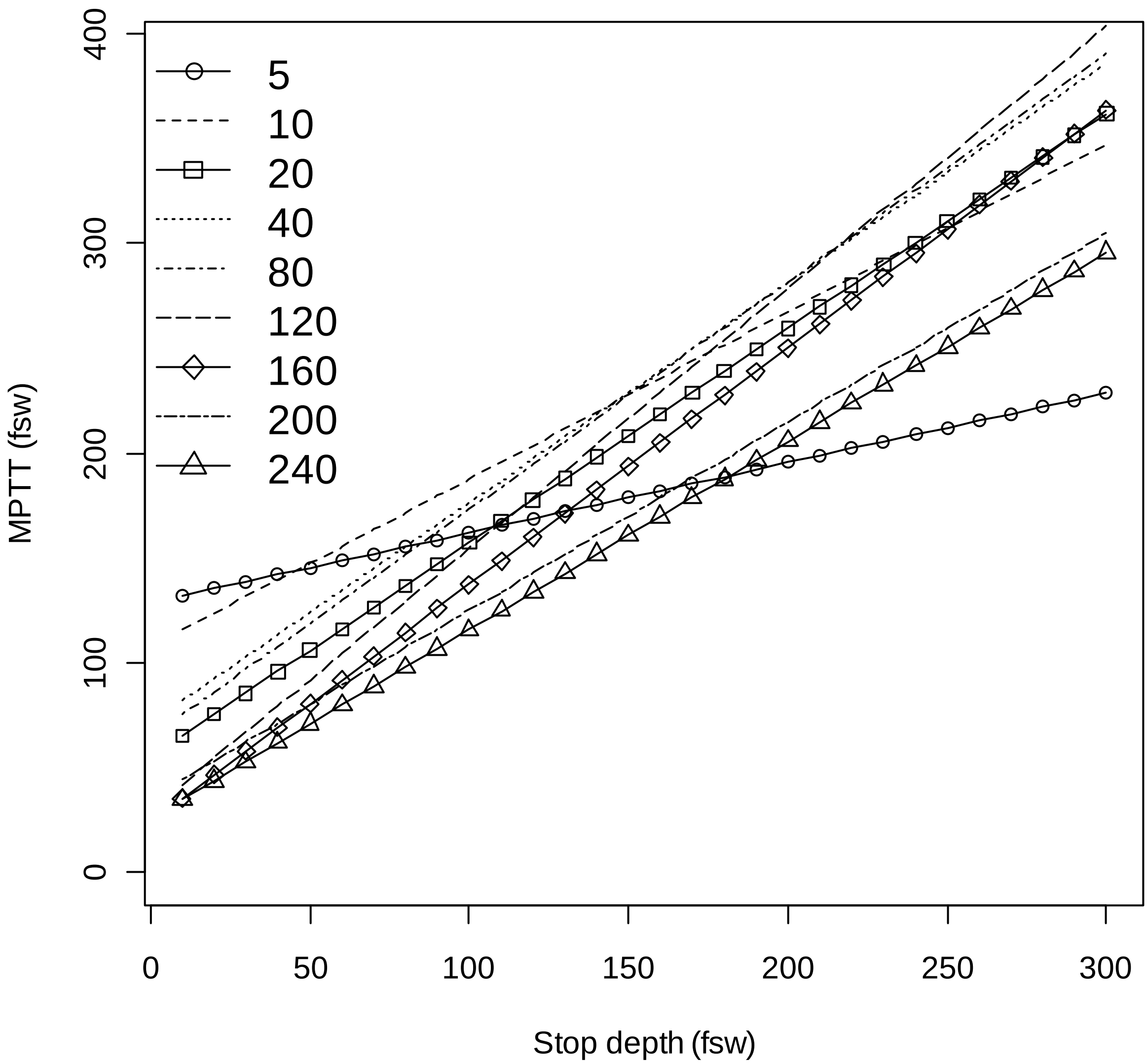

Figure 1. XVal-He-4 MPTTs. MPTTs for compartments that control decompressions in schedules tabulated in the MK 16 MOD 1 He-O_2 Decompression Tables in the *U.S. Navy Diving Manual* are drawn with symbols and solid lines.

There has been recent impetus to implement a real-time decompression algorithm in the Navy Dive Computer (NDC) to support MK 16 MOD 1 He-O_2 diving to maximum depths of 200 fsw with approximately one-hour maximum bottom time. Wrist-worn dive computers like the NDC currently have insufficient computing power to calculate probabilistic decompression schedules in real-time and instead run less demanding deterministic decompression algorithms. The NDC and its supporting dive planning tool, the U.S. Navy Thalmann Algorithm Navy Dive Planner (NDP), use implementations of the deterministic Thalmann Algorithm.[7,8] XVal-He-4 was developed for use in this algorithm to generate the MK 16 MOD 1 He-O_2 Decompression Tables in the *U.S. Navy Diving Manual*, tables that have been extensively man-tested[2] and used in the field since before 2005. Implementation of the XVal-He-4 Thalmann Algorithm in currently existing NDC hardware would thus not only be relatively straightforward, but would also provide guidance fully consistent with the existing MK 16 MOD 1 He-O_2 Decompression Tables, making it the most obvious candidate algorithm for a MK 16 MOD 1 He-O_2 NDC.

However, XVal-He-4 was not developed for use in the Thalmann Algorithm to support real-time applications. Indeed, the unconventional structure of XVal-He-4 makes it unsuitable for such applications. This report evaluates the behavior of the Thalmann Algorithm with XVal-He-4 beyond that explored previously[2] and shows how XVal-He-4 is readily modified and made suitable for use in the Thalmann Algorithm to provide real-time support for MK 16 MOD 1 He-O_2 diving.

METHODS

Decompression tables were generated with the Thalmann Algorithm TBLP7R routine, and compartment gas tensions at each node in the tabulated schedules were obtained from output provided by the Thalmann Algorithm DMDB7 routine.[7,8] Output of the computed schedules in Augmented NMRI Standard format was used to estimate the P_{DCS} of computed schedules with LEM–he8n25.

RESULTS

XVAL-He-4

The XVal-He-4 Thalmann Algorithm MK 16 MOD 1 He-O_2 Decompression Tables in the *U.S. Navy Diving Manual, Revision 6* have schedules for dives with up to 60 minutes bottom time at 200 fsw and schedules for dives with considerably longer bottom times at shallower depths. These schedules have a mean LEM–he8n25 estimated P_{DCS} of 2.3% (SD = 0.4%) with only five schedules having estimated P_{DCS} of more than three SDs greater than the mean (bottom times near one hour at 190 fsw and 200 fsw, see Figure 2). Although the MK 16 MOD 1 He-O_2 Decompression Tables cover the intended operational depth-time range for a future NDC, a real-time implementation of the XVal-He-4 Thalmann Algorithm must produce reasonable schedules for a small range of longer than intended bottom times or deeper than intended depths in case inadvertent violation of depth and time limits occurs in a dive.

Figure 3 illustrates that in the 150 to 200 fsw depth range, XVal-He-4 produces low P_{DCS} schedules for bottom times substantially longer than one hour. Although DCS risk is not as well controlled at 190 fsw and 200 fsw as at shallower depths, the maximum estimated P_{DCS} is an acceptable 5.1%. For dives to a given depth, the estimated P_{DCS}

peaks at bottom times near one hour and returns to values near 2.3% at longer bottom times.

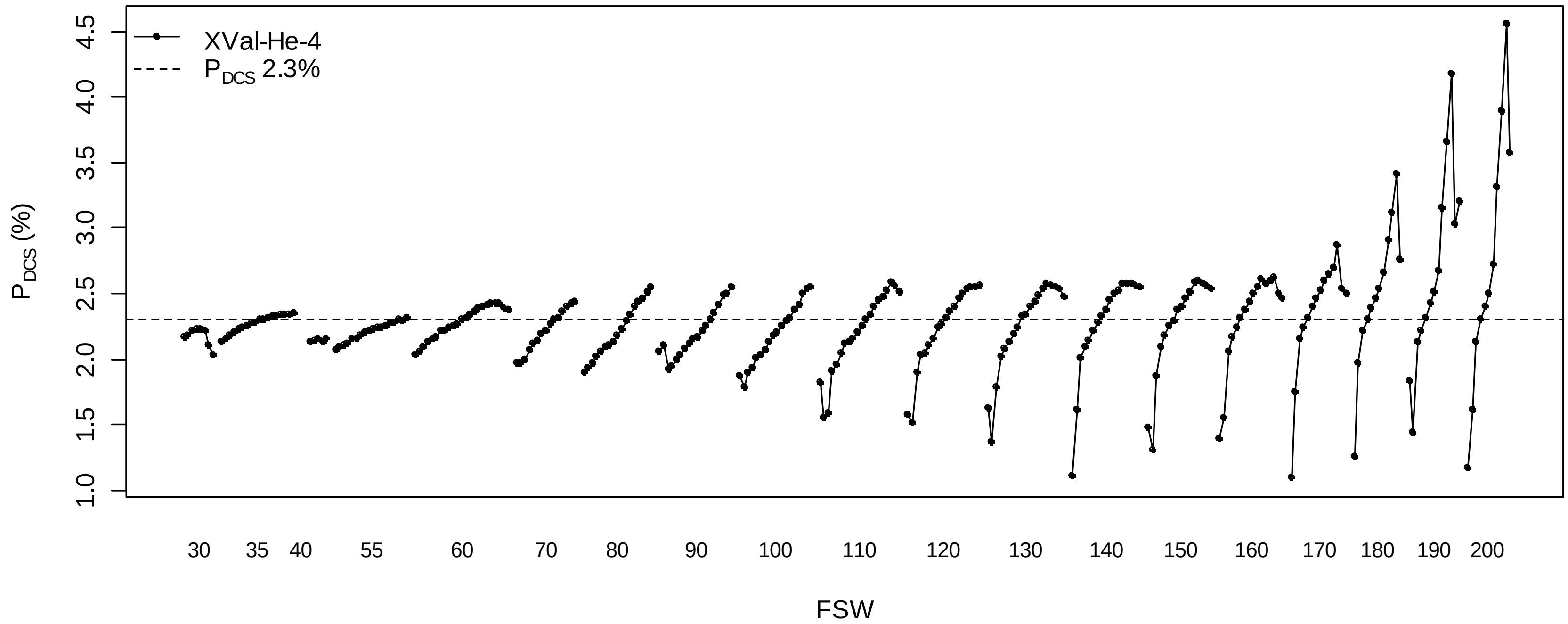

Figure 2. P_{DCS} of XVal-He-4 Thalmann Algorithm MK 16 MOD 1 He-O_2 decompression schedules in the *U.S. Navy Diving Manual, Revision 6*. Points correspond to the LEM–he8n25 estimated P_{DCS} values for schedules with increasing bottom time in each dive depth group indicated on the x-axis. No-stop dives are not shown. The maximum plotted bottom times, in minutes, in the region of interest are (fsw/BT) 150/90, 160/90, 170/80, 180/70, 190/65, and 200/60.

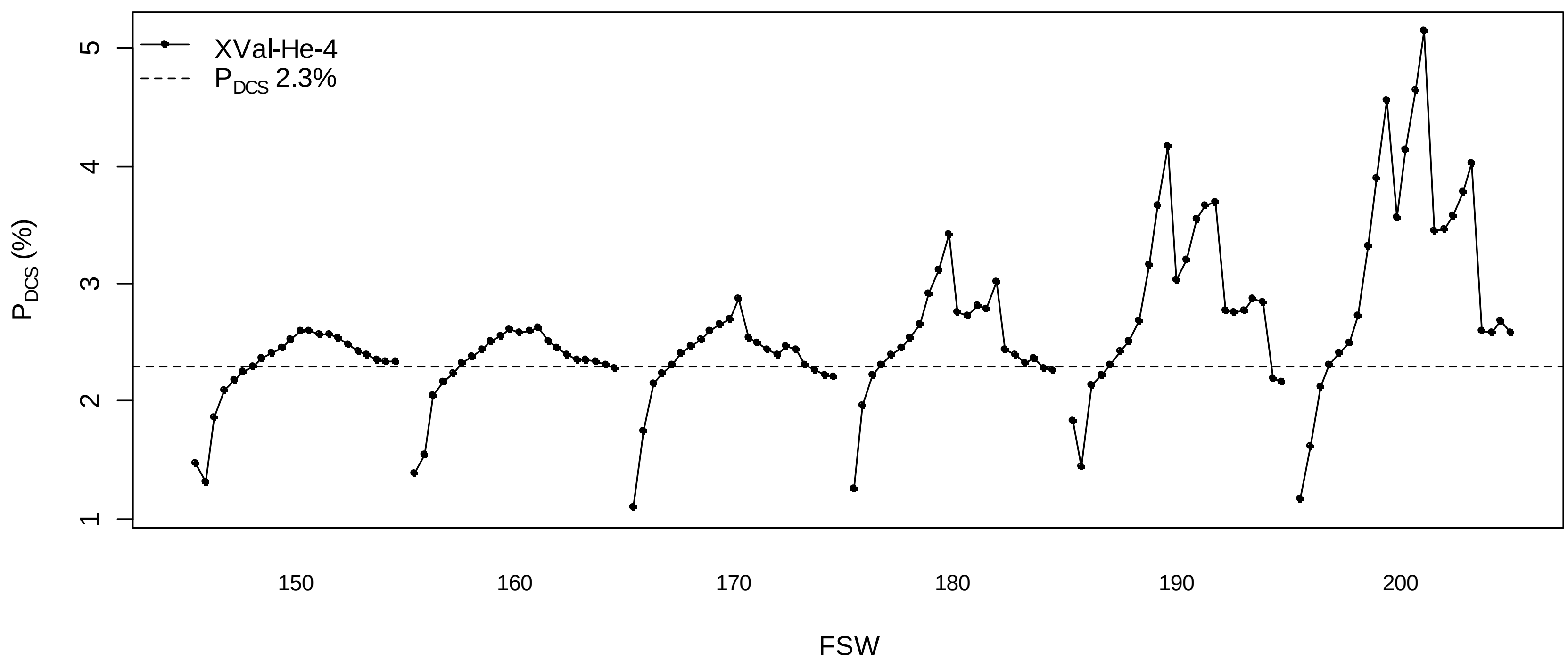

Figure 3. P_{DCS} of XVal-He-4 Thalmann Algorithm MK 16 MOD 1 He-O_2 decompression schedules for extended bottom times. Points correspond to LEM–he8n25 estimated P_{DCS} of decompression schedules at the indicated dive depths with bottom times shown in 5-minute increments up to 120 minutes, presented in the same manner as in Figure 2.

A controlling compartment is one for which a decompression stop is required to allow gas washout to the MPTT for ascent to the next stop before continued ascent. Only the compartments with half-times of 5, 20, 160 and 240 minutes control decompression in the *U.S. Navy Diving Manual* MK 16 MOD 1 He-O_2 Decompression Tables to 200 fsw or less, or in the extended schedules shown in Figure 3. Of these compartments, the 5-minute half-time compartment controls stops only in the 190 fsw and 200 fsw schedules, where it imposes the unconventional deep stops (see Table 1).

Failure of XVal-He-4 deeper than 211 fsw

The XVal-He-4 Thalmann Algorithm will not provide reliable decompression guidance for 1.3 atm constant PO_2-in-helium dives to depths deeper than 211 fsw, because the arterial helium tension exceeds the 5-minute half-time compartment MPTT at such depths. As the compartment approaches equilibrium with the arterial helium tension, washouts of compartment helium tension to less than the MPTT — and ascents without violation of the MPTT — become impossible. The algorithm consequently inserts an infinite duration decompression stop at the depth where this condition first develops, which may be at maximum depth or at the next shallower decompression stop depth. In either case the diver is “trapped” at depth. This unacceptable situation is a consequence of the low slope of the 5-minute half-time compartment MPTT generating function.

With a 10 fsw stop depth increment and breathing 1.3 atm constant PO_2-in-helium from the MK 16 MOD 1 underwater breathing apparatus (UBA), the shallowest depth at which this problem occurs is 214 fsw, where helium uptake can result in compartmental tension greater than the 5-minute half-time compartment MPTT for 220 fsw. Once these greater tensions occur, the algorithm prescribes that divers take an infinite duration 220 fsw decompression stop which has already been omitted without leaving the bottom. In dives to depths deeper than 220 fsw, this problem first manifests as an infinite duration decompression stop at a depth shallower than bottom depth, but as bottom time increases, infinite duration stops develop at increasing depths that eventually exceed bottom depth.

Because gas exchange in the 5-minute half-time compartment is rapid by definition, these infinite duration stops arise after only relatively short bottom times. Also, the entire time at depth does not need to be spent at 214 fsw or deeper. For instance, after a substantial bottom time at 200 fsw, a brief unplanned excursion to a depth deeper than 214 fsw could result in an infinite duration stop.

XVAL-HE-4B

Three fixes for this behavior are readily implemented. The first is to truncate XVal-He-4 at 200 fsw and set the maximum operating depth of the NDP or NDC to 200 fsw. This would be transparent in the NDP, which will not accept depth entries deeper than the maximum depth in the MPTT table. But this fix would be unacceptable in the NDC as it would preclude NDC support of inadvertent excursions to depths deeper than 200 fsw.

Table 1. Comparison of 200 fsw MK 16 MOD 1 He-O_2 schedules

A. XVal-He-4

	Decompression Stops																
BT	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	TST
8																	0
10																5	5
15														1	1	15	17
20								1	0	0	2	0	0	5	7	25	40
25				1	0	0	0	2	0	1	1	1	7	7	7	47	74
30		1	0	0	2	0	0	0	2	0	1	7	7	8	7	69	104
35		1	0	1	1	0	0	2	0	0	7	7	7	8	7	87	128
40	1	0	1	1	0	0	2	0	0	5	8	7	7	8	7	104	151
45	1	0	1	1	0	0	2	0	2	7	8	7	8	7	7	120	171
50	1	0	1	1	0	1	0	1	6	7	7	8	7	8	7	139	194
55	1	0	1	1	0	1	0	2	8	7	7	8	7	8	8	155	214
60	1	0	1	1	0	1	0	5	7	8	7	7	8	7	22	161	236

B. XVal-He-4B

	Decompression Stops																
BT	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	TST
8																	0
10																5	5
15															2	15	17
20														5	8	22	35
25													7	7	8	43	65
30												8	7	7	8	63	93
35											7	7	8	7	7	83	119
40										5	8	7	7	8	7	100	142
45									3	7	7	8	7	8	7	115	162
50									7	7	7	8	7	7	8	134	185
55								3	7	8	7	7	8	7	7	153	207
60								6	7	7	8	7	8	7	20	160	230

C. LEM–he8n25

	Decompression Stops																
BT	170	160	150	140	130	120	110	100	90	80	70	60	50	40	30	20	TST
5																	0
10																3	3
15													1	3	3	10	17
20												3	3	2	3	19	30
25											4	3	2	3	3	47	62
30									2	2	3	3	2	3	9	68	92
35										6	2	3	3	9	12	86	121
40								3	3	2	3	2	8	12	12	102	147
45								4	3	2	3	5	12	12	12	118	171
50									7	2	3	12	12	11	13	134	194
55								5	3	2	8	12	12	11	11	151	215
60							3	3	2	4	11	12	12	10	12	166	235

The second fix is to alter the 5-minute compartment MPTTs in XVal-He-4 so that none are less than the arterial helium tension when a diver is breathing from a MK 16 MOD 1 UBA at the corresponding depth. Such a MPTT table, designated XVal-He-4A, was created by altering the 5-minute compartment MPTT values for depths deeper than 170 fsw to values greater than the corresponding arterial helium tension when breathing from MK 16 MOD 1 UBA. Retaining the original values at 170 fsw and shallower allows the Thalmann Algorithm with XVal-He-4A to produce schedules identical to those tabulated in the *U.S. Navy Diving Manual, Revision 6* for depths of 200 fsw or shallower. Beginning the changes deeper than 170 fsw prevents the algorithm from producing schedules with inordinately long decompression stops at depths between 180 and 210 fsw. However, the current implementation of the Thalmann Algorithm in the NDC calculates MPTTs from linear MPTT generating functions that cannot reproduce the XVal-He-4A MPTT. Therefore, details of XVal-He-4A performance are not given in this report.

The third and most satisfying solution is to eliminate the 5-minute compartment from XVal-He-4 since it controls very few schedules in the intended depth range. The resulting MPTT table, designated XVal-He-4B, allows the Thalmann Algorithm to produce schedules identical to those tabulated in the *U.S. Navy Diving Manual, Revision 6* for dives to depths of 180 fsw and shallower. Table 1 gives the decompression schedules for 200 fsw dives as tabulated in the *U.S. Navy Diving Manual, Revision 6* (XVal-He-4 Thalmann Algorithm), as calculated by using the Thalmann Algorithm with XVal-He-4B, and as calculated with LEM–h8n25 at 2.3% target P_{DCS}. Note that XVal-He-4B schedules differ from XVal-He-4 schedules by not having deep one-minute-duration decompression stops. These XVal-He-4 deep stops are unconventional and appear only in the 190 and 200 fsw schedules for MK 16 MOD 1 He-O_2 Decompression Tables. In fact the XVal-He-4B schedules are more similar than the XVal-He-4 schedules are to the LEM–h8n25 schedules that the XVal sets are intended to emulate. A similar pattern occurs in the 190 fsw schedules which are not given here.

Figure 4 illustrates the estimated P_{DCS} of schedules calculated with the XVal-He-4B Thalmann Algorithm for dives with bottom times up to 60 minutes at depths from 190 to 300 fsw. The estimated P_{DCS} are acceptable for short bottom times such that XVal-He-4B Thalmann Algorithm can support brief excursions deeper than its maximum operating depth of 200 fsw. Estimated P_{DCS} increase to unacceptable levels with increasing bottom time at all depths deeper than 200 fsw. Only compartments with 10, 20, 160 and 240 minute half-times control decompression in the illustrated schedules. Of these compartments, the 10-minute half-time compartment controls stops only for dives to depths of 230 fsw and deeper.

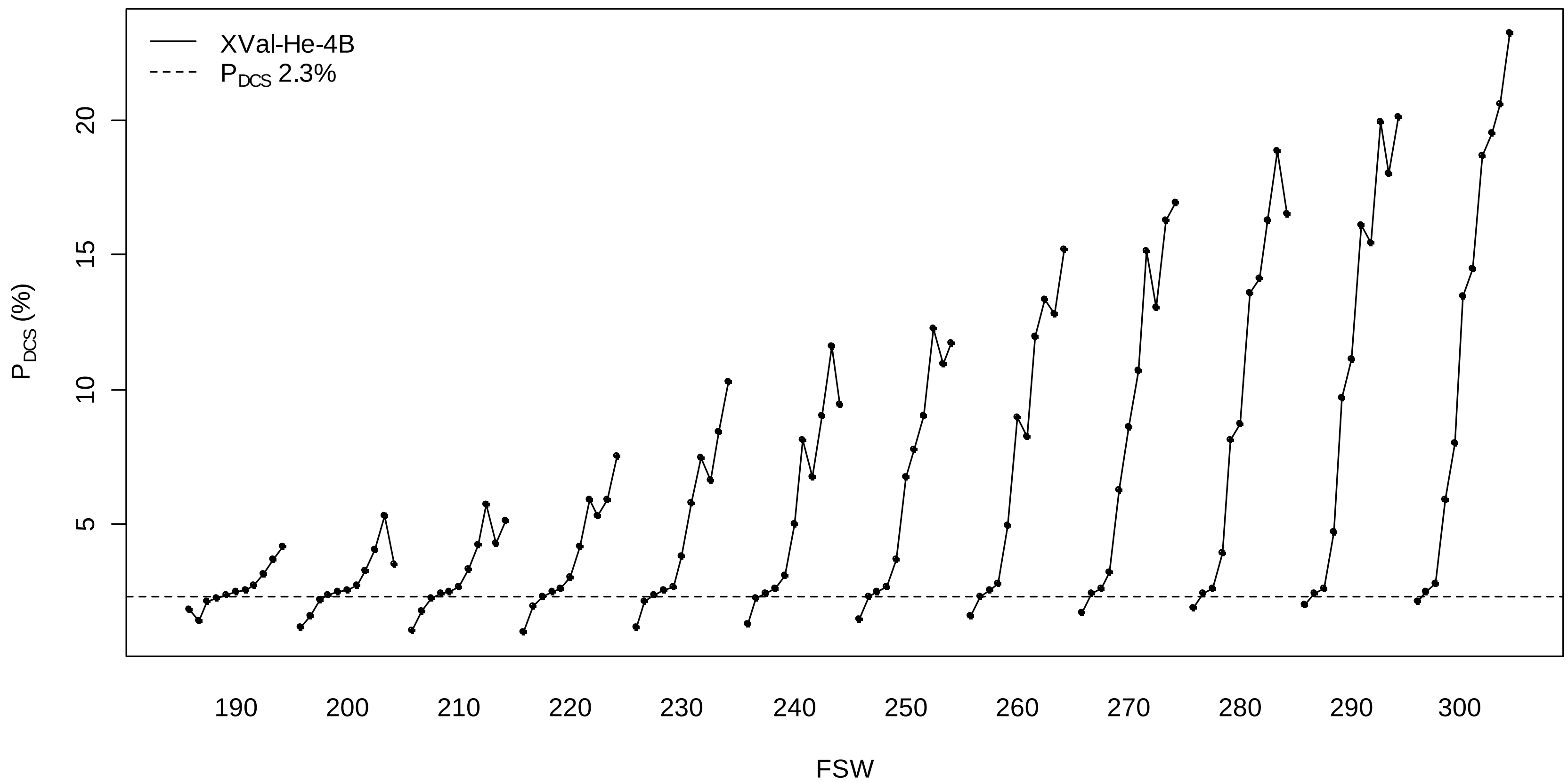

Figure 4. P_{DCS} of XVal-He-4B Thalmann Algorithm MK 16 MOD 1 He-O_2 decompression schedules for depths to 300 fsw. Points correspond to LEM–he8n25 estimated P_{DCS} of decompression schedules at the indicated dive depths with bottom times shown in 5-minute increments from 10 to 60 minutes, presented in the same manner as in Figure 2.

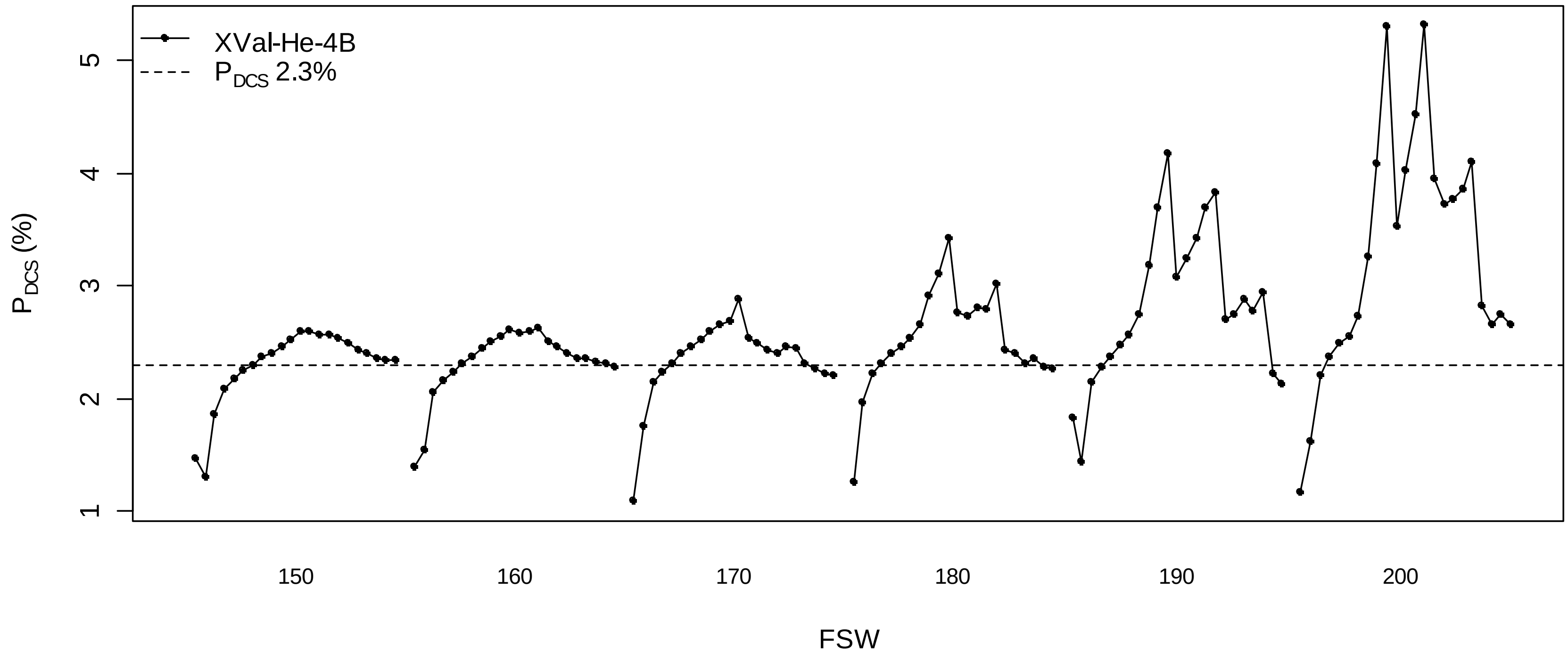

Figure 5. P_{DCS} of XVal-He-4B Thalmann Algorithm MK 16 MOD 1 He-O_2 decompression schedules for extended bottom times. Points correspond to LEM–he8n25 estimated P_{DCS} of decompression schedules at the indicated dive depths with bottom times shown in 5-minute increments up to 120 minutes, presented in the same manner as in Figure 2.

Figure 5 illustrates the estimated P_{DCS} of schedules calculated with the XVal-He-4B Thalmann Algorithm for dives with bottom times up to two hours at depths in the 150 to 200 fsw range. In the 150 to 180 fsw range, XVal-He-4B schedules and estimated risks are identical to those of XVal-He-4 (see Figure 2). At 190 and 200 fsw, XVal-He-4B schedules have mean estimated P_{DCS} 0.07% greater than XVal-He-4 schedules, but the maximum estimated P_{DCS} among the XVal-He-4B schedules is an acceptable 5.3%. Thus a real-time implementation of the XVal-He-4B Thalmann Algorithm will produce reasonable decompression guidance for dives to maximum depths of 200 fsw with bottom times up to at least 120 minutes.

Figure 3 and 5 show that the highest P_{DCS} occurs for dives to a given depth with bottom times near one hour, and that the estimated P_{DCS} returns to values near 2.3% for dives with longer bottom times. This pattern holds for schedules prescribed by either the XVal-He-4 or XVal-He-4B Thalmann Algorithm. The peak P_{DCS} values generally occur as a result of high accumulation of risk following ascent from the 40 fsw or 30 fsw decompression stops. The lower risks at longer bottom times — risks that are back in accord with the target 2.3% — result from substantial lengthening of these stops. For instance, a principal difference between the 200 fsw/55-minute schedule (P_{DCS} = 5.3%) and the 200 fsw/60-minute schedule (P_{DCS} = 3.6%) prescribed by the XVal-He-4B Thalmann Algorithm is a substantially longer 30 fsw decompression stop (see Table 1). The relatively abbreviated decompression stops in the higher risk schedules are always controlled by the 160-minute half-time compartment MPTT, indicating that a higher slope in the MPTT generating function for this compartment would be inappropriate.

DISCUSSION

The Thalmann Algorithm parameterized with XVal-He-4 produces acceptable P_{DCS}-constrained decompression schedules for dives to depths with bottom times that span the depth/time ranges for which it was developed. It also produces acceptable schedules for dives to depths in the 150 to 200 fsw range with bottom times considerably longer than previously explored.[2] This success results in part from the unconventional structure of XVal-He-4. Conventional MPTT tables have M_0-values that decrease monotonically with increasing compartment half-time and MPTT generating function slopes that may also decrease monotonically with increasing compartment half-time, but that remain of value one or greater. Represented graphically as functions of depth, conventional MPTTs for different compartments do not intersect as do the XVal-He-4 MPTTs (Figure 1). Algorithms parameterized with conventional MPTT tables or similar safe ascent criteria prescribe decompression schedules with estimated P_{DCS} values that increase with increasing depth and bottom time.[9] In contrast, the low slopes of some of the XVal-He-4 MPTT generating functions produce lower MPTTs that result in more conservative, lower P_{DCS} decompression schedules than would be obtained with MPTTs generated from functions with higher slopes. Indeed the 160-minute half-time MPTTs, which were generated with the highest slope of any controlling compartment in XVal-He-4, are marginally too permissive and result in occasional abbreviated decompression stops and associated higher risk schedules.

XVal-He 4 has five “silent” compartments (10-, 40-, 80-, 120, and 200-minute half-times) that never control decompression. These compartments result from the development technique that forced parameterization of nine compartments to describe a standard set of decompression schedules that are adequately described with fewer compartments. The unconventional pattern of M_0-values in XVal-He-4, a pattern in which the M_0-values do not decrease monotonically with increasing compartment half-time, arises largely from these silent compartments and is therefore inconsequential.

The low slopes of the XVal-He-4 MPTT generating function do cause problems if XVal-He-4 is applied at depths deeper than the range for which it was developed. At such depths, MPTT can be less than the arterial helium tension and can cause the Thalmann Algorithm to prescribe infinite-duration decompression stops. Eliminating the largely silent 5-minute half-time compartment from XVal-He-4 (and thus creating XVal-He-4B) prevents the Thalmann Algorithm from prescribing infinite-duration stops at depths from 220 to 300 fsw. Although some of the remaining XVal-He-4B compartments (10-, 200-, and 240-minute half-times) have MPTT generating functions with slopes less than one and are therefore susceptible to this same problem, none of these MPTT generating functions intersect the arterial helium tension at depths shallower than 372 fsw. This depth is well beyond the maximum operating depth of XVal-He-4B (200 fsw) or of the MK 16 MOD 1 UBA (300 fsw).

Although the XVal-He-4B 120-minute half-time compartment does not control any decompression, it is retained because it is the reference compartment for repetitive dive calculations and allows the NDP implementation of XVal-He-4B-Thalmann Algorithm to calculate repetitive groups consistent with the MK 16 MOD 1 He-O_2 decompression tables in the *U.S. Navy Diving Manual*.[1] The remaining silent compartments in XVal-He-4B could be eliminated without altering the decompression prescriptions, but they have been retained.

CONCLUSIONS AND RECOMMENDATIONS

1. The XVal-He-4 Thalmann Algorithm cannot reliably prescribe decompression schedules for dives to depths deeper than 211 fsw. It should therefore not be used in a diver-worn NDC intended to support MK 16 MOD 1 He-O_2 dives to depths up to 200 fsw, in case this depth is inadvertently exceeded. This issue is solved by removing the 5-minute compartment from XVal-He-4, producing XVal-He-4B.

2. XVal-He-4B produces decompression guidance to maximum depths of 200 fsw that is consistent with the MK 16 MOD 1 He-O_2 Decompression Tables in the *U.S. Navy Diving Manual*.

3. The XVal-He-4B Thalmann Algorithm will reliably produce decompression schedules to depths of 300 fsw, but it should not be used for planning dives to depths deeper than 200 fsw.

4. The XVal-He-4B Thalmann Algorithm will provide reasonable decompression guidance in cases of inadvertent and short-duration excursions to depths deeper than 200 fsw. Decompression schedules for dives with bottom times longer than 20 minutes at these depths have P_{DCS} that can be substantially above 3%.

5. The XVal-He-4B Thalmann Algorithm will produce DCS risk-constrained decompression guidance for dives to maximum depths of 200 fsw with bottom times of more than one hour.

6. The XVal-He-4B Thalmann Algorithm is recommended for incorporation into the NDC and NDP to support MK 16 MOD 1 He-O_2 diving operations to planned depths up to 200 fsw and with one-hour maximum time deeper than 140 fsw.

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APPENDIX A
CALCULATION OF XVAL-HE-4B

A full explanation of XVal-He-4 MPTT table development is given in NEDU TR 02-10.[2] Surfacing MPTTs for a fixed number of nine hypothetical gas exchange compartments with assumed gas exchange half-times ranging from 5 to 240 minutes, and slopes for projecting these surfacing MPTTs to depth according to the linear relationship first forwarded by Workman[6] were found by closest fit to the highest tissue tension prevailing among the compartments at the end of each decompression stop in a standard set of LEM-he8n25 2.3% P_{DCS} iso-risk decompression schedules. The number of compartments (*ntiss = 9*) and their half-times were the same as in the VVal-18 MPTT table used with the Thalmann Algorithm to compute MK 16 MOD 0 and MK 16 MOD 1 N_2-O_2 decompression tables. In NEDU TR 2-10, there is an inconsistency in notation between the description of this method and the results given in Tables 9 and 10 of that report, which is reconciled below.

In a Thalmann Algorithm MPTT table, the MPTTs for the $i = 1, 2, \ldots, ntiss$ compartments at depth D, $M_{i,D}$, are offset by one stop depth increment ($DINC$) to depth $D+DINC$, because it is at this deeper depth that the $M_{i,D}$ are used to assess when ascent to depth D will be allowed. Thus, for $DINC$ = 10 fsw, the surfacing $M_{i,0}$ (often called M_0-values, here designated $M0_i$) values appear in the 10 fsw row. For stops at depths D equal to integral multiples of $DINC$ ($D = \lambda \cdot DINC;\ \lambda = 1, 2, 3, \ldots$), the offset MPTT values are given generally by

$$M'_{i,D_\lambda} = M_{i,D_{\lambda-1}}\,, \tag{1}$$

where the offset values are designated with a prime and

$$M_{i,D_{\lambda-1}} = M0_i + a_i D_{\lambda-1}\,. \tag{2}$$

Eq. (2) is Workman's original expression for the MPTTs at depth D not offset by $DINC$ (equation 7 in NEDU TR 02-10). In comparison, the following equation of form similar to the combined Eq. (1) and Eq. (2) was fit to obtain the XVal-He-4 Thalmann Algorithm MPTT table:

$$M'_{i,D_\lambda} = \beta_{0,i} + a_i D_\lambda\,. \tag{3}$$

Noting that $D_\lambda - DINC = D_{\lambda-1}$, Eq. (3) reduces to the combined Eq. (1) and Eq. (2) with

$$\beta_{0,i} = M0_i - a_i \cdot DINC\,. \tag{4}$$

The fitted parameters for Eq. (3) are given in Table A.1 reproduced from Table 10 of NEDU TR 02-10. The label for the intercept column is changed from M_0 ($\equiv M0$) in the original to β_0 to correct a notational inconsistency that obfuscated the relationship between $M0_i$ and $\beta_{0,i}$ in Eq. (4).

The XVal-He-4B table (Appendix B) is obtained from the XVal-He-4 table simply by deleting the 5-minute half-time compartment.

Table A.1. Coefficients for the XVal-He-4 MPTT Table Generating Function

Compartment half-times* (min)	Extracted parameters	
	intercept, β_0 (fsw)	slope, *a*
5	128.5499	0.334190
10	107.6041	0.800407
20	54.63454	1.024465
40	71.36153	1.050153
80	64.31289	1.087502
120	29.25403	1.247708
160	23.79577	1.132558
200	35.12578	0.898802
240	25.58696	0.900324

* assumed and fixed

APPENDIX B
XVAL-He-4B MPTT TABLE

	Tissue Compartment Half-times							
	10	20	40	80	120	160	200	240
Depth				SDR				
(fsw)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	115.608	64.879	81.863	75.188	41.731	35.121	44.114	34.590
20	123.612	75.124	92.365	86.063	54.208	46.447	53.102	43.593
30	131.616	85.368	102.866	96.938	66.685	57.773	62.090	52.597
40	139.620	95.613	113.368	107.813	79.162	69.098	71.078	61.600
50	147.624	105.858	123.869	118.688	91.639	80.424	80.066	70.603
60	155.629	116.102	134.371	129.563	104.117	91.749	89.054	79.606
70	163.633	126.347	144.872	140.438	116.594	103.075	98.042	88.610
80	171.637	136.592	155.374	151.313	129.071	114.400	107.030	97.613
90	179.641	146.836	165.875	162.188	141.548	125.726	116.018	106.616
100	187.645	157.081	176.377	173.063	154.025	137.052	125.006	115.619
110	195.649	167.326	186.878	183.938	166.502	148.377	133.994	124.623
120	203.653	177.570	197.380	194.813	178.979	159.703	142.982	133.626
130	211.657	187.815	207.881	205.688	191.456	171.028	151.970	142.629
140	219.661	198.060	218.383	216.563	203.933	182.354	160.958	151.632
150	227.665	208.304	228.884	227.438	216.410	193.679	169.946	160.636
160	235.669	218.549	239.386	238.313	228.887	205.005	178.934	169.639
170	243.673	228.794	249.888	249.188	241.364	216.331	187.922	178.642
180	251.677	239.038	260.389	260.063	253.842	227.656	196.910	187.645
190	259.681	249.283	270.891	270.938	266.319	238.982	205.898	196.648
200	267.686	259.528	281.392	281.813	278.796	250.307	214.886	205.652
210	275.690	269.772	291.894	292.688	291.273	261.633	223.874	214.655
220	283.694	280.017	302.395	303.563	303.750	272.959	232.862	223.658
230	291.698	290.261	312.897	314.438	316.227	284.284	241.850	232.661
240	299.702	300.506	323.398	325.313	328.704	295.610	250.838	241.665
250	307.706	310.751	333.900	336.188	341.181	306.935	259.826	250.668
260	315.710	320.995	344.401	347.063	353.658	318.261	268.814	259.671
270	323.714	331.240	354.903	357.938	366.135	329.586	277.802	268.674
280	331.718	341.485	365.404	368.813	378.612	340.912	286.790	277.678
290	339.722	351.729	375.906	379.688	391.089	352.238	295.778	286.681
300	347.726	361.974	386.407	390.563	403.567	363.563	304.766	295.684

Blood Parameters
(pressure in fsw; 33 fsw/atm)

PaCO2	PH2O	PvO2	PvCO2	AMBAO2	PBOVP
1.5	0.00	2.30	2.00	0.00	0.00

APPENDIX C
XVAL-HE-4B DECOMPRESSION TABLES

BT (min)	Time to 1st Stop (m:s)	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first stop 120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
50 fsw															
325	1:40											0	1:40	K	2.138
330	1:00											1	2:40	K	2.130
360	1:00											5	6:40	K	2.135
60 fsw															
134	2:00											0	2:00	L	2.013
140	1:20											3	5:00	L	2.032
150	1:20											8	10:00	L	2.055
160	1:20											12	14:00	L	2.098
170	1:20											16	18:00	L	2.132
180	1:20											20	22:00		2.156
190	1:20											24	26:00		2.171
200	1:20											27	29:00		2.211
210	1:20											31	33:00		2.211
220	1:20											34	36:00		2.236
230	1:20											37	39:00		2.255
240	1:20											40	42:00		2.267
270	1:20											47	49:00		2.338
300	1:20											53	55:00		2.400
330	1:20											59	61:00		2.424
360	1:20											66	68:00		2.382
70 fsw															
86	2:20											0	2:20	M	1.937
90	1:40											3	5:20	M	1.974
95	1:40											8	10:20		1.974
100	1:40											12	14:20		2.000
110	1:40											19	21:20		2.067
120	1:40											26	28:20		2.114
130	1:40											33	35:20		2.142
140	1:40											39	41:20		2.186
150	1:40											45	47:20		2.215
160	1:40											50	52:20		2.263
170	1:40											55	57:20		2.297
180	1:40											60	62:20		2.320
190	1:40											64	66:20		2.366
200	1:40											68	70:20		2.401
210	1:40											72	74:20		2.427
220	1:40											76	78:20		2.443
80 fsw															
63	2:40											0	2:40	M	2.245
65	2:00											2	4:40	M	1.900
70	2:00											8	10:40		1.938

BT (min)	Time to 1st Stop (m:s)	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first stop											Total Ascent Time (m:s)	RG	P_{DCS}*
		120	110	100	90	80	70	60	50	40	30	20			
75	2:00											14	16:40		1.965
80	2:00											19	21:40		2.014
85	2:00											24	26:40		2.055
90	2:00											29	31:40		2.087
95	2:00											34	36:40		2.111
100	2:00											39	41:40		2.128
110	2:00											48	50:40		2.175
120	2:00											56	58:40		2.228
130	2:00											63	65:40		2.293
140	2:00											70	72:40		2.337
150	2:00											76	78:40		2.397
160	2:00											82	84:40		2.440
170	2:00											88	90:40		2.468
180	2:00											93	95:40		2.516
190	2:00											98	100:40		2.551
90 fsw															
44	3:00											0	3:00	K	2.372
45	2:20											1	4:00	K	2.060
50	2:20											2	5:00	L	2.109
55	2:20											7	10:00	M	1.919
60	2:20											15	18:00		1.948
65	2:20											22	25:00		1.994
70	2:20											29	32:00		2.027
75	2:20											35	38:00		2.079
80	2:20											41	44:00		2.121
85	2:20											47	50:00		2.152
90	2:20											53	56:00		2.173
95	2:20											58	61:00		2.218
100	2:20											63	66:00		2.254
110	2:20											73	76:00		2.303
120	2:20											82	85:00		2.355
130	2:20											90	93:00		2.416
140	2:20											97	100:00		2.489
150	2:20											105	108:00		2.506
160	2:20											112	115:00		2.548
100 fsw															
31	3:20											0	3:20	J	2.210
35	2:40											2	5:20	K	1.872
40	2:40											4	7:20	L	1.784
45	2:40											6	9:20	M	1.897
50	2:40											16	19:20		1.928
55	2:40											24	27:20		2.003
60	2:40											33	36:20		2.029
65	2:40											41	44:20		2.069
70	2:40											48	51:20		2.126

DECOMPRESSION STOPS (FSW)
Stop times (min) include travel time, except first stop

BT (min)	Time to 1st Stop (m:s)	120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
75	2:40											55	58:20		2.174
80	2:40											62	65:20		2.199
85	2:40											68	71:20		2.255
90	2:40											74	77:20		2.290
95	2:40											80	83:20		2.319
100	2:40											85	88:20		2.372
110	2:40											96	99:20		2.416
120	2:40											105	108:20		2.497
130	2:20										1	114	118:00		2.537
140	2:20										1	124	128:00		2.553
110 fsw															
24	3:40											0	3:40	I	2.091
25	3:00											1	4:40	I	1.820
30	3:00											4	7:40	J	1.546
35	3:00											7	10:40	L	1.584
40	3:00											10	13:40	M	1.911
45	3:00											21	24:40		1.963
50	3:00											31	34:40		2.042
55	3:00											40	43:40		2.117
60	2:40										1	49	53:20		2.134
65	2:40										2	57	62:20		2.160
70	2:40										3	64	70:20		2.210
75	2:40										4	71	78:20		2.248
80	2:40										5	77	85:20		2.305
85	2:40										5	84	92:20		2.338
90	2:40										6	89	98:20		2.402
95	2:40										6	95	104:20		2.445
100	2:40										6	101	110:20		2.476
110	2:40										7	112	122:20		2.526
120	2:40										7	123	133:20		2.587
130	2:40										7	136	146:20		2.565
140	2:20									1	7	149	160:00		2.512
120 fsw															
20	4:00											0	4:00	I	2.106
25	3:20											4	8:00	J	1.571
30	3:20											8	12:00	K	1.519
35	3:20											12	16:00	M	1.892
40	3:20											23	27:00		2.030
45	3:00										2	34	39:40		2.048
50	3:00										4	43	50:40		2.104
55	3:00										6	52	61:40		2.156
60	3:00										7	60	70:40		2.238
65	2:40									2	7	68	80:20		2.267
70	2:40									3	7	76	89:20		2.310
75	2:40									3	8	83	97:20		2.362

BT	Time to 1st Stop	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first stop											Total Ascent Time		
(min)	(m:s)	120	110	100	90	80	70	60	50	40	30	20	(m:s)	RG	P_{DCS}*
80	2:40									4	7	91	105:20		2.397
85	2:40									5	7	97	112:20		2.461
90	2:40									5	8	103	119:20		2.500
95	2:40									6	7	110	126:20		2.531
100	2:40									6	7	117	133:20		2.550
110	2:40									7	7	131	148:20		2.555
120	2:40									7	7	145	162:20		2.565
130 fsw															
17	4:20											0	4:20	H	2.067
20	3:40											3	7:20	I	1.622
25	3:40											8	12:20	K	1.362
30	3:40											13	17:20	L	1.791
35	3:20										2	21	27:00	L	2.025
40	3:20										5	32	41:00	L	2.083
45	3:00									1	7	43	54:40	L	2.136
50	3:00									3	7	53	66:40		2.192
55	3:00									5	7	63	78:40		2.239
60	3:00									6	8	71	88:40		2.322
65	2:40								1	7	7	81	99:20		2.342
70	2:40								2	7	7	89	108:20		2.397
75	2:40								3	7	7	97	117:20		2.439
80	2:40								3	8	7	104	125:20		2.492
85	2:40								4	8	7	111	133:20		2.543
90	2:40								5	7	7	119	141:20		2.571
95	2:40								5	8	7	127	150:20		2.567
100	2:40								6	7	7	136	159:20		2.552
110	2:40								6	8	7	152	176:20		2.537
120	2:40								7	7	18	159	194:20		2.480
140 fsw															
15	4:40											0	4:40	H	2.124
20	4:00											7	11:40	J	1.101
25	4:00											12	16:40	K	1.612
30	3:40										3	16	23:20	M	2.011
35	3:40										7	29	40:20		2.095
40	3:20									3	7	42	56:00		2.138
45	3:20									6	7	53	70:00		2.217
50	3:00								1	8	7	64	83:40		2.275
55	3:00								3	8	7	74	95:40		2.330
60	3:00								5	8	7	84	107:40		2.373
65	3:00								7	7	7	93	117:40		2.448
70	2:40							1	7	8	7	101	127:20		2.501
75	2:40							2	7	8	7	110	137:20		2.519
80	2:40							3	7	8	7	118	146:20		2.572
85	2:40							4	7	7	8	127	156:20		2.578
90	2:40							4	8	7	7	137	166:20		2.572

BT (min)	Time to 1st Stop (m:s)	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first stop 120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
95	2:40							5	7	7	8	146	176:20		2.557
100	2:40							5	8	7	8	155	186:20		2.545
110	2:40							6	7	8	23	160	207:20		2.461
120	2:40							6	8	7	37	165	226:20		2.397

150 fsw

BT (min)	Time to 1st Stop (m:s)	120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
13	5:00											0	5:00	H	1.975
15	4:20											3	8:00	H	1.474
20	4:20											10	15:00	J	1.309
25	4:00										2	14	20:40	L	1.866
30	4:00										7	24	35:40	L	2.088
35	3:40									4	8	37	53:20	L	2.176
40	3:20								1	7	8	50	70:00		2.248
45	3:20								4	8	7	63	86:00		2.294
50	3:20								7	7	8	74	100:00		2.371
55	3:00							2	8	7	7	86	113:40		2.404
60	3:00							4	8	7	7	96	125:40		2.459
65	3:00							6	7	7	8	105	136:40		2.518
70	3:00							7	7	8	7	114	146:40		2.591
75	2:40						1	8	7	7	8	124	158:20		2.594
80	2:40						2	8	7	7	8	135	170:20		2.569
85	2:40						3	7	8	7	7	146	181:20		2.565
90	2:40						4	7	7	8	9	155	193:20		2.533
95	2:40						4	8	7	7	17	159	205:20		2.488
100	2:40						5	7	7	8	25	162	217:20		2.427

160 fsw

BT (min)	Time to 1st Stop (m:s)	120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
12	5:20											0	5:20	H	2.171
15	4:40											5	10:20	I	1.390
20	4:40											13	18:20	K	1.547
25	4:20										6	16	27:00	M	2.050
30	4:00									4	8	31	47:40		2.166
35	3:40								2	7	8	46	67:20		2.239
40	3:40								6	8	7	60	85:20		2.318
45	3:20							3	7	7	8	73	102:00		2.373
50	3:20							6	7	7	8	85	117:00		2.444
55	3:00						1	7	8	7	7	97	130:40		2.504
60	3:00						3	7	8	7	8	107	143:40		2.547
65	3:00						5	7	8	7	7	118	155:40		2.609
70	3:00						6	8	7	7	8	130	169:40		2.580
75	3:00						8	7	7	8	7	142	182:40		2.596
80	2:40					2	7	7	8	7	7	154	195:20		2.627
85	2:40					2	8	7	8	7	16	158	209:20		2.504
90	2:40					3	8	7	7	8	25	161	222:20		2.457
95	2:40					4	7	8	7	7	35	164	235:20		2.398
100	2:40					4	8	7	7	8	43	167	247:20		2.356

170 fsw

BT	Time to 1st Stop	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first stop											Total Ascent Time		
(min)	(m:s)	120	110	100	90	80	70	60	50	40	30	20	(m:s)	RG	P_{DCS}*
11	5:40											0	5:40	H	2.262
15	5:00											8	13:40	I	1.090
20	4:40										2	15	22:20	K	1.751
25	4:20									2	8	22	37:00	L	2.153
30	4:00								2	7	7	39	59:40	L	2.240
35	4:00								7	7	8	55	81:40		2.309
40	3:40							4	8	7	7	70	100:20		2.402
45	3:20						1	7	8	7	7	84	118:00		2.460
50	3:20						4	7	8	7	8	96	134:00		2.520
55	3:20						7	7	7	8	7	108	148:00		2.599
60	3:00					2	7	8	7	7	8	120	162:40		2.654
65	3:00					4	7	8	7	7	8	134	178:40		2.694
70	3:00					5	8	7	8	7	7	148	193:40		2.876
75	3:00					7	7	8	7	7	12	157	208:40		2.542
80	2:40				1	7	8	7	7	8	22	160	223:20		2.497
85	2:40				2	7	8	7	7	8	32	164	238:20		2.437
90	2:40				3	7	7	8	7	8	42	167	252:20		2.395
95	2:40				3	8	7	7	8	7	52	169	264:20		2.462
100	2:40				4	7	8	7	7	8	61	171	276:20		2.441
180 fsw															
10	6:00											0	6:00	H	2.247
15	5:20											11	17:00	J	1.256
20	5:00										6	14	25:40	L	1.966
25	4:40									6	8	29	48:20	L	2.216
30	4:20								6	7	8	47	73:00		2.307
35	4:00							4	8	7	8	64	95:40		2.394
40	3:40						2	8	7	7	8	80	116:20		2.459
45	3:40						6	8	7	7	8	94	134:20		2.540
50	3:20					3	7	7	8	7	7	108	151:00		2.661
55	3:20					5	8	7	8	7	7	121	167:00		2.911
60	3:00				1	7	8	7	7	8	7	136	184:40		3.112
65	3:00				3	7	8	7	7	8	7	151	201:40		3.416
70	3:00				5	7	7	8	7	7	16	158	218:40		2.755
75	3:00				6	7	8	7	8	7	27	162	235:40		2.725
80	3:00				7	8	7	7	8	7	38	166	251:40		2.806
85	2:40			1	8	7	7	8	7	8	48	169	266:20		2.785
90	2:40			2	8	7	7	8	7	7	60	171	280:20		3.021
95	2:40			3	7	8	7	7	8	11	66	174	294:20		2.438
100	2:40			4	7	7	8	7	7	22	65	178	308:20		2.394
190 fsw															
9	6:20											0	6:20	H	2.127
10	5:40											2	8:20	H	1.835
15	5:40											14	20:20	J	1.444
20	5:00									2	7	16	30:40	M	2.153
25	4:40								3	8	7	36	59:20		2.287

DECOMPRESSION STOPS (FSW)

Stop times (min) include travel time, except first stop

BT (min)	Time to 1st Stop (m:s)	120	110	100	90	80	70	60	50	40	30	20	Total Ascent Time (m:s)	RG	P_{DCS}*
30	4:20							3	8	7	7	56	86:00		2.376
35	4:00						2	8	7	7	8	73	109:40		2.475
40	4:00						7	8	7	7	8	89	130:40		2.572
45	3:40					4	8	7	8	7	7	105	150:20		2.752
50	3:20				1	7	8	7	8	7	7	119	168:00		3.179
55	3:20				4	8	7	7	8	7	7	137	189:00		3.694
60	3:20				7	7	8	7	7	8	7	153	208:00		4.170
65	3:00			2	7	8	7	7	8	7	19	159	227:40		3.075
70	3:00			4	7	8	7	7	8	7	31	164	246:40		3.238
75	3:00			5	8	7	7	8	7	8	43	167	263:40		3.428
80	3:00			7	7	7	8	7	8	7	55	170	279:40		3.695
85	2:40		1	7	7	8	7	8	7	8	65	173	294:20		3.827
90	2:40		2	7	7	8	7	8	7	19	66	177	311:20		2.702
95	2:40		2	8	7	8	7	7	8	30	65	181	326:20		2.742
100	2:40		3	7	8	7	8	7	7	41	65	184	340:20		2.888
200 fsw															
8	6:40											0	6:40	G	1.891
10	6:00											5	11:40	H	1.172
15	5:40										2	15	23:20	K	1.616
20	5:20									5	8	22	41:00	L	2.209
25	5:00								7	7	8	43	70:40	L	2.366
30	4:40							8	7	7	8	63	98:20		2.485
35	4:20						7	7	8	7	7	83	124:00		2.553
40	4:00					5	8	7	7	8	7	100	146:40		2.728
45	3:40				3	7	7	8	7	8	7	115	166:20		3.264
50	3:40				7	7	7	8	7	7	8	134	189:20		4.083
55	3:20			3	7	8	7	7	8	7	7	153	211:00		5.294
60	3:20			6	7	7	8	7	8	7	20	160	234:00		3.527
65	3:00		1	7	8	7	7	8	7	8	33	164	253:40		4.028
70	3:00		3	7	8	7	7	8	7	8	46	169	273:40		4.515
75	3:00		5	7	7	8	7	7	8	7	59	172	290:40		5.307
80	3:00		6	7	8	7	7	8	7	14	65	175	307:40		3.950
85	3:00		7	8	7	7	8	7	7	26	66	179	325:40		3.724
90	2:40	1	8	7	7	8	7	7	8	37	66	183	342:20		3.765
95	2:40	2	7	8	7	7	8	7	8	48	69	183	357:20		3.855
100	2:40	3	7	7	8	7	8	7	7	61	71	184	373:20		4.105

*P_{DCS} estimated with LEM-he8n25

Other DCS Parameters

sPBOVP=	0	BTMAX=	60	TATMAX=	720	STIME=	0.2
O2TIME=	30	AIRTIME=	5	O2TIME_FO2=	0.70	CNDSDR_FO2=	0.00
FFP=	F	FORCE_STOP=	F	O2CEIL=	30	GSWLAT=	0
GS_DEAD=	T	AB_DEAD=	T	OMIT_TRVL=	T	TTIS=	T
RNTMODE=	0	RGD_SPPRSS=	1	SRF_CNTRLT_MODE=	1	RE_MODE=	2
RNDUPD=	T	LST_DOMode=	1	PVSATerr=	F	FRSTOPerr=	F