THE “NOBENDEM” AIR/NITROX DECOMPRESSION PROFILE CALCULATOR

A physiologic model extension based on the US Navy Standard Air Decompression Tables

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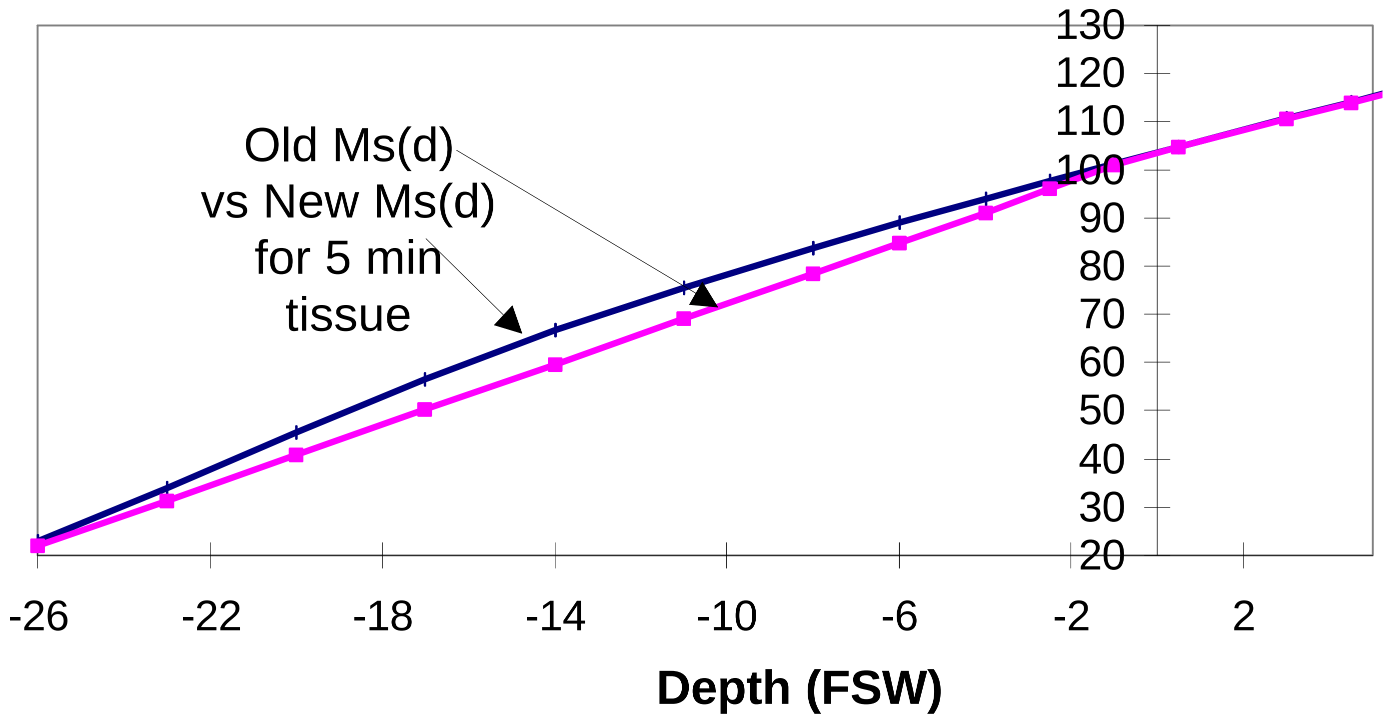
Revision Chronology - Update 5

01 October 1998

Prior to presenting the Nobendem Methodology to the US Navy Operational Medical Institute (NOMI) in October of 1998, I wanted to ensure that I had appropriately accounted for two effects which may occur simultaneously during ascent. Nobendem cleverly weights the differential nitrogen partial pressure during depth changes by an amount which is dependent on the relative sizes of the tissue compartment half time and the duration of the ascent or descent. I needed to ensure that I only applied this correction factor to the portion of the nitrogen driving function that was due to the depth change, and NOT to the portion which may have resulted from a change in breathing gas at the start of the transition. After scratching my head for a few hours, and re-deriving several formulas, I determined to my satisfaction that I had correctly implemented the equations to account for the factors mentioned above. During this time I noted that I had inadvertently plotted the graph for **Update 3** using the parameters for the 640 minute tissue group instead of the 5 minute tissue group as labeled. The graph has been replotted for the 5 minute tissue model in this update.

In actuality, this has become a moot point, because as of this release, I have gone back to my original thoughts for diving at altitude putting the knee at -16 FSW (17400 feet altitude) and choosing an action exponent of 3.5. I made these changes because I found using a safety enhancement of 20, plus the additional conservatism of **Update 3's** early slope change, was producing some extremely long decompressions for diving at altitude. I strongly wanted to keep the safety enhancement consistent between sea level diving and diving at altitude, and so chose to return to my original thoughts on how the supersaturation curves should behave as atmospheric pressure decreases. A smooth transition between slopes seems much more likely as there is no reason to suspect that an abrupt model change at 760 torr is likely. Furthermore, **Update 3's** model with no safety enhancement predicts a low likelihood of decompression sickness prior to 14800 ft, while this update predicts 16500 ft - much closer to the accepted value of 18000.



Update 5 - Continued:

I have attempted to revise all of the examples and the relevant Nobendem Quizzes to reflect the new altitude model - however may have missed a point here or there. If you find a residual glitch, please let me know. Some of the more illustrative problems have been reworked to reflect a Nobendem Safety Enhancement (SE) of 20. Those using lower SE's should be clearly marked.

In addition, I have edited the Reset_Long_Dive macro to position the cursor back at the beginning of the long 2-sheet dive once the spreadsheet has been reset. This just makes it a little more convenient to use.

Revision Chronology - Update 4

30 August 1998

A relatively minor addition to the Nobendem spreadsheet: I added two linked sheets named "Long Part A", and "Long Part B". I ran across an instance where I needed to calculate a decompression profile that was longer than 6 segments! I added two sheets after the multi-dive sheets and linked them together so that sheet B is a continuation of the dive on sheet A. This lets me enter a total of 12 segments for a single exposure. The model used is exactly the same as before, and there are no other additions. I have not provided this longer profile with subsequent links to a repet dive since the longer dive is likely to be all you'd want on a given day.

Just as an aside - - the residual nitrogen index provides a fairly interesting point of comparison between two different dive profiles having the same safety enhancement factor. The more conservative dive of the two should be the one with the lowest residual nitrogen index at the end of the dive. It might be interesting at some time in the future to examine DCS risk in terms of the residual nitrogen index, or perhaps some combination of the residual nitrogen index with the safety enhancement factor.

Preface to 3rd Update

30 June 1998

So the proof of the pudding is - would you dive this thing?? Gee! I had to think about that! Being somewhat the chicken when it comes to DCS (having been bit once in an earlier life) gave me pause! I began to think about the various safety factors that have crawled into the US Navy tables over the years, and decided to examine the expected risks of DCS versus what I would routinely accept. The Nobendem calculator was designed to match the Navy tables for ocean diving at the various node points - that is - an integer multiple of 10 feet for an integer multiple of tens of minutes. This works well for precise, square dives, but what if I want to dive at 75 FSW for 43 minutes, then go to 83 FSW for 15 minutes, then surface? Applying the Navy Rules, one would enter the first segment as 80 FSW for 50 minutes, go to 90 FSW for 20 minutes, and then calculate your ascent (use a descent rate of 60 fpm).

The various Nobendem calculations are tabulated below:

		Comparison: Nobendem Safety Models						
	Depth	Time	Depth	Time	Ascent	Deco 20	Deco 10	Tot Deco
Straight Nobendem	75	43	83	15	2.7		15	17.7
Navy Rules	80	50	90	20	2.7	2	26	30.7
Nobendem w/ Safety = 20	75	43	83	15	2.7	3	31	36.7

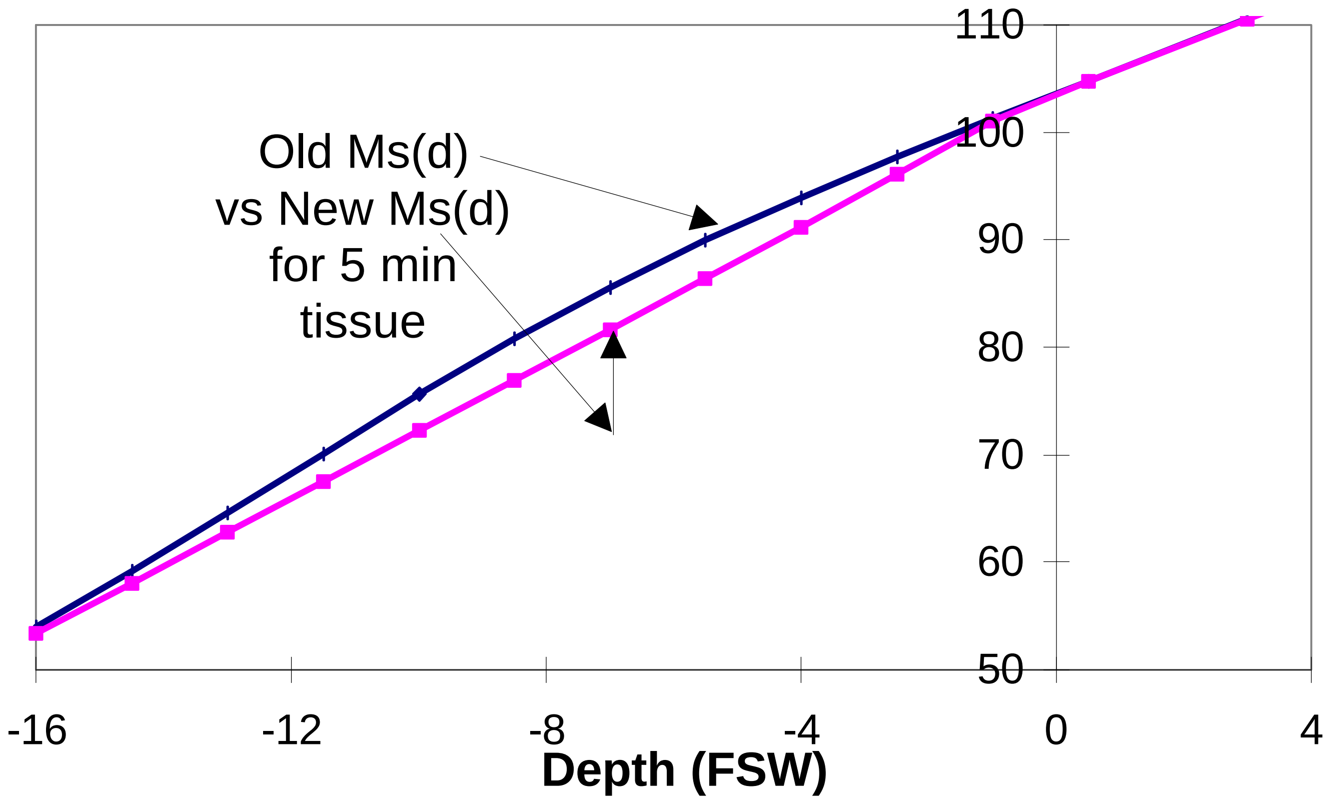
Since the straight Nobendem calculation is targeted to reproduce the Navy tables, one might assume that the DCS risks would be similar for the straight calculations - namely 2% for no-deco dives, 5% for deco dives, and up to 7.5% for repet deco dives. That's a bit high for the "sport" in me - so I'd definitely want some sort of a hedge! Adding a safety factor of 20 allows us to approximate the results expected after modifications typically applied to the US Navy table. In addition, whatever the decrease in DCS risk might be, it would be applied uniformly to any other profiles run through the calculator. Using a safety enhancement of 20 predicts a no-deco time of 43 minutes at 60 FSW. Sounds pretty conservative to me, but that's the way I'd like it! The "RESET" Macro has been modified to insert a default safety enhancement of 20. Sure - - you can increase or decrease it to suit your risk-taking nature, but I'm a 20, and maybe more!

In examining the standard treatment table profiles for an inside chamber tender (inside observer - or IO) on a TT-5 or a TT-6, Nobendem predicts the TT-5 is a no-deco air table with a safety enhancement of 29, and the TT-6 is a no-deco with a safety enhancement of 16. Back in 1964, Bruce Bassett knew dry diving was riskier than wet, and so developed the USAF modifications to the Navy Deco tables for use with chamber IO's. Using the recommended oxygen breathing intervals, the TT-5 has a safety enhancement of 59, and the TT-6 is a 52. I have come to recommend using a minimum IO safety enhancement of 55 for all dry divers and IOs. For those older than 39, or any with a history of an undeserved DCS hit, I use a safety enhancement of 65. To set this up on a TT-6, I always have my IO breathe O_2 for 20 minutes during the 3rd patient oxygen period at 60 FSW, and again during the 30 minute ascent to 30 FSW if there were any extensions at 60 FSW. This leaves us in great shape should any extensions be needed at 30 FSW.

As an end note - Nobendem seems to predict reasonably well the Sur-D O_2 tables when you consider the surface recompression a repet dive to 40 FSW with a 5 minute surface interval. I have not investigated this in great depth however, so apply with caution!

Revision Chronology - Update 3

May 98: This release represents an update to the earlier May 1998 version. Inaccuracies regarding the Cross Correction methodology were corrected. An error in the Buhlmann comparison was corrected. The major design change implemented in this revision shifts the point at which the permissible nitrogen critical supersaturation values change slope so as to become zero when the atmospheric pressure does. The earlier models had used -9 FSW altitude equivalent (or 8500 ft) for the knee and an exponent of 9 which blended the slope change in over a range of about +/- 12 FSW. The new methodology uses a knee of -1.5 FSW (or 1400 ft) and an exponent of 50, moving the implementation point much closer to sea level and incorporating the full slope change over a period of +/- 2.5 FSW. The overall effect is to make the spreadsheet calculator a bit more conservative when diving at altitude, and more closely match the predictions of Cross. Although the old methodology closely matched the standard prediction of no risk of altitude DCS until 18000 feet (model predicted 17500), this new method predicts a no-deco ascent from sea level to only 15000 feet. The surface interval recommended for flying after diving now matches the PADI recommendations of a "D" repet group without needing a safety enhancement value of 10. As a final comparison, the no-deco time for a 60 foot dive at an altitude of 8000 feet changes from 42 min to about 37 minutes.



Revision Chronology - Update 2

May 98

This release represents an update to the April 1998 version. Several numerical transcription errors have been corrected. The major calculator modification involves only the manner in which the “Safety Enhancement” is applied to the model, and does not affect any other modeling concepts or parameter changes. Although the earlier mechanism of adding a decompression buffer that was loosely interpretable as “safety feet of seawater” was conceptually comfortable at depth, the mechanism was potentially flawed when diving at high altitudes, as it was possible to extrapolate to pressures less than 0 Torr for safety enhancement values greater than 80. This paper has been re-written to incorporate the new Safety Enhancement methodology. Divers should also remember the following caution: following the straight Nobendem calculator predictions with a safety enhancement value of zero (0) can be expected to produce diving profiles with a risk similar to that which underlies the Standard Navy Air Decompression Tables (2% for No-Deco, 5% for Deco, and up to 7% for Repet-Deco dives). This means that if you dive 100 profiles which incur a decompression obligation using a zero safety enhancement, you might expect to experience 5 cases of DCS!! Although not yet formalized, I have found the safety factor consistent with the current TT6 for an Inside Observer (IO) using recommended amounts of oxygen is a little more than 50. For longer, more stressful tables, IO safety factors of 60 or more may be beneficial. Such high safety factors produce prohibitively long decompression recommendations when applied to air diving, however. Taken to the extreme, using a safety enhancement of 100 would produce an infinitely long decompression schedule, since you would never be able to ascend without violating the imposed 1:1 maximum supersaturation ratio (see discussion in the text). As a suggestion, divers might choose to calibrate the Nobendem calculator for their own use by taking a known dive profile that they are very comfortable with and entering it into Nobendem. By increasing the safety enhancement value as high as possible without producing any red (negative) buffer values in the final transition section before reaching the surface, you will determine a safety enhancement value which, when applied to other profile calculations, should produce recommendations of comparable risk. Remember that Nobendem does not attempt to adjust for age, physical conditioning, hydration, water temperature, gender, phases of the moon, or other cosmic phenomenon. A diving profile which has been used successfully for years, may well bend the heck out of you for no good reason one day in the future! If you use the Nobendem recommendations you do so with the knowledge that the sport of diving has its own, inherent risks, and that you, not I, assume those risks. If you are uncomfortable with that, I can only suggest you confine all your diving activities to the bathtub!

ABSTRACT

For decades, reliable tables have been available to help divers develop reasonably safe profiles based on time and depth. The Standard US Navy Air Decompression Tables are a well known resource frequently used to produce a relatively safe day of diving, and include a method for performing several dives in one day (repetitive dives, or "repets"). There are several areas not addressed by the Navy tables which are included in my Nobendem model, and are explained in the text. These enhancements include coverage of 'repet" dives and varying surface intervals, no restriction to "deepest dive first", accounting for ascent and descent time, permitting the use of any mix of Nitrogen and Oxygen (Nitrox), an adjustable safety factor modification, compensation for diving at altitude, where the surface of the water may be at mountain level altitudes up to 20,000 feet, and flying after diving. As with all diving, the calculation of dive tables and excursion profiles is not an exact science. Although the calculator presented is based on solid principles, it is a new entry in a well established field, and has NOT been experimentally validated. The responsibility for balancing depth, bottom time, breathing gas mix, and decompression time always rests with the diver!

As a Clinical Hyperbaric Medicine Fellow working at the Jefferson Davis Hyperbaric Medicine Laboratory in San Antonio, Texas, I was frequently confronted by the problem of verifying safe denitrogenation profiles for our Inside Observers (IO's) tending the needs of patients undergoing modified or extended hyperbaric treatment protocols. Traditionally, this has been done by using 100% O_2 at depth to "stop" the dive and begin denitrogenation while still under pressure. Since there were no existing methods to calculate residual nitrogen times for environments other than air, the IO was saddled with the repet group for a 130 minute air dive at 45 Feet of Sea Water (FSW) following a standard wound-care dive, discounting the O_2 breathing and prolonged ascent/descent times (often 15 min each). In addition, IO oxygen dosing was often added to a Treatment Table (TT) 5 or 6 at the discretion of the diving medical officer or hyperbaricist monitoring the dive, particularly when extensions were required. A standard method to determine when and how to apply supplemental oxygen to produce equivalently "safe" profiles was needed.

The process began in September 1997 when, as a part of my fellowship program, I was sent to the Virginia Institute of Marine Science (VIMS) to study under Dr. Morgan Wells, and his colleague, Dick Rutkowski. The concepts of Haldane's tissue compartment model, and later refinements to the critical supersaturation parameters were introduced. Essentially, the body is modeled as several, independent compartments, each of which absorbs and releases nitrogen based on the external environmental absolute pressure and the fraction of nitrogen in the inspired gas mix (0.79 for air). If one considers any single compartment as a differential system in which the rate of absorption/release of a gas depends on the difference between the amount of the material currently in solution, and the amount that will be in solution at final equilibrium, you produce the standard exponential equation to describe your system as follows:

$$N(t) = N_0 + (N_f - N_0)*(1 - e^{-.693*t/k})$$

where N_0 and N_f are the initial and final steady state values of nitrogen stored in the tissue compartment, respectively, "e" is the base of the natural logarithms (approximately 2.718), and "k" is the tissue compartment specific "half time" during which one half of the remaining concentration change will occur. You may recognize the constant exponent coefficient of -.693 as the natural log of ½ , factored out simply to make the value of "k" more intuitive, scaling exactly to that of a half-time. Thus, the exponential could be expressed:

$$N(t) = N_0 + (N_f - N_0)*(1 - (1/2)^{t/k})$$

It is now very easy to see that as time progresses in multiples of the half-life value “k”, the above expression progresses from N_0 at time t=0, to N_f at time t=infinite, making up half the difference for every multiple of “k” that passes. The world of math and calculus long ago settled on using logarithms based on the number “e” (for the simple reason that the slope of the curve $y=e^x$ is the value of y for any point along the curve). Scientists and engineers preferred using logarithms based on a factor of 10 because they mapped nicely to our counting system of 1, 10, 100, 1000. Tables were laboriously generated permitting the evaluation of various exponents of “e” and 10 (or natural and Naperian), and since formulas existed to convert any other base to these tables, there was no reason to generate tables for a base of ½! The advent of scientific calculators and portable personal computers has greatly enhanced our ability to manipulate these formulas over just the past 25 years. In seconds, using today’s computerized spreadsheets, we can calculate formulas that would previously have taken months of laborious, error-prone, hand calculation!

Almost a century ago J.S. Haldane was commissioned by the British Navy to establish a method to permit divers to work under the sea and return to the surface without suffering the decompression disease described by French physiologist Paul Bert in 1878. Haldane postulated that the body could be modeled by five, independent tissue compartments, each having different half-times. At the surface of the water we are in equilibrium with the nitrogen in air under a partial pressure calculated using Dalton’s Law (Total Pressure = the sum of the constituent partial pressures). As the total pressure at sea level is nominally 760 Torr (mmHg) and the nitrogen fraction is 0.79, the nitrogen partial pressure at sea level is 0.79*760 = 600 Torr. By descending to 33 FSW, we double the total pressure to 1520 Torr, which increases the partial pressure of nitrogen in air to 1200. Henry’s Law states that the amount of gas that will dissolve in a fluid is directly proportional to the partial pressure of the gas over the fluid. Thus, the amount of nitrogen that can exist in our tissues at 33 FSW breathing air is twice that which can exist at sea level. Fortunately, we do not reach that new equilibrium instantly, rather the tissue compartments absorb (and release) nitrogen as determined by their specific half-times. Haldane developed his model using five tissue compartments with half-times of 5, 10, 20, 40, and 75 minutes. His supposition was that the body would be completely saturated (reach equilibrium) after 6 hours, and the 75 minute tissue (8 half-times) met this requirement.

There was just one more piece to the puzzle. In 1670, Sir Robert Boyle observed bubble formation in the eye of a snake exposed to rapid decompression in a vacuum chamber. Paul Bert later linked this nitrogen bubble formation to the development of decompression sickness. What wasn’t known was how much excess nitrogen could exist in tissues (supersaturation) before bubbles would form. Experimenting with goats, Haldane arrived at a value of two-to-one, the critical supersaturation ratio above which bubbles should be expected. This meant that any time the amount of nitrogen dissolved in a tissue compartment exceeded twice that which would exist under steady-state conditions, bubble formation should be expected. He applied this threshold to each tissue compartment in deriving his decompression tables, and how long each stop should be at 10 foot increments along the ascent. In 1908, Haldane published his first set of air decompression tables, which were widely adopted. The multi-compartment, supersaturation model he developed is still used, with modification, by most of today’s commonly accepted diving tables.

Divers soon found that the Haldanian tables overestimated the amount of decompression needed for low nitrogen loading dives, and underestimated that required for high nitrogen loading dives. Later developments resulted in the assignment of tissue compartment specific supersaturation ratios, and a realignment of tissue compartment nitrogen half-times. The current US Navy tables were derived using compartment half-times of 5, 10, 20, 40, 80, and 120 minutes. The nitrogen excess remaining in the 120 minute compartment upon completion of a dive was used as a single-point indicator to reduce the permissible bottom times of subsequent dives so that the standard Navy tables could be reapplied to repetitive dives (within 12 hours of a previous dive). I have chosen a 10-tissue model, extending the Navys’ model through the addition of 160, 320, 480, and 640 minute compartments. I have then duplicated the RNT mechanism for tissue compartments of 120 minutes or less, and for compartments of greater half-time, I recalculate each compartments' residual nitrogen load applying a 4/3 conservatism factor (explained later) through any surface interval, and apply them (or the RNT load, whichever is greater) as the starting value at the beginning of the next dive.

Crucial to the implementation of a computerized solution was the development of a model to predict the critical nitrogen supersaturation values versus depth for each tissue compartment. Work has been done by Dr. Wells and others to expand the values underlying the standard US Navy tables. As the US Navy tables have been used and adjusted for years based on actual diving experience, they form the most common basis on which to form subsequent models. The values selected for my model are expressed as partial pressures of nitrogen in FSW equivalent, and are known as "Ms" values. By convention, FSW represents that component of pressure due only to the column of water over the diver; however, the "Ms" values represent the absolute partial pressure of nitrogen sustainable within a tissue compartment at a specific depth, <u>including</u> the pressure component attributable to the atmospheric pressure at the waters surface (nominally 1 ATA, or 760 Torr). The values incorporated into the Nobendem calculator are:

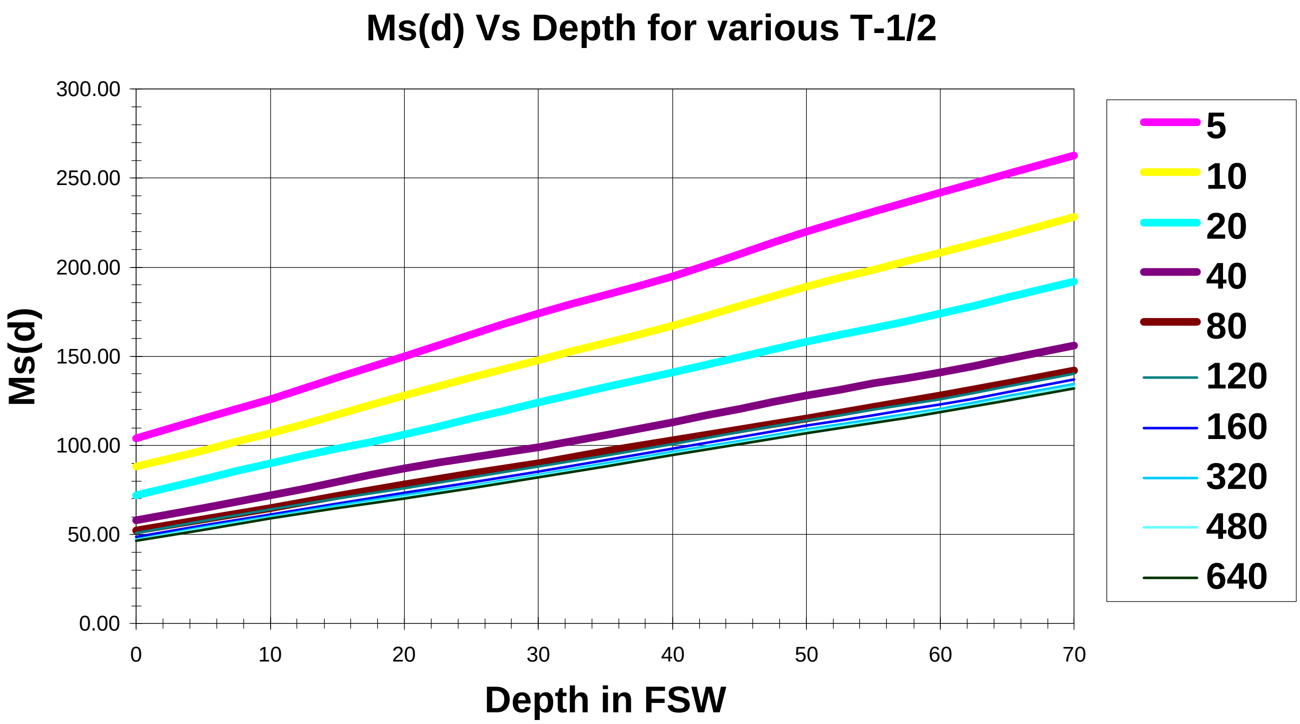
						Depth-specific Critical Values For Various Tissue Compartments					
	T1/2	**5**	**10**	**20**	**40**	**80**	**120**	**160**	**320**	**480**	**640**
Ms(d)											
Ms(0)		104.00	88.00	72.00	58.00	52.00	51.00	48.50	47.40	46.90	46.40
Ms(10)		126.00	107.00	90.00	72.00	65.00	64.00	61.43	60.12	59.48	58.90
Ms(20)		150.00	128.00	106.00	87.00	78.00	76.00	73.36	71.87	71.09	70.44
Ms(30)		174.00	148.00	124.00	99.00	90.00	88.00	85.29	83.61	82.69	81.99
Ms(40)		195.00	167.00	141.00	113.00	103.00	101.00	98.22	96.33	95.27	94.49
Ms(50)		220.00	189.00	158.00	128.00	115.00	114.00	111.15	109.06	107.85	106.99
Ms(60)		242.00	208.00	174.00	141.00	128.00	126.00	123.08	120.80	119.46	118.53
Ms(70)		263.00	228.00	192.00	156.00	142.00	140.00	137.00	134.50	133.00	132.00

Lookup tables are fine for cranking out specific calculations on a one-time basis. To be useful in a calculator, we must be able to represent the Ms values as a function of an independent variable, in this case the depth, d. Since the tissue compartment half-times describe the model, each tissue compartment will generate its own equation for Ms(d). Remember, the depth used as the argument of the function is depth in FSW below the surface of the water, assuming a standard sea-level atmospheric pressure of 760 Torr. This becomes important when extending the tables for use at altitude, since the value of Ms(0) really represents the permissible level of tissue nitrogen with an external pressure of 760 Torr.

Using the statistical functions within Microsofts' Excel spreadsheet, a least squares linear regression for Ms(d) was obtained for each of the tissue compartments. The standard point - slope equation is:

$$Ms(d) = I + Md$$

where I is the "zero intercept" and M is the calculated slope of the line. Before calculating the regression coefficients, I plotted the data to establish whether a linear model would be appropriate. The graph below of the raw Ms(d) demonstrates that a linear model should produce a good fit.



When the data from the linear regression model were plotted, they formed an excellent match with the original data. The coefficients of the equation for Ms(d) in the 5-minute tissue compartment were modified slightly, since there was a slight bump in the fit at the most critical portion of the decompression schedule near the surface. I elected to detune the least squares fit slightly at the deeper portions of the table in favor of a better fit closer to the surface. The final model residual errors, along with the linear coefficients are listed below:

				Ms(d)	Resid	Errors				
T-1/2	5	10	20	40	80	120	160	320	480	640
d										
0	-0.40	-0.42	0.42	0.08	0.08	-0.17	-0.17	-0.16	-0.16	-0.16
10	0.59	0.67	-0.52	-0.01	-0.19	-0.55	-0.54	-0.54	-0.53	-0.53
20	-0.42	-0.25	0.54	-1.11	-0.46	0.07	0.07	0.07	0.07	0.07
30	-1.43	-0.17	-0.40	0.80	0.26	0.69	0.69	0.68	0.67	0.66
40	0.56	0.92	-0.35	0.70	-0.01	0.31	0.31	0.30	0.30	0.30
50	-1.45	-1.00	-0.29	-0.39	0.71	-0.07	-0.07	-0.07	-0.07	-0.07
60	-0.46	0.08	0.77	0.51	0.44	0.55	0.54	0.54	0.53	0.53
70	1.53	0.17	-0.17	-0.58	-0.83	-0.83	-0.83	-0.82	-0.81	-0.80

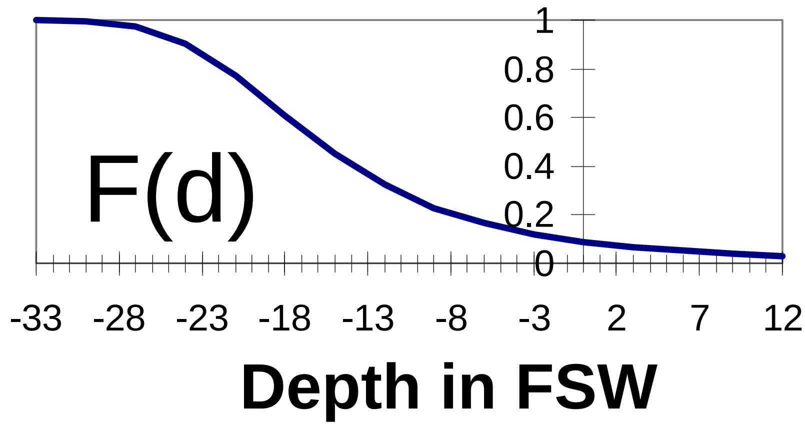
Slope - Intercept coefficients for a given tissue compartment

T-1/2	5	10	20	40	80	120	160	320	480	640
Slope	2.2990	2.0083	1.7060	1.3905	1.2726	1.2619	1.2548	1.2350	1.2208	1.2137
Intercept	103.60	87.58	72.42	58.08	52.08	50.83	48.33	47.24	46.74	46.24

With the basic concepts explained, the only exercise remaining was to build the appropriate formulas and equations into the calculator. For purposes of extrapolation to altitude, I considered the correction used by Cross; however, I found the concept of decreasing the depth of the Navy Table by a factor related to the absolute atmospheric pressure at altitude much too simplistic. I reasoned from Henry's Law, at an external pressure of true 0, there should be NO nitrogen left in solution. Therefore, the permissible supersaturation value of Ms(d) should go smoothly to zero. At 1 ATA, we have well accepted values for Ms(d), and those must not be changed by whatever modification we apply to the overall equation. I chose to apply a varying correction to the slope of the line in such a fashion that Ms(d) would be driven to zero at a depth of -33 FSW (0 ATA). The function used to apply the incremental slope was a sigmoid curve varying between 1 and 0 as the depth (d) varied from -33 to 0 FSW. The function is listed and plotted:

$$F(d) = 1/(1+((d+33)/B)^n)$$

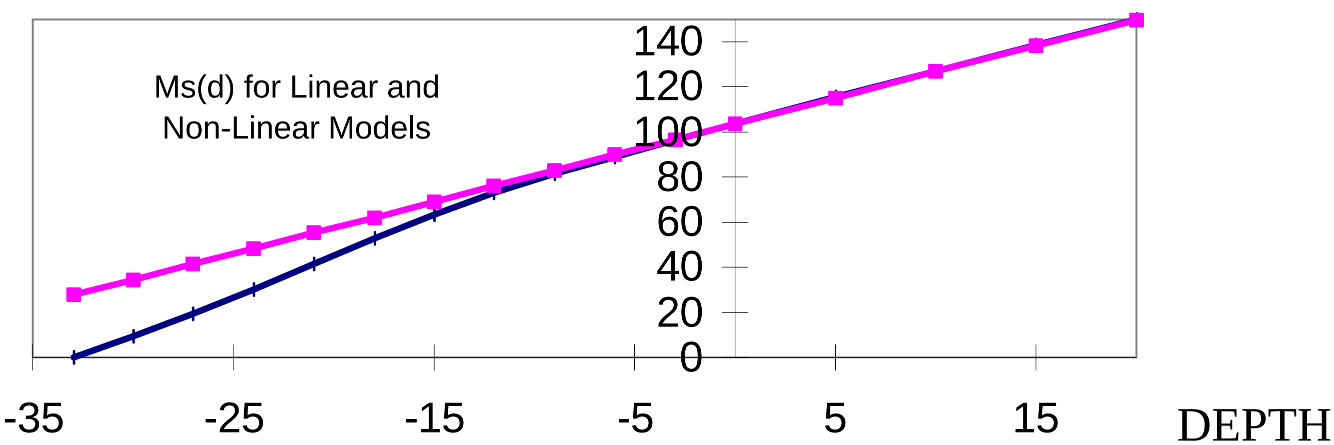
$B=17 \qquad n=3.5$



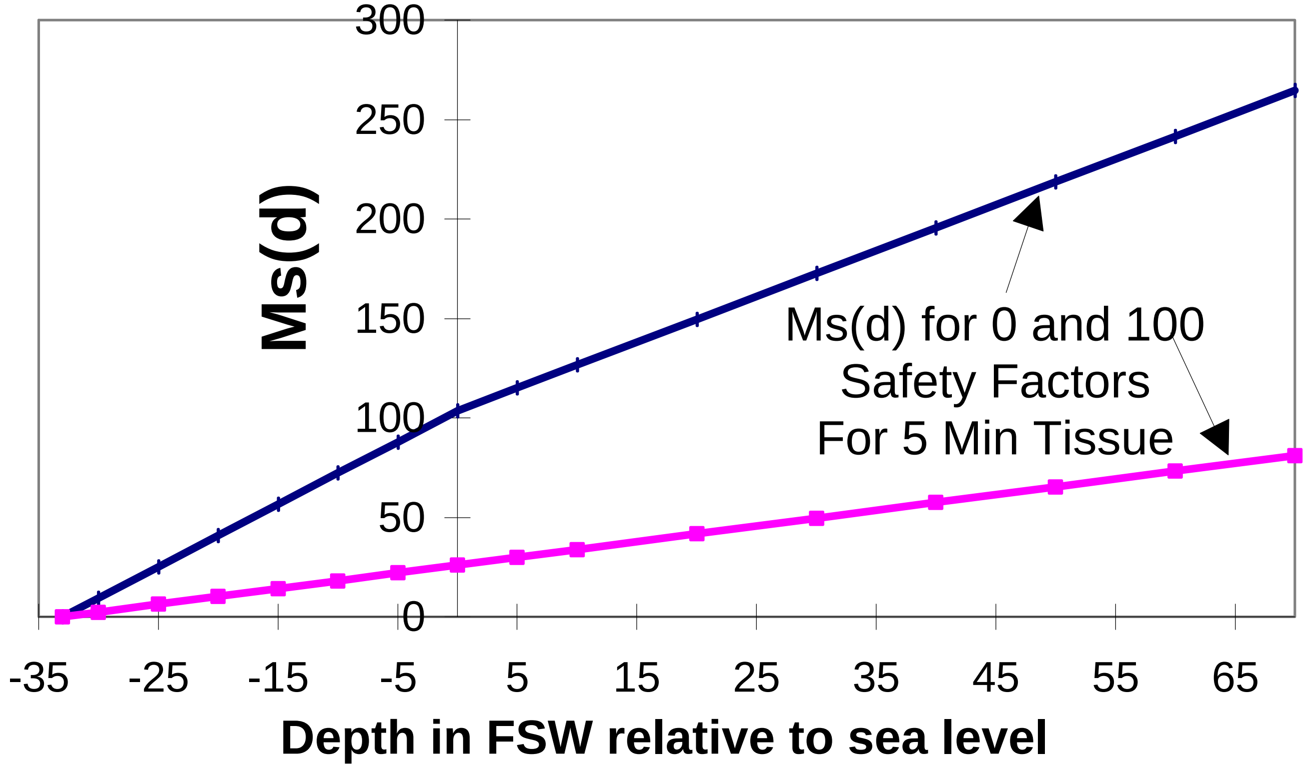
This now provides us with a physiologically sound mechanism to extrapolate the critical values of Ms(d) at altitude. Since I modified the slope, the actual value of Ms(d) will still equal the intercept value at a depth of 0. The final form of the Ms(d) equation becomes:

$$Ms(d) = I + d*(M+(I/33 - M)/(1+((d+33)/17)^{3.5}))$$

This curve is plotted below for the 5-minute tissue compartment with I=103.6 and M=2.2990

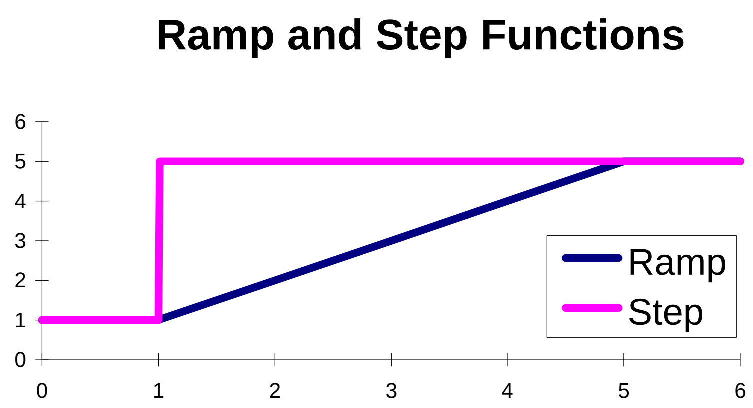


In addition, I built a "safety enhancement" term into the model seen as the "Safety Ms" in the spreadsheet. The mechanism drops the zero intercept of each tissue compartment safety Ms(d) equation in a linear fashion from its nominal value toward that predicted by a straight line (the "Index Line") passing through zero at a depth of -33 FSW (space) and 26 (the equilibrium value of tissue nitrogen at sea level) at a depth of zero FSW. The slope of the safety Ms(d) equation is also mapped linearly toward that of the Index Line mentioned above. The significance of the specified Index Line is that it represents a supersaturation ratio of 1:1 (or no excess nitrogen permitted in solution) compared to Haldanes original assumption of a 2:1 permissible supersaturation ratio. Thus as the safety enhancement factor is varied from 0 to 100, the model changes from the currently accepted tissue compartment supersaturation values to a model in which no excess nitrogen is permitted. With a safety enhancement of "0", my calculator very closely matches the Standard US Navy Air Decompression Tables. The value of the safety enhancement term also allows me to compare the relative safety of two conservative Inside Observer denitrogenation profiles. By increasing the safety enhancement value until a given profile just zeroes out (no negative buffer values in the dive segments), an objective index of comparison may be had for any other decompression profile.



Remembering that Henry's Law allows determination of the initial and final tissue nitrogen concentrations based on the partial pressure of nitrogen in the breathing gas, it was a simple matter to expand the calculator to include a variable term permitting Nitrox use. Since air is a special form of Nitrox with 79% N_2, 21% O_2, I included a term for the fraction of oxygen inspired during each segment of the dive. This permits calculation of the nitrogen fraction as (1.0 - FiO2). Although this calculator is valid only for Nitrox, (each gas has its own values for Ms(d)) a similar mechanism could be developed for Heliox, or even a Helium/Nitrogen/ Oxygen trimix, given the appropriate Ms(d) values for Helium. The trimix model may be much more complicated if the assumption that inert gas solubilities are independent is false!

With the purpose of using this calculator to predict nitrogen loads accumulated inside hyperbaric chambers, a method to account for a prolonged linear ascent or descent was desired. Although I'm certain an exact differential solution could be determined for each case, I decided that an "engineering approximation" would suffice. Realizing that the exponential response is that which results from applying a step function (changes instantly from the initial value to the final value) as input to our differential system, I wanted to determine what the expected response to a linear ramp would be. If one realizes that the driving function behind the uptake of gas molecules is the difference between those currently in solution and the absolute partial pressure of gas above the solution, then the following explanation will be intuitive. In one extreme, the linear ramp will proceed much more rapidly than the tissue half-time will permit the response to follow. In this case, the effect of the driving function, related to the area under the driving curve (here a triangle) will only be ½ that found under a rectangular step function. Thus, for cases where the pressure change occurs over a period much less than the tissue half-time, I would only expect ½ of the nitrogen transfer predicted by the straight exponential response. On the other hand, if the pressure change occurs much more slowly than the tissue half-time, I would expect the tissue to keep pace with the changing external nitrogen environment, reaching the same level of nitrogen loading at the end of the transition as if a step function had been applied. A simple function of the linear transition time (dt) and the tissue half-time was derived which varies between 0.5 and 1.0 as desired:



$$F(t\text{-}½ , dt) = (0.5 + 0.5*dt /(t\text{-}½ + dt))$$

This function was applied to all of the linear transition sections in the calculator. If you do not wish to use this feature of the calculator, simply enter your transition time as "0", and the section will have no effect. If, on the other hand, you wish to gain a more reasonable approximation of the actual nitrogen loading than simply adding your transition time to the bottom time, entering data in the appropriate transition section of the segmental calculations will do just that.

Since my calculator was designed for use at altitude, the question may arise regarding the incorporation of the alveolar gas equation into the gas partial pressures, since the partial pressures of water vapor (47 Torr) and CO_2 (variable) become significant at the 10% level at 12,500 feet (P_b = 471 Torr). By ignoring this altitude effect, the calculator factors in a higher alveolar nitrogen exposure than what actually occurs, thus building in a desirable conservative factor that increases the higher you go (and the further into the untested Ms extrapolations you extend).

The last challenge I faced was determining how to formulate the currently implemented repet (repetitive dive) group residual nitrogen time (RNT) calculations. One might suppose that with a multi-compartment model, you could simply decay the nitrogen loads in each tissue compartment according to their specific half-times on a minute-for-minute basis equivalent to the surface interval, and then begin the next dive segment using those as starting values. I discussed such a proposal with Dr. Edward Thalmann whose work was instrumental in revising the Navys' Air Decompression Tables. He indicated that those had been his initial assumptions when first developing the repet dive process, but found through experimental dives that the tables underestimated the decompression time required for the repet dives and you'd "bend the hell outa people if you did that." Dr. Thalmann kindly supplied me with a reference list, and suggested that I might benefit from reviewing that information before proceeding. The mechanism used to calculate the repet group and corresponding RNT was to take the single value of nitrogen in the 120 minute tissue group at the end of the most recent dive and decay that value over the time period of the surface interval back toward the inspired nitrogen partial pressure at the surface. Once that was accomplished, you needed to determine the depth of your next dive, and decide how long it would take at that depth to accumulate a nitrogen load in your tissues equivalent to that predicted for the 120 minute compartment at the end of the surface interval. The time resulting from this calculation was the RNT, and was added to your planned bottom time to factor back in the effects of your previous dive. On the first runs through my model, the repet groups that were predicted worked out fine, but the RNTs wouldn't line up using the 120 minute tissue as target. Recalling Dr. Thalmanns' caveat, I surmised that this may have been the spot where an adjustment could have been built in, based on actual dive testing of the table-driven profiles. Tweaking the numbers, it appears that using a reloading target tissue half-time of 157.1 (note that 160/120 = 4/3, or 133%) minutes produces an extremely close match to the RNTs found in the Standard Navy Air Tables! While I could not postulate any physiological reason for this factor of 133% to work, I assume it was chosen to match the model to the actual observations of which diving profiles were actually safe. One must remember that for the testing done back then, a profile which never, ever produced any bends may have been considered too conservative, resulting in a lowering of the decompression obligation (Navy tables accepted a DCS incidence of about 2% for no-deco dives, and around 5% for deco dives)! This is one of the important reasons for including the safety enhancement feature in the calculator. Experienced divers may enter a profile which they have come to regard as tried and true, safe to dive, and see what, if any, safety enhancement factor is required to zero out the decompression obligation. This factor could then be applied to other profiles to add whatever margin of safety was desired. While I suspect a better solution might be generated through application of tissue compartment specific surface interval decay rates that are longer than their nominal onloading rates, testing such assumptions would require several years and hundreds of actual dives - not a likely scenario in today's environment where we already have tables that work quite well.

As expected, applying an RNT derived for the 120 minute tissue group to groups with a shorter half-time will yield a more conservative table as the initial compartment nitrogen levels will be overestimated. However, for the longer half-times, the residual values will be underestimated! Although this is usually not a problem for routine dives, it well may be problematic for extended dives which accumulate large tissue nitrogen loads, as well as dives at altitude after equalization periods substantially shorter than 48 hours. In order to correct for this, I have included a background calculation for the tissue compartments with half-times of 160, 320, 480, and 640 minutes. If the residual nitrogen load predicted by the RNT method following a specified surface interval is less than that which would have resulted from an exponential decay at a rate of 1.33 times the compartment half time (33% conservative), then my spreadsheet calculator defaults to the more conservative exponential model. As recognized by Thalmann, Workman, et al, the Navy Tables break down for more prolonged exposure times in that they underestimate the amount of decompression required. Although the Navy Tables probably overestimate the decompression required for certain shorter profiles, my method of providing a correction permits correlation of my predictions with the dive-tested Navy tables for shorter dives, while permitting extension of the tables for prolonged dives, as well as dives at altitude, using rational, physiologically based constructs.

To illustrate these principles, I have constructed a comparison between the Nobendem predictions and the Navy Dive Tables.

		Comparison: Nobendem VS US Navy Dive Tables								2 Hr RNT	
	Depth	Time	Ascent	Deco 40	Deco 30	Deco 20	Deco 10	Tot Deco	RNT 40	RNT 100	RNT 160
Navy	40	270	1.3				15	16.3	101	34	20
Nobendem							15	16.3	105	36	22
Nobendem Safety = 10							33	34.3	97	34	21
Navy	100	50	3.3			2	24	29.3	73	26	16
Nobendem							26	29.3	78	28	17
Nobendem Safety = 10						8	28	39.3	77	28	17
Navy	100	240	3.3	14	42	84	142	285.3	**	**	**
Nobendem				17	43	101	199	363.3	68	25	15
Nobendem Safety = 10				31	53	122	263	445.3	52	19	12
Navy	160	15	5.3			1	4	10.3	49	18	11
Nobendem							4	9.3	47	18	11
Nobendem Safety = 10							8	13.3	47	18	11
Navy	160	60	5.3	9	19	33	69	135.3	101	34	20
Nobendem				10	19	33	73	140.3	108	37	23
Nobendem Safety = 10				17	20	45	105	192.3	89	32	19

You can see excellent comparisons for low nitrogen loading dives, and that for the high loading dives, Nobendem requires longer decompression stops at the shallower depths to account for the longer tissue half-times not included in the Navy model. You can also see that the Navy RNT value becomes shorter than expected as it does not account for the longer tissue groups (the Nobendem model does as explained previously through the use of a background calculation for the tissue compartments with half-times of 160, 320, 480, and 640 minutes). Note the increase in total decompression times for a moderate safety enhancement of 10! Also note that for a short, deep dive, Nobendem may predict a shallower first stop than the Navy tables do. This is because Nobendem credits you for decompression which occurs during your controlled ascent.

I will next run through a step-by-step example of how the calculator system should be used. When you first open the spreadsheet, you should look at all of the yellow blocks to ensure they are set at their default values. I recommend setting all of the FiO_2's to 0.21, the transition and segment times to 0, change the safety enhancement (SE) to 0 (not recommended for actual dives), and the local barometric pressure to 760. I have included a macro within the spreadsheet to accomplish this automatically. Simply choose “Tools”, “Macro”, and run the macro named “Reset Short Dive” (this sets the SE to 20!). Provided there are no severe tropical weather systems in the area, and you are diving at sea level, you may keep the value of 760 as the local barometric pressure. If you have a current weather report telling you more up-to-date information, or if you are diving at altitude, you may enter the appropriate value for local barometric pressure (ensure your depth gauge is recalibrated to read 0 FSW at the waters surface!). If you have no clue as to what the local pressure should be, but you know your altitude, a barometric pressure estimator based on an exponential model has been derived from the standard NOAA pressure tables and is included at the bottom of the spreadsheet.

(For those diving at altitude, you should allow at least four to five half-times of the slowest tissue compartment before assuming you have equilibrated at the new altitude. Applied to the 640 minute compartment, this comes to about 2.2 days! Your other option would be to "begin" your dive at sea level, with data only in segment 1 of the multi-dive calculator (Profile M1). Enter your altitude as a negative "depth" in FSW (as predicted by the "Torr Estimator" at the bottom of the spreadsheet), and enter the length of time it took you to make the majority of the ascent as the "Linear Descent Time". Zero out the rest of the segment and ascent times in M1. Then open data sheet M2 of the multi-dive calculator, enter the appropriate barometric pressure and length of time you have been at altitude as the surface interval in the top data block, and proceed with your profile generation in segment 1. The nitrogen loads predicted by your "surface interval at altitude" are conservatized via the RNT 133% conservative factor and loaded at the top of table M2. I strongly recommend using this method of starting a dive at altitude after less than 2 days of acclimatization since you are basically performing a repet dive at altitude following a "saturation dive" at sea level in air.)

Next, enter your first stop depth into segment 1, along with the amount of time you intend to spend there. A suggested linear transition time, based on 30 feet per minute, shows in the square next to the yellow block in the section above. If you descend more quickly, enter your actual planned descent time in the yellow linear transition time block (enter ½ the suggested time for a rate of 60 feet per minute). If you decide not to use the transition time component, simply enter the transition time as 0, and include your transition time with your bottom time when entering your time for segment 1. Also, be sure to enter the breathing gas fraction of oxygen for each section as indicated. For those diving on air, this number will always be 0.21. Nitrox divers should enter the appropriate fraction for the mix they are using. You may switch the mix at any time corresponding to the dive you actually plan to make.

As long as you are descending, simply fill out your segmental data and proceed to the next segment. Once you begin to ascend, the calculator really starts to do its work. Suppose you want to make a dive to 110 FSW, on air, starting at normobaric sea level, and taking 1.5 minutes for the descent. You want 60 minutes on the bottom, then plan to ascend. In order to find your first required stop, enter values of depth in <u>segment 2</u> in increments of 10 feet that are as shallow as possible WITHOUT producing any RED (negative) numbers in any of the segment 1 tissue compartment "buffer" cells. If you try to enter 0 as the segment 2 depth, you will notice that the buffer values for the 5 through 120 minute tissue compartments become red, indicating you must decompress before proceeding to the surface! Likewise, you may not ascend to 10 FSW since the 10 through 40 minute compartments still require decompression. Entering 20 FSW into segment 2 gets all of the buffer values in segment 1 into the black, indicating your first Deco stop must be at 20 FSW. You will also note that the suggested linear transition time, based on 30 feet per minute, reads 3.0 (90 feet at 30 fpm ➔ 3 minutes). I do recommend using the linear transition model (and for the sake of this example, will assume that you have), as it accounts for the fact that while many compartments will start to decompress during the ascent, the slower ones may actually continue to onload gas and this may become important during later stages of decompression.

Now that your first Deco stop has been determined, enter 20 for the depth of segment 2, 10 for segment 3, and 0 in all remaining segments. You may also fill in the linear ascent times of 0.33 minutes where indicated, zeroing the rest, and ensure all FiO_2s are set to 0.21. Now go back up to segment 2 and enter increasing values of your segment time until none of the segmental buffer values are red (negative). If all has gone according to plan, you should require 17 minutes at 20 FSW. Proceeding to 10 FSW in the indicated 0.3 minutes (20 seconds) puts you in segment 3, where 39 minutes are required to denitrogenate sufficiently to make the ascent safely to the surface. Another 20 seconds to the surface completes the dive, and proceeding to the bottom of the table shows that the total length of the planned dive is 121 minutes. Comparing our profile to that generated by the Standard US Navy Air Tables shows excellent agreement: we determined 17 minutes at 20 FSW compared to the Nave Tables 18, and we required 39 minutes at 10 FSW compared to the Navy Tables 36. The same dive using 28% O2 Nitrox would require only 7 minutes at 20 FSW and 28 minutes at 10 FSW for a total dive time of 95 minutes. Looking at the nitrogen load remaining in the 120 minute tissue compartment shows 47.71 for the air dive and 46.44 for the Nitrox dive. A weighted average of all the tissue compartments excess nitrogen loads shows 10.74 for the air dive and 9.902 for the Nitrox dive. If desired, you may enter values of time into segment 4 as a surface interval to see when you may ascend to altitude (use the Torr estimator to find -10.45 FSW equivalent to 10,000 feet, and enter that value in segment 5 as the depth). If after the dive on air you took a 175 minute surface interval, the calculator predicts you could ascend to 10,000 feet in altitude. Finally, the same air profile using the recommended safety enhancement of 20 predicts a decompression requirement of: 30 FSW for 11 min; 20 FSW for 25 min; 10 FSW for 68 min; and predicts you should wait at least 444 minutes before ascending to 10,000 feet altitude!

While we're discussing altitude, lets check back on the Cross Correction idea. Looking in the Navy Tables for the No-Deco limit for 60 FSW, we find we should be able to stay 60 minutes before incurring a decompression obligation. At 8,000 feet, the barometric pressure (according to the Torr estimator) is 561 Torr. Multiplying (760/561)*60 FSW ➔ 81.2 FSW. This indicates that you should use the No-Deco recommendations for the "81" foot table, or about 40 minutes at an altitude of 8,000 feet. Entering 561 for the local barometer, 0 for the SE, and 0 for the descent transition time, you will find the Nobendem calculator predicts you may spend 45 minutes at 60 FSW before incurring a decompression obligation (this drops to 26 min with a SE of 20). Please note that both the Cross and the Nobendem mechanisms used in the above example assume you have spent the time necessary at 8,000 feet to fully equilibrate before you dive (2.2 days for Nobendem)! Nobendem can provide a profile, using the multi-dive instructions above, prior to full equilibration.

Looking at the Buhlmann tables for diving at altitude, lets assume we have equilibrated at 8,000 feet and want to make a dive to 80 FSW for 40 minutes. Buhlmann predicts we should stop at: 23 FSW for 5; 13 FSW for 7; and 7 FSW for 20 before surfacing (34.66 minutes total deco including ascent time). Nobendem (SE 20) predicts you could ascend safely to 11 FSW (taking 2.3 min for the ascent) for 12 min; then 5 FSW for 19 min before surfacing (total deco = 33.66). For the same dive, Cross would use the 110 FSW table, recommending a 2 min stop at 15 FSW, and 21 min at 7.4 FSW (total deco = 25.66).

Finally - the graduation exercise! You live in Galveston, Texas (sea level) and plan to drive to the Sandia mountains in New Mexico for a little mountain lake diving at 8,000 feet. You figure the ascent will occur more or less linearly over the last 4 hours of your drive, but plan on waiting for 12 hours at altitude before your first dive. Being the adventurous sort, you plan on diving with Homebrew Nitrox XXX (32% O2), and as you are the bold, invulnerable, non-bubbling sort, you decide to use a safety enhancement of only 15 in the calculator. You plan your first dive, stopping at 30 FSW (your gauge only reads FSW, not FFW - but you did remember to zero the reading at altitude!) for 15 min, then drop to 80 FSW for 60 min (figure descent rates at 60 fpm, ascents at 30). After decompressing, you plan a 2 hour surface interval and a repet dive on air (no Nitrox in the Sandias - gotta jam with air) straight down to 100 FSW to retrieve the flashlight and car keys you dropped (plan 15 minutes at depth). Then you'll ascend to 60 FSW to spend 45 min looking at some interesting beer can formations before beginning your final ascent. What should your decompression schedules be for your first and second dives. If you can't find your car keys and have to fly home, how long do you have to wait after your last dive before you climb into your friends unpressurized Cessna kept in storage at your mountain lake resort for just such an emergency and ascend to 15,000 feet (keep the safety factor of 15) for the trip home? Being the clever sort, you realize that there is no air at 15,000 feet, at least not enough to power a mighty aviator brain, and so you will be using an aviators oxygen mask, delivering about 60% O2, for 15 minutes of ground time, and the 20 minute, nearly linear ascent, to FL 150.

For starters, go to the Multi M1 spreadsheet and run the “Reset_Short_Dive” macro to clear things. Then enter 240 into the Linear Transition time (to simulate the ascent to altitude) and enter -8.63 into the segment 1 depth (obtained from entering 8,000 feet into the Torr Estimator at the bottom of the spreadsheet). Then go to spreadsheet Multi M2 (remember to run the “reset” macro) and enter 720 into the surface interval and enter the safety enhancement of 15. The local barometer will be 561 (from the Torr Estimator). Be sure to enter the FiO_2 as .32 in all active segments (non-zero times) to correctly account for your Homebrew Nitrox XXX. This chore can be easily performed by running the “ChangeOxy” macro after entering your Nitrox FiO_2 into cell B10. Enter your descent time as 0.5 minutes (60 fpm descent) to the initial 30 FSW entered into the segment 1 depth. The segment time is 15 minutes. Next enter 60 min at 80 FSW into segment 2. 1.7 minutes appears next to the segment 1 transition time - enter ½ that or 0.83 minutes for the descent rate of 60 fpm. Now go to segment 3 and ascertain where your first deco stop will be. Entering 0 for the depth leaves red numbers in the segment 2 buffer, indicating inadequate decompression for the 0 FSW level. Entering 10 clears the red in the segment 2 buffers, and suggests entering a 2.3 minute transition time ascent (do that). 33 minutes at 10 FSW are required to clear the segment 3 buffer values indicating you are clear to ascend to the segment 4 depth (0 = surface). If you didn’t get 33 minutes, check to ensure all your FiO_2s have been set to 0.32, your safety enhancement value of 15 has been entered, and you are using the Oct 98 version of Nobendem (file, properties). Enter the transition time to the surface as 0.33 minutes and proceed to the M3 spreadsheet.

Again - run the “reset_short” macro. Then enter the surface interval of 120 minutes, safety enhancement of 15, and the local barometer of 561. Since this dive is on air, leave the FiO_2 as 0.21. Entering 100 FSW for 15 minutes into segment 1 gives a suggested 3.33 minute descent (use half that, or 1.66, for 60 fpm rate), and entering 60 FSW for 45 minutes into segment 2 predicts 1.33 minutes for the ascent (keep that as a 30 fpm ascent rate). Going to segment 3, we find we must stop at 20 FSW, giving 1.33 minutes as the ascent time from segment 2. Enter 10 FSW into segment 4, and enter the remaining 0.33 minute times for the linear ascents. Going back to segment 2, the required deco time works out to 18 minutes, and the time required at 10 FSW zeros out at 97 minutes. Segment 5 at 0 FSW will be our variable to determine the surface interval required before flying at 15,000 feet, so drop down to the Torr Estimator and enter 15,000 feet to see that the altitude equivalent would be -14.42 FSW. Remembering that we are already at -8.63 FSW at 8,000 feet, the relative altitude increment to 15,000 feet is a -5.79 FSW (ooohhh - tricky!). Entering that value as the final depth (past segment 6), move back to segment 6 and enter our preflight and ascent oxygen fractions as 0.60. Enter 15 minutes as the segment 6 time, and 20 minutes as the linear ascent time. Now go back to segment 5 and enter trial times into the calculator to determine when the buffer values in the linear transition section of segment 6 go to zero. At 244 minutes you should find that the segment 6 transition time buffer value just flips positive, even though the buffer at the end of the ground time reads a negative 0.37. It would take an additional 44 minutes on air prior to entering the plane if the 60% oxygen were not available. This emphasizes the positive effect of the oxygen enhanced denitrogenation during the 35 minute taxi and ascent to 15,000 feet.

As a final thought, optimum dive planning may be accomplished by discarding the 10-foot steps typically used in a staged ascent and by ascending as far as possible before making the first stop. Using this concept produces the following sample comparison:

		Comparison: Nobendem (SE = 0) VS US Navy Dive Tables								2 Hr RNT	
	Depth	Time	Ascent	Deco 40	Deco 30	Deco 20	Deco 10	Tot Deco	RNT 40	RNT 100	RNT 160
Navy	160	60	5.3	9	19	33	69	135.3	101	34	20
Nobendem				10	19	33	73	140.3	108	37	23
	160/:60	Ascent	Deco 36	Deco 28	Deco 20	Deco 12	Deco 6				
Nobendem		5.3	13	15	20	32	41	126.3	110	38	23

One quickly notes that this is 9 minutes less deco time than the Navy table, and 14 minutes less than the more conservative 10-foot estimate by Nobendem. The reason for this is that by spending less time at the deep deco stops you limit the continued onloading of nitrogen by the slow tissue groups, thus shaving those slow minutes off the decompression required at the shallower depths.

Using a single linear ascent from the first stop at 36 feet to the surface taking 102 minutes, Nobendem (SE-0) predicts you could decrease your deco time to 102 + 4.1 = 106.1 minutes (4.1 represents the ascent from 160 to 36 FSW at 30 fpm). This is only included as an interesting outcome of the Nobendem model and should not be used to plan a dive since the prolonged nature of the linear ascent would place greater emphasis on the untested assumptions made when building the linear portions of the Nobendem calculator. I actually believe that a logarithmic ascent, being faster at depth and slowing toward the surface, would be the correct, optimal ascent profile.

As with all diving, the calculation of dive tables and excursion profiles is not an exact science due to an infinite number of personal factors that can change from day to day. Although the calculator presented is based on solid principles, it is a new entry in a well established field, and has NOT been experimentally validated. The responsibility for balancing depth, bottom time, breathing gas mix, and decompression time always rests with the diver! Plan your dive, then dive your plan!

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