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USING THE RECREATIONAL DIVER PLANNER FOR MULTI-LEVEL DIVING

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Both the PADI Recreational Dive Planner (RDP) and the PADI Wheel are table-based implementations of the DSAT Rogers-Powell model. Since they use the same model, it should be possible to use the RDP to compute multi-level profiles which are consistent with those allowed by the Wheel. This paper presents the derivation and verification of a concise set of rules which maintain all parameters of the underlying model. These very simple rules allow one to use the RDP to compute multi-level profiles which are at least as safe as those permitted by the Wheel.

UNDERLYING DECOMPRESSION MODEL

The DSAT model developed by Rogers and tested by Powell *et al.* 1988) is a modified Haldanean model employing 8 compartments with halftimes ranging from 5 to 120 minutes. However, only the fastest six, ranging from 5 to 60 minutes, were considered to control "recreational diving," and thus the 60-minute compartment acts as the control for the offgassing rate.

Figure 1 compares the DSAT model parameters to the US Navy model parameters. There are no delta-M values reported in the literature for the DSAT model. It is of some interest that the M-values used in the DSAT model are all within 93-99% of their Navy counterparts (Workman 1965). These M-values result in shorter initial no-decompression limits (NDLs) consistent with those determined by Spencer (Spencer 1976). Repetitive dive NDLs, however, are often significantly extended since the DSAT model uses a 60-minute offgassing control, as opposed to the 120-minute control used in the Navy and Spencer models.

This 60-minute control appears sufficient for almost all profiles allowed in this model, but a series of long shallow dives can bring the slower 80- and 120-minute compartments into play. Special prophylactic rules known as the "WXYZ Rules" were created specifically for these situations. These rules extend surface intervals to avoid overloading the slower compartments, thus patching the only apparent hole in the table implementation. The main advantage of this rather bold elimination of slower compartments is that the recreational diver can now earn much longer repetitive bottom times after much shorter surface intervals than allowed by the U.S. Navy tables. Results presented below , however, indicate that multi-level diving to table limits can cause significant loadings in the 60-, 80-, and 120-minute compartments with far greater frequency than single-level diving to table limits. This fact should be kept in mind when diving multi-level profiles, especially when short surface intervals are observed.

DESIGN CRITERIA

There were three main concerns in the undertaking of this project. First and foremost, the resulting set of rules had to be extremely simple, even at the expense of bottom time. One of the motivations behind the project was that the Wheel was too difficult to use, and that different users frequently computed different repetitive pressure groups for the same profiles. If the rules could be kept simple, perhaps greater proficiency and accuracy would result. Ideally, the resulting system would be easier to use than the Wheel.

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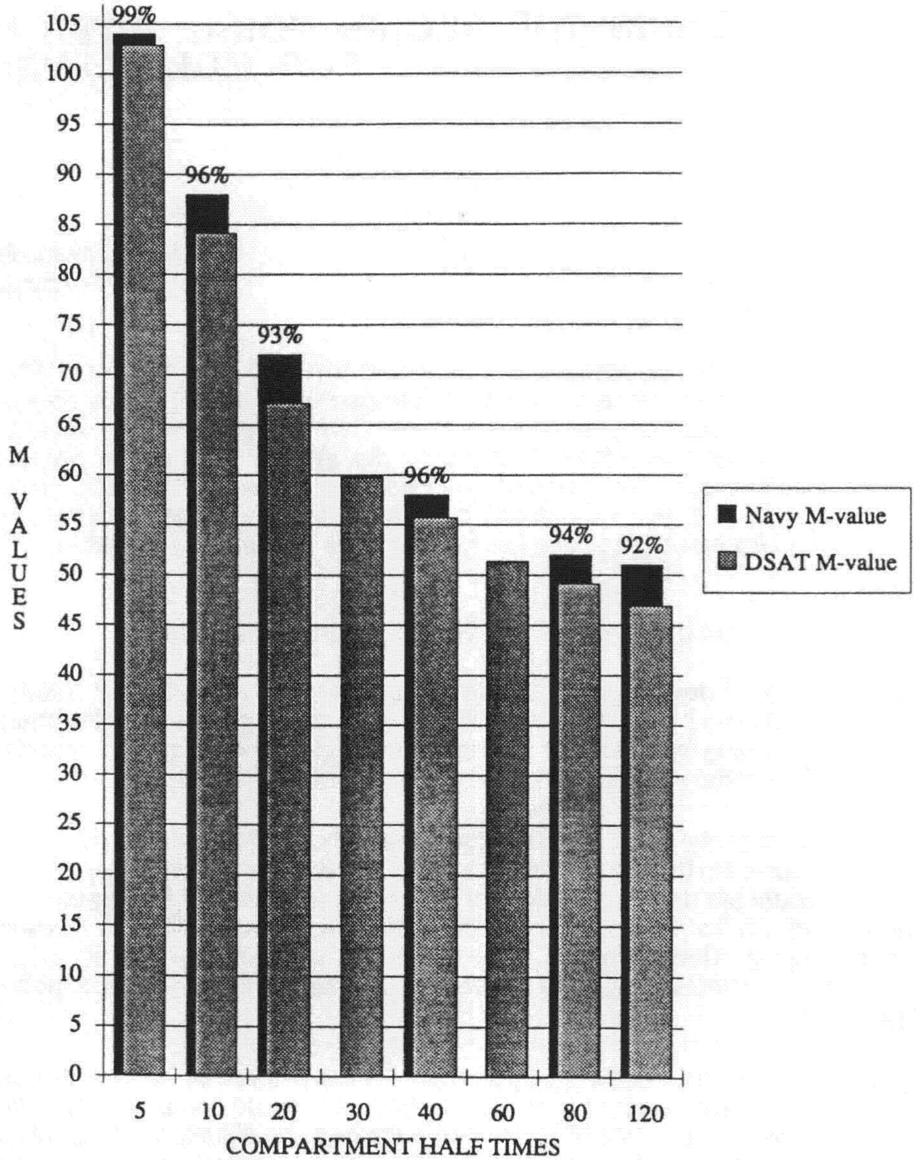

Figure 1. Comparison of DSAT and Navy model parameters.

Second, the resulting rules had to produce profiles that were uniformly the same as or more conservative than those allowed by the Wheel. Were even a single profile to produce higher gas loadings than allowed by the Wheel, then the safety of the entire technique would be called into question, and the rules would not benefit from adherence to the constraints which governed the manned testing conducted by DSAT.

Finally, the rules had to fit on existing PADI RDP tables. Producing the smallest possible set of mnemonic annotations for the familiar RDP was the goal, not producing an entirely new table.

SIMPLIFYING ASSUMPTIONS

Towards these ends, and to limit testing of a potentially vast set of two- and three-level profiles, several simplifying assumptions were made.

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First, only the maximal-length profiles allowed by the tables would be tested. Since these produced the highest compartment gas loadings, it was deemed safe to assume that shorter profiles would fall within the boundaries of these dives. Using only the extremes significantly reduced the total number of profiles to be tested.

Second, only those repetitive depths allowed by the Wheel would be tested, allowing us to conform with the practices instituted with the Wheel, while also limiting the number of profiles to be tested to on the order of 100 two- and three-level profiles. Though it was tempting to simulate gas loadings for non-Wheel profiles, the results would have been experimental at best, and would require validation studies which were outside the scope of this project.

Finally, for the purposes of computer simulation, profiles were considered square, with instantaneous descents. DSAT M-values converted to conventional-style square profiles were used in our simulation. Ascents between levels were considered to be instantaneous and final ascents were not simulated. This allowed us to capture the highest theoretical gas loadings achieved during the profile. (Lower gas loadings would have resulted had we chosen to model all ascents and descents at 60 fpm). These modeling assumptions provided the most conservative gas loading estimates possible while greatly simplifying the computer simulation of the profiles.

COMPUTER SIMULATION

A very flexible dive computer simulator written by David Waller was used to simulate the compartment loadings produced by both the Wheel and table-method profiles. Waller's program allowed simulations of all profiles to be run with relative ease. The accuracy of the simulator was carefully calibrated against published DSAT profiles and gas loadings. All eight compartment loadings were recorded at one-minute intervals throughout all profiles. At the end of each depth segment, the simulator-predicted allowed bottom time, controlling compartment, and gas loading were transcribed directly into a spreadsheet. Gas loading figures were then converted into percentages.

SIMULATION RESULTS

All maximum profiles allowed by the table method were simulated, and the resulting gas loadings at the end of each profile segment were recorded. Of concern in this endeavor was the fact that different depths of the profile are controlled by different half-time compartments. Exceeding the allowable maximum loading of each compartment was to be most strenuously avoided at all stages of the profile, an important aspect of the underlying model which previous table-based multilevel methods have violated (Graver 1976, corrected in Huggins and Somers 1981).

In all cases, the loadings permitted by the table method were lower than those permitted by the model, and the same as or lower than those permitted by the Wheel. In some cases, longer times were allowed by the table method on the third profile level, but these were always associated with shorter allowed times at the second level, and always maintained a lower pressure group than allowed by the Wheel.**

The results are reproduced in Table 1. The table method presented in this paper permitted only those multi-level profiles which were uniformly more conservative than those permitted by the Wheel. At each depth, the allowed bottom time and resulting pressure group for both Wheel and table method are displayed, followed by the computer-simulated NDL, controlling compartment, and percentage gas loading.

** The perceptive reader will notice a number of profiles in which the simulated gas loading exceeds that allowed by the model. Recall that only the strict definition of bottom time used in the RDP instructions has been simulated; ascent time is not included. Further simulation shows that if an ascent is subsequently conducted at 60 fpm, all gas loadings are reduced below model limits during the ascent. However, it remains surprising how easily model loadings can be exceeded if over-rapid ascents are combined with limit-pushing dives.

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Of concern in these results is the discovery that the Wheel allows surprisingly high theoretical gas loadings in the 80- and 120-minute compartments. Of the two-level profiles tested 11% (4/35) produced loadings greater than 95% in the 80-minute compartment. When two- and three-level profiles are analyzed, 60% (53/89) produced loadings of at least 85% in the 80-minute compartment, and 25% (22/89) produced loadings of at least 80% in the 120-minute compartment. Further research into these surprisingly high allowed gas loadings certainly appears warranted.

Table 1. Results of computer simulation of all profiles.

FIRST DEPTH						SECOND DEPTH								THIRD DEPTH							
	Wheel		Computer				Wheel		Table		Computer				Wheel		Table		Computer		
D1	T1	PG	AT	CC	GL	D2	T2	PG	T2	PG	AT	CC	GL	D3	T3	PG	T3	PG	AT	CC	GL
130	10	H	9	1	100.2%	80	11	P	11	P	11	2	99.6%	60	6	S	5	R	2	3	100.8%
														50	20	V	17	U	18	4	99.6%
														40	59	Z	51	X	70	6	96.9%
														35	105	Z	103	Y	128	6	98.4%
						70	16	Q	16	Q	17	3	99.5%	50	17	V	14	U	12	4	100.3%
														40	55	Z	46	X	62	5	98.8%
														35	99	Z	96	Y	117	6	98.7%
						60	23	R	21	R	28	4	95.9%	40	48	Z	41	X	60	6	96.9%
														35	91	Z	88	Y	113	6	98.4%
						50	42	V	39	U	49	4	97.2%	40	25	Y	23	X	39	5	98.9%
														35	57	Z	61	Y	84	6	98.6%
						40	90	Y	83	X	102	6	97.0%	35	12	Z	20	Y	43	6	97.0%
						35	147	Z	144	Y	163	7	98.2%								
												6	98.4%								
120	13	K	11	1	102.3%	80	8	Q	7	P	4	2	101.1%	60	4	S	5	R	0-	3	100.8%
														50	17	V	17	U	19	4	99.3%
														40	54	Y	51	X	72	6	96.6%
														35	99	Z	103	Y	131	6	98.3%
						70	11	Q	11	Q	11	3	99.8%	50	17	V	14	U	14	4	99.9%
														40	54	Y	46	X	65	6	96.9%
														35	99	Z	96	Y	121	6	98.5%
						60	17	S	15	R	21	3	97.8%	40	43	Y	41	X	62	6	96.5%
														35	85	Z	88	Y	117	6	98.2%
						50	35	V	31	U	41	4	97.5%	40	24	Y	23	X	41	5	98.7%
														35	56	Z	61	Y	89	6	98.2%
						40	80	Z	72	X	93	6	96.6%	35	0-	Z	20	Y	48	6	98.3%
						35	134	Z	131	Y	154	7	97.9%								
												6	98.3%								
110	16	M	15	1	100.6%	70	8	Q	8	Q	7	3	100.4%	50	14	V	14	U	13	4	100.2%
				2	100.2%									40	49	Y	46	X	65	5	98.6%
														35	91	Z	96	Y	121	6	98.5%
						60	13	S	11	R	14	3	98.8%	40	43	Y	41	X	63	6	96.4%
														35	85	Z	88	Y	118	6	98.1%
						50	29	V	26	U	33	4	98.1%	40	25	Y	23	X	38	5	98.9%
														35	56	Z	61	Y	89	6	98.2%
						40	72	Z	65	X	86	6	96.7%	35	0-	Z	20	Y	48	6	98.3%
						35	123	Z	121	Y	146	7	96.3%								
												6	98.3%								
100	20	0	19	2	101.4%	70	5	R	4	Q	0-	3	100.6%	50	14	V	17	U	0-	4	100.7%
												2	100.3%	40	49	Y	51	X	66	6	97.6%
														35	91	Z	103	Y	122	6	98.8%
						60	9	S	7	R	6	3	100.1%	40	43	Y	41	X	61	5	98.5%
														35	85	Z	88	Y	116	6	98.2%
						50	24	V	20	U	24	4	98.8%	40	25	Y	23	X	35	5	99.1%
														35	56	Z	61	Y	90	6	98.2%
						40	64	Z	56	X	87	6	96.6%	35	12	Z	20	Y	48	6	91.8%
						35	112	Z	109	Y	136	7	96.1%								
												6	98.2%								

Table 1. (con'd)

FIRST DEPTH							SECOND DEPTH							THIRD DEPTH							
	Wheel		Computer				Wheel		Table		Computer				Wheel		Table		Computer		
D1	T1	PG	AT	CC	GL	D2	T2	PG	T2	PG	AT	CC	GL	D3	T3	PG	T3	PG	AT	CC	GL
90	25	Q	24	3	100.1%	60	5	S	2	R	0-	3	100.7%	40	43	Y	41	X	62	5	98.4%
				2	100.6%									35	85	Z	88	Y	118	6	98.1%
						50	17	V	14	U	15	4	99.6%	40	25	Y	23	X	32	5	99.3%
														35	56	Z	61	Y	90	6	98.2%
						40	54	Z	46	X	68	6	96.5%	35	12	Z	20	Y	50	6	98.1%
						35	99	Z	96	Y	114	6	98.2%								
80	30	R	30	3	99.6%	60	2	S	0-	R	1	3	99.6%	40	43	Y	41	X	63	6	96.3%
														35	85	Z	88	Y	118	6	98.1%
						50	14	V	10	U	13	4	99.2%	40	25	Y	23	X	37	5	99.0%
														35	56	Z	61	Y	93	6	97.9%
						40	49	Y	41	X	63	6	96.3%	35	12	Z	20	Y	51	6	98.0%
						35	99	Z	88	Y	118	6	98.1%								
70	40	T	39	3	100.5%	50	7	V	4	U	0-	4	100.3%	40	25	Y	23	X	27	5	99.7%
												3	100.1%	35	56	Z	61	Y	87	6	98.4%
						40	37	Y	29	X	40	5	99.2%	35	12	Z	20	Y	27	6	98.3%
						35	77	Z	71	Y	97	6	98.4%								
60	55	W	53	4	100.6%	40	18	Y	9	X	13	5	99.7%	35	12	Z	20	Y	56	6	97.7%
						35	43	Z	36	Y	72	6	97.6%								
50	80	X	80	5	100.0%	40	10	Y	0-	X	0-			35	12	Z	0-	X			
						35	28	Z	20	Y	43	6	98.6%								
40	140	Z	140	6	100.0%	35	0-	Z	0-	Z											
35	205	Z	206	7	99.9%																
				6	99.5%																

Clearly, diving to the Wheel's limits can load even the RDP's slowest compartments quite completely. A multi-level dive as short at 68 minutes (110/:16->60/:11->40/:41) can produce higher loadings than a single-level dive to 40 ft for 117 minutes. This again highlights how much easier it is to saturate the slower compartments when diving multi-level profiles than when diving square profiles, and points out the need for added conservatism and longer surface intervals.

THE TABLE METHOD FOR MULTI-LEVEL DIVING

Only three simple rules were necessary in addition to the general and special rules commonly associated with the use of the RDP and explained in the instructions which accompany the RDP (PADI 1988). These are, briefly:

1) Only the first depth is allowed to be greater than 80 fsw and to the full table NDLs.

2) Repetitive depths are limited depending on the previous depth.

3) Repetitive depth NDLs are reduced for the second and third depths.

The first two rules avoid having multiple levels of the dive controlled by the same compartment, and force the profiles to move stair-wise shallower, thus causing progressively slower compartments to control the profile. Rule Three takes into account the gas loadings incurred at previous levels in the profile.

Figure 2 presents these modifications to Table 1 of the RDP. As can be seen, the rules can be added to the RDP with only six arrows, six boxes, and a heavy line. All other rules applying to the

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RDP still apply to the table method. Repetitive diving is controlled, as it was before, by the repetitive pressure group and surface interval. Tables II and III of the RDP are consulted as usual, and the results of Table III are applied to the first level of the Table I profile exactly as if the diver had performed a single-level dive.

	35	40	50	60	70	80	90	100	110	120	130	140	
A	10	9	7	6	5	4	4	3	3	3	3	4	A
B	19	16	13	11	9	8	7	6	6	5	5	4	B
C	25	22	17	14	12	10	9	8	7	6	6	5	C
D	29	25	19	16	13	11	10	9	8	7	7	6	D
E	32	27	21	17	15	13	11	10	9	8	7	7	E
F	36	31	24	19	16	14	12	11	10	9	8	8	F
G	40	34	26	21	18	15	13	12	11	10	9		G
H	44	37	28	23	19	17	15	13	12	11	10		H
I	48	40	31	25	21	18	16	14	13	11		I	
J	52	44	33	27	22	19	17	15	13	12		J	
K	57	48	36	29	24	21	18	16	14	13		K	
L	62	51	39	31	26	22	19	17	15		L		
M	67	55	41	33	27	23	21	18	16		M		
N	73	60	44	35	29	25	22	19		N			
O	79	64	47	37	31	26	23	20		O			
P	85	69	50	39	33	**28**	24		P				
Q	92	74	53	42	**35**	29	25		Q				
R	100	79	57	**44**	36	30		R					
S	108	85	60	47	38		S						
T	117	91	63	49	40		T						
U	127	97	**67**	52		U							
V	139	104	71	54		V							
W	152	111	75	55		W							
X	168	**120**	80		X								
Y	**188**	129		Y									
Z	205	140		Z									

Figure 2. Modifications to RDP Table I: Multiple depth limits and new multilevel NDLs.

The best way to explain this technique is to run through a sample profile, explaining at each step. The following profile, 120/:10-->70/:10-->40/:35, is a reasonable example of a multi-level profile permitted by our method. The proper method for working the full profile using the table method is reproduced in Figure 3.

Step One: Descent to 120 ft for 10 minutes. Our diver is now in pressure group "G."

Step Two: Ascend to 70 ft. The theory behind this technique is that the gas loading from a dive to 120 ft for 10 minutes is the same as that from a dive to 70 ft for 18 minutes. The remaining allowable bottom time at 70 ft is now 17 minutes, the difference between 18 and the multi-level NDL indicated by the black box. In this case, our diver stays only 10 minutes, an easily remembered figure, entering pressure group "N."

Step Three: Ascend to 40 ft. Remaining allowable bottom time is now 60 minutes, more than enough time to exhaust our diver's air supply. Our diver chooses to remain for 35 minutes, and surfaces in repetitive group "U."

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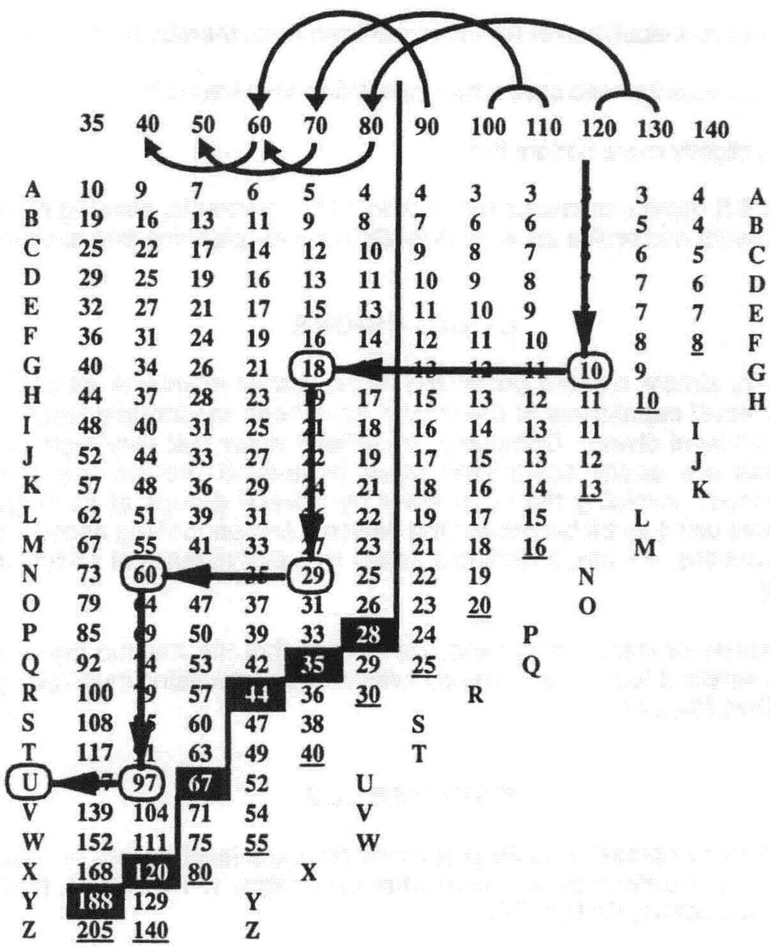

Figure 3. Working a sample profile.

DIFFERENCES BETWEEN THE TABLE METHOD AND THE WHEEL

Although these rules seem simple enough, perhaps even simpler than the Wheel's, there are inevitably tradeoffs when using a simpler instrument. A few of the most salient benefits of each method are summarized below. This list is not intended to be complete, merely indicative of the major tradeoffs between the methods.

Advantages of the Table Method:

* As an extension to familiar table-based planning methods, the method presented appears easier to learn, use, and remember than the Wheel.

* Table method is not subject to device calibration errors.

* Results are more repeatable. This is no uncertainty in eye-table alignment through three layers of plastic, and no possibility of inaccurate arrow alignment.

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Advantages of the Wheel:

* Requires no calculation of repetitive nitrogen time, thereby eliminating Table III.
* Requires no arithmetic save when calculating time intervals.
* Allows slightly more bottom time.
* Allows 5 ft depth increments rather than 10 ft increments, allowing more bottom time if instruments and profile allow sufficiently accurate planning and execution.

CONCLUSIONS

While the very simple method presented in this paper maintains all aspects of the DSAT model, and the multi-level capabilities of the Wheel have been moderately tested, caution is urged when performing multi-level diving. Computer simulations show that very high gas loadings in the slower compartments are easily achievable when multi-level profiles are allowed, and extra conservatism is advised. Avoiding the table limits by several groups at all stages of the profile, monitoring ascent rates using available measuring devices, and performing ascents at slower than 60 fpm are all wise precautions. Finally, including a safety stop of 5 minutes at 15 feet after every dive is strongly encouraged.

With these safety precautions in mind, we believe that the method presented in this paper provides the easiest, simplest technique currently available for calculating multi-level profiles using the DSAT Recreational Dive Planner.

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