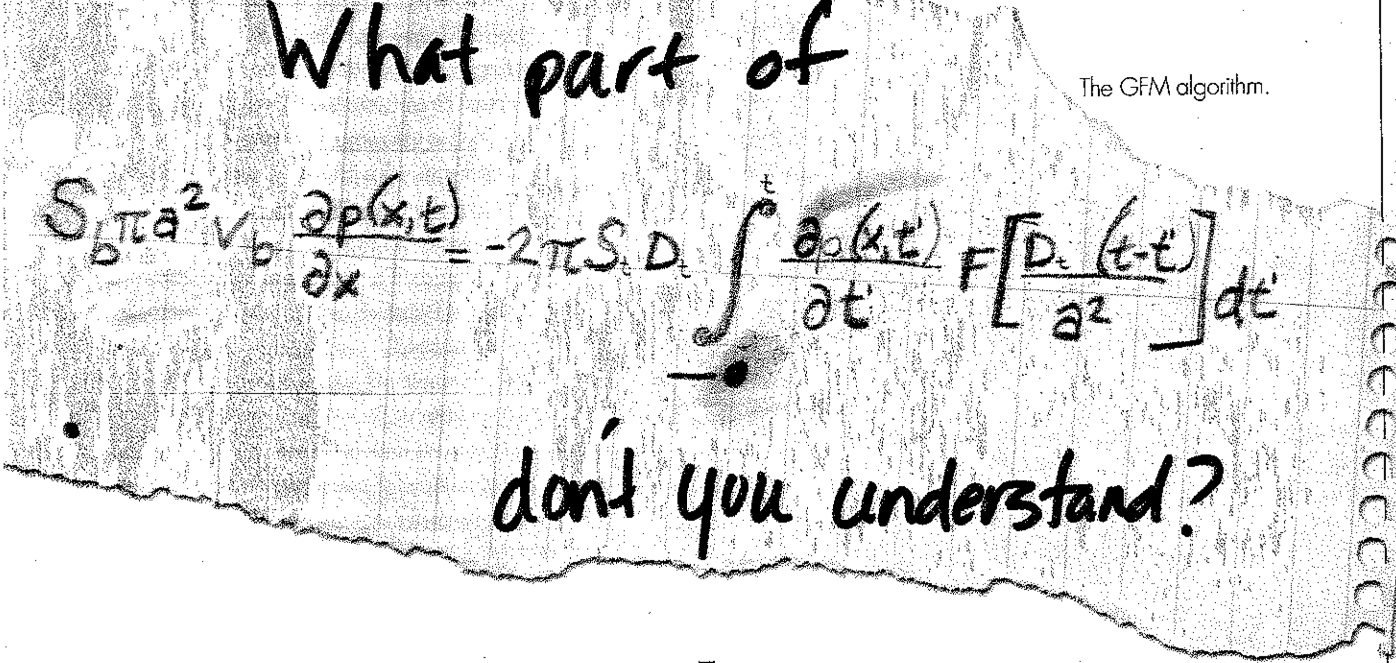

The GFM algorithm.

Introducing the *Gas Formation Model*

by [illegible]hn Lewis, PhD and Steven Crow, PhD

For nearly 100 years, divers have relied on Haldanean decompression models to determine no stop limits and decompression requirements. These models have an excellent track record and will likely continue to be useful for many years, but like all models they have limits beyond which they become less reliable. Since the mid 1980s, researchers have been developing *free gas models* (sometimes called "bubble models") in an attempt to extend the useful predictive limits of decompression models.

One of the newest and most promising free gas models is the Gas Formation Model (GFM), which is the result of a research program initiated by Bob Hollis of Oceanic in 2003. Because I had worked on the decompression model used in Oceanic and Aeris computers, Hollis appointed me project manager of the GFM project in collaboration with Steven C. Crow, PhD, a well-known physicist and expert in applied mathematics. Our goal was to develop a new gas model based on human physiology, with a thorough validation based on comparing model predictions with documented experimental data that included the works of physician and US Navy Captain Albert R. Behnke (1919-1990); Merrill P. Spencer, MD (1922-2006); Andrew A. Pilmanis, PhD; and M[illegible]hael R. Powell, PhD, among others. The GFM met the design [illegible]rements, and was patented (U.S. Patent No. 7.313.483) on 25 December 2007.

Haldanean Versus Free Gas Models

To understand how GFM differs from existing models, it's important to distinguish between conventional Haldanean models and free gas models. In forming his model, Haldane hypothesized that free gas formation (i.e., nitrogen bubbles) after a dive could be avoided by limiting the amount of nitrogen in solution in the body. In other words, Haldane believed if you have free gas, you get bent, and if you don't have free gas, you don't get bent.

Based on his experiments with goats, Haldane concluded one could saturate at one pressure and safely decompress to one-half of that pressure without forming bubbles. In addition, his experiments showed the body doesn't absorb and release nitrogen on a single time scale, so he modeled the body with five tissues having different half-times from 5 to 75 minutes. Since Haldane, Robert D. Workman, MD; Albert A. Bühlmann, MD; and Rogers and others have refined Haldane's original model with different half-times and allowable saturation depths, but these are all accurately characterized as Haldanean models. Most PADI Members are familiar with the basic concepts behind these models from the PADI Divemaster course and *The Encyclopedia of Recreational Diving.*

Although Haldanean concepts are based on avoiding decompression sickness by keeping free gas from forming, in reality many bends-free dives produce free gas. We know this from the early work of Spencer and Pilmanis, who were among the first to use Doppler ultrasound to detect bubbles in venous flow after a dive. Since then, Doppler measurements have documented the presence of free gas following many bends-free dives, and dive physiologists consider free gas formation without decompression sickness (DCS) a fact, not a hypothesis.

Over the years, Haldanean models have handled the effects of free gas through the previously mentioned revisions, which is why they work even though the underlying assumptions are not completely accurate. That is, with respect to the calculations, the model chooses half times and allowable saturation to conform to what manned dives show work. Free gas models, on the other hand, *calculate* the formation of free gas and attempt to predict how free gas affects no stop limits and decompression requirements.

Free Gas Formation

So when and where does free gas form? At present, if you have not dived recently (within 12-24 hours), you have no free gas within your body (or at least so little it can be disregarded). During your first dive (non repetitive), you don't have any free gas in your body until you ascend and surface. Free gas forms during *decompression*, and on no stop dives, does so largely *after* you reach the surface. Therefore, free gas may be an issue on a repetitive dive, but not on a first dive.

In modeling free gas, we not only need to know that it forms, but *where* and *when* it forms. Free gas formation is physiologically complex, but we can create a useful model based on relatively basic concepts. First, we know from Doppler measurements that free gas forms within the vascular system, and that it forms when the sum of the tensions of the constitutive gases (oxygen, carbon dioxide, water vapor and nitrogen) exceeds the local ambient pressure. We also know that formation requires a surface, and the body's capillary beds provide by far the greatest surface area in the body. Therefore, it follows that most free gas forms intravascularly (i.e., in the bloodstream), and a reasonable hypothesis is that the volume of extra-vascular gas (bubbles in tissues other than the bloodstream) is directly related.

The Gas Formation Model

The importance of free gas in a diver's body has been recognized since Haldane's time, if not before. In 1986, physicist David E. Yount, PhD, and D.C. Hoffman presented a quantitative means for computing the expansion of free gas bubbles in the body, and their work on the Varying Permeability Model (VPM) became the basis for the Reduced Gradient Bubble Model (RGBM) introduced by physicist Bruce Wienke. The RGBM assumes gas bubbles reside in tissue at all times and treats the expansion of a single, typical bubble, rather than the volume of free gas in the body as a whole. As presently implemented in available dive computers, it uses mainframe computer computations to modify Haldane gradients to allow for the effects of three specific circumstances: Repetitive, reverse profile (deeper than previous) and multiday diving.

GFM calculates the total volume of free gas *in real time* in response to the actual circumstances of a dive. To do so, GFM makes use of the fact that free gas forms most readily on boundaries between media (substances) with differing properties. You can test that bit of science by opening a bottle of soda water and looking at where the bubbles form (on the inside surface of the bottle, not in the middle of the liquid). The free gas actually forms in a microscopic layer next to the surface, and capillary action causes the gas to consolidate into bubbles.

GFM transforms these principles into an algorithm for computing the total amount of free gas in a diver's body. It performs the computations in real time by solving a set of equations that account for the inhalation of inert gas (nitrogen) by the lungs, and its subsequent transfer into the blood stream, absorption by body tissues, release back into the bloodstream during ascent and exhalation by the lungs. The GFM algorithm is super sophisticated, but there is no mystery about what it does: It computes and predicts the volume of free gas in millilitres. As an example, GFM calculates a typical dive to Recreational Dive Planner limits results in the release of a peak volume of about 30 millilitres/1 ounce of free gas after ascent.

GFM Predictions: What's the Same and What Differs

Interestingly, even with advances in free gas modeling, when it comes to determining maximum allowable decompression stress (i.e., the amount of dissolved nitrogen and/or free gas) without DCS, we must turn to human test data because no model creates these limits. Rather, we look at what real world dive results tell us, and impose those limits on the model. When we improve a model, we extend the range and circumstances over which the model's predictions conform with real world data. Furthermore, it's important to note that while there's actually a *range* of acceptable decompression stress due to variations in physiology, dive circumstances, risk acceptance, etc., to create a model you must draw a line somewhere, and only a *single* number can be used for – to give an example – a no stop limit.

Depth	GFM	RDP
40	2:09	2:20
50	1:13	1:20
60	0:53	0:55
70	0:38	0:40
80	0:30	0:30
90	0:23	0:25
100	0:18	0:20
110	0:15	0:16
120	0:13	0:13
130	0:11	0:10
140	0:09	0:08
150	0:08	—

First dive, single depth no stop limits. In developing the GFM, we turned to Diving Science and Technology's (DSAT) classic experiments conducted by Michael R. Powell in 1987 and 1988 during validation tests of the Recreational Dive Planner. In the beginning of our research, we chose 30 metres/100 feet for 20 minutes. However, for a statistically more meaningful value, we weighted values in the data by the number of exposures Powell tested, which changed this slightly but in the end produced GFM no stop limits that are remarkably similar to the DSAT RDP distributed by PADI.

Repetitive dives. GFM no stop predictions for repetitive dives may depart substantially from existing models, depending upon specific dive behaviors. Recall that most free gas forms after surfacing, and it is the existence of free gas that alters the uptake and release of nitrogen on subsequent dives. Therefore, GFM predicts substantially reduced repetitive no stop times if you have very short surface intervals. In these instances, GFM is similar to RGBM despite the two models having virtually nothing in common with respect to calculation details. If you make a safety stop as required by the RDP (three minutes at 5 metres/15 feet), then GFM's repetitive no stop predictions are quite similar to the RDP's, even with very short surface intervals. We'll come back to this.

Multilevel diving. What is quite remarkable about multilevel diving is that while it resulted from Haldanean model concepts, the GFM model predicts allowable no stop times that are quite similar to tested values. GFM therefore not only allows multilevel dives, but will extend your dive time much as you're used to already.

GFM in Action

You can see how GFM differs from other models by looking at its prediction in action as you would see in a dive computer. As mentioned, free gas forms during the surface interval, reaching a theorized peak value typically during the first 10 or 15 minutes. GFM can predict the consequences of this in real time, so that if you were to dive to a no stop limit and begin to ascend rapidly, the predicted free gas value would exceed the allowable maximum and the computer would require a decompression stop. Slowing the ascent may eliminate the need for the stop or shorten its duration.

Using a dive computer, GFM stands apart with respect to safety stops, and reveals why safety stops are so beneficial. If you make a deep stop and/or a stop at 5 metres/15 feet, a GFM dive computer would show you the reduction in future peak free gas volume. Our calculations show, for example, that the predicted peak volume initially falls about *one percent per second* during a typical safety stop, which translates into lower DCS stress upon surfacing and longer repetitive no stop times for a given surface interval. From an instructional point of view, imagine how easy it is to demonstrate to students the benefits of safety stops.

Mathematically, the relationship between peak free gas volume and DCS probability is that reducing peak free gas volume by 20 percent reduces DCS risk by 50 percent. Both GFM and actual human test dives show that both deep stops and a final stop at or near 5 metres/15 feet can reduce the predicted DCS risk by as much as a factor of 10 or more.

The more we learn about safety stops, the more benefit we discover. Haldanean-based computers and tables are still as reliable as ever and will more than likely continue to be used for many years, but GFM tells us what we already knew: Make safety stops.

GFM Availability

Given that the development of GFM was an Oceanic project, it's hardly surprising Oceanic plans to introduce GFM-based dive computers. As of this writing, the anticipated roll out date is October 2008 at the DEMA Show in Las Vegas, Nevada, USA. ◆