DEEP STOPS

B.R. Wienke
NAUI Technical Diving Operations
Tampa, Florida

The Basics

Deep stops – what are they?

Actually, just what the name suggests. Deep stops are decompression stops made at deeper depths than those traditionally dictated by classical (Haldane) dive tables or algorithms. They are fairly recent (last 15 years) protocols, suggested by modern decompression theory, but backed up by extensive diver practicum with success in the mixed gas and decompression arenas - so called technical diving. Tech diving encompasses scientific, military, commercial, and exploration underwater activities. The impact of deep stops has been a revolution in diving circles. So have slower ascent rates across recreational and technical diving. In quantifiable terms, slower ascent rates are very much akin to deep stops, though not as pronounced as decompression stops. Deep stops plus slow ascent rates work together. And they work together safely and efficiently.

Many regard deep stops as the most significant development in modern diving. Here's why.

Deep stops usually reduce overall decompression time (hang time) too. And when coupled to the use of helium in the breathing mixture (trimix) to reduce narcotic effects of nitrogen, technical divers report feeling much better physically today when they leave the water. The reduction in hang time ranges from 10% to as high as 50%, depending on diver, mix, depth, and exposure time. Feeling better while decompressing for shorter periods of time is certainly a win-win situation that would have been thought an impossibility not too long ago. The basic tenets of Haldane decompression theory (and neo-classical dissolved gas theory) postulate that deeper exposures (deep stop plus bottom time) incur greater offgassing penalties in the shallow zone. Just look at those deco tables based upon Haldane methodolgy. You know, the ones you used before you bought a dive computer. Even the bulk of dive computers still stage divers using Haldane approaches. But that is changing too. New computers invoking the dual science of dissolved gases and bubbles are emerging. And deep stops are a natural result of their operation.

The depth at which the first deep stops are made can be dramatically deeper than those required by conventional tables. For instance, a dive to 300 ft on trimix for 30 minutes, with switches to progressively higher enrichments of nitrox at 120, 70, and 20 ft, calls for the first deep stops in the 250 ft range. Conventional tables require the first stops in the 100 ft range.

For most early technical divers, obtaining deep and mixed gas decompression tables constituted one of many road-blocks to safe deep and exploration diving. Existing tables ranged from ultra-conservative as an insulation against harm to a hodgepodge of protocols based on total misunderstanding. From this background, and driven by a need to optimize decompression schedules, deep stops steadily advanced as a safe and efficient change to diver staging. And this even though formal tests were usually not conducted in controlled environments, like hyperbaric chambers.

The History

Though deep stops are regarded as a major development in diving, the first experiments were more trial-and-error than scientific in nature. Just like so many other important developments in the real world. Underlying science with mechanistics would follow in the late 80s and 90s, albeit with considerable flack from the *experts* of the time. And so with helium breathing mixtures, the voodoo gas that "does not decompress".

Maybe experiments is too strict a description. Individuals, particularly in the cave diving community, toyed with decompression regimens in hopes of mimimizing their decompression time. The cave exploration Woodville Karst Plain Project (WKPP), mapping subsurface topographies in Florida, pioneered deep stop technology, establishing many rule-of-thumb protocols to be imposed on conventional tables. Irvine and Jablonski stand at the forefront here, successfully conducting 6 hour dives at 280 ft in the Wakulla cave complex with deep stop decompression times of 12 hours versus traditional Haldane hang times of 20 hours. Also, the horizontal penetrations of 19,000 ft are world records (Guinness). Figure 1 sketches comparison profiles, along with mixtures, times, switches, and depths. Spectacular is a gross understatement. Certainly such contributions to diving science and spinoff model validation parallel Haldane a hundred years ago.

WKPP initially found that common decompression assumptions subjected divers to extremely long decompression obligations, and ones that, regardless of their length, were inefficient. Divers also felt badly upon surfacing from extended deco dives. Operationally (many dives over many years), WKPP divers found that the insertion of deep stops permitted shortening of shallower stops with an overall reduction in total decompression time. The decompression schedule was more effective, with effectiveness represented by subjective diver health and sense of well being.

But even before these deep stop protocols emerged, utilitarian diving practices among diving fisherman and pearl gatherers suggested traditional staging was in need of rethinking. And early deco models, such as the so called thermodynamic model of Hills, suggested why and how. Deep stops likely evolved from cognizance of both by tech divers.

Pearling fleets, operating in the deep tidal waters off northern Australia, employed Okinawan divers who regularly journeyed to depths of 300 ft for as long as one hour, two times a day, six days per week, and ten months out of the year. Driven by economics, and not science, these divers developed optimized decompression schedules empirically. As reported by Le Messurier and Hills, deeper decompression stops, but shorter decompression times than required by Haldane theory, were characteristics of their profiles. Such protocols are entirely consistent with minimizing bubble growth and the excitation of nuclei through the application of increased pressure, as are shallow safety stops and slow ascent rates. With higher incidence of surface decompression sickness, as expected, the Australians devised a simple, but very effective, in-water recompression procedure. The stricken diver is taken back down to 30 ft on oxygen for roughly 30 minutes in mild cases, or 60 minutes in severe cases. Increased pressures help to constrict bubbles, while breathing pure oxygen maximizes inert gas washout (elimination). Recompression time scales are consistent with bubble dissolution experiments.

Similar schedules and procedures have evolved in Hawaii, among diving fishermen, according to Farm and Hayashi. Harvesting the oceans for food and profit, Hawaiian divers make beween 8 and 12 dives a day to depths beyond 350 ft. Profit incentives induce divers to take risks relative to bottom time in conventional tables. Repetitive dives are usually necessary to net a school of fish. Deep stops and shorter decompression times are characteristics of their profiles. In step with bubble and nucleation theory, these divers make their deep dive first, followed by shallower excursions. A typical series might start with a dive to 220 ft, followed by 2 dives to 120 ft, and culminate in 3 or 4 more excursions to less than 60 ft. Often, little or no surface intervals are clocked between dives. Such types of profiles literally clobber conventional tables, but, with proper reckoning of bubble and phase mechanics, acquire some credibility. With ascending profiles and suitable application of pressure, gas seed excitation and bubble growth are likely constrained within the body's capacity to eliminate free and dissolved gas phases. In a broad sense, the final shallow dives have been tagged as prolonged safety stops, and the effectiveness of these procedures has been substantiated *in vivo* (dogs) by Kunkle and Beckman. In-water recompression procedures, similar to the Australian regimens, complement Hawaiian diving practices for all the same reasons.

So deep stops work and are established. But why?

The Science

The science is fairly simply. It's just a matter of how dissolved gases and bubbles behave under pressure changes. We use to think that controlling dissolved gas buildup and elimination in tissue and blood was the basis for staging divers and astronauts. And that bubbles didn't form unless dissolved gas trigger points were exceeded. At least that was the presumption that went into conventional (Haldane) tables. Chemists, physicists, and engineers never bought off on that. When *silent bubbles* were tracked in divers not experiencing any decompression problems, of course, this changed. And since bubbles need be controlled in divers, focus changed and switched from just-dissolved-gases to both-bubbles-and-dissolved-gases. Within such framework, deep stops emerge as a natural consequence. So do *dual* phase (bubbles plus dissolved gas) models.

Here's how.

To eliminate dissolved gases, the driving *outgassing gradient* is maximized by reducing ambient pressure as much as possible. That means bringing the diver as close to the surface as possible. But, to eliminate bubbles (the gases inside them), the *outgassing gradient* is maximized by increasing ambient pressure as much as possible. That means holding the diver at depth when bubbles form. Deep stops accomplish the latter.

But the staging paradigm has a few more wrinkles.

Clearly, from all of the above, dominant modes for staging diver ascents depend upon the preponderance of free (bubbles) or dissolved phases in the tissues and blood, their coupling, and their relative time scales for elimination. This is now (will always be) a central consideration in staging hyperbaric or hypobaric excursions to lower ambient pressure environments. The dynamics of elimination are directly opposite, as stated and depicted in Figure 2. To eliminate dissolved gases (central tenet of Haldane decompression theory), the diver is brought as close as possible to the surface. To eliminate free phases (coupled tenet of bubble decompression theory), the diver is maintained at depth to both crush bubbles and squeeze gas out by diffusion across the bubble film surface. Since both phases must be eliminated, the problem is a playoff in staging. In mathematical terms, staging is a *minimax* problem, and one that requires full blown dual phase models, exposure data, and some concensus of what is an acceptable level of DCI incidence.

Enter dual phase models which generate deep stops consistently within free and dissolved gas phase constraints.

The Models And Diving Algorithms

The earliest prescriptions for deep stops were imbedded in conventional tables. Something like this was employed, trial and error, and this one is attributed to Pyle, an underwater fish collector in Hawaii:

1. calculate your decompression schedule from tables, meters, or software;
2. half the distance to the first deco stop and stay there a minute or two;
3. recompute your decompression schedule with time at the deep stop included as way time (software), or bottom time (tables);
4. repeat procdeure until within some 10 -30 ft of the first deco stop;
5. and then go for it.

Within conventional tables, such procedure was somewhat arbitrary, and usually always ended up with a lot of hang time in the shallow zone. Such is to be expected within dissolved gas deco frameworks. So, deep stop pioneers started shaving shallow deco time off their schedules. And jumped back into the water, picking up the trial and error testing where it left off.

Seasoned tech divers all had their own recipes for this process. And sure, what works works in the diving world. What doesn't is usually trashed.

Concurrently, full up dual phase models, spawned by the inadequacies and shortcomings of conventional tables, emerged on the diving scene. Not only did deep stops evolve self consistently in these models, but dive and personal computers put deco scheduling with these new models in the hands of real divers. And real on the scene analysis and feedback tuned arbitrary, trial and error, and theoretical schedules to each other.

One thing about these bubble models, as they are collectively referenced, that is common to all of them is deeper stops, shorter decompression times in the shallow zone, and shorter overall deco times. And they all couple dissolved gases to bubbles, not focusing just on bubbles or dissolved gas.

Without going into gory details, a few of the more important ones can be summarized. The thermodynamic model of Hills really got the ball rolling so to speak:

1. thermodynamic model (Hills, 1976) – assumes free phase (bubbles) separates in tissue under supersaturation gas loadings. Advocates dropout from deco schedule somewhere in the 20 ft zone.
2. varying permeability model (Yount, 1986) – assumes preformed nuclei permeate blood and tissue, and are excited into growth by compression-decompression. Model patterned after gel bubbles studied in the laboratory.
3. reduced gradient bubble model (Wienke, 1990) – abandons gel parametrization of varying parmeability model, and extends bubble model to repetitive, altitude, and reverse profile diving. Employed in recreational and technical diving meters, and basis for new NAUI tables;
4. tissue bubble diffusion model (Gernhardt and Vann, 1990) – assumes gas transfer across bubble interface, and correlates growth with DCI statistics. Probably employed in the commercial diving sector.

Not all these models have seen extensive field testing, but since they are all similar, the following, addressing testing and validation of the reduced gradient bubble model (RGBM), holds in broad terms. The 1000s of tech dives on deep stops, of course, already validate deep stop technology and models to most, but the testing and validation described next spans deep stops to recreational diving in single model framework. And that is a very desired feature of any decompression theory and/or model.

The Testing And Validation

Models need validation and testing. Often, strict chamber tests are not possible, economically nor otherwise, and bubble models employ a number of benchmarks and regimens to underscore viability. The following are some supporting the RGBM phase model and NAUI released nitrox, heliox, and trimix diving tables:

1. counterterror and countermeasures (LANL) exercises have used the RGBM (full up iterative deep stop version) for a number of years, logging some 456 dives on mixed gases (trimix, heliox, nitrox) without incidence of DCI – 35% were deco dives, and 25% were repets (no deco) with at least 2 hr SIs, and in the forward direction (deepest dives first);
2. NAUI Technical Diving has been diving the deep stop version for the past 3 yrs, some estimated 500 dives, on mixed gases down to 250 fsw, without a single DCI hit. Some 15 divers, late 1999, in France used the RGBM to make 2 mixed gas dives a day, without mishap, in cold water and rough seas. Same in the warm waters of Roatan in 2000 and 2001.
3. modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse profile, repetitive, and multiday diving), as coded into ABYSS software and Suunto, Plexus, and Hydrospace decometers, lower an already low DCI incidence rate of approximately 1/10,000 or less. More RGBM decompression meters, including mixed gases, are in the works;
4. a cadre of divers and instructors in mountainous New Mexico, Utah, and Colorado have been diving the modified (Haldane imbedded again) RGBM at altitude, an estimated 450 dives, without peril. Again, not surprising since the altitude RGBM is slightly more conservative than the usual Cross correction used routinely up to about 8,000 ft elevation, and with estimated DCI incidence less than 1/10,000;
5. within decometer implementations of the RGBM, only two DCI hits have been reported in nonstop and multidiving categories, beyond 40,000 dives or more, up to now;
6. extreme chamber tests for mixed gas RGBM are in the works, and less stressful exposures will be addressed shortly – extreme here means 300 fsw and beyond;
7. probabilistic decompression analysis of some selected RGBM profiles, calibrated against similar calculations of the same profiles by Duke, help validate the RGBM on computational bases, suggesting the RGBM has no more theoretical risk than other bubble or dissolved gas models (Weathersby, Vann, Gerth methodology at USN and Duke).
8. all divers and instructors using RGBM decometers, tables, or NET software have been advised to report individual profiles to DAN Project Dive Exploration (Vann, Gerth, Denoble and many others at Duke).
9. ABYSS is a NET sotware package that offers the modified RGBM (folded over the Buhlmann ZHL) and the full up, deep stop version for any gas mixture, has a fairly large contingent of tech divers already using the RGBM and has not received any reports of DCI,
10. NAUI Worldwide is releasing a set of tested no-group, no-calc, no-fuss RGBM tables for recreational sea level and altitude air and nitrox diving, with simple rules linking surface intervals, repets, and flying-after-diving.

It almost goes without saying that models such as these have reshaped our decompression horizons – and will continue doing so.

One last item concerning deep stops remains. What about controlled laboratory testing?

The Experiments

Doppler and utrasound imaging are techniques for detecting moving bubbles in humans and animals following compression-decompression. While bubble scores from these devices do not always correlate with the incidence of DCI, the presence or non-presence of bubbles is an important metric in evaluating dive profiles.

So let's consider some recent tests, and see how they relate to deep stops.

Analysis of more than 16,000 actual dives by Diver's Alert Network (DAN), prompted Bennett to suggest that decompression injuries are likely due to ascending too quickly. He found that the introduction of deep stops, without changing the ascent rate, reduced high bubble grades to near zero, from 30.5% without deep stops. He concluded that a deep stop at half the dive depth should reduce the critical fast gas tensions and lower the DCI incidence rate.

Marroni concluded studies with DAN's European sample with much the same thought. Although he found that ascent speed itself did not reduce bubble formation, he suggested that a slowing down in the deeper phases of the dive (deep stops) should reduce bubble formation. He will be conducting further tests along those lines.

Brubakk and Wienke found that longer decompression times are not always better when it comes to bubble formation in pigs. They found more bubbling in chamber tests when pigs were exposed to longer but shallower decompression profiles, where staged shallow decompression stops produced more bubbles than slower (deeper) linear ascents. Model correlations and calculations using the reduced gradient bubble model suggest the same.

Cope studied 12 volunteer divers performing conventional (Haldane tables) dives with and without deep stops. His results are not available yet – but should be very interesting.

The Bottom Line

To most of us in the technical and recreational diving worlds, the bottom line is simple.

Deep stop technology has developed successfully over the past 15 years or so. Tried and tested in the field, now some in the laboratory, deep stops are backed up by diver success, confidence, theoretical and experimental model underpinnings, and general acceptance by seasoned professionals.

Amen.

And dive on.

Author Sketch

Bruce Wienke is a Program Manager in the Nuclear Weapons Technology/ Simulation And Computing Office at the Los Alamos National Laboratory (LANL), with interests in computational decompression and models, gas transport, and phase mechanics. He contributes to underwater symposia, educational publications, technical periodicals and decompression workshops, having authored seven monographs *(Technical Diving In Depth, Decompression Theory, Physics, Physiology And Decompression Theory For The Technical And Commercial Diver, High Altitude Diving, Basic Diving Physics And Applications, Diving Above Sea Level, Basic Decompression Theory And Application)* and over 200 technical journal articles. Diving environs include the Caribbean, South Pacific, Asia, inland and coastal United States, Hawaii, and polar Arctic and Antarctic in technical, scientific, military, and recreational activities. He functions on the LANL Nuclear Emergency Strategy Team (NEST), in exercises involving Special Warfare Units (SEAL, Delta), above and below water. He heads Southwest Enterprises, a consulting company for computer research and applications in wide areas of applied sciences and diving, functions as an Expert Witness in diving litigation, especially in areas of decompression theory, meter operations. algorithms. dive table applications.

Wienke is an Instructor Trainer/Tech Instructor with the National Association Of Underwater Instructors (NAUI), serves on the Board Of Directors (Vice Chairman for Technical Diving, Technical and Decompression Review Board Member), is a Master Instructor with the Professional Association Of Diving Instructors (PADI) in various capacities (Instructor Review Committee), is an Institute Director with the YMCA, and is an Instructor Trainer/Tech Instructor with Scuba Diving International/Technical Diving International (SDI/TDI). Wintertime he hobbies skiing, coaching, and teaching as a Racing Coach and Instructor, certified United States Ski Coaches Association (USSCA) and Professional Ski Instructors of America (PSIA), and races in the United States Ski Association (USSA) Masters Series Competition, holding a 8 NASTAR racing handicap. Other interests include tennis, windsurfing, and mountain biking. He quarterbacked the 63 Northern Michigan Wildcats to an NCAA II Championship (Hickory Bowl), earning All American honors.

Wienke received a BS in physics and mathematics from Northern Michigan University, MS in nuclear physics from Marquette University, and PhD in particle physics from Northwestern University. He belongs to the American Physical Society (APS), American Nuclear Society (ANS), Society Of Industrial And Applied Mathematics (SIAM), South Pacific Underwater Medical Society (SPUMS), Undersea And Hyperbaric Medical Society (UHMS), and American Academy Of Underwater Sciences (AAUS). He is a Fellow of the American Physical Society, and a Technical Committee Member of the American Nuclear Society.

Wienke, a former dive shop owner in Santa Fe, presently serves as a Consultant for decompression algorithms in the Industry. He works with DAN on applications of high performance computing and communications to diving, and is a Regional Data Coordinator for Project Dive Exploration. Scubapro, Suunto, Abysmal Diving, and Atomic engage him as Consultant for meter algorithms. He is the developer of the Reduced Gradient Bubble Model (RGBM), a dual phase approach to staging diver ascents over an extended range of diving applications (altitude, nonstop, decompression, multiday, repetitive, multilevel, mixed gas, and saturation). Suunto, Hydrospace, Plexus and other dive computers incorporate the RGBM into staging regimens, for recreational and technical diving. ABYSS, a commercial software product, features some of the RGBM dynamical diving algorithms developed by him for Internet users and technical divers. He is also Associate Editor for the International Journal Of Aquatic Research And Education, and is a former Contributing Editor of *Sources*, the NAUI Training Publication. The NAUI RGBM Tables and related products have been developed exclusively for NAUI Technical Diving and NAUI Training Operations.