The *Atlantis* Series and Other Deep Dives

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Introduction

Diving deeper into the water became operationally important at the turn of the century, with the availability of more sophisticated breathing equipment and the use of compressed air from the surface. Practical limits were investigated by Haldane[1] (Boycot et al., 1908) and set at a useful depth of 90 fsw in well-trained individuals, because of the onset of severe narcosis, leading to reductions in manual dexterity and severe mental impairment. It was noted, however, that brief exposures were better tolerated. A proposal in the U.S. Navy by Thompson (1919) to utilize helium as inert gas at greater depths because of reduced breathing resistance did not achieve success because of the reluctance of operators to abandon "safe" air tables and the unexpected risks of the decompression. It was left to two individuals working alone outside the U.S. Navy, Mr. Nohl and Dr. End, to demonstrate the practical use of helium-oxygen mixtures into a solo dive to 420 feet in Lake Michigan[2] (Nohl, 1938). The U.S. Navy acknowledged the practicality of heliox diving by rapidly adopting this gas in a large multiperson rescue operation in 1939 to 243 fsw for the salvage of the crew of the submarine USS *Squalus* in the open sea.

The "High Pressure Nervous Syndrome"

During the early 1960s, relatively rapid compression in oxygen-helium to depths of 600 fsw and 800 fsw demonstrated surprising decrements in motor and intellectual performance, while a narcotic effect had been predicted based on helium lipid-solubility. These decrements were accompanied by dizziness, nausea, vomiting and marked tremors of the hands, arms and torso. Rapid compression in helium-oxygen was clearly associated with the phenomenon. Brauer (1971)[3] had reported similar neurological signs in various mammalian species at increased pressure and noted that the intensity of the symptoms was increased in species with more developed cortical structures. Together, the complex picture was named "High-Pressure Nervous Syndrome" (HPNS). HPNS effects were well characterized in its onset, especially in selected subjects. Rapid compression was usually accompanied by an increase in the tremor activity in subjects with subsequent attention during stages at pressure. A different component of HPNS that appeared less adaptable was the progressive reduction of overall EEG electrical activity as a function of increasing depth. This last component showed no improvement over time and became more intense with increasing depth of the stage. Multiple study dives from the early 1970s attempted to tease out various components to suppress HPNS and to achieve compression profiles and gas mixtures compatible with practical dives: Even after best subject selection, exponential compression, use of static stages and saturation exposures with excursions from shallower depths, it was not possible to ablate HPNS. It appeared necessary to add "anesthetics" such as nitrogen to produce a working gas mixture at depth. This gas mixture was quickly named "trimix" (helium, nitrogen, oxygen).

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Another factor was also studied in detail at Duke University in 1974: the effect of CO_2 on narcosis (Bennett et al. 1974)[4]. In a study completed with several volunteers at 287 fsw, marked narcosis was demonstrated while breathing compressed air but not helium-oxygen at the same PO_2. Gas analysis of arterial blood showed that $PaCO_2$ was not different while breathing the two gas mixtures, indicating that significant narcosis can co-exist with normal (and low) arterial CO_2.

Trimix mixtures were used empirically in the '70s by Vigreux at COMEX (personal communication), with high levels of nitrogen, for thermal comfort, improved speech intelligibility and gas mixture cost reduction, but not in response to the intellectual probe to test for a "pharmacological" reversal of untoward helium effects (Bennett et al.)[5]. The clear formulation of this strategy awaited 1972 at Duke University with the arrival of Dr. Peter Bennett. His plan was to utilize nitrogen as a pharmacologic narcotic in addition to helium-oxygen to ameliorate HPNS onset and manifestations.

The *Atlantis* Series at Duke University

Several short duration dives of three or four volunteers to 700, 1,000 and 1,400 fsw were completed in preparation to the deeper dive series to calibrate nitrogen concentrations effective to minimize or reverse the tremors. The preliminary empirical studies suggested that 10 percent N_2 would be sufficient to minimize tremors. Further theoretical and biological observations on lipid monolayer surface tension changes with exposure to various gases appeared to confirm the validity of this N_2 concentration (Simon et al.)[6].

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Thus on April 19, 1979, the first of the *Atlantis* dives was initiated at Duke University F.G. Hall Laboratory for Environmental Studies with three trained subjects as volunteers inside the chambers. A large group of research specialists were on hand in the laboratory to provide gas mixtures, precise environmental controls and comfortable conditions, exercise studies with intra-arterial catheters, blood and expired gas analysis, psychomotor and psychological evaluations, for a multiday study. The principal goal was to assess HPNS at different times while breathing Trimix 5 (5 percent N_2 in helium-oxygen). After the first day compression an overall reduction of 30 percent in psychomotor performance was measured at 1,509 fsw with significant nausea and tremors. Fortunately, the psychomotor performance at the beginning of the second day was reduced by only 10 percent, and an extensive and complex set of exercise studies could be completed, demonstrating more dyspnea during heliox breathing at a work-intensity level less than in Trimix 5, despite the lesser breathing-gas density. Modifications in EEG power were noted from day 1, with ameliorations during the subsequent days, but the EEG never quite returned to normal (Salzano et al., 1984).[7]

Atlantis II was primarily a Trimix 10 dive completed a few months later. The same three subjects were tested first at 1,500 fsw depth, where the subjects arrived "remarkably well" with minimal performance reduction. During the subsequent three days they demonstrated excellent work capacity, up to exercise levels of 180 W, with mild CO_2 accumulation during work; and less dyspnea than before despite substantial respiratory load was induced by Trimix 10. The excellent performance was further tested by compressing the habitat further on helium and oxygen, thereby reaching 2,132 fsw in Trimix 7 in excellent conditions for physical and psychological performance.

Atlantis III followed a few months later to 2,250 fsw while breathing Trimix 10. Two new subjects plus a veteran of the previous Atlantis I and II reached and stayed 4.5 days at this depth, with excellent work performance and no dyspnea. This dive was complex and required more than 40 days at pressure but showed that depths of 1,500 to

2,000 fsw could be reached in stages of one or two days with a crew able to start work in excellent psychological conditions and capable of moderate to heavy physical work.

Atlantis IV proved more challenging due to the Trimix 5 choice, but especially the use of a subject who experienced euphoric hallucinations during the later stages of compression, became hypomanic over several hours and required medication. He slowly improved, but the joint work/exercise/performance needed to be severely curtailed. This experience further proved how the subject selection was crucial in the closed, interdependent work environment of a crew depending heavily on collaborative efforts to produce team results. During the five years of *Atlantis* dives and during the preparatory dives, another precious asset that was developed was the pioneering work of surface-based technicians, doctors, physiologists and other specialists who supported the studies, readied unique equipment and adapted to grueling study schedules to often improvise a rapid "fix" in the studies that had in fact limited resources but very resourceful people.

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Conclusions

Subsequent deep diving research continued in France, especially at COMEX (Marseilles), in Norway (NUTEC) and in Germany (GUSI-Duke University collaboration). This last joint enterprise lasted several years, from 1983 to 1986, expanded the experience of Trimix 5, exposed several divers to 14 dives to depths between 980 and 1,968 fsw and added significant numbers of volunteers to the operational experience of deep diving. In all, the collaborative studies generated 1,919 mean-days in saturation for more than 225 days.

In recent years the interest for staged deep diving has been reduced as more suitable submersible diving robots are being utilized, but the principal results of these years of experimentation remain forever valid. The corroboration of experimental compression, stages and Trimix diving has demonstrated the practical utility of deep diving from 1,000 to 2,300 fsw in an economical and practical way, and Dr. Peter Bennett was instrumental at Duke University to pioneer the way.

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