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Diving Technologies and Techniques for the 21st Century

Front Cover: J.F. White Contracting Company diver test pilots the Exosuit Atmospheric Diving System (photo by M. Lombardi).
Back Cover: Background image–Scientific diver Jeff Godfrey (UConn) explores the vertical Mesophotic coral ecosystem using a mixed-gas rebreather (photo by M. Lombardi, courtesy of National Geographic Society/Waitt Grants Program). Thumbnail images, clockwise from top left: PVC structure for mounting camera for benthic surveys (photo by Barrett Brooks); HUD system from Sieber et al. paper, this issue; Figure 4 from Clark paper, this issue; Rebreather prototype from Sieber et al. paper, this issue; Portable inflatable habitat deployed to augment lengthy decompression (photo by M. Lombardi, courtesy National Geographic Society/Waitt Grants Program).

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Diving Technologies and Techniques for the 21st Century
Guest Editor: Michael Lombardi

In This Issue

PAPER

A New Generation of ADS Capabilities

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ABSTRACT

This paper presents a case study describing submerged work at Shaft 19 of the Delaware Aqueduct, which evolved to become the most complex atmospheric diving suit (ADS) project ever undertaken. The limitations imposed by existing atmospheric systems are considered along with very significant improvements in ADS capability now being developed for both commercial and scientific diving.

For more than a century, ADS has offered the enticing potential of allowing men to work effectively at great depths without suffering the effects of increased pressure. Unfortunately, early suits did not function well at depth, and pilots could be more accurately described as observers peering through the small viewports of "diving bells" outfitted with crippled appendages. The modern rotary joint was patented in 1985 offering great promise, but even during the past 25 years, atmospheric diving has remained specialized, underutilized, and largely left in the wake of remarkable advances in saturation diving and remotely operated vehicle (ROV) technology.

Underwater work performed at Shaft 19 contributed to development of Exosuit™, the next generation in atmospheric diving. Substantial improvements in mechanical suit design have been integrated with an optical fiber umbilical, computerized control systems, and modern electronics to dramatically improve ADS capabilities.

The Exosuit itself can power multiple tools, a variety of hand pod end-effectors are presently maturing, and atmospheric diving may now be poised to assume far greater significance in deep diving operations.
Keywords: Exosuit™, atmospheric diving suit, ADS

Background of CAT/DEL 210-G

In 2007, New York City Department of Environmental Protection (NYCDEP) awarded a $1.1 billion contract to the SEW Joint Venture (Skanska/Ecco/White) for construction of the largest drinking water treatment facility ever built anywhere in the world. This massive project, CAT/DEL 210-G, was designed to provide ultraviolet light disinfection for the principal water supply to New York City at a site in Westchester County where the Catskill and Delaware Aqueducts pass in close proximity. The Delaware Aqueduct at this location is a deep rock tunnel, but during construction in the 1930s, the Board of Water Supply (predecessor of NYCDEP) designed a massive underground vault structure as an accessible connection to the aqueduct near ground level. It was originally anticipated that water treatment could be required someday in the future. After 75 years, the future had arrived, and ultraviolet treatment was the process designated for the main water supply to New York City (Figure 1).

Underwater Inspection and Repair

At the outset of our work in 2010, a 16-inch blow-off line connected the uptake shaft to the sidewall of the adjacent but deeper downtake shaft. This interconnection was originally intended to allow gravity drainage of the upstream aqueduct tunnel by discharge though the blow-off line, which could be controlled by a water hydraulic valve installed within a sump at the base of the uptake. NYCDEP recognized that this blow-off valve was no longer operational, and remotely operated vehicle (ROV) inspections performed during the project design phase also revealed that it was not fully closed. SEW was, therefore, directed to either repair or permanently seal the blow-off system to prevent water from being shunted directly from the uptake into the downtake shaft without passing through the requisite ultraviolet treatment process due to this unacceptable cross-connection (Figure 2).

FIGURE 1

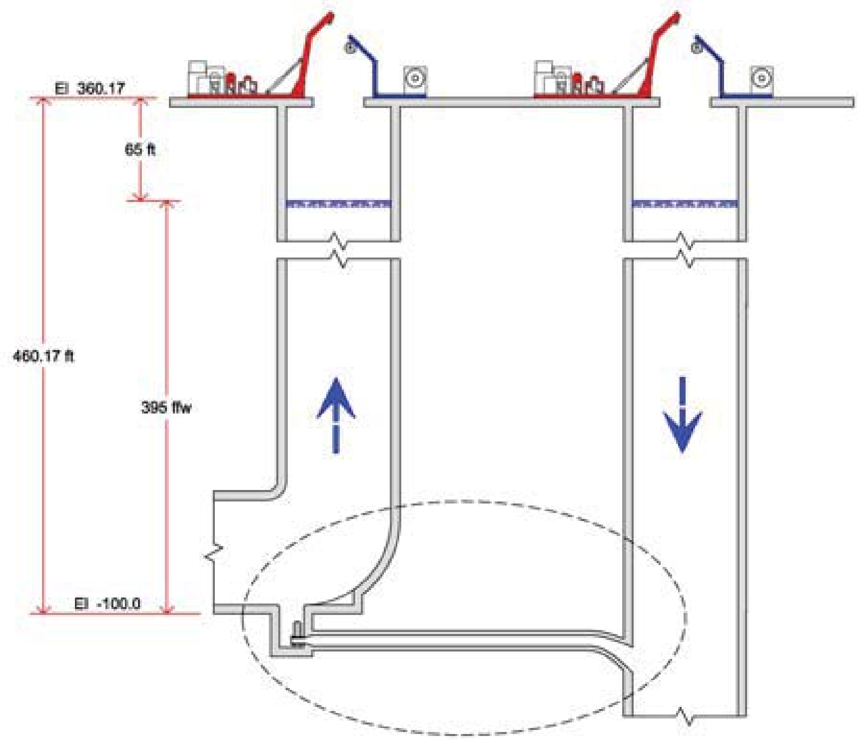
UV plant construction in 2010.

Operational Difficulties and Constraints

The Diving Division of J. F. White Contacting Company was initially tasked by SEW with the responsibility

FIGURE 2

Depiction of shafts and interconnecting blow-off line.



of developing appropriate underwater procedures for remediation of the 16-inch bypass. All operations and equipment had to accommodate a variety of project-specific requirements and constraints imposed by NYCDEP. These challenges ultimately influenced developments of a new generation of atmospheric diving suit (ADS) with improved capacity for scientific as well as commercial operations.

When work commenced at Shaft 19, there appeared to be a possibility that the blow-off valve could be repaired or perhaps actuated once to be fully closed and sealed. The valve was situated in a small sump beneath sediment, debris, and cast iron gratings at the bottom of the uptake shaft elbow; therefore, it was difficult to gain access and perform an evaluation. Once this valve had been inspected, NYCDEP needed time to fully assess remediation alternatives with respect to cost, long-term durability, and security of the water supply. Even after engineering decisions had been resolved for Shaft 19, underwater operations had to be integrated with other repairs within the aqueduct system and coordinated with changing environmental conditions affecting water quality.

Remediation of the blow-off system was undertaken in phases with the schedule restricted to intervals of reduced water demand between October and May.

Phase 1: Expose and inspect blow-off valve so that NYCDEP and consulting engineers could develop remediation criteria. Phase 1 was performed during the spring and fall of 2010 and resulted in a determination that the blow-off line would be permanently sealed at both ends and then completely filled with grout.

Phase 2: Install a special 250-lb (pressure rating) "oil field blind flange" on the intake flange of the 16-inch blow-off valve in the sump at the base of the uptake shaft. Mount a permanent stainless steel bulkhead plate (5-feet square by 1-inch thick) on the curved wall of the downtake shaft to seal the discharge outlet from the blow-off line. Phase 2 sealed both ends of the blow-off line and was completed during the spring of 2011.

Phase 3: Completely fill the blow-off line with 5,000 psi grout between the oil field blind flange and the downtake bulkhead plate. Phase 3 was completed during the fall of 2011.

This interrupted work schedule dictated multiple mobilizations and demobilizations, but additional constraints imposed by NYCDEP also affected our underwater protocols.

- Work hours were generally restricted between 2200 and 0600, 6 days per week excluding Sundays. Operations also had to respond on a daily basis to DEP interruptions determined by ambient turbidity or work in progress at other locations.
- Available deck space at Shaft 19 was very limited, and numerous other topside construction activities had to be accommodated. The deck area was actually an "island" surrounded by a 60-foot-deep excavation and accessible only by footbridge or crane lift for significant loads.

- All underwater equipment had to be removed from the submerged shafts after each work shift. Ultimately, a support truss (Figure 3) was allowed to remain underwater between shifts, but it was jacked in place with a water hydraulic system and then additionally tethered by four synthetic fiber lines tensioned to strong-back beams at deck level.
- Work performed at Shaft 19 had to comply with NYCDEP water quality regulations:

  All equipment entering shafts was disinfected in accordance with American Water Works Association standards.

  No wire rope was permitted to contact the water surface due to contamination by lubricants.

  Only water-powered hydraulics were allowed underwater due to a potential for contamination with even benign hydraulic oils. Only electrically powered launch and recovery systems or double encapsulated hydraulic units were allowed on deck.
- All diving operations had to incorporate provisions to prevent turbidity:

  Underwater debris was loaded into closing containers lined with filter fabric.

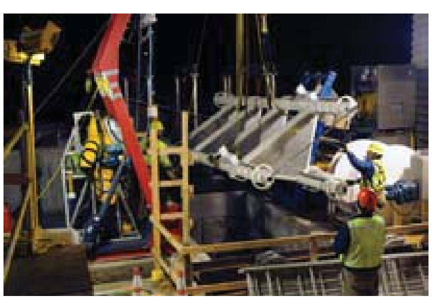
  Decant water from all sediment extraction operations was pumped topside for off-site disposal.

  Fines created by concrete drilling had to be filtered, contained, and removed from the shafts.

  All grout, slurry, and decant water was contained and removed from the water supply.

FIGURE 3

Support truss being lowered into downtake shaft.



Our initial project responsibility was to determine the underwater procedures and equipment that could best accomplish the blow-off remediation safely, economically, and on schedule.

Designation of Manned Diving System

Our initial surveys at Shaft 19 were undertaken by an inspection class Falcon ROV outfitted with a five-function manipulator. This effort identified the difficult tasks that would subsequently be required to gain access at the blow-off valve and then implement a repair. ROVs provided regular inspection capabilities and very significant diving support throughout the course of this project, but we determined at the outset that remote vehicles alone could not perform all the operations that would be needed. Manned diving was required, and it could have been accomplished either by saturation diving or ADS. Atmospheric diving was clearly the preferred economic choice.

The restricted deck area of the Shaft 19 "island" could not accommodate most saturation systems, and significant engineering costs would have also been incurred for the design and refit of bell handling systems with synthetic line (wire not allowed by NYCDEP). Ultimately, a second bell and launch and recovery systems would also have had to be deployed to support simultaneous diving operations in both the uptake and downtake shafts during grout injection. Recurring phases of mob/demob for a saturation system would have been expensive, and work postponements imposed by NYCDEP water supply requirements would also have been extremely costly. These considerations made ADS the logical choice of diving system, but many unique challenges still had to be overcome.

Management of ADS Operations

The selection of ADS for manned diving intervention was an easy decision principally driven by economics, but the appropriate integration of suit, support systems, and tooling proved to be immensely more complex. The evolution of this process exposed many practical limitations of atmospheric diving for unique, complex, and nonrepetitive applications.

On behalf of SEW, the CAT/DEL 210-G joint venture general contractor, we initially attempted to engage an ADS provider as a full-service subcontractor to perform all the atmospheric diving work. After our initial ROV inspections, it became apparent that the ADS systems would have to be equipped with special tooling, unique installation fixtures would have to be designed and fabricated within a very restrictive time frame, and the ADS team would also have to be prepared to develop engineering adaptations on site in response to unforeseen problems.

One major ADS provider offered suits and pilots on a day-rate basis but determined that they could not perform the specialized engineering required for this project. Another provider offered sophisticated design engineering, but they could not offer a convincing fabrication program for specialized underwater tooling or deployment of the construction oriented ADS diving teams required.

R. T. (Phil) Nuytten, the principal of Nuytco Research, Ltd., patented the modern rotary joint (Nuytten, 1985), and he is widely recognized as the innovator most responsible for developing effective atmospheric diving systems. We naturally contacted Nuytco for ADS services; however, they already had submersible operations scheduled within the same time frame. They could not deliver their regular subsea products while additionally fulfilling SEW demands for field operations combined with the design, development, and fabrication of multiple ADS tooling systems.

It soon became apparent that there was no sole source provider offering the comprehensive ADS capabilities within the time frame required by SEW and NYCDEP. We, therefore, developed an operational partnership by which the J. F. White Dive Division teamed with Nuytco Research to provide ADS capabilities and SeaView Systems to provide ROV support services to complete the underwater operations at Shaft 19. This cooperative effort resulted in successful project performance for SEW and also directly contributed to development of the Exosuit™.

Performing ADS Operations

Although the underwater work at Shaft 19 was only a minute component of the overall SEW construction effort, it was critical in nature, and the schedule was very demanding. There was absolutely no flexibility available to the contractor when the water supply to New York City was designated for night shift shutdowns (2200–0600 h) months in advance to facilitate the work. We were given, for example, an interval of 6 months to design, fabricate, and proof test a system for mounting a 5-foot square stainless steel bulkhead plate on the curved wall of the downtake shaft. This bulkhead was intended to seal the 16-inch blow-off line at the downtake shaft during grout injection. This might not have been difficult even at 400 ffw except for unusual constraints:

- The blanking plate had to be removed and reinserted on a daily basis until eight preliminary mechanical anchor studs could be properly torqued to secure the bulkhead during normal aqueduct flow. We were unable to install and torque eight studs during a single work shift (8 hours between opening and closing concrete shaft covers); therefore, a triangular support truss was allowed to remain underwater between shifts after being jacked in place with a water hydraulic system and additionally tethered by four synthetic fiber lines tensioned to strong-back beams at deck level.
- The 1,200-lb blanking plate had to be positioned during each shift within a tolerance of 0.025 inch, and all studs had to be drilled parallel, with axial run-out along the stud less than 0.010 inch despite the curvature of the concrete shaft wall.
- The shaft wall was core drilled to accept 1 × 16-inch stainless steel mechanical anchor studs utilizing a custom-built electrical drill system, which also collected and extracted drill fines.

In the 6-month interval following the Phase 1 inspections, our underwater team had to develop a variety of ADS-compatible tooling and fixtures to seal the blow-off piping (Phase 2) in preparation for the subsequent grouting phase.

J. F. White was responsible for the downtake support truss, downtake blanking plate, and alignment frame. These fixtures were adjustable to accommodate discontinuities in the shaft, actuated by water hydraulic jacks or rams, and designed to position the blanking plate within a 0.025-inch tolerance each time it was brought into position on the wall of the downtake shaft. The blanking plate and its alignment frame were removed at the conclusion of each work shift until 8 of the total 30 stainless anchor studs (1 × 16 inch) had been installed and torqued to secure it permanently in position. As the support frame was being lowered during the beginning of each work shift, the ROV could set it on the support truss and the ADS would make hose connections for the water hydraulic lines (Figures 3 and 4).

Concurrently, Nuytco Research developed the oil field blind flange and practiced installing it by ADS on a full-scale valve mock-up in their test tank. This mechanism was simple in concept but required considerable practice and coordination with very skilled ADS pilots to seal the blow-off flange during a single work shift (Figure 5).

SeaView Systems developed and fabricated electrically powered tooling for core drilling, stud installation, and torqueing the bulkhead nuts. This machinery was designed around their proprietary "backbone system" for integrated topside electronic control, and each tool was configured to be handled and engaged by ADS. The topside electronics could adjust rotation speed, torque, quill feed pressure,

FIGURE 4

Blanking plate with alignment frame being lowered into downtake shaft.

FIGURE 5

ADS practicing in mock-up replicating sump and blow-off valve.

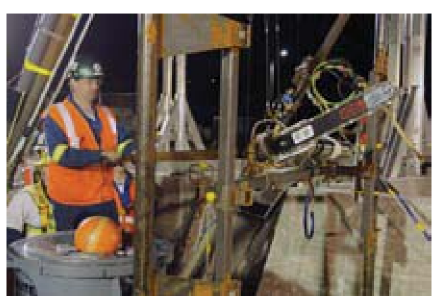
quill travel distance, and position by use of a touch-screen computer interface. The SeaView rotary torque tool was also deployed to actuate mechanisms on the sump blanking plate and the oil field blind flange.

Work-class ROVs can perform very complex tasks, but the support tooling and control systems must be developed in advance. We believed from the outset of this project that ADS operations could be more quickly adapted to unforeseen conditions than an ROV. This proved true when NYCDEP determined that a bronze grate and debris within the blow-off discharge line had to be removed rather than grouted in place. We were directed with only 24 hours of notice to remove the grate at 405 ffw within the downtake shaft. This became a relatively simple construction site mechanical problem because we had only to develop tooling that could be manipulated by the ADS. Our blanking plate alignment frame was quickly modified so that the ADS could control an abrasive blade saw (Figure 6).

The deep diving work at Shaft 19 was successfully completed, and ADS was undoubtedly the best choice for this underwater intervention. Our ADS costs are estimated between 25% and 35% of saturation diving when considering only the multiple mobilizations and time delays imposed by NYCDEP. Special engineering costs associated with bell deployment into the active water supply would further favor ADS. Even multiple work-class ROVs could not have operated effectively in the limited visibility of Shaft 19 as the combination of ADS with ROV support.

FIGURE 6

Abrasive saw tested topside by ADS pilot, Doug Bishop.



Lessons Learned

Lessons learned during the underwater construction at Shaft 19 may well be applicable to similar projects as well as deep water (1,000 fsw) science. If a project cannot be completed solely by ROVs and the working duration or depths encountered are too great for bounce diving, a choice will probably be made between saturation diving and ADS. The decision will be determined by considering all the interrelated operational factors.

Mobilization for ADS diving is perhaps an order of magnitude less expensive than a saturation spread, but that disparity must be balanced against project duration and underwater work requirements.

Atmospheric diving suits can offer manned performance with respect to range of motion, manipulation, and dexterity that is perhaps 50–85% the capacity of a working gas or saturation diver. ADS capabilities improve toward the higher end of that range when special tooling can be developed and tested in advance.

ADS can successfully perform many basic diver functions, but an atmospheric diving operation has to be supported with tooling developed for the anticipated tasks and adapted to function with the suit. Tooling for atmospheric diving must be carefully planned as it is for ROV operations. The tool must be integrated with the atmospheric suit; it is not as simple as handing a new underwater tool to a gas diver and expecting effective performance. Tools can be standardized for repetitive work, but unusual tasks undertaken for construction or science will likely require special tooling and pilot training to handle each specific application.

Next-Generation ADS

All diving at Shaft 19 was performed with the Newtsuit designed by Phil Nuytten in 1985 but now utilizing technology nearly 25 years old and perhaps past its prime. Nuytco Research had been gradually developing a new generation ADS, designated as the Exosuit, for a number of years prior to our work for SEW in 2010 and 2011. ADS performance at Shaft 19 was so successful that J. F. White placed an order for the first Exosuit. At the time of this writing, this first Exosuit has passed pressure testing certification to 1,400 fsw and has been delivered to J. F. White. It incorporates modern developments in electronic control and optical fiber data transmission with multiple mechanical improvements gained during operational experience at Nuytco.

- Thrusters: Exosuit thrusters have approximately twice the bollard pull of thrusters on the older Newtsuit. This added power can be a significant advantage working in a current or applying force to tooling. The maneuverability and positioning capability of the Exosuit is further improved because forward and reverse thruster power is controlled by the speed and direction of rotation, not by a variable pitch propeller as in older suits. This new ADS can be more easily flown by less experienced pilots and more accurately controlled by skilled divers.
- Power Ports: The Exosuit includes four additional power supply ports, each capable of delivering approximately 1 hp. Additional thrusters could be added to the suit to accommodate special circumstances, but these ports also provide the capacity to run additional electric tooling directly by a suit whip, not a separate power umbilical from the surface.
- During our work at Shaft 19, we often had six synthetic tether lines deployed in addition to the ADS umbilical, ROV umbilical, water hydraulic supply line, and then an electrical power supply to each tool. The ability to power tools directly from the Exosuit will be a significant advantage for construction as well as scientific applications where suction motors for biological collection, drills for coral coring, or special tooling for archaeological specimen preparation could be directly powered from the Exosuit.
- Topside Control: Most modern thruster-powered ADS have been controlled with foot pedals leaving the hand pods available for other tasks. The Exosuit can be flown in this manner, but it can also be independently piloted by topside control. It could be utilized as an ROV equipped with its standard high-definition cameras if that deployment proved advantageous, but perhaps, more importantly, an incapacitated pilot could be flown around obstructions to safely clear the umbilical for retrieval to the surface. An inexperienced ADS pilot with appropriate safety training but little suit time could also be flown by topside control to a particular work site. A skilled archaeologist, for example, could be flown to a site where he would only have to manipulate the ADS hand pods or specialized tooling to evaluate a critical specimen.
- Suit Flexibility: Atmospheric diving capabilities were very limited until invention of the rotary joint (Nuytten, 1985). Modern ADS then became practical for underwater work, but friction in a joint exposed to pressure can limit suit dexterity and tire the working pilot. The Exosuit utilizes a newly designed rotary joint, which reduces friction under pressure by approximately 50% as compared to previous ADS. Every pilot movement of the suit legs, arms, or hand pods is more precise and less tiring. This flexibility will clearly assist positioning of the suit when working on bottom or in restricted areas.
- Fiber Optics: The Exosuit umbilical includes optical fiber in addition to power conductors and strength members. This fiber provides data transmission for high-definition video, sonar, and other digital sensor systems. Voice transmission over fiber is superior to copper, and unlike older suits, cabin life support data can be monitored directly by the topside supervisor without interrupting pilot attention to the task at hand.

The Exosuit also incorporates many small modifications that would go unnoticed by a general observer, but they will be immensely appreciated by pilots and will become obvious during an assessment of work performance. The pilot's range of vision through the new face dome is exceptional, slight modification of the torso eases pilot entry into the arms, and hand pods have been improved and include threaded mounting lugs to accommodate special tooling. In combination, these and other advances qualify the Exosuit as a new generation of ADS, but they also set the stage for development of additional capabilities (Figures 7 and 8).

New ADS Capabilities

Nuytco Research is presently developing a free-swimming untethered version of the Exosuit. This capability would be derived from the reduced

FIGURE 7

Newtsuit in operation.

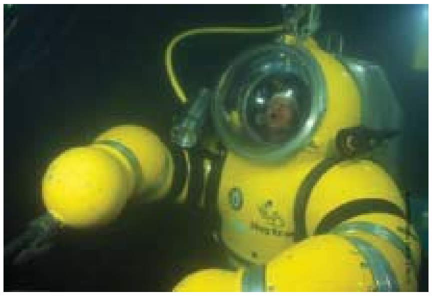


FIGURE 8

Exosuit performing acceptance tests.

friction offered by Phil Nuytten's new joint design and could benefit specific scientific or military applications.

J. F. White and Nuytco Research are both presently evaluating the advantages of mating an Exosuit with a tether management system mounted aboard a small submersible. This combination would be free of any umbilical to the surface; incorporate the capacity for self-rescue; and offer a very capable platform for underwater construction, science, or salvage.

Atmospheric suits are usually equipped with manipulators resembling pliers that can open, close, and lock a grip. This limited dexterity often slows a pilot's work as compared to a gas diver and creates the need for special adaptive tooling. The development of a manipulator more closely

FIGURE 9

Prototype prehensor developed by Nuytco Research.

FIGURE 10

Anthropomorphic ADS prehensor invented by Vishwa Robotics.

replicating a human hand would provide immense advantage underwater. Nuytco Research has been developing their prehensor hand as depicted below, and concurrently, several other designs are emerging from robotic and biomedical laboratories. It is probably a safe prediction that improved hand mechanisms will be working underwater within the next few years (Figures 9 and 10).

Acknowledgments

The author wishes to express his appreciation to Nuytco Research, Ltd., of Vancouver, BC, and SeaView Systems, Inc., of Dexter, MI, for their effort and cooperation during the Shaft 19 project and other underwater endeavors. The anthropomorphic prehensor mechanism depicted above has been invented by Bhargav Gajjar of Vishwa Robotics in Cambridge, MA.

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