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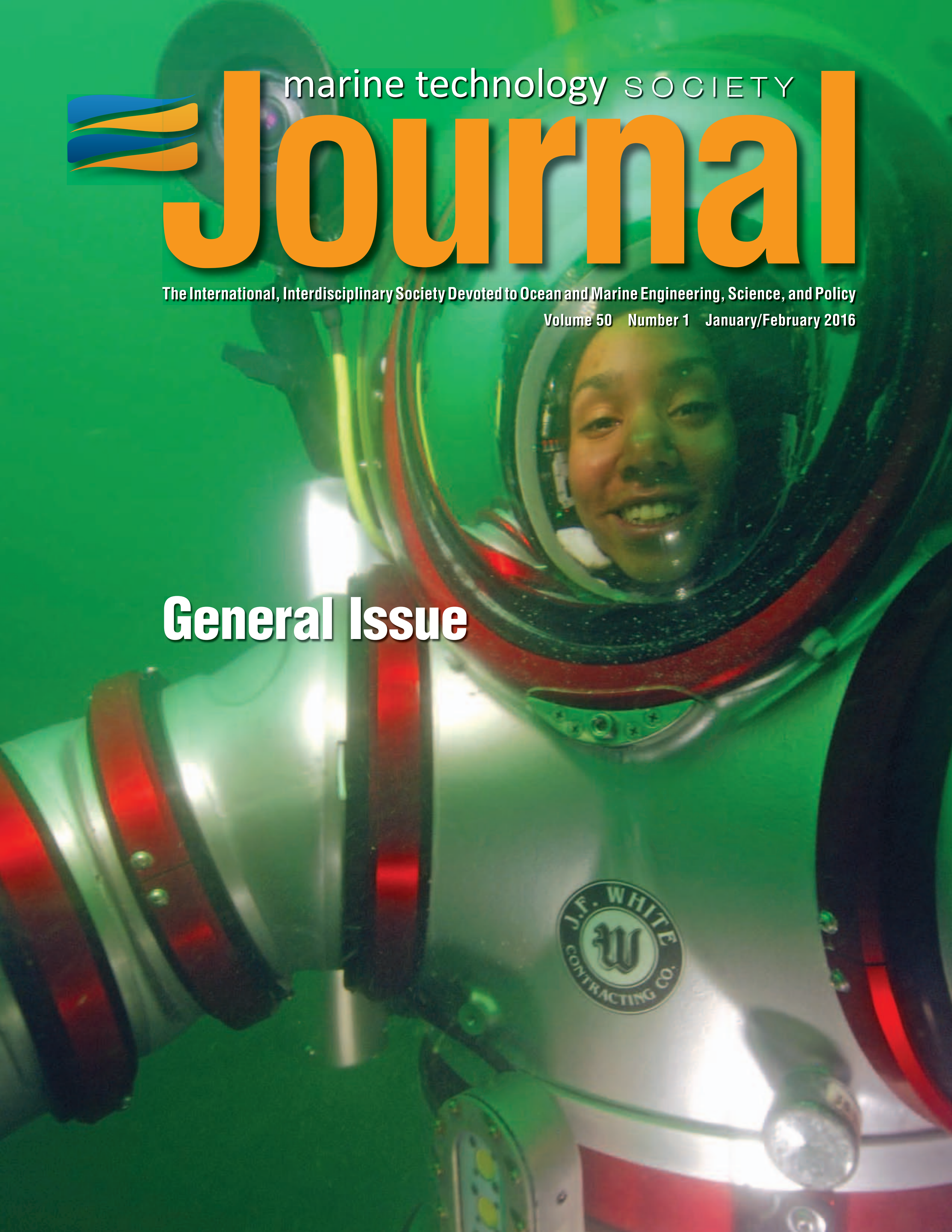
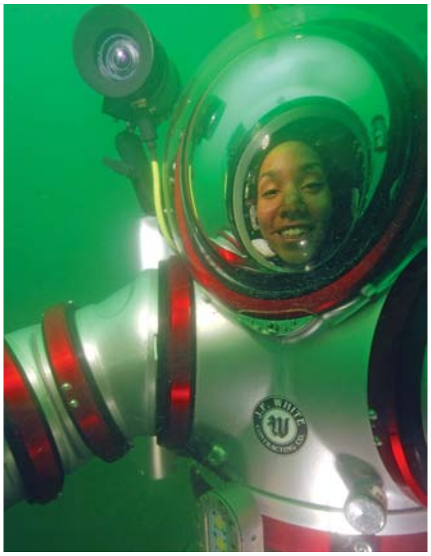
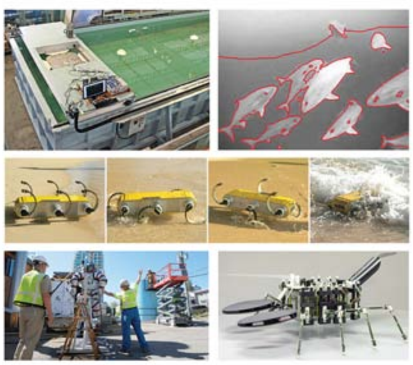




Cover Images (all images can be found in this issue): **Front:** Lombardi, Figure 1. **Back:** Zhou et al., Figure 1 (top left); Shortis et al., Figure 3 (top right); Chen et al., Figure 10 (middle); Lombardi, Figure 2 (bottom left); Chen et al., Figure 2 (bottom right).



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COMMENTARY

A Paradigm Shift for Human Exploration of the Sea: Standards of Practice, Training, and Program Development for Atmospheric Diving

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Introduction

In the last 50 years, the practice of diving has matured into a commonplace tool within the diving scientist's toolkit, where the availability of affordable equipment is sufficient to allow routine diving at-will. That is certainly exciting and engaging for many and has permitted five decades of marine science to be achieved within relatively shallow coastal depths. With these activities becoming commonplace, however, the art and science of diving itself has largely been taken for granted, especially by the new generation of divers with little exposure to older equipment and practices that provided the baseline innovations for our current technologies and techniques. For instance, two-stage regulators, dive computers, and buoyancy compensators are now mainstay and commodity items, but bold bodies of work similar to those which brought us those innovations are lacking. This may be due to this current equipment being very good and that it affords relative safety. Although incremental improvement of this equipment continues, significant continued innovation in diving technology has stalled. However, we should never assume that major innovations can no longer be made.

The most recent "golden age" of technology development took place during "Man in the Sea" programs during the 1960s and 1970s. At that time, program-related investments made by sponsoring agencies such as the Office of Naval Research and the National Science Foundation into diving technology and practices, with projects such as Sealab, Hydrolab, Tektite, and others, provided a focal point that fueled multidisciplinary interests. These programs were model platforms for science, defense, industry, and, indirectly, even space exploration. Human physiological limits became a limiting factor that resulted in risk-adverse practices and policies favored by funding agencies, which were often the result of legal and liability concerns. Thereafter, further use of this critical platform model was left to the wayside due to lack of funding support. Innovation in underwater intervention continued, but attention switched to new technologies, such as piloted (ROV) and autonomous (AUV) underwater vehicles with which work could be carried out. As has happened in many fields, direct human activity, particularly within environments beyond reach of the accepted at-will commodity approach, is being displaced by other technologies.

Because of the intimate relationship afforded by direct human activity within the most biologically rich shallow water, there remains a significant niche for the human in underwater research and exploration. The ability to use our own eyes and hands to experience and interpret this space remains unparalleled and far better satisfies our innate human curiosity than through the use of remote technology. This very perspective is why we are considering and validating manned Mars missions during the 21st century. I can verify this perspective through my own discovery of new species, literally within a few short minutes spent at depth within the Mesophotic zone (Slattery, 2002; Sparks & Gruber 2012) while utilizing conventional wet diving techniques.

Current diving technology and techniques including open-circuit and closed-circuit mixed-gas technical diving have been used during the most recent "honeymoon" Mesophotic discovery period for the better part of two decades (Sharkey & Pyle, 1993). While promising, these specialized techniques require efforts on training and proficiency that are difficult for diving scientists (large, routine end-user groups) to maintain. The imminent challenge in preserving any future innovations for the scientific diving community is to again embrace the art and science of diving itself and catalyze new innovative solutions to the problems faced in extended range human intervention. With that changed perspective—of prioritizing the human as a valuable mode of intervention—future program-related investments can and will be made to advance the field, thus taking the science (and people) more routinely to new depths and environments.

This challenge can be met through a program that satisfies three critical points, where (1) the technology must adequately protect humans at their physiological limits, (2) the technology must be accessible (affordable and available), (3) focused programs and initiatives must be undertaken that engage multidisciplinary interests across academic, defense, industry, and exploration sectors to ensure financial sustainability.

Recent Efforts

Although the days of wet diving may have reached their limits, direct human intervention underwater can be pushed beyond wet diving's physiological limits. When surveying the field for a manned diving platform that satisfies these requirements to justify program-related investments, atmospheric diving systems (ADS) stand out as a best fit for the diving community's needs. ADS have been traditionally utilized within the industrial sector and with only limited exposure and success in underwater science. My belief is that this is due to social misperceptions of the technology's capability and value, as well as its accessibility.

In July 2013, representatives and guests of the J.F. White Contracting Company participated in the first end-user training and familiarization activities for the long-awaited Exosuit ADS at Nuytco Research Ltd. in North Vancouver, British Columbia, Canada. The manufacturer's training regimen (Lombardi & Clark, 2013) specifically exposed areas for potential standardization of training practices across industry sectors. We also considered improvements for future training activities in order that the technology may be more broadly introduced and accepted following demonstration of its usefulness.

Standards of Practice

The first production Exosuit was then accepted by J.F. White Contracting Company in September 2013. Operational, technical, and health and safety documentation supporting the Exosuit was drafted, compiled, and edited, citing and leveraging previous manned submersible vehicle standards and references (International Marine Contractors Association [IMCA], 1984; Germanischer Lloyd, 2009; American Society of Mechanical Engineers, 2007; University-National Oceanographic Laboratory System, 2009). While the Exosuit is designed and constructed to meet the Lloyd's Register (1989), standards of construction for classification as a manned submersible, review of the manufacturer's product documentation (Nuytco, 2013), and follow-on discussion with the manufacturer provided evidence that actual ADS operations do not fall within the specific scope of any single set of regulations cited above. Considerable regulatory overlap exists within and among these standards for manned submersibles; however, because the technology was not foreseen by the regulations, they are only selectively applicable for ADS given the unique operational nature of the system. In short, review of current standards of manufacture, operations, technical utility, and end-user health and safety revealed that ADS stands as an outlying mode for human intervention that requires both manned submersible and wet diving considerations that have yet to be met from a regulatory point of view.

Its outlying nature, somewhere between wet diving and manned submersibles as a mode of intervention, is just one of several factors causing barriers to entry for ADS to more routinely and more broadly reaching market opportunities. However, isolated successes have been demonstrated across both scientific (Earle, 1983) and commercial sectors (Clark, 2013). Other factors include accessible training opportunities, dexterity and human ergonomics considerations, and misperceptions of risk in human intervention at an institutional or regulatory level.

With very limited existing literature describing the utility of ADS and further no standards of practice, the protocol has been for ADS owners/operators to draft and adopt internal safe practices manuals (i.e., J.F. White, 2010). These usually reflect particular circumstances and operations and have been expanded from the manufacturer's recommendations to deal only with limited conditions. ADS standards of practice or protocols are vetted to meet health and safety requirements for individual private companies and their insurance underwriters and thus often deal with limited subsets of operational conditions rather than diving science applications as a whole. This specificity is among the points of failure in providing guidance for a broader population of end-users. A code of practice for ADS diving has yet to be compiled.

Training

With ambitions to pursue new market opportunities for the Exosuit, specifically within scientific diving, it is necessary to provide training opportunities for scientific end-users. Next to availability of the ADS, training is the critical bottleneck to further program development. Thus, a sequence of documents based on owner/operator standards for operations (Lombardi, 2014a, 2014b) provides a template for owner/operator training activities. Following J.F. White's acceptance of the Exosuit in September 2013, efforts needed to be placed on structuring a training regime that satisfied a broad end-user group as well as regulatory requirements.

IMCA (1984) provides a well-structured training paradigm for submersible pilots and further distinguishes ADS pilots citing that "physical demands made on the occupant of an atmospheric diving suit require his general standard of fitness to be in some respects the same as that applied to commercial divers." Lloyd's Register (1989) does not specify an ADS training regimen in detail but does cite that "Detailed knowledge is required of the effects of buoyancy, heel and trim, equipment handling… together with the medical effects of gas mixtures." When considering both the IMCA (1984) and Lloyd's Register (1989) documents, logic suggests that an ADS trainee and prospective pilot would be most effective if first trained as a wet diver, maintained some degree of diving proficiency, and had an understanding of diving physics and physiology.

Exosuit operations are similar to wet surface supplied diving where a Diving Supervisor has a direct means for intervention and diver interaction via an umbilical to the surface but also leaves a degree of autonomy to the diver. The most significant distinction between surface supplied diving and ADS operation is that control of life support and atmospheric management is the responsibility of the ADS pilot versus the Diving Supervisor in a surface supplied operation. Manned submersibles, by contrast, often leave autonomous control to a uniquely qualified pilot with scientists taking a very passive role as passengers. This unique hybridized approach to coupling wet diving conventions and manned submersibles provided validation for developing ADS end-user training within the standardized framework of a diver training regime.

In late 2013 and early 2014, I worked with Technical Diving International to develop an Exosuit training standard (Lombardi, 2014c) that reflected IMCA (1984) primarily but also drew upon practical experiences during the 2013 training regime (Lombardi & Clark, 2013). This was followed by development of an end-user Exosuit training and proficiency guide (Lombardi, 2014d). Technical Diving International approved and sanctioned this program in early 2014. In Spring 2014, this training program was implemented at Woods Hole Oceanographic Institution (WHOI) during four successful and incident-free training and proficiency sessions. WHOI granted approval for this training regime under the auspices of their scientific diving program, which established the precedent of ADS as a mode of diving (as opposed to manned vehicle) within the institutional and academic setting (Figure 1).

Twenty-one end-users were granted "try dives," formally trained as pilots, or attained additional proficiency using the Exosuit during the Woods Hole sessions. This activity resulted in 49 h of cumulative dive time. End-users ranged from highly experienced technical divers, working professional commercial divers, academic scientific divers, to nondivers. A wealth of data and information was obtained during these training activities. Perhaps most important was the establishment of a distinction between pilot end-user responsibilities and topside-owner/operator responsibilities—specifically as they relate to affording broader end-user access within the scientific community (Table 1; Figure 2).

Generally, while the consensus of those participating in training activities was that the Exosuit was simple and intuitive to operate at the end-user level, it is critical for end-users or prospective end-users to understand the full scope of operational support required and degrees of operational complexity that may need to be introduced (or mitigated) to ensure that mission-specific tasks are completed.

The training program (Lombardi, 2014d) introduces student trainees to the full Exosuit operation, though emphasis is on atmospheric management theory and repetition of life support control operations. Observation of student trainees with varying experience levels revealed that basic Exosuit life support control operations can be learned very quickly. However, students with more wet diving experience demonstrated better aptitude for situational and spatial awareness of the diving environment and appeared to respond to atmospheric management requirements more fluidly.

Following training sessions, discussion with student trainees quickly revealed renewed appreciation for operational complexity in deploying and recovering ADS, as well as maintaining readiness for emergency intervention. These factors are critical to incorporate into program development discussions so as not to fall severely

FIGURE 1

USNA Midshipman Brianna Bilunas, a nondiver, very happily participates in Exosuit training at WHOI. Photo by M. Lombardi.

short on safe operational requirements and establishing a productive work environment.

Adopting formal standards of practice that highlight items required for both training and basic Exosuit operations will provide the critical blueprint for successful program development. The onus for implementation lies with the owner/operator of the system, which may or may not be a scientific end-user group or institution. Understanding these minimum standards is required to guide program development efforts in cooperation with partners within both industry and the private sector.

Recommendations for Program Development

While public perception is that the ADS pilot is the party with primary operational responsibilities, assessment of health and safety conditions (Lombardi, 2014a, 2014b) indicates that topside responsibilities are equal, if not more critical, to ensuring safety and productivity. In many cases, both topside and end-user/pilots share responsibilities to take responsive action when health and safety conditions are breached. In general, topside has the primary responsibility for launch, recovery, and emergency intervention, while the pilot has primary responsibility for personal welfare. The pilot's responsibility requires an aptitude for understanding basic atmospheric management principles and the mechanical capacity to actuate life support system controls. While topside can intervene via voice communications to guide pilot corrective actions, life support operation is solely the pilot's responsibility.

This element of trust between pilot and topside reflects a partnership that is culturally engrained in commercial diving through the use of surface supplied diving techniques. This type of partnership is foreign to most scientific diving programs where the convention is more commodity-type wet diving scuba techniques. To implement a successful program, this trusting partnership between pilot/end-user and owner/operator must be established early.

Likewise, to develop a financially sustainable program for ADS use, it is logical to seek program-related investment with the focal point on the technology platform and its operators. Subsequent partnerships with various end-user groups may serve to financially subsidize ongoing maintenance, training, and proficiency, leaving the major investment expense to the operation of the vehicle itself. It would be illogical for infrequent end-users of this niche technology to pursue individual ownership given the major capital expenditure and operational costs. However again, with the technology providing a centralized platform by which to form partnerships across industry, academia, the private sector, and defense community, a modest investment

TABLE 1

Responsibilities for immediate action to ADS health and safety conditions.

Health and Safety Conditions	Responsible Party for Immediate Action	
	Topside/Supervisor	End-User/Pilot
Emergency Conditions and Response Protocols		
Lost Communications	Shared	Shared
Entrapment	Shared	Shared
Structural Damage/Joint Seizure	N/A	Primary
Life Support System Faults	N/A	Primary
Unconscious or Disabled Pilot	Primary	N/A
Electrical Supply Failure	Shared	Shared
Thruster Pack Failure	Shared	Shared
Umbilical Damaged/Severed	Shared	Shared
Water Ingress - Drowning	N/A	Primary
Fires and Fire Extinguishing Methods	N/A	Primary
Emergency Recovery Procedures		
Controlled Emergency Ascent	Primary	N/A
Back-Up Recovery System	Primary	N/A
Emergency Recovery using the Original Umbilical	Primary	N/A
Emergency Procedures for Attaching the Secondary Lifting Line	Primary	N/A
Open Water Vessel Support	Primary	N/A
Free Ascent or Controlled Free Ascent	N/A	Primary
Handling System Failure	Primary	N/A
Pilot Welfare		
Medical Well-Being	N/A	Primary
Medical Considerations	N/A	Primary
Medical Hazards and Conditions		
Inadequate Oxygen Supply - Hypoxia	N/A	Primary
Oxygen Poisoning - Oxygen Toxicity	N/A	Primary
Carbon Dioxide Poisoning - Hypercapnea	N/A	Primary
Soda Lime Chemical Burn	N/A	Primary
Cold Exposure - Hypothermia	N/A	Primary
Dehydration	N/A	Primary

Health and safety conditions were extracted from Lombardi (2014b).

could result in sustainability and, perhaps more important, continued ADS innovation, provided that projects are successful in achieving the mission objectives and are performed safely.

Conclusion

Establishing Exosuit operations as a mode of diving, rather than manned submersible operations, could enable a new type of scientific diving program, with broader end-user groups. Within the United States, most academic institutions and many private companies incorporate diving as a tool for underwater research and operate

FIGURE 2

ADS operations require a team effort for safe and efficient operations, with critical responsibilities shared by both topside personnel and the pilot. Photo by M. Lombardi.

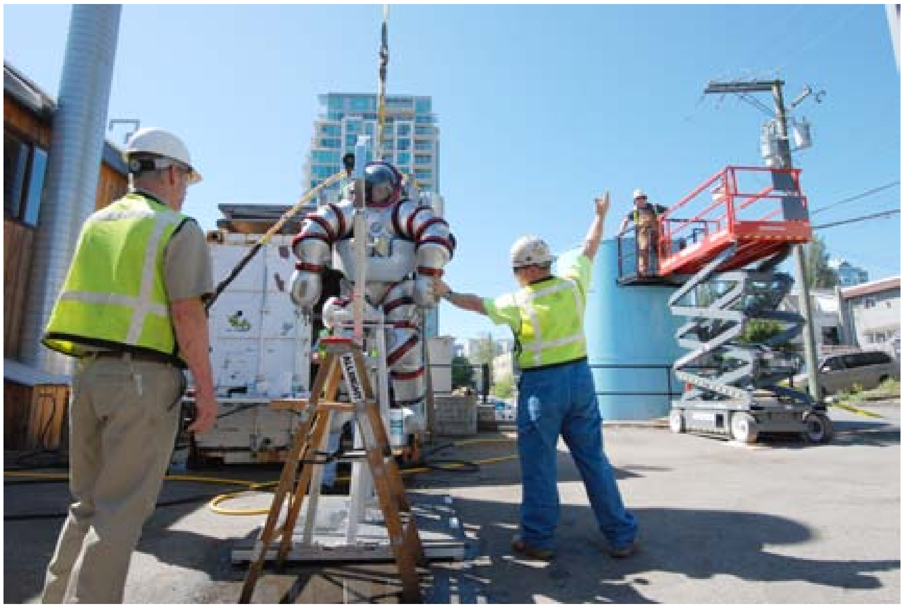

FIGURE 3

The author test dives the Exosuit ADS at Nuytco Research Ltd. Photo by J. Clark.

using a scientific exemption to OSHA 29 CFR 1910 Subpart T (Commercial Diving), which leverages a community consensus standard for safe practices defined by the American Academy of Underwater Sciences (AAUS). These operational standards afford for relatively easy adoption of new technologies and techniques for scientific programs in the United States, with the organizational membership of AAUS bearing responsibility for introducing additional new standards of practice as technologies and techniques for scientific diving continue to evolve. Outside of U.S. legal domain, the nonbinding Code of Practice for Scientific Diving published through UNESCO (Flemming & Max, 1996) may also provide a basis on which to build.

For perhaps the first time, ADS is relatively within reach of diving scientists as a safe and productive alternative to deep wet diving. Critical to successful program implementation is embracing standards for operation to mitigate liability concerns of the home organization and most importantly working cooperatively with Exosuit owner/operators in a partnership capacity to ensure operational considerations are well met in advance of field missions to ensure both safety and productivity.

Taking this approach, with the diving operation being the focal point for program development, has the potential to shift the social and cultural norms in the diving community, and one day, perhaps, humans will reclaim their niche role in ocean exploration to forge onward and to the deep.

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