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CCR Validation Protocol and Associate Training

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Abstract

Failure to maintain preventative maintenance of life support technology is known to contribute to the risk of diving accidents. AAUS has clear standards and many options to address OC scuba technology. Closed-circuit rebreathers (CCR), while older than open-circuit (OC) scuba, have little similarity with traditional underwater life support technology, and as such, find little formal maintenance standards or training available nationally. Platforms that are purchased either by universities or by individuals working under university auspices are seldom monitored for maintenance schedules or validated for functionality as is the tradition for OC scuba technology. Under AAUS standards, a regulator and cylinder must be serviced at least once a year to a manufacturer's standard and by a qualified service center. More affluent university programs hire a technician, secure training and provide this required monitoring in-house. Most University programs send their participants to a dive shop for the service of their life support technology. There are precious few dive shops that provide any CCR validation service at this time. We propose a validation protocol for CCR platforms that is specific to manufacturer's specifications which, like cylinder inspections, may be applied on a specific schedule as defined by the university's Diving Control Board (DCB). This protocol may be adopted by a qualified dive program technical staff or serve as a standard for third party to whom the university may contract for service. We also propose a training program for University CCR technicians which in concert with this protocol will enable the university administration more options when managing the condition of their supervised CCR technology.

Keywords: protocol, rebreather, safety, training, validation

Introduction

Regulator and cylinder maintenance and repair have seen a rocky early history. The local Dive Shop that sold the technology also became the repair facility, where a person, often the owner and a diver him or herself, provided repairs based upon their own experience and help from the manufacturer. Many owners repaired their own equipment back then, getting the parts from a dive shop. Manufacturers improved their oversight of this service as warranty requirements demanded better service. Manufacturers reached a point where their product could not be repaired by the owner because access to parts was restricted to only those they certified. Today we see facilities that repair all brands of dive equipment following a generic protocol often taught by a single company (such as PSI/PCI) using generic parts or manufacturer assembled repair kits with unknown origins. Training to complete these repairs is now available on the Internet as are most repair manuals.

The Interstate Commerce Commission (ICC) and later the Department of Transportation (DOT) have provided standards for cylinder safety testing since the inception of the scuba industry. In the early 80s, Bill High began a search to codify the DOT and other compressed gas agencies cylinder standards as they might relate to the recreational and scientific diver (High and Gresham, 2010).

Based upon his findings, a simple non-destructive test protocol was developed for the early identification of critical cylinder failures, which, if unmonitored, endanger those handling and using scuba cylinders. We continue to use this industry self-policing 18 step protocol throughout our scuba community today. The DOT insists upon the 5 year hydrostatic test. The Diving Community insists upon the annual Visual Inspection.

Additionally, manufacturer mandated regular service intervals for scuba regulators fulfill the same preventative malfunction role or warranty support is lost to the customer. Failure to perform preventative maintenance has been cited as a contributor to diving accidents over the years, leading the diving industry to press for improved maintenance requirements. When the American Academy of Underwater Sciences (AAUS) set forth their diving standards, they specified Diving Control Boards (DCB) enforce life support preventative maintenance policies.

The AAUS, by their standard, mandates that each program assures compliance with community standards regarding cylinder, regulator, BC and other critical components of the diving life support package or diving status is lost to the participant. More affluent university programs hire a technician, secure training and provide this required maintenance in-house. Most University programs however, send their participants to an independent dive shop, not the manufacturer, for the service of their life support technology. Advantages for in-house technical programs include greater assurance of quality control and greater technical support capability for their community. Disadvantage of in-house technical program is the cost is born by the university and has less transfer of liability value should an incident occur.

We have witnessed the revival of an old technology for new applications. For over a decade now, rebreathers and training for their use have become increasingly available. Rebreathers have become the technology of choice for advanced underwater excursions. The logistical footprint of a rebreather (greater deployment both in depth, gas efficiency and cost) over open-circuit (OC) scuba technology has allowed many diving scientists to gather data previously inaccessible to them (compare Suárez-Morales and Iliffe, 2005). Graduate students and faculty have used personal funds to purchase closed-circuit rebreathers (CCR) and used them under university auspices, raising concern from their respective DCB. Also, because the initial investment of the platform is high, some universities have purchased rigs from their contracts or grants, thus exposing their university to the liability of their monitoring and maintenance.

We feel like the 1960s all over again! When open-circuit technology was first introduced, an aging-process of knowledge and technical development also lead to injuries and fatalities from which we learned a great deal. It seems during this past decade, we are going through this same process with regards to the application of CCR technology to our scuba community and unfortunately we see the same onset of incidents and accidents. Yes, as in the 1960s human error is often the culprit with CCR incidents. But at least the same level of oversight is needed for the safe application of CCR technology as is required for OC technology. Universities can no longer rely upon their participants to validate CCR technology.

Methods

Areas of Concern

We propose three areas of concern specific to the use of CCR technology, beyond those that can cause incidents in open-circuit diving:

1) Technological design

Technological designs determine the function of a rebreather. Examples include choice of dimensions, diameter of breathing hoses, size of one-way valves, dimensions of CO_2 absorption canister, etc. The design is determined by the manufacturer, and defines the performance of a new, properly built and adequately configured rebreather. After-market modifications however, can alter the manufacturer's design, and thus the rebreather's performance.

2) Appropriate (or inappropriate) use

Inappropriate use is either based on bad training, ignorance, complacency, distraction or simple neglect. Examples include the over-use of sensors, batteries or CO_2 absorbent material beyond its conceptual limits, or simply to forget to fill one of the breathing gas tanks. Unfortunately, history gives plenty of real-world examples of such accidents.

3) State of Performance

The state of technology determines the actual state of the rebreather, either during use or at the time of testing. It is mostly a question of wear and tear (thus upkeep), but also includes predictable reduced performance due to manufacturing tolerances. Examples include the age and performance of sensors, valves, flow performance of injection and mushroom valves, breathing loop integrity, and the reliability of electronics (such as limitations due to corrosion).

Unfortunately, the separation of these three classifications is not always possible, and thus results in heated debate. Is the injury or death due to an omitted O-ring, a question of design or the result of limited training? Can a more advanced (foolproof) design cause even more fatalities due to increased complexity? While such discussions should and will hopefully improve the future safety record of rebreathers, they are not topic of this paper.

Validation Paradigm

In the introduction to this paper, the need for the validation of closed-circuit systems is compared to the established validation requirements for the much simpler open-circuit apparatus. While rebreather technology in its crudest form predates OC diving, the implementations of today's electronically controlled mixed-gas closed-circuit systems are far more complicated than their bubbly counterpart. It is the detail rather than the concept that has demonstrated the potential for catastrophic failure. These failure points in their details are not impossible to monitor, but require their identification, and a measurement criterion to judge their state of performance.

In an ideal world, all potential failures are considered and investigated, in order to ensure the safe performance of the system. In the real world, however, even peer-reviewed test criteria, such as the European CE test, only consider a limited range of scenarios, under which the CCR system as a whole has to demonstrate an agreed upon performance. An example to illustrate this abstract point: A requirement for the CE test is the absorption of carbon dioxide for a predetermined amount of time while applying a high, somewhat human-like breath-pulsed gas flow pattern. All tests are completed using a machine, not human testing. Although pulsed, the volume flow pattern is maintained constant and static during a test run, and so is the simulated depth. Detailed investigations (Hess, J, in: Mount, T *et al.*, 2004) however indicate that a more life-like, dynamic alteration of both breathing pattern, as well as depth has the potential to greatly influence the longevity of carbon dioxide absorption capacity, even negatively. However, such dynamic tests have so far not been described or applied.

The CE test, or any other for that matter, only monitors a very limited range of potential scenarios. As stated in the beginning of this chapter, all failure points require identification. The example demonstrates that this is not as simple as it sounds. Even more to the point, it becomes obvious that the term "performance" is poorly defined.

Thus the CE-test is concerned with the technological design of a rebreather. This, however, is not the purpose of the validation protocol discussed here, and neither is the appropriateness of the use. The paradigm of the proposed validation protocol is to compare test units to a functioning and new rebreather as a performance term of reference. The validation thus provides a measure for the wear and tear, as well as upkeep of the CCR. Consequently, the validation tests are not to be destructive in nature, just like the inspection of scuba cylinders (commonly referred to as "visual inspection") does not require the destruction of the tank. Have in mind that the fuzziness of the term "performance" and "functioning," as well as the limitation in test criteria, still applies. While this may appear philosophical, the paradigm's practical realization will be based on empirical knowledge, which is to be contributed to over time. Consequently, the protocol introduced here has to be understood as a living paper, which is to be augmented or altered based on future experience. Furthermore, the validation test cannot predict future performance.

Validation Contents

All of the following tests are either judged by an experienced/trained technician, to be determined acceptable/not acceptable, or compared to values derived from like-new systems.

Periphery

1. HP and LP gas hoses
    a. Visual deterioration / wear (rubbing)
    b. Leaks
2. Gauge and display accuracy
    a. Cleanliness (oxygen environment)
    b. Swivel performance
    c. Harness and webbing damaged
    d. Properly routed cables, harness, wiring
3. Stage (bail-out) cylinder

Gas supply

1. Cylinder (PSI/PCI inspection protocol)
    a. Hydro, (DOT testing protocol)
    b. Valves, cleanliness (PSI/PCI protocol)
2. Regulators (manufacture protocol)
    a. Service
    b. Cleanliness (oxygen environment)
3. Solenoid(s)
    a. Rust
    b. Wear
    c. Flow performance
4. Trickle valve
    a. Volume flow
    b. Cleanliness
    c. Rust

5. Schraeder valves (ADV, BC, manual injection)
    a. Cleanliness (oxygen environment)
6. DSV
    a. Damage
    b. Ease of operation
    c. Cleanliness and lubrication
7. OPVs
    a. Cracking pressure
    b. Leaks

Electronics

1. Cell health
2. Wire health
    a. Connector corrosion
    b. Wire damage/ sensor load
3. Battery health
4. Firmware health
    a. Power consumption
    b. Latest version/known bugs
    c. All menus accessible
    d. Injection settings
    e. Injection algorithm performance *in situ* (P, PI, PID?)

Integrity

1. Replace O-rings in rig (full replacement as in a regulator?)
2. Negative/positive test for integrity
3. Check lid, can for damage
4. Pressure test counter lungs
5. Pressure test rig to 250 ft
6. Flow resistance
7. Cracks/leaks in components

It is to be understood that such a validation can only document the performance at the date of the test and not after the unit has left the validation station. The simple action of dismantling the gas cylinders breaches the integrity of the system as a whole. The validation does however define a point in time, at which the unit fulfilled the criteria as described, and thus either meets the expected criteria, or requires specific service, improvement or replacement.

Unfortunately, not all components of every rebreather model available today can be tested using the same protocol. Reasons can range from absence of components, to their integration into a black-box system. Experience and training of the evaluator is mandatory.

Associate Training

The authors have gained experience in providing the technical training to permit CCR validation. Such a training course should include the following:

1. A solid understanding of the fundamentals of scuba technical repair
    a. Cylinder inspection (PSI protocols) and handling

    b. Regulator repair and configuration
    c. BC/dry and wet suit repair
    d. Dive computer maintenance and basic repair
    e. Blending (blender certification)
2. A solid understanding of the fundamentals of CCR technology
    a. CCR loop integrity, work of breathing,
    b. Sensor/battery performance and pressure pot testing
    c. Oxygen clean (PSI oxygen protocol) and compatibility
    d. Dive computer applications to CCR
3. Specific principles used in CCR
    a. Mechanical
    b. Chemical
    c. Pneumatic
    d. Electronic
4. Manufacturer specific requirements
    a. Performance download software
    b. Component testing protocols
5. Technical Internship approach preferred (two week minimum class)
    a. Week one (basics)
        I. Safety overview
        II. PSI core class
        III. Oxygen cleaning and compatibility
        IV. Regulator maintenance, configuration and repair
        V. BC, dry suit and wet suit maintenance and repair
        VI. Dive computer maintenance and repair
        VII. Blender course
    b. Week two (CCR)
        I. Electrostatic protection,
        II. Fundamentals for soldering electronics (build a circuit)
        III. CCR diagnostic tools
        IV. Batteries, Sensors and Solenoids
        V. O-ring, lubricant and sensor tutorials
        VI. Wrist, HUD and remote displays
        VII. Basics CCR computer performance
        VIII. Canisters and absorbent performance

Results

The sequence of validation of each of the elements listed in section (cross-reference) is not pre-determined per se, although follows a logical order. At conclusion of the protocol, the system has to have undergone a complete test. Unlike a forensic system examination, it is to be expected that the rebreather arrives disassembled at the time of validation. It is recommended that testing of each and all components is performed in a concise and timely manner to avoid age-related deterioration. Suggested is the following sequence for the validation protocol:

1. Case integrity (cracks in and disintegrated components)
2. HP and LP gas hoses
3. Gauge and display integrity and accuracy
4. Cylinder (PSI/PCI Inspection protocol) including all stage (bail-out) cylinders
5. Regulators (manufacture protocol)

6. Solenoid(s)
7. Trickle valve
8. Schraeder valves (ADV, BC, manual injection)
9. DSV
10. OPVs
11. Cell health
12. Wire health
13. battery health
14. Firmware health
15. Assembly of rig
16. Negative/Positive test for integrity
17. Component flow resistance tests
18. Pressure test counter lungs
19. Pressure test rig to 250 ft wet and dry

Conclusions

The requirement for a codified evaluation protocol for closed-circuit rebreathers is highlighted in comparison to the tests performed on standard Scuba equipment. No such evaluation program exists today. The limitations of such a test are considered, in the areas of concept as well as practicability.
Listed are the detailed areas for investigation, but no performance values are considered as of yet. Such values will be derived from experience as well as extensive training for the investigator. A training scheme is laid out, which is available today for the interested technician. The sequence of investigation is suggested based on identified areas of concern.

It can be expected that regular adherence to the evaluation protocol eliminates the risks associated with wear and tear of the rebreather. Wear and tear is one of the three areas that have been identified as foundation for rebreather incidents. Following the proposed protocol is a viable agency option when managing the condition and liability of their supervised CCR technology.

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