Findings & Recommendations

1. There are many outstanding issues that must be addressed if rebreather technology is to safely and reliably be incorporated into non-professional diving applications.

The challenge involved should not be dismissed lightly. At the present time, the two largest users of rebreathers in the world—the US and British Navies—combined only have about 240 mixed gas rebreathers in service (excludes pure oxygen sets) from an inventory of approximately 600, and an extensive infrastructure to support them. With nearly a dozen manufacturers offering or planning to offer rebreathers to nonprofessional divers, the industry hopes to produce and support many times the military number on a regular basis.

2. Rebreathers are far more complex than open circuit scuba equipment due to their design and function.

A rebreather is a closed life-support system that is designed to extend gas supplies by providing the required amount of oxygen to meet the diver's metabolic needs, while conserving the diluent gas in the system, and removing CO2. Fully closed systems control oxygen levels by means of a series of electronic sensors; activating an injection valve when the partial pressure of oxygen (PO2) is too low, and an alarm when the PO2 too high. Semiclosed systems perform this function mechanically by attempting to match a preset flow of oxygen-rich gas to the diver's consumption and exhausting excess gas into the water. In both cases oxygen levels dynamically vary around a target range.

Rebreathers passively remove excess carbon dioxide by passing the gas through a canister of CO2 absorbent material, the duration of which may vary significantly even under seemingly identical conditions.

3. Because of their complexity, rebreathers have a number of insidious risks not found in open circuit scuba.

Major risks include: hypoxia (too little oxygen), hyperoxia (too much oxygen, i.e. CNS oxygen toxicity), and hypercapnia (too much CO2). All of these can lead to unconsciousness, usually with little or no warning. Drowning is likely to occur, especially when using a conventional mouthpiece rather than a full face mask. In addition, there are the secondary risks such as inhaling a "caustic cocktail" — a toxic mixture of CO2 absorbent material and water, and decompression illness due to increased duration or in semiclosed sets, due to unanticipated variations in PN2. Thermal considerations and mechanical and electronic failures pose other risks.

4. The military have been successful in managing the risks through the use of a large supporting infrastructure, a high degree of discipline and training. Comparable infrastructure, discipline and training have not been needed in sport diving until now, and currently don't exist in the market.

The military objective is to eliminate human error and exercise a degree of control over rebreather usage through written procedures, testing and certifying units before they are released to the fleet, mandatory pre and post-dive checklists, adherence to the buddy system, reliance on dive supervisors, and tracking problems in the field.

According to military spokesmen, the US Navy has had four incidents in 16,000 hours on the Mark 16 rebreather, one of them a fatality. It was pointed out, however, that this record may not directly apply to the sport divers because they do not have a comparable training and support program.

Some participants questioned the relevance of military protocols to the sport market. In response, it was pointed out that both military and civilian divers breathe air, neither can breathe water, and aside from the possibility of being shot at, little separates the risks of rebreather diving within the two communities.

5. Manufacturers and training agencies must provide appropriate warnings and documentation to the risks of rebreather diving, with an emphasis on those that differ from open circuit scuba.

6. Some attendees stated that the relative simplicity and low cost of constant mass flow semiclosed systems, which have no electronics, may make them more suitable for recreational divers.

However, not all the experts agreed. They countered that electronically controlled closed circuit systems provide much better oxygen control, alarm systems, and user feedback increasing the potential safety for users.

Either way, it should be noted that diving a semiclosed set is still a lot more complicated than open circuit enriched air diving. With semiclosed systems, enriched air training is only the first step.

7. In spite of their relative simplicity, mass flow semiclosed systems can be problematic. A major concern is dilution hypoxia. A secondary concern is decompression illness.

Mass flow systems supply a preset flow of enriched air (nitrox) to the diver based upon an assumed oxygen consumption rate. However, actual oxygen levels in the system depend on the diver's actual workload relative to the preset flow and are independent of depth and manufacturer. If a diver is working harder than anticipated and "out-breathes" the system (i.e. oxygen consumption exceeds the range designed in by the manufacturer), hypoxia can occur very rapidly, particularly at or near the surface or during ascent where there is insufficient depth to maintain a safe PO2, and the diver may drown. Published data suggest that a diver's oxygen consumption can be as high as 3.0 liters per minute in extreme conditions, such as swimming hard against a current or struggling to free oneself from underwater entrapment, particularly in athletic individuals.

Oxygen levels in the breathing loop are extremely sensitive to small changes in mixture flow rates. For example, decreasing mixtures flows from 6.0 to 5.1 liters per minute with a 60% enriched air mix, and without an effective bypass, can reduce oxygen levels in the system from 20% to 3% in a hard working diver. At or near the surface, this could cause hypoxia.

A higher than anticipated oxygen consumption can also affect equivalent air depth (EAD) decompression calculations used when diving these systems. The problem is that because actual inspired oxygen levels can fluctuate, it may be unclear what the decompression schedule should be based on.

8. Military semiclosed units are designed to handle workloads as high as 3.0 liters per minute oxygen consumption. However, at this time, there are no similar specifications for consumer rebreathers, and some systems may not handle this high of an oxygen requirement.

Several solutions were offered including designing in adequate flow rates, thorough testing of the rig under extreme conditions, always "flushing" the system before ascent, and incorporating oxygen monitoring systems as soon as possible.

It was also pointed out that these systems should be calibrated by the user or retailer before each dive, because any blockage in the mass flow reducer valve can dramatically reduce flows and therefore oxygen levels.

9. Compared to open circuit scuba, rebreathers require significant ongoing maintenance and support to function properly. Manufacturers must provide written procedures, pre and post dive checklists, and a schedule for required maintenance.

Supporting a rebreather in the field can require as much as an hour or more preparation before each dive, an hour or more after the dive, and includes disinfecting the unit between uses and often between users (as in a training situation). There is also regularly scheduled maintenance.

These are probably best accomplished through the use of mandatory pre and post dive checklists, and written maintenance procedures supplied with the product. Having a dive supervisor oversee the checklist process also appears valuable.

10. Supporting rebreathers on a retail level will likely involve far more work and expense than open circuit scuba equipment. Proper oxygen cleaning and handling procedures will need to be used.

11. Consumer rebreather training is in its infancy and is not yet standardized.

Though many agencies have rudimentary programs in place, there are no common standards. One of the challenges is the lack of hands-on rebreather experience within the community. A second is the lack of sufficient rebreathers to enable trainers to get that experience. Typical training courses range anywhere from about 30 hours on a semiclosed system to 40 or more hours for closed circuit training.

12. Taking a manufacturer-approved rebreather course is only the first step. Rebreather diving must be learned by experience, and some times may require many more hours than open circuit scuba to attain comparable competence as a result of their complexity.

Experienced users pointed out that, among the hazards of rebreather diving, two of the most critical are complacency, and allowing confidence to exceed ability. It was strongly recommended that divers gain extensive experience with systems in shallow water until sufficient user competence is developed before making deeper dives. New users were advised to go slowly.

13. Ideally, rebreather instructors should own, or have on-demand access to the rebreather that they plan to train other divers on. It is recommended that they have the necessary experience for competence before qualifying as instructors, which may be more than 100 hours with some models and types.

It was recommended that training emphasize manual operation of automated systems in the case of electronically controlled rebreathers as well as proper response to different types of failure modes.

14. Because many aspects of training are specific to individual models, manufacturers need to work closely with training organizations that are developing instruction courses. Manufacturers need to include documentation and manuals with their units.

15. There is no way to know how a rebreather will perform in the field without conducting manned and unmanned testing, which can determine performance under worst-case conditions.

Testing should look at the system as a whole, scrubber duration, and recommended decompression procedures. As noted above, canister duration times may vary considerably even under what appear to be identical conditions. In addition they will be affected by type of inert gas used (N2 and He duration's are not the same) and the water temperature. The military determines an average duration for each set of environmental conditions usually based on 5 or 6 trials. They then specify an operational limit taking into the statistical variation among the runs, usually one standard deviation below the mean.

The only validated constant PO2 tables to date are the US Navy 0.7 ata constant PO2 in N2 and He tables. The Canadian forces are working on tables for their semiclosed rebreather. Simply reprogramming a dive computer to calculate oxygen levels according to what the rebreather supplies may not work. Using EAD tables may be more appropriate since the air stop times are still used, but a higher PO2 is breathed at each stop.

16. Manufacturers should ensure that proper testing has been conducted before releasing their product to the market. The tests document performance over the entire range of conditions for which the rebreather is designed.

The results of this testing should be made available, with the recommdnation that the rebreather be used only under conditions in which it was tested. Documented rebreather testing and performance standards exist and are readily available. Navy Experimental Diving Unit reports can supply a wealth of information and document testing and standards for just about all USN breathing apparatus. [An index of NEDU Reports can be obtained by writing to: Commanding Officer, Navy Experimental Diving Unit, 321 Bullfinch Road, Panama City, FL 32407-7015] In the future, it is hoped that an international testing standard will be established for consumer rebreathers.

17. In many circumstances, the use of full face masks and adherence to the buddy system can improve rebreather diver safety. It's recommended that organizations and individuals using rebreathers look closely at incorporating these into their products, programs and operations.

Though the use of full face masks is not widely used in open circuit sport diving applications; the body of comments at the Forum emphasized their importance in rebreather diving. No opposing views were offered.

It was also noted that the addition of an onboard CO2 monitor would represent a great improvement in safety. Though several manufacturers are developing such devices, at the present time there are no proven CO2 monitors on the market. The use of dive supervisors is also recommended for rebreather diving, particularly in technical diving operations.

It should be noted that the US Navy has adopted a PO2 of 1.3 ata as its maximum for closed circuit diving. Though a maximum PO2 of 1.4 to 1.6 ata is the community standard in open circuit mix diving, sport divers were advised to consider adopting the lower USN standards for rebreather diving, as a result the dynamic variability of PO2s within a given system, and the nature of constant PO2 diving versus that of open circuit equipment.

18. There don't appear to be any unusual product liability problems that should keep rebreathers off the market, but, regulatory concerns appear to be a more significant issue.

During the third quarter of 1996, the Occupational Health & Safety Administration (OSHA), which regulates the US workplace, declined to grant a recreational exemption to instructors engaged in rebreather training. That means that those who use rebreathers as employers/employees fall under commercial diving regulations until the issue can be resolved. The sport industry will have to accumulate a good track record for rebreather use to make its case for an exemption.

In the UK, the Health & Safety Executive office has included non-professional rebreather use as a part of the recreational exemption, and has put the responsibility for safe practices back on the manufacturers and training organizations.

19. Developing a consumer market for rebreathers will take time. To be successful, the industry must move forward one step at a time, fulfill requirements, identify and document problems, and communicate with each other.

20. The forum consensus was that holding another rebreather forum would be desirable in the coming year to share experience and data gained since Forum 2.0.