MANNED EVALUATION OF UNDERWATER BREATHING APPARATUS

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INTRODUCTION

UK commercial diving operations have to comply with the Health and Safety at Work Act 1974 and the Diving Operations at Work Regulations (DOWR) (1). It is Government policy that, where possible, military diving should also comply with the DOWR. It is thereby inferred that diving equipment will meet unmanned performance guidelines such as those developed jointly by the Norwegian Petroleum Directorate (NPD) and the UK Department of Energy (DEn) (2).

Since 1994 the European Community (EC) directive for Personal Protective Equipment has required that all respiratory protective equipment used in diving (except that designed and manufactured specifically for use by the armed forces) should also meet an approved standard - indicated by a CE mark. At present an approved European Standard (EN 250) (3) exists for open-circuit Self Contained Underwater Breathing Apparatus (SCUBA). This includes basic ergonomics tests, but, like the NDP/DEn guidelines, does not cover manned performance testing.

Over several years, this laboratory has evaluated a wide range of civilian and military diving equipments. This expertise is being used to develop guidelines for manned performance evaluation - especially ergonomics and performance. This paper highlights the need for such evaluations, particularly in more complex equipment, and outlines current evaluation techniques.

CURRENT TRENDS

Technological developments and safety features - such as secondary breathing systems (to meet the DOWR requirement for an emergency reserve supply of breathing gas) - can greatly reduce the risks of diving. In modern semi-closed circuit sets that use electronics to monitor and control the oxygen partial pressure (PO_2) in, or supplied to the breathing loop, safety to life information is conveyed to the diver via a mask mounted red-green indicator. Other information about the equipment and dive status (e.g. depth, battery state) are typically available from a hand-held alphanumeric display. Electronic PO_2 control should increase safety by reducing the risk of hypoxia or hyperoxia and by enabling decompression tables to be optimised.

However, a manned evaluation of 3 such sets identified a number of problems. For example, PO_2 control systems did not always behave as specified and failures occurred which could have been life threatening in operational use. One set had more than 12 user operated controls some of which were difficult to access. An unquantified risk factor is the use of red-green indicators.

MANNED EVALUATION PROCEDURES

Test Subjects

All subjects must be informed volunteers with a satisfactory medical history. They are medically examined and certified fit to undertake the test procedures. Where possible, subjects are from the user population and should be familiar with the type of equipment under test. For novel or complex equipment, subjects must receive adequate training with at least one training dive. For equipment using alphanumeric visual displays and colour indicators, subjects should meet a minimum standard of visual acuity and colour perception.

Anthropometric data are obtained for the interpretation of data relating to fit, comfort and harness adjustment (4). Subjects' ability to reach over the head and up the back may also be required: such movements are frequently needed to reach controls and don / doff equipment. Subjects should, as far as possible, span the 5th to 95th percentile of the user group. No anthropometric criteria are given in EN 250.

Ergonomic Assessment

The first part of the manned assessment is a formal ergonomic evaluation in the dry and in enclosed shallow water under controlled conditions (e.g. a diving tank). Tests are normally carried out at 15 °C, which is suitable for light work in thick and thin clothing assemblies and equivalent to maximum UK sea temperatures. Other water temperatures can be set for equipment designed for more extreme climates. Subjects carry out tasks and set manoeuvres appropriate to the equipment, with and without gloves and in the dark (as required) to mimic zero visibility. Activities are recorded on video-tape. They include:

- donning / doffing the equipment on land and in water
- movement, particularly of the head and arms
- harness fit, comfort, ease and adequacy of adjustment, security of fastenings
- ability to achieve and maintain positive, neutral and negative buoyancy
- routine in water activities e.g. clearing ears, clearing a flooded face mask
- access to and use of controls
- ability to locate, read and interpret visual displays and indicators
- clarity and field of vision adequate for task and unimpeded by bubbles
- the accessibility and adequacy of fixing points for ancillary equipment

- emergency procedures such as the ability to ditch weights and the activation and use of emergency breathing systems
- use of the equipment as a standby set, buddy drills
- use of a buoyancy compensator

EN 250 prescribes 5 subjects for the ergonomic assessment for SCUBA. We recommend 8 for complex equipment. If each diver performs 2 dives as in EN 250, assessment will take 1 - 2 days. Each subject completes a questionnaire post-dive.

Shallow water assessment should be mandatory for new or prototype equipment where reliability is uncertain and our experience is that unpredicted safety-to-life problems can occur even after extensive unmanned testing.

Manned Performance Tests

The second part of the manned assessment consists of simulated wet dives in the controlled conditions of an hyperbaric chamber to the maximum operational depth of the equipment. Equipment is evaluated during all phases of the dive. Performance is measured during graded work on an underwater ergometer. Test posture should reflect equipment design, especially hydrostatic effects, and use. The aim is to extend the unmanned evaluation which makes no allowance for variability in subject physiology and behaviour or for subject-equipment interaction.

A minimum of 4 subjects is recommended. Instrumentation includes heart rate, skin and rectal temperatures, and Respiratory Inductive Plethysmography (RIP) for respiratory volume. Equipment instrumentation includes inspired PO_2 and inert gas content for PO_2 control, PCO_2 in the canister effluent for canister endurance, inspired gas temperature, end-tidal and end-inspired PCO_2 and respiratory pressure at the mouth. Since RIP tends to overestimate ventilation, an independent measure of ventilation is obtained whenever practicable (e.g. using a pressure drop method).

The measurement of manned Work of Breathing (WoB) - the area enclosed by a respiratory pressure-volume loop - is a new technique developed in this laboratory (5). Preliminary work suggests that NPD/DEn unmanned performance criteria can normally be applied to manned WoB. Manned WoB is also a valuable tool for real-time diagnosis of under or overinflation of a counterlung, operation of relief valves and failure to switch fully from a primary to an emergency breathing system.

Because of subject variability, manned performance is assessed on overall physiological and subjective response during underwater work but within pre-set limits for safety. For example, to reduce the risk of CO_2 poisoning, end-tidal PCO_2 should not exceed 8.5 kPa for more than 5 consecutive breaths. Manned tests have shown that some semi-closed circuit sets cannot meet this CO_2 limit during work on oxy-nitrogen mixtures at depths (40 - 50 msw) within the equipment specification.

Manned tests on a free flow helmet have found that the noise of the breathing gas was so great that, for comfort and communication, divers reduced the flow to half that recommended. This allowed inspired PCO_2 to exceed 2 kPa due to inadequate helmet ventilation. The preferred limit is 1 kPa.

Operational User Trials

The final part of manned assessment consists of user trials to the full operational envelope of the equipment. Endurance swims at operational workrates should be conducted on swimming sets to identify problems such as postural strain, collapse of hoses and excessive drag. Poor harness, equipment design or fit can cause undue rotational moments which are exacerbated by wave action. Rotational moments reduce swimming efficiency and may cause back and neck ache. Video recording is used to aid diagnosis. For closed or semi-closed circuit sets the workrate can be estimated by gravimetric analysis of soda-lime (6).

CONCLUSION

Diving equipment must undergo satisfactory manned as well as unmanned evaluation to reduce the risk to the end user. Standards have lagged behind EC legislation and technological developments. The three part assessment described in this paper is proposed as a framework for a manned evaluation standard that will complement existing guidelines and standards.

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