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Breathing performance of 'Octopus' demand diving regulator systems

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Breathing performance of 'Octopus' demand diving regulator systems

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Self Contained Underwater Breathing Apparatus (SCUBA) often use an 'Octopus' system as an alternative air supply. QinetiQ at Alverstoke were contracted by the Health and Safety Executive (HSE) (Contract D5008) to conduct a review and breathing performance test of 'Octopus' systems. It was shown that SCUBA single demand valve systems capable of meeting the breathing performance requirements of BS EN 250, cannot be relied upon to meet the same requirements when used as part of an 'Octopus' system. Reduced breathing performance of 'Octopus' systems (when compared to single valve systems) was found to be a result of the use of low performance first stage regulators, second stage demand valves of different and poor performance and breathing in phase as opposed to out of phase. Recommendations on the use of 'Octopus' systems are presented. Appropriate test procedures and acceptance criteria should be identified for 'Octopus' systems, and proposed for the next revision of BS EN 250.

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Executive Summary

When using Self Contained Underwater Breathing Apparatus (SCUBA) it is recommended to use an appropriate alternative breathing gas source/secondary life support system. 'Octopus' systems are often used to fulfil or support this requirement.

BS EN 250:2000 specifies the performance requirement of a single demand valve, first stage regulator combination. This, however, gives no indication as to how an 'Octopus' two demand valve, first stage regulator combination might perform.

The Centre for Human Sciences at QinetiQ Alverstoke was contracted by the Health and Safety Executive (HSE), Contract D5008, to conduct a review and breathing performance test of 'Octopus' systems.

A literature review was conducted. Based on data available from the review and in consultation with the HSE, six configurations of 'Octopus' systems were selected and purchased anonymously for test. The selections sought to emulate purchases likely to be made by UK divers.

The systems were evaluated for compliance with elements of BS EN 250 and the Norwegian Petroleum Directorate/UK Department of Energy guidelines for breathing apparatus, when used both as single demand valves and in tandem as 'Octopus' systems. The pass/fail criteria adopted encompassed both BS EN 250 and the NPD/DEn guidelines.

Test data obtained showed that SCUBA single demand valve systems capable of meeting the breathing performance requirements of BS EN 250 cannot be relied upon to meet the same requirements when used as part of an 'Octopus' system.

Reduced breathing performance of 'Octopus' systems (when compared to single valve systems) was found to be a result of the use of low performance first stage regulators, second stage demand valves of different and poor performance and breathing in phase as opposed to out of phase.

The observed breathing performance of 'Octopus' systems may go some way to explaining the number of divers who inexplicably break contact with their buddies during alternative air supply (AAS) ascents using SCUBA 'Octopus' systems.

The results support the view that the preferred system for an alternative air supply is a completely independent gas supply and demand regulator.

If 'Octopus' systems are to be used it is recommended that:

- Divers are made aware that although CE marked valves to BS EN 250 may be considered as 'fit for purpose' when used alone, their performance cannot be assured when configured as part of an 'Octopus' system.
- Octopus systems should be based on a high performance first stage regulator.
- Octopus systems should be configured with demand valves of similar performance.
- Older valves, or valves whose performance may have degraded should not be used.
- The diving community should be made aware of the effects of breathing in and out of phase.

Appropriate test procedures and acceptance criteria should be identified for 'Octopus' systems and proposed for inclusion in future diving apparatus standards, including the next revision of BS EN 250.

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1 Introduction

1.1 Background

For safety reasons when using Self Contained Underwater Breathing Apparatus (SCUBA) it is recommended to use an appropriate alternative breathing gas source/secondary life support system [1, 2, 3, 4, 5]. It is common practice within recreational diving agencies and during some commercial diving activities to use an 'Octopus' system to fulfil or support this requirement. A SCUBA 'Octopus' system consists of a first stage regulator connected to a 'primary' second stage demand valve and a 'secondary' second stage demand valve, the 'Octopus'. The 'Octopus' provides a back up demand valve in cases of primary demand valve failure and may also act as an alternative air source (AAS) for the diving 'Buddy'. An AAS does not require the 'Donor' diver to remove their own primary demand valve when supplying air to a 'Buddy' diver who has experienced regulator failure or an out of air situation. Figure 1-1 shows an 'Octopus' system.

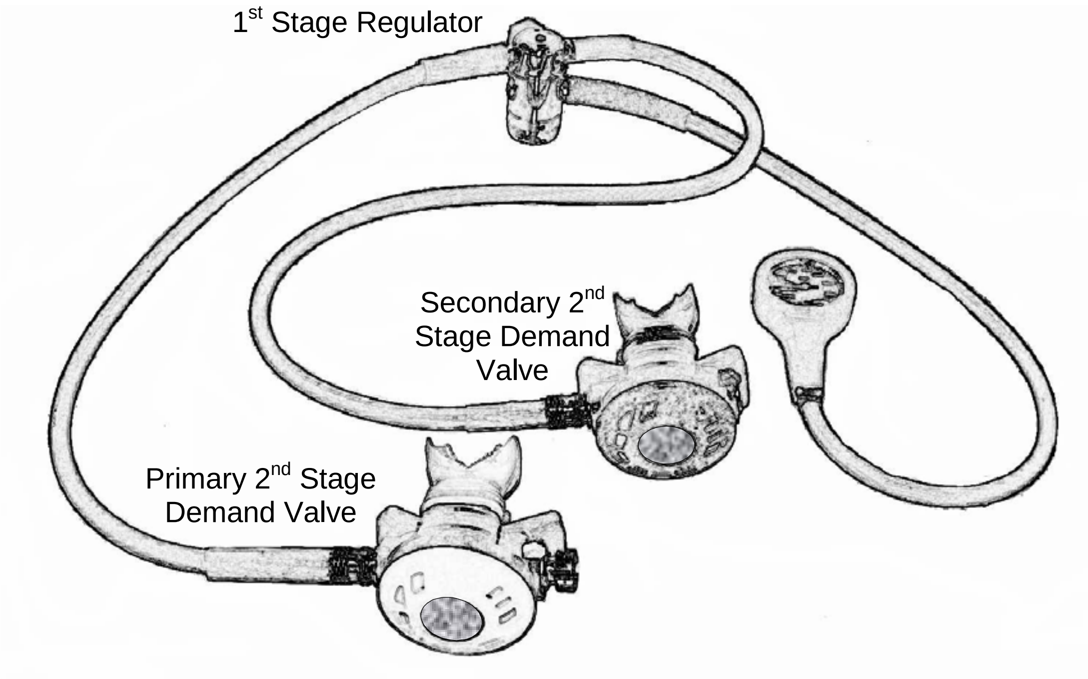

Figure 1-1: SCUBA 'Octopus' system

The current European standard for open circuit compressed air breathing apparatus, BS EN 250 [6] specifies the performance requirement of a single demand valve, first stage regulator combination. This, however, gives no indication as to how an 'Octopus' (two demand valves, single first stage regulator combination) might perform. By its very nature (other than during training exercises) this type of apparatus configuration is only expected to be used during emergency situations and is therefore likely to experience very high ventilatory demand. When two people are in close proximity and with visual and audible indicators as to respiratory rate, there can be a tendency for breathing to 'fall in step' and a degree of synchronisation to occur. If two divers breathing patterns become synchronised or 'in phase', peak ventilatory demand may be effectively double that required of a single demand valve configuration.

There is also a tendency among divers to view the ‘Octopus’ valve as an extraneous piece of equipment, frequently ‘making do’ with an older or cheaper demand valve, an approach not endorsed by recreational diving agencies [7]. This may impose further performance limitations upon the configuration as a result of mismatching the demand valve and first stage regulator.

Following growing concerns over the use of ‘Octopus’ systems and incidents involving them [8, 9] the Centre for Human Sciences (CHS) at QinetiQ Alverstoke was contracted (Contract number D5008) by the Health and Safety Executive (HSE) to conduct a review and breathing performance testing of ‘Octopus’ systems. This report covers the review and selection of ‘Octopus’ systems for test and their unmanned breathing performance.

1.2 Review process

A literature and internet search was conducted; this identified several review articles in a popular main stream diving magazine [10, 11, 12, 13]. These featured both objective breathing performance evaluation of single primary valves (pressure/volume loops to BS EN 250 standard) and subjective evaluation in the form of comments by a team of divers. The same articles also contained subjective comments on the performance of the primary valves when used as part of an ‘Octopus’ system.

These articles were representative of the data readily available to United Kingdom (UK) divers, and likely to be used when selecting apparatus. None of the published data was confirmed or endorsed by QinetiQ.

This search also identified nineteen manufacturers of SCUBA diving regulators, and over fifty models on sale in the UK. All manufacturers appeared to sell ‘Octopus’ demand valves. ‘Octopus’ valves are typically a standard unit with the modification of bright colours and a longer than standard hose length. Where stated, the hose length was typically 1.0 metre (m). Some manufacturers also produced dedicated ‘Octopus’ units. These were normally of reduced size compared to standard units and often did not have exhaust deflectors in order to improve streamlining. Units which combine the function of an ‘Octopus’ demand valve and Buoyancy Control Device (BCD) inflator were also identified.

1.3 Apparatus selection

Drawing upon the review data and following consultation with the HSE an ‘Octopus’ system test matrix was produced (Table 1-1).

When selecting ‘Octopus’ systems for test, QinetiQ Alverstoke sought to emulate purchases likely to be made by UK divers. The logic for the systems included in the testing matrix is presented in Table 1-1.

Due to logistical constraints only six configurations could be tested.

System Identification Number	First Stage and Primary Demand Valve	Secondary 'Octopus' Demand Valve	Justification
1	Supplier A	Supplier A	System 1 was a high cost, high performance option assembled as per supplier's recommendations.
2	Supplier A	Supplier B	System 2 envisages the assembly of a high performance option utilising a low cost regulator as an 'Octopus'.
3	Supplier A	Supplier C BCD Combination unit	System 3 was a high cost, streamlined option assembled as per supplier's recommendations.
4	Supplier B	Supplier B	System 4 was a low cost, low performance option assembled as per supplier's recommendations.
5	Supplier B	Supplier D Used	System 5 envisages the assembly of a low performance option utilising a well used older model regulator as an 'Octopus'.
6	Supplier B	Supplier C BCD Combination unit	System 6 was a low cost, streamlined option assembled as per supplier's recommendations.

Table 1-1: Testing matrix

Supplier A was selected as a high cost, high performance system. The system scored consistently well in published tests. The 'Octopus' demand valve was selected following supplier/vendor recommendations.

Supplier B was selected as a low cost, low performance system. The system scored poorly in published tests. The 'Octopus' demand valve was selected following supplier/vendor recommendations.

Supplier C was selected as a BCD inflator combination unit. No third party performance data was available.

Supplier D was selected to supply a used demand valve. The demand valve was a well used older model and was representative of valves whose performance may have degraded and other poorly performing demand valves. It has been available on the UK market for several years. Its use as an 'Octopus' demand valve was not recommended by any supplier or diving training agency but is representative of equipment configuration practised by many UK divers.

All suppliers were established market brands within the UK.

All regulators were purchased anonymously from retail outlet(s). Regulators were tested as received, except in the case of the BCD combination unit, which was adjusted as per the instructions for use.

2 Procedures

2.1 General

Unmanned evaluation was conducted at QinetiQ Alverstoke using dual hyperbaric breathing simulators and associated equipment within the Life Support Systems Laboratory (LSSL). This laboratory is able to evaluate the apparatus in a range of simulated environments and operational conditions. All monitoring was carried out using calibrated instrumentation and software that give results in real time [14].

Three different units for pressure are used extensively in this report. It is common to use metres to describe the pressure a diver is exposed to; i.e. depth below the water surface. Gas supply pressures are measured in bar. Any other pressures mentioned have been quoted in the S.I. unit of Pascal (Pa). Throughout the work carried out to produce this report it has been assumed that a pressure change of 100 kilo Pascal (kPa) = 1 bar = 10 m (assuming a density of seawater of 1.01972 at 4 ° Celsius (C)) and that the air pressure at sea level = 0 m = 101.3 kPa (one standard atmosphere).

2.2 Breathing performance

The systems were evaluated for compliance with elements of BS EN 250 Respiratory equipment - Requirements, testing, marking and the Norwegian Petroleum Directorate/Department of Energy (NPD/DEn) guidelines [15] for underwater breathing apparatus.

The systems were rigged in the vertical attitude, immersed in fresh water at a regulated temperature of 5 °C and evaluated at simulated depths of 0, 10, 20, 30, 40 and 50 m.

Air complying with BS EN 12021:1999 [16] was supplied to the apparatus, at nominal pressures of 50 and 150 bar.

Where present, the Dial-a-Breath settings of demand valves were placed in mid positions. Venturi levers/pre-dive controls were set as per supplier's recommendations.

Breathing performance was assessed at the nominal ventilation rates shown in Table 2-1.

Ventilation rate ($l \cdot min^{-1}$)	**Tidal volume (litres)**	**Breaths per Minute**
15.0	1.5	10
22.5	1.5	15
40.0	2.0	20
62.5	2.5	25
75.0	3.0	25
90.0	3.0	30

Table 2-1: Ventilation rates

The breathing performance of the regulators was assessed with each of the second stage demand valves (primary and 'Octopus') attached to a dedicated breathing simulator configured for synchronous control. Operating the breathing machines 'in phase' simulated maximum demand as both divers inhale and exhale at exactly the same time and rate. Conversely, operating the machines 'out of phase' simulated minimum demand as one diver inhales whilst the other exhales, both at the same rate of breathing.

Some degree of 'in phase' breathing can occur between divers sharing a single air supply but precise synchronisation of ventilation rate is unlikely. As such the selected testing regime includes both best case (out of phase) and worst case (in phase) conditions.

Inhale and exhale respiratory pressures were recorded throughout the breathing cycle and work of breathing was calculated.

2.3 Pass/fail criteria

The pass/fail criteria adopted for this evaluation encompass both the current European Standard BS EN 250 and the NPD/DEn guidelines published in 1991.

BS EN 250 specifies limits for breathing performance at a ventilation rate of 62.5 l·min^{-1} and at a depth of 50 m. The specific limit of BS EN 250 is derived from the maximum limit of the NPD/DEn guidelines.

The NPD/DEn guidelines for breathing performance of diving apparatus include testing at ventilation rates from 15.0 to 90.0 l·min^{-1} Body Temperature Pressure Saturated (BTPS) and are applicable to any selected depth.

Due to logistical constraints and in order to overcome the Ambient Temperature Pressure (ATP) and BTPS differences of the two systems and standardise output for this evaluation all data has been recorded, presented and analysed as ATP in accordance with BS EN 250.

The results obtained at a ventilation rate of 62.5 ($\pm$5%) l·min^{-1} at 50 m were compared directly with the requirements of BS EN 250.

The data obtained at additional ventilation rates and depths were analysed along side BS EN 250 data using the pass/fail criteria for work of breathing shown in Figure 2-1 and for respiratory pressure in Figure 2-2.

There are some concerns that the NPD/DEn guidelines do not fully reflect current knowledge of diving physiology and equipment design. They appear to be unduly stringent at low ventilation rates, applying criteria for work of breathing that are not physiologically significant whilst only requiring ‘functional performance’ rather than physiologically relevant testing at ventilation rates greater than 75.0 l·min^{-1}.

For this reason, where apparatus has failed to meet the required criteria for work of breathing at ventilation rates of 15.0 and 22.5 l·min^{-1}, while passing at the remainder of the evaluated ventilation rates, it has been designated a borderline fail, indicated by a pink coloured box in summary tables.

In addition the pass/fail limit lines for both work of breathing and respiratory pressure have been extended to provide physiologically relevant guidance at ventilation rates up to 90 l·min^{-1}. This results in a pass/fail limit line for work of breathing of 4.1 J·l^{-1} at 90.0 l·min^{-1}, as opposed to the 5.0 J·l^{-1} limit in the NPD/DEn guidelines.

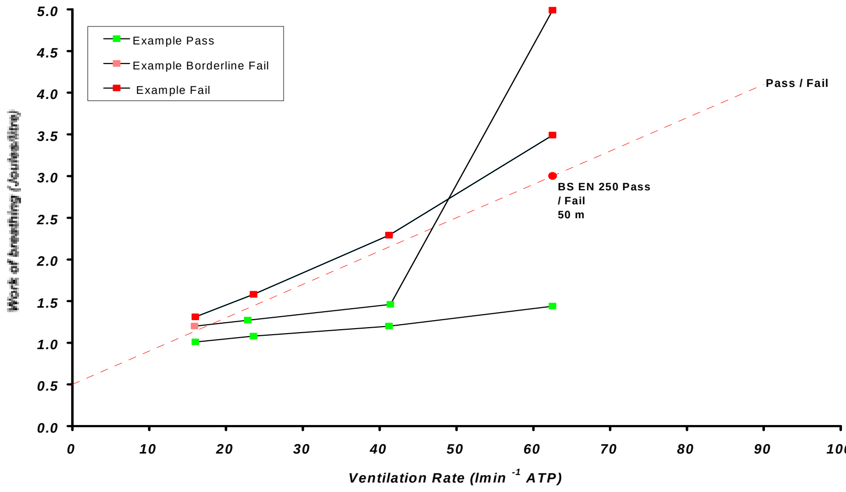

Figure 2-1: Pass/Fail criteria Work of breathing

Data points falling below the dotted red line were considered to have passed, those above to have failed. Borderline failures at low ventilation rates are indicated by pink colour (See above).

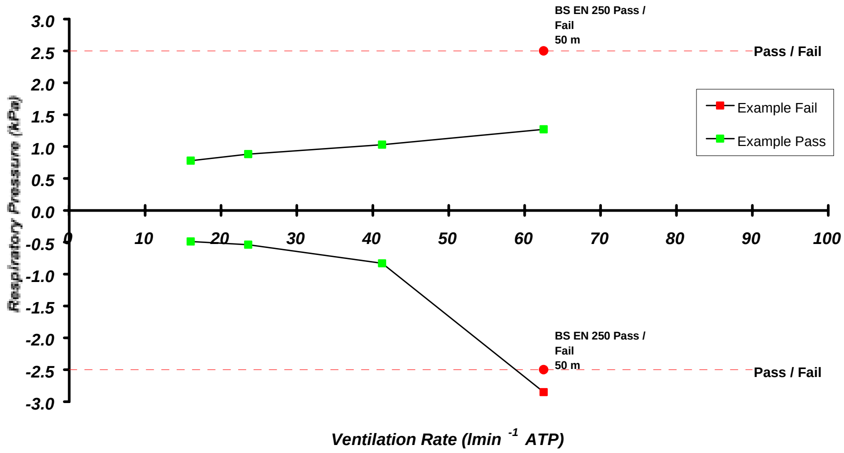

Figure 2-2: Pass/Fail criteria Respiratory pressure

Data points falling between the dotted red lines were deemed to have passed, those above or below to have failed.

3 Results

3.1 Results presentation scheme

In excess of 2,500 breathing performance tests were conducted during the course of this evaluation. In order to simplify the presentation and comprehension of the available data, summary tables have been used. Examples of summary tables using the nominal data presented in Figures 2-1 and 2-2 are shown in Table 3-1 and Table 3-2.

Demand valve	Supply pressure (bar)	**Depth (m)**					
		0					
		Nominal ventilation rate ($l \cdot min^{-1}$ ATP)					
		15.0	22.5	40.0	62.5	75.0	90.0
Example Pass	150						
Example Borderline Fail	150						
Example Fail	150						

	Pass WoB< 0.5 J/l at 0 $l \cdot min^{-1}$- 4.1 J/l at 90.0 $l \cdot min^{-1}$
	Fail WoB> 0.5 J/l at 0 $l \cdot min^{-1}$- 4.1 J/l at 90.0 $l \cdot min^{-1}$
	Fail WoB-Not significant (see text)
	No data

Table 3-1: Example Summary Table for Work of breathing

Demand valve	Supply pressure (bar)	Depth (m)					
		0					
		Nominal ventilation rate (l·min^{-1} ATP)					
		15.0	22.5	40.0	62.5	75.0	90.0
Example	150	Pass	Pass	Pass	Fail		

(green)	Pass Respiratory Pressure < 2.5 kPa
(red)	Fail Respiratory Pressure > 2.5 kPa
(white)	No data

Table 3-2: Example Summary Table for Respiratory pressure

A white box in summary tables indicates either a ventilation rate where data could not be gathered (due to poor performance of the system under test) or it was assessed that obtaining data would risk damage to the test apparatus that would preclude further evaluation.

3.2 Breathing performance results

The BS EN 250 pass/fail results are summarised in Table 3-3.

Demand valve	Supply pressure (bar)	Depth (m) 50 Nominal ventilation rate ($l \cdot min^{-1}$ ATP)					
		62.5	62.5	62.5	62.5	62.5	62.5
System		**1**	**2**	**3**	**4**	**5**	**6**
Primary	150	Pass	Pass	Pass	Pass	Pass	Pass
Octopus	150	Pass	Pass	Pass	Pass	Fail	Fail
Primary	50	Pass	Pass	Pass	Pass	Pass	Pass
Octopus	50	Pass	Pass	Pass	Pass	Fail	Fail
Primary (out of phase)	150	Pass	Pass	Pass	Pass	Pass	Pass
Octopus (out of phase)	150	Pass	Pass	Pass	Pass	Fail	Fail
Primary (out of phase)	50	Pass	Pass	Pass	Pass	No data	Pass
Octopus (out of phase)	50	Pass	Pass	Pass	Pass	No data	Fail
Primary (in phase)	150	Pass	Pass	Pass	Pass	No data	Pass
Octopus (in phase)	150	Pass	Pass	Pass	Pass	No data	Pass
Primary (in phase)	50	Pass	Pass	Pass	No data	No data	No data
Octopus (in phase)	50	Pass	Pass	Pass	Fail	No data	No data

Pass: Pass BS EN 250 breathing performance recommendations

Fail: Fail BS EN 250 breathing performance recommendations

No data

Table 3-3: Pass/fail summary for BS EN 250 criteria

Table 3-4 indicates the pass/fail summary tables for work of breathing and respiratory pressures presented in Appendix A:

	Work of breathing	Respiratory pressures
System 1	Figure: A-1	Figure: A-2
System 2	Figure: A-6	Figure: A-7
System 3	Figure: A-11	Figure: A-12
System 4	Figure: A-16	Figure: A-17
System 5	Figure: A-21	Figure: A-22
System 6	Figure: A-26	Figure: A-27

Table 3-4: Pass/fail summary Tables in Appendix A

Selected work of breathing data (supply pressure 50 bar, depths of 30, 40 and 50 m and ventilation rates of 40.0, 62.5, 75.0 and 90.0 $l \cdot min^{-1}$) are presented in bar chart form to show emerging trends in breathing performance. The data presented in these charts is highlighted in the summary tables (as per Table 3-4) by a blue border.

Table 3-5 indicates the work of breathing bar charts presented in Appendix A:

	Work of breathing 30 m	Work of breathing 40 m	Work of breathing 50 m
System 1	Figure: A-3	Figure: A-4	Figure: A-5
System 2	Figure: A-8	Figure: A-9	Figure: A-10
System 3	Figure: A-13	Figure: A-14	Figure: A-15
System 4	Figure: A-18	Figure: A-19	Figure: A-20
System 5	Figure: A-23	Figure: A-24	Figure: A-25
System 6	Figure: A-28	Figure: A-29	Figure: A-30

Table 3-5: Work of breathing Bar charts in Appendix A

4 Discussion

4.1 Single valve performance

Open circuit self-contained compressed air breathing apparatus is required to meet the performance specified in BS EN 250. This harmonised European standard specifically gives a requirement for the breathing performance of a single valve system at a ventilation rate of 62.5 $l \cdot min^{-1}$; this is in respect of work of breathing < 3.0 $J \cdot l^{-1}$ and respiratory pressures within ± 2.5 kPa (± 25 mbar). As the systems purchased were sold as complying with BS EN 250 it is reasonable to expect that the test data obtained during this evaluation would confirm this.

Observation of the data (Table 3-3) indicates that all the primary valve systems complied with the BS EN 250 requirement and that only the 'Octopus' systems (when tested as a single valve) of System 5 (the used demand valve with low cost regulator first stage) and System 6 (the BCD with low cost regulator first stage) fell short of the required performance. However, it should be noted that the same 'Octopus' valve (the BCD) as in system 5 when configured in System 3 (the BCD with high cost regulator first stage) complied with the BS EN 250 requirement.

The old, 'used', but routinely maintained, demand valve configured as the 'Octopus' in system 5 did not meet the BS EN 250 requirement, and would only meet the principle of the standards breathing performance requirement to a maximum depth of 20 m (Figures A-21 and A-22).

This study has confirmed that the regulators as purchased complied with the breathing performance requirements of BS EN 250.

4.2 Two valve 'Octopus' performance

4.2.1 General

Initial evaluation of the results of the testing shows a clear demarcation between the Systems (Table 3-3).

All test configurations of Systems 1, 2 and 3 (those based on the high cost and performance first stage regulator) fulfilled the principle of the breathing performance requirements of BS EN 250 and had acceptable breathing performance with combined ventilation rates up to 75 $l \cdot min^{-1}$, both in and out of phase, at depths to 50 m with a low (50 bar) supply pressure (Figures A-1 to A-15).

Although some test configurations of Systems 4, 5 and 6 (those based on the low cost first stage regulator) were able to meet the principle of the BS EN 250 breathing performance requirement (Table 3-3 and Figures A-16, A-17, A-21, A-22, A-25 and A-26) they were unable to do so under all conditions. The worst performing of these was System 5; assembled from a low cost, low performance apparatus with the addition of a well-used older model 'Octopus'.

It is apparent that single valves with a breathing performance that meets the requirements of BS EN 250 may be unable to do so when assembled and used as part of an 'Octopus' system.

4.2.2 Individual component performance

Both demand valves of System 4 (Supplier B, low cost regulator and 'Octopus') were capable of meeting BS EN 250 guidelines alone but failed when used in tandem under the most demanding evaluation conditions (Figure A-16, A-17 and A-20).

When comparing results from System 2 (high cost regulator with low cost ‘Octopus’) tests with those from System 4 (low cost regulator with low cost ‘Octopus’) (Figure A-16, A-17 and A20) it can be seen that the same component (Supplier B ‘Octopus’ demand valve) that failed as part of System 4 was capable of meeting BS EN 250 guidelines for breathing performance when paired with Supplier A high cost/performance first stage regulator (Figure A-6, A-7 and A-10).

The same phenomenon is evident with System 6 (low cost regulator with BCD ‘Octopus’). Under several test conditions System 6 failed the BS EN 250 and NPD/DEn guidelines for breathing performance (A-26, A-27 and A-30); the majority of the failures were associated with the ‘Octopus’ BCD inflator combination unit. Comparison of the results from System 6 (Figure A-26, A-27 and A-30) with those from System 3 (Figure A-11, A-12 and A-15) shows that the same component (Supplier C ‘Octopus’ BCD inflator combination unit) was capable of meeting BS EN 250 guidelines for breathing performance when paired with supplier A first stage but not when paired with Supplier B.

It is clear that the true performance of an ‘Octopus’ system cannot be derived by simple combination of components that individually or as a single valve system meet current performance criteria. It is essential that either the whole system performance is identified or, that if components are tested, the acceptance criteria are appropriate to subsequent use as an ‘Octopus’ system.

4.2.3 First stage regulator

Analysis of the data indicates that the performance of the first stage regulator is a vital factor when determining the final performance of a complete system.

Systems 1, 2 and 3 were all assembled with the same high cost/performance first stage regulator (Supplier A). When tested as ‘Octopus’ systems with two divers breathing simultaneously these three systems were able to meet the breathing performance requirements of BS EN 250 and would be able to support two divers undertaking hard work at depths down to 50 m (Table 3-3).

Evidence presented above also shows that the breathing performance of components paired with the high cost/performance first stage regulator (i.e. Systems 2 and 3) is improved over that when they are used with the low cost, low performance regulator (i.e. Systems 4 and 6 respectively).

It is recommended that if ‘Octopus’ systems are to be used that they should only be based on high performance first stage regulators.

4.2.4 Diver adjustable controls

When examining the data presented in Figures A-3 to A-5 and Figure A-8 to A-10 it can be seen that in Systems 1 and 2 the breathing performance of the ‘primary’ demand valve is *worse* than the ‘Octopus’. This is particularly of note with System 2 in that the ‘Octopus’ is nominally a low cost/performance component. The primary demand valve in these systems has a ‘dial-a-breath’ diver adjustable control. For this study the ‘dial-a-breath’ was set to a nominal halfway position, this may not be the optimum setting and may have resulted in a slight ‘de-tuning’ of the primary demand valve.

It should be noted that improvements in breathing performance could be gained by a diver by adjusting the valve during the course of a dive.

4.2.5 Differential performance

There is a progressive degradation in breathing performance with increasing depth and ventilation rate in all systems. A noteworthy, yet logically obvious, phenomenon is that it is the poorer performing demand valve of any pair (regardless of its performance in any other system in which it is assembled) which, when compared to the better performance valve, is affected the most (differential performance).

In Systems 1 and 2 the primary valve (while still achieving BS EN 250 guidelines) performs less well than either of the 'Octopus' valves. At 50 m when ventilated at 90.0 $l\cdot min^{-1}$, in phase, it is this valve which experiences a noticeable increase in work of breathing, while the 'Octopus' valves are relatively unaffected (Figures A-5 and A-10). However, this can be compared with System 3 where the same primary valve is this time the better performer (Figures A-13 to A-15). At 50 m when ventilated out of phase at 90.0 $l\cdot min^{-1}$ it is the poorer performing 'Octopus' valve (while still achieving BS EN 250 guidelines) which demonstrates a markedly increased work of breathing while the primary valve is relatively unaffected (Figure A-15).

There is a safety concern with 'differential performance' affecting a buddy pair working hard (i.e. at elevated ventilation rates) using an 'Octopus' system. One of the divers may be content breathing from the system with 'acceptable' breathing performance and be unaware that the other diver is experiencing some respiratory limitation and distress.

The effect of 'differential performance' may be reduced if the two demand valves are of similar performance, as illustrated by comparison of System 1 with System 3 (Figure A-5 with Figure A-15) and System 4 with System 6 (Figure A-18 with Figure A-28). Accordingly it would seem appropriate that 'Octopus' systems should be configured with demand valves of similar performance.

4.2.6 In and out of phase

When two divers are breathing on an 'Octopus' system their synchronisation may range from completely out of phase, i.e. one is breathing out whilst the other is breathing in, to completely in phase, both breathing in and out at the same time. There are considerably different demand and performance requirements on a system for the two extremes; in phase being much more severe than out of phase.

The effect on performance of being in and out of phase is illustrated by the test results of System 4 (Figure A-19 and A-20). The breathing performance of two divers breathing completely out of phase with a ventilation rate of 62.5 $l\cdot min^{-1}$ at a depth of 50 m, or 75 $l\cdot min^{-1}$ at a depth of 40 m, easily complies with the defined pass/fail criteria. In this situation the divers would feel comfortable and would not experience any difficulty in breathing. However, if under the same conditions they simply switched to breath in phase, the breathing performance would become unacceptable and such that they may perceive that the system had 'failed' or 'run out of air'. The nature of this perceived failure would thus be rapid, extreme and could result in a significant diving incident.

A similar effect was observed with System 5 (Figure A-23) and System 6 (Figure A-30).

It is worth noting that when two people are in close proximity and particularly with visual and audible indicators as to respiratory rate, there can be a tendency for breathing to 'fall in step' and a degree of synchronisation (in-phase breathing) to occur. This would lead to the Octopus system being used in a worst case scenario.

4.3 Breathing performance standard (BS EN 250:2000)

This study has confirmed that the single regulators, as purchased, complied with the breathing performance requirements of BS EN 250 and that a consumer/user may reasonably expect that the regulators, both high and low cost, are 'fit for purpose'.

A further consideration is that the single valve work of breathing of all the primary demand valves and the 'Octopus' valves of Systems 1 to 4 is in the order of one half of the maximum BS EN 250 limit of 3.0 $J{\cdot}l^{-1}$ (Figures A-5, A-10, A-15, A-20, A-25 and A-30). Thus the purchased valves may all be considered as comfortably meeting the current standard and any associated legislation.

The study has also shown (see above) that when used as part of an 'Octopus' system, and with two divers breathing from the system, the breathing performance of the regulators may become unacceptable (e.g. System 4, Figure A-20) and as a result this could lead to an incident.

The introduction of the breathing performance requirements of BS EN 250 has provided a means for improving the safety of diving demand regulators. However, the results of this study lead to the conclusion that the single valve tests as currently presented in the BS EN 250, are inappropriate for determining the performance of an 'Octopus' system with two divers breathing from a single first stage regulator.

It is recommended that revised tests and acceptance criteria be identified for 'Octopus' systems, and that these are proposed for inclusion in future diving apparatus standards including the next revision of BS EN 250.

4.4 Operational considerations

The shortfall in breathing performance of 'Octopus' systems in this report is may be used to assemble operational guidance in respect of the configuration and use of bail-out systems and AAS. It may also go some way to explaining the number of divers who inexplicably break contact with their buddies during AAS ascents using SCUBA 'Octopus' systems.

The fact that performance of 'Octopus' systems may be degraded over that of the single valve system reinforces the view that an AAS should ideally comprise a completely independent gas supply and demand regulator.

However, if 'Octopus' style systems are to be used then the following should be considered:

- Although single valves purchased as CE marked to BS EN 250 may be considered as 'fit for purpose' when used alone, their performance when configured, as an 'Octopus' system cannot be assured.
- To have the best chance of configuring an 'Octopus' system with acceptable breathing performance it should be based on a high performance (possibly higher cost) first stage regulator.
- Assembling systems using second stage demand valves of different performance may, during use, lead to the diver with the poorer performing valve becoming distressed with the other diver being unaware of this. Accordingly, 'Octopus' systems should be configured with demand valves of similar performance.
- The use of older model demand valves, valves whose performance may have degraded and other poorly performing demand valves (e.g. System 5) in 'Octopus' systems may result in unacceptable breathing performance (Figures A-21 to A-25), and as such are not recommended for use as 'Octopus' valves.

- The diving community should be made aware of the effects on breathing performance of breathing in and out of phase when using 'Octopus' systems.

5 Conclusions

The CE marked regulators purchased for this study complied with the breathing performance requirements of BS EN 250.

SCUBA single demand valve systems capable of meeting the breathing performance requirements of BS EN 250 cannot be relied upon to meet the same requirements when used as part of an ‘Octopus’ system.

As the performance of ‘Octopus’ systems may be worse than that of the single valve system, an AAS should ideally comprise a completely independent gas supply and demand regulator.

The performance of an ‘Octopus’ system can not be derived by simple combination of components that individually or as a single valve system meet current performance criteria.

Performance of the first stage regulator is a vital factor when determining the final performance of a complete system. Breathing performance of components paired with a high cost/performance first stage regulator was better than that with a low cost/performance regulator.

A poorer performing demand valve of any ‘Octopus’ pair will experience a greater degradation in performance with increasing depth and ventilation rate when compared to the better performing valve (differential performance).

The effect of ‘Differential performance’ may be reduced if the two demand valves are of similar performance.

Differential performance of an ‘Octopus’ system may be such that a diver who is content breathing from the system may be unaware that the other diver is experiencing some respiratory limitation and distress.

A considerable degradation in breathing performance may occur when breathing in phase compared to out of phase. The magnitude of this affect may be such that divers breathing out of phase who switch to breathing in phase may perceive that the ‘Octopus’ system has failed or run out of air.

The observed breathing performance of ‘Octopus’ systems may go some way to explaining the number of divers who inexplicably break contact with their buddies during AAS ascents using SCUBA 'Octopus' systems.

Open circuit SCUBA single valve tests as currently presented in BS EN 250 are inappropriate for determining the performance of an ‘Octopus’ system with two divers breathing from a single first stage regulator.

It is essential that either whole system performance is identified or that, if components are tested, the acceptance criteria are appropriate to subsequent use as an ‘Octopus’ system.

6 Recommendations

The preferred system for an alternative air supply is a completely independent gas supply and demand regulator.

If 'Octopus' systems are to be used it is recommended that:

- The consumer/user is made aware that CE marked valves to BS EN 250 may be considered as 'fit for purpose' when used alone, but their performance cannot be assured when configured as part of an 'Octopus' system.
- Octopus systems should be based on a high performance (possibly higher cost) first stage regulator.
- Octopus systems should be configured with demand valves of similar performance.
- The use of older model demand valves, valves whose performance may have degraded and other poorly performing demand valves is not recommended.
- The diving community should be made aware of the effects on breathing performance of breathing in and out of phase when using 'Octopus' systems.

Appropriate test procedures and acceptance criteria should be identified for 'Octopus' systems, and proposed for inclusion in future diving apparatus standards including the next revision of BS EN 250.

7 References

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A Breathing performance data

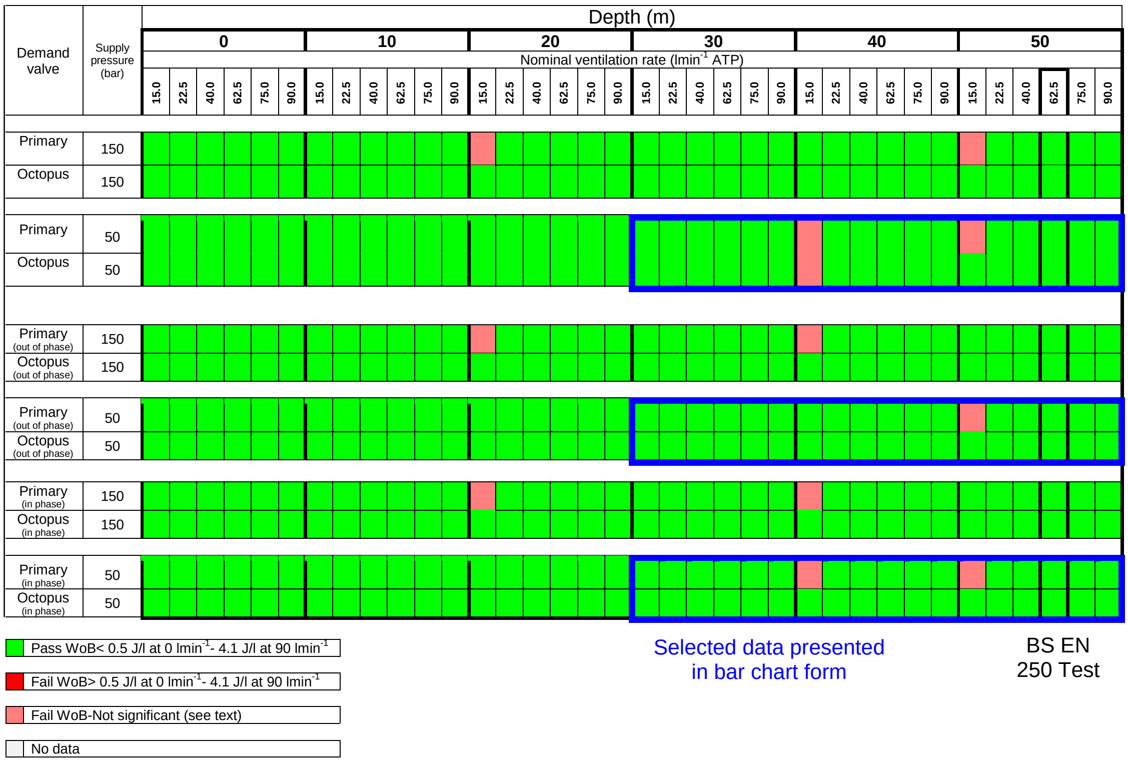


Figure A-1: Summary Table for Work of breathing. System 1

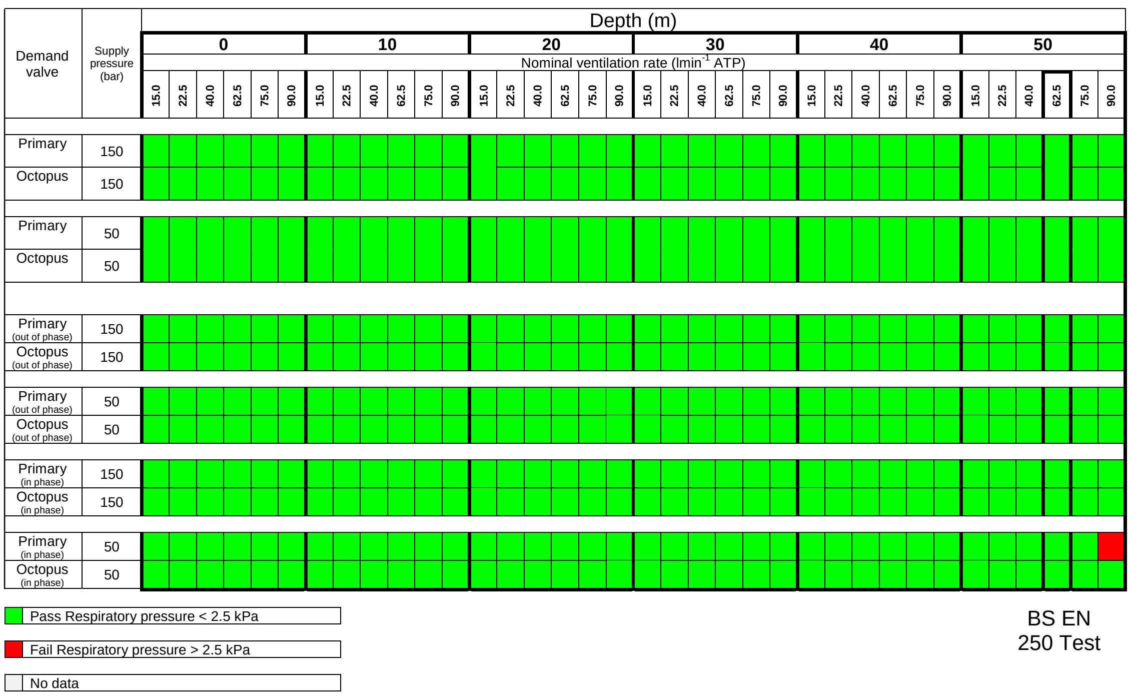


Figure A-2: Summary Table for Respiratory pressure. System 1

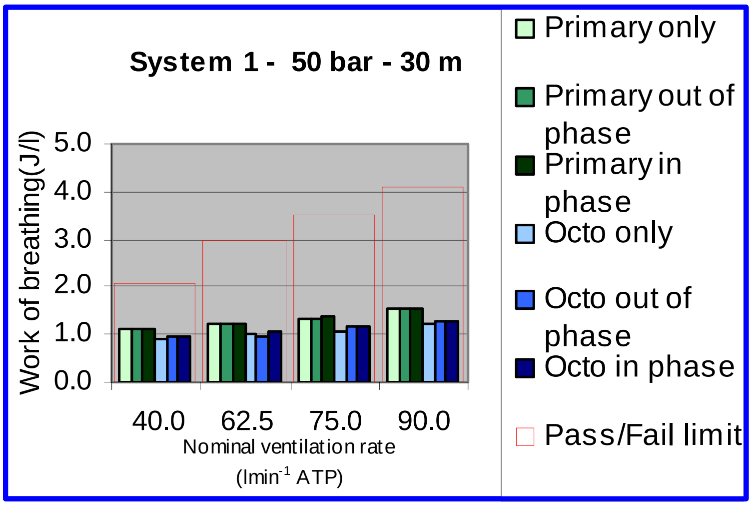


Figure A-3: Selected Work of breathing Data. System 1

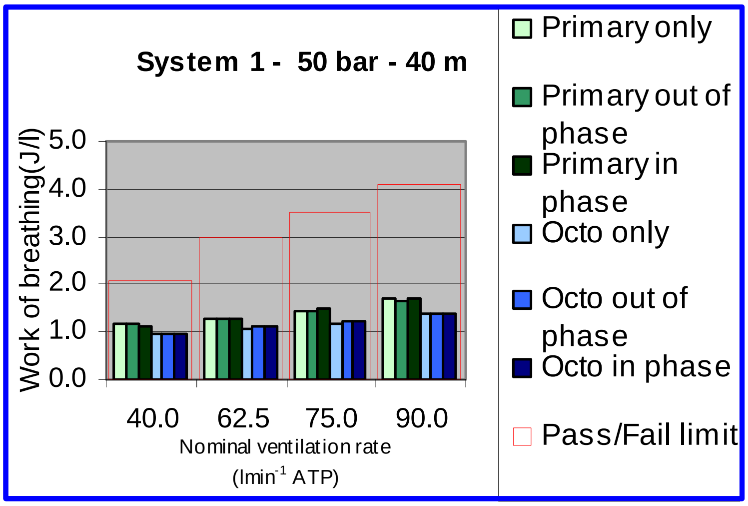


Figure A-4: Selected Work of breathing Data. System 1

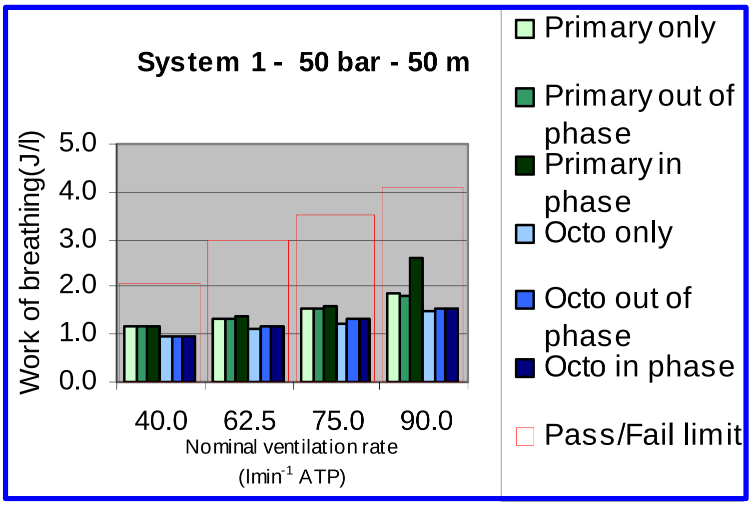


Figure A-5: Selected Work of breathing Data. System 1

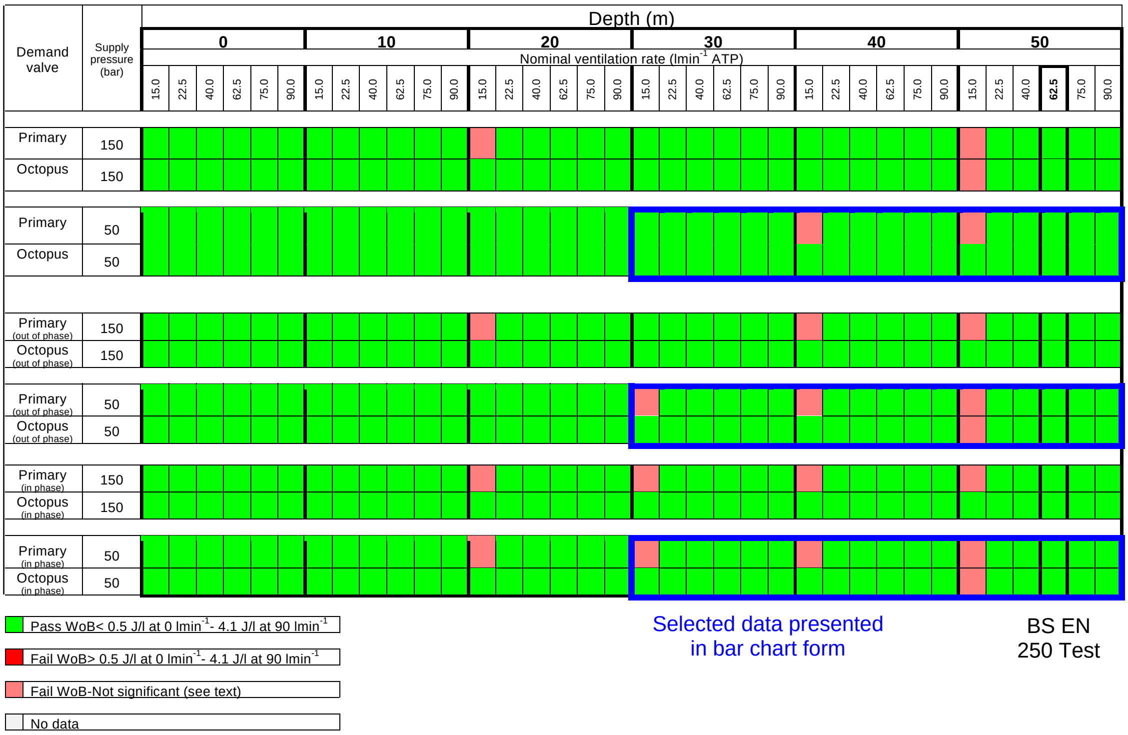


Figure A-6: Summary Table for Work of breathing. System 2

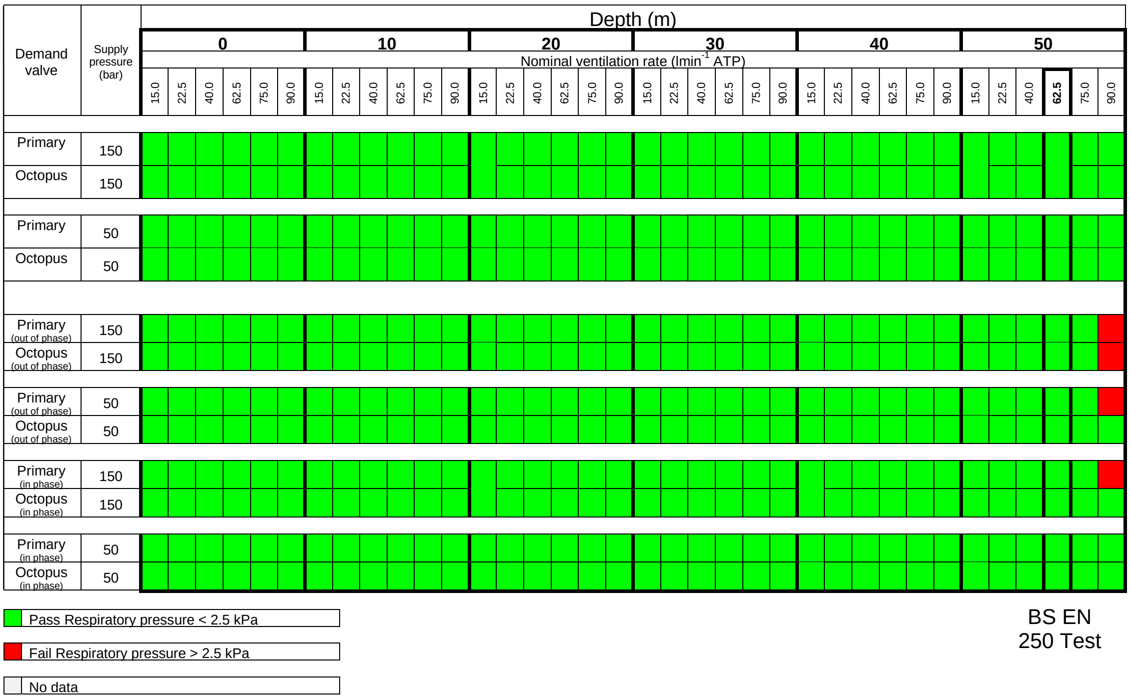


Figure A-7: Summary Table for Respiratory pressure. System 2

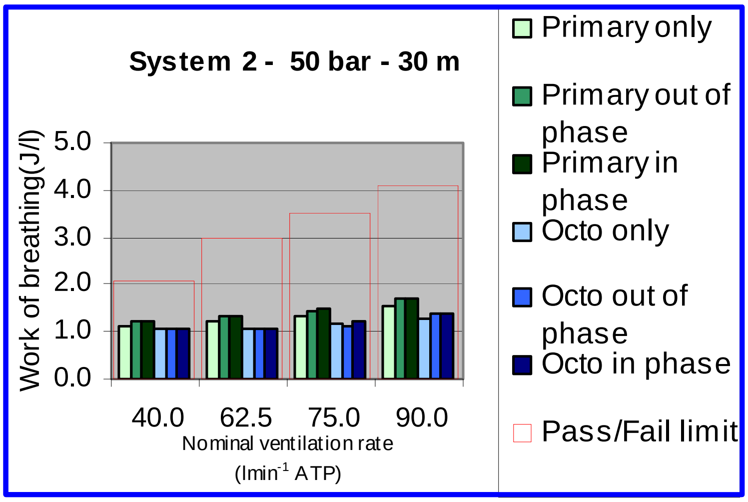


Figure A-8: Selected Work of breathing Data. System 2

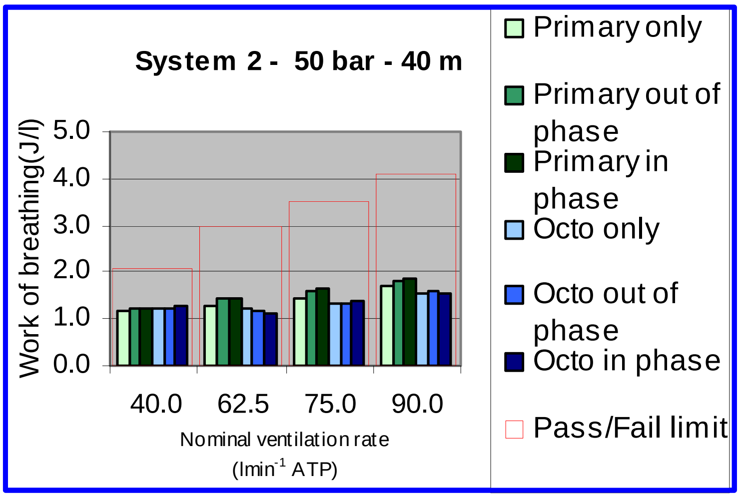


Figure A-9: Selected Work of breathing Data. System 2

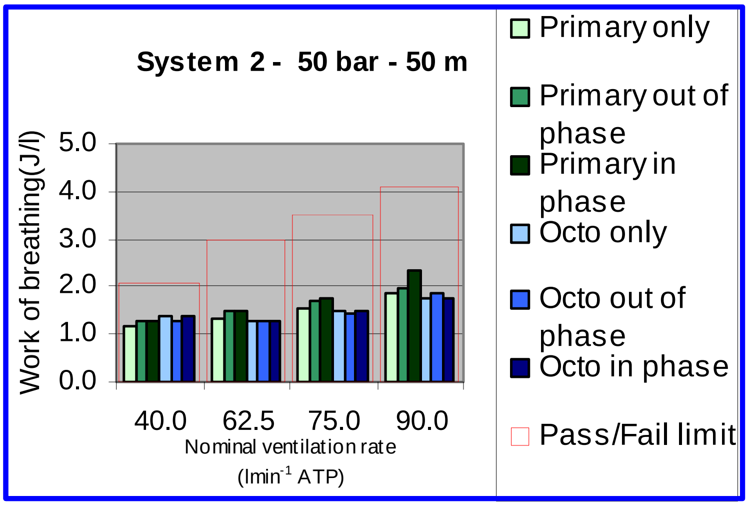


Figure A-10: Selected Work of breathing Data. System 2

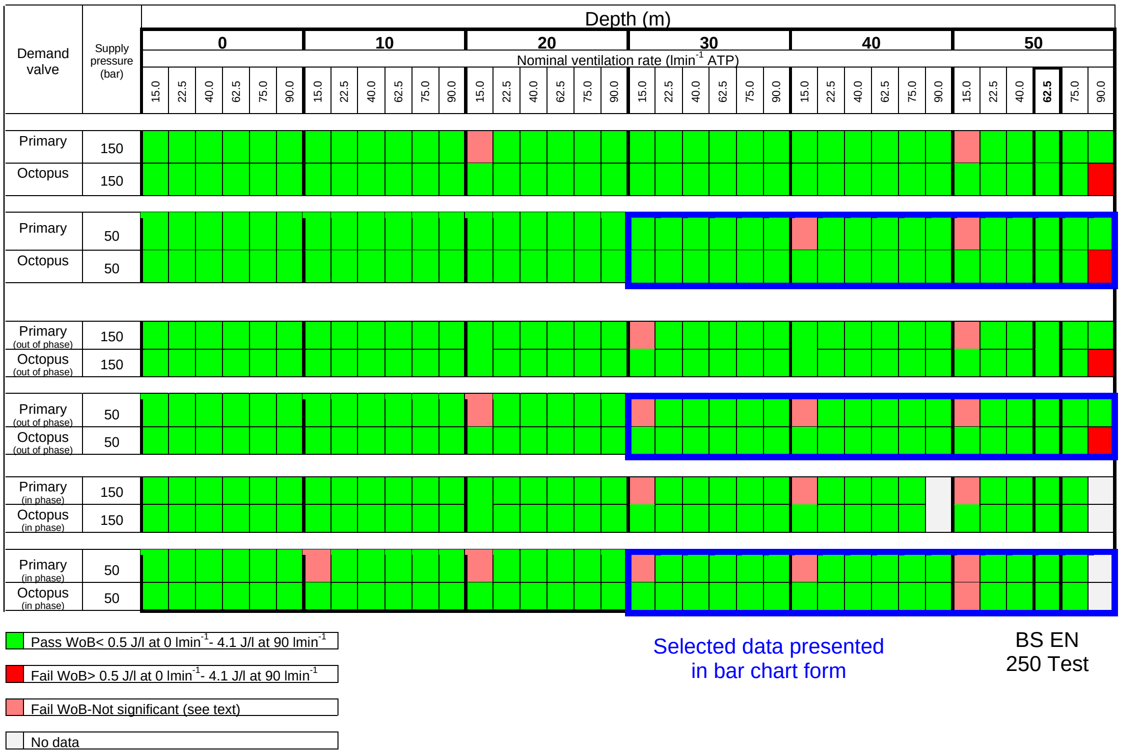


Figure A-11: Summary Table for Work of breathing. System 3

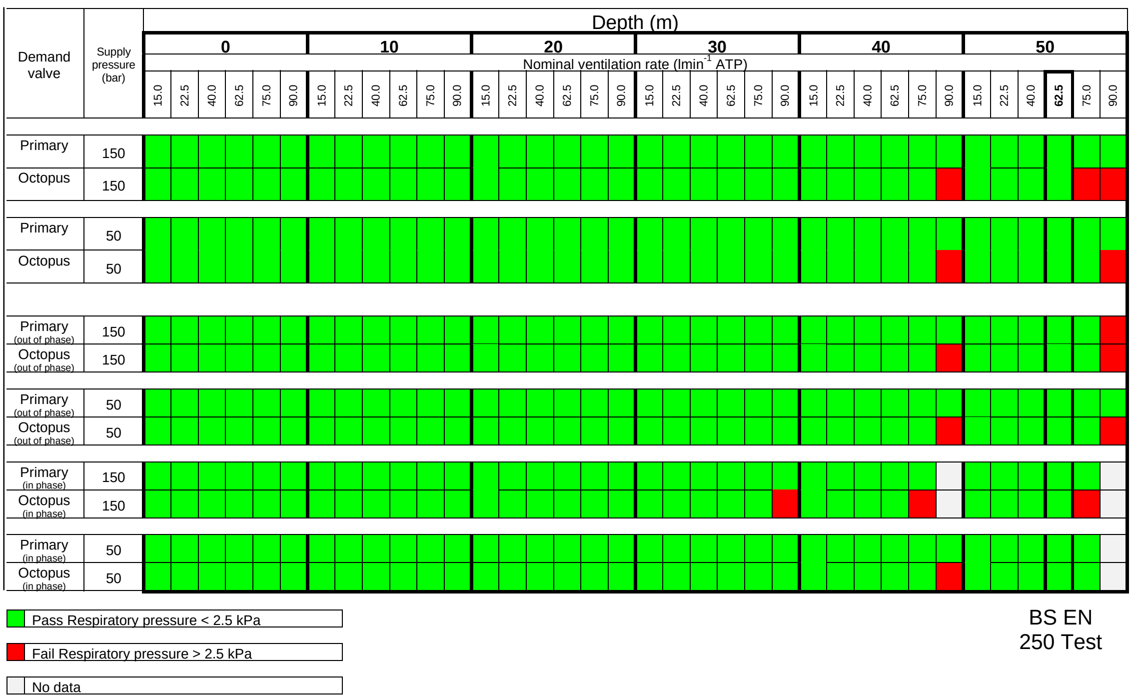


Figure A-12: Summary Table for Respiratory pressure. System 3

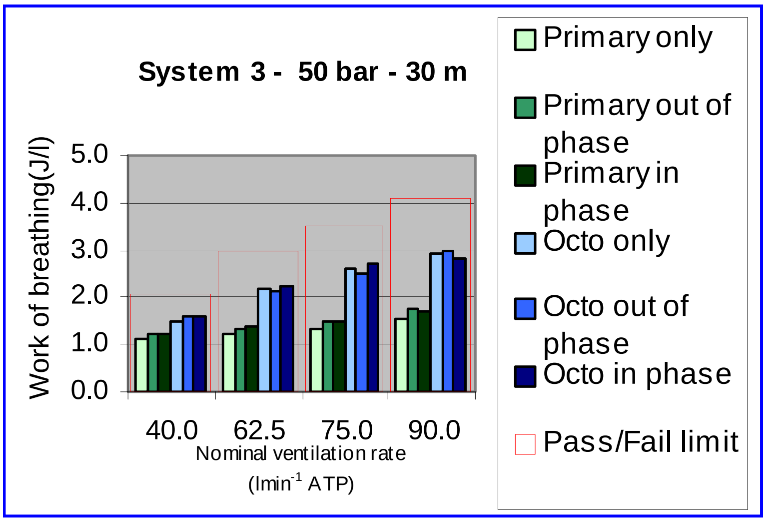


Figure A-13: Selected Work of breathing Data. System 3

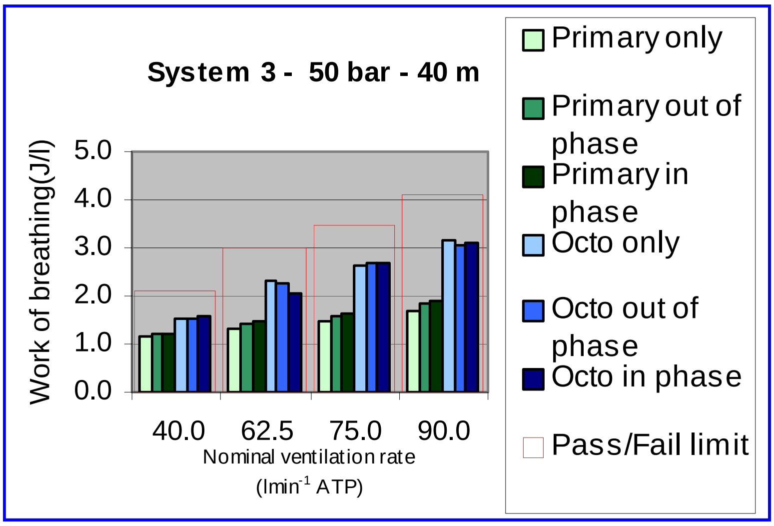


Figure A-14: Selected Work of breathing Data. System 3

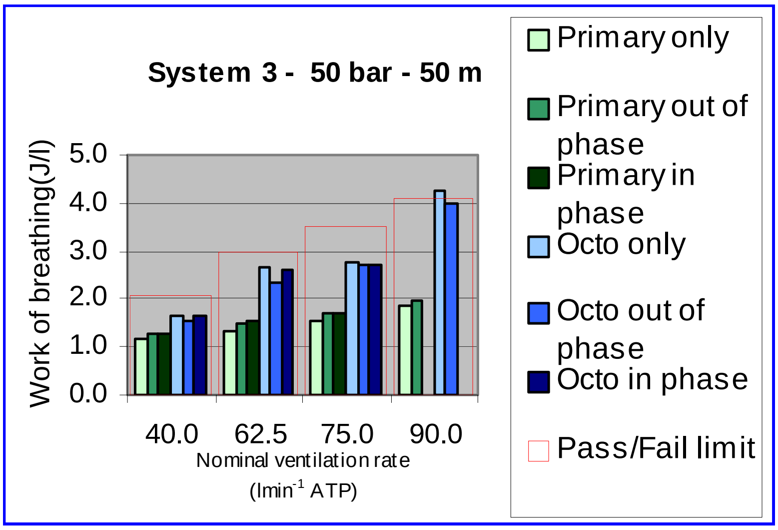


Figure A-15: Selected Work of breathing Data. System 3

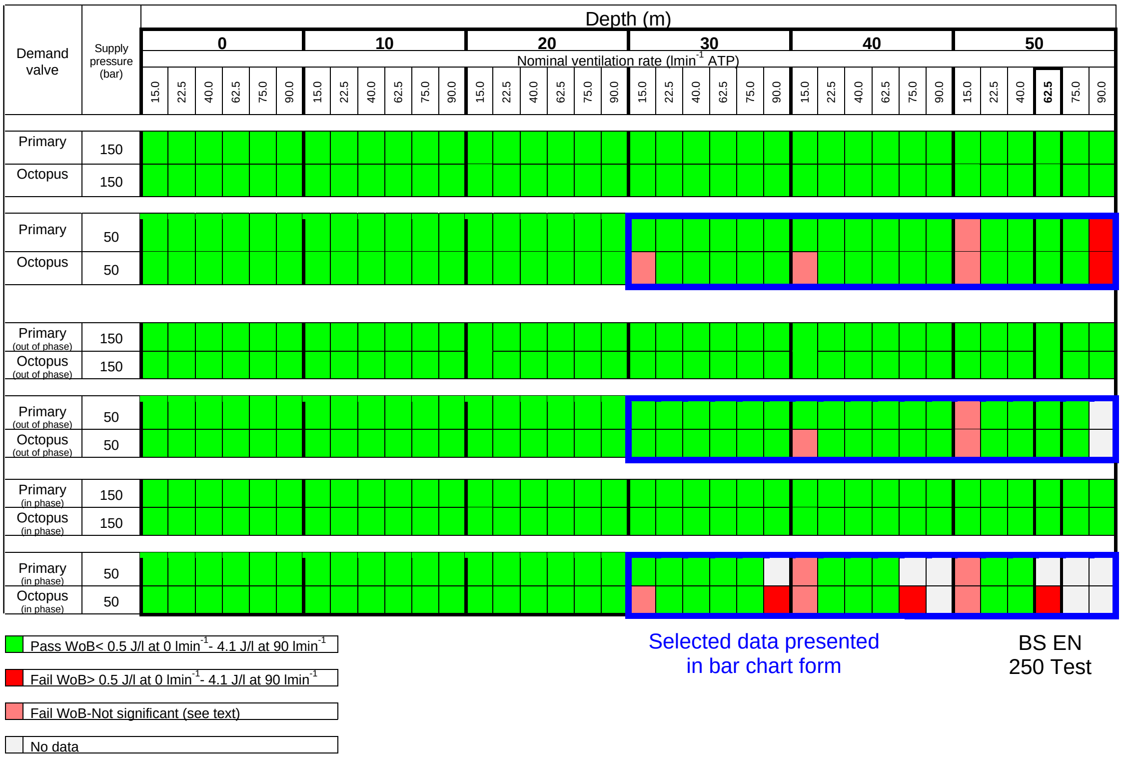
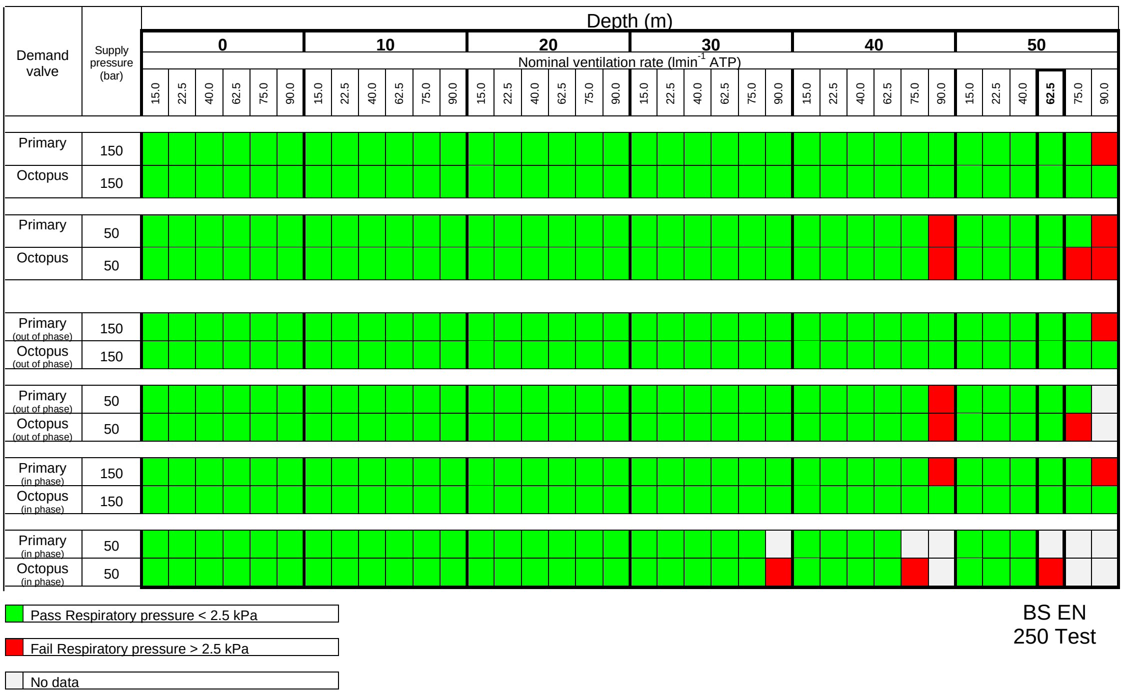


Figure A-16: Summary Table for Work of breathing. System 4



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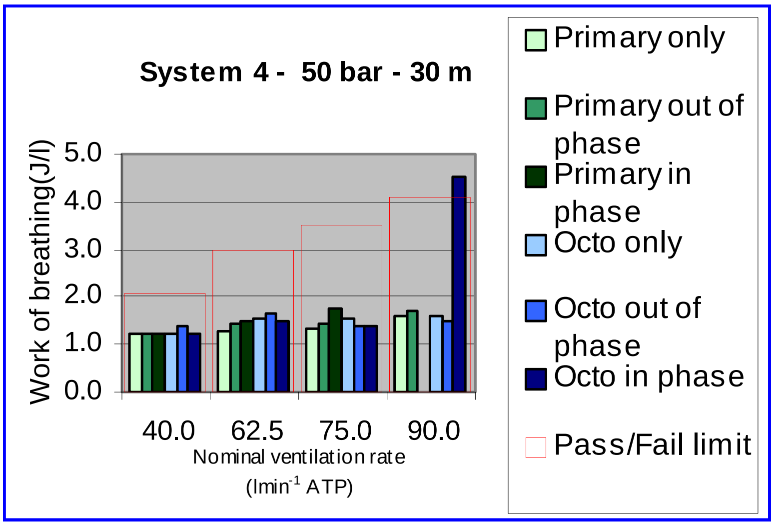


Figure A-18: Selected Work of breathing Data. System 4

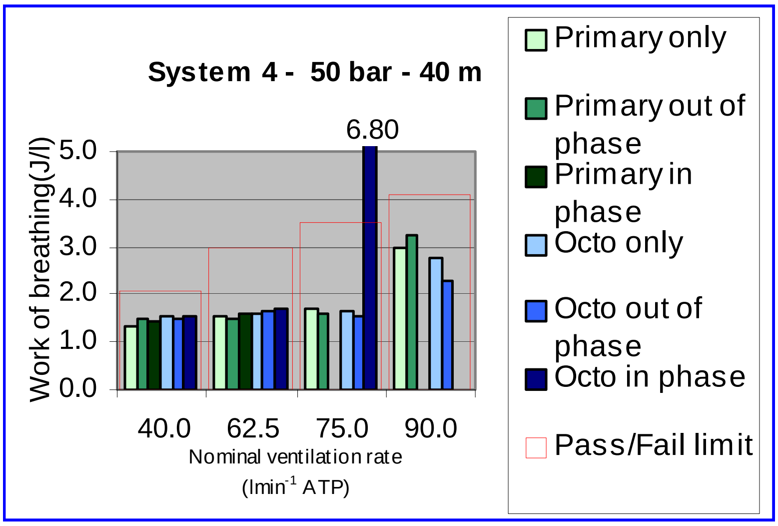


Figure A-19: Selected Work of breathing Data. System 4

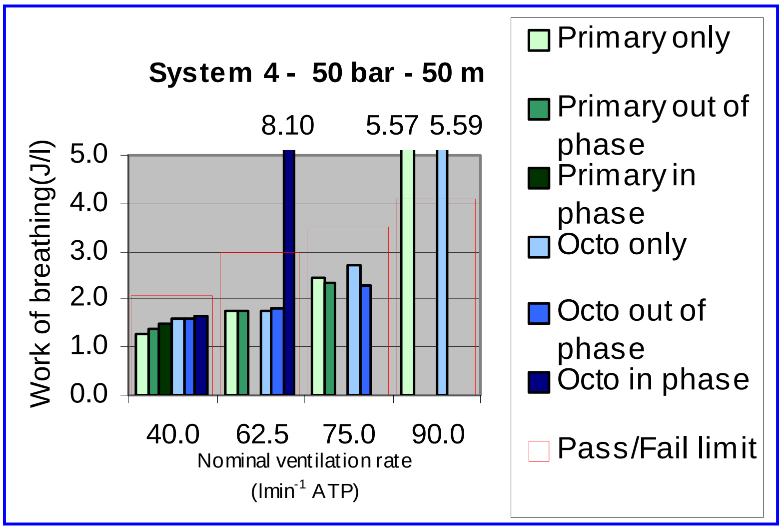


Figure A-20: Selected Work of breathing Data. System 4

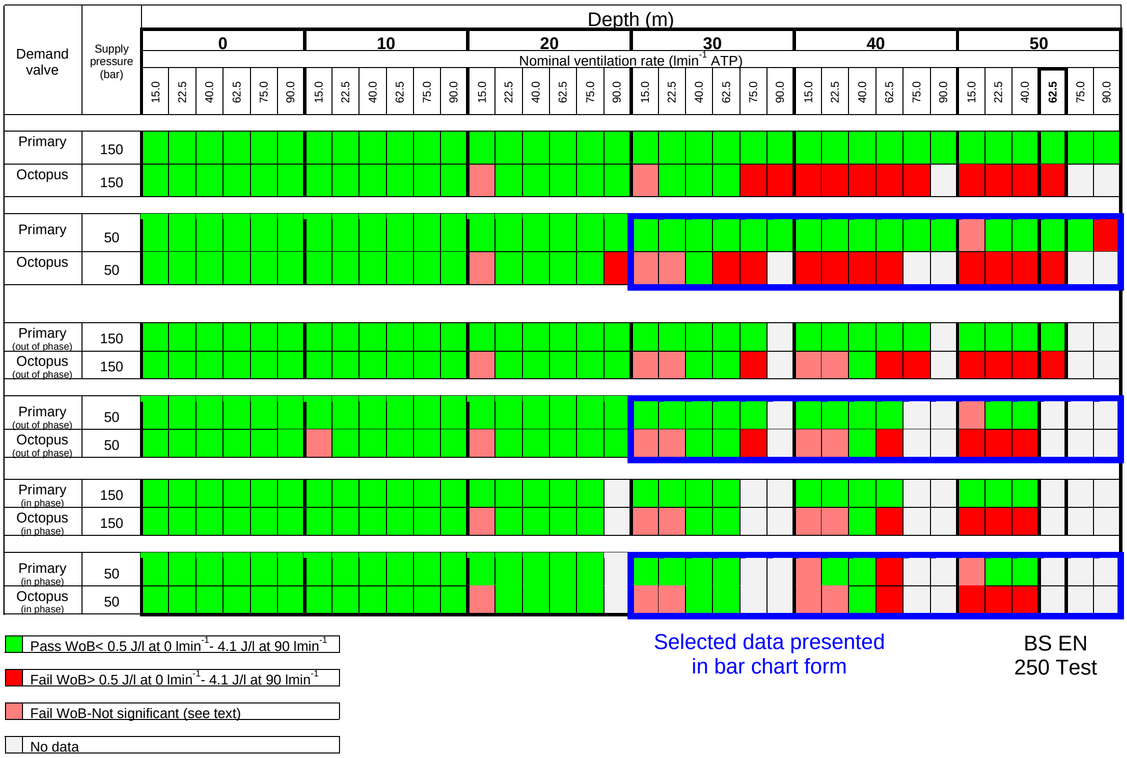


Figure A-21: Summary Table for Work of breathing. System 5

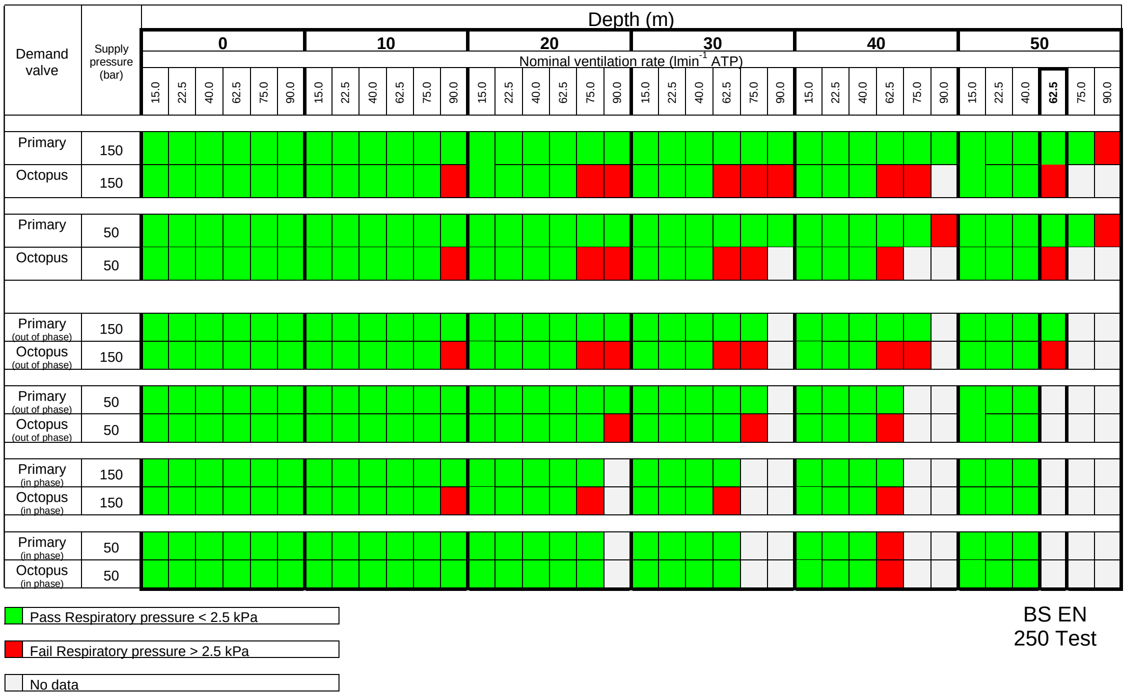


Figure A-22: Summary Table for Respiratory pressure. System 5

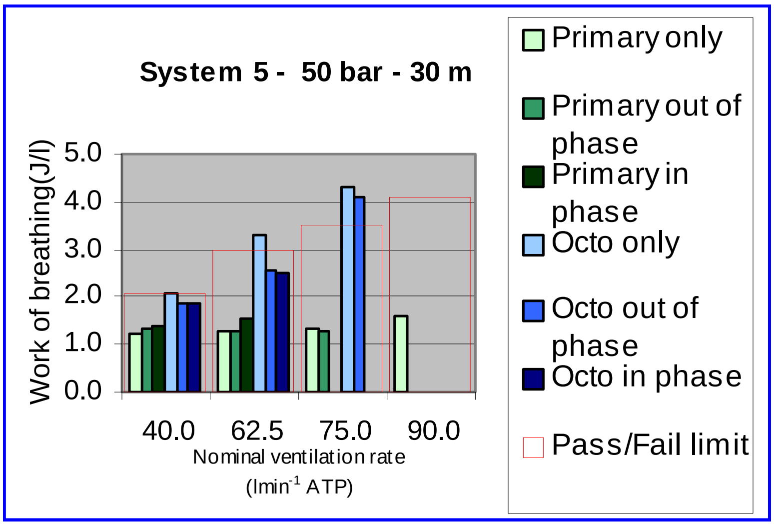
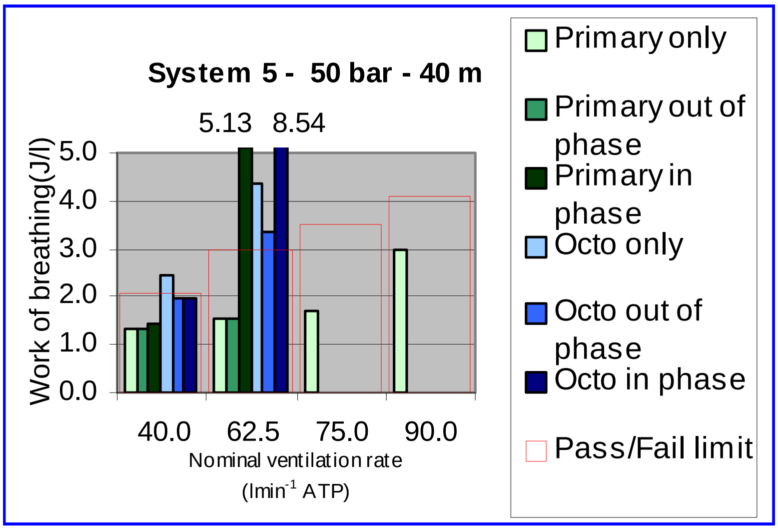


Figure A-23: Selected Work of breathing Data. System 5



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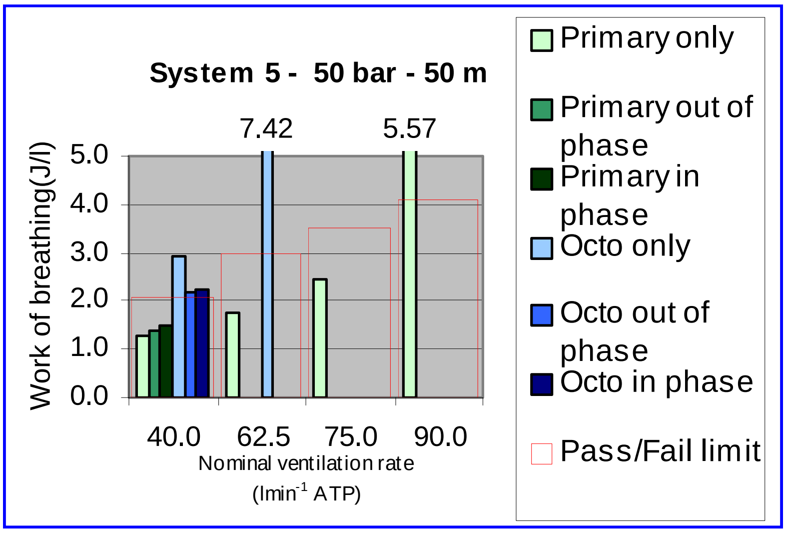

Figure A-25: Selected Work of breathing Data. System 5

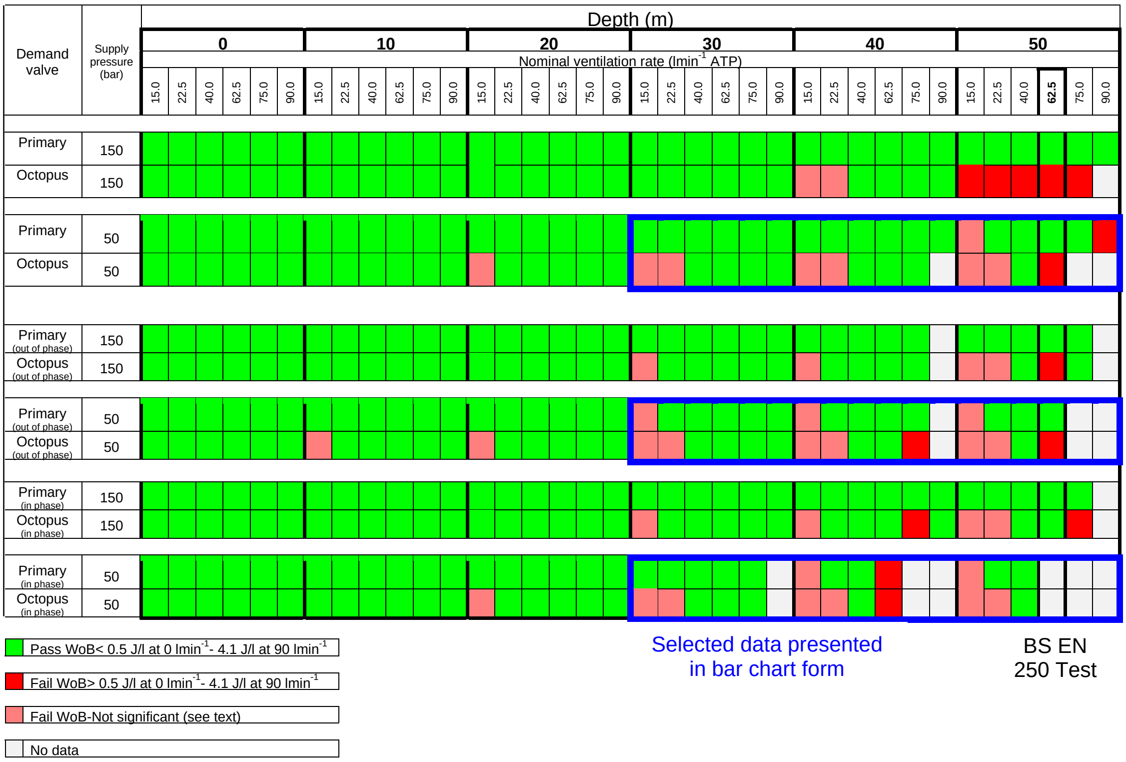

Figure A-26: Summary Table for Work of breathing. System 6

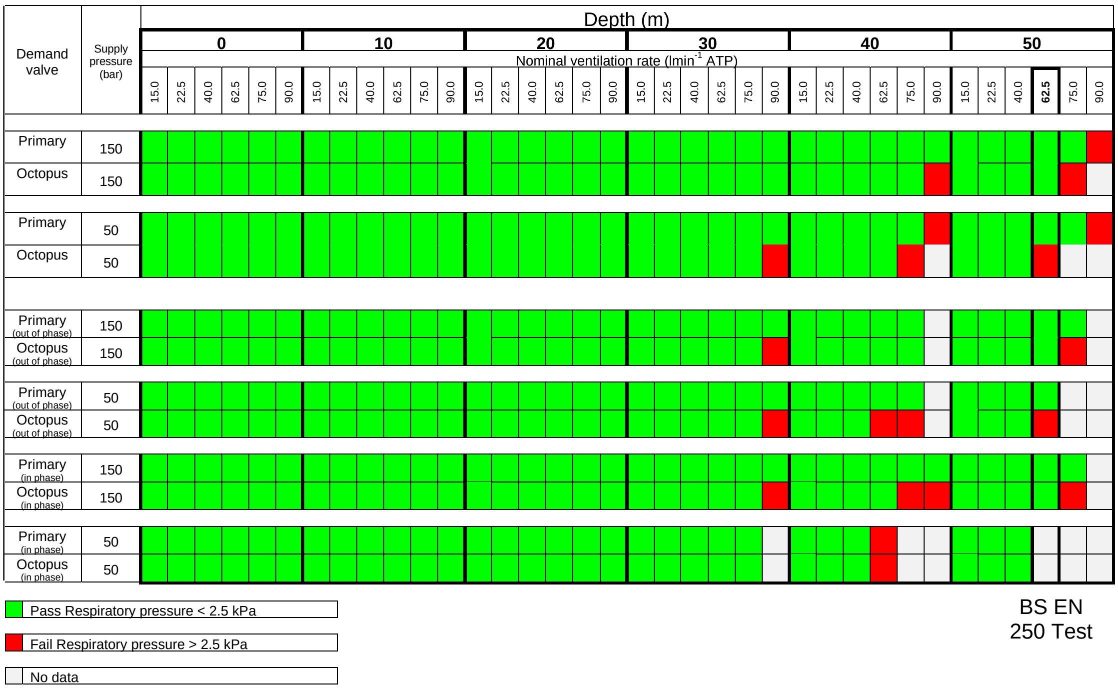

Figure A-27: Summary Table for Respiratory pressure. System 6

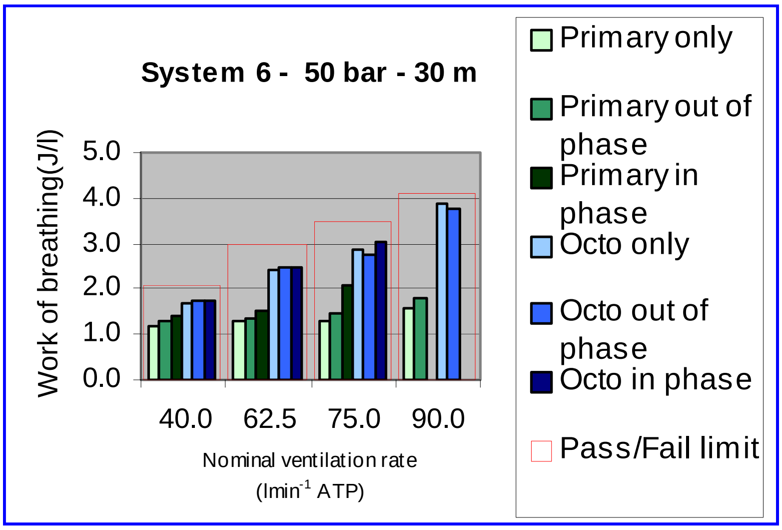

Figure A-28: Selected Work of breathing Data. System 6

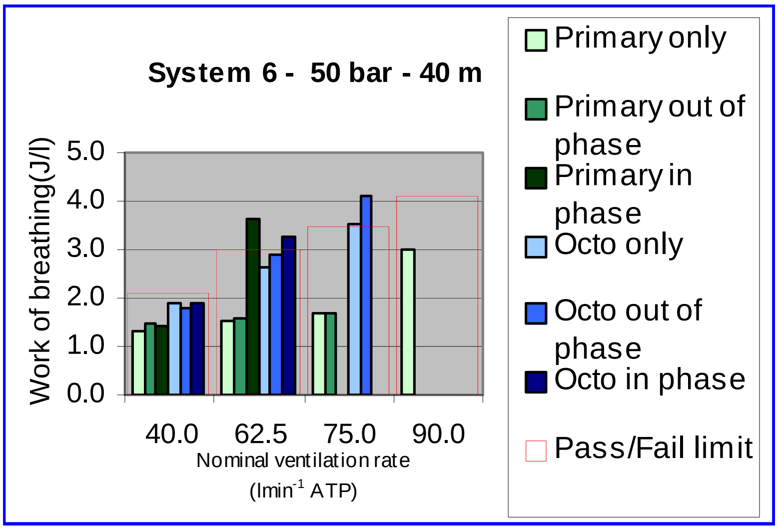

Figure A-29: Selected Work of breathing Data. System 6

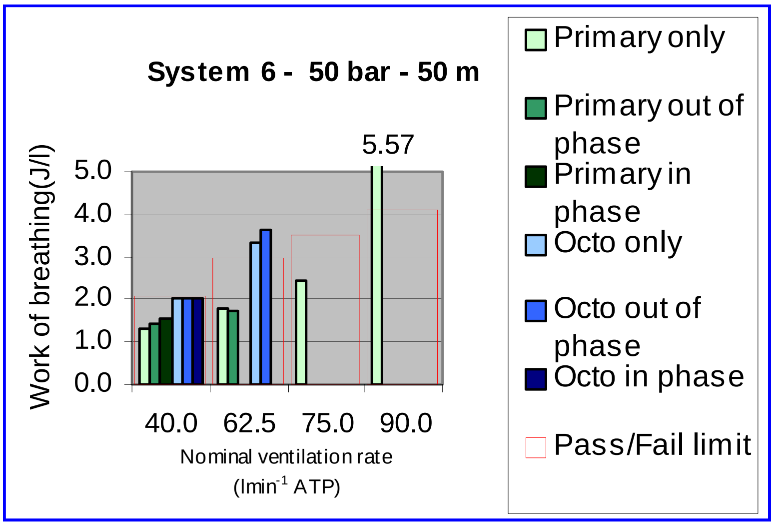

Figure A-30: Selected Work of breathing Data. System 6

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