VERIFICATION REPORT: EFFECT OF WATER INGRESS ON BREATHING RESISTANCE OF A CO2 SCRUBBER USING GRANULAR MEDIA

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ORIGINATOR:	**Dr. Alex Deas, Dr. Bob Davidov**
DEPARTMENT:	**Engineering**
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Revision History

Revision	Date	Description
A	4th Sep 2006	Initial draft
A1	27th Oct 2006	Proof reading completed and approved for issue

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1. PURPOSE AND SCOPE

Most rebreather accidents end with a unit which is flooded. This document assesses the effect of a flood in a granular scrubber, for forensic examination purposes. It also looks at the effect of small amounts of water from condensation or minor ingress on breathing resistance.

The purpose of this study is to enable breathing resistance measurements to be taken in a forensic environment, to determine whether the scrubber had an excessive Work Of Breathing prior to the flood occurring.

The scope of this document is to record measurements of the breathing resistance and pressure drop of an Inspiration Classic scrubber cartridge, before and after flooding, along with the effect of the measurement system with sufficient detail to allow other researches to reproduce the data.

2. ABBREVIATIONS

DL: Deep Life Ltd

Canister: The unit a scrubber cartridge fits into to, with the connection to the breathing hoses.

Cartridge: The unit that holds the scrubber granules, that fits into the scrubber canister.

CBM: Compact Breathing Machine, recording absolute pressure, temperature and humidity, PPO2 and differential pressure, with up to 2000 measurements per breathing cycle. The machine supports respiratory rates up to 90l/min.

SNR: Signal to Noise Ratio.

3. METHOD

Uses CBM Serial number 01, with calibrated Druck high precision differential sensor fitted. The accuracy of this has been determined in a separate verification report.

All measurements are made at 90l/m to allow the experiments to be conducted at 1ATM and give results with as large a SNR as possible.

A separate report available to Deep Life's clients, entitled "Relationship of pressure drop to depth, flow rate and gas composition" by Dr. Bob Davidov and Dr. Alex Deas, shows how the resistance can be scaled with depth and for different flow rates.

The scrubber packing uses the method described in August 2006 by Martin Parker of APD using 4 – 8 mesh L Grade Sofnolime (to CS 2580).

The method used for this experiment was:

1. Measure the resistance of the breathing machine itself: this is determined by the orifice to connect to any tube to the scrubber.
2. Measure the resistance of a straight tube to the scrubber.
3. Measure the resistance of a curved tube to the scrubber.
4. Measure the resistance of the scrubber housing.
5. Measure the effect of the scrubber being vertical or horizontal, and record difference if there is any.

6. Measure the weight and resistance of a scrubber packed using the method described by APD's latest advice, posted onto the Inspiration User Forum.
7. Soak the scrubber in water and drain.
8. Measure the gain in weight, and resistance.
9. Allow the scrubber to dry in air for a day, then measure again.

4. TEST RESULTS

1. Pressure drop of connection to CBM

The purpose of the experiment is to determine the effect of fitting the output connector to the breathing machine (CBM), and to provide a base point calibration: the connector is a 36mm internal diameter orifice.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Tue_Oct_17_10_04_50	36	5 ms	1 ATM	22.3 deg C	50%

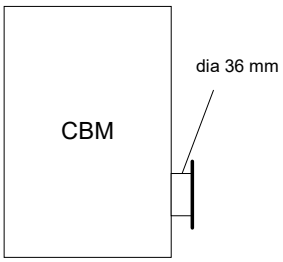

Fig 4-1. CBM without load.

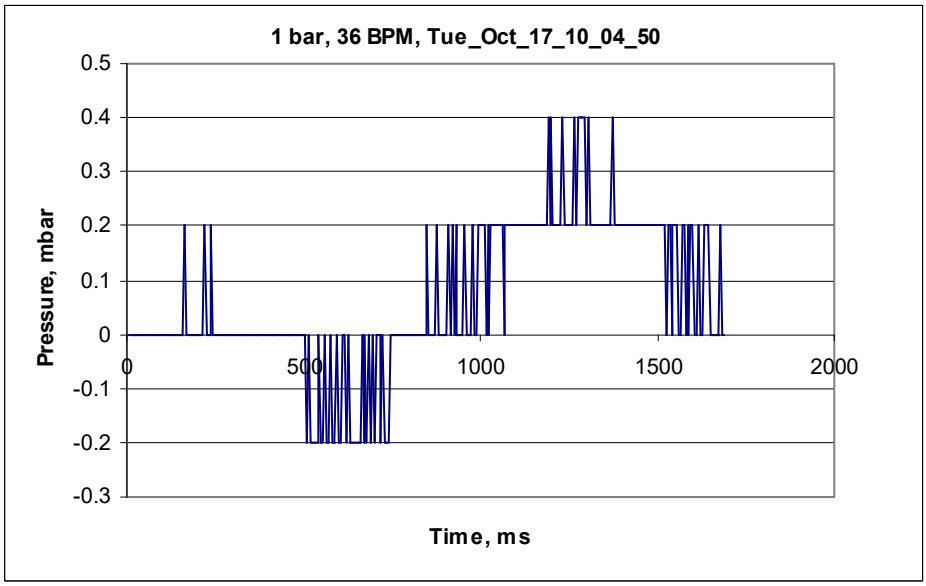

Fig 4-2. Pressure drop of CBM port without load. The peak to peak is 0.55mbar, which is 0.19 mbar RMS. The resolution of the reading is 0.1mbar, taken into account in performing this calculation.

2. Pressure drop of straight tube

The purpose of the experiment is to determine the pressure drop of the CBM when connected to 530 mm of EPDM corrugated tube, 36mm I.D, positioned such that it is straight.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Tue Oct 17 10 14 32 2006	36	5 ms	1 ATM	22.9 deg C	49%

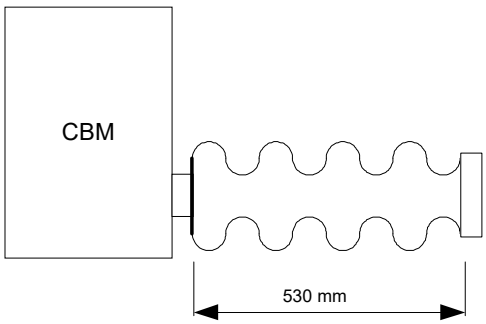

Fig 4-3. CBM with tube.

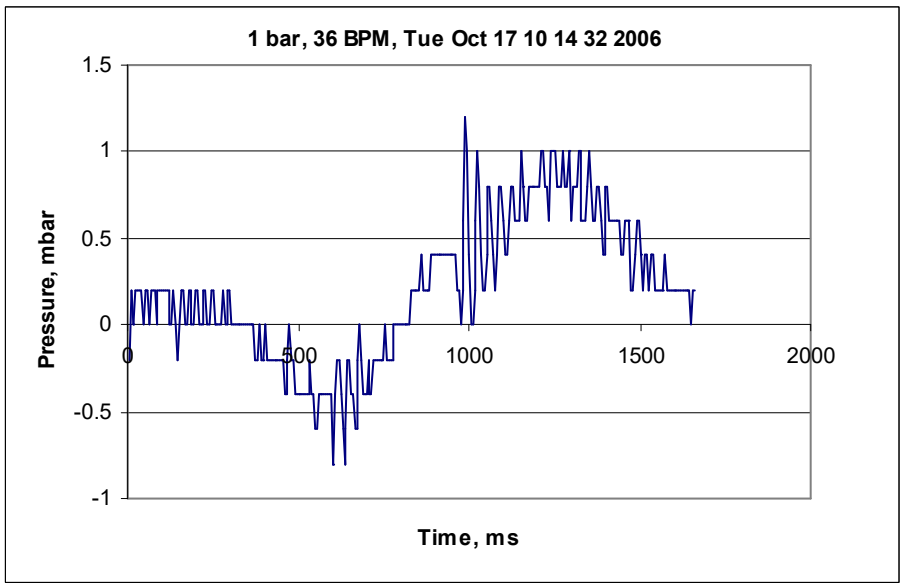

Fig 4-4. Pressure drop with 530 mm of straight tube. The resistance is 1.8mbar peak to peak.

3. Pressure drop of empty canister with straight tube.

The purpose of the experiment is to determine the flow resistance of the empty scrubber canister.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Tue Oct 17 10 29 41 2006	36	5 ms	1 ATM	23.6 deg C	49%

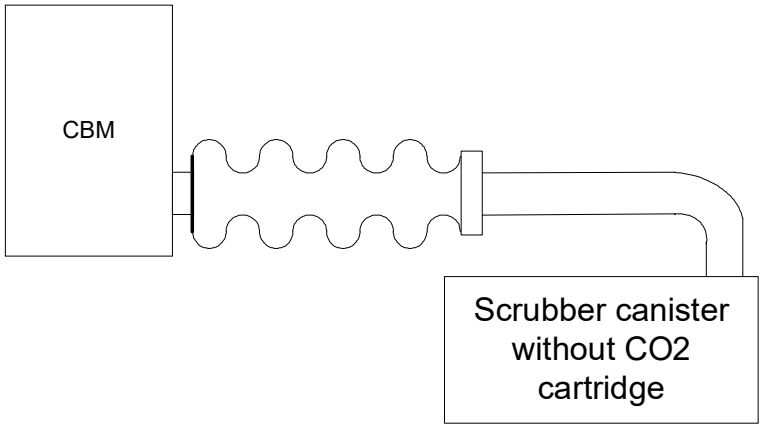

Fig 4-5. CBM with empty scrubber canister .

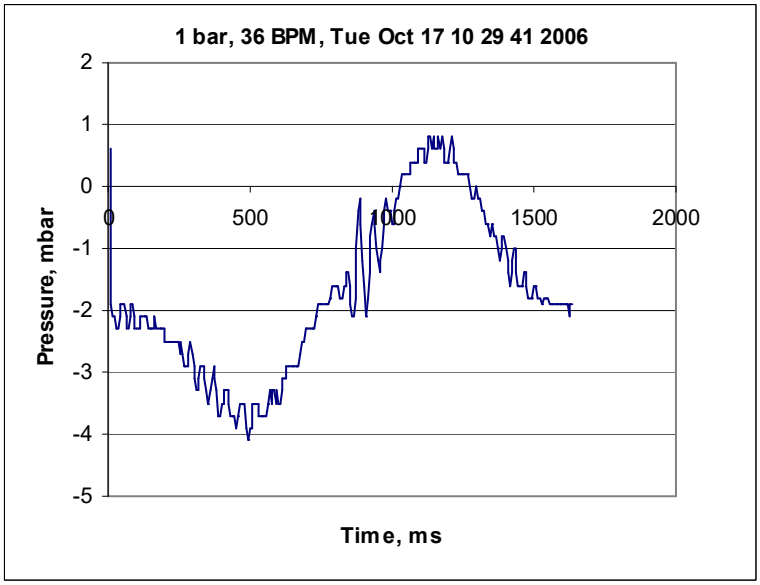

Fig 4-6. Pressure drop of empty scrubber canister . The canister drops 4.8mbar peak to peak. Subtracting the CBM and tube resistance, using the sum of squares method, gives a resistance for the scrubber canister on its own of 4.45mbar pk-pk, or 2.2 mbar pk, which is 1.53mbar RMS. The sum to separate the individual components is sqrt(4.8^2 – 1.8^2).

4. Effect of a curved breathing tube

The purpose of the experiment is to determine the pressure drop of the CBM when connected via a curved tube to a horizontal empty scrubber canister.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Tue Oct 17 10 35 14 2006	36	5 ms	1 ATM	23.8 deg C	48%

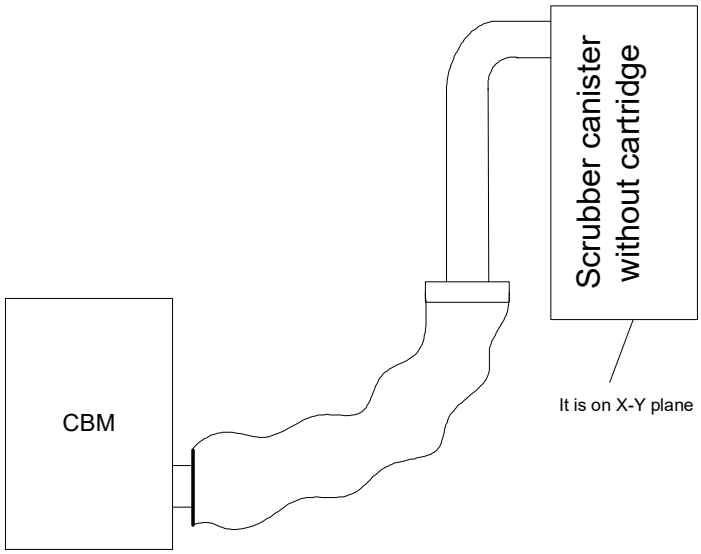

Fig 4-7. CBM with scrubber canister and curved tube.

Fig 4-8. CBM with empty scrubber canister and curved tube.

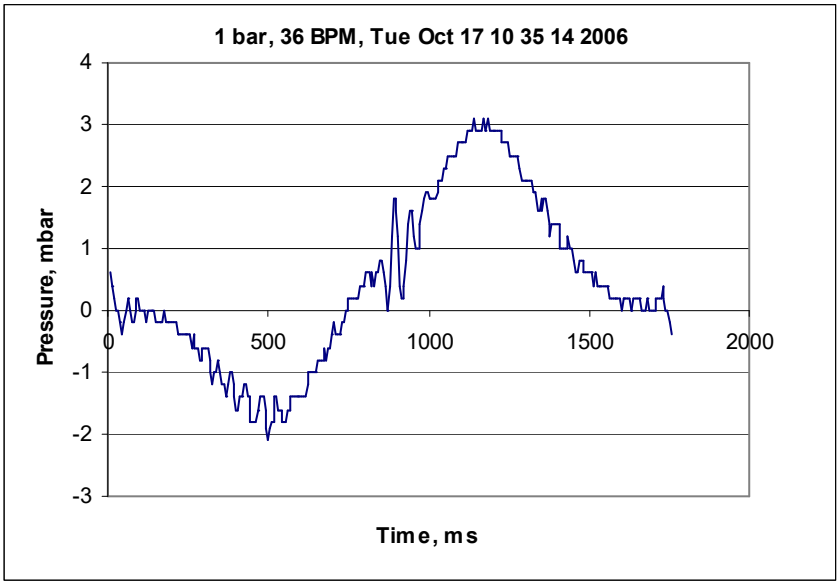

Fig 4-9. Pressure drop of curved tube and empty scrubber canister.

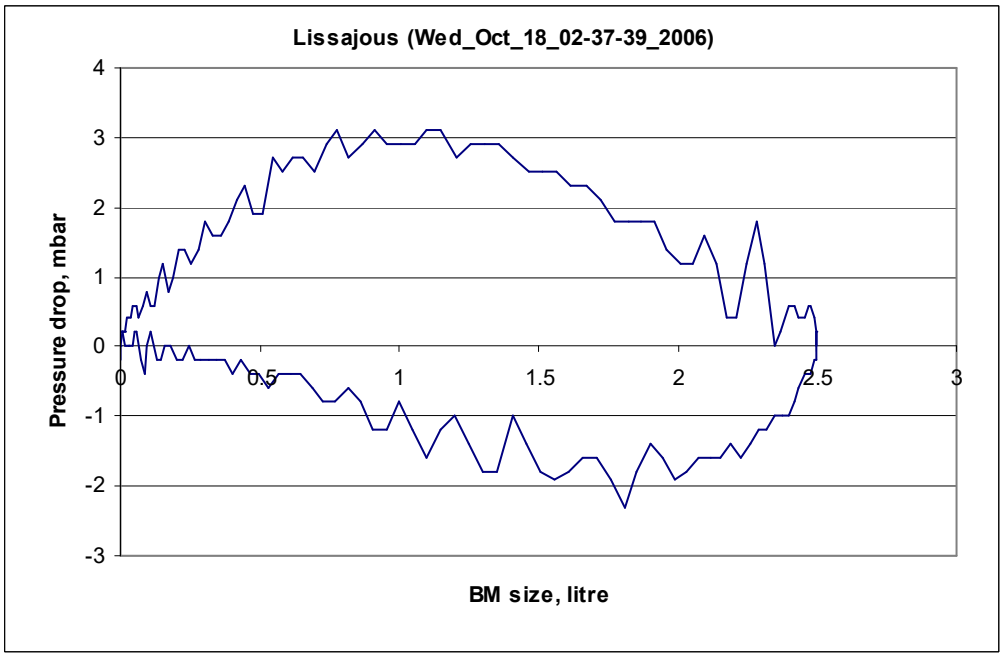

Fig 4-10. Lissajou figure with curved tube connected to empty scrubber canister. The result is a resistance of 5.1mbar peak to peak. The conclusion is that adding a curve in the breathing hose increases the breathing resistance by 0.7mbar peak to peak, and also adds 0.5mbar of noise due to the hose moving during the breathing cycle and from turbulence.

5. Effect of vertical orientation

The purpose of the experiment is to determine the effect of positioning the empty canister vertically instead of horizontally. The experiment used the curved tube, with a vertical empty scrubber canister.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_02-49-20_2006	36	5 ms	1 ATM	22.5 deg C	50%

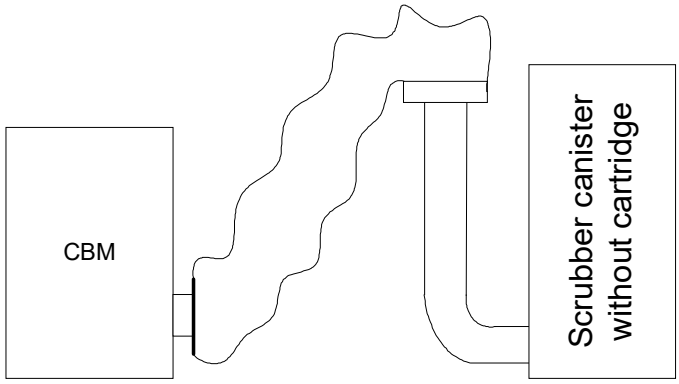

Fig 4-11. CBM with scrubber canister and curved tube.

Fig 4-12. Position of scrubber canister. Note the electronics was removed and the sensor ports blocked with tape, as the purpose was to measure the scrubber canister characteristics, not that of the electronics.

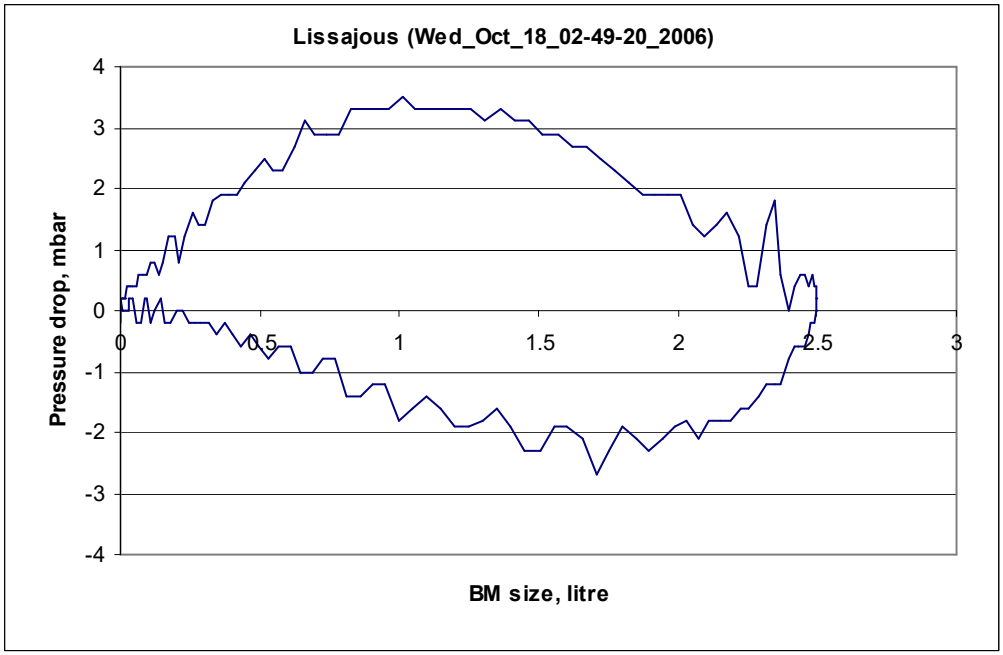

Fig 4-13. Lissajou of vertical empty scrubber canister. There is more noise, and this appears to account for the reading of 5.8mbar peak to peak. Other than the noise, when the canister is vertical, there is more load on the hose causing an increase in resistance of 0.4mbar.

6. Effect of humidity

The purpose of the experiment is to determine the effect of the gas being humid.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_03-12-45_2006	36	5 ms	1 ATM	23.5 deg C	84%

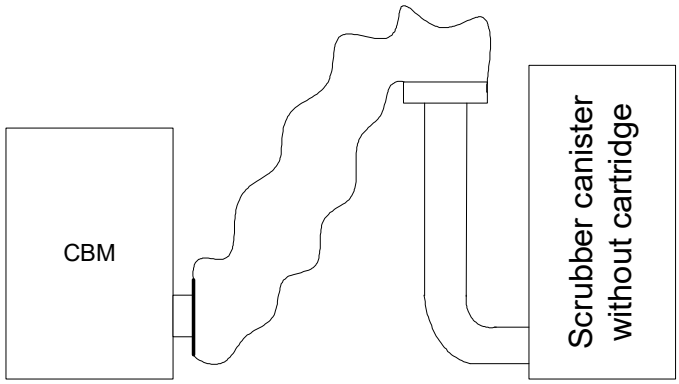

Fig 4-14. CBM with empty scrubber canister.

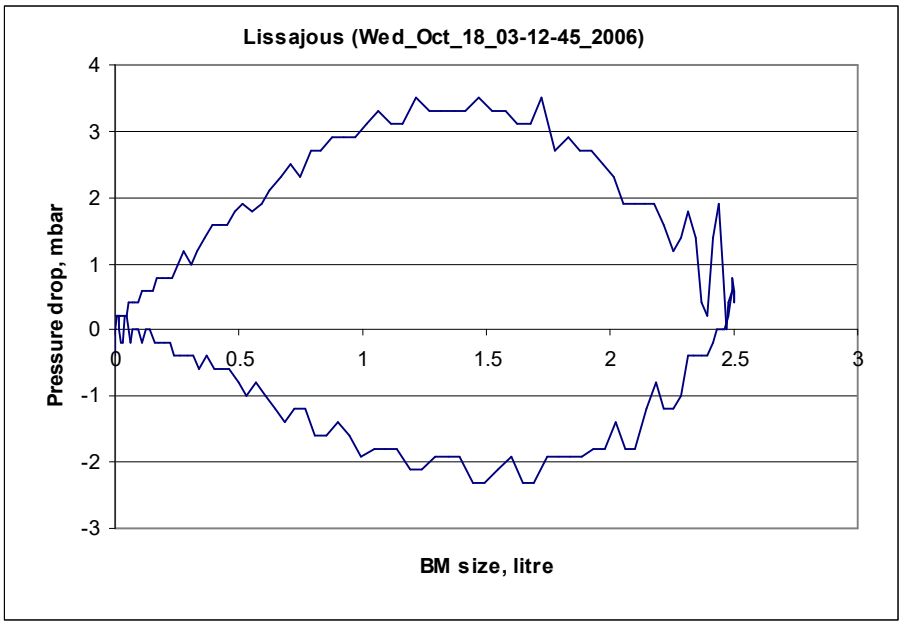

Fig 4-15. Lissajou with vertical empty scrubber canister. There is no significant change due to gas humidity.

7. Resistance of dry cartridge

The purpose of the experiment is to determine the pressure drop of the CBM when connected via 530mm of straight tube to a scrubber canister containing a dry cartridge.

The weight of the dry CO2 cartridge is 3.5 kg.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Tue Oct 17 10 22 15 2006	36	5 ms	1 ATM	23.4 deg C	50%

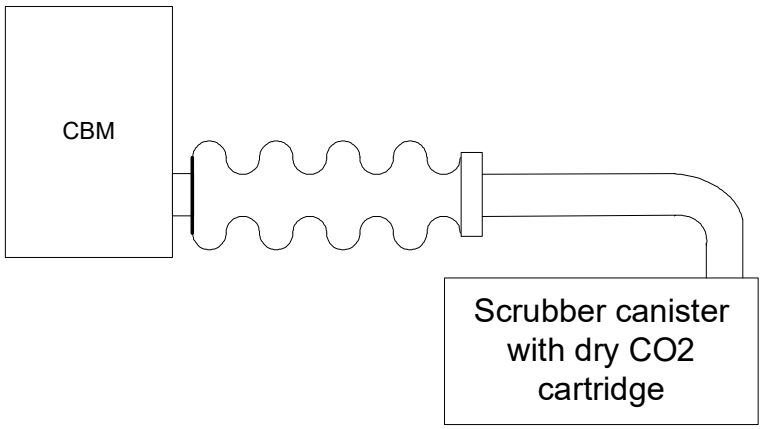

Fig 4-16. Scrubber canister containing dry cartridge.

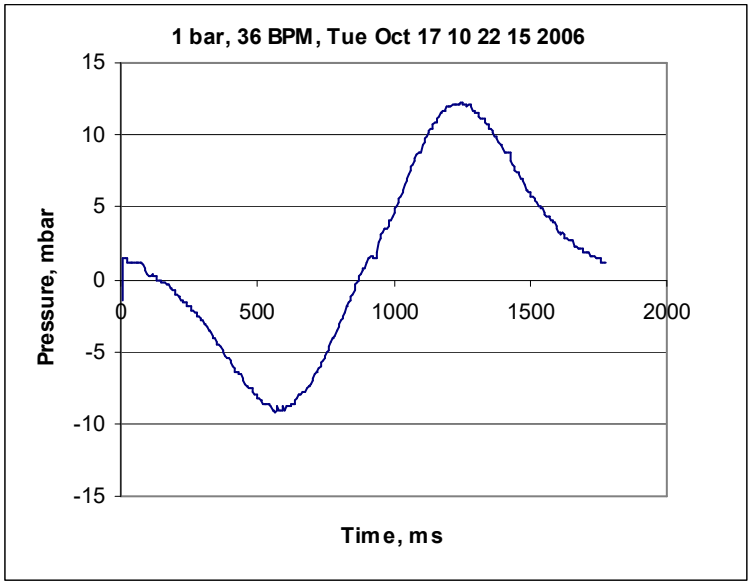

Fig 4-17. Pressure drop of scrubber canister containing dry cartridge. The peak to peak reading is 21mbar. Deducting the resistance of the empty canister, the resistance of the dry Sofnolime is 13.7mbar (using the sum of squares to isolate the two elements).

8. Resistance of flooded cartridge

The purpose of the experiment is to determine the pressure drop of a wet cartridge.

The cartridge was immersed in clean fresh water for 2 hours and then removed and put into the scrubber canister immediately.

The weight of the wet scrubber cartridge is about 3.65kg: the exact weight is difficult to determine as it changes with the water draining off.

Fig 4-18. Cartridge in water. After two hours, it was removed and transferred straight into the scrubber housing.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_03-00-54_2006	36	5 ms	1 ATM	23.1 deg C	79%

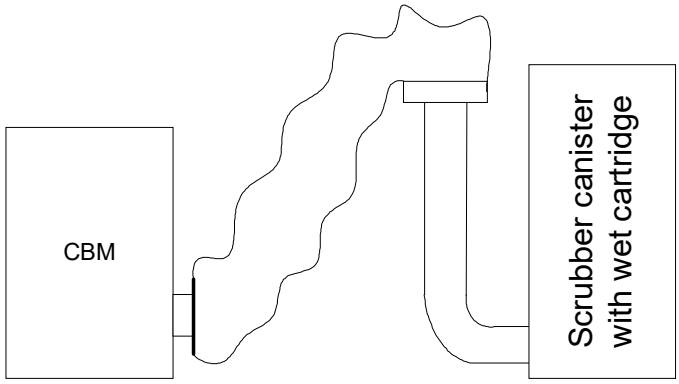

Fig 4-19. CBM with scrubber canister and curved tube.

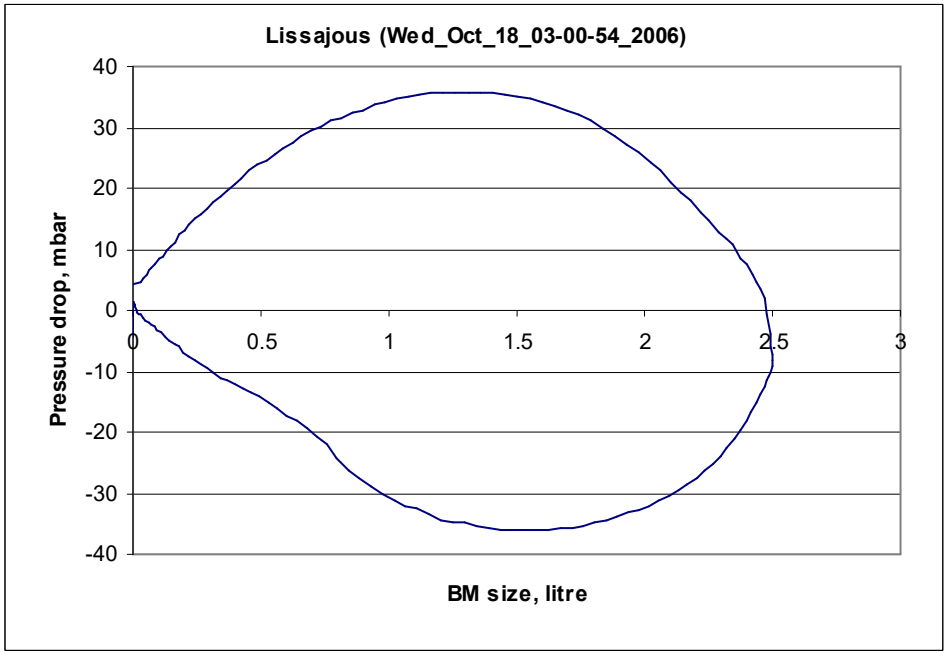

Fig 4-20. Lissajou of scrubber canister with wet cartridge. The peak to peak drop is 72mbar.

The experiment was repeated two minutes later. The results are shown below.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_03-02-32_2006	36	5 ms	1 ATM	23.6 deg C	84%

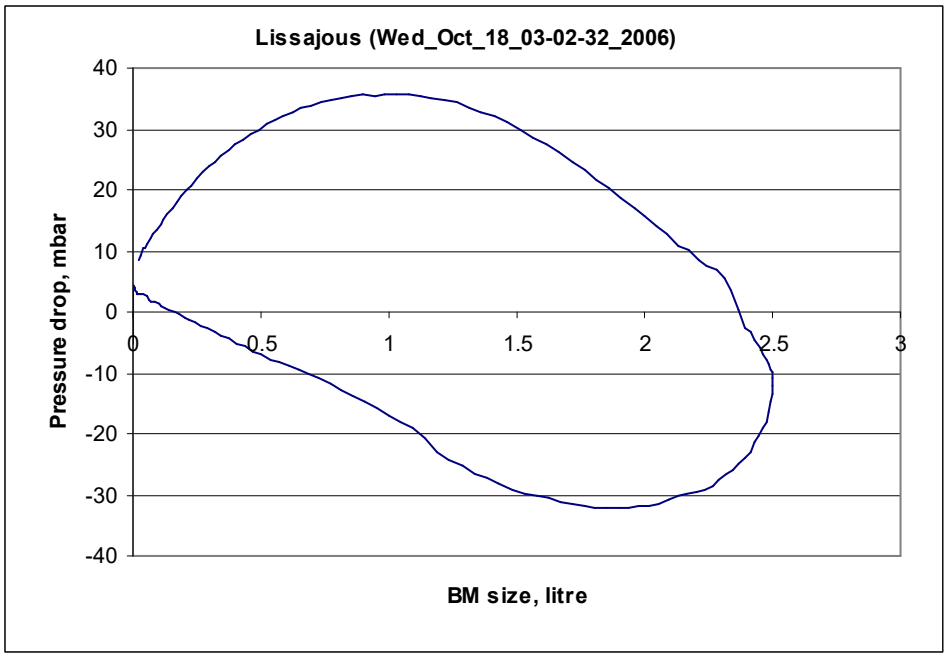

Fig 4-21. The second lissajou of scrubber canister with wet cartridge. The drop is 69mbar peak to peak.

No experiment was performed of the scrubber full of water, as a simple function of the height of the water column.

9. Resistance of drained cartridge

The purpose of the experiment is to determine the pressure drop of the wet cartridge after it has been drained for 3.5 hours and 20 hours.

Fig 4-22. The cartridge draining.

The weight of the cartridge after 3.5 hours of drainage is 3.63 kg.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_05-31-37_2006	36	5 ms	1 ATM	23.1 deg C	84%

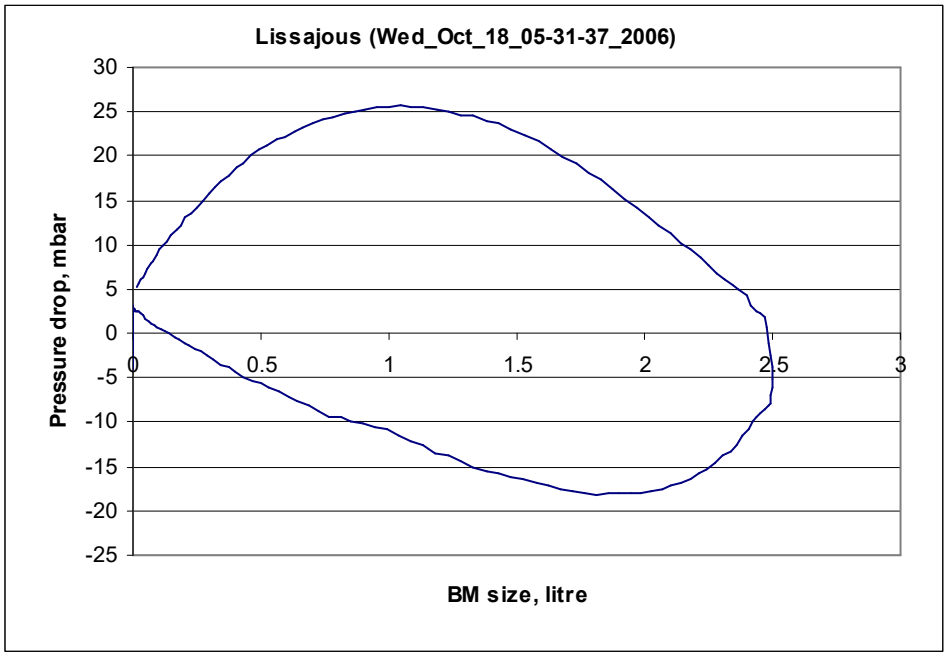

Fig 4-23 Lissajou figure showing scrubber canister with drained cartridge (after 3.5 hours). The resistance is 48mbar peak to peak.

The cartridge was allowed to drain for a further 16.5 hours in the open air in the laboratory, to give a total of 20 hours drainage time. The weight of the drained CO2 cartridge is 3.60 kg after 20 hours drainage.

Time code	BPM	Samples	Pressure	Temperature	Humidity
Wed_Oct_18_16-06-48_2006	36	5 ms	1 ATM	23C	82%

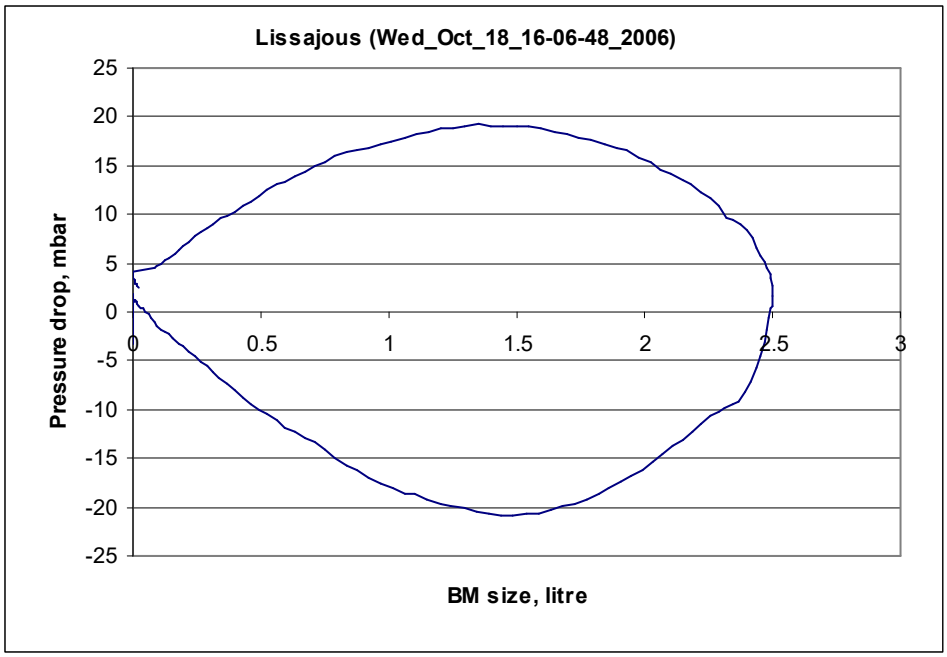

Fig 4-24. Lissajou of scrubber canister with drained cartridge (after 20 hours). The resistance is 40mbar peak to peak.

5. OTHER EFFECTS OF WATER INGRESS

The fluid draining from the scrubber canister was tested for pH and for ionic content. The pH exceeded 11 even after a few seconds of contact, with a high ionic content. The fluid drained was sufficiently caustic to soapify the surface of skin immediately. The fluid poses a serious risk of "caustic cocktail" to the diver, should it make its way to the diver's mouthpiece.

When unpacking the scrubber following these experiments, the granular media had formed into dense clumps that would appear to block the passage of gas. This clumping is the most likely mechanism by which the breathing resistance increases within the scrubber.

6. CONCLUSIONS

1. The pressure drop of the empty scrubber canister at 90l/m at 1 ATM, is 4.4 mbar peak to peak, or 2.2mbar peak, which is 1.53mbar RMS.

2. If the breathing hose is curved, the pressure drop increases by 0.8mbar peak to peak and noise increases by 0.5mbar peak to peak due to movement of the hose.

3. If the empty canister is vertical, the hose is pinched slightly, causing the peak to peak resistance of the combined hose and scrubber assembly to rise from 5.1mbar to 5.8mbar.

4. Adding the dry canister produces a total breathing resistance of 21mbar peak to peak. Deducting the resistance of the empty canister, the resistance of the dry Sofnolime is 13.7mbar peak to peak (using the sum of squares to isolate the two elements). The dry cartridge weighed 3.50kg.

5. The cartridge with its Softnolime was immerserd in water and allowed to drain. The pressure drop of the flooded cartridge was 72mbar/69 mbar peak to peak, and weighed

3.65kg after a few seconds of drainage. The experiment was constructed to flood only the cartridge, not the canister. The water retained is 165grams.

6. If the cartridge is allowed continue to drain, after 3.5 hours the resistance is 48mbar peak to peak, and after 20 hours it is 40mbar peak to peak. The cartridge weighs 3.63kg and 3.60kg after 3.5 and 20 hours drainage respectively. This rise appears to be from swelling and clumping of the scrubber media.

7. Soaking the cartridge increases its gas resistance 3.5 times (70mbar compared to 21 mbar), when it has absorbed just 150g of water. The pressure drop of the cartridge with 130 g absorbed water is about 48 mbar. The pressure drop of the cartridge with 100 g absorbed water is about 40 mbar: twice the pressure drop of the dry cartridge.

8. In draining the cartridge, it lost just 50g of water in the open air in laboratory conditions over a period of 20 hours.

9. To determine the resistance at depth, the resistances should be scaled linearly up to 50m, after which a more aggressive polynomial scaling should be used. This is detailed in a separate verification report available to clients of Deep Life Ltd, as is the scaling as a function of the gas mixture and flow rate.

10. The scrubber generates water vapour in the chemical reaction of absorbing CO2 from the gas stream. The diver also produces water vapour from his lungs. These two sources of water vapour cause condensation within the rebreather, which can exceed 150ml on a dive. This implies the work of breathing may rise during the dive, and can rise for a scrubber with granular media that is used for one dive, stored, and then used for a second dive.

11. These results suggest that use of granular CO2 scrubber media in a rebreather would not meet the ALARP safety requirements. Alternative means of removing CO2 should be used where possible.