# Submarine Air Monitoring and Atmosphere Purification Conference 2009

## A NEW APPROACH TO NON-REGENERATIVE CO2 REMOVAL

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## SUMMARY

Control of carbon dioxide (CO2) in a contained space is essential for the maintenance of a life supporting atmosphere. Submarines are the prototypical examples of life support in isolation from our atmosphere. Rescue shelters, dive habitats, sealed control rooms and space capsules also maintain self supporting atmospheres.

Micropore has developed a cube, manufactured from a stack of absorbent sheets, that replaces granules in CO2 control applications. This product is call PowerCube™ and provides increased capacity and increased rate of absorption based on the equivalent storage volume of granules. Comparative testing with granules showed this product contained 33% more mass; absorbed 50% longer (to 0.5% break through time) and absorbed 50% more CO2 when operated in a powered scrubber. This paper reports the physical properties of the new PowerCube™ absorbent, defines performance characteristics and provides a model of its deployment.

## BACKGROUND

For CO2 control over long periods of time, such as nuclear submarine operations, a regenerative scrubbing process is employed. A system developed for nuclear submarines in the 1950's and incrementally improved over the subsequent 30 years, uses monoethanolamine to absorb CO2 at room temperature and liberate CO2 at 250$^{O}$F (reference 1). Figure 1 is a picture of a United States Navy's scrubber. These scrubbers can operate for over 90 days with minimal onboard maintenance supplies. For long duration missions, this regenerative scrubber offers advantages of reduced volume and weight when compared to non-regenerative systems. The disadvantages of this system are high power requirements (in the range of 50 kw per 100 people); high initial cost and mechanical/chemical complexity.

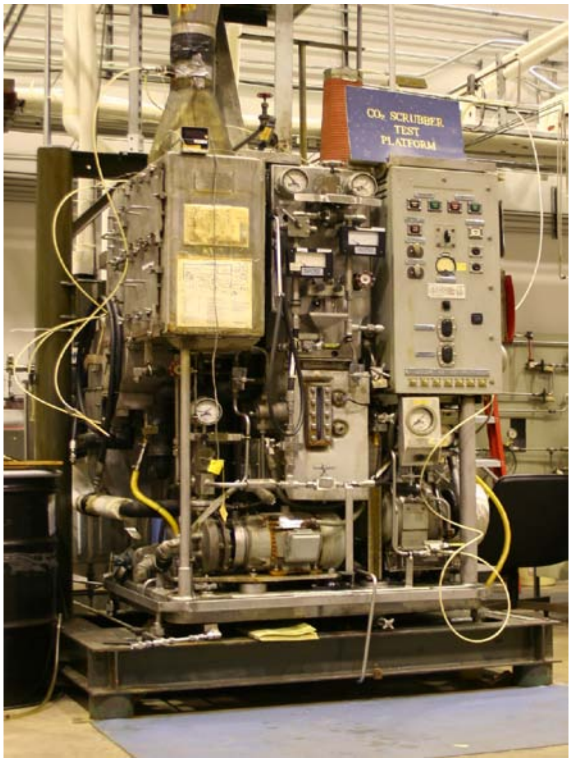


Figure 1  Regenerative Monoethanolamine Scrubber

Non-regenerative CO2 control systems are typically used to support shorter operations such as diesel submarines and shelters. A popular process uses alkaline absorbents to react CO2 into a stable carbonate. Calcium hydroxide reacts CO2 to form calcium carbonate.  The calcium hydroxide absorbent has been supplied in granular form and used in canisters or drawers.  Air is forced through the granular bed where the ambient CO2 is removed.

In place of granular absorbents, Micropore uses a unique process to encapsulate fine grains of alkaline chemical into a ribbed sheet.  The granules are bound into this solid sheet by microscopic filaments of polymeric material. Figure 2 is a micrograph of a solid sheet of ExtendAir® illustrating the small open granules (advantageous for absorption of CO2) and the small amount of binder polymer that firmly holds the particles together.   The resultant density of absorbent is comparable to granules. Ribbed Micropore sheets are stacked or wound into absorbent canisters (see Figure 3). Contaminated air is passed through the flow channels where CO2 reacts with the absorbent.  The ExtendAir® manufacturing process leaves a highly pure product that has been tested by NASA (White Sands Test Facility) and approved for submarine service (Reference 2).

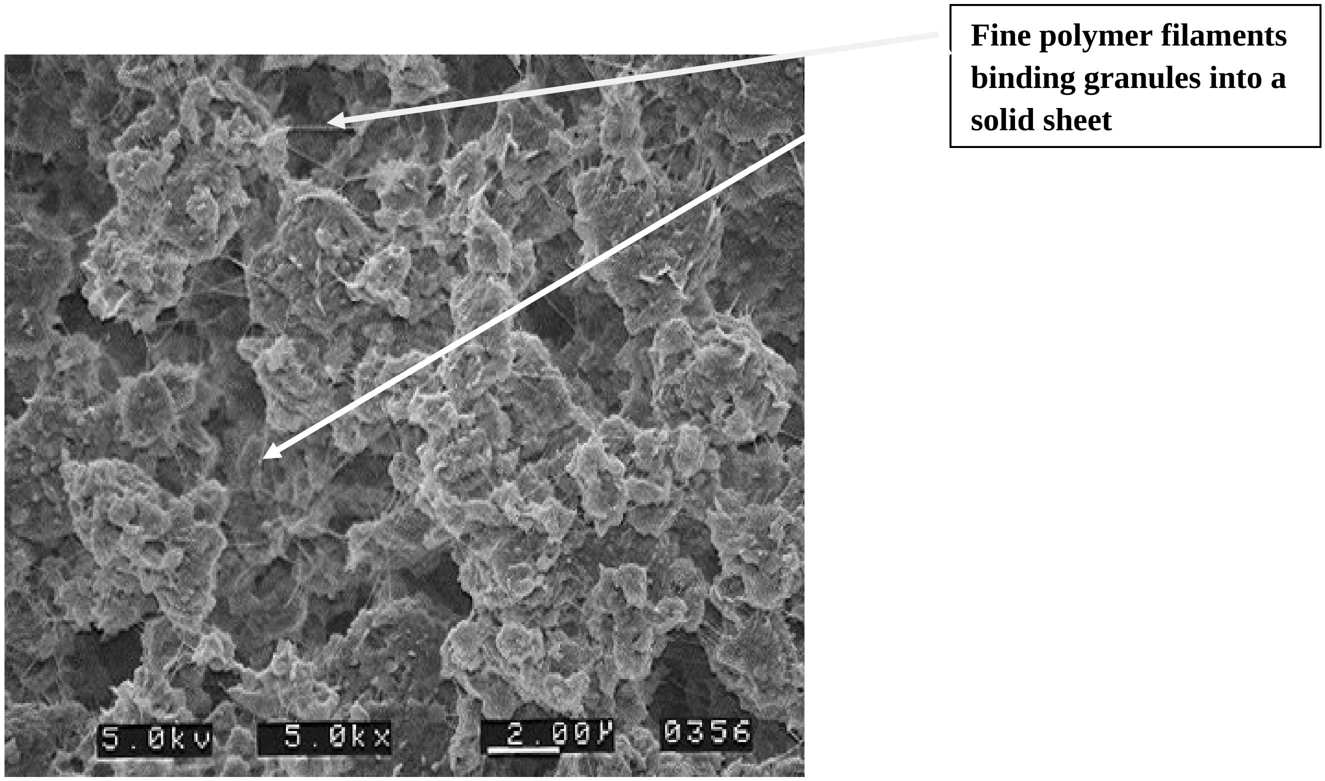


Figure 2  Micrograph of calcium hydroxide particles bound into a solid ExtendAir® sheet

Micropore's ExtendAir® products offer multiple advantages when compared to granular systems.  There is no handling of absorbent (no pouring, tamping and filling) that can cause non-uniform performance. ExtendAir® CO2 absorbents are manufactured with calcium hydroxide or lithium hydroxide.  Calcium hydroxide ExtendAir® is sold for diving rebreathers. ExtendAir® lithium hydroxide absorbents are sold into mines shelters, safety shelters, submarines for DISSUB, and emergency rebreathers.

Micropore has developed a cube, manufactured from a stack of absorbent sheets, that replaces granules in CO2 control applications.  This product is call PowerCube™ and provides increased capacity and increased rate of absorption based on the equivalent storage volume of granules. Comparative testing of PowerCube™ and granules indicates the PowerCube™ contained 33% more mass; absorbed had 50% longer (to 0.5% break through time) and absorbed 50% more CO2 when operated in a powered scrubber.  This paper reports the physical properties of the new PowerCube™ absorbent, defines performance characteristics and provides a model of its deployment.

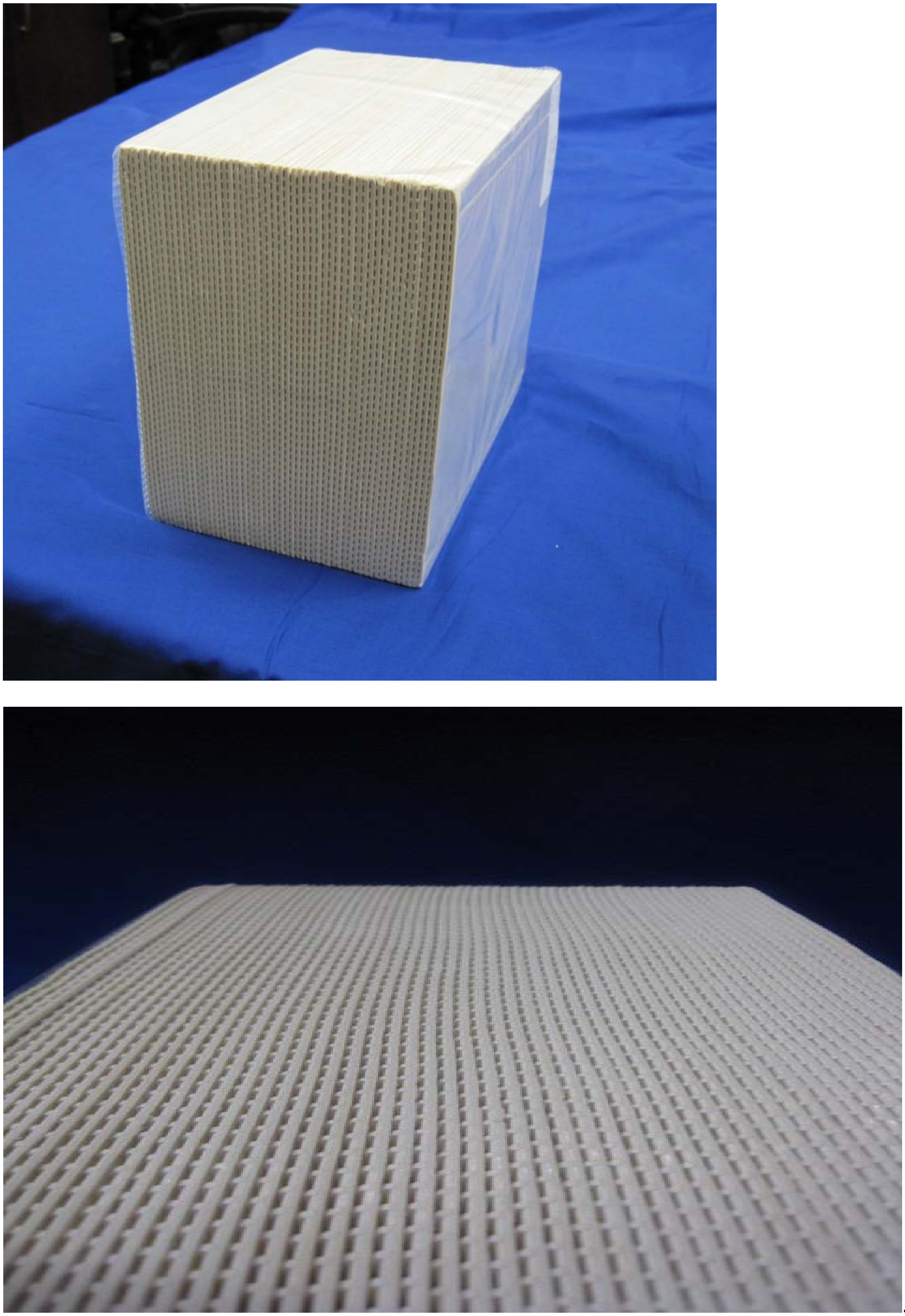

Figure 3  Block of ExtendAir® absorbent and close up of flow channels

## FINDINGS

General Description

PowerCube™ absorbents are packed in a vacuum evacuated foil bag that blocks the ingress of $CO_2$ or the outflow of moisture from the absorbent. The foil bag is wrapped in a high density polymer wrap that adds abrasion protection. The protected pack is designed for storage onboard submarines in lockers or spaces protected from mechanical damage. The ExtendAir® PowerCube™ dimensions are the same as the granule plastic container it replaces and so stores in the same spaces. The absorbent package is shipped in a cardboard box to protect against shipping damage. When ready for use the cube is removed from its packaging and installed in its canister (see Figure 4). The canister is mounted in the scrubber system or connected to a fan powered air supply. The canister contains the necessary flow distribution system to direct a uniform air stream across the absorbent. The canister shown in Figure 4 is symetric about the axis perpendicular to the flow stream. This permits flow in either direction and is compatible with the Royal Dutch Navy's granular scrubber and likely adaptable to many other diesel/electric submarines including Type-209s and newer Type-212/214. This scrubber, pictured in Figure 5, holds six cubes of absorbent. This scrubber can support approximately 24 crew when operating with granules and 32 crew when operating with the PowerCube.™

Figure 4 PowerCube™ absorbent canister

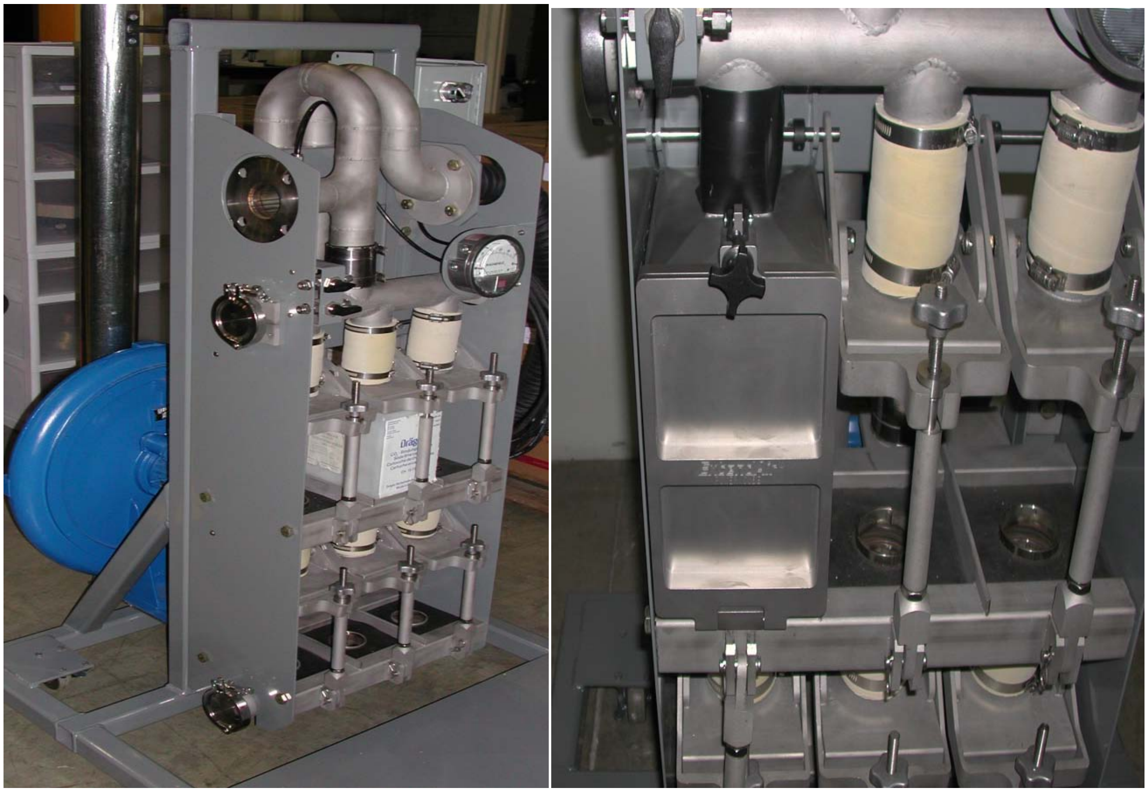

Figure 5 Six canister scrubber and close-up of an installed canister

Physical Properties

The calcium hydroxide PowerCube™ has the weights and dimensions listed in the Table 1. The absorbent density, 735 kilograms (kg) of absorbent per cubic meter, refers to the net absorbent weight contained in a cubic meter of storage space.

| | Length cm / inches | Width (cm/inches) | Height (cm/inches) | Gross Wt. Kg/lb | Net Wt. Kg/lb | Remarks |
|---|---|---|---|---|---|---|
| Stowed Shipboard | 240 /9.34 | 210/8.27 | 135/5.25 | 5.15 / 11.33 | 5.00 / 11.0 | Cube with foil and outer wrap<br>Compatible with existing storage<br>735 kg absorbent per cubic meter |
| Packed for shipment | 260/10.10 | 215/8.50 | 170/6.60 | 5.50 / 12.1 | | Cube shipped in cardboard box |

Table 1 Physical properties of the calcium hydroxide power cube

Test Bed

Figure 6 provides a schematic of the test bed used to develop the PowerCube™. The air and CO2 mass flow controllers are labeled MFC. The % CO2 indicators refer to the infrared CO2 analyzer. This analyzer can be valved to measure either the inlet or outlet stream. The analyzer is calibrated prior to each test. The differential pressure is measured with an inclined tube manometer (0 to 3 inches full scale). A u-tube manometer is used for higher differential pressure measurements which can occur at high flow rates through granular beds. Temperature is measured with standard chromel/alumel thermocouples.

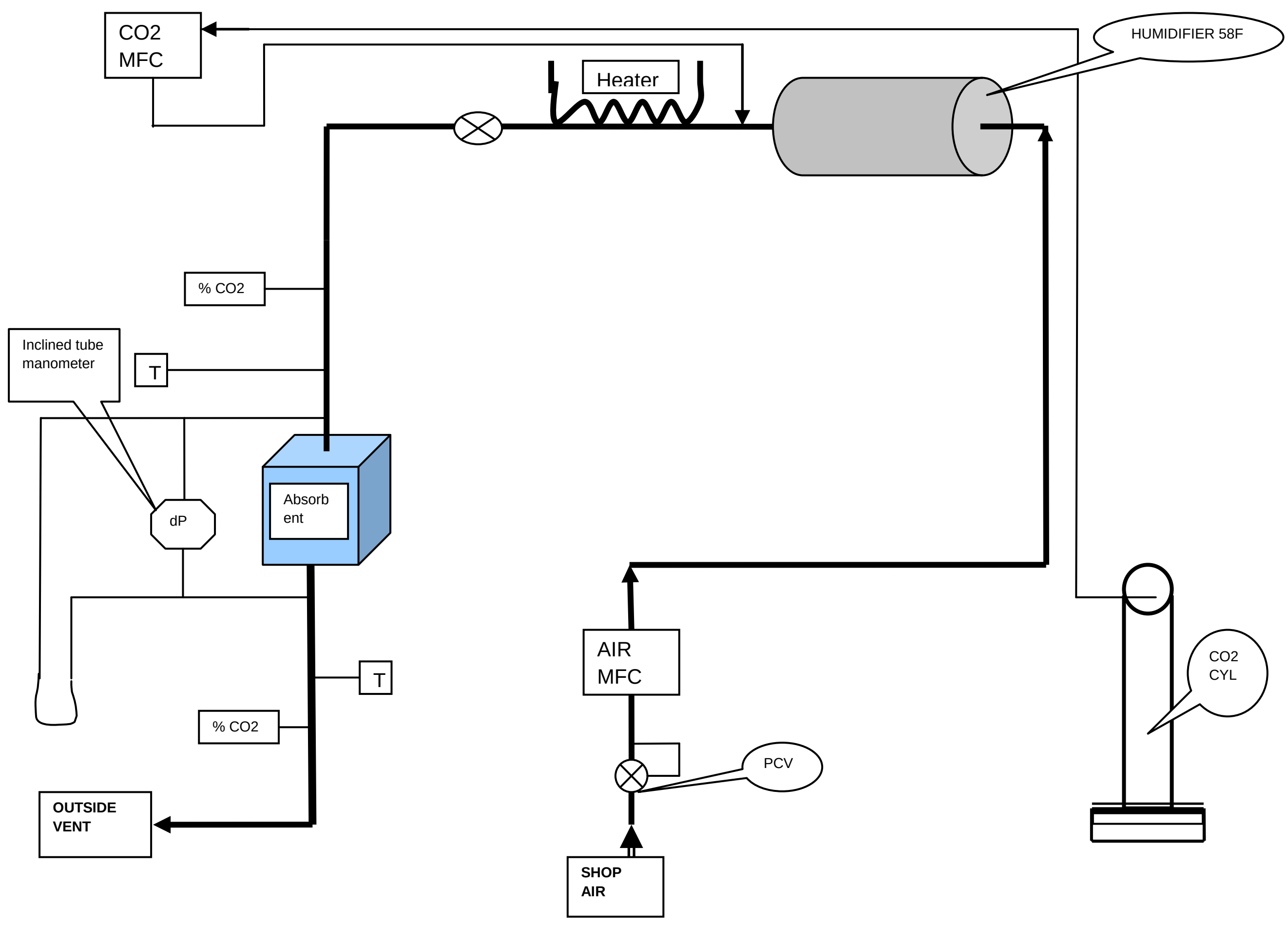


Figure 6 Test bed schematic

## Performance Test Results

Flow Tests

Flow rate and pressure drop were measured through the PowerCube$^{TM}$. For comparative purposes granular flow characteristics were also recorded. This test used 8-12 mesh granules that exhibit higher pressure and also have improved absorption rate and capacity. Table 2 reports the results of the flow testing. Testing granules at the higher flow rates was not conducted due to system limitations at the high pressure drop.

| FLOW RATE (SLPM) | 100 | 150 | 200 | 250 | 300 |
|---|---|---|---|---|---|
| PowerCube$^{TM}$ dP (inches water) | .22 | .30 | .45 | .54 | .68 |
| Granules dP (inches water) | | 1.8 | 2.2 | | |
| PowerCube$^{TM}$ dP (Pascals) | 56 | 77 | 115 | 138 | 174 |
| Granule dP (Pascals) | | 461 | 563 | | |

Table 2 Flow test comparison PowerCube$^{TM}$ and granules

Carbon Dioxide Removal Rate

Figure 7 shows the absorption curve for the PowerCube block of absorbent when processing 1% CO2 in air. The x axis is the operational time in minutes and the y axis is the outlet CO2 concentration. The test condition of 70$^{O}$F and 50% relative humidity is slightly conservative. Higher air stream humidity will improve the performance of the calcium hydroxide based system. The two curves represent inlet flows of 200 and 250 standard liters per minute (slpm). As expected when feeding less CO2 into the absorbent (200 slpm times 1% versus 250 slpm times 1%), the break through time to 0.5% is longer for the lower flow of 200 slpm. In most submarine applications, the operational time is rate based (not break through based). Typically removal efficiency must be at least 50% which is the 0.5% outlet concentration point in figure 7. Figure 8 is a plot of the liters of CO2 absorbed (at standard temperature and pressure, 0$^{O}$C and 1 atmosphere absolute) versus time. It is based on the same series of tests (same test conditions) as figure 7. This plot is more useful for designers and system engineers as it reports the quantity of CO2 removed over time. The 250 slpm case shows more CO2 being removed. This is due to a

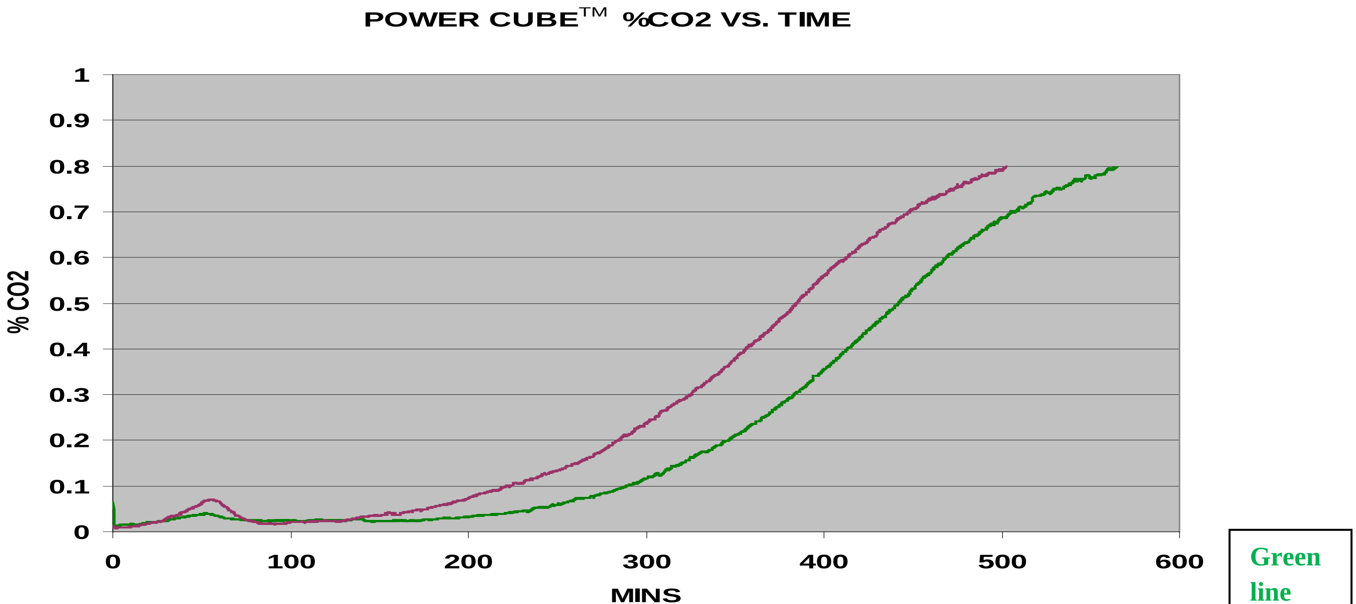


Figure 7 Performance curve (%CO2 versus time) for PowerCube™

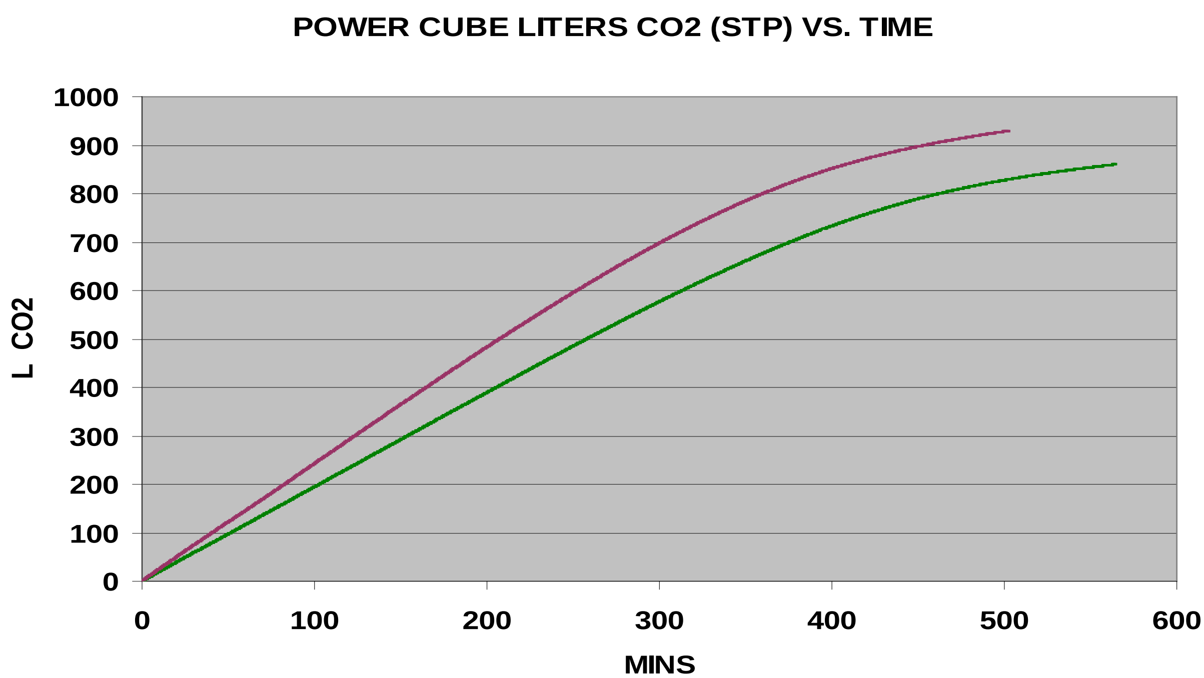


Figure 8 Performance curve (liters CO2 removed versus time) for PowerCube™

greater quantity of $CO_2$ being supplied to the absorbent. The average removal rate from time zero to any time on the graph is the y axis value in liters divided by the x axis value in minutes. For example; the 200 slpm curve shows 600 liters of $CO_2$ removed in 300 minutes for an average removal rate of 2 slpm of $CO_2$.

Figure 9 provides a comparison of PowerCube™ and granular performance. As with prior tests, the conditions are 1% $CO_2$ inlet, 70°F and 50% relative humidity, 1 atmosphere absolute pressure. The graph indicates the PowerCube™ is able to operate for longer periods of time to the 0.5% break through point. Figure 10 uses the data from the tests of Figure 9 to compare PowerCube™ and granule tests based on the total liters of $CO_2$ removed. Figure 10 shows the 200 slpm PowerCube ™ (green line) and the 200 slpm granules (blue line) performed identically for approximately the first 200 minutes. This is because both absorbents removed over 98%

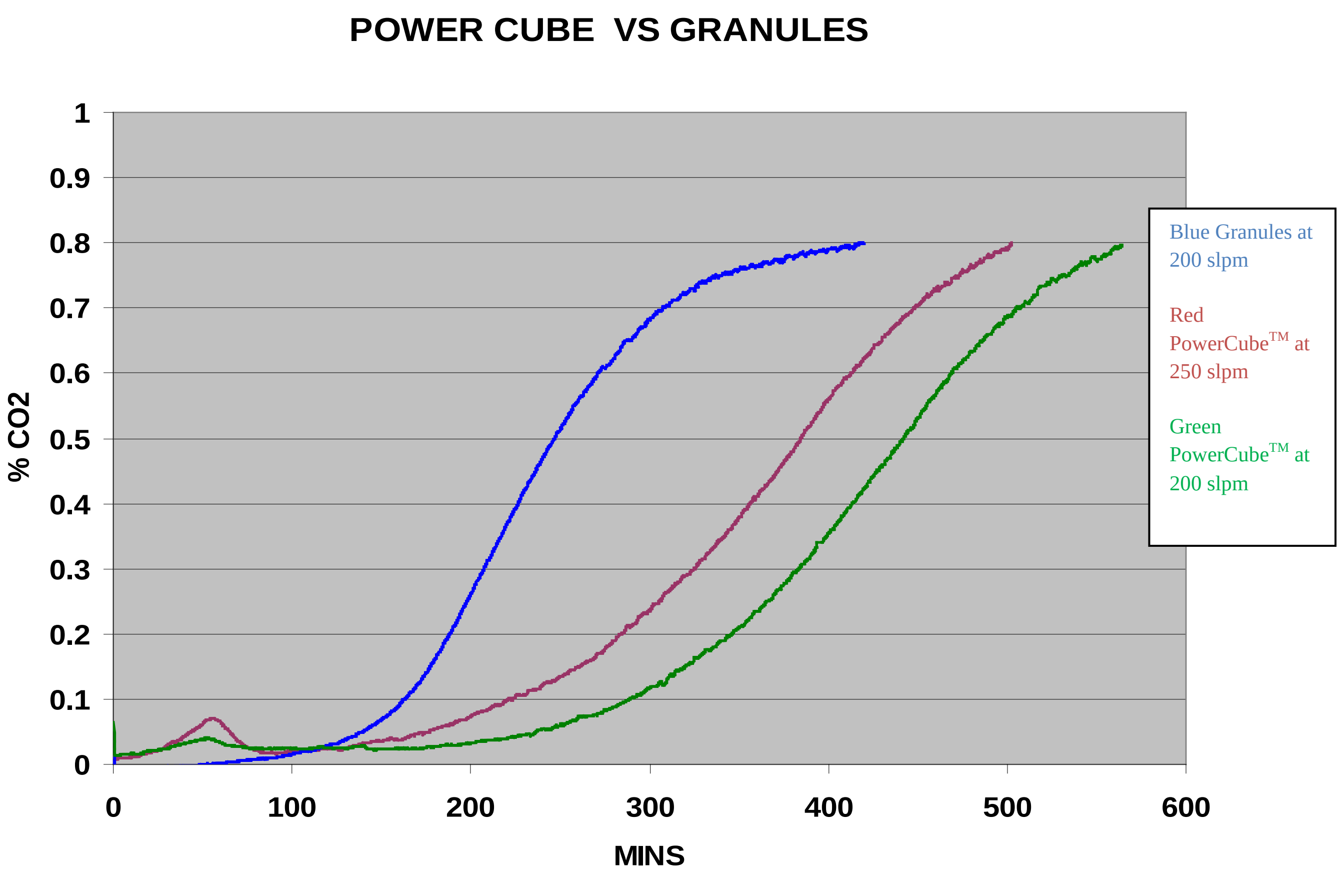


Figure 9 Comparison of PowerCube™ and Granules, %CO2 versus time

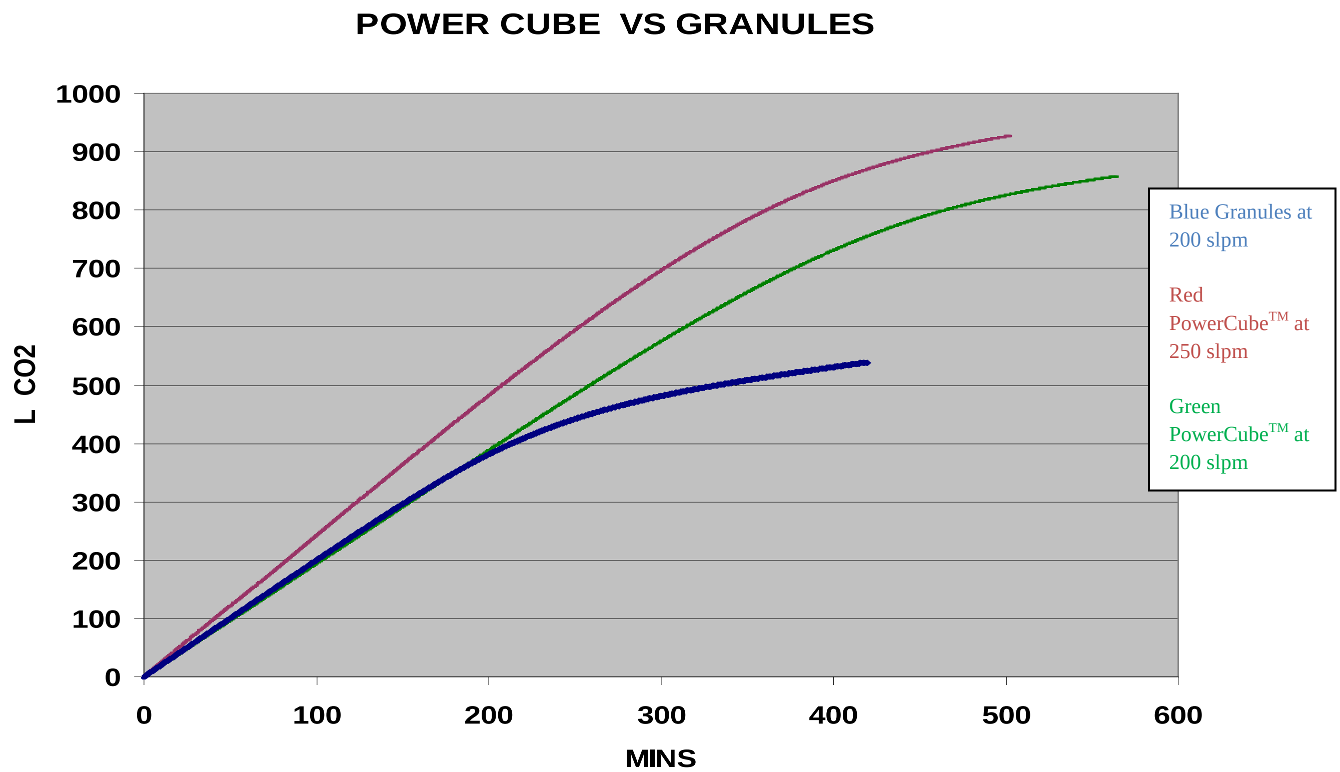


Figure 10 Comparison of PowerCube™ and granules, liters CO2 versus time

of the CO2 in the feed stream. At equal efficiencies and equal flow rates the performance must also be equal. The PowerCube™ had greater capacity as is indicated after 200 minutes. Figure 10 also shows the 250 slpm PowerCube™ (red line) is removing more CO2 than granules at any point in time. Over the first 200 minutes the 250 slpm cube removes more CO2 because more CO2 is being supplied to the absorbent. After 200 minutes the higher CO2 rate is due to a combination of higher flow and higher efficiency.

Operational Model

Figure 11 plots the CO2 concentration within a submarine based on a model using the test data reported above. The submarine is a Type 209 with a crew of 62. The metabolic rate is 0.38 slpm CO2 per person (reference 3). There are 12 cans or cartridges of absorbent operating. The granules are flowing 200 slpm of air per can; considered to be the maximum capacity of the fan. The PowerCube ™ is operating at 250 slpm (a flow much less than the fan's capacity due to the reduced pressure drop). The scrubber absorbent is replaced at 1% CO2 in the compartment. Figure 11 shows a plot of the performance of the fresh absorbents. In this case the granules (blue line) must operate at near 100% efficiency to hold the atmosphere concentration. As the granule efficiency falls below 98% at approximately 3 hours, the submarine $CO_2$ level rises above 1.0%. PowerCube™ performance is shown by the red line, where the increased absorption rate allows more $CO_2$ to be removed than is being produced metabolically. This results in an initial decline in the submarine $CO_2$ concentration. As the PowerCube™ bed becomes depleted, the $CO_2$ concentration will begin to rise and returns to 1% after 7 hours.

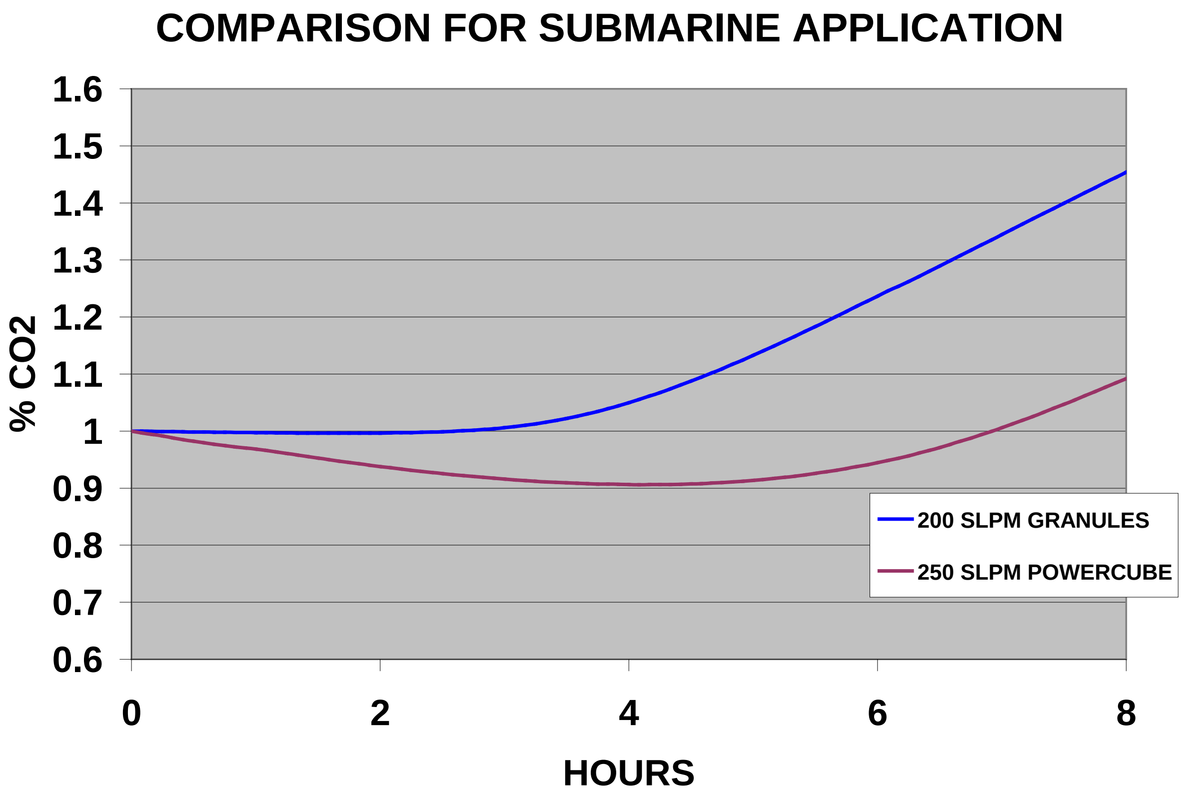


Figure 11 Submarine atmosphere concentration model for granules and PowerCube™

## Summary

Micropore's has developed a new PowerCube™ $CO_2$ absorbent based on its ExtendAir® technology. Fine alkaline absorbent power is encapsulated into a polymer sheet. This solid sheet format overcomes the dusting and settling problems associated with granules. This new absorbent is operated in a canister designed to provide uniform airflow to the absorbent cube. The new canister is a simple retrofit on Type-209 submarines and likely other submarine classes. It can be installed into an existing scrubber, or connected to a fan powered air supply. Low pressure drop through this system enable operation at higher airflows. This is extremely useful when accommodating increased crew size or added riders. PowerCube™ absorbent offers increased capacity and rate when compared to granules. In an operational scrubber, this new product provides increased capacity and increased rate of absorption based on the equivalent storage volume of granules. Comparative testing showed PowerCube™ contained 33% more mass; absorbed 50% longer (to 0.5% break through time) and absorbed 50% more CO2 when operated in a powered scrubber.

## References

1 U. S. Navy Submarine Life Support Systems, T. Shadle, T. Daley; International Conference of Environmental Systems Paper 911329; July 1991

2. Naval Sea Systems Command letter 4720 Ser: 395/064 of 3 August 20043

3. United States Nuclear Powered Submarine Atmosphere Control Manual S9510-AB-ATM-010 Revision 2

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