Oxygen Storage Module with Physisorption Technology for Closed-Circuit Respirators

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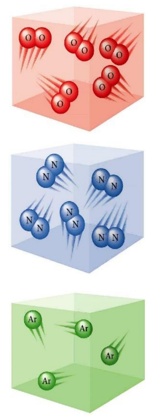
Introduction

- The new Cryogenic Flux Capacitor (CFC) technology employs nano-porous aerogel composites to store large quantities of fluid molecules in a physisorbed solid-state condition at moderate pressures and cryogenic temperatures.
- By its design architecture, a CFC device can be "charged" and "discharged" quickly and on-demand according to standby/usage requirements. For example, a CFC device can be designed to store hydrogen for fuel systems, nitrogen for refrigeration systems, or oxygen for life support systems.
- Test the feasibility of applying the CFC technology to closed-circuit escape respirators (CCERs)
- The CFC Oxygen Storage Module stores oxygen in solid-state form, according to physisorption processes at any cryogenic temperature, and delivers it as a gas upon demand.
- Gaseous oxygen (GO_2) is admitted into the breathing loop of the CCER by introducing heat into the module.
- Potentially replacing the gaseous or chemical based oxygen supply used in today's closed-circuit respirators (CCRs), the new device is a high-capacity, conformal, small-size solution for future life support equipment. In particular, are the CCER devices that must to be carried on the person, ready to be quickly deployed and used for escape in an emergency.
- Test data for physisorption of oxygen in aerogel materials and CFC core modules are presented and basic operational parameters for charging and discharging are summarized through prototype testing of the cryogenic oxygen storage module.

KEY BENEFITS:
1. Low-pressure storage at high density (approximately the same as liquid density) but without the problems of liquid storage
2. Quick charging and discharging through application of heat to the module's thermally conductive structural design
3. Inherently high thermal insulative properties due to the use of aerogel composite materials.
4. Potential for high-capacity, small-size apparatus in conformal shapes for wear-ability.



Cryo Flux Capacitor for Storage of O_2

- The CFC device is an energy system for the storage (charging) and un-storage (discharging) of fluids in a practical way. The stored energy in this case is represented by fluid molecules accumulated in a solid-state manner. Solid-state in this context means that the fluid atoms or molecules are physically bonded within the pores of a meso-porous or nano-porous storage media.
- A CFC device, for an effective means of storing and un-storing O_2 molecules, is being developed for new CCER. The O2 molecules can be liquid or gas coming in and will always be gas coming out. Problems with liquid behavior such as sloshing or liquid level management are avoided because the fluid is stored in a physisorbed state that is not liquid, no matter the density or temperature.
- Three chief design problems for the module are summarized as follows: 1) stand-by (ambient heat leak), 2) capacity for one hour at a nominal withdrawal rate of 1.35 lpm oxygen, and 3) regulation of demand from 0.5 to 3.0 lpm oxygen.
- In the stand-by mode the module must be as thermally isolated as possible, but in the discharge mode the heat exchange with the ambient process is needed. As the CO2 scrubber material generates a lot of heat, future module designs may be able to take advantage of this heat to drive the discharge flow rate.

Main requirements for CCER (per CFR42 special case, Subpart O, for escape applications):
- Flow: 1.35 liter per minute (lpm) average flow rate or 81 liters of oxygen gas supplied in one hour (minimum)
- With a liquid expansion ratio of 860, the LO_2 equivalent is 94.2 milliliters
- The 1.35 lpm oxygen flow corresponds to an exhalation CO_2 flow of 1.15 lpm. The respiratory coefficient is therefore 1.15/1.35 = 0.8 to 0.9 range on average.
- Maximum and minimum oxygen flow rates: 3.00 lpm and 0.5 lpm, respectively
- Duty cycle: respirator has to be available to work during a 10-hour shift (9 hours stand-by time)
- Charging: There will be a charging rack for multiple respirators.
- Stand-by: stand-by time depends on the heat leakage rate.

CFC Modules Test Results

Prototype CFC core modules being charged in liquid oxygen (left) and placed in dewar flask on weight scale for long-duration burn-down test (right).

Burn-down test results of three CFC core module test articles.

Module	Dry Mass	Fluid	Loaded Mass	Net Fluid Mass	Avg Burn-down rate*	Flow Rate of Gas	Burn-down Time*	Total Gas Volume	Inc. time vs. N_2 baseline
	g		g	g	g/min	SLM	hours	L @STP	%
I	124	N2	387	265	0.42	0.34	10.5	214	-
		Air	423	299	0.39	0.32	12.7	243	21
		O2	501	377	0.41	0.29	15.5	267	48
II	123	N2	239	116	0.36	0.29	5.5	95	-
		Air	267	144	0.36	0.29	6.3	111	15
		O2	306	182	0.34	0.24	9.0	125	64
III	503	N2	1,145	642	0.51	0.41	21.0	514	-
		Air	1,273	769	0.53	0.43	24.3	631	16
		O2	1,466†	963†	0.52†	0.36†	31.5†	688†	50†

*Tested in pre-cooled two-liter dewar flask with foam cap (baseline flask heat leak of 1.6 W with LN2)
†Estimated based on test data from Modules I and II

Performance of three CFC core module test articles in a 2-liter dewar flask (1.6 W)

Module	Description	Volume	Dry Mass	Aerogel Mass	O_2 Mass	Burn Rate	Burn Time	Time @116g O_2 left
		cm^3	g	g	g	g/min	hr	hr
I	Plain coil w/ heater and lead wires	261	124	60	381	0.41	15.5	9.5
II	G10 case w/ G10 tube (30 g)	157	123	30	182	0.34	9.0	3.7
III	Black case w/ concentric fittings	550	503	64	963	0.50*	31.5*	28.0*

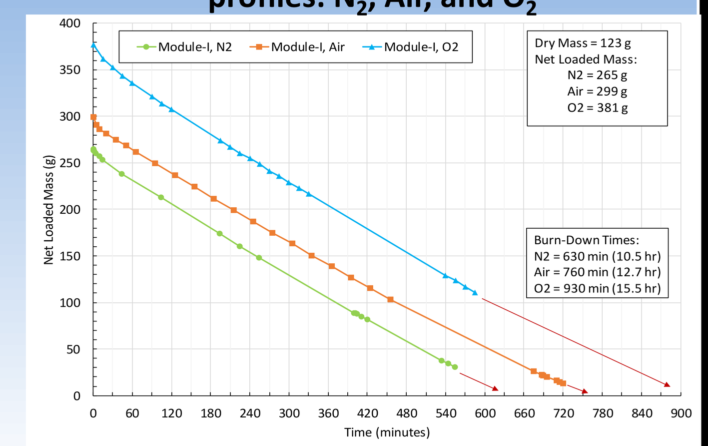
*Estimated

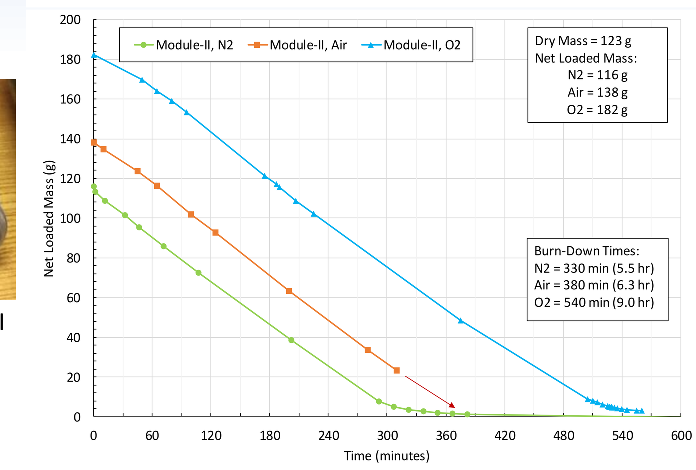
Module I

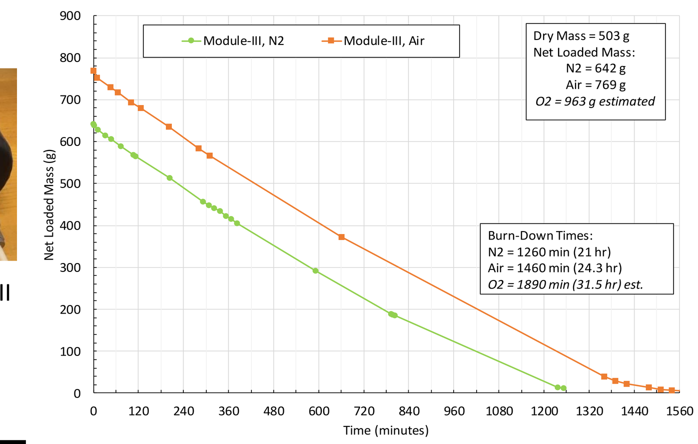
Module II

Module III

Net loaded mass burn-down profiles: N_2, Air, and O_2







Storage of O_2 for Breathing Apparatus

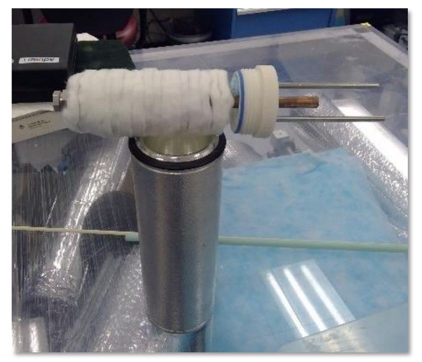
- Storage of oxygen for breathing apparatuses is typically done as low pressure, cryogenic liquid (LO_2) or as high-pressure gas (GO_2).
- A CCR functions in a re-circulatory mode whereby the user breathes the life support gas in a closed loop. Exhaled carbon dioxide (CO_2) is removed by an absorber and oxygen is added to the system according to the user's metabolic needs.
- CCERs are smaller versions of CCRs used for escape purposes and usually carried by the person at all times, ready to be used in an emergency.
- Next Generation CCER are needed for comfortable and continuous wear by persons during their daily work routines as well as for function as an escape breathing apparatus in the event of an emergency.
- Using physisorption technology combined with cryogenic refrigeration, an alternative method of fluid storage is being developed for oxygen storage. The net storage density is more than high pressure gas storage and on par with liquid density but without the limitations of these storage methods. The CFC technology includes a core module for oxygen charging at any cryogenic temperature and then discharging upon demand for GO_2 supply.
- As part of the NIOSH funded Liquid Oxygen Storage Module (LOXSM) project to develop new oxygen breathing equipment, prototypes of the CFC modules have been produced and tested by the Cryogenics Test Laboratory at NASA Kennedy Space Center.

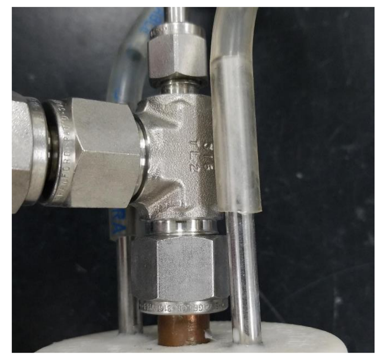
Prototype CFC module and charging station

In the US, CCER designs must meet the applicable provisions within the **Code of Federal Regulations Title 42, Part 84, including Subpart O**. The gaseous oxygen capacity (at standard conditions) of the units for shipboard escape, as required by the US Navy is 1-25 liters GO_2 and for mine escape it is 3-81 liters GO_2, as defined in Subpart O, to meet mining regulatory requirements.

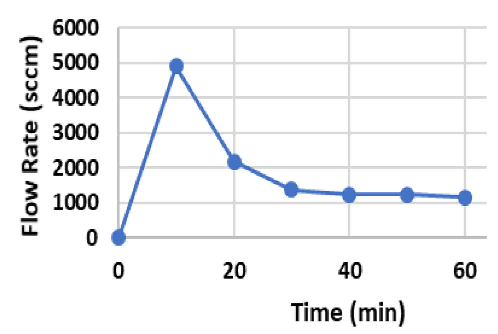
Design Basis and Heat Exchange Process

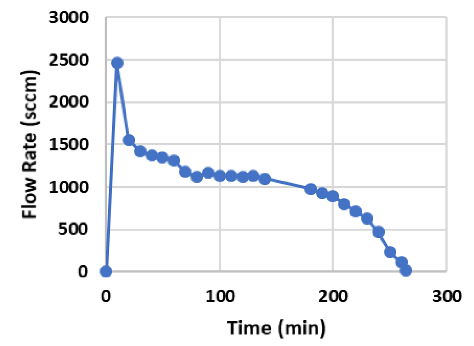
- Requirements for emergency oxygen 1-hour rescue pack: 1.35 liter/min at STP (1.93 g/min or a total mass of 116 g for one hour). The equivalent volume of gaseous O_2 supplied is 81 liters (81,000 cm^3) which corresponds to a liquid volume equivalent (LVE) of approximately 102 cm^3 of liquid O_2.
- From cryogenic testing of aerogel composite materials in different fluids, design parameters were found: for O_2 in Cryogel® by Aspen Aerogels (bulk density of 0.167 g/cm^3), the mass ratio (MR) is 7.1 while the volume ratio (VR) is 1.03. For example, storing 116 g of O_2 requires 16.3 g of Cryogel, or about 100 cm^3 in volume.
- To liberate (or "un-store") the cryo-adsorbed molecules within the core of the CFC-based module, a heat source in required. Heating can be provided by a solid conduction path from the ambient environment, the exhaled breathing air, and/or the exothermic reaction of the associated CO_2 scrubber material for optimum balancing effect to meet demand cycles from steady-state to high flow.
- A CFC module prototype using a counter-flow (tube-in-tube) heat exchanger was designed with a parallel-plate stack-up arrangement 10-mm aerogel composite disks
- For Test 1, the total mass uptake at the start (time zero) was 260 g. As the flask reached thermal equilibrium the flow rate became stable at approximately 1,200 sccm. For Test 2 the flask was pre-cooled for 30 minutes by filling it with LN_2. After cooldown the same process for Test 1 was repeated and the charged mass was measured to be 329 g.





Prototype-1 with flask (left); detail of tube-in-tube counter-flow heat exchanger (right)





Module Prototype-1, discharge Test 1, left, and Test 2 (with pre-cooling), right.

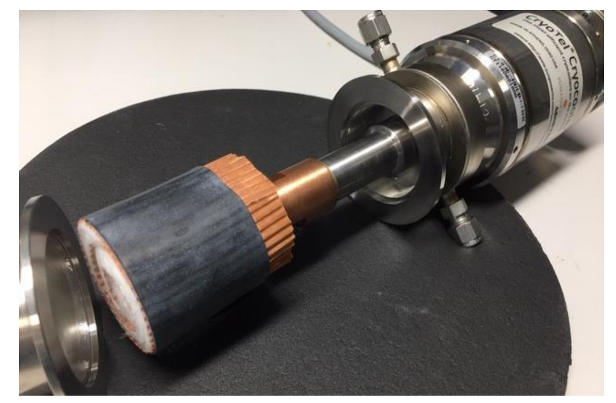
Conclusions

- The technology of using the phenomena of cryo-adsorption afforded by the Cryogenic Flux Capacitor (CFC) device appears feasible for the breathing oxygen application.
- For the core modules tested, the storage density shows the opportunity for compact, lightweight storage of oxygen:
  - The liquid volume equivalent for oxygen is approximately 103% (that is, the solid-state molecular storage density is slightly higher than that of the liquid phase).
- The size and weight should be well within the current bounds.
- Promise is shown for additional features and capabilities such as CO_2 sequestration and longer usage durations for a relatively smaller envelope/weight.

Physical characteristics of three CFC core module test articles.

Module	Description	Overall Dimensions	Dry Weight	Aerogel Weight
I	Plain coil w/ heater and lead wires	83-mm diameter x 10-mm long	124 g	60 g
II	G10 case w/ G10 tube (30 g)	50-mm diameter x 100-mm long	123 g	30 g
III	Black case w/ concentric fittings	100-mm diameter x 175-mm long	503 g	64.4

Prototype CFC modules tested: Module I, Module II, and Module III (from left to right).



Notional concept of a future systems for liquid-free charging of CFC modules: the cryocooler (right) provides the refrigeration to a cryogenic temperature in parallel with supplying low-pressure gaseous oxygen to module for molecular adsorption to the fully charged state.