Oxygen Storage and Supply for Closed-Circuit [Breathing] Apparatus

OSCG 2023 Annual Meeting - Davenport IA

August 1st - 3rd, 2023

Rohan D. Fernando Senior Research Engineer
National Institute for Occupational Safety and Health (NIOSH)
National Personal Protective Technology Laboratory (NPPTL)
Pittsburgh, PA USA

Department of Health and Human Services

Centers for Disease Control and Prevention

National Institute for Occupational Safety and Health

National Personal Protective Technology Laboratory

Prevent work-related injury and illness by advancing the state of knowledge and practice of personal protective technologies

Background to Research Work

- NIOSH embarked on a R&D program in collaboration with the Navy (NSWCPCD) and NASA-KSC to develop, produce prototypes, test, and demonstrate closed-circuit apparatus (referred to as closed-circuit breathing apparatus hereafter to align with common mining language) for emergency use in underground coal mines.
- These breathing apparatus are either:
    - Short duration (< 60 min) devices used for self-escape that are person wearable or stored in caches along the escape route
    - Long duration (~4 hr) devices used by rescue teams to help with escape and/or mine stabilization
- Self-contained breathing apparatus, using the closed-circuit principle where the breathing gas from the user is recirculated and reconditioned in a closed loop within the apparatus is the most efficient, and leads to a small-sized design.
- This presentation will be on the oxygen delivery systems (ODS) using very high pressure gaseous and liquid oxygen systems developed in this program for short and long duration breathing apparatus

Closed-circuit escape respirators (CCERs)

- Function in a recirculatory 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 (O_2) is added to the breathing loop according to the user's metabolic needs
- Chemicals such as calcium hydroxide and lithium hydroxide are used as CO_2 absorbents
- Gaseous O_2 stored in high pressure cylinders or O_2 generating chemicals such as potassium superoxide serve as the oxygen source

BREATHING CIRCUIT

Closed-Circuit Self-Contained Breathing Apparatus

Photos and Graphics by NIOSH-NPPTL

USER INTERFACE

Breathing Loop

- Docking Valve
- Breathing Hose/ Bag Assembly
- Chemical CO_2 Absorber Canister

Oxygen Delivery Systems

- Chemical oxygen – Potassium Superoxide (KO2) and additives
- Demand Valve
- VIPR* - pressure reducer, gauge etc.
- High pressure oxygen cylinder

*Valve Integrated Pressure Reducer

Research on Oxygen Delivery Systems (ODS)

- **Gaseous oxygen ODS**
  - Pure oxygen stored in very high-pressure cylinders (up to 10,000 psi)
  - Pressure reduction in a cylinder mounted reducing valve
  - Oxygen added to the breathing loop via a demand valve

- **Liquid oxygen ODS**
  - Liquid oxygen stored in aerogel material
  - Gaseous oxygen is released into breathing loop by heating the aerogel
  - Freeze some of the carbon dioxide to remove from the breathing loop

CCER Approval Requirements—Title 42 CFR Part 84 sub-part O

- ❖ For a CAP 3 CCER that meets the nominal use time of 1 hour as required by the Mine Safety and Health Authority (MSHA)
  - Volume of oxygen consumed per minute (required O_2 generation rate) = 1.35 L/min
    - ➢ Total of 81 L of gaseous O_2 required during use; or roughly 100 mL of Liquid oxygen
  - Volume of carbon dioxide produced per minute (CO_2 sequestration rate) = 1.15 L/min
    - ➢ Total of 69 L of CO_2 sequestration required during use
  - Stressor limits:
    - Average inhaled $O_2 > 19.5\%$
    - Average inhaled $CO_2 < 1.5\%$ with acceptable excursion ranges as given in 42CFR84.304-Table 1

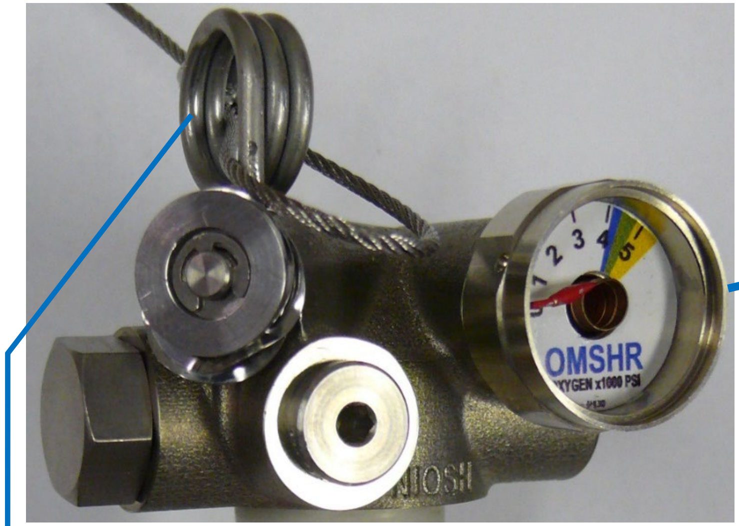
Very High Pressure Gaseous ODS

IAA: Naval Surface Warfare Center-Panama City Division
Contracts: Cobham, Luxfer, others

Fully functional prototypes of Gaseous Oxygen Delivery Systems were produced, comprising of:

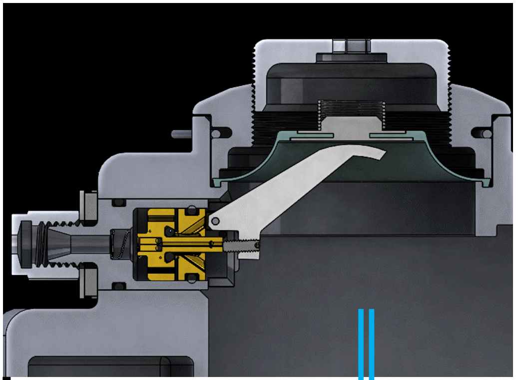
- Valve integrated pressure reducer (VIPR) that is a combination pilot valve, main valve, two stage pressure reducer, gauge, safety relief device (burst disc), and fill port in a single assembly
- Demand valve (the 3rd stage) supplied by the VIPR and attached remotely to the breathing loop
- Very high pressure oxygen cylinder (5,000 psi or 10,000 psi) threaded directly to the VIPR

Gaseous Oxygen Delivery System (ODS)



Pull pin for 'quick-on' activation

Valve Integrated Pressure Reducer assembled onto a 10,000psi oxygen cylinder



Demand Valve (3rd Stage)

Oxygen flow

CO_2 Scrubber space

Photos and Graphics courtesy of NSWC

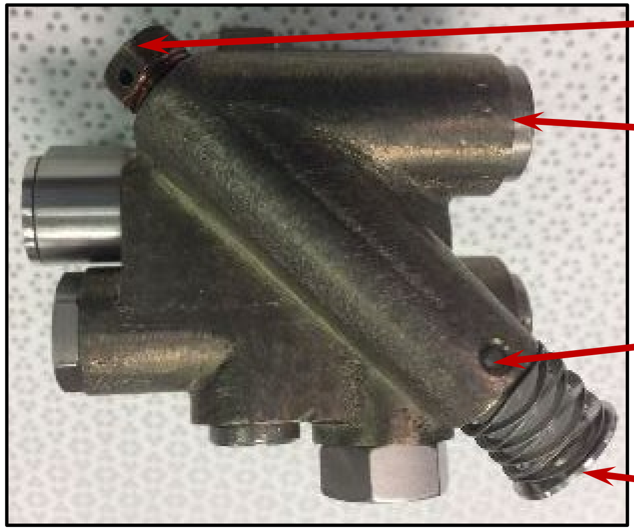
VIPR Design

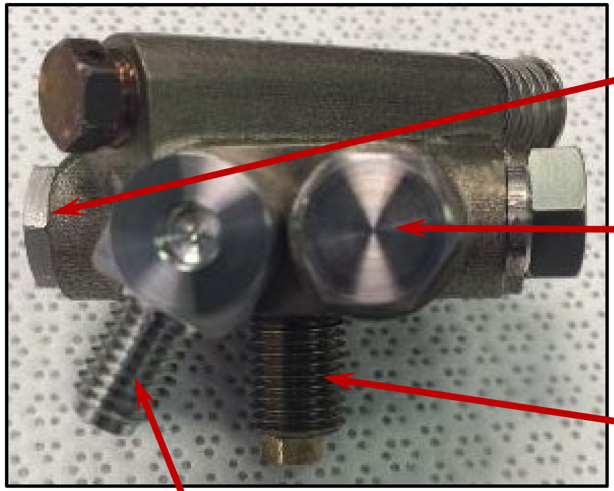
- 3D printed Monel K500 ([1]DMLS) body and with complex internal flow path structure and high pressure oxygen compatibility
- Post precision machined to have tolerances, and surface finishes required for internal components and thread forms

[1]Direct Metal Laser Sintering

Unique VIPR design features

- Heat treated body for high strength while reducing overall size
- Pilot valve allowing rapid activation while delaying pressurization of high pressure internal chambers to mitigate oxygen fires
- Combination fill and gauge port with check valve to decrease long term leak and reduce size





Photos courtesy of NSWC

Luxfer Gas Cylinders VHPC
- Service pressure 5,000psi

- **Two sizes produced – L3B and L3C**
- **DOT-SP 10915-5000** permit granted for oxygen use up to 3,000 psi and other gases to 5,000 psi via **DOT-CFFC** (5th Revision)
- **DOT-SP 21032** permit granted for 5,000 psi oxygen duty via **ISO 11119-2(E)**

L3B
- W.Vol. = 19.7 cu.in. (0.32 L)
- L = 6.58” (167 mm)
- Wt. = 1.1 lbs (0.50 kg)

L3C
- W.Vol. = 28.1 cu.in. (0.46 L)
- L = 8.51” (216 mm)
- Wt. = 1.3 lbs (0.59 kg)

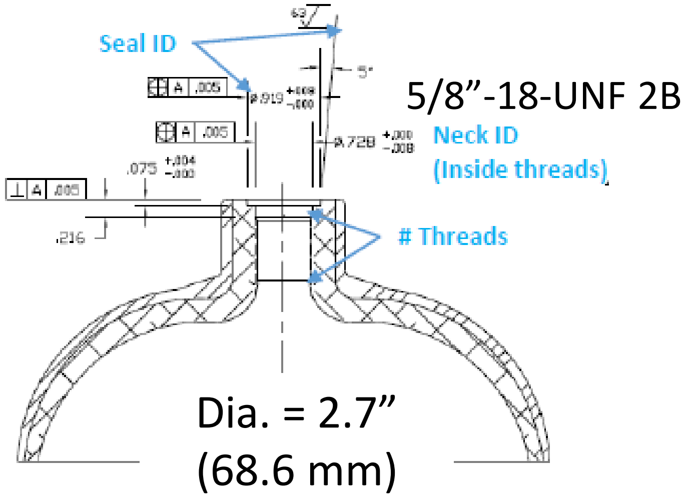


Photo & Graphic by NIOSH-NPPTL

Cobham Mission Systems VHPC
- Service pressure 10,000 psi

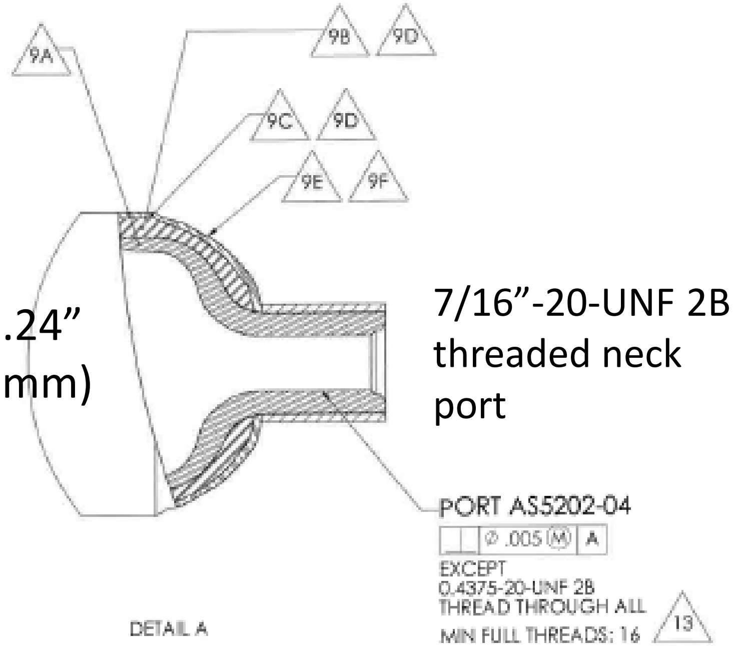
- Two sizes produced **6354-1 and 6354-3**
- **DOT-SP 20579** permit granted for 10,000 psi oxygen duty via **ISO 11119-2(E)**

<u>6354-1</u>

- W.Vol = 8.3 cu.in. (0.14 L)
- L= 5.77” (146.6 mm)
- Wt. = 0.66 lbs (0.30 kg)

<u>6354-3</u>

- W.Vol = 16.9 cu.in. (0.28 L)
- L= 9.57” (243.1 mm)
- Wt. = 1.12 lbs (0.51 kg)



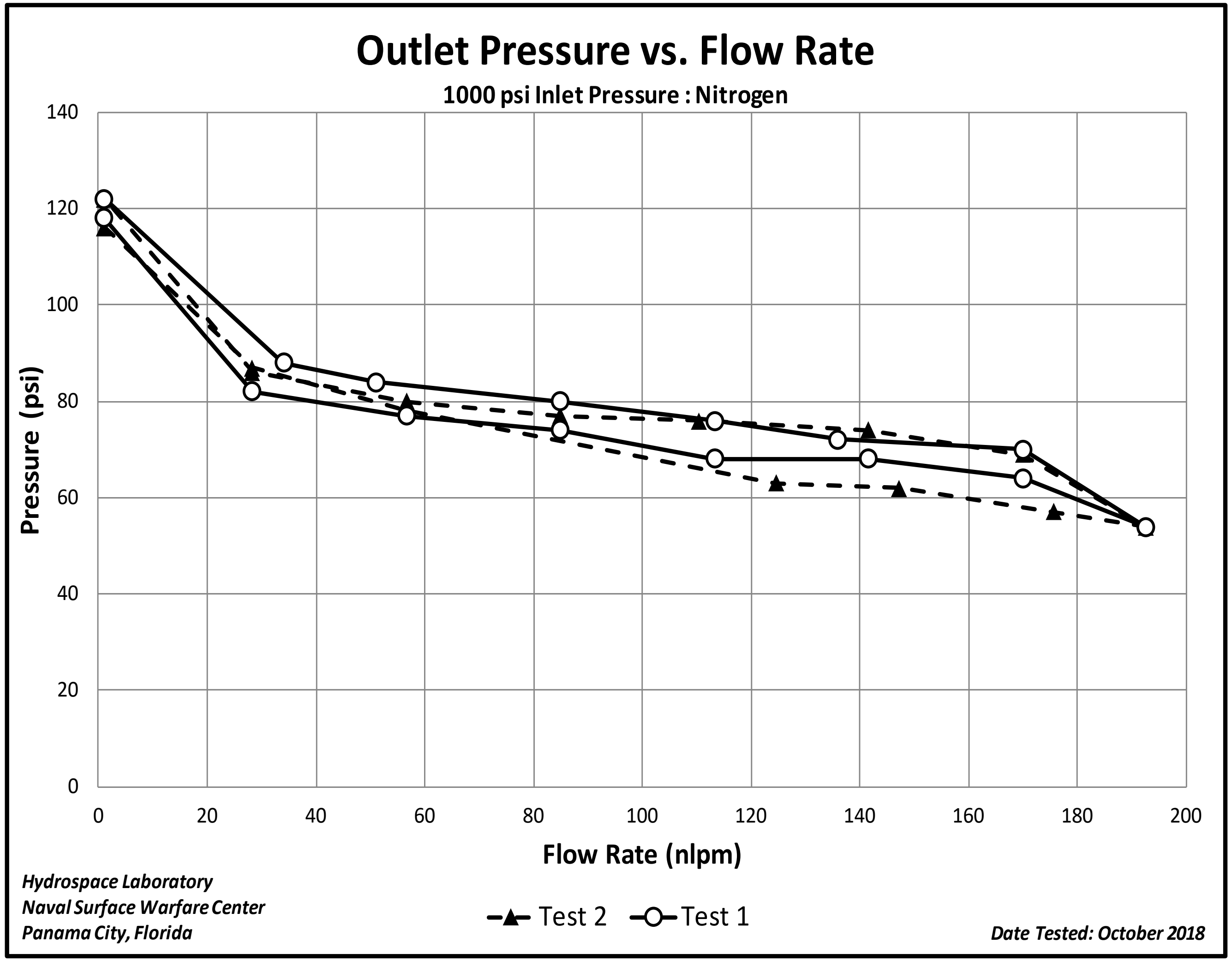
Dia. 2.24”
(50.9 mm)

7/16”-20-UNF 2B
threaded neck
port

Photo & Graphic by NIOSH-NPPTL

VIPR Flow Test Data

- Max flow 195 liters/min – approx. equivalent to 62.5 RMV open circuit breath
- Minimum outlet pressure drop is just over 50 psi at max. flow
- Hysteresis is about 10 psi maximum throughout the performance curve
- VIPR will support the minimum pressure that will be delivered to the Demand Valve at the maximum flow


Outlet Pressure vs. Flow Rate

1000 psi Inlet Pressure : Nitrogen

Hydrospace Laboratory
Naval Surface Warfare Center
Panama City, Florida

Date Tested: October 2018

Graphic courtesy of NSWC

Liquid Oxygen ODS

IAA: NASA-Kennedy Space Center-Cryogenics Laboratory

LOXSM – Liquid Oxygen Storage Module

- Stored LOX can be released as a gas and metered into the breathing loop using heat generated by the user and CO_2 absorber in a CCER
- Core of the LOXSM is a cryogenic flux capacitor (CFC) where LOX is stored in a matrix of aerogel material
- The NASA-patented cryogenic flux capacitor is an energy-based device for the storage (charging) and release (discharging) of fluids
- Remove some of the CO_2 in the breathing loop produced by the user by freezing

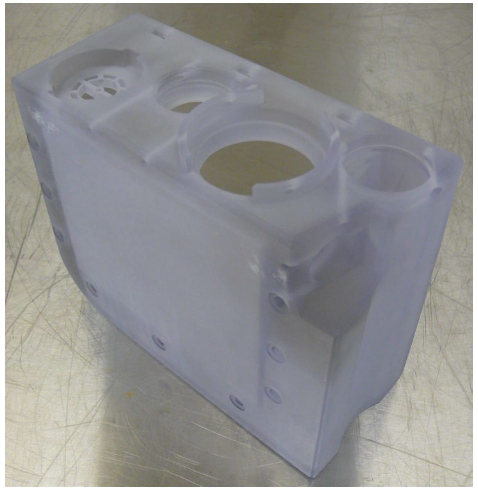
Capacity 3 (CAP3) CCER **Integrated Component Test Platforms (ICTP)**

CCER-B ICTP for **CAP3-80L**

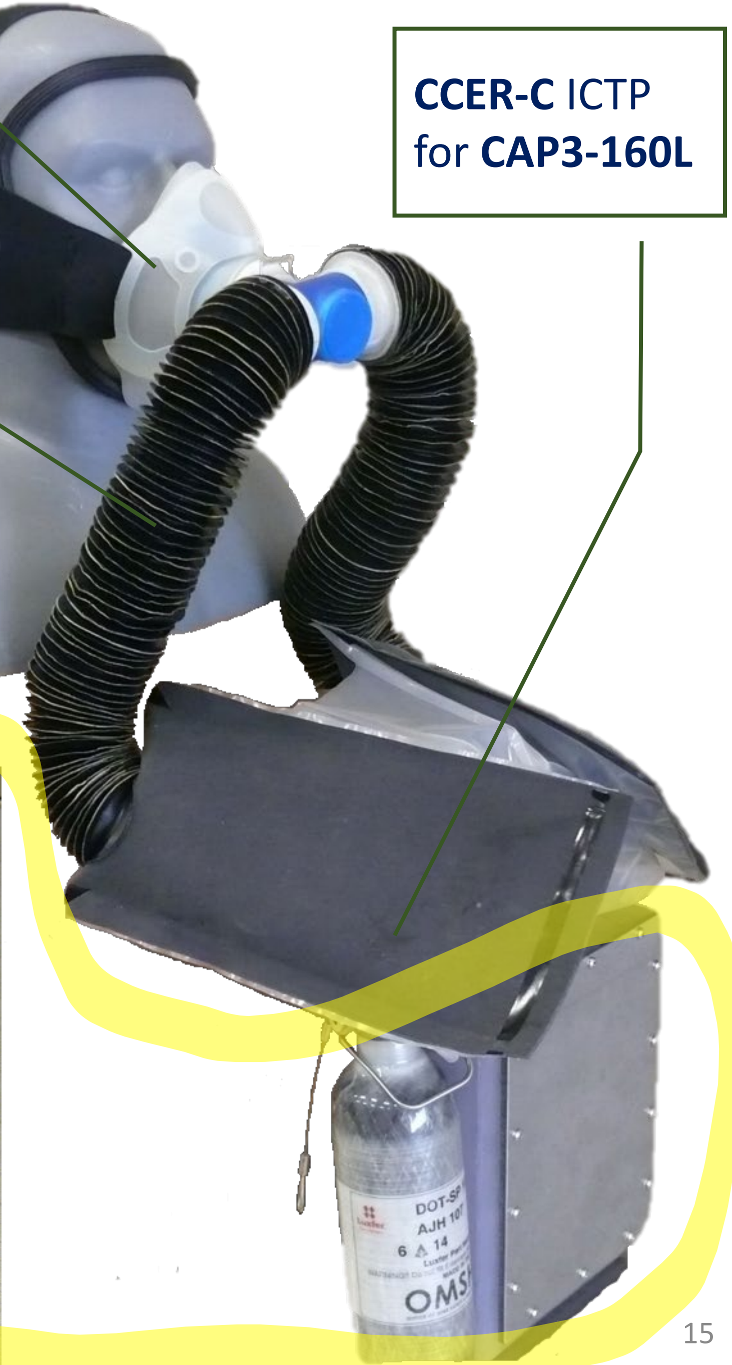
Photos courtesy of NSWC

REPLACE with LOXSM

80L CO_2 Absorber Canister



160L CO_2 Absorber Canister



Facepiece with Improved T-DOK

Breathing Hose/ Bag Assembly

CCER-C ICTP for **CAP3-160L**

LOXSM – Core

- Best CFC candidate for LOXSM Core was identified after testing 10 different aerogel composite materials at cryogenic temperatures
- Calculations show that a CFC charged using a supply of LOX, roughly 40-mm diameter by 100-mm length has the adequate storage capacity to provide the CAP3 – 80 Liters (one hour) of breathable oxygen
- Three prototype CFC modules were prepared for tests using Liquid N_2, Liquid Air, and Liquid O_2 for both the cooling and the molecular charging of the modules
- Additional capacity must be added for standby or dormancy requirements up to nine hours to cover a full 10-hour work shift

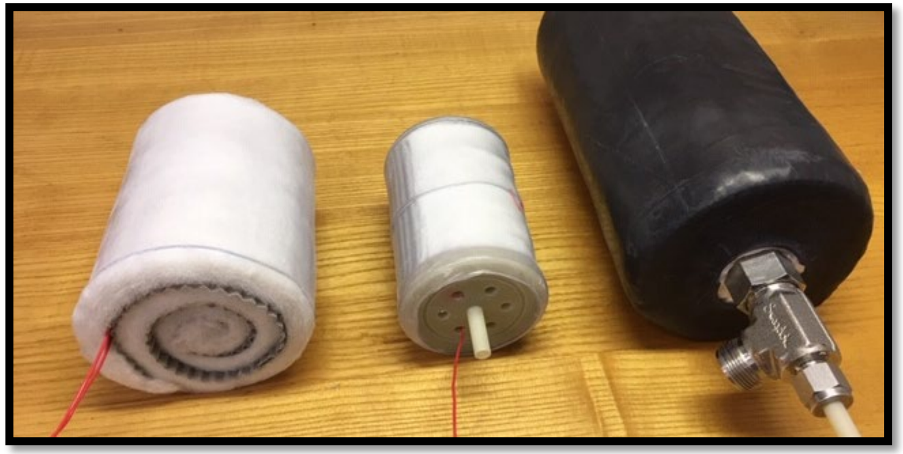


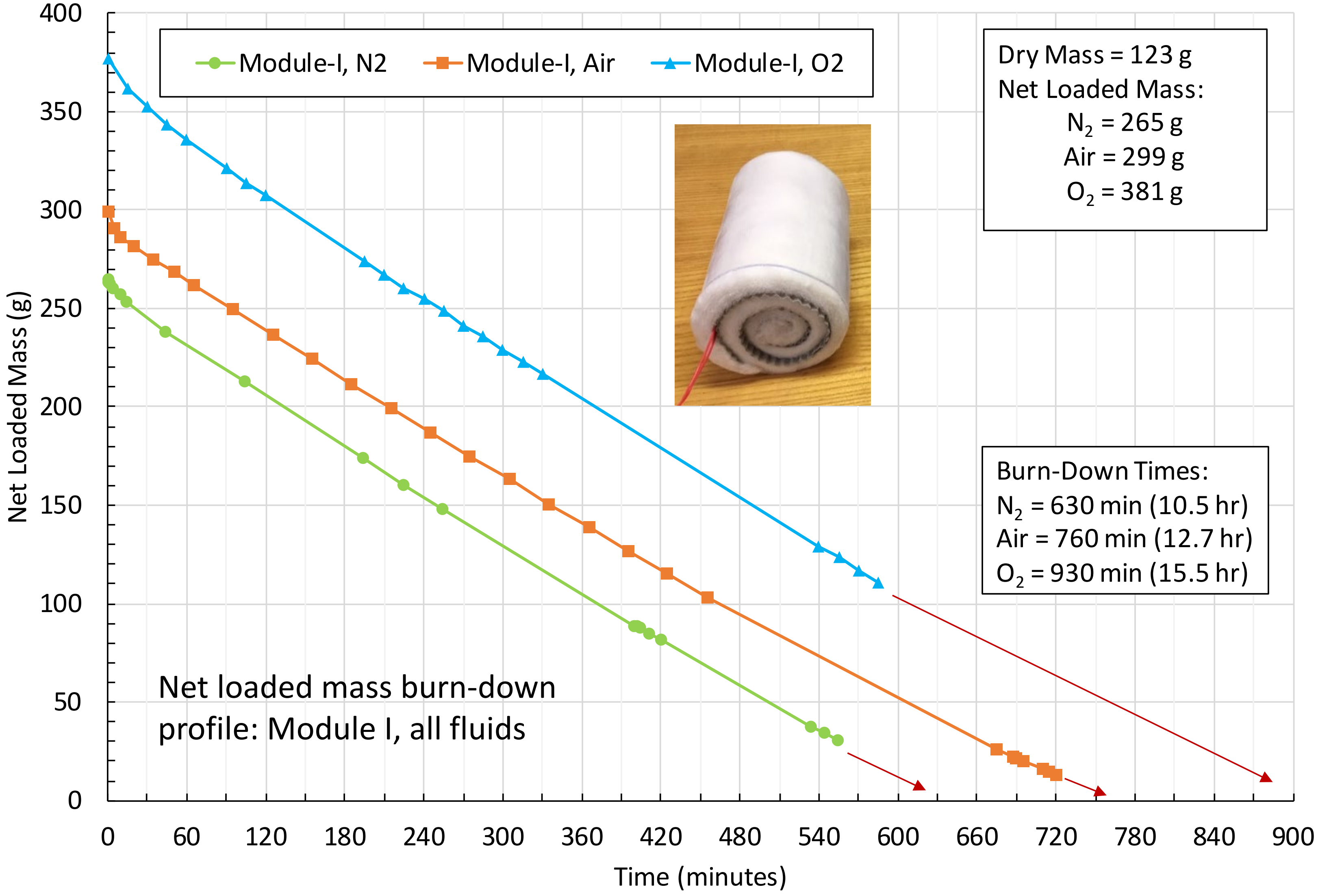
Photo courtesy of NASA

Module	Description	Overall Dimensions	Dry Weight	Aerogel Weight
I	Plain coil w/ heater and lead wires	83-mm diameter x 100-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

Physical characteristics of the CFC core module test articles

LOXSM – Core

- Desorption, or burn-down, test results for CFC core Module I is shown in the graph.
- The module was loaded with the 3 liquid gases and burn time recorded
- The loaded mass of O_2 for Module I was 381 grams and had the highest total burn time of 930 minutes (15.5 hours)



Dry Mass = 123 g
Net Loaded Mass:
N_2 = 265 g
Air = 299 g
O_2 = 381 g

Burn-Down Times:
N_2 = 630 min (10.5 hr)
Air = 760 min (12.7 hr)
O_2 = 930 min (15.5 hr)

Net loaded mass burn-down profile: Module I, all fluids

Photo & graph courtesy of NASA

CO_2 removal by LOXSM

Devising full-scale LOXSMs aimed at
CO_2 sequestration in addition to O_2 generation

Utilize the cryogenic cold-power to capture the CO_2

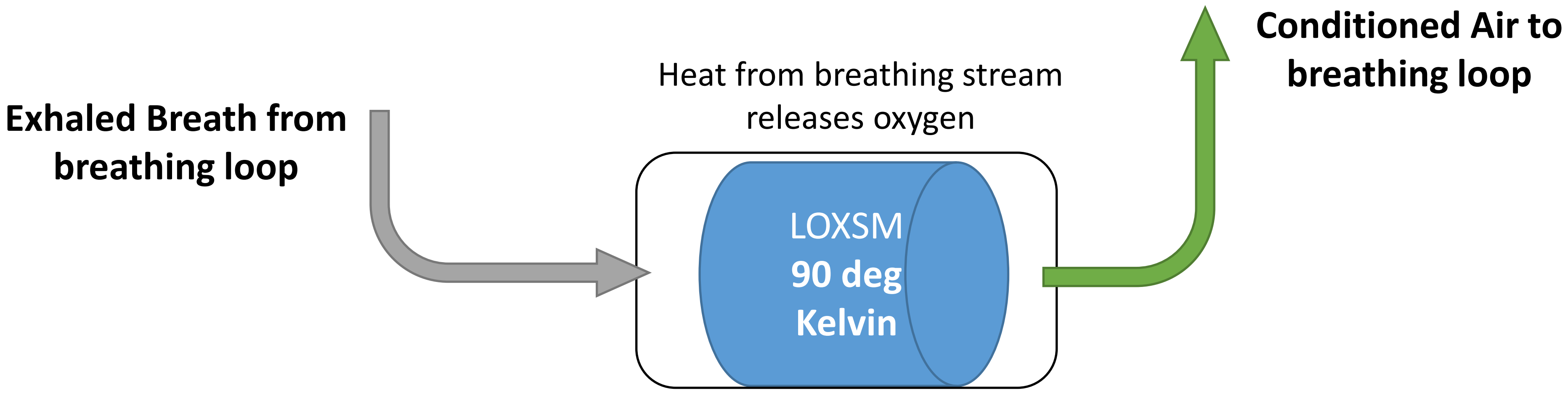
↓

Reduce/eliminate the chemical CO_2 scrubber

↓

Reduce mass/volume of CCER

Maximize the "Cold Path" to maximize the probability that the CO_2 will be trapped within the LOXSM



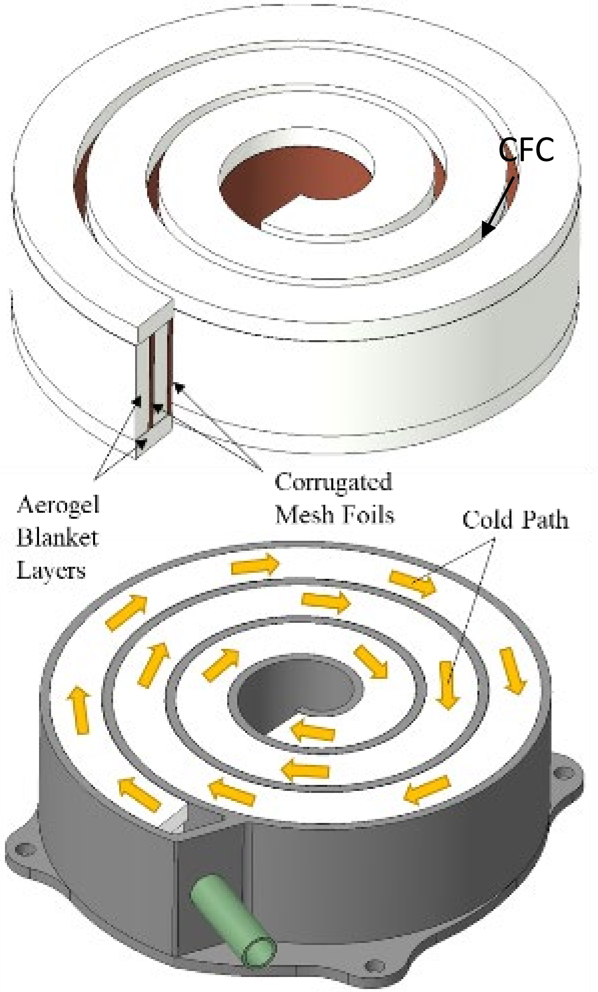
Exhaled Breath from breathing loop

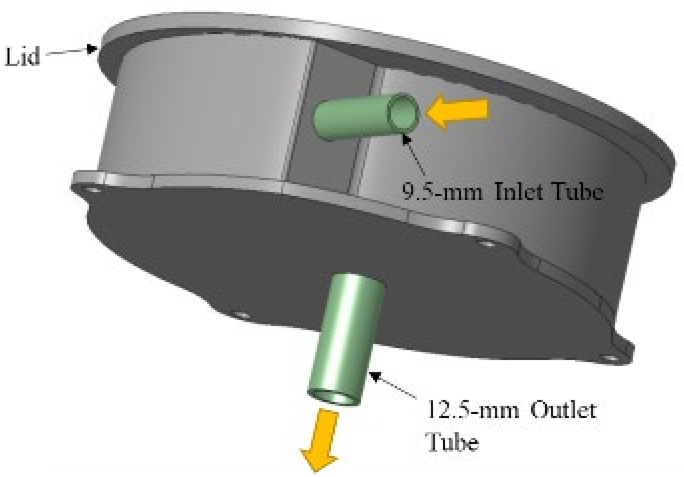
Heat from breathing stream releases oxygen

Conditioned Air to breathing loop

CO_2 removal by LOXSM

- <u>Prototype v2.0</u>
  - Long Cold Path
  - Spiral geometry, 3-D printed from Ultem®
  - Roughly 5” diameter, 1.6” thick
  - 35 g of aerogel total
    - 225.8 mL of LN_2 or 218 mL of LOX





Images courtesy of NASA

CO_2 removal by LOXSM

- Tested in vacuum jacketed container
- Testing done with 99.8% CO_2 and gas mixture
- Gas Mixture (5% CO2, 16% O2, and 79% N2)
- 1.6 L/min flow rate

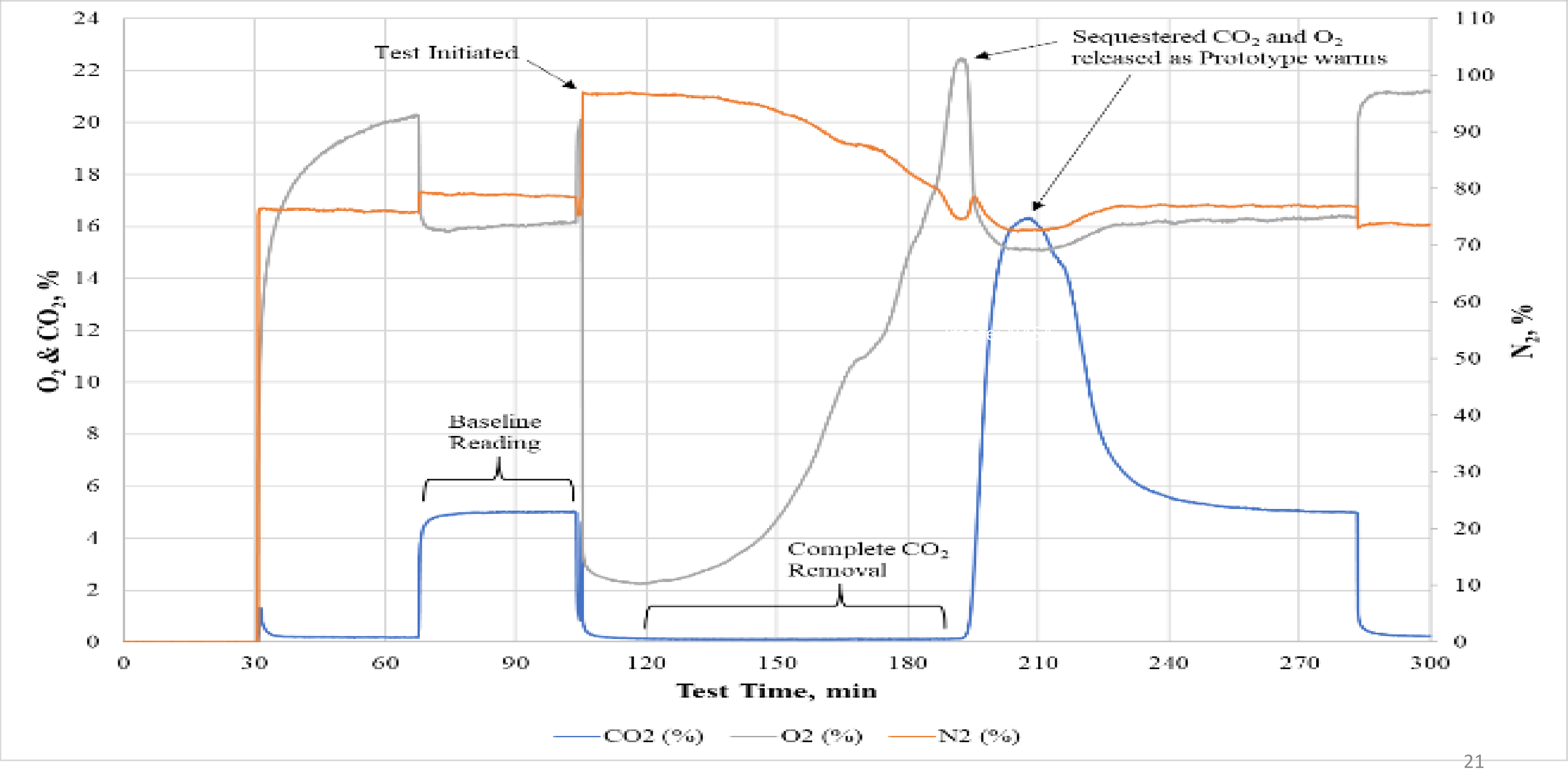
- Estimated time for complete CO_2 removal = 80 min
- Estimate for total CO_2 captured = 6.7 L, 13.8 g
- 99.9% CO_2 testing: Shorter time (34.5 min), but more mass removed (40.7 L)

Photo courtesy of NASA

CO_2 removal by LOXSM

Prototype v2.0 Test Results

Testing done with 99.8% CO_2 and gas mixture



Images: NASA

Future Work

- Need actual LOX testing instead of LN_2
- Testing on NIOSH Integrated Component Test Platform (ICTP)

- Designing/Testing for proper dormancy time
  - CCER needs to be able to be charged at the beginning of a work shift, taken into the mine for 8-10 hours, and then provide 1 hour of oxygen to the user in the event of an incident
  - Proper insulation system, vapor shielding, etc.

Conclusions – Gaseous ODS

- VIPR ODS will support the maximum flow of approx. 195 liters/min equivalent to 62.5 RMV open circuit
- VIPR ODS flow performance is capable of meeting 42 CFR-Part 84-Subpart O requirements for CCERs
- Delayed pressurizing design with orifice installed will eliminate auto-ignition allowing the safe use of the VIPR in ODS up to 10,000 psi
- VIPR ODS prototypes are close to production quality
- Carbon composite cylinders for 5K psi and 10K psi oxygen duty are DOT approved

Conclusions – LOXSM ODS

- The LOXM as the ODS for closed-circuit breathing apparatus seem feasible
- LOXSM prototypes developed/tested generate O_2 while sequestering CO_2
- Testing confirmed total CO_2 removal for a time using a breathing loop gas mixture and 99.8% CO_2 supply using LN_2
- There is potential to reduce the size of the chemical CO_2 absorber
- The LOXSM, when developed after further research, would need to perform according to 42 CFR - Part 84 requirements to be used in a closed-circuit breathing apparatus

NIOSH is helping to bridge the research gap by conducting this design work and information will be available to any interested manufacturers to use in their CCER designs and submit for the required approvals

For more information, contact:

Rohan D. Fernando
CDC-NIOSH-NPPTL
RFernando@cdc.gov

THANK YOU
FOR YOUR ATTENTION

QUESTIONS?

Visit the NIOSH NPPTL website:
https://www.cdc.gov/niosh/npptl/default.html

Photo credit: NIOSH, Shutterstock, or Microsoft images unless otherwise noted