Integrated Component Test Platforms for Closed Circuit Escape Respirators

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NPPTL
National Personal Protective Technology Laboratory

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

Purpose and Objective

- When developing a fully functional closed circuit escape respirator (CCER), one of the main tasks is to ensure that the breathing circuit is designed to meet the required standard and explore different options.
- The other components of the CCER such as the respirator enclosure, carrying/ harness system, user interface (e.g. facepiece), oxygen delivery system, hardening to withstand the use environment etc. can be done afterwards.
- Design of some of these other components are driven by the breathing circuit design, to result in a complete CCER that can be certified for use.
- Focusing initially on the beathing circuit design saves time, cost and resources for developing CCERs to meet the end user's requirement, conform to required standards, then have a product with the reliability to survive and operate in the use location.

Photo courtesy of NIOSH

Applying this approach, NIOSH used integrated component test platforms to design and test CCER breathing circuits to meet the performance and capacity requirements of Title 42 Code of Federal Regulations Part 84 sub-part O

Breathing circuits

- Open circuit
  - Breathing gas is inhaled by the user from a source and exhaled to the ambient
- Recirculating circuit
  - Breathing gas supplied to the user is recirculated where the oxygen consumed is replenished and carbon dioxide produced is removed
- Breathing gases
  - Air - ~21%O_2 /79%N_2 for open circuit
  - Pure Oxygen - 100%O_2 for closed circuit
  - Nitrox - mixture of N_2 and O_2 (32/68, 40/60, 60/40, etc.) for open and closed circuit systems
  - Other gas mixtures (e.g. Heliox) and tri-gas mixtures are used in diving applications for open and closed circuit systems

Photo courtesy of Draeger

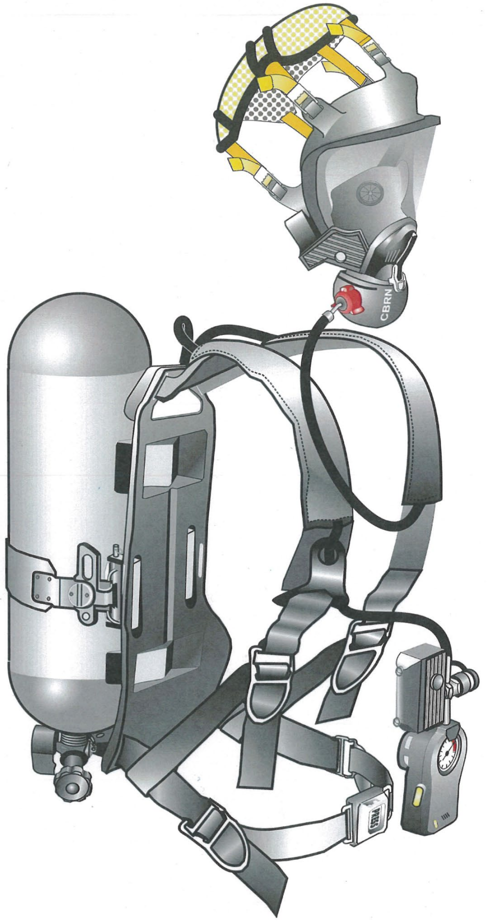


Image courtesy of NIOSH

Photo courtesy of NSWCPCD

Recirculating circuits can be further categorized as closed and semi-closed circuits

- Closed circuit – no gas leaves the circuit*
  - Pure oxygen apparatus and mixed gas apparatus maintaining a constant partial pressure of oxygen

  **Some apparatus have an overpressure valve to vent excess gas*

- Semi-closed circuit– some gas exits the circuit to ambient
  - *These are mixed gas apparatus and systems*
  - Constant injection into breathing circuit
  - Constant injection and demand by user

Recirculating circuit principle applied in breathing apparatus

These have different forms tailored to their application and includes:

- Escape (short duration) and rescue (long duration) applications in 1 atm ambient, or ‘surface’ pressure.
- Diving applications in greater than 1 atm ambient pressure. Also, apparatus for working in pressurized tunnels is akin to diving.
- Breathing systems that have a common oxygen supply and carbon dioxide removal for multiple users, for e.g., in hyperbaric chambers.

Integrated Component Test Platform (ICTP)

What is the ICTP?

- Test platforms for integrating and testing components used in the breathing circuit of a closed-circuit respirator
- Allows testing and refining metabolic performance parameters before fully developing the respirator
- Allows exploring design changes quickly and cost effectively

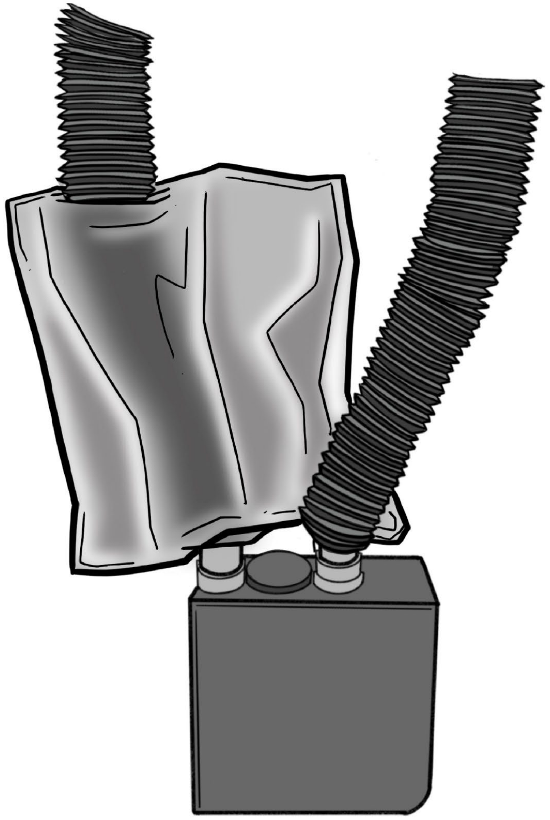
ICTPs were built for testing components for closed-circuit escape respirators (CCER) by NIOSH with collaboration with NSWCPCD

ICTP-CCER

for integrating and testing components used in the breathing circuit of a closed circuit escape respirator

Breathing Loop

- User interface – half mask, bitepiece
- Breathing hoses
- Breathing bags – one or two bags
- Exhaust Valve
- Chemical CO_2 Absorber



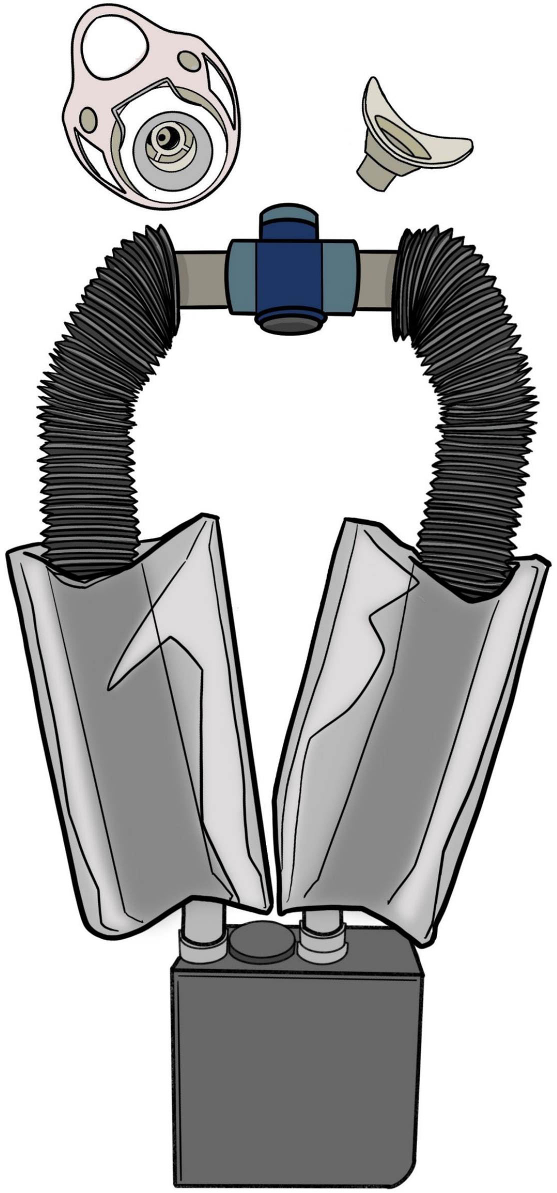
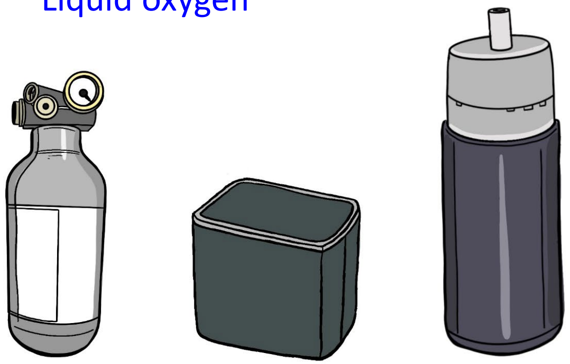


Illustration by NIOSH

Oxygen Delivery Systems

- High pressure gas
- Chemical oxygen
- Liquid oxygen



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

eCFR :: 42 CFR Part 84 Subpart O -- Closed-Circuit Escape Respirators

For designing a CAP 3 CCER that meets the nominal use time of 1-hour as required by the Mine Safety and Health Authority (MSHA) for escape from an underground mine emergency; and we selected 2 hours duration to change to a cached device for continued escape, the conditions to meet are:

- 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 for a 1-hour device
  - Total of 162 L of gaseous O_2 required during use for a 2-hour device
- 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 for a 1-hour device
  - Total of 138 L of CO_2 sequestration required during use for a 2-hour device
- Stressor limits as given in 42CFR84.303-Table 1 (*with acceptable excursion ranges as in table*):
  - Average inhaled O_2 > 19.5% *with ≥15% excursion*
  - Average inhaled CO_2 < 1.5% *with ≤4% excursion*
  - Peak Breathing Pressures ΔP ≤200 mm H_2O *with -300 ≤ΔP≤200 mm H_2O excursion*
  - Wet-bulb Temperature <43°C (109 °F) *with ≤50°C (122°F) excursion*
- Also, these stressor limits must be met during performance tests for 3 work-rates i.e., Peak, High & Low specified in Table 3 in 84.305 of the Code, until the oxygen supply of the device is exhausted

Integrated Component Test Platforms for CAP 3 CCERs

- ICTPs were configured for CAP 3 tests as twin breathing bag/hose with a docking valve, facepiece assemblies, CO_2 absorbent canister and an oxygen delivery system
- Three configurations ICTP CCER-A, ICTP CCER-B & ICTP CCER-C were constructed, and bench tested
- ICTP CCER-A was the initial configuration. After tests, improvements were made to the breathing bag/ hoses, docking valve, Lithium Hydroxide (LiOH) CO_2 absorbent and canister sizes
- The oxygen delivery system underwent its own development using very high pressure cylinders and now exploring liquid oxygen supplies. It is the subject of a separate presentation
- ICTP CCER-B & ICTP CCER-C had improvements implemented resulting from ICTP CCER-A bench tests. ICTP CCER-C was designed to have twice the capacity of ICTP CCER-B. It has the exact components except the CO_2 absorbent canister which is larger

Key test data from these ICTPs are shown and discussed in the slides below

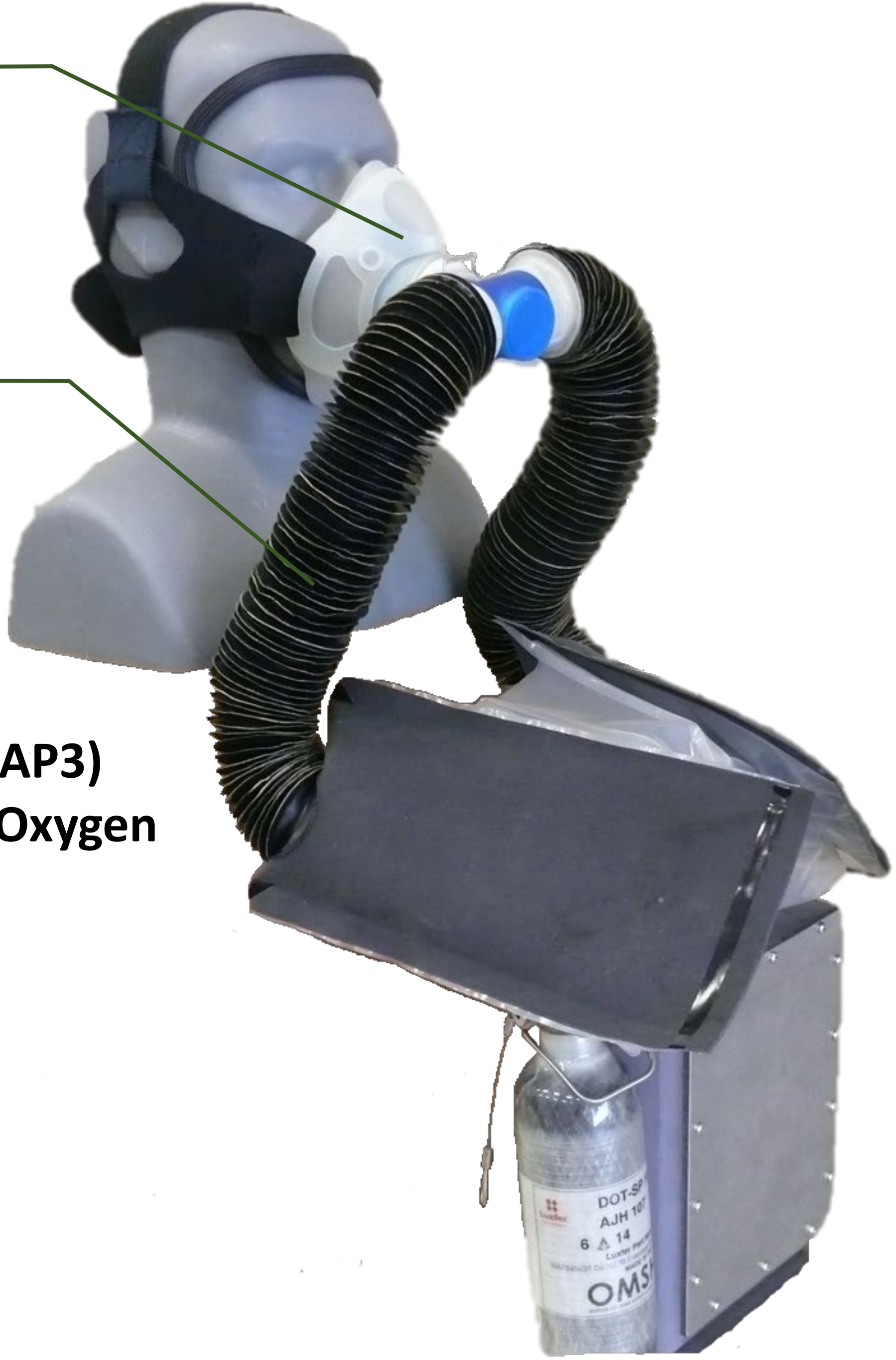
ICTP Capacity 3 (CAP3)
CCER – 81 Liters Oxygen

User Interface - Facepiece with Docking Valve

Twin Breathing Hose/ Bag Assembly

Chemical Carbon Dioxide Absorber Canister

Oxygen Delivery System - High pressure Gas

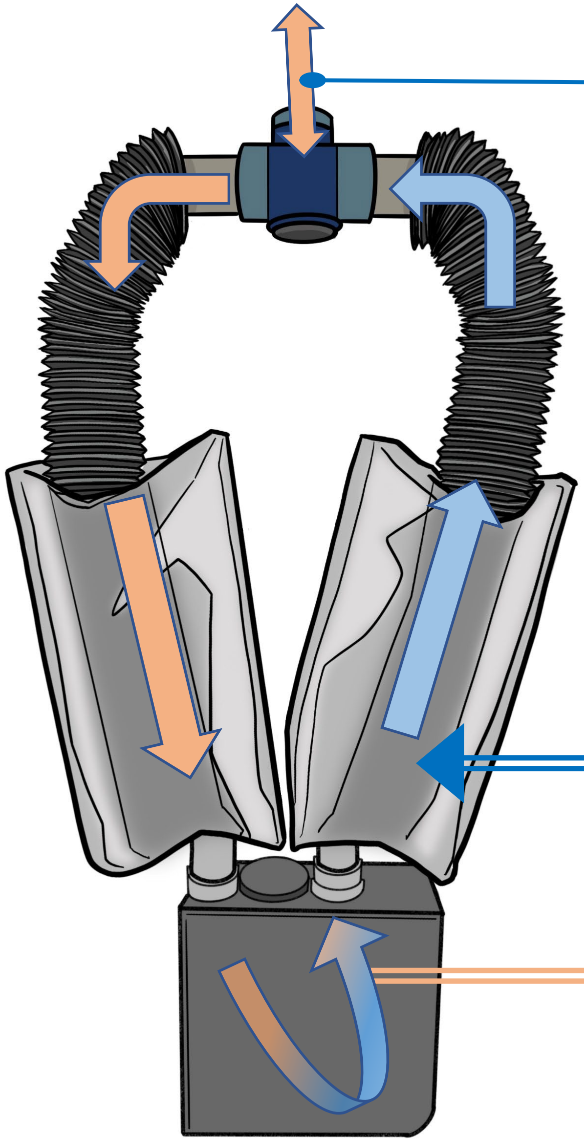


ICTP Capacity 3 (CAP3)
CCER – 162 Liters Oxygen

Integrated Component Test Platforms
for Capacity 3 (CAP3) CCERs

Photos courtesy of NSWCPCD

Design Conditions for the ICTP to meet 42CFR84-O



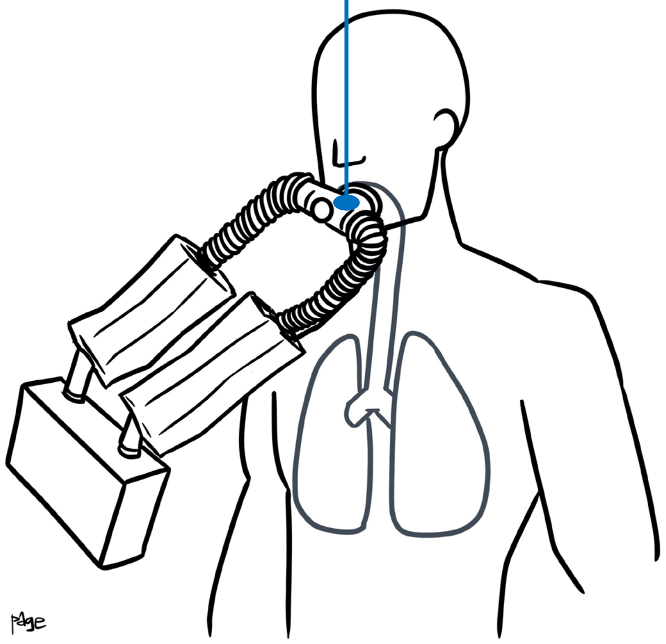
Inspired Conditions

- Average inhaled O_2 > 19.5%
- Average inhaled CO_2 < 1.5%
- Peak Breathing Pressures ΔP ≤200 mm H_2O (7.8” H_2O)
- Wet-bulb Temperature <43 °C (109 °F)

Breathing Pressures and temperature are controlled by hardware design

VO_2 range: 0.5 L/min - 3.0 L/min
(based on work-rate)

VCO_2 range: 0.4 L/min - 3.2 L/min
(based on work-rate)



VO_2 = Volume of oxygen consumed per minute
VCO_2 = Volume of carbon dioxide produced per minute

Illustrations by NIOSH

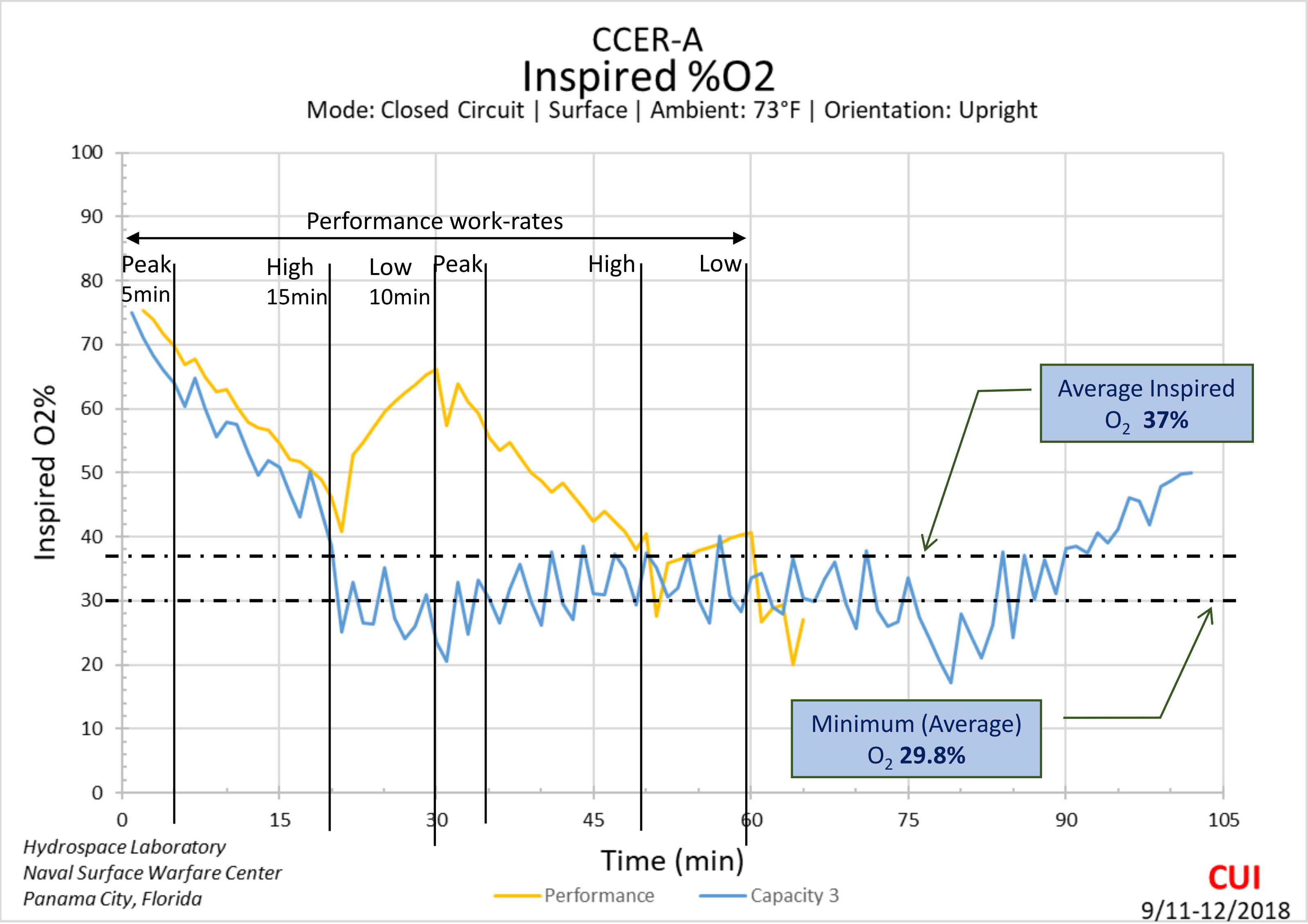
Test Setup at Naval Surface Warfare Center Panama City Division

- Automatic Breathing Metabolic Simulator (ABMS) used with adjustable sinusoidal breathing waveforms for different work-rates.
- Four stressors (CO_2, O_2, Breathing Pressure, and Temperature) are measured by instruments capable of breath-by-breath measurement at the interface between the ICTP and ABMS, then evaluated as one-minute averages.
- During testing the ABMS maintains 'body temperature and pressure with saturated water vapor' (BTPS) having a lung temperature of 37°C (98°F)
- Tidal volume for each of the work-rates corrected for testing at BTPS

Test Type	Work Rate	Duration Per Cycle	VO_2 (SLPM)	VCO_2 (SLPM)	Ve (SLPM)	RF (breaths /min)	**TV (@ 0°C) (Liters)**	**TV (@ 37°C) (Liters)**	**Actual Ve (SLPM)**
Capacity 3	Constant	Constant Throughout	1.35	1.15	30	18	1.67	**1.9**	**34.2**
Performance	Peak	5 minutes	3	3.2	65	25	2.60	**2.9**	**72.5**
	High	15 minutes	2	1.8	44	20	2.20	**2.5**	**50.0**
	Low	10 minutes	0.5	0.4	20	12	1.67	**1.9**	**22.8**

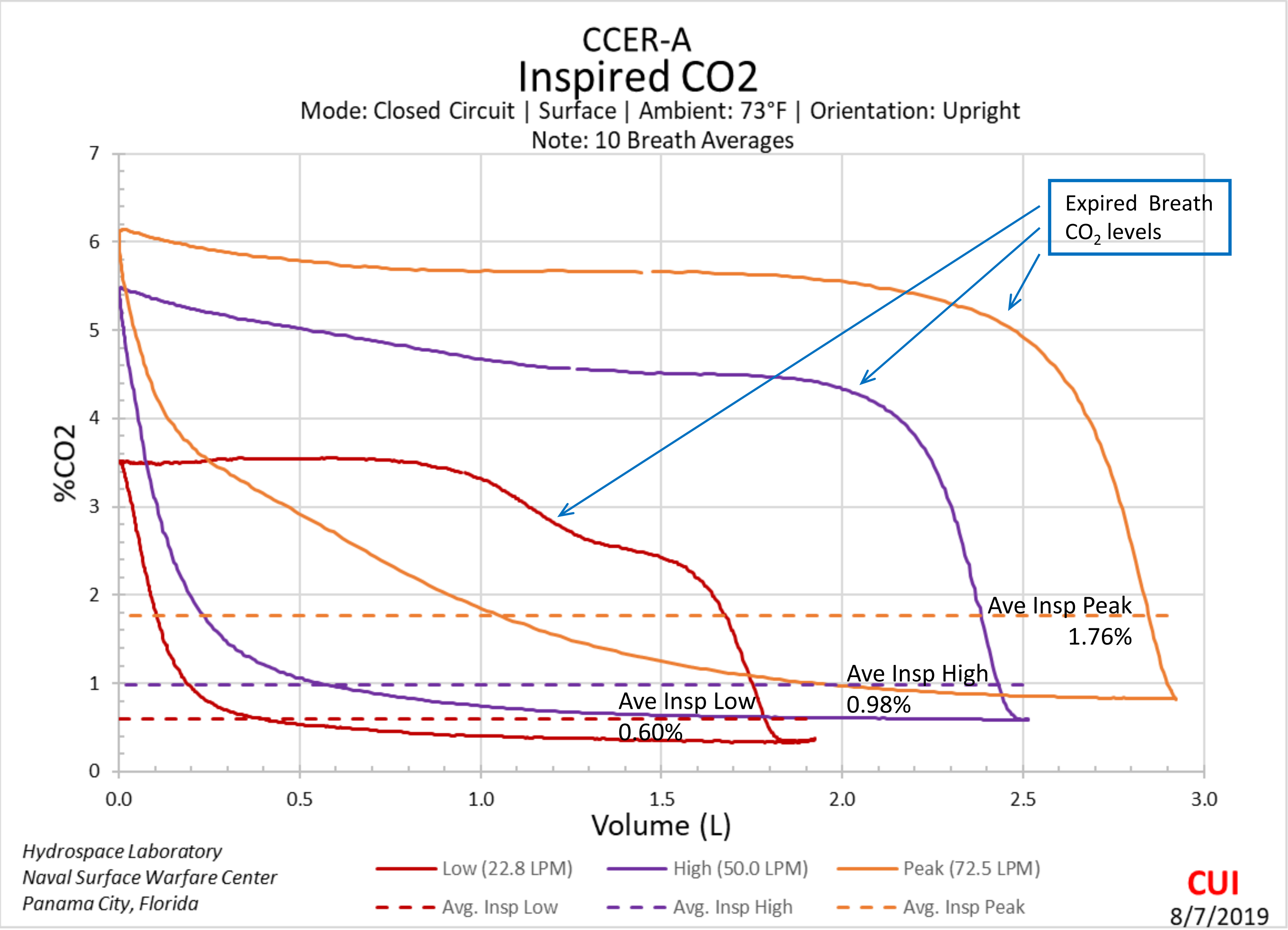
SLPM = Standard Liters Per Minute (0° C, 1 ata)
RF = Respiratory frequency
Ve = Ventilation rate
TV = Tidal volume

Results – Inspired Oxygen



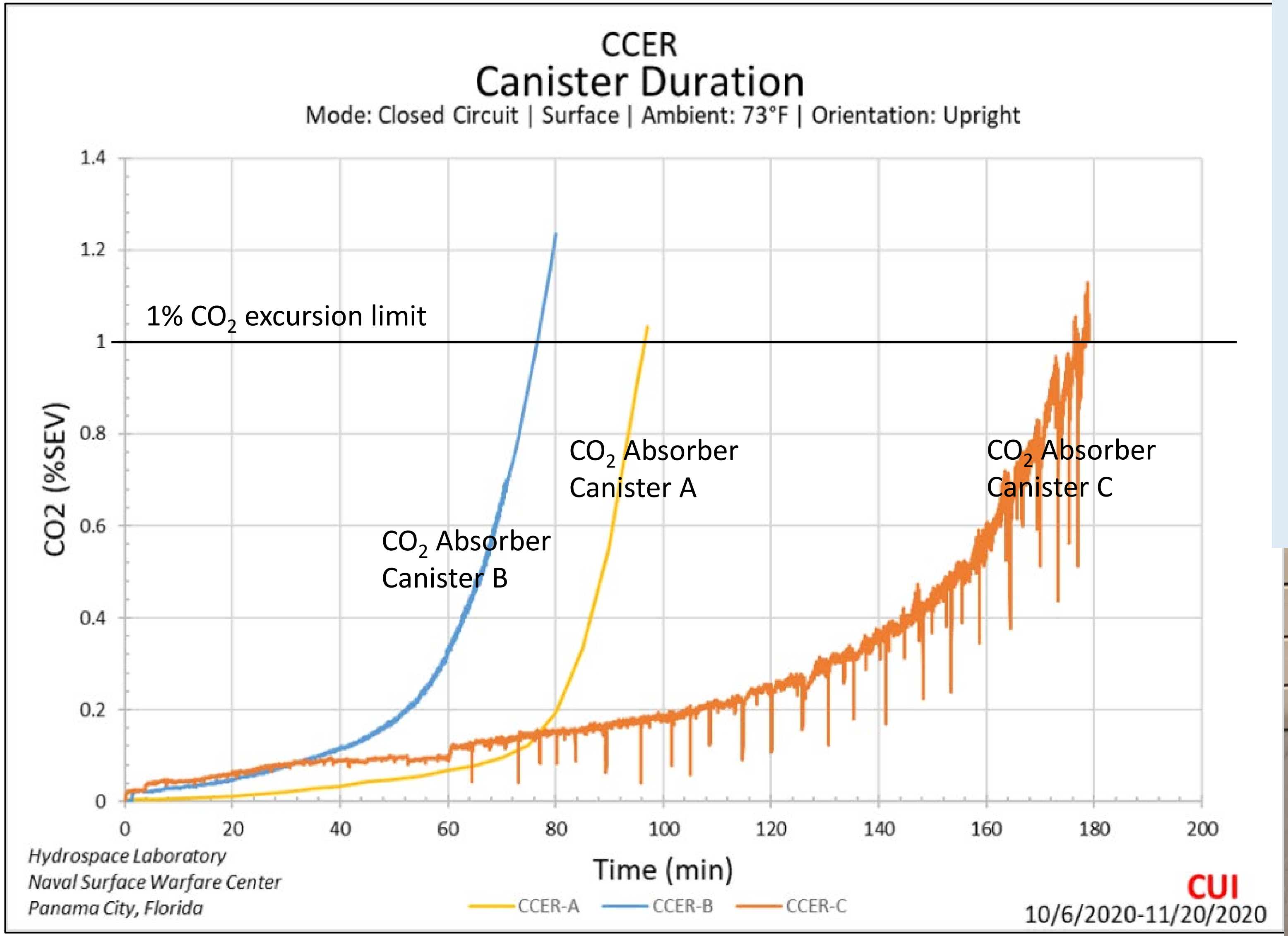
- At start, oxygen concentration is high, ~75% as the breathing loop is filled
- Average Inspired and minimum O_2% is within stressor limits for capacity test at VO_2 = 1.35 L/min
- Average Inspired and minimum O_2% (50.5% and 46.8%) does not fall below 19.5% for the performance test at peak, high and low VO_2

Results – Inspired Carbon Dioxide, Steady State



- Average Inspired CO_2% would be highest at the performance work rates
- Average Inspired CO_2% for the high and low work rates are well below the allowable operating average of 1.5%
- Peak work rate can only be sustained for a short time and the overall operating average will be less than the 4% excursion limit over the use time

Results – Carbon Dioxide Absorber Canister Duration



Chemical Carbon Dioxide Absorber durations to exceed the 1% CO_2 excursion limit

- **Canister A – 1hr 37mins**
- **Canister B – 1hr 17mins**
  Optimal canister size for a CAP3 – 81L CCER with about 22% reserve capacity
- **Canister C – 2hrs 58mins**
  Canister size too big for a CAP3 – 162L CCER but good for a CAP3 – 243L CCER with a slight increase in size

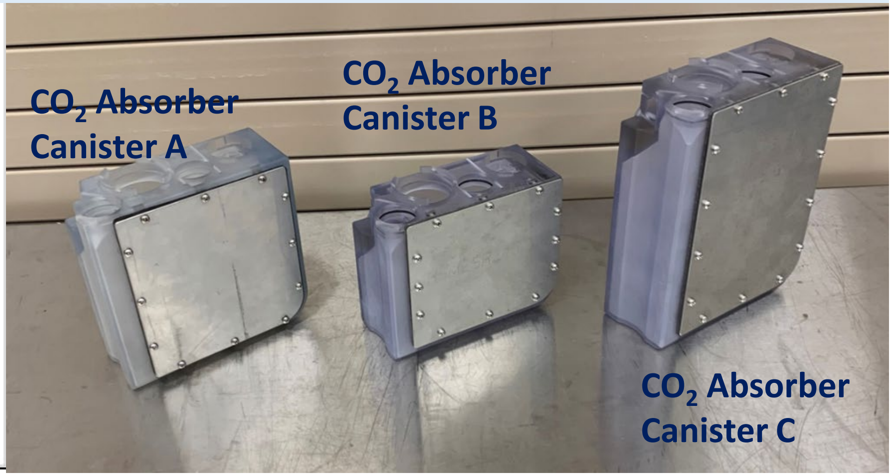
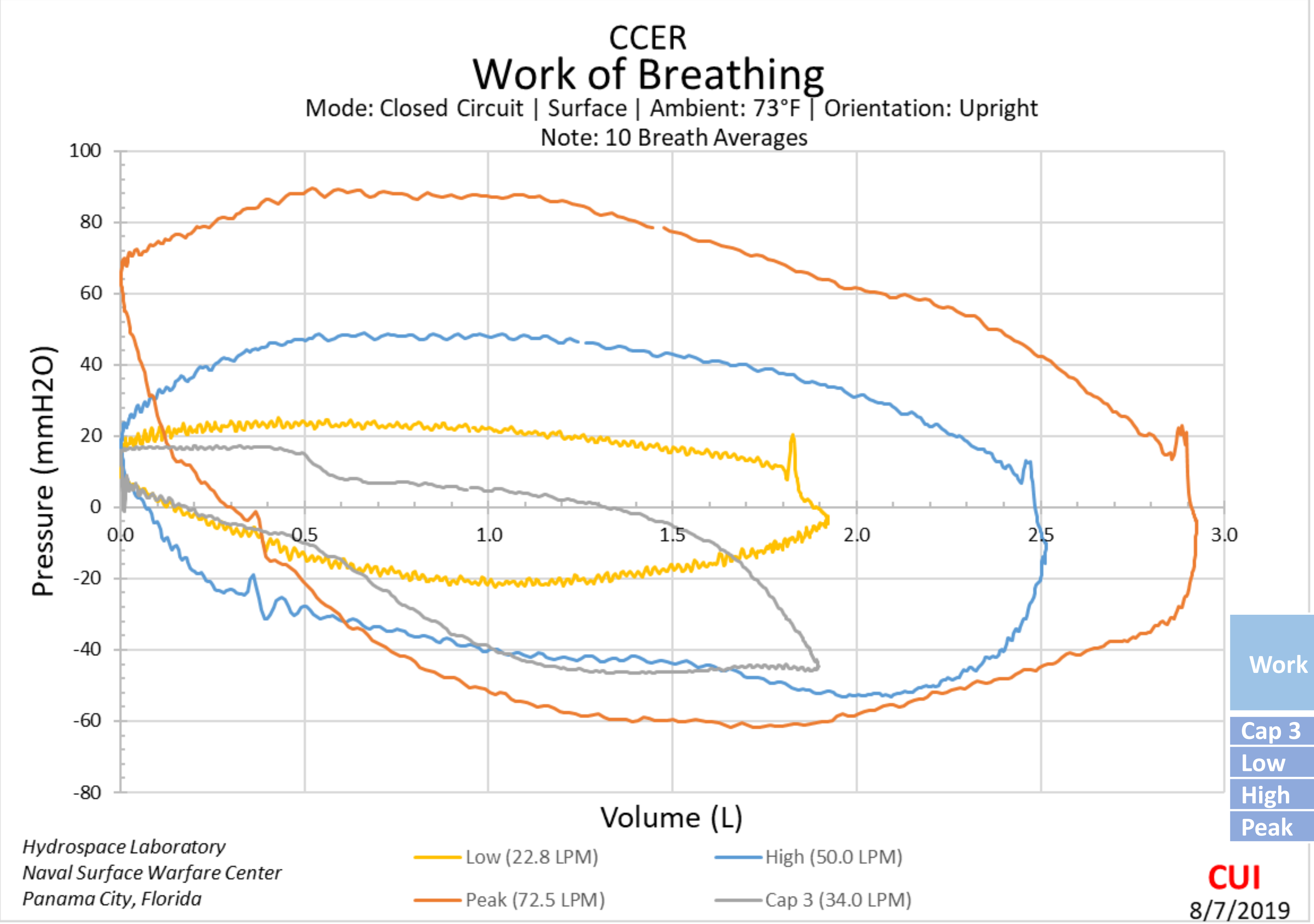


Photo courtesy of NSWCPCD

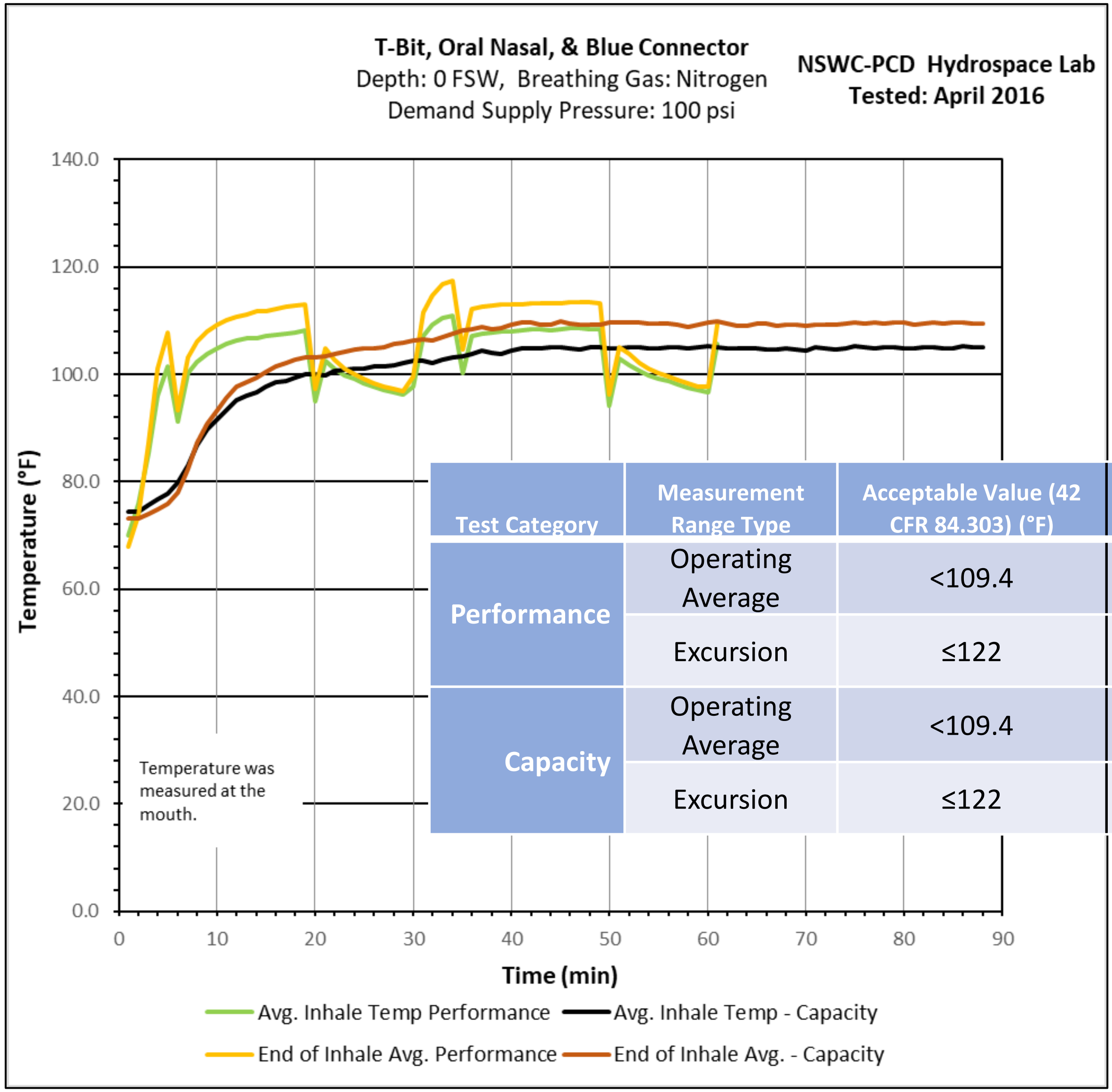
Results – Breathing Pressure



- All pressures fall within the acceptable stressor values
- Low, High & Peak performance work rates have similar waveforms
- Cap 3 work rate shows effect of exhaust valve and demand valve settings

Work Rate	Pressures (mm H_2O)			Work of Breathing (J/L)
	Minimum	Maximum	Peak-to-Peak	
Cap 3	-46.84	17.43	64.27	0.303
Low	-23.12	25.84	48.96	0.320
High	-54.15	49.98	104.14	0.736
Peak	-62.89	90.14	153.03	1.053

Results – Inspired Temperature



Test Category	Measurement Range Type	Acceptable Value (42 CFR 84.303) (°F)	Vol. Avg. Inspired Temp (°F)	Avg. Inhale Temp (°F)	Ambient (°F)
Performance	Operating Average	<109.4	102	102	73
	Excursion	≤122	112	112	73
Capacity	Operating Average	<109.4	101	101	73
	Excursion	≤122	105	106	74

- Tests conducted for CAP3 capacity and performance work-rates
- For more accurate temperature data stiffer exhaust valve used to minimize heat loss due to activation
- Main contributor to elevated temperatures in the breathing loop is the exothermic reaction of lithium hydroxide absorbent with the metabolically produced CO_2
- Both volume and time average temperatures were recorded and were below the stressor limits

Conclusions

- ICTPs allow optimizing breathing circuits of closed circuit respirators before fully developing the respirator for its intended purpose
- ICTPs can be quickly configured to test with different components in the breathing circuit
- ICTPs built for a CAP3 CCER as stated in 42CFR84-O yielded valuable data on metabolic parameters towards meeting set stressor limits
- Results from tests defined the component designs for CAP3-81 Liter and CAP3-162 Liter CCERs
- These ICTPs can be modified and configured to test closed and semi-closed breathing circuits in surface and underwater applications

National Personal Protective Technology Laboratory

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

Thank You

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