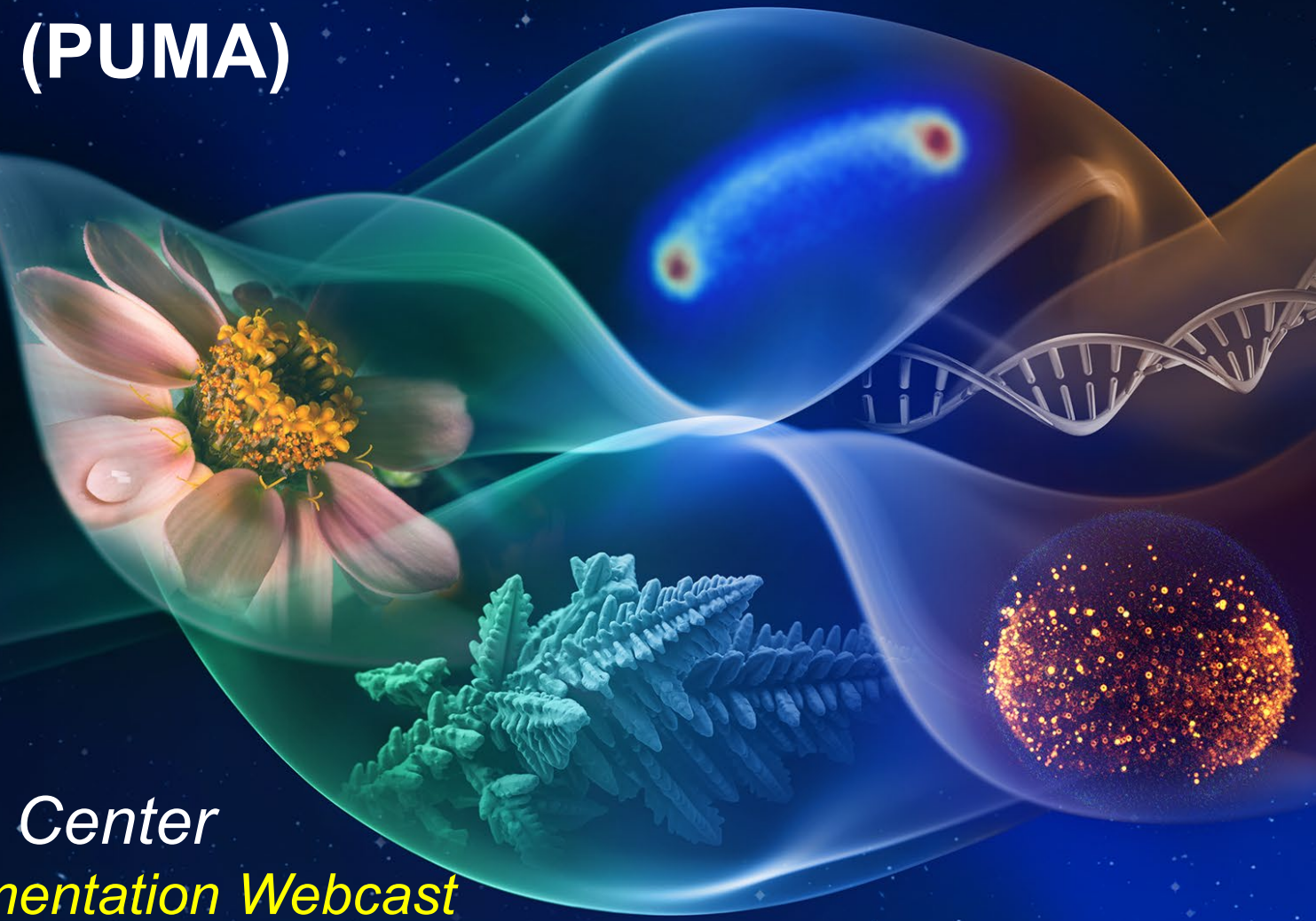
National Aeronautics and Space Administration

Development of a Portable Unit for Metabolic Analysis (PUMA)



Biological and Physical Sciences

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NESC Sensors and Instrumentation Webcast
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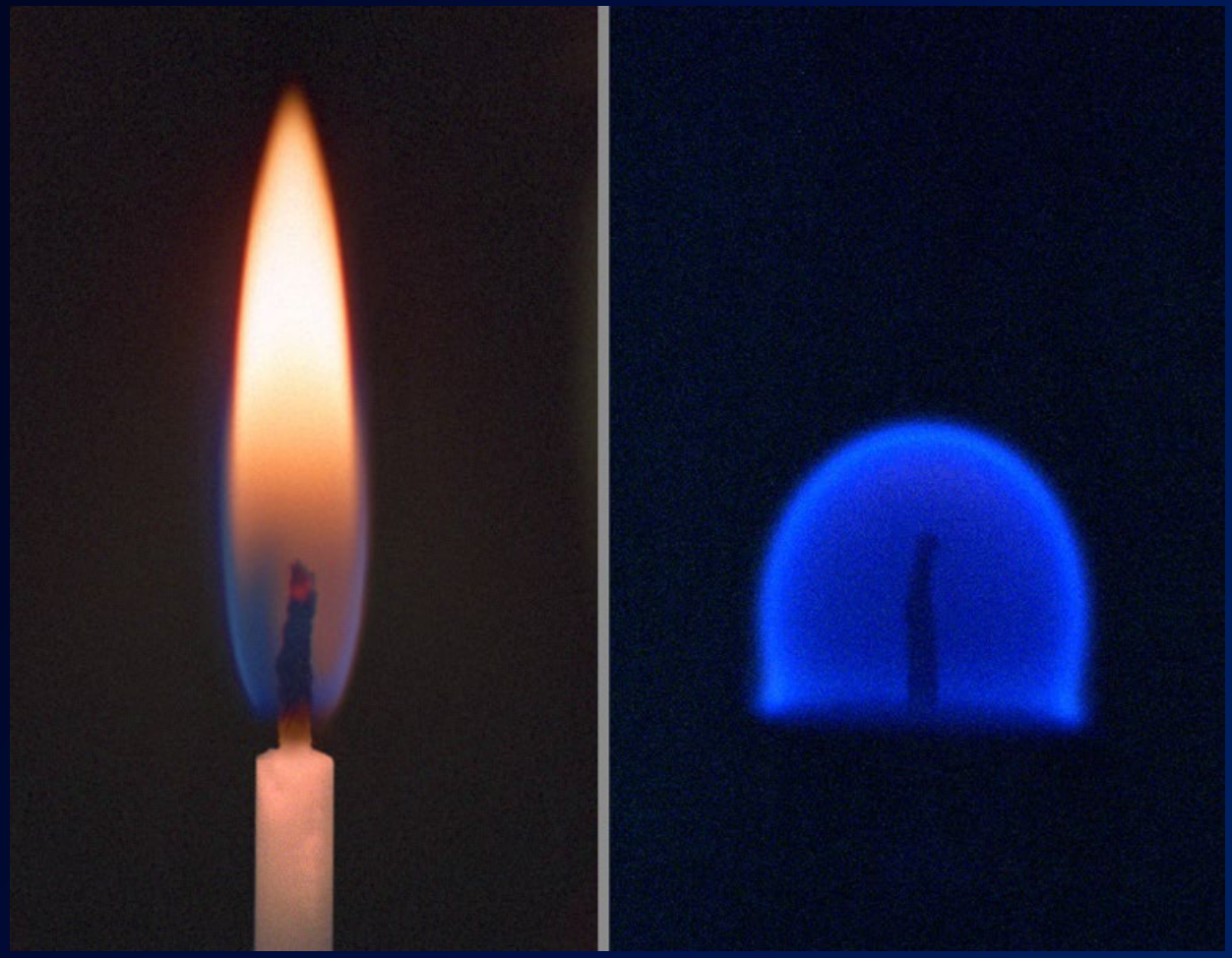
Background

- Long-standing question as to whether a candle flame can burn in a quiescent zero-gravity environment (spoiler alert: it can)
- Question centers on two related ideas
  - Oxygen diffusion is insufficient to sustain the flame
  - Combustion products (e.g. carbon dioxide) accumulate to extinguish the flame
- Definitive proof would be a candle experiment in a space-based platform where we measure
  - Oxygen (O_2)
  - Carbon Dioxide (CO_2)
- Develop instrumentation to measure O_2 and CO_2 in a spaceflight experiment



The experiment was cancelled, but can some of the technology and ideas can be re-purposed ?

Applications of Combustion Sensors

- If only there were another application for sensors that measured O_2 and CO_2
- What else consumes a hydrocarbon fuel along with O_2 to produce CO_2

Carbohydrate

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + (37*ATP)$$

Fatty Acid

$$C_{16}H_{32}O_2 + 23O_2 \longrightarrow 16CO_2 + 16H_2O + (130*ATP)$$

- Metabolic measurements are a clinically-proven method of monitoring fitness levels, energy expenditure, cardiovascular and pulmonary health and nutritional requirements
  - V_e – Minute Ventilation: Average expiratory gas flow (l/min)
  - V_{O2} – Oxygen Uptake: Average oxygen consumption (l/min)
  - V_{CO2} – Carbon Dioxide Output: Average carbon dioxide production (l/min)
- NASA has a wide range of needs for accurate physiological measurements

Intravehicular Activity (IVA)

- Astronauts lose bone and muscle mass
- Cardiovascular de-conditioning

- Exercise and pharmaceutical countermeasures
- Need to quantify the efficacy of countermeasures

- General-purpose medical diagnostic

Extravehicular Activity (EVA)

- **Temperature ranges from -200 to 200 F on the moon**
- **Carry all consumables on back (O_2 supply, CO_2 removal, thermal control**
- **All consumables tie directly to crewmember metabolic rate**
- **Accurate measurement of metabolic rate critical to mission safety and success**
  - Pre-EVA testing (fitness assessments)
  - In-situ during EVA
  - Develop *Smart Suit*

Project Objectives/Requirements

- Develop a portable unit that can accurately measure metabolic rate at rest, during exercise and in field environments.
  - Battery-powered, minimize mass and volume, self-contained, etc.
  - *Breath-by-breath* system.
  - Easy to use, minimal calibration or maintenance.
- Miniaturize critical sensors and locate close to inhale/exhale stream
  - Eliminate remote sampling and timing issues present on all commercial cart and portable metabolic units.
  - Requires high frequency response sensors
    - Capable of *within-breath* measurements.
    - Integrate flow and gas concentration data to get *breath-by-breath* measurements.
- Develop sensor technology and measurement algorithms that can be incorporated into future EVA suits to accurately measure instantaneous metabolic rate.

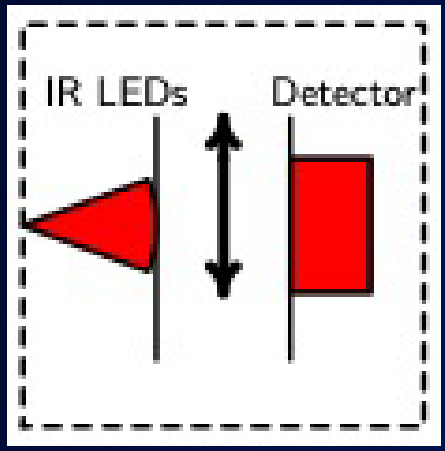
* Items in yellow are the requirements driving the avionics system design

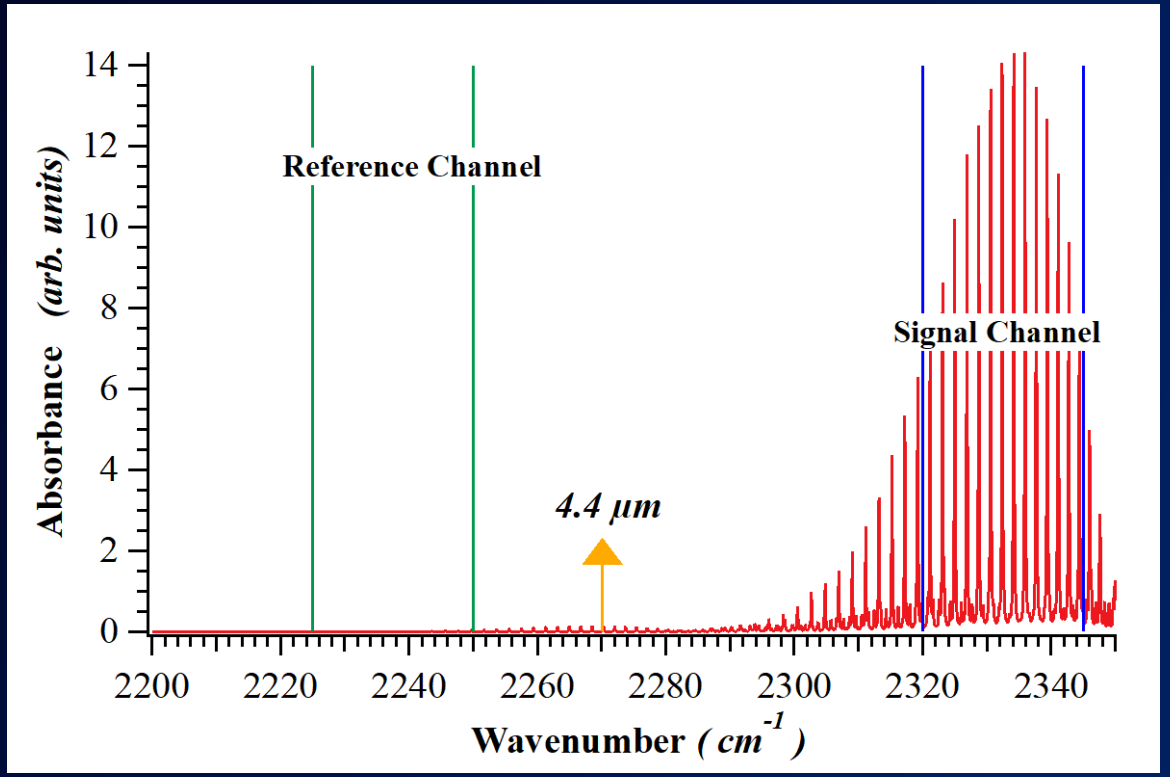
Required Measurements

- Pressure
  - COTS solutions meet requirements
- Temperature
  - COTS solutions meet requirements
- Volumetric Flow
  - Trade study of COTS and research technologies
  - Settled on custom-modified COTS technology
- Heart Rate
  - COTS solutions meet requirements
- Carbon Dioxide
  - Custom solution required
- Oxygen
  - Custom solution required
- Integration required custom solution

CO_2 Sensor Subsystem

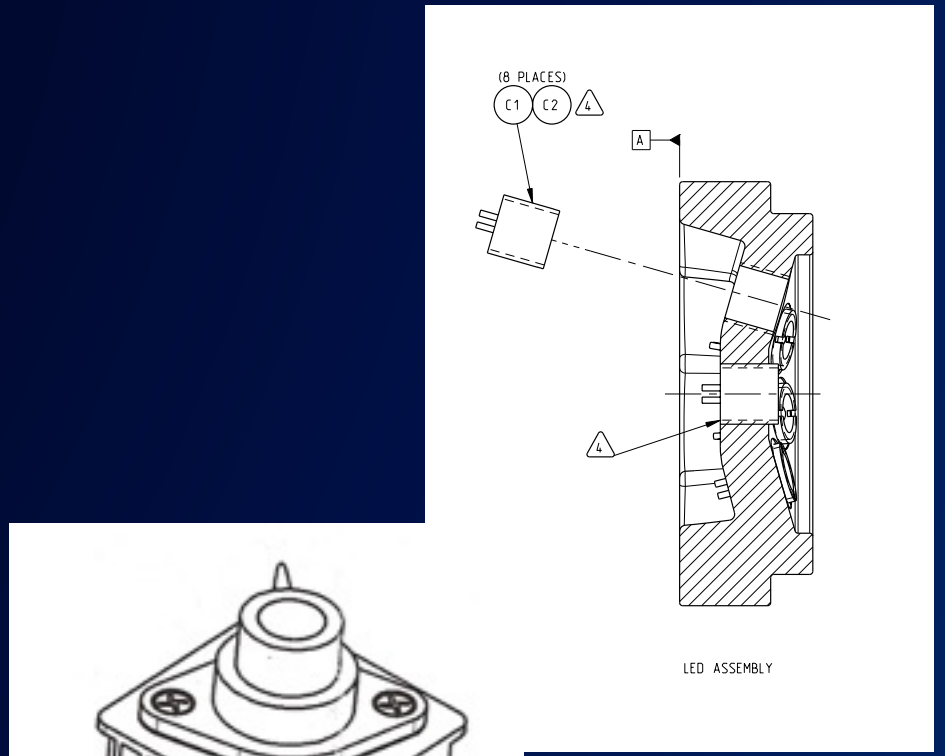
- Non-dispersive infrared absorption (NDIR)
- Uses the strong absorption band of CO2 around 4.3 μm
  - Almost no overlap from competing species (H2O)
- Initial design used incandescent light source and cooled detector
  - Heat from light source made detector unstable
- Chop the light source to reduce heat load to detector
  - Too much power consumption
- Use IR LED reduce power consumption
  - Not enough light on detector

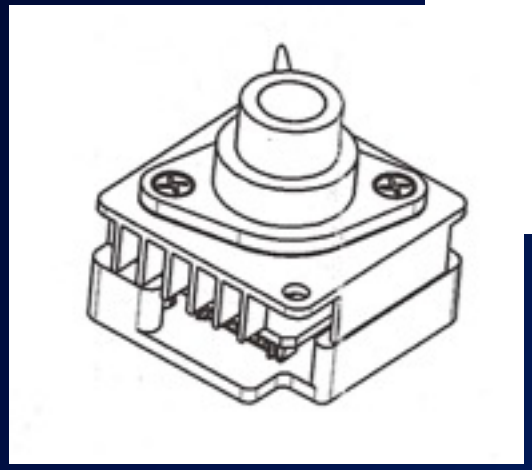




CO_2 Sensor Final Design

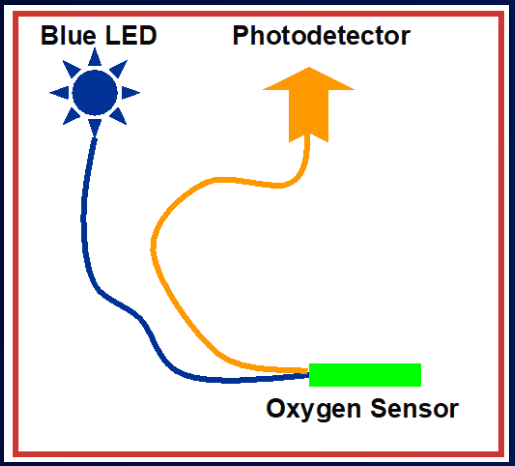
- Optimize optical pathlength
  - Longer pathlength – more absorption
  - Longer pathlength – more light divergence
- Cooled detector
  - Power consumption vs. S/N
- Use multiple IR LEDs focused on detector
  - Weak signal (poor S/N) if LEDs in continuous wave mode
- Pulse the LED bank at high current, low duty cycle
  - Optimize duty cycle for LED life vs. sensor performance
  - Need LEDs to achieve steady light output for long enough to get stable CO_2 reading
- *Final design had stable, accurate operation, reasonable power budget and good life expectation*

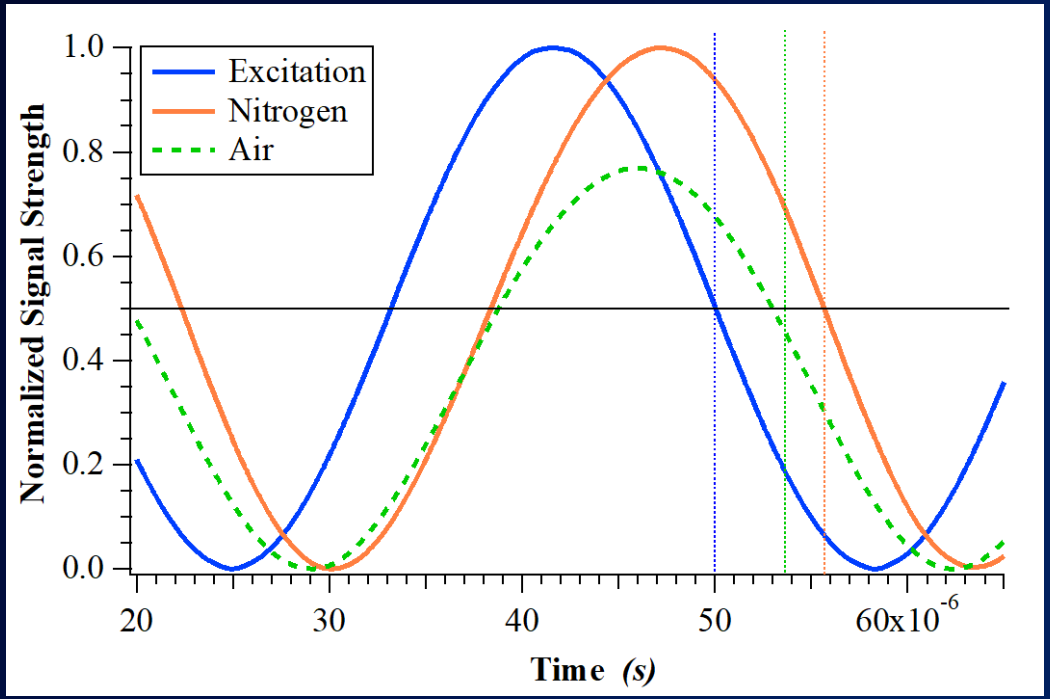




Oxygen Sensor Subsystem

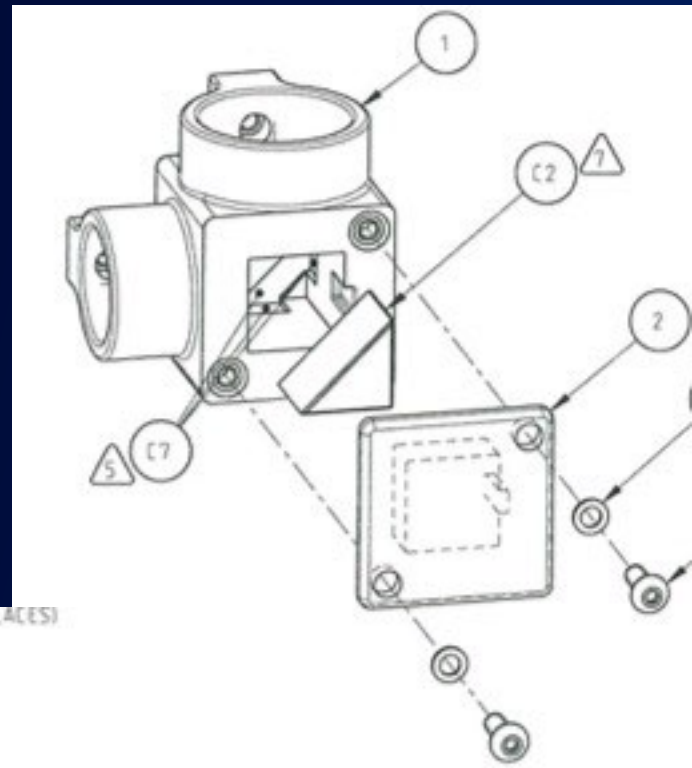
- Candle flame experiment investigated COTS oxygen sensor
  - Oxygen-induced quenching of fluorescence from ruthenium-based dye
  - Used absolute intensity of fluorescence
    - Poor stability and repeatability
    - Frequent (constant) calibration
- The fluorescence is phase-shifted relative to incident light if source is modulated
  - Modulation characteristics – wave shape, frequency, etc.
- Design optimization
  - Signal strength vs. S/N
  - Photobleaching
  - Dye lifetime
  - Calibration frequency
  - Temperature correction

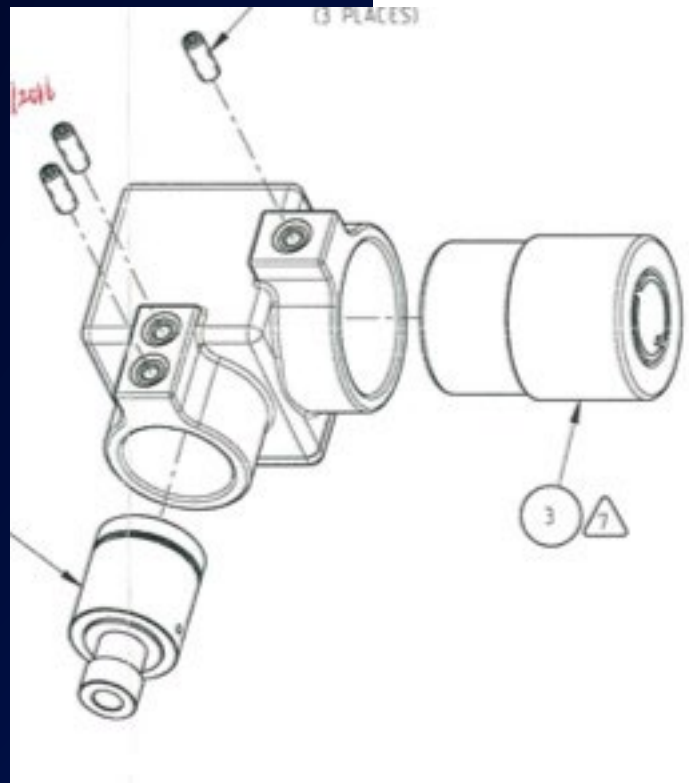




O_2 Sensor Final Design

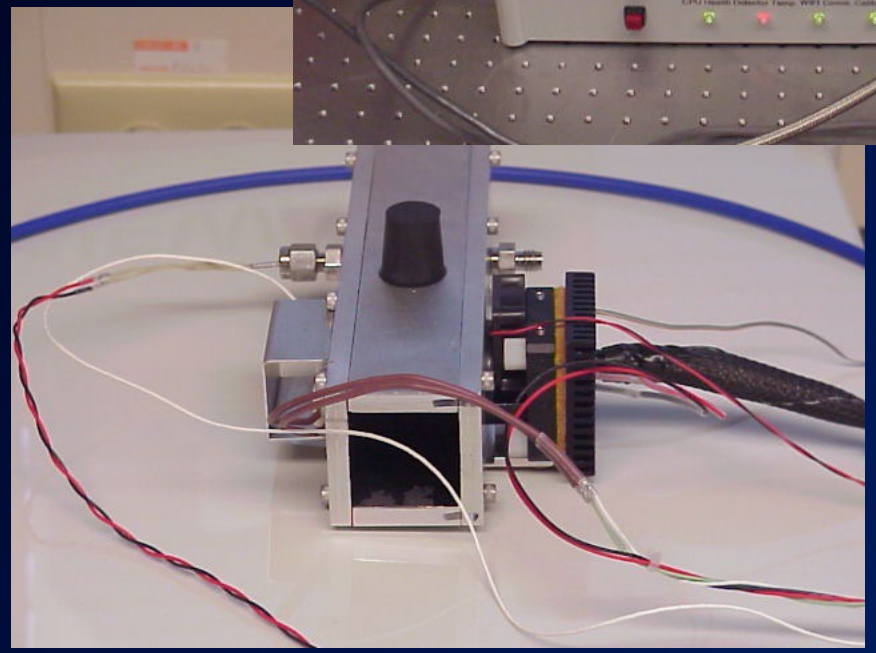
- Light source a blue LD sinusoidally modulated at 40 kHz
  - Mounted in avionics box and fiber-optically coupled to the head gear
  - Rhuthenium-dye disk mounted in the flow tunnel
  - Fast response t/c mounted next to disk
- Fluorescence signal travels back to avionics box via the fiber optic cable
- Fiber-optic splitter and filter to separate source and fluorescence signal
- Sensor modulated to mimimize photobleaching
  - Relatively weak signal with low S/N
- Custom software algorithm to deconvolute weak fluorescence signal





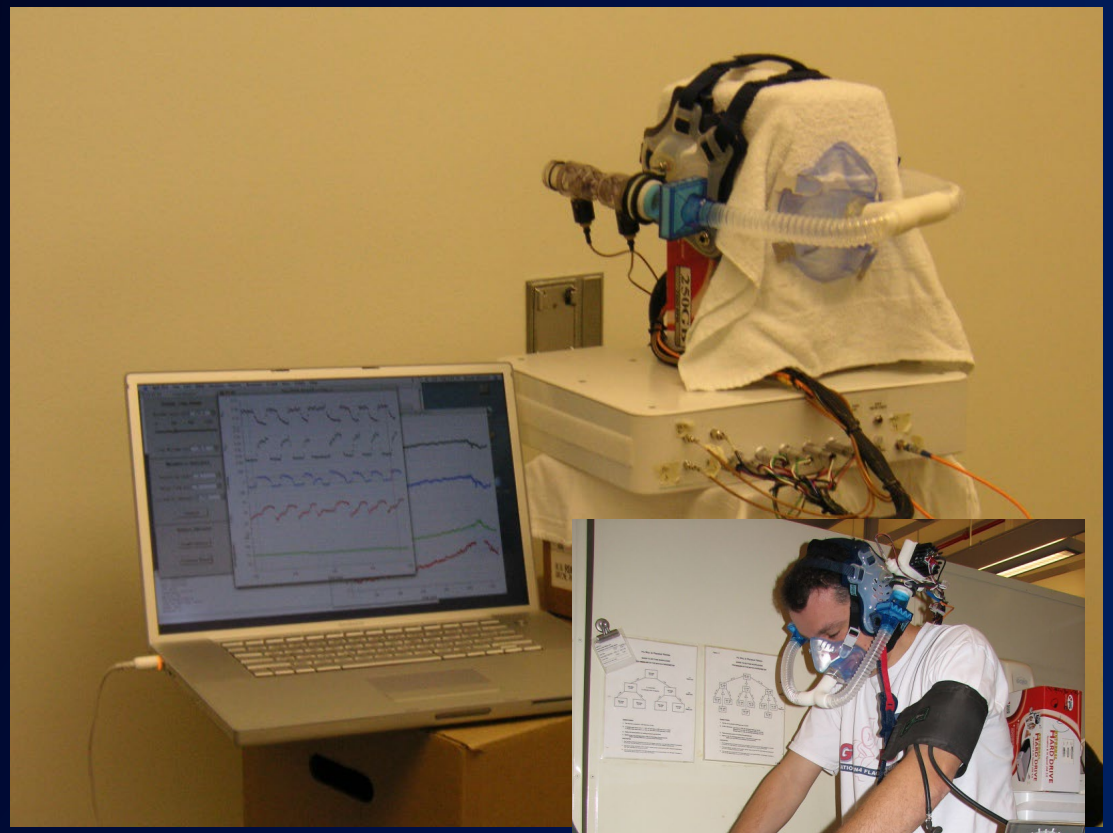
Integrated System Design Evolution - 1

- First integrated system design the size of a small suitcase
  - AC powered
  - Individual sensor boards communicate with single processor
- Large aluminum flow tunnel with sensors mounted
- All measurements made simultaneously
- Used to test and optimize sensor design



Integrated System Design Evolution - 2

- Design evolved to a single box the size of an old VCR player
  - Battery powered
  - Single, single layer board
- Further sensor characterization and optimization
- Software interface to user
  - Physiologists want to see real physiological data
- Human subject testing
  - IRB approval

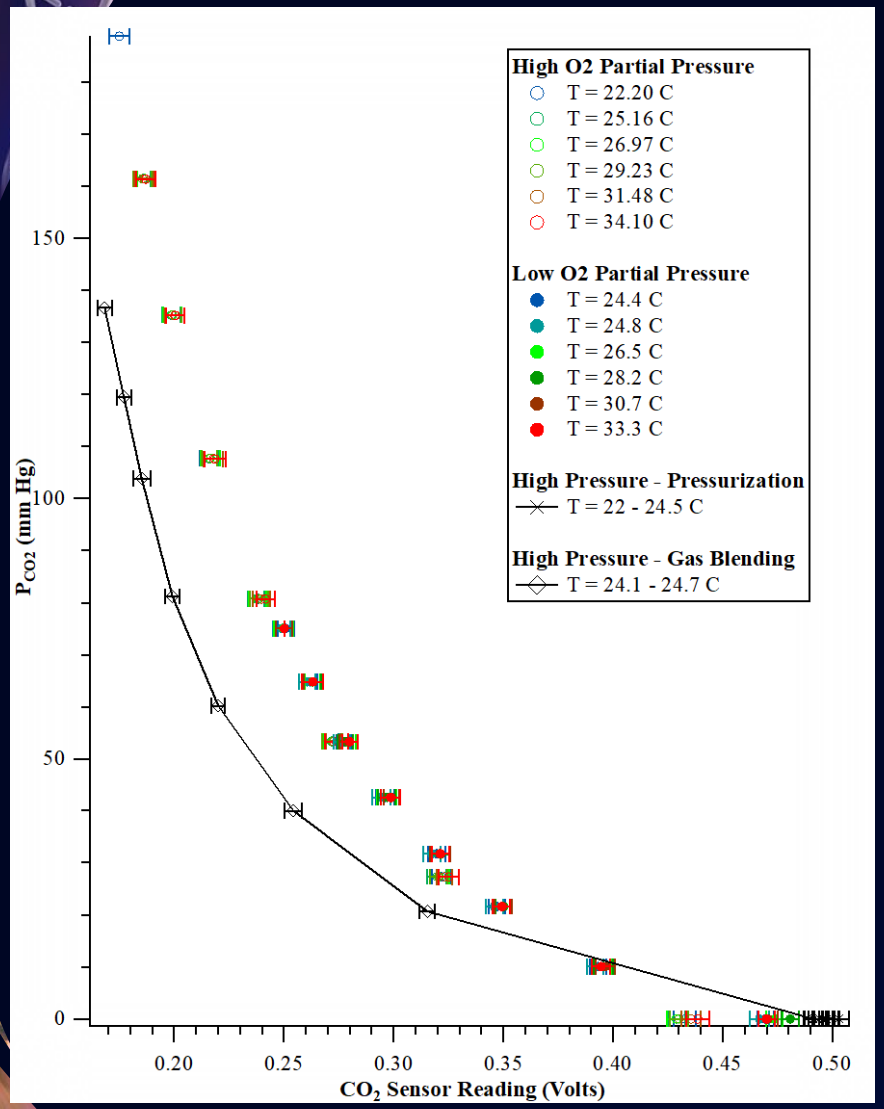


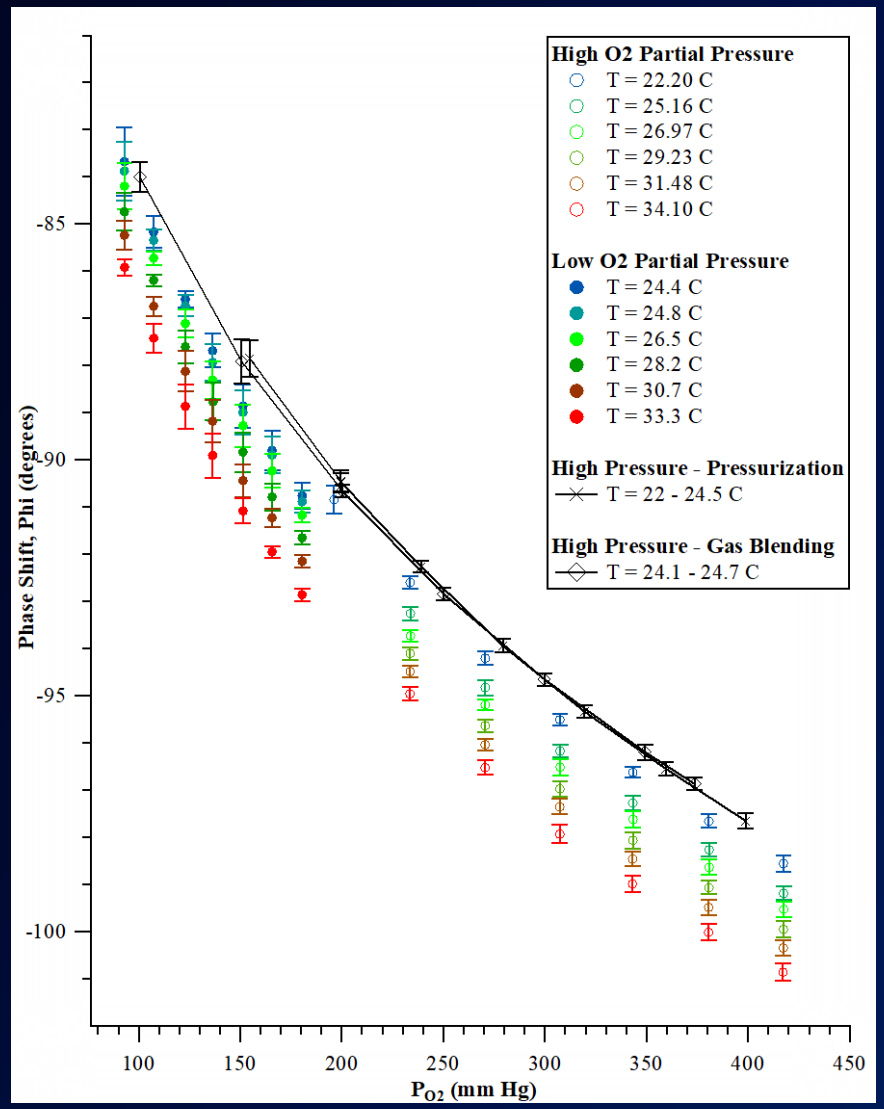
Integrated System Design Evolution - 3

- Third iteration
  - Battery powered – 4 hr life
  - Bluetooth connection to laptop
  - Avionics box fits in Camelback with hydration bladder removed
  - Optical/electrical tether to headgear
- System characterization
- Human subject testing
  - IRB approval

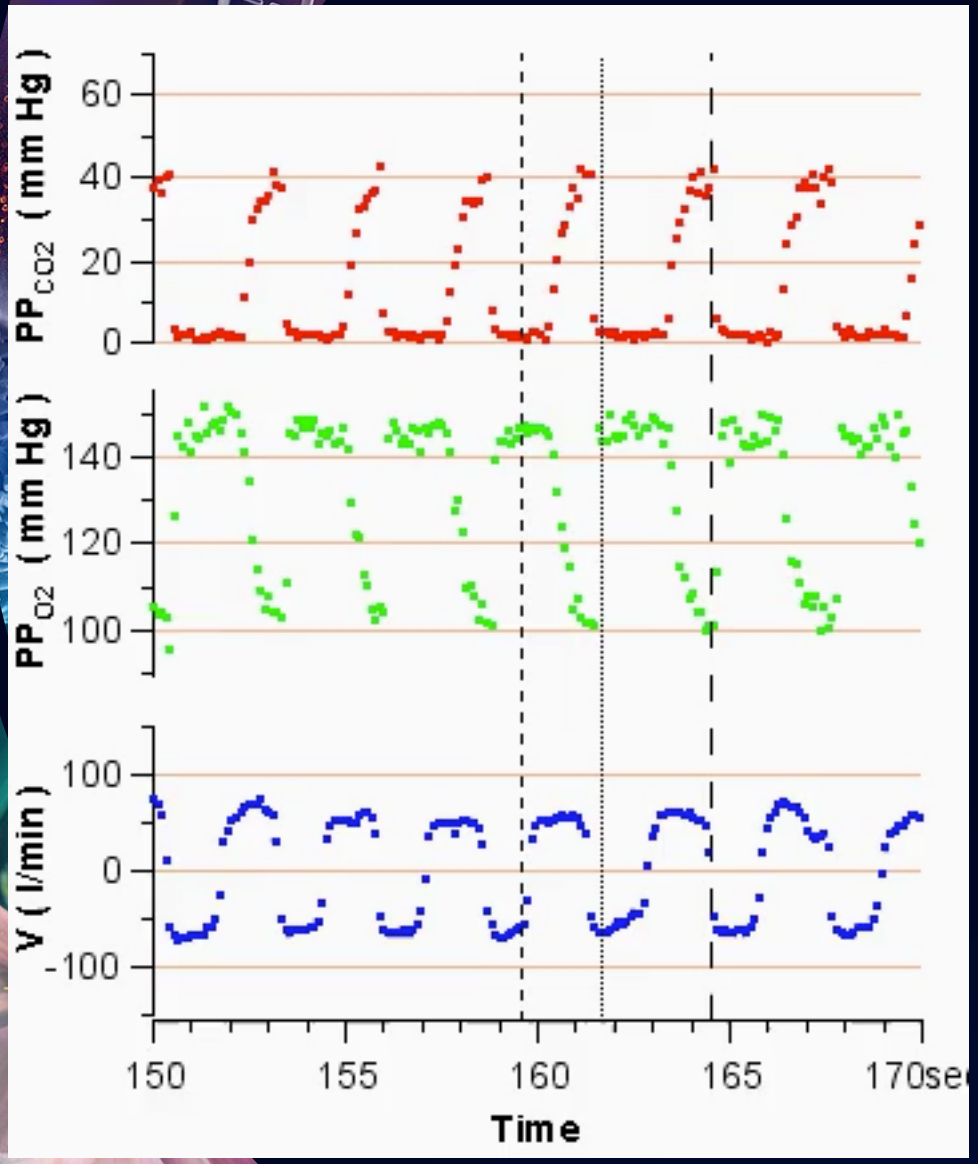
PUMA-3 met, and typically exceeded all initial design requirements !!!

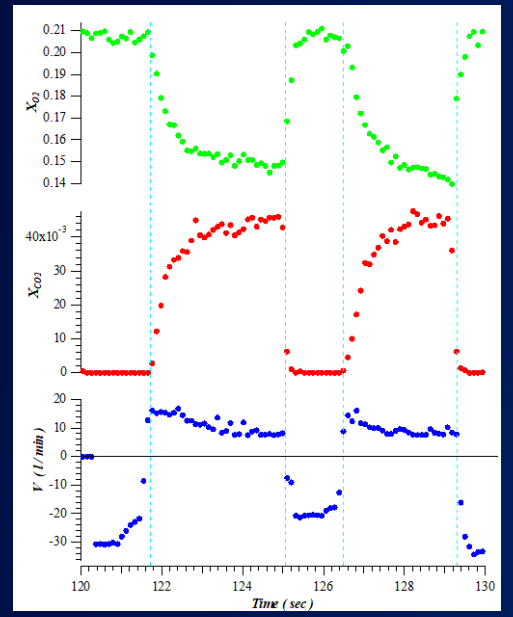
Sensor Characterization





Getting Physiological Data





- Integrate time-resolved flow and concentration data over each breath to get *breath-by-breath* data:

$$\dot{V}_e = \frac{\int_{t_{be}}^{t_{ee}} \dot{V}(t)\,dt}{(t_{ee} - t_{bi})}$$

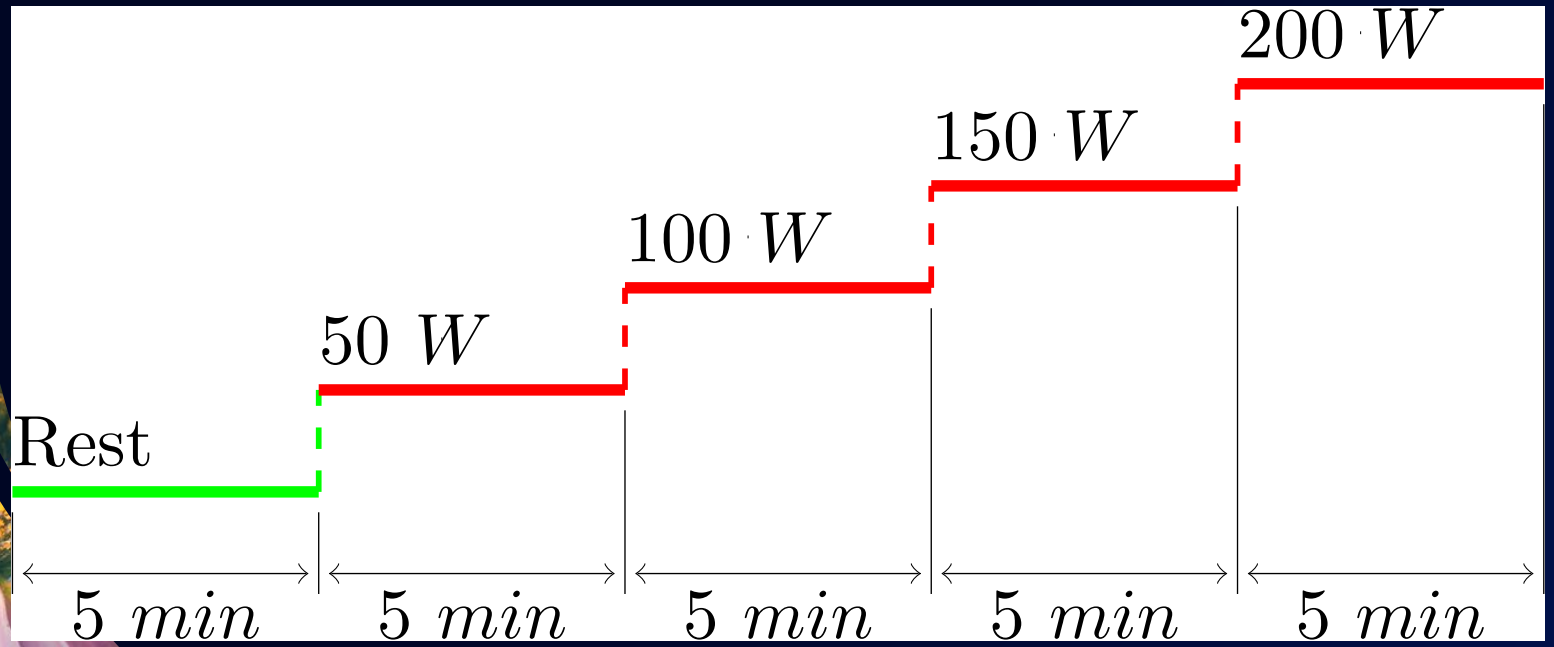
$$\dot{V}_{O_2} = \frac{\left[\int_{t_{bi}}^{t_{be}} \dot{V}(t)\ X_{O2}\,dt\right] - \left[\int_{t_{be}}^{t_{ee}} \dot{V}(t)\ X_{O_2}\,dt\right]}{(t_{ee} - t_{bi})}$$

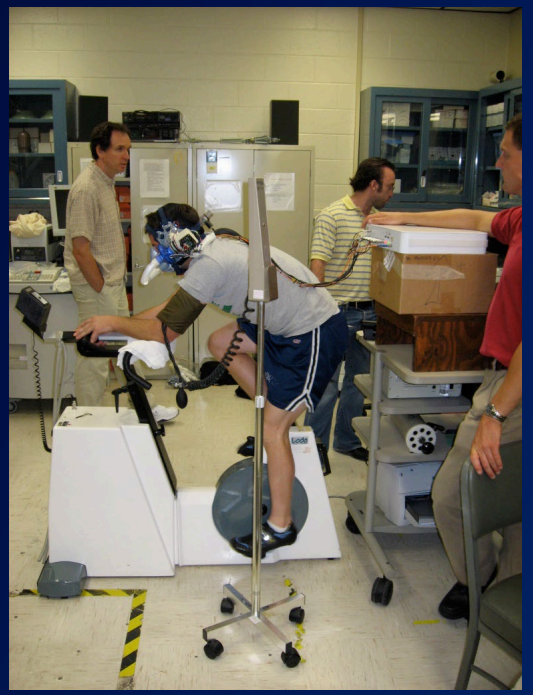
$$\dot{V}_{CO_2} = \frac{\int_{t_{be}}^{t_{ee}} \dot{V}(t)\ X_{CO_2}\,dt - \int_{t_{bi}}^{t_{ei}} \dot{V}(t)\ X_{CO_2}\,dt}{(t_{ee} - t_{bi})}$$

- PUMA measures both inspired and expired data eliminating the need for the Haldane correction.

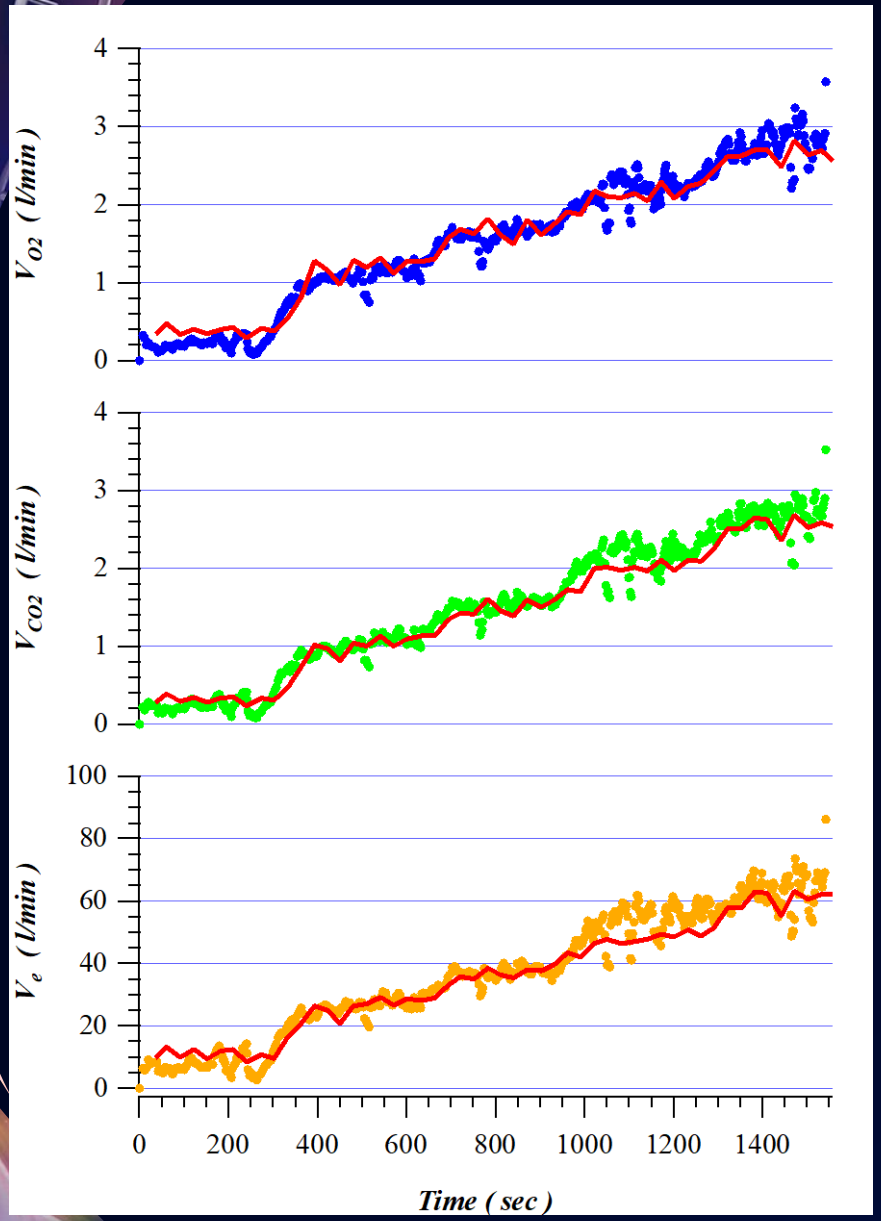
Yeah, but does it actually work ?

- Tested PUMA (PUMA-2) and ParvoMedics TrueOne 2400 metabolic cart on consecutive days
- All tests were sub-maximal and performed on a Lode Excalibur Sport cycle ergometer.
- All testing approved by the JSC CPHS. Test subjects received written and verbal explanations of testing protocols





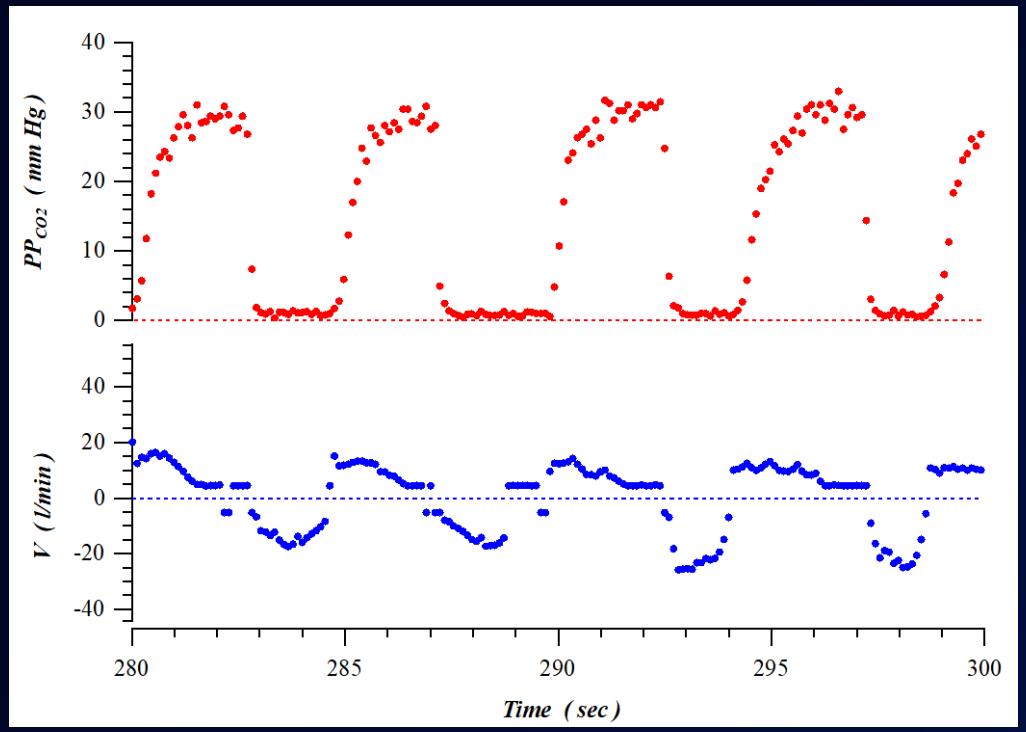
Benchmark Test Results



- Good correlation between the PUMA and ParvoMedics.
  - PUMA can accurately measure V_{O2}, V_{CO2} and V_e
  - More test subjects required to draw statistical conclusions
- The PUMA resting V_e is a bit higher than the ParvoMedics.
  - Different technology for flow.
  - PUMA software improvements.
- PUMA data displays a bit more scatter than ParvoMedics data.
  - ParvoMedics samples from mixed gas volume.
  - PUMA software improvements.

Field Testing - NEEMO

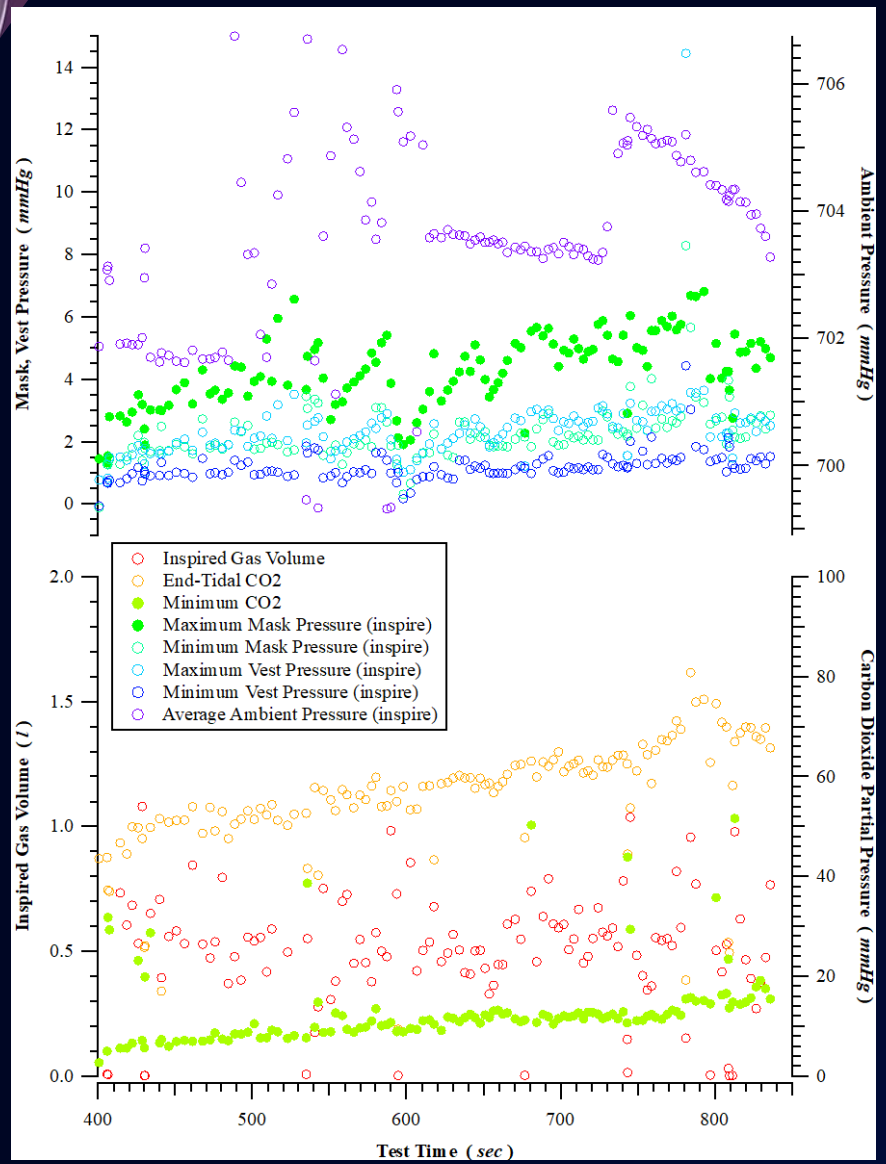
- PUMA used to measure resting metabolic rate during the NEEMO-12 and NEEMO-13.
- All PUMA sensors calibrated up to the Aquarius working pressure (2.5 atm)
- Crew trained to operate PUMA (30 minutes training)

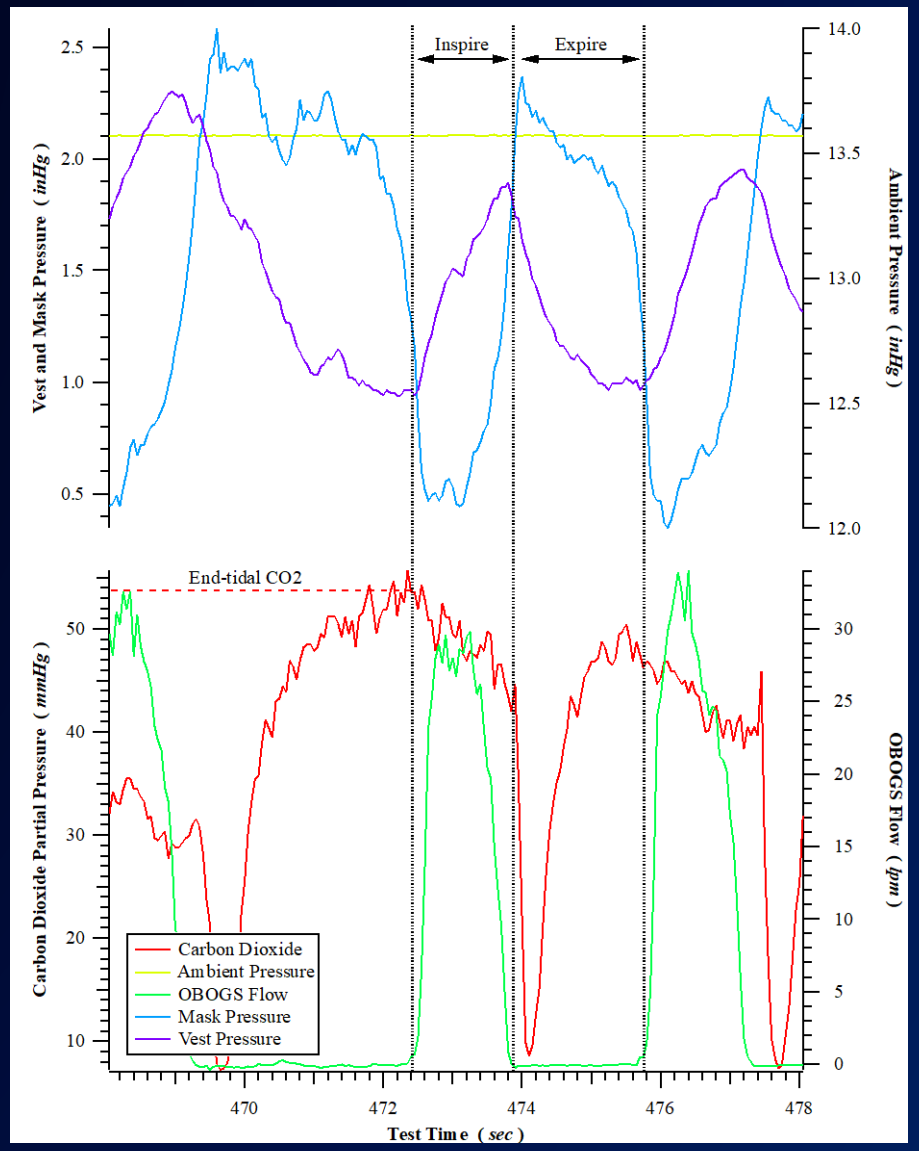


Pilot Breathing

- Collaboration with SBIR company to develop instrumentation to measure in-flight pilot physiology
- Funding from Navy and Air Force
- Built hardware for Lockheed-Martin/Air Force
- Over 50 flights on F-22

F-22 Sample Data



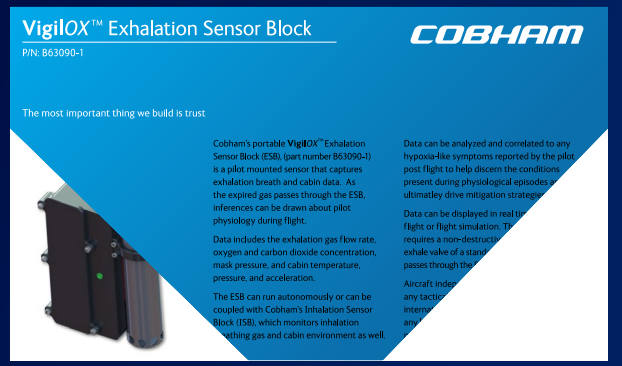


Pilot Breathing Assessment (PBA)

- 2012 NESC asked to investigate UPEs in USAF F-22
- 2017 NESC asked to investigate increase in UPEs in USN F/A-18 and E/A-18 aircraft
- Conclusion from both studies was the need to instrument the pilot

- NASA collaboration with SBIR company to develop pilot-mounted instrumentation to measure physiological state
- Cobham purchased technology in ~2016 and developed VigilOX

- 2018 NESC initiates the Pilot Breathing Assessment (PBA). Multi-year study to fly VigilOx equipped NASA pilots and NASA aircraft to better understand in-flight pilot physiology
- https://www.nasa.gov/centers/armstrong/features/pilot-breathing-assessment-program-completes-final-phase.html
- Used PUMA breath-by-breath analysis methods to help understand data



Summary

- The origins of PUMA were in sensor development for an experiment to study candle burning in microgravity
- The goal of PUMA was to develop a portable unit to measure human metabolic function
  - Small, portable, battery-powered
  - Easy to use, no elaborate calibrations
- The design of PUMA required innovations in avionics design
  - S/N vs. sensor lifetime
  - Power consumption vs. S/N
- The evolution of the PUMA avionics occurred in stages
  - Individual sensor designs using COTS lab equipment
  - Individual sensor boards in a single unit
  - Integrated sensor boards with battery power
  - Optimized, integrated system
- The final design met or exceeded all initial requirements/objectives
- The individual elements all worked together as a fully-functional metabolic unit
  - Limited Human Subject Testing confirmed functionality
- PUMA technology (hardware and software) an instrumental part of the NESC Pilot Breathing Assessment