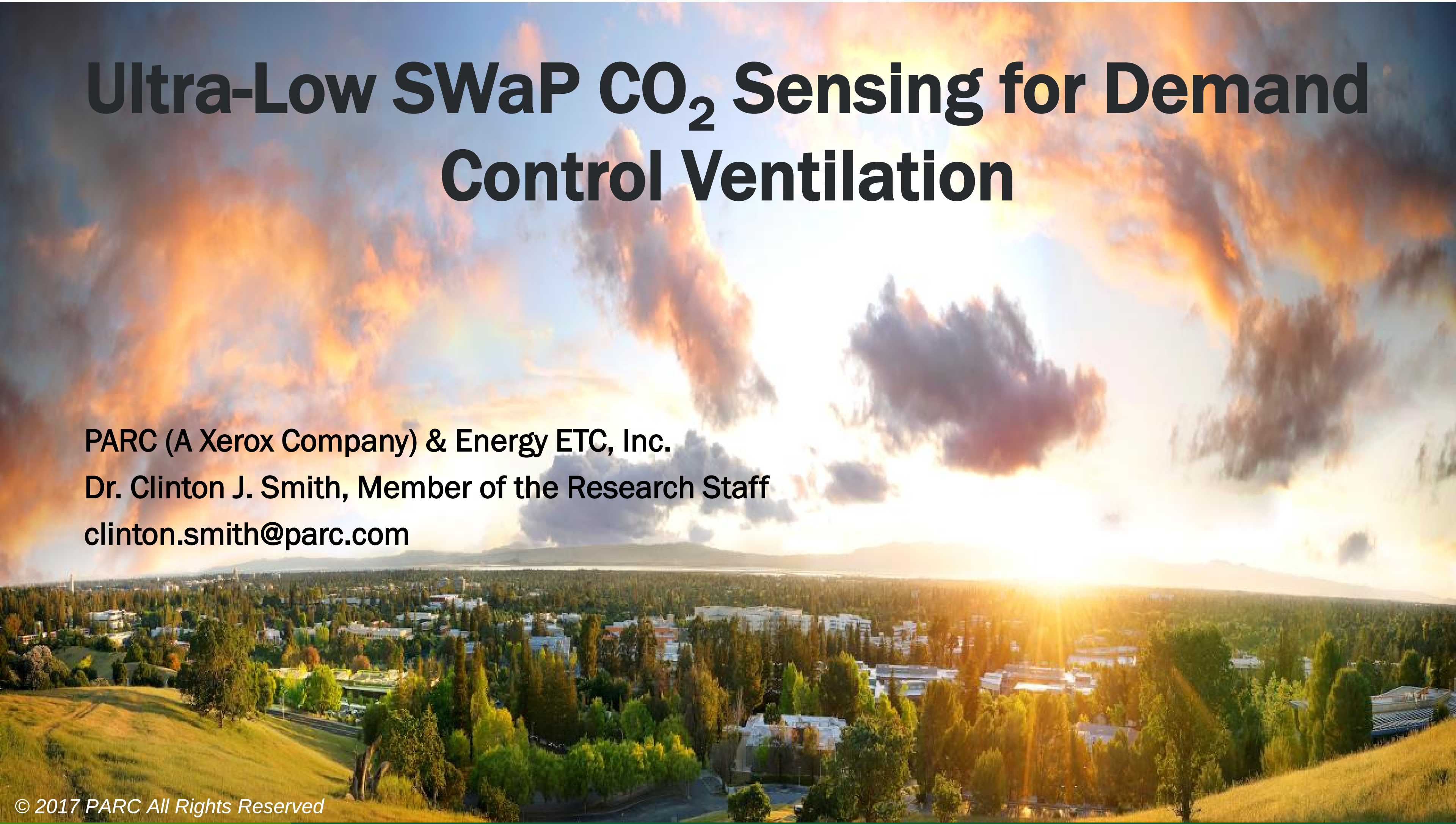

Ultra-Low SWaP CO_2 Sensing for Demand Control Ventilation

PARC (A Xerox Company) & Energy ETC, Inc.
Dr. Clinton J. Smith, Member of the Research Staff
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Project Summary

Timeline:

Start date: 1/1/18

Planned end date: 6/30/19

Key Milestones:

1. CO_2 sensitivity <100 ppm; range of 100-2000 ppm demonstrated under expected operating conditions. (Month 13)
2. CO_2 measurement precision <50 ppm and drift <50 ppm/year (Month 18)

Budget:

Total Project $ to Date:

- DOE: $56,074
- Cost Share: $14,018

Total Project $:

- DOE: $500,893
- Cost Share: $125,223

Key Partners:

energy etc

efficiency - technology - connectivity

Project Outcome:

- Ultra-low cost, size, weight, and power (SWaP) printed CO_2 sensor system
  - Occupancy detection
  - Enable DCV on a per-room basis
- Improve energy efficiency and facilitate healthy indoor air quality (IAQ)
- Effective DCV can lead to a nationwide savings estimate of **~0.38 Quad**.

(https://www.eia.gov/consumption/commercial/reports/2012/buildstock/)

Team

parc®
A Xerox Company

open innovation, printed & flexible electronics, ML, sensor systems, RF

- Clinton Smith, Ph.D. (PI)
- Austin Wei, Ph.D. (materials)
- Mahati Chintapalli, Ph.D. (materials/characterization)
- Joseph Lee (circuit design & layout)
- Elif Karatay, Ph.D. (thermal modeling, design)
- Eric Cocker, Ph.D. (data analytics, DoE)
- Victor Nguyen (embedded software development)
- Frances Yan (Industrial Design)

energy etc
efficiency - technology - connectivity

Supplier-agnostic BMS integration leader

- Rick Costanza (Co-owner, VP Operations)
- Brian Schroeder (Director of Engineering)

Challenge

To ensure healthy air quality, buildings are over-ventilated by 6 × required rates*

Up to 18% energy savings are available through greater DCV adoption: up to 0.4 Quad/yr**

BUT

Gas (CO_2) sensors are expensive, inaccurate; occupancy sensors are unreliable or violate privacy

AND

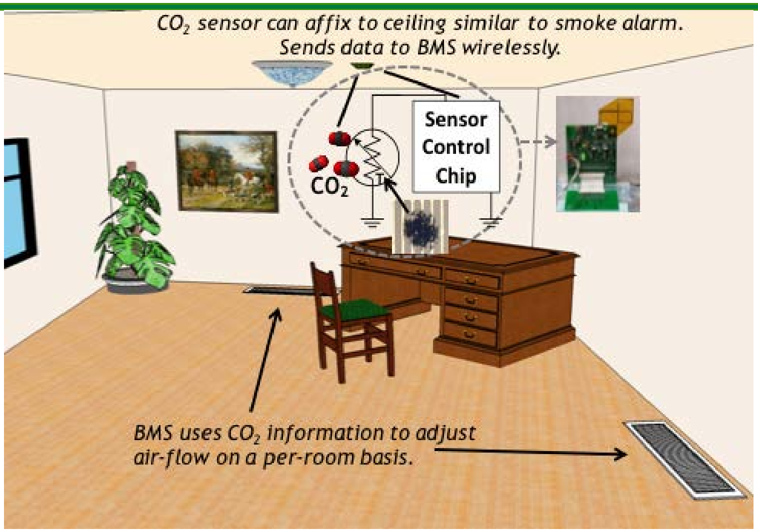
Existing platforms that can measure IAQ *en suite* for indoor comfort are cost prohibitive

Solution: Printed low-cost, sensitive, accurate, CO_2 sensor to enable per-room feedback for DCV

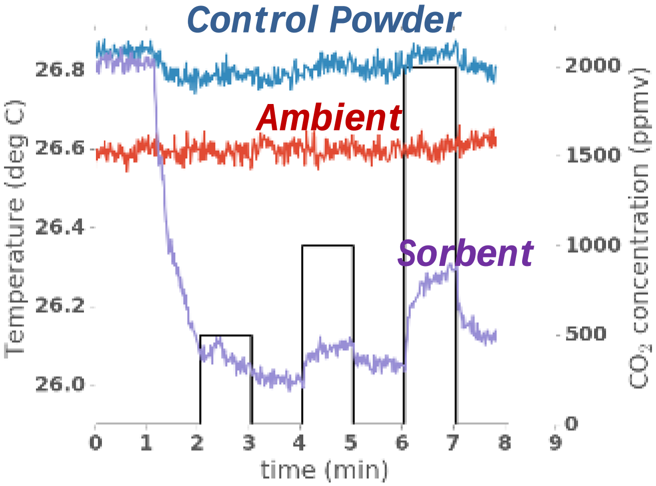
*Persily, A. et al. Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study (2004).
**Zhang, J. et al. Pnnl-22072 1–79 (2013).

Approach

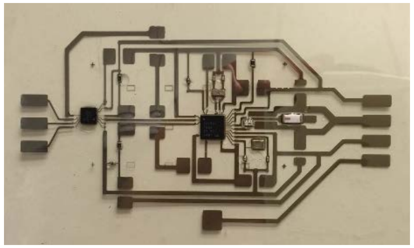
- Printed sorbent detects ppm-level CO_2
    - Costs pennies → $15 installed cost
        - Flexible form factor
    - Commercial optical devices cost ~$100
- Utilize heat of adsorption for self-calibration
- Designed to be plug-and-play for integration with existing BMS
- Integrate into PARC's growing gas sensing IoT technology platform
- Integration into the BMS at PARC's facility for prototype validation

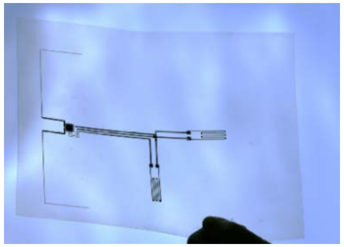

CO_2 sensor can affix to ceiling similar to smoke alarm. Sends data to BMS wirelessly.

BMS uses CO_2 information to adjust air-flow on a per-room basis.



Data

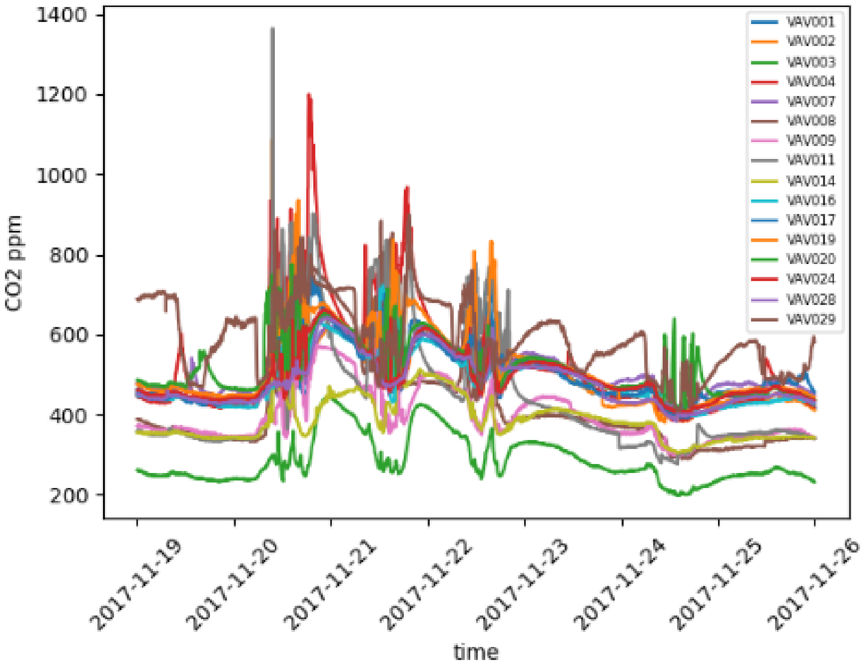




Impact

- Expected 1.2 year payback based on energy cost savings
- Have observed commercial sensors to drift by ±200 ppm
  - BMS CO_2 threshold settings vary from 600 – 800 ppm
  - Not actively utilized due to over ventilation
- Accurate CO_2 sensor will enable less ventilation without exceeding ppm limit
- Platform extensible to overall indoor air quality monitoring without added cost
  - Healthier environment, increased comfort

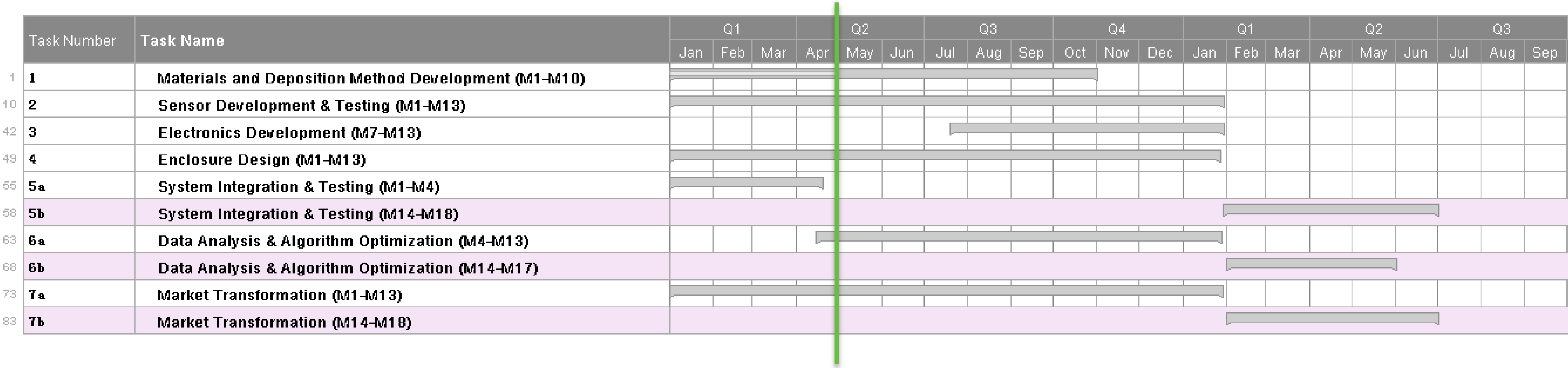
Commercial	
	HVAC
Cost/sensor tag ($)	$15.00
Area covered by base station (sq. ft.)	2000
Sensors/base station	20
RF hub installed cost ($)	$80.00
System installed cost ($/sq. ft.)	$0.19
Baseline energy use (kWh/sq. ft./y)	8.0
Energy cost ($/kWh)	$0.11
Projected energy savings (%)	17.8%
Energy cost savings ($/sq. ft./y)	$0.25
Simple payback (y)	**1.2**



Overall Project Plan

- Project Goals
  - Precision <50 ppm CO_2
  - Drift <50 ppm CO_2/year
  - 50-2000 ppm CO_2 dynamic range
  - <1 minute response time
  - Deployment to office scenario on FHE compatible substrate/system

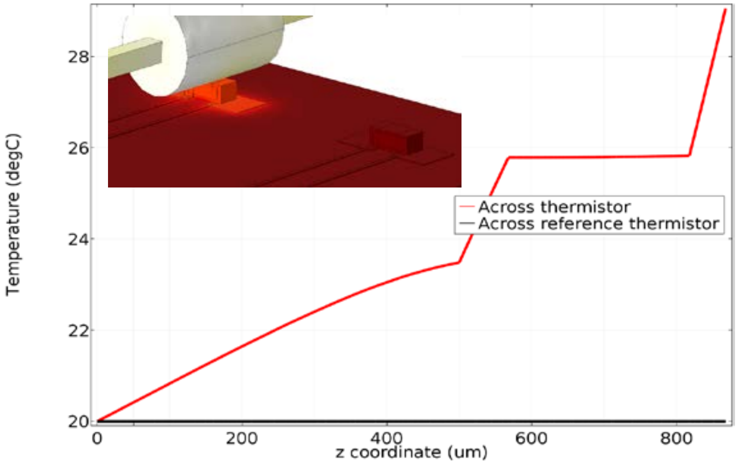
- BP1 Goals
  - Precision <100 ppm CO_2
  - <1 minute response time
  - Preliminary estimate of 1.2 year payback
  - Electronics platform capable of measurement requirements



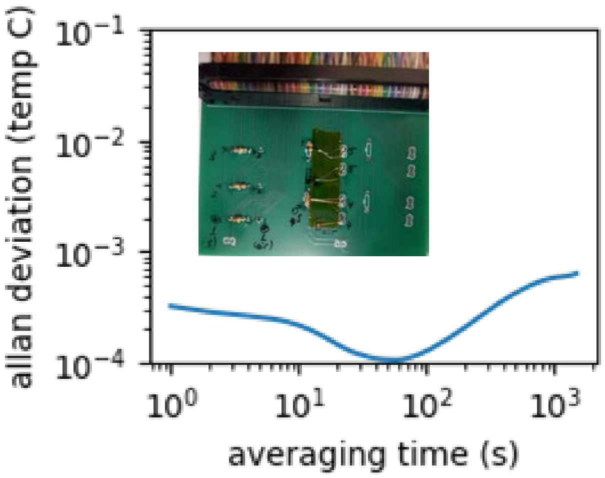
	Task Number	Task Name
1	1	Materials and Deposition Method Development (M1-M10)
10	2	Sensor Development & Testing (M1-M13)
42	3	Electronics Development (M7-M13)
49	4	Enclosure Design (M1-M13)
55	5a	System Integration & Testing (M1-M4)
58	5b	System Integration & Testing (M14-M18)
63	6a	Data Analysis & Algorithm Optimization (M4-M13)
68	6b	Data Analysis & Algorithm Optimization (M14-M17)
73	7a	Market Transformation (M1-M13)
83	7b	Market Transformation (M14-M18)

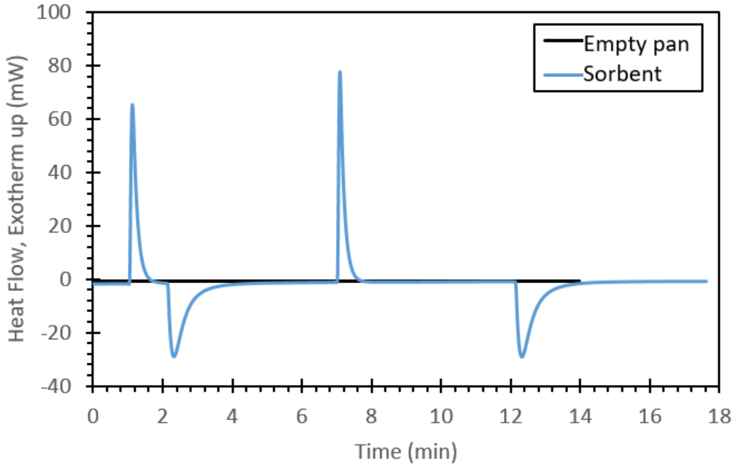
Progress

- Currently in Q2
- Accomplished all Q1 milestones
  - Thermistor performance, thermal model developed
- Characterizing sorbent & binder mixtures to enable effective printing and thermal coupling to thermistors
  - On track to meet milestones (50% efficiency in M7)
- Validating thermal model experimentally



	100 % N_2 → 100 % CO_2		100 % CO_2 → 100 % N_2	
Polymer Type	Peak Area J/g	Efficiency %	Peak area (J/g)	Efficiency %
Type 1	32.9	42	37.6	42
Type 1	35.4	46	38.2	43





Stakeholder Engagement

- Actively engaging with Xerox (parent company) along with other companies in the HVAC and BMS space.
- Conversations with companies in HVAC and BMS space (including Energy ETC, our team-member) are enabling us to understand the market state-of-the art along with target price points.

Remaining Project Work

Primary Goal: Effectively measured heat produced in sorbent by CO_2 adsorption*

Current Efforts:

- Optimizing printed mixtures to maximize heat conduction to thermistors.
  - Sorbent adsorption efficiency goal of 50% in M7, 75% in M10
  - Heat transfer efficiency goal of 50% in M7, 70% in M10

Future Efforts:

- Quantify sensor precision and accuracy
  - BP goal of 100 ppm precision; Project goal of 50 ppm precision and 50 ppm/year accuracy
- Develop algorithms and custom electronics to deploy the printed sorbent in long-term office tests.
  - Low-noise, low-power circuits for thermistor measurement
  - Device layout to minimize drift
  - Controls and algorithms to calibrate, send data to cloud

*Hornbostel, M. D. *et al. Carbon N. Y.* **56,** 77–85 (2013)

Thank You

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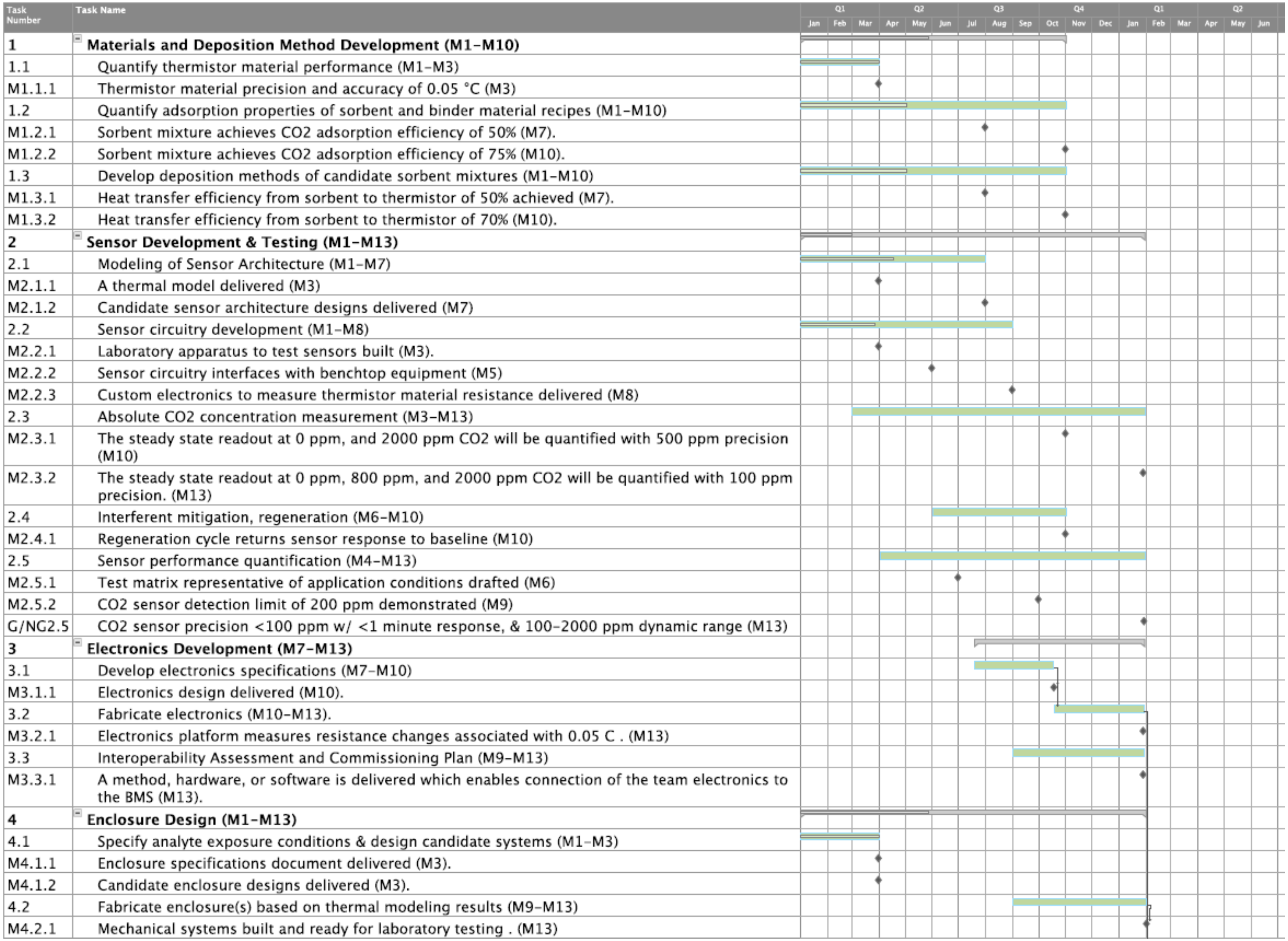
REFERENCE SLIDES

Project Budget

Project Budget: Pre-award began November 2017. First quarter began 1/1/19.
Variances: Proceeding according to budget.
Cost to Date: 11% of budget spent to date.

Budget History					
11/1/2017– FY 2017 (past)		FY 2018 (current)		FY 2019 – 4/30/2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$21,588	$5,397	$397,385	$99,346	$81,920	$20,480

Project Plan and Schedule (1)



Task Number	Task Name
1	**Materials and Deposition Method Development (M1–M10)**
1.1	Quantify thermistor material performance (M1–M3)
M1.1.1	Thermistor material precision and accuracy of 0.05 °C (M3)
1.2	Quantify adsorption properties of sorbent and binder material recipes (M1–M10)
M1.2.1	Sorbent mixture achieves CO2 adsorption efficiency of 50% (M7).
M1.2.2	Sorbent mixture achieves CO2 adsorption efficiency of 75% (M10).
1.3	Develop deposition methods of candidate sorbent mixtures (M1–M10)
M1.3.1	Heat transfer efficiency from sorbent to thermistor of 50% achieved (M7).
M1.3.2	Heat transfer efficiency from sorbent to thermistor of 70% (M10).
2	**Sensor Development & Testing (M1–M13)**
2.1	Modeling of Sensor Architecture (M1–M7)
M2.1.1	A thermal model delivered (M3)
M2.1.2	Candidate sensor architecture designs delivered (M7)
2.2	Sensor circuitry development (M1–M8)
M2.2.1	Laboratory apparatus to test sensors built (M3).
M2.2.2	Sensor circuitry interfaces with benchtop equipment (M5)
M2.2.3	Custom electronics to measure thermistor material resistance delivered (M8)
2.3	Absolute CO2 concentration measurement (M3–M13)
M2.3.1	The steady state readout at 0 ppm, and 2000 ppm CO2 will be quantified with 500 ppm precision (M10)
M2.3.2	The steady state readout at 0 ppm, 800 ppm, and 2000 ppm CO2 will be quantified with 100 ppm precision. (M13)
2.4	Interferent mitigation, regeneration (M6–M10)
M2.4.1	Regeneration cycle returns sensor response to baseline (M10)
2.5	Sensor performance quantification (M4–M13)
M2.5.1	Test matrix representative of application conditions drafted (M6)
M2.5.2	CO2 sensor detection limit of 200 ppm demonstrated (M9)
G/NG2.5	CO2 sensor precision <100 ppm w/ <1 minute response, & 100-2000 ppm dynamic range (M13)
3	**Electronics Development (M7–M13)**
3.1	Develop electronics specifications (M7–M10)
M3.1.1	Electronics design delivered (M10).
3.2	Fabricate electronics (M10–M13).
M3.2.1	Electronics platform measures resistance changes associated with 0.05 C . (M13)
3.3	Interoperability Assessment and Commissioning Plan (M9–M13)
M3.3.1	A method, hardware, or software is delivered which enables connection of the team electronics to the BMS (M13).
4	**Enclosure Design (M1–M13)**
4.1	Specify analyte exposure conditions & design candidate systems (M1–M3)
M4.1.1	Enclosure specifications document delivered (M3).
M4.1.2	Candidate enclosure designs delivered (M3).
4.2	Fabricate enclosure(s) based on thermal modeling results (M9–M13)
M4.2.1	Mechanical systems built and ready for laboratory testing . (M13)

Project Plan and Schedule (1)

5a	**System Integration & Testing (M1–M4)**
5a.1	Analysis of BMS CO2 control data (M1–M4)
M5a.1.1	Figures of merit are verified using existing BMS historical data (M4).
5b	**System Integration & Testing (M14–M18)**
5b.1	Develop embedded program (M14–M15)
M5b.1.1	Embedded control software delivered (M15)
5b.2	Deploy the system to office environments (M16–M18)
M5b.2.1	CO2 sensor system streams data useful for DCV (M18).
6a	**Data Analysis & Algorithm Optimization (M4–M13)**
6a.1	Develop algorithms for quantifying CO2 concentration. (M4–M13)
M6a.1.1	Algorithms for compensating for humidity delivered. (M13)
6a.2	Perform signals analysis on thermally modulated signals (M4–M13)
M6a.2.1	Algorithms to produce concentration readings from thermally modulated signals will be delivered (M13).
6b	**Data Analysis & Algorithm Optimization (M14–M17)**
6b.1	Develop algorithms for quantifying CO2 concentration. (M14–M17)
M6b.1.1	CO2 precision <50 ppm & drift <50 ppm/year (M17)
6b.2	Refine & port algorithms from benchtop to electronics or cloud (M14–M17)
M6b.2.1	Ported algorithms meet Milestones 6a.1.1, 6a.2.1, and 6b.1.1. (M17)
7a	**Market Transformation (M1–M13)**
7a.1	Intellectual Property (M1–M3)
M7a.1.1	The IP management plan signed by all relevant parties & approved by BTO (M3)
7a.2	Technoeconomic Analysis (TEA) and Cost Model (M1–M13).
M7a.2.1	First version of completed TEA including estimates of all constituent costs (M10).
M7a.2.2	Updated TEA delivered (M13).
7a.3	Market Discovery (M1–M13)
M7a.3.1	Competitive landscape survey and value chain mapping complete (M13).
7a.4	Technology to Market (T2M) Plan (M1–M13)
M7a.4.1	T2M Draft Plan for advancing BTO funded technology toward commercial viability (M13).
7b	**Market Transformation (M14–M18)**
7b.2	Technoeconomic Analysis (TEA) and Cost Model (M14–M16)
M7b.2.1	TEA will achieve a 3-year payback for at least one potential application (M16).
7b.3	Market Discovery (M14–M16)
M7b.3.1	Preliminary commercialization strategy complete (M16).
7b.4	Technology to Market (T2M) Plan (M14–M16)
M7b.4.1	Revised T2M Plan incorporating feedback received from DOE (M16)
7b.5	Transition Activities (M14–M18)
M7b.5.1	Present at quarterly review meeting a transition plan and progress made securing transition partne (M16)
M7b.5.2	Final report on transition (M18).