U.S. Department of Energy
Energy Efficiency and Renewable Energy

Hydrogen, Fuel Cells & Infrastructure Technologies Program

Fiber Optic Temperature Sensors for PEM Fuel Cells

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Oak Ridge National Laboratory
U. S. Department of Energy

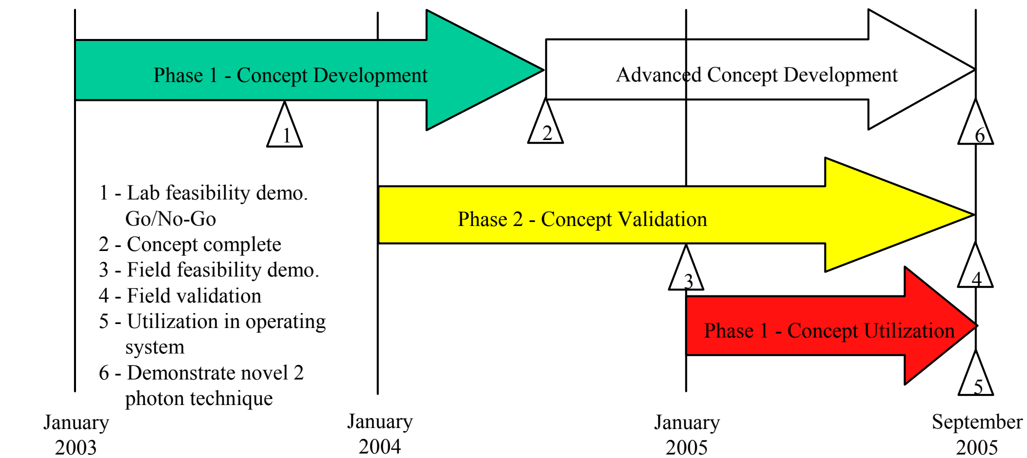
Project ID# FC42

UT-BATTELLE

Project Overview

Project Timeline

△ Project Milestone



Partners

plugpower
GM
RoMack inc. Better By Design - Fiberoptics Since 1982
Oregon State University OSU
NUFERN Driven To Light
UCF
Translume
MicroMaterials
United Technologies

Project Budget

FY 2005 = $405k, all DOE funds

Technical Barriers and Targets

Barriers - Transportation Systems B.

- Automotive sensors required to meet performance and cost targets for measuring physical conditions and chemical species in fuel cell systems.
- Current sensors do not perform within the required ambient and process conditions, do not possess the required accuracy and range, and/or are too costly.

Targets - Automotive Fuel Cell Systems, Temperature

- Sensors must conform to size, weight, and cost constraints of automotive applications
- Operating range: -40 to 150°C
- Response time: -40 to 100°C range <0.5 seconds with 1.5% accuracy; 100 to 150°C range <1.0 seconds with 2% accuracy
- Gas environment: high humidity reformer/partial oxidation: H_2 30% - 75%, CO_2, N_2, H_2O, CO at 1 - 3 atm total pressure.
- Insensitive to flow velocity.

Overview of Reviewer Feedback

Review Comment: Develop a multiplexing approach for thermal mapping

- Demonstrated a 5 sensor platform that could easily be scaled to over 10

Review Comment: More interaction with auto companies

- Beginning collaborative efforts with GM

Review Comment: Focus more on robust measurement to acquire new information than low-cost system

Review Comment: Perform sensor durability/compatibility testing

Review Comment: Demonstrate measurements in operating fuel cells, forget about low cost

- 2 parallel demonstration/evaluation programs (Plug Power and in-house)
- Sensors have been demonstrated in operating fuel cells.

Project Objective

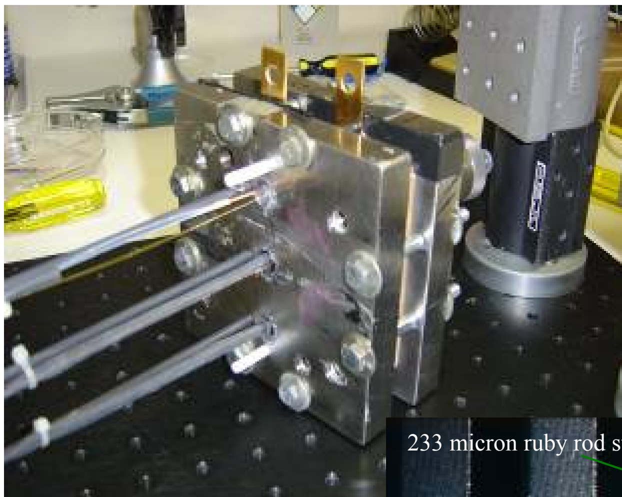
Provide measurement and diagnostic tools to fuel cell developers for system performance optimization and model validation.

Real-time intra-fuel cell measurements of temperature and species (Humidity) made within operating PEM fuel cells.

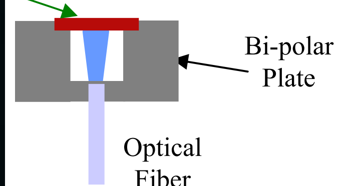
- Demonstrate intra-fuel cell transient temperature diagnostic
- Characterize 'typical' intra-fuel cell temperature distributions
- Demonstrate intra-fuel cell species diagnostic (developed in separate DOE program)
    - * Combining temperature and species measurements provides dynamic humidity distribution
- Identify performance characteristics of fuel cell that suggest operational/design limits

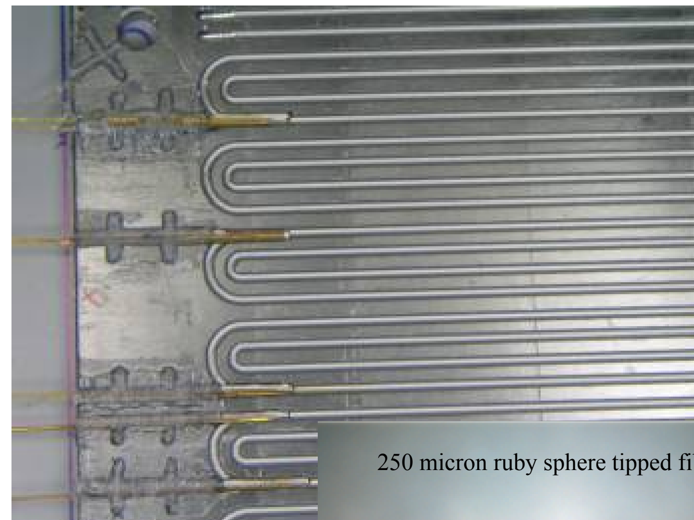
Technical Approach

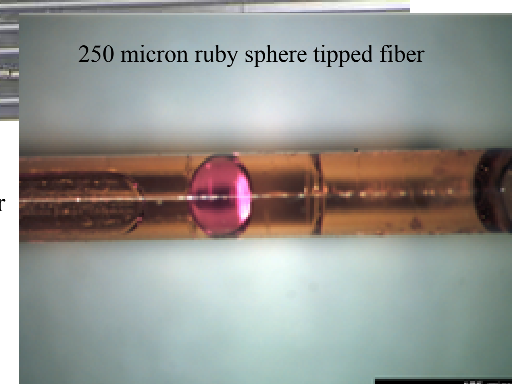
- Construct luminescence-based sensors w/micro-ruby transducers
- Instrument fuel cells (multiple testing platforms and sensor configurations)
- Operate fuel cells to characterize operational relationships



Fuel cell courtesy of plugpower





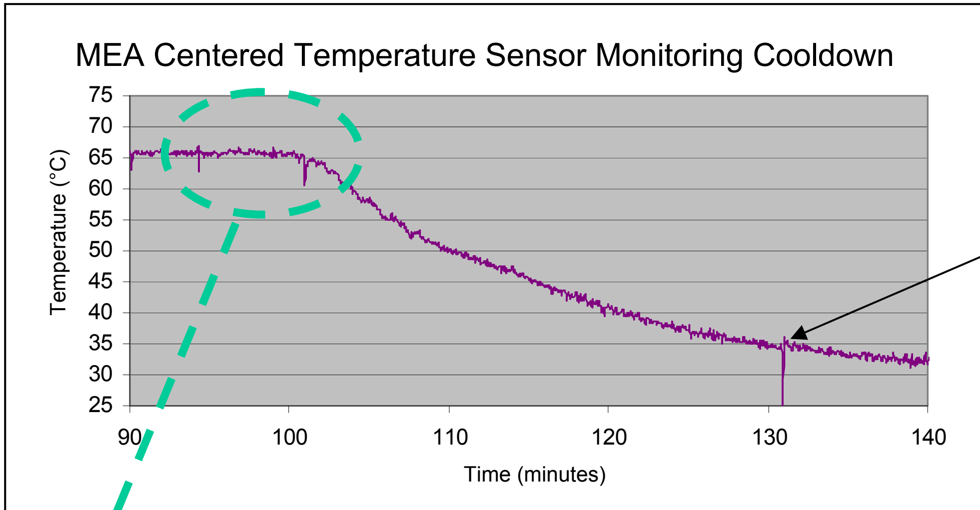


Technical Accomplishments

- Demonstrated intra-fuel cell temperature and species measurements within operating fuel cell(s)
- Characterized spatial distributions of temperature and humidity
- Demonstrated correlation between temperature and humidity distributions
- Characterized time and temperature dynamics for improved diagnostics
- Demonstrated approach for improving detailed understanding of realistic fuel cell system kinetics/chemistry
  - * Pathway for optimizing operational and design parameters (e.g. flow rates, pressure, concentrations, Pt distribution, flow path geometry, materials characteristics, etc.)

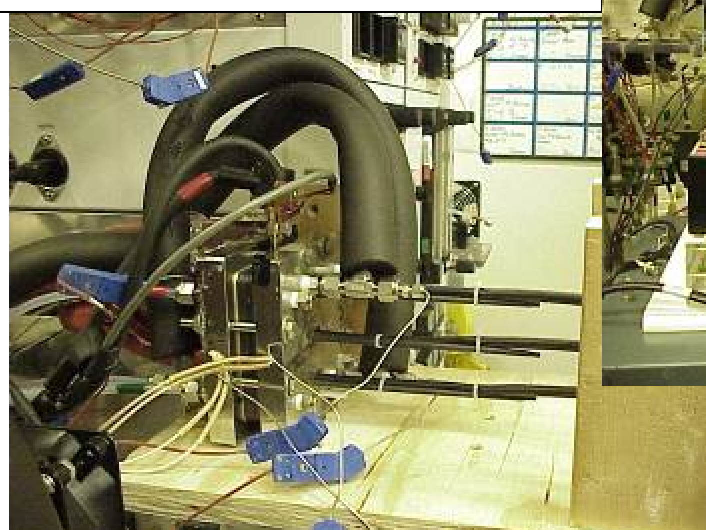
Fuel Cell Platform

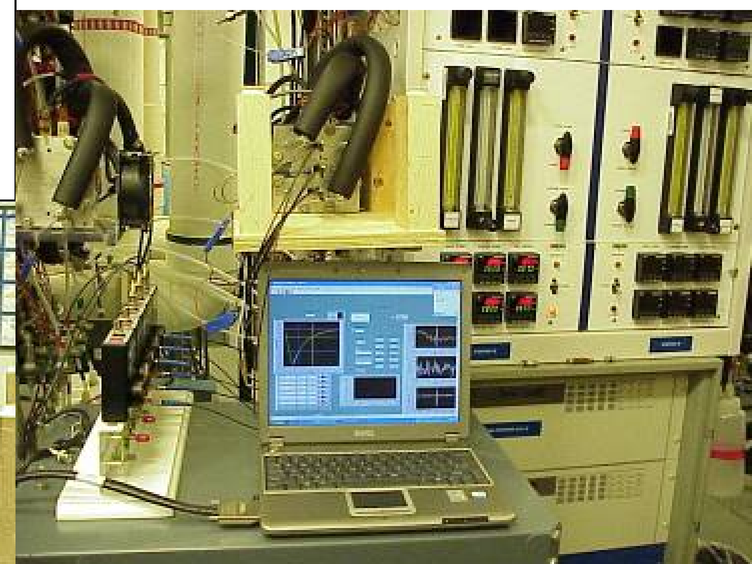
(Plug Power)



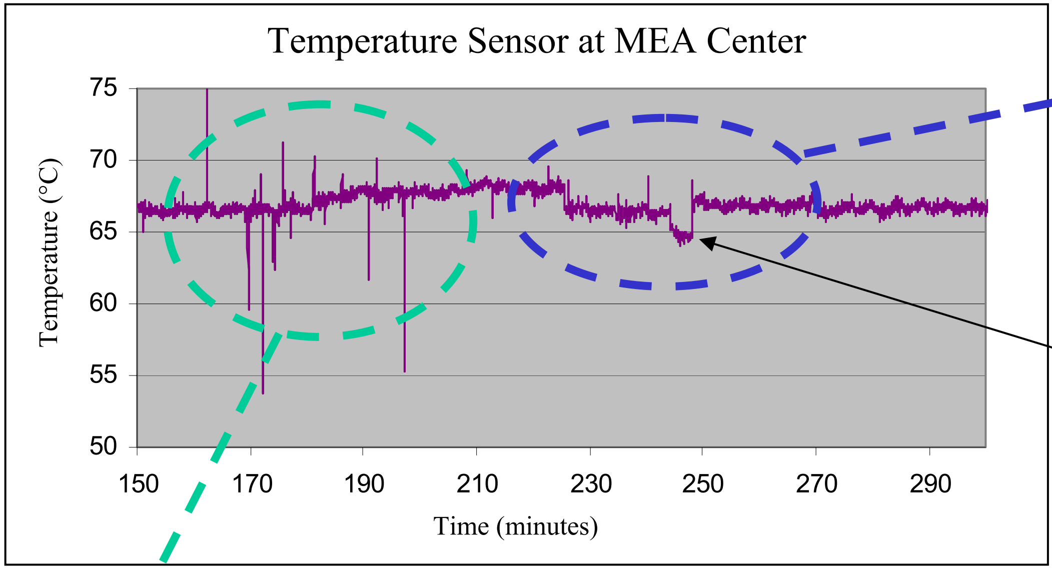
Water droplet passing sensor due to nitrogen purge

Water droplet events observed prior to shutdown





Thermography Data from Experiments at Plug Power

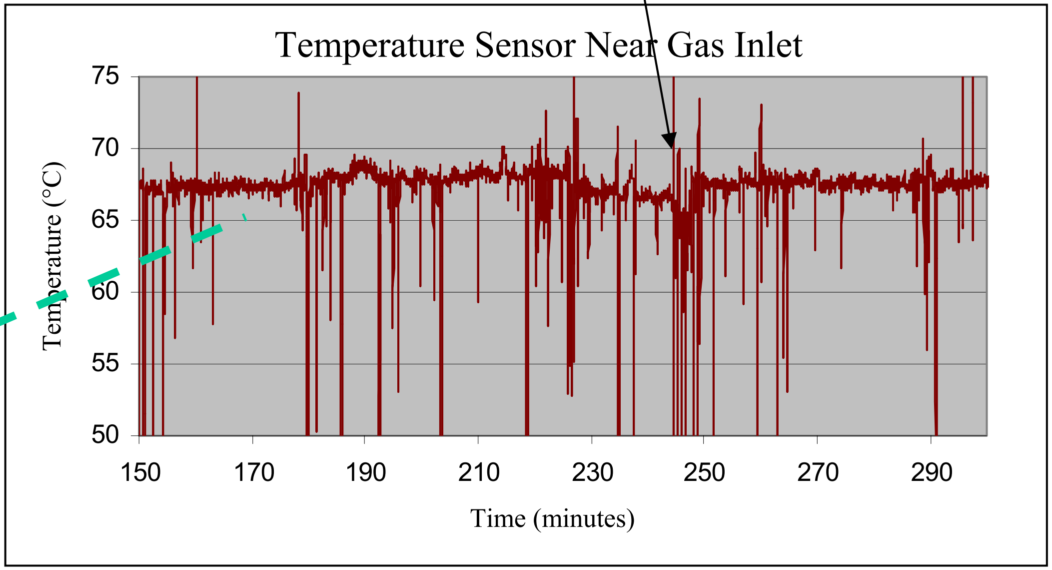


Cell temperature varies with applied load and operating parameters

Sensors show similar trends in fuel cell temperature.

Water droplet formation rate varies with Operating Parameters

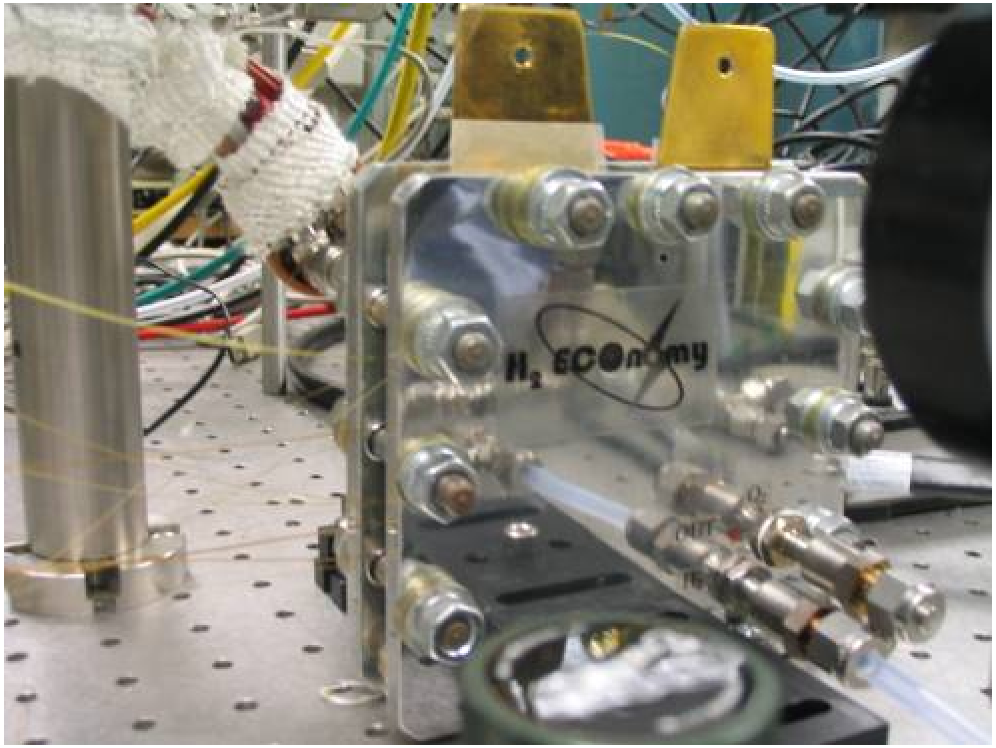
And position in cell

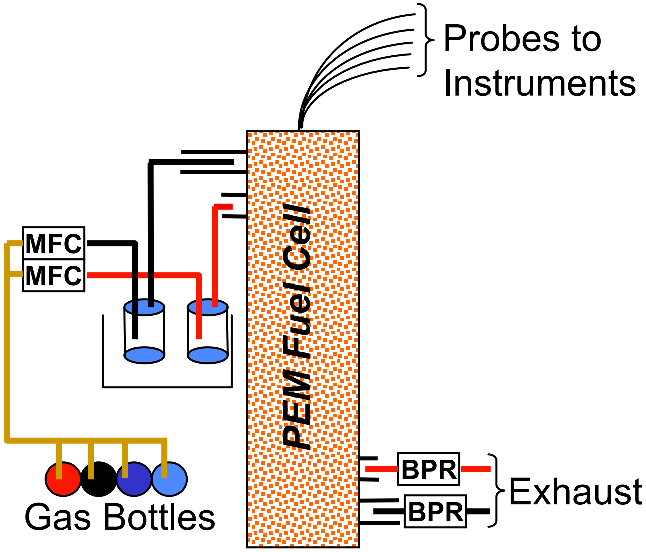


Fuel Cell Platform

(in house)

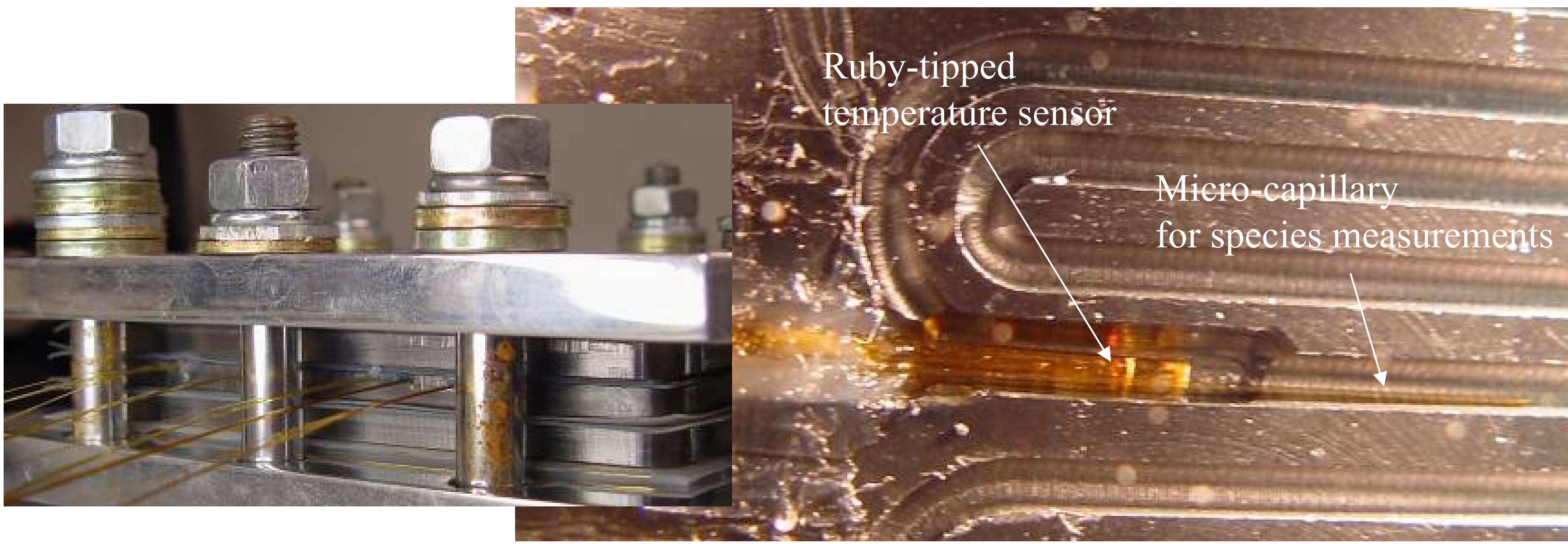
- Commercially available 2-cell stack
- 7-cm x 7-cm active area per cell
- Flow path: 13-pass, 918-mm dual-serpentine, crossed anode-cathode flows, ~1.27-mm diameter half channel, 0.633-mm^2 flow area





Probe Access for Intra-Fuel Cell Measurements

- Fiber and capillary probes were installed at the inlet, 2x, 6x, 8x, 10x, (0, 0.2, 0.4, 0.6, 0.8, and 1L) and outlet positions
- Temperature Probes ~0.4-mm OD: 19.9% flow area (next generation 80 micron probe: 0.8% flow area)
- Species Probes ~0.15-mm OD: 2.8% flow area
- Thermocouples at fuel cell inlet and outlet



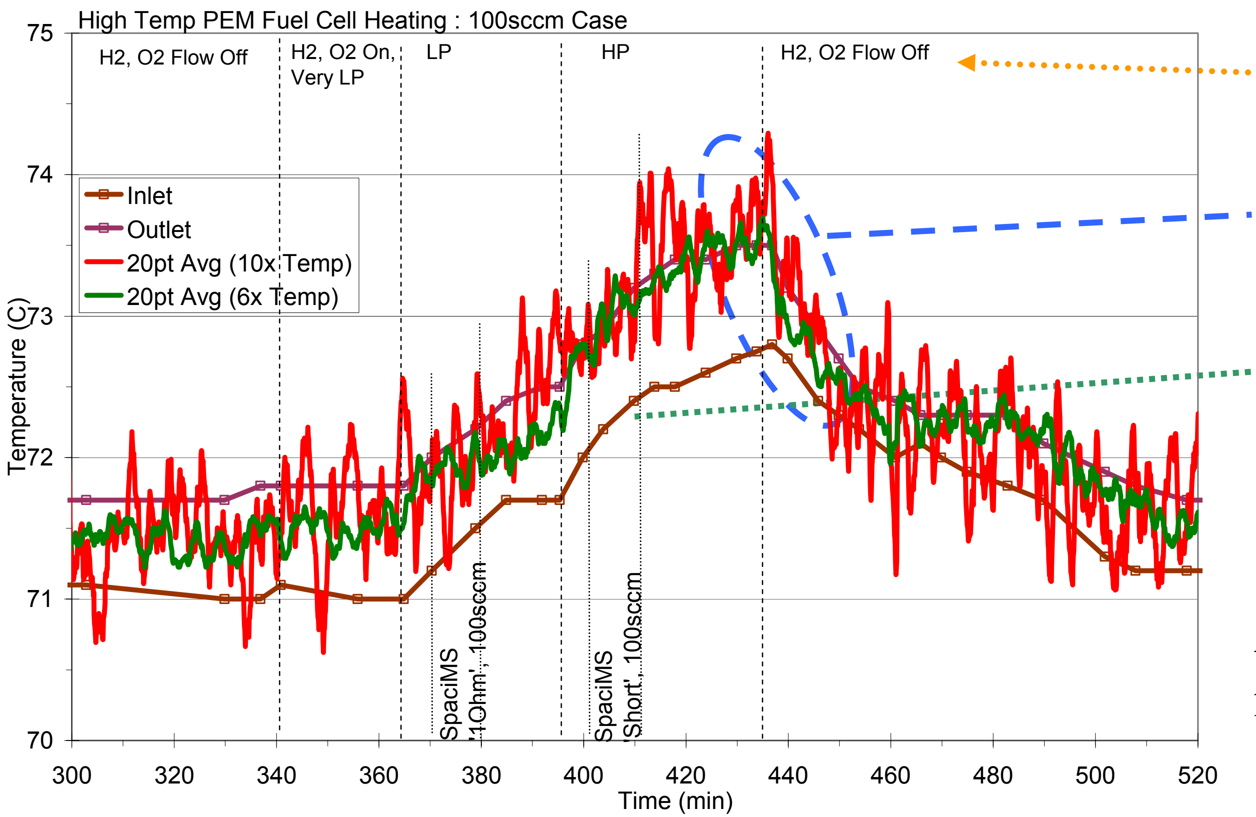
Experimental Conditions

The fuel cell was evaluated at :

- Two temperatures: 30° and 72°C
- Three gas flow rates: 50, 100 and 200 sccm
- Two power levels: Low Power (LP), & High Power (HP)

	Room Temp	High Temp
Nominal Inlet/Outlet FC Temp (°C)	30	72
Water Bath Temp (°C)	27	58.9
Inlet Relative Humidity (%)	84	56
Anode (dry)	50% H_2 in N_2, 10 psig	50% H_2 in N_2, 10 psig
Cathode (dry)	20% O_2 in N_2, 12.5 psig	20% O_2 in N_2, 12.5 psig

High-Temp Operation Shows Stepped Temperature Changes



Fuel Cell Conditions

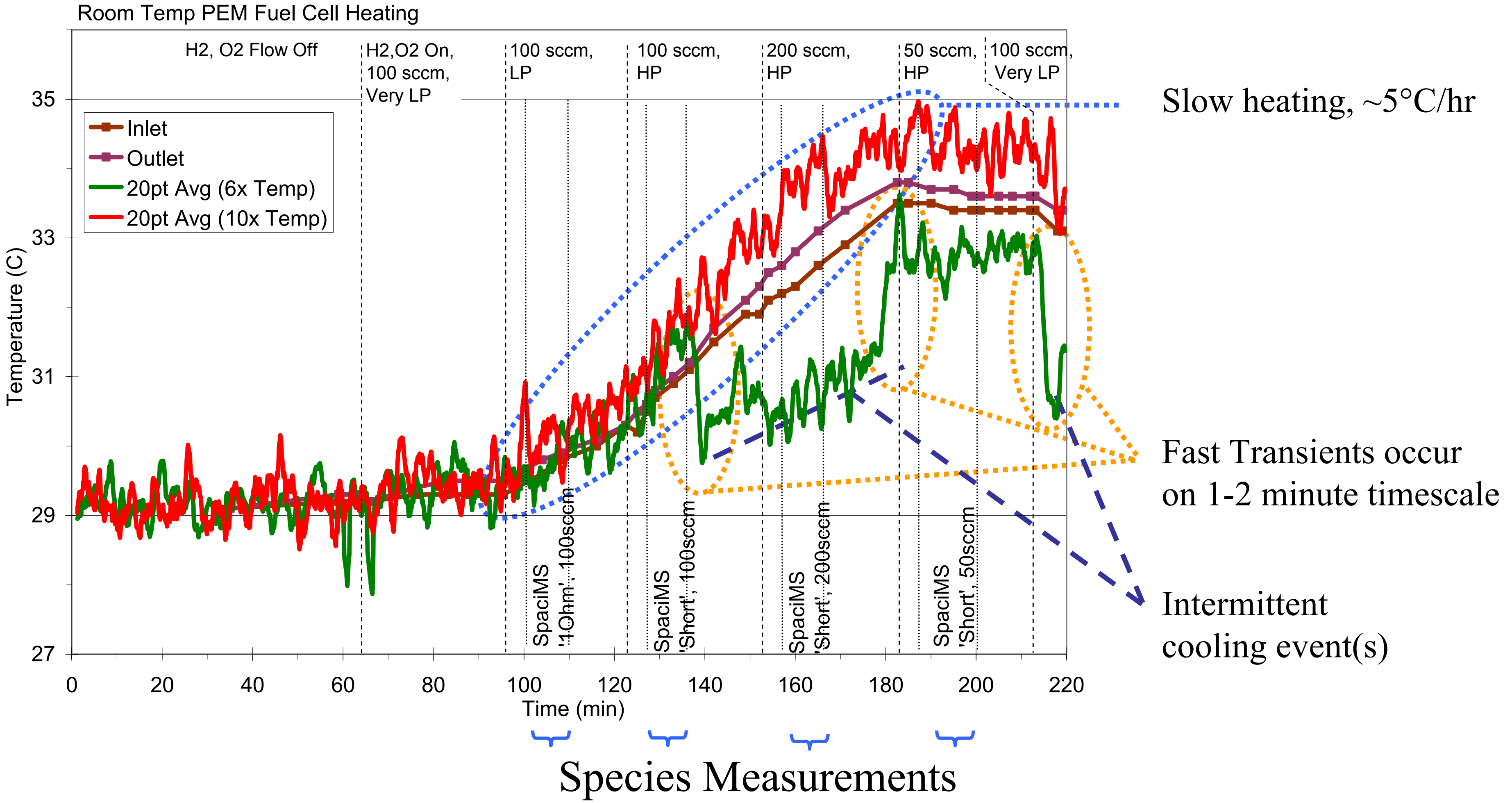
Slow cooling, ~4°C/hr

Inlet heats up too – strong front-end reaction?

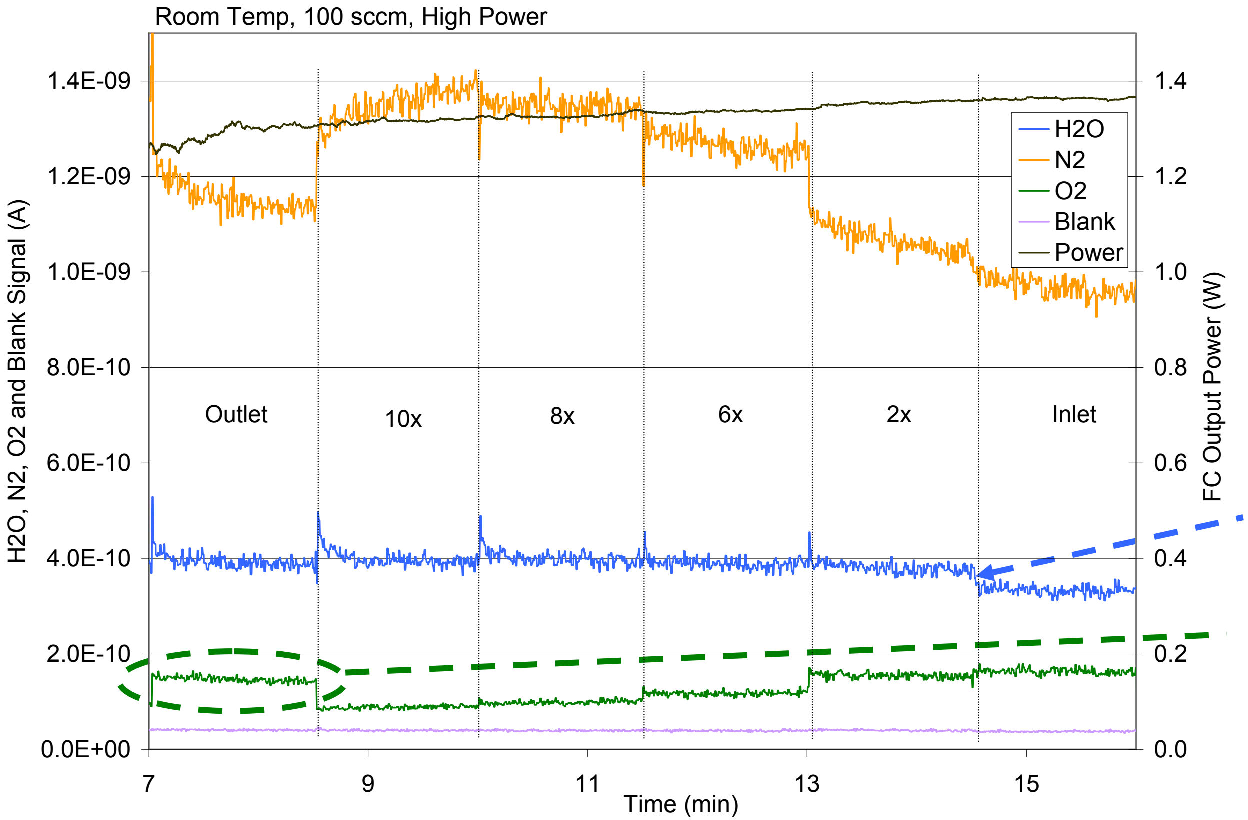
All temperature measurements show stepped behavior

- Fuel cell heating ~ on the order 3-5°C
- Interior temperatures can be > or < inlet and outlet temperatures
- Temperature dynamics occur on 1-10 minute time scales
- Even fast dynamics occur on the order of ~1 minute

Phosphor Thermography Resolves Transient Intra Fuel Cell Temperature Distributions



SpaciMS Resolves
Transient Intra Fuel Cell Water and Species Distributions



Fuel cell power shows dynamic behavior at 'stationary' conditions

Local N_2 ~ mirrors O_2

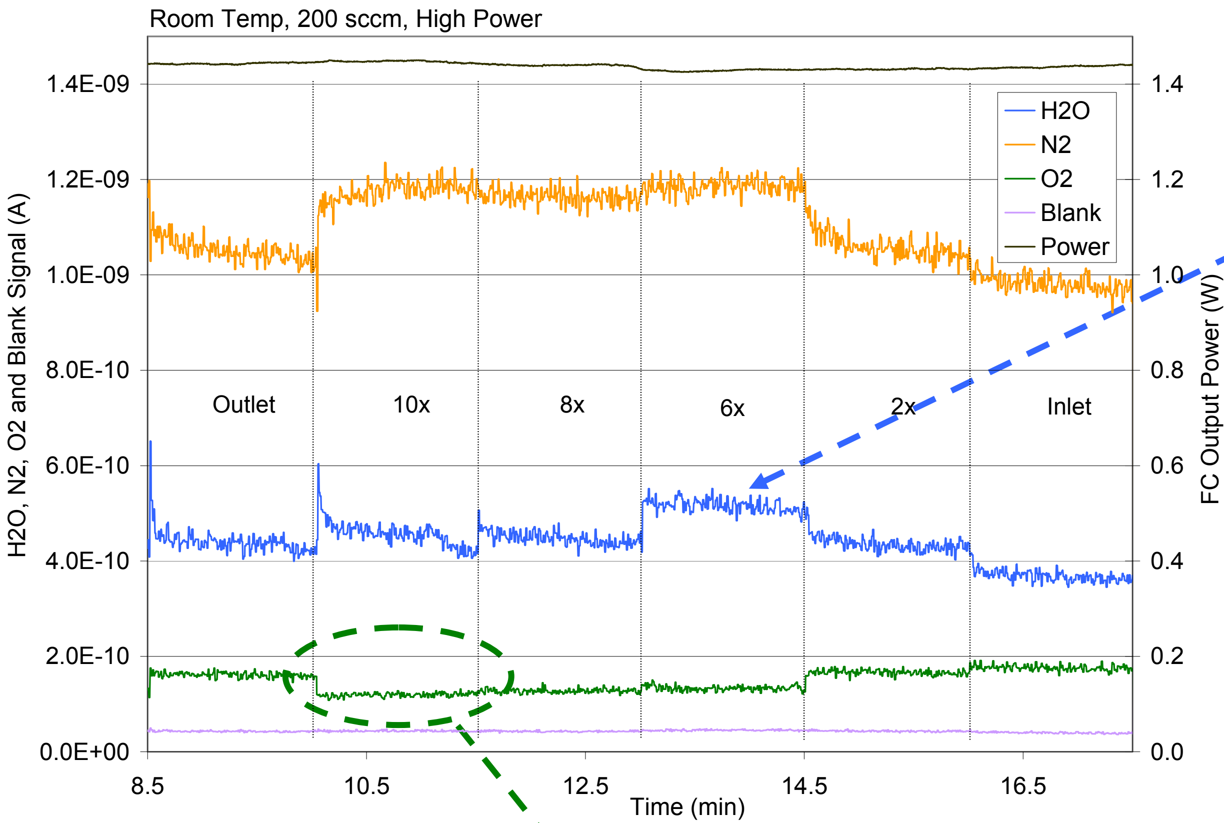
Humidity increases inside fuel cell

O_2 increases in outlet manifold to ~ inlet value

- un-instrumented cell inactive or degraded

With temperature and pressure can determine relative humidity from H_2O

High Humidity at 6x Location for Room Temp 200 sccm Case

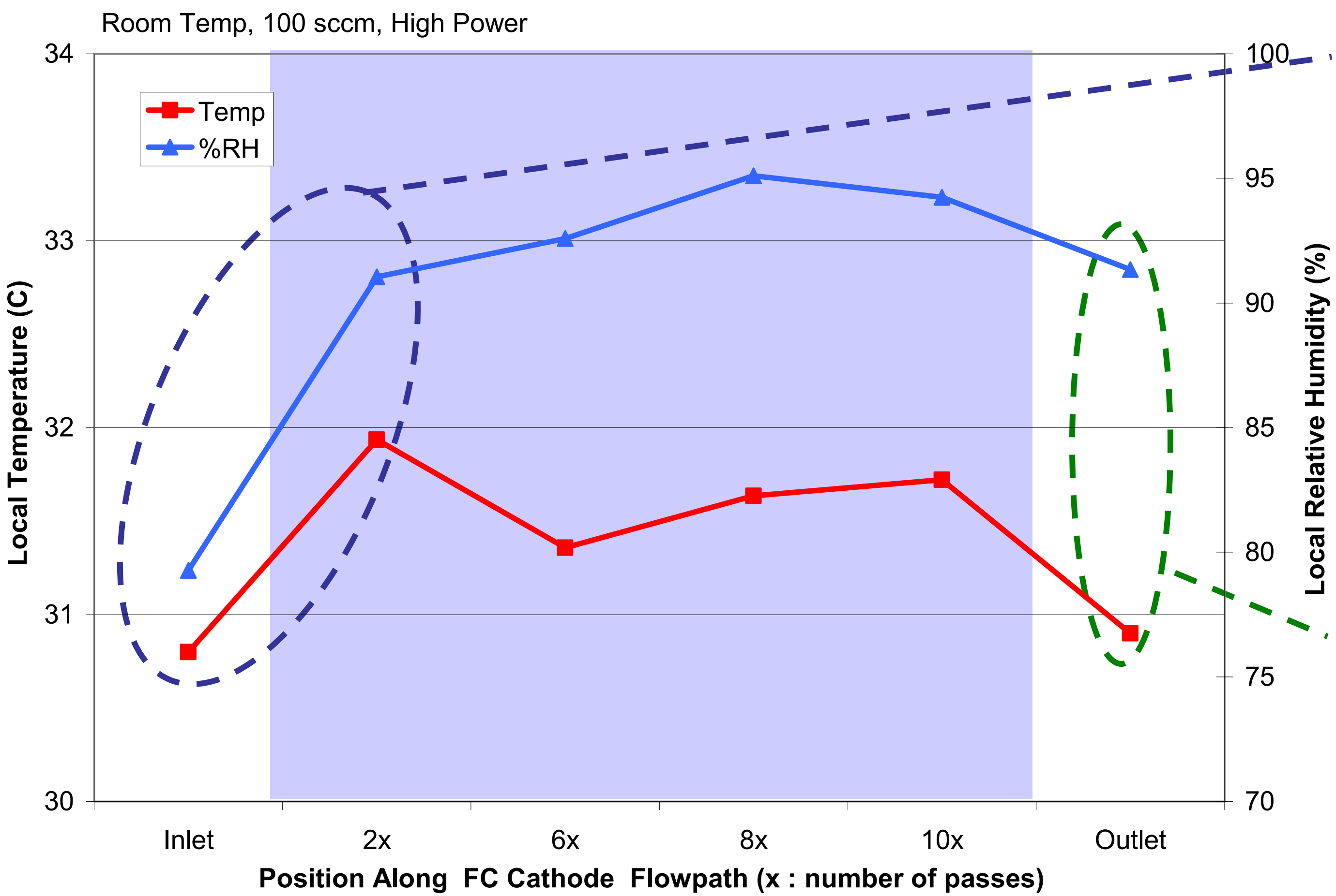


8% Power increase

Distinct and localized high humidity

O_2 depletion is greater in lower-flow case

Without Condensation, Temperature and Relative Humidity Profiles are Flat within Fuel Cell

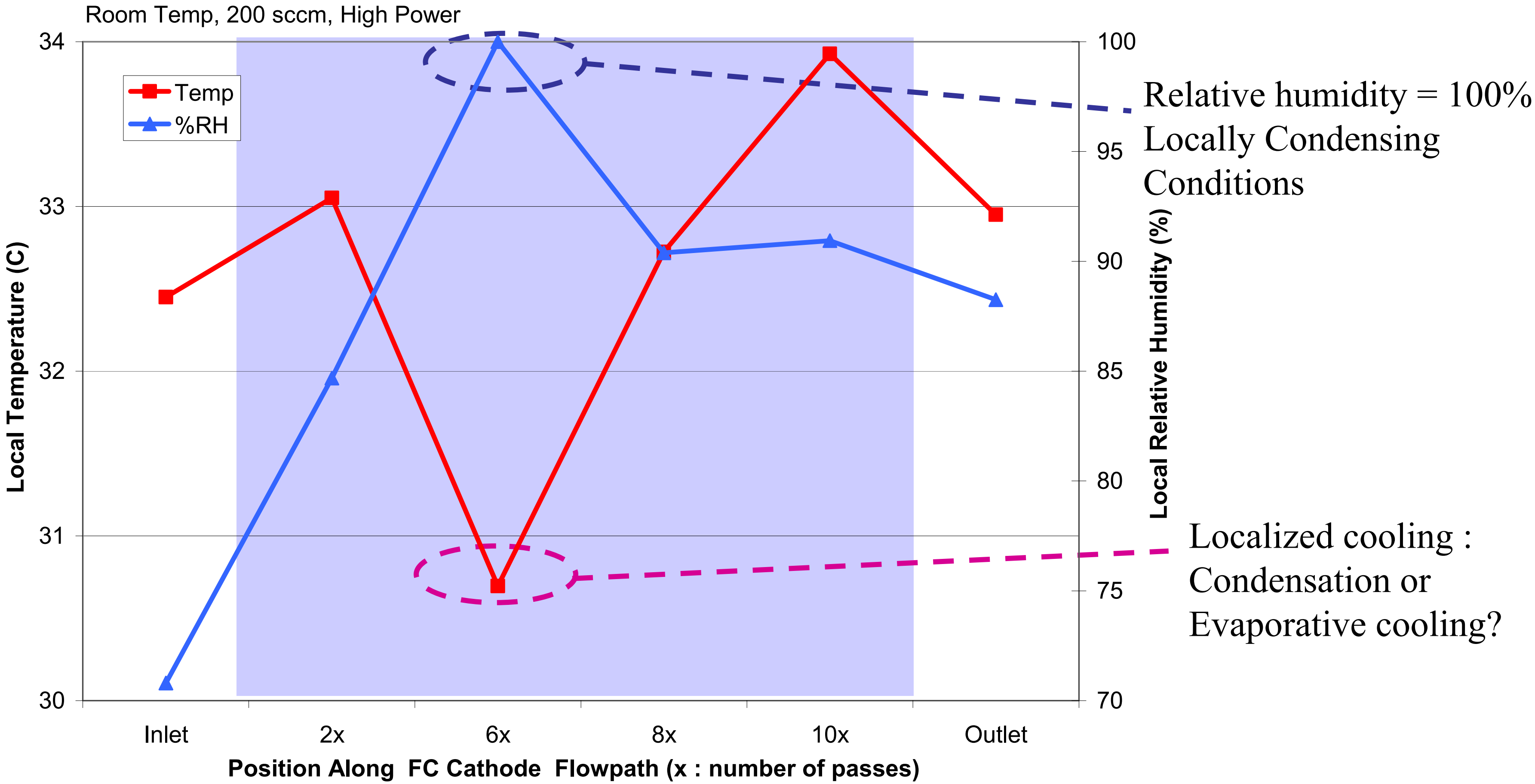


Largest temperature and relative humidity gradients occur in front 2x of fuel cell

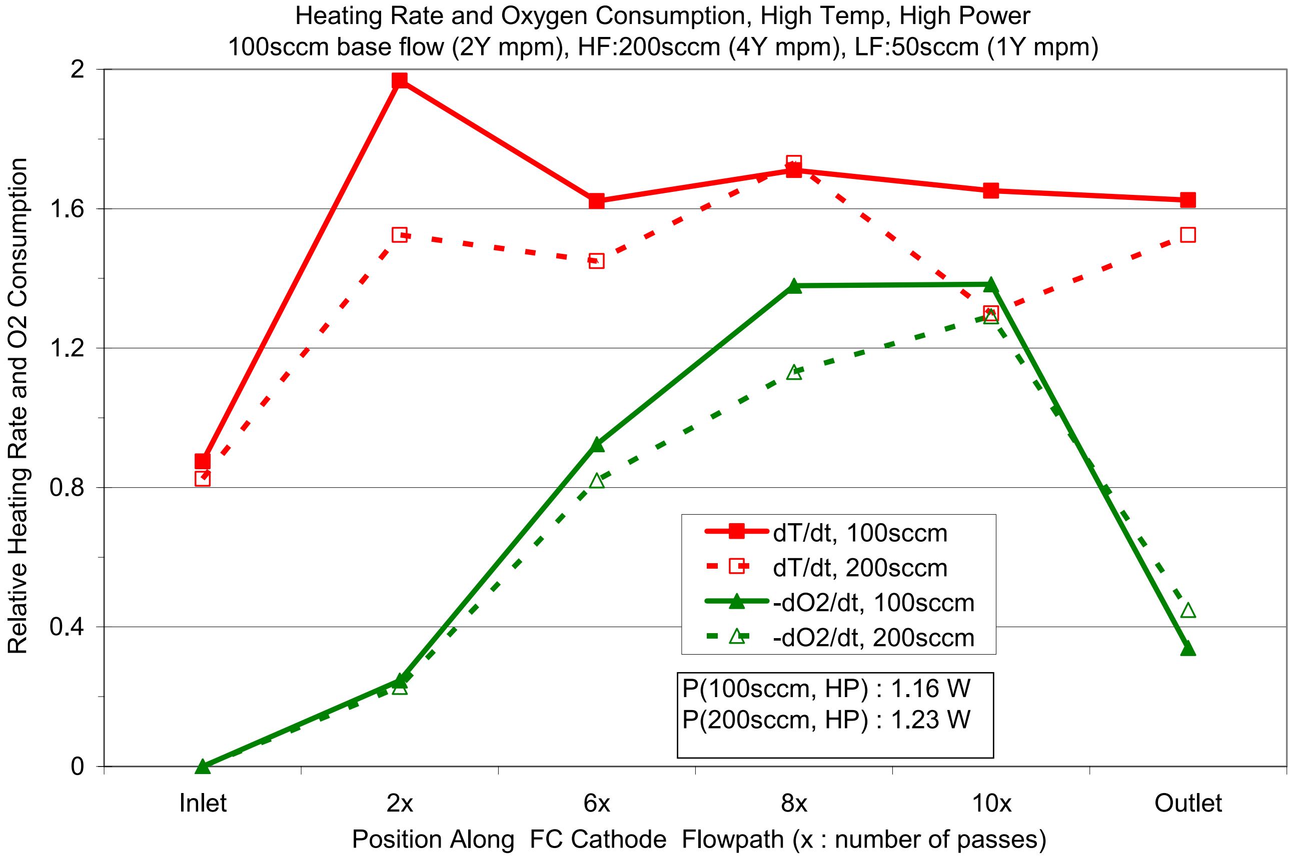
Temperature and relative humidity decrease at outlet

- consistent with degraded parallel cell

Locally Condensing Conditions Create Localized Cooling



Increasing Reactant Flow Rate Cools Fuel Cell and Decreases O_2 Consumption Rate



6% power increase

Major heating is in fuel cell front end (like at room temperature)

Overall cooling trend

O_2 rate difference primarily 6x to 10x

O_2 rate similar at fuel cell front

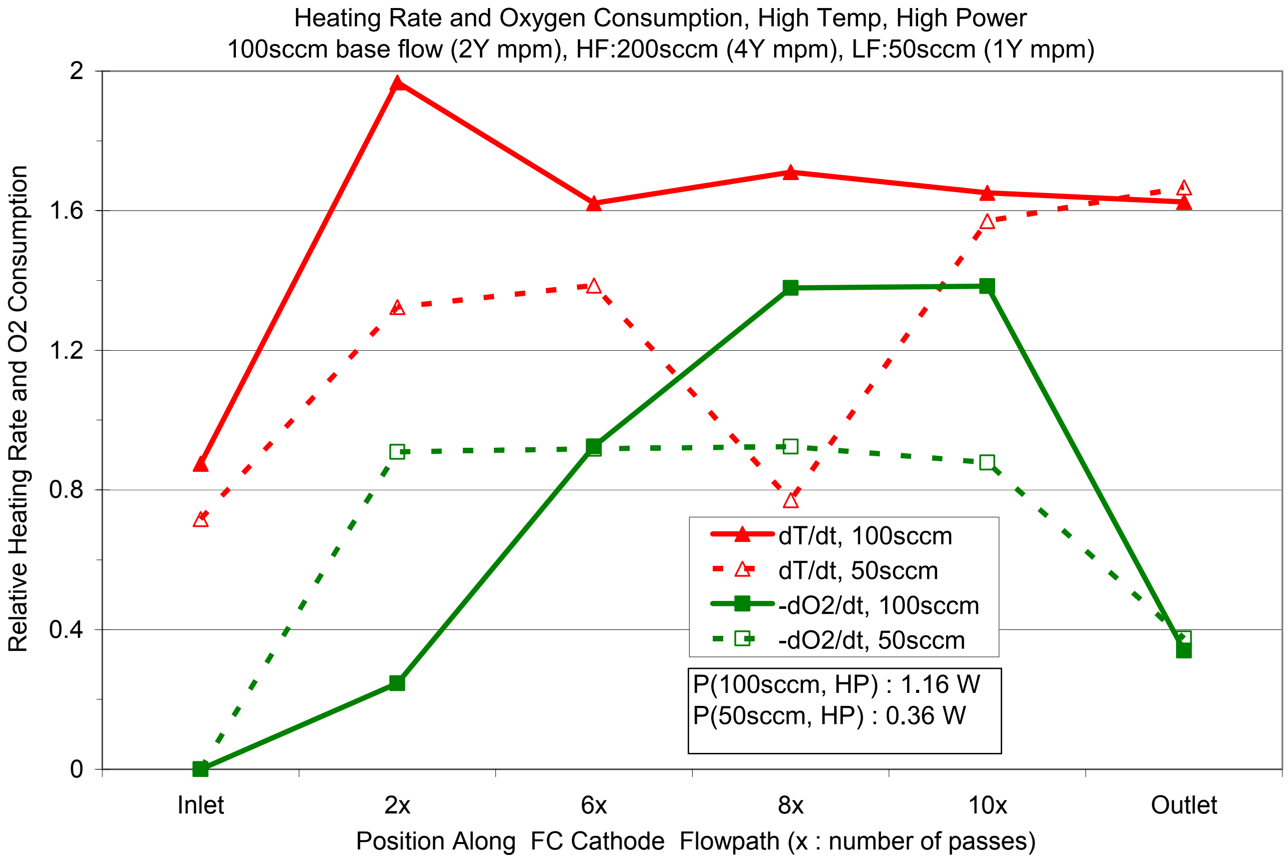
Output power increases despite less O_2 consumption

- Due to cooling effect?

Halving residence time did not half O_2 consumption

- Not reactant limited at 100sccm; maybe diffusion limited

Decreasing Reactant Flow Rate Cools Fuel Cell and Increases O_2 Consumption Rate



69% power decrease

Overall cooling trend

O_2 is depleted by the 2x position

Back >80% of the flow path is inactive

Relative humidity was near or at saturation throughout fuel cell

Significant heating at 50 sccm indicative of strong spatially confined reaction?

Doubling residence time completely depleted O_2

- Reactant limited at 50 sccm
- Further indicates diffusion limitation at 100 sccm

Intra Fuel Cell Temperature and Species Measurements can Identify Performance Limitations

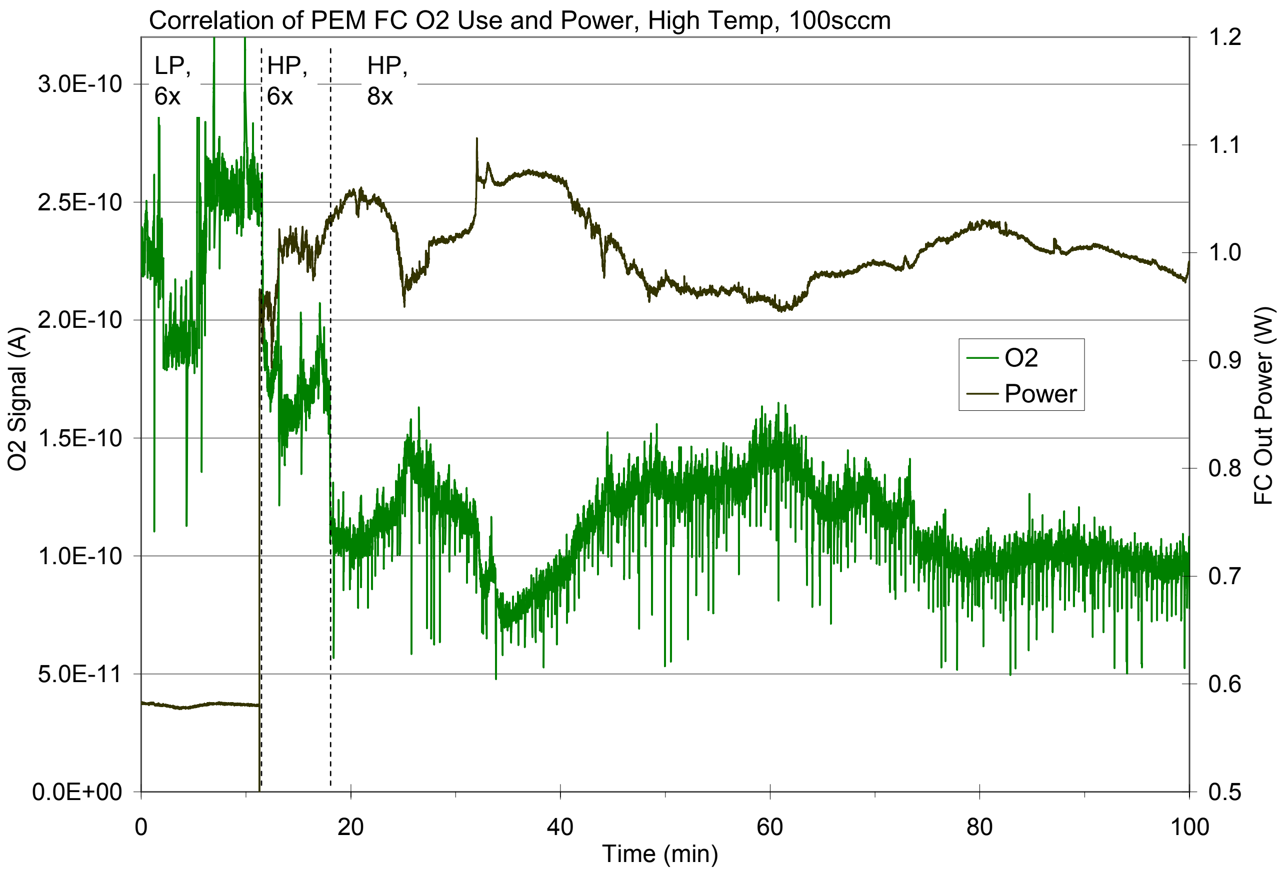
- The performance-limiting process can vary across the fuel cell (e.g., reactant depletion, diffusion, product surplus, localized site blocking,…)

- Intra fuel cell measurements can identify the local limiting processes

- More detailed experiments required
  - * Change anode and cathode flows individually
  - * Change concentration at constant residence time
  - * Change residence time at constant molar flow rate

- Better understanding of these processes in realistic systems may improve performance via improved design and materials selection
  - * Temperature profile, Pt distribution, transport characteristics (O_2, H_2, H^+, H_2O)

Fuel Cell Performance can be Dynamic Even at 'Stationary' Conditions



- Power dynamics may indicate regulation by limiting process
- O_2 dynamics correlate with fuel cell output power
- Temperature and humidity may also correlate similarly
- Power-chemistry relationships are observable
  - Suggests meaningful chemical insights are accessible

Summary Conclusions and Technical Accomplishments

- Intra-fuel-cell measurements demonstrated
  * Temperature
  * Humidity
  * Species including H_2, O_2, H_2O, N_2, Ar (others possible)

- Dynamics are slow, ~ minutes, and temperature changes are small, ~5°C

- No localized dry zones were observed

- Dynamic behavior routinely observed under stationary conditions
  * Symptomatic of detailed process limitations?

- Diffusion layer appears to efficiently transport water along flow path

- Methods demonstrated for achieving next-level performance understanding and improvements

Future Work

More extensive spatial mapping

- Stacks, not just cells?
- Does feed gas short circuit flow path via diffusion layer?

Anode and cathode side instrumentation

- Balance of reactants and products?

More extreme operating conditions to highlight barriers

- Localized drying/flooding?

More controlled operation variations (drive cycle) to identify origins of local efficiency limitations.

Further instrument improvements

- Advanced measurement methods instead of single probes, probe size, signal-to-noise, temperature and time resolution, etc.

Presentations, Publications and Patents

Presentations

Fiber Optic Temperature Sensors for PEM Fuel Cells: Progress Report, Fuel Cell Expo, San Antonio, TX, 2004.

Publications

1. Development of Fiber Optic Sensors for Fuel Cells: Issues and Results, Cates, M. R., S. W. Allison, L. C. Maxey, and T. J. McIntyre, Instrument Society of America, 2005.
2. Development of Optical Fuel Cell Temperature Measurements, Maxey, L. C., and T. J. McIntyre, Instrument Society of America, 2005.

Patents

1. Duel-mode Optical Temperature and Humidity Sensor for PEM Fuel Cells.
2. 2-photon Induced, Spatially Resolved Temperature Sensing.
3. Embedded Waveguide Sensors and Thin Polymer Membranes.

Project Summary

Relevance: **Help to answer fundamental questions necessary for energy-efficient PEM fuel cell implementation.**

Approach: **Develop and apply intra-FC diagnostics to characterize transient performance characteristics**

Technical Accomplishments and Progress: **Demonstrated dynamic temperature, humidity and species distributions throughout an operating PEM fuel cell**

Technology Transfer/Collaborations: **Active partnership with Plug Power and others, new partnership with GM, presentations, publications and patents**

Proposed Future Research: **Apply intra-FC diagnostics to identify performance barriers and pathways for performance**

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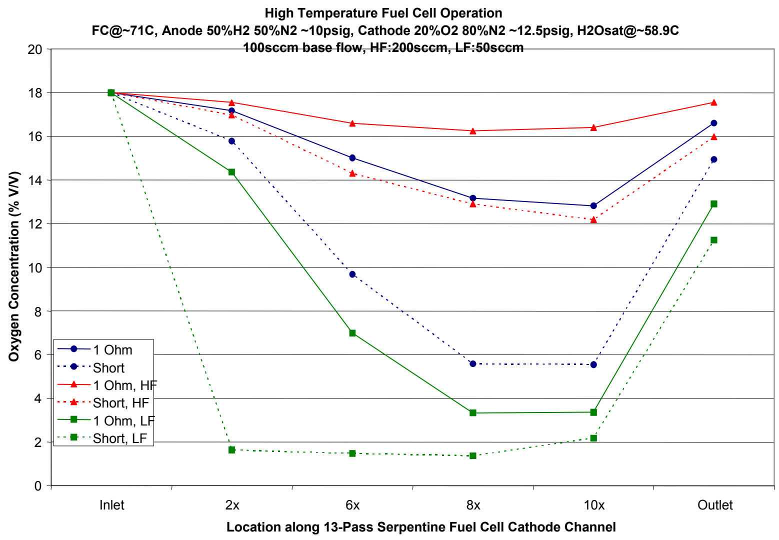
Hydrogen Safety

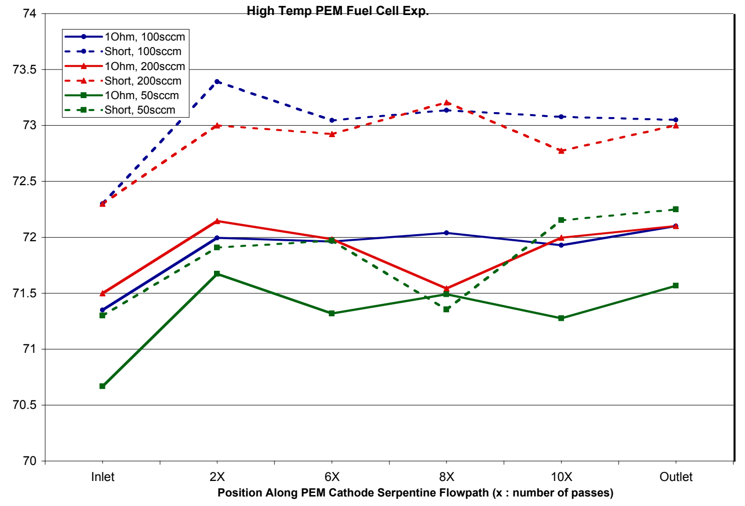
The most significant safety risk would be a hydrogen supply gas leak or mishandling of unutilized hydrogen exhausted from the fuel cell.

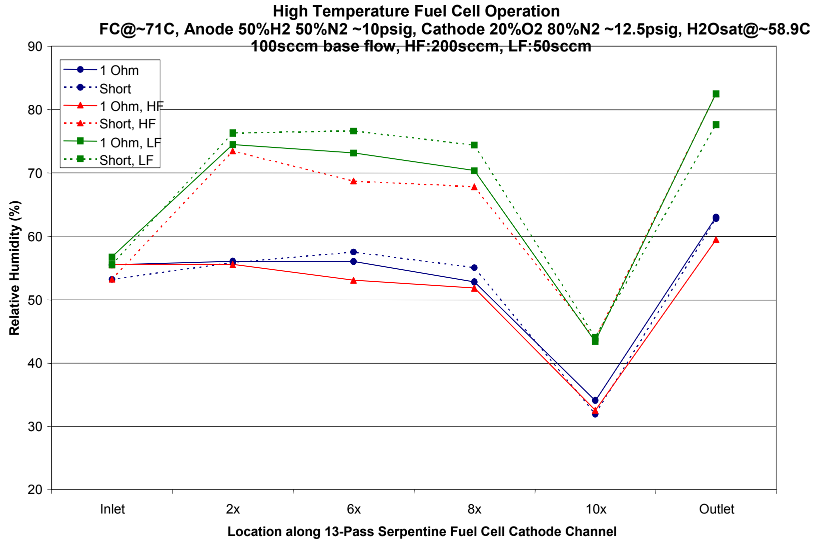
To minimize any potential safety risks on this project the following actions are taken:

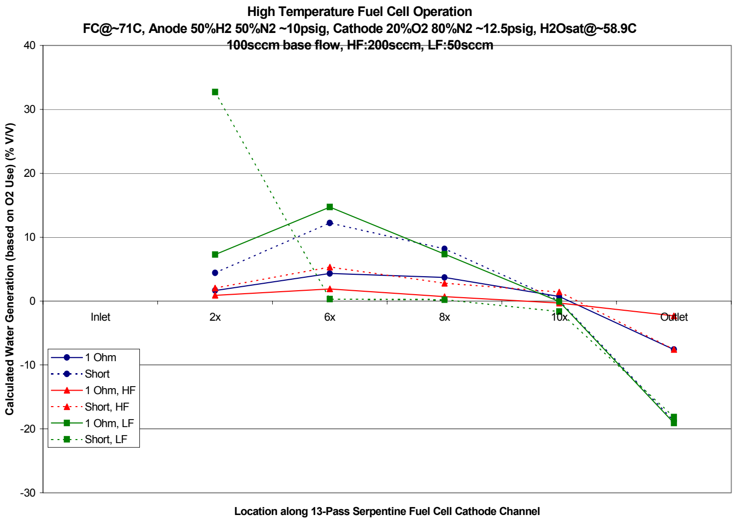
- All project activities at ORNL are covered by a formal, integrated work control process for each project/facility
  - Definition of task
  - Identification of hazards
  - Design of work controls
  - Conduct of work
  - Feedback
- Each work process is authorized on the basis of a Research Safety Summary (RSS) reviewed by ESH subject matter experts and approved by PI's and cognizant managers
- RSS is reviewed/revised yearly, or sooner if a change in the work is needed
- Staff with approved training and experience are authorized through the RSS

Interesting Observations via Multiple Diagnostics

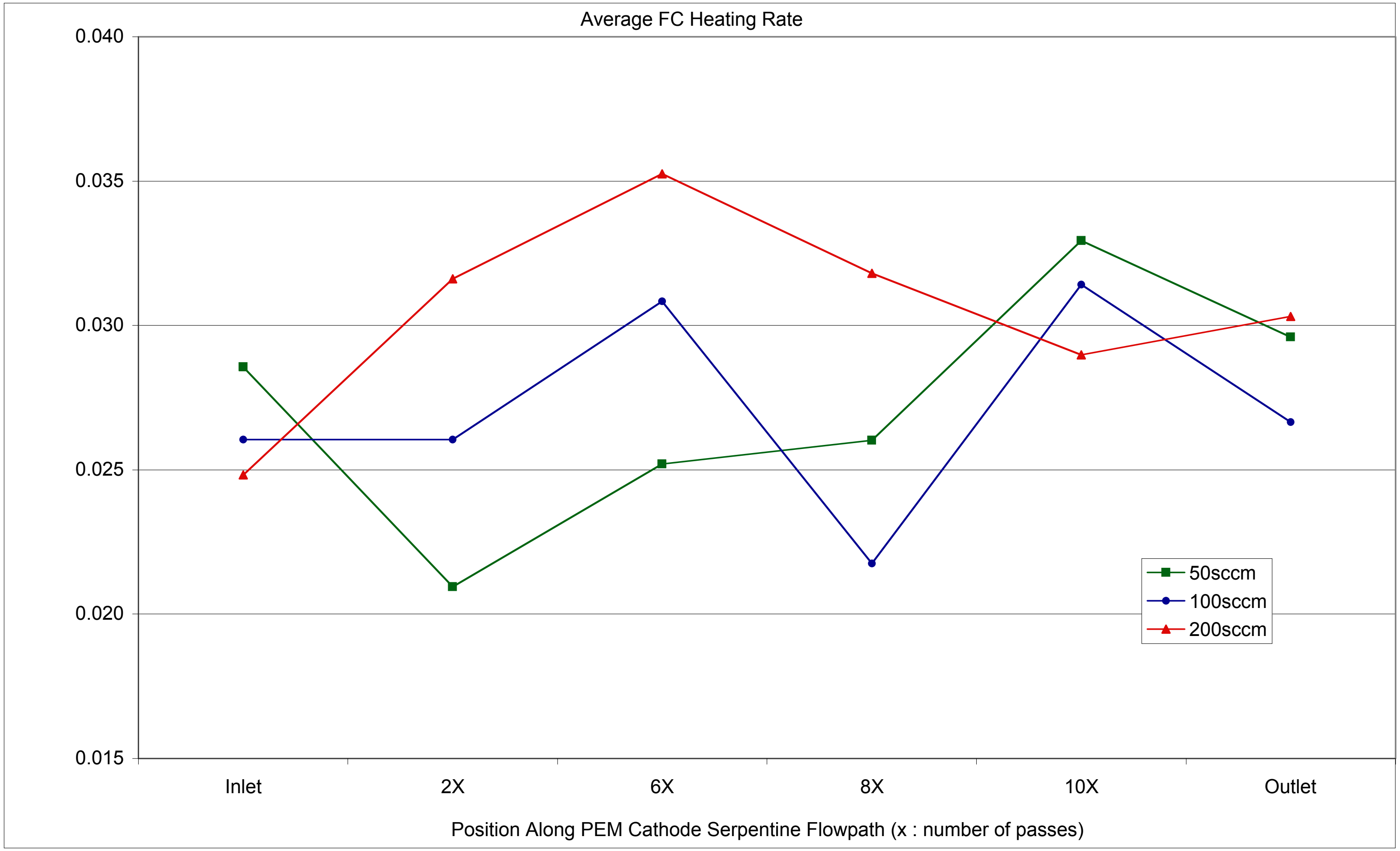








Under Differing Operational Conditions the Fuel Cell Thermal Profile Varies



Observed Power Output from Fuel Cell During Testing