# Fuel Cells Systems Analysis

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2013 DOE Hydrogen and Fuel Cells Program Review

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**Project ID: FC017**

# Overview

## Timeline

- Start date: Oct 2003
- End date: Open
- Percent complete: NA

## Barriers

B. Cost

C. Performance

E. System Thermal and Water Management

F. Air Management

J. Startup and Shut-down Time, Energy/Transient Operation

## Budget

- FY13 funding: $400K
  DOE share: 100%
- FY12 funding: $600K

## Partners/Interactions

- Eaton, Gore, Ford, dPoint
- SA
- 3M, Nuvera
- ISO-TC192 WG12, JARI, LANL
- IEA Annexes 22 and 26
- Transport Modeling Working Group
- U.S. DRIVE fuel cell tech team

- This project addresses system, stack and air management targets for efficiency, power density, specific power, transient response time, cold start-up time, start up and shut down energy

# Objectives and Relevance

Develop a validated system model and use it to assess design-point, part-load and dynamic performance of automotive and stationary fuel cell systems.

- Support DOE in setting technical targets and directing component development
- Establish metrics for gauging progress of R&D projects
- Provide data and specifications to DOE projects on high-volume manufacturing cost estimation

# Approach

Develop, document & make available versatile system design and analysis tools.

- GCtool: Stand-alone code on PC platform
- GCtool-Autonomie: Drive-cycle analysis of hybrid fuel cell systems

Validate the models against data obtained in laboratories and test facilities inside and outside Argonne.

- Collaborate with external organizations

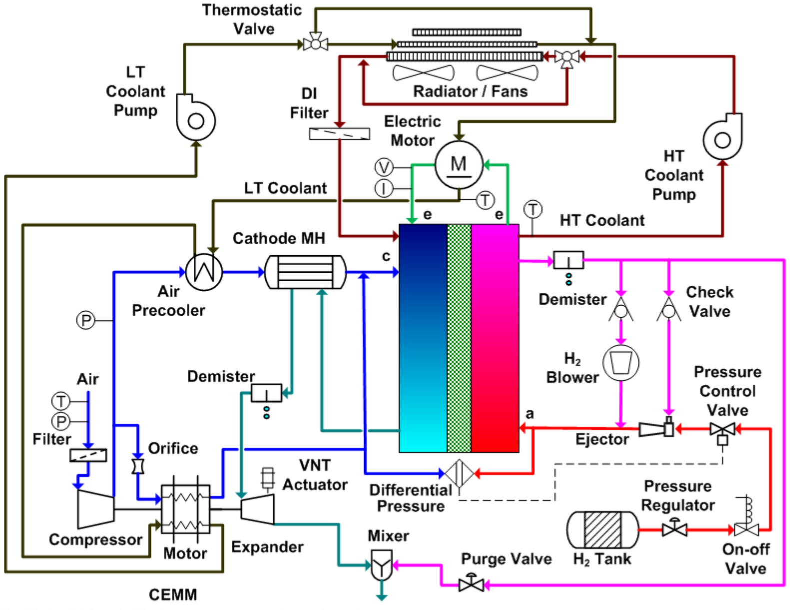
Apply models to issues of current interest.

- Work with U.S. DRIVE Technical Teams
- Work with DOE contractors as requested by DOE

# Summary: Technical Accomplishments

Validate and document models for pressurized (S1, 2.5-3.0 atm at rated power) and low-pressure (S2, 1.5 atm at rated power) configurations

- **Stack:** Collaborated with 3M in taking cell data to validate the model for NSTFC MEAs and stacks at pressures up to 3 atm
- **Air Management:** Collaborating with Eaton to develop and model Roots compressors, expanders and other components for fuel cells
- **Water Management:** Collaborated with Gore, dPoint and Ford to validate the model for a cross-flow humidifier using Gore’s sandwich membrane structure
- **Fuel Management:** Collaborated with 3M and Ford to validate the model for anode subsystem, including impurity buildup and $H_2$ ejectors
- **System Analysis:** Updated and optimized system performance at rated power and part loads (FCS with Honeywell air system)

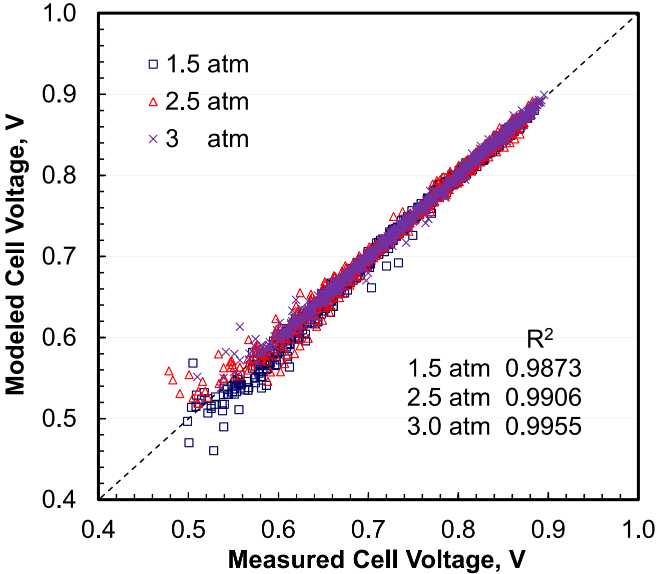


**Interim Argonne 2013 FCS**

# Stack Model Validation and Documentation

Collaboration with 3M to obtain reference performance data on 50-$cm^2$ cells with 3M MEAs and ternary NSTF catalyst: 0.05(a)/0.1(c) mg-Pt/$cm^2$

- Cathode Pt loadings, $L_{Pt}$(c): 0.054, 0.103, 0.146 and 0.186 mg/$cm^2$
- Pressures: 1.5, 2.5, 3.0, 1-2.5 atm
- Temperatures: 35 -90°C
- RH: 35-100%
- Anode stoichiometry ($SR_a$): 1.2-5
- Cathode stoichiometry ($SR_c$): 1.5-10
- $H_2$ pump tests for HOR kinetics: 0.7-2.5 atm $P_{H_2}$, 45-90°C

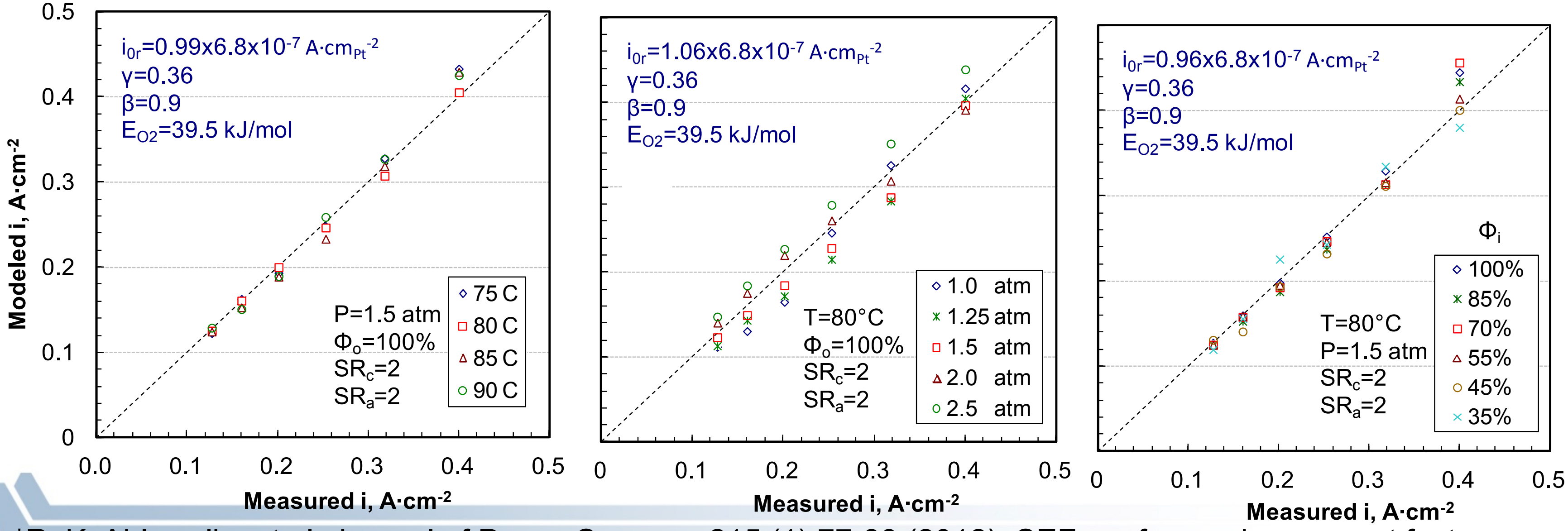


- Effect of $N_2$ dilution on anode mass transfer: 0-75% $N_2$ in $H_2$, 70-85°C, 1.5-2.5 atm pressure, 1.2-2 $SR_a$
- Dynamic response to step changes in cell current density
- ORR kinetics on NSTF catalyst
- Cathode mass transfer overpotentials
- Model validation and calibration

# ORR Kinetics on PtCoMn/NSTF

- Determined kinetic parameters for $P_{O_2}$, T and RH ($\Phi$) dependence ($\gamma$, $E_{O_2}$ and $\beta$) of ORR on NSTF catalyst ,and validated against the measured mass activities for eight cells with 0.054-0.186 $mg/cm^2$ Pt loading*

| Cell Designation | 19574 | 19577 | 19453 | 19478 | 19504 | 19524 | 19530 | 19531 |
|---|---|---|---|---|---|---|---|---|
| Pt Loading, $mg.cm^{-2}$ | 0.054 | 0.054 | 0.103 | 0.103 | 0.146 | 0.146 | 0.186 | 0.186 |
| ECSA, $m_{Pt}^2.g^{-1}$ | 12.4 | 12.6 | 9.8 | 9.8 | 9.2 | 8.4 | 7.2 | 7.0 |
| SEF, $cm_{Pt}^2.cm^{-2}$ | 6.7 | 6.8 | 10.1 | 10.1 | 13.4 | 12.2 | 13.4 | 13 |
| Catalyst Layer Thickness, μm | 0.16 ± 0.018 | | 0.32 ± 0.034 | | 0.47 ± 0.048 | | 0.61 ± 0.061 | |
| $H_2$ Crossover, $mA.cm^{-2}$ | 3.2 | 3.1 | 2.8 | 2.9 | 3.0 | 2.4 | 3.5 | 3.1 |
| Short Resistance, $\Omega\cdot cm^2$ | 588 | 267 | 933 | 664 | 182 | 216 | 340 | 379 |
| Absolute Activity, $mA.cm^{-2}$ | 11.3 | 13.5 | 17.6 | 18.8 | 23.5 | 23.3 | 25.5 | 24.1 |
| Mass Activity, $A.mg_{Pt}^{-1}$ | 0.21 | 0.25 | 0.17 | 0.18 | 0.16 | 0.16 | 0.14 | 0.13 |
| Specific Activity, $mA.cm_{Pt}^{-2}$ | 1.69 | 1.99 | 1.74 | 1.86 | 1.75 | 1.91 | 1.90 | 1.85 |



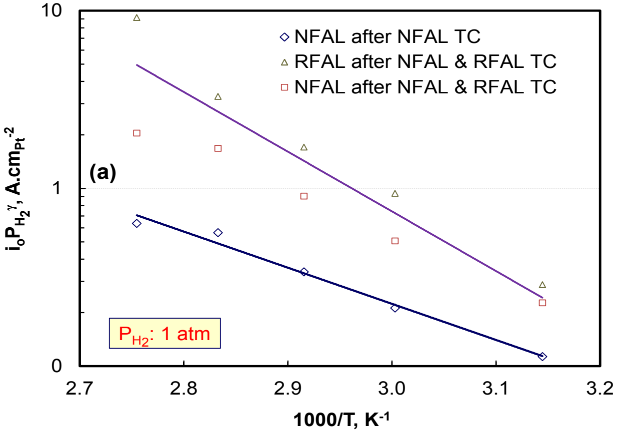
*R. K. Ahluwalia, et al, Journal of Power Sources, 215 (1) 77-88 (2012); SEF: surface enhancement factor

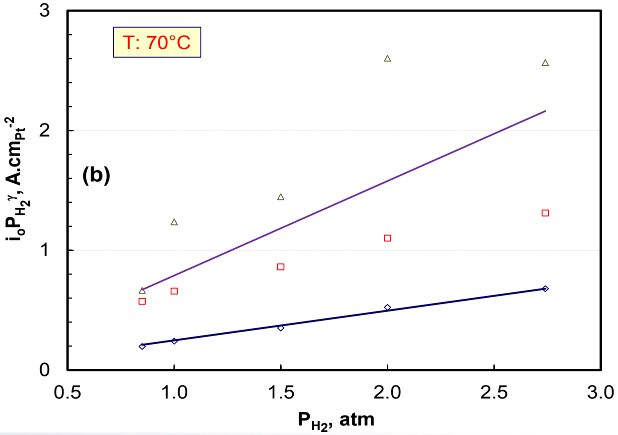
# HOR/HER Kinetics on PtCoMn/NSTF

Specific exchange current density for HOR/HER on NSTF catalyst with 0.05(a)/0.1(c) mg.cm$^{-2}$ Pt loading, measured in 50-cm$^2$ cell in $H_2$ pump mode, at 80°C is 60-110% higher than on Pt/C (NFAL conditioning). Four-fold increase in activity if anode conditioned more completely (RFAL)*.

- Oversaturated $H_2$: 45-80°C, 0.7-2.5 atm $P_{H_2}$, 1750 sccm $H_2$
- Anode outlet stream fed to cathode inlet, concurrent flow

| Catalyst / Support | Pt Loading mg.cm$^{-2}$ | Reaction | Catalyst Conditioning | T °C | $E_{HOR}$ kJ.mol$^{-1}$ | n | g | $i_0$ mA.cm$_{Pt}^{-2}$ |
|---|---|---|---|---|---|---|---|---|
| PtCoMn / NSTF[1] | 0.05 (a)<br>0.1 (c) | HOR | NFAL | 80 | 38.9 | 2 | 1 | 489 |
| PtCoMn / NSTF[2] | 0.05 (a)<br>0.1 (c) | HOR/HER | NFAL & RFAL | 80 | 64.3 | 2 | 1 | 2727±563 |
| 5 wt% Pt / Carbon[3] | 0.003 (a)<br>0.4 (c) | HOR/HER | | 80 | Not measured | 2 | Not Measured | 235-300 |

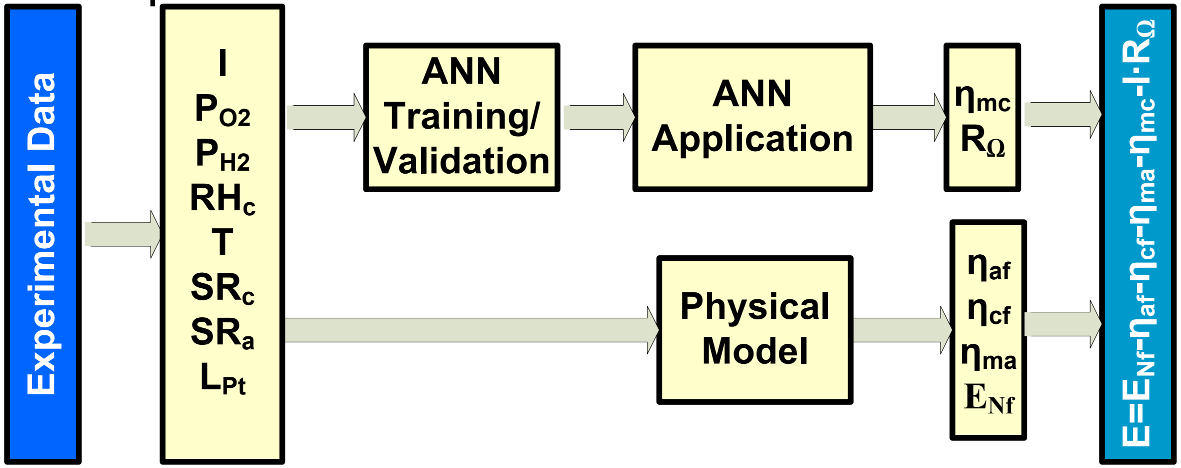




*X. Wang, R.K. Ahluwalia, and A.J. Steinbach, Journal of the Electrochemical Society, 160 (3) F251-F261 (2013).

# Cathode Mass Transfer in NSTF

- Artificial Neural Network (ANN) model for cathode mass transfer overpotential ($\eta_{mc}$) and high-frequency resistance (HFR)
- Multilayer Perceptron (MLP) Feed-Forward Network with one hidden layer and 20 neurons, hyperbolic tangent activation function
- Separate sets of weights and biases for 1.5, 2.5 and 3 atm data and for part-load performance



**Experimental Data**

$I$, $P_{O2}$, $P_{H2}$, $RH_c$, $T$, $SR_c$, $SR_a$, $L_{Pt}$

**ANN Training/ Validation**

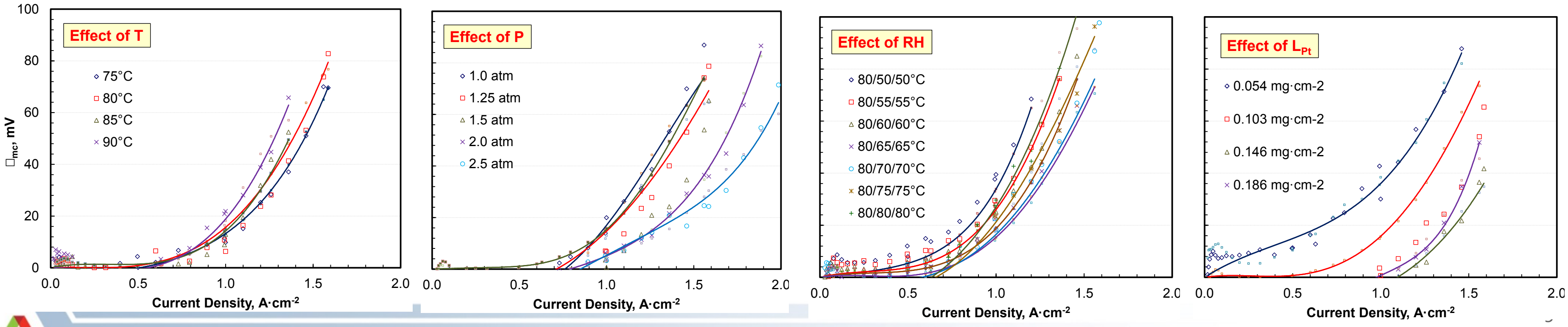
**ANN Application**

$\eta_{mc}$, $R_\Omega$

**Physical Model**

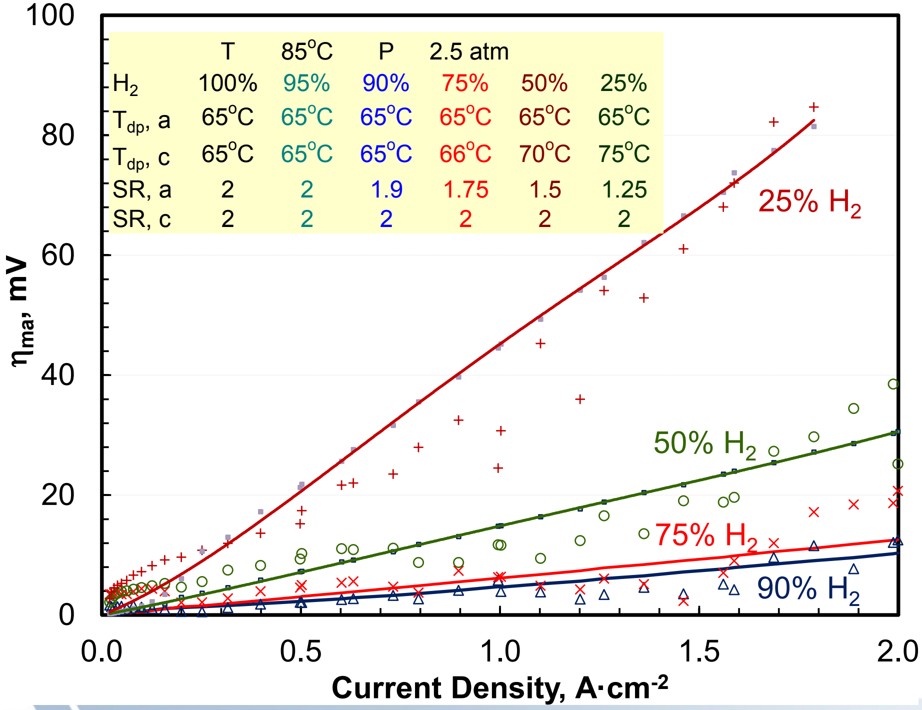
$\eta_{af}$, $\eta_{cf}$, $\eta_{ma}$, $E_{Nf}$

$E = E_{Nf} - \eta_{af} - \eta_{cf} - \eta_{ma} - \eta_{mc} - I \cdot R_\Omega$

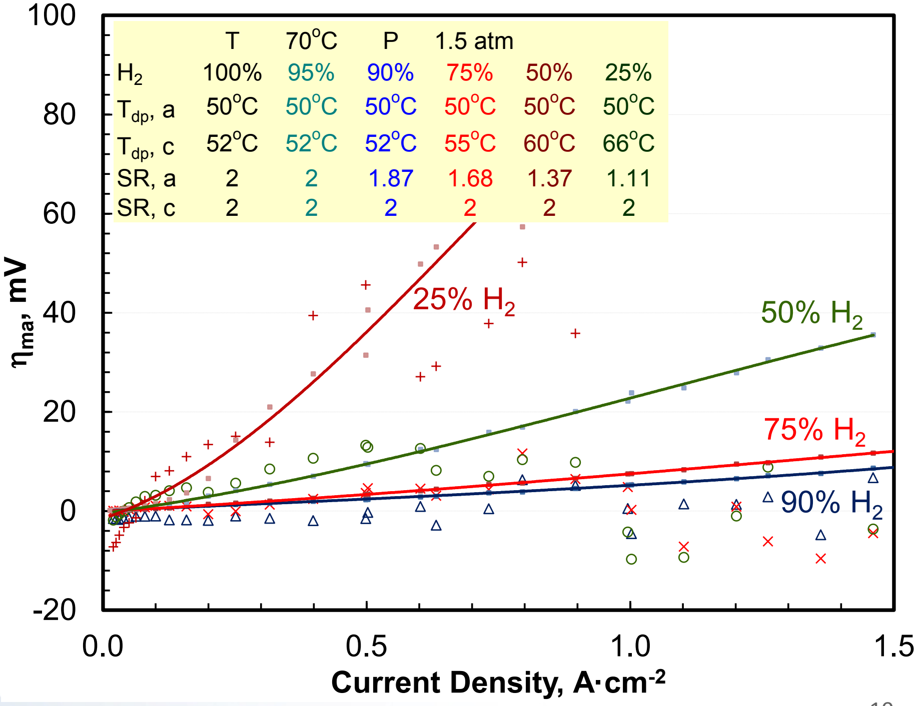


# Anode Mass Transfer in NSTF

- Determined mass transfer overpotentials ($\eta_{ma}$) from tests: 0-75% $N_2$ in $H_2$, variable anode stoichiometry and cathode dew points, 70-85°C, 1.5-2.5 atm.
- Derived and correlated anode mass transfer coefficient as a function of Reynolds number, P, T and $H_2$ fraction.
- Identified performance losses due to HOR kinetics, anode mass transfer, and decrease in Nernst potential.



|  | T | 85°C | P | 2.5 atm |  |  |
|---|---|---|---|---|---|---|
| $H_2$ | 100% | 95% | 90% | 75% | 50% | 25% |
| $T_{dp}$, a | 65°C | 65°C | 65°C | 65°C | 65°C | 65°C |
| $T_{dp}$, c | 65°C | 65°C | 65°C | 66°C | 70°C | 75°C |
| SR, a | 2 | 2 | 1.9 | 1.75 | 1.5 | 1.25 |
| SR, c | 2 | 2 | 2 | 2 | 2 | 2 |

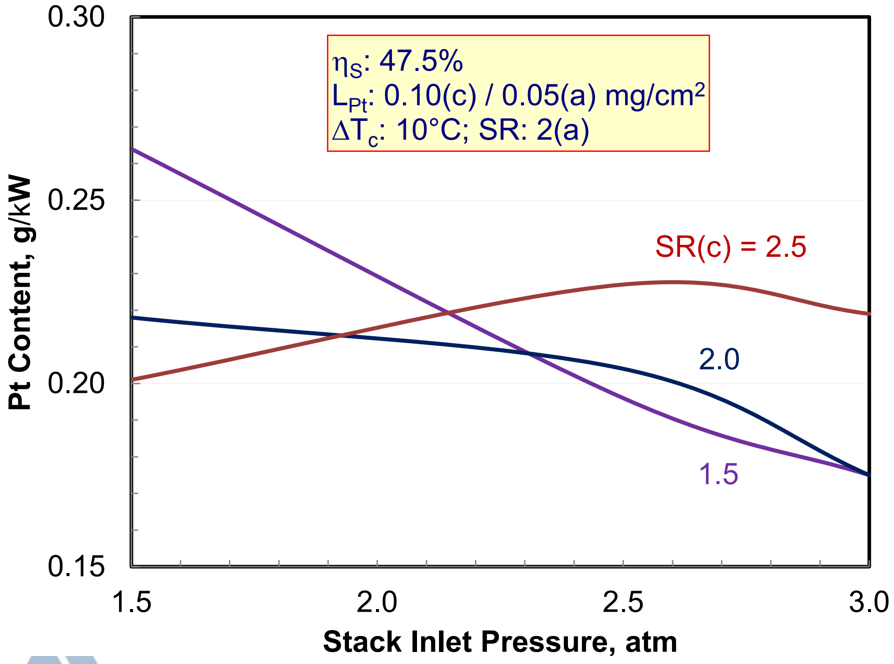


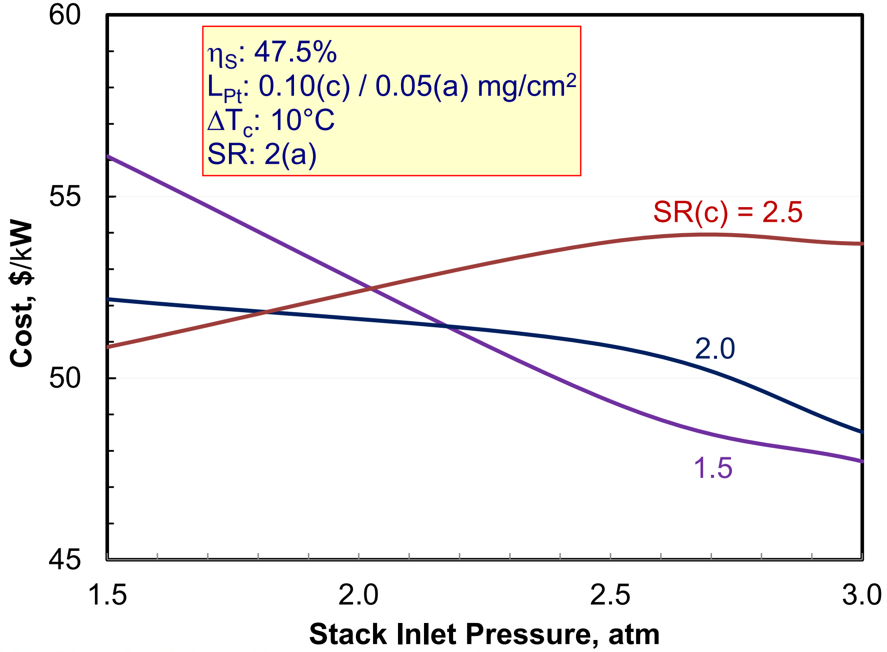
|  | T | 70°C | P | 1.5 atm |  |  |
|---|---|---|---|---|---|---|
| $H_2$ | 100% | 95% | 90% | 75% | 50% | 25% |
| $T_{dp}$, a | 50°C | 50°C | 50°C | 50°C | 50°C | 50°C |
| $T_{dp}$, c | 52°C | 52°C | 52°C | 55°C | 60°C | 66°C |
| SR, a | 2 | 2 | 1.87 | 1.68 | 1.37 | 1.11 |
| SR, c | 2 | 2 | 2 | 2 | 2 | 2 |

# Pt Content and System Cost – Interim 2013 FCS

Two-variable optimization study to determine stack T (exit coolant T) and inlet $RH_c$ for lowest system cost* for specified $SR_c$ and system efficiency, $27^oC$ ambient temperature

- Optimum stack T depends on the operating P and $SR_c$
- Optimum $SR_c$: 2.5 for P < 1.8 atm, 2 for 1.8 < P < 2.2 atm, 1.5 for P >2.2 atm
- Assumed CEM performance: 71% compressor, 73% expander, 80% combined motor & motor-controller



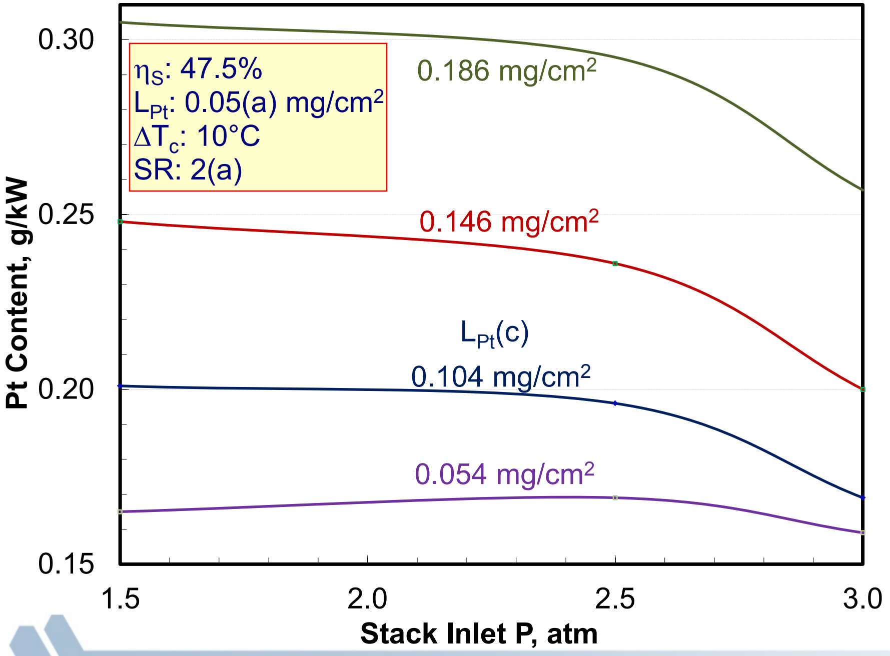


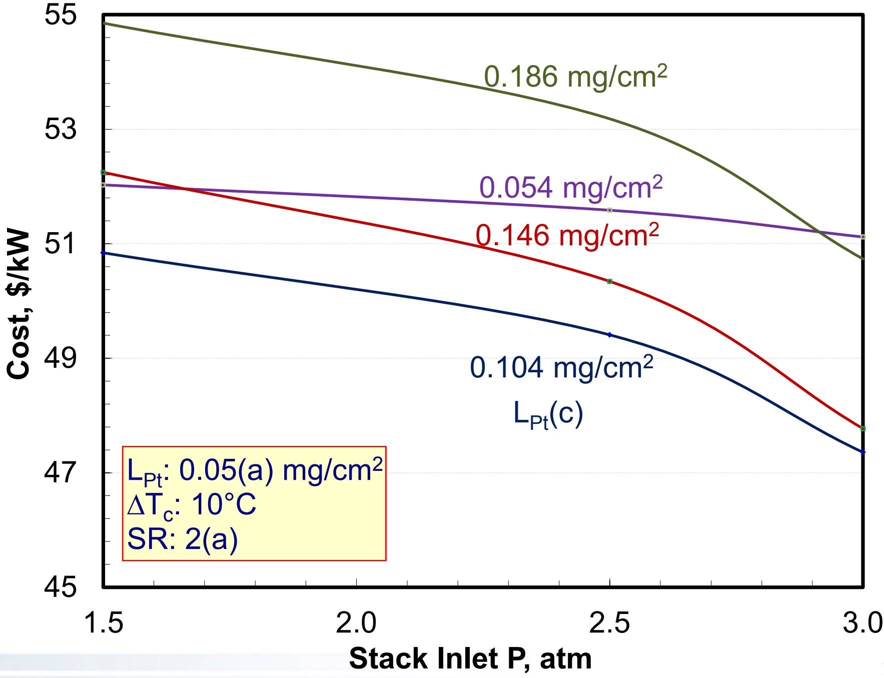
*Cost estimates from SA correlations for high volume manufacturing

# Optimum Pt Loading in NSTF Cathode Catalyst

Three-variable optimization study to determine the combination of stack T, inlet $RH_c$ and $SR_c$ for lowest system cost for specified Pt loading in cathode catalyst ($L_{Pt}$(c)) and system efficiency, 27°C ambient temperature

- Lowest Pt content with 0.05 mg/cm$^2$ Pt loading in cathode catalyst
- Lowest system cost with 0.1 mg/cm$^2$ Pt loading in cathode catalyst
- Stack and BOP contribute almost equally to the system cost. Raising pressure increases power density even though higher cell V required for specified system efficiency.



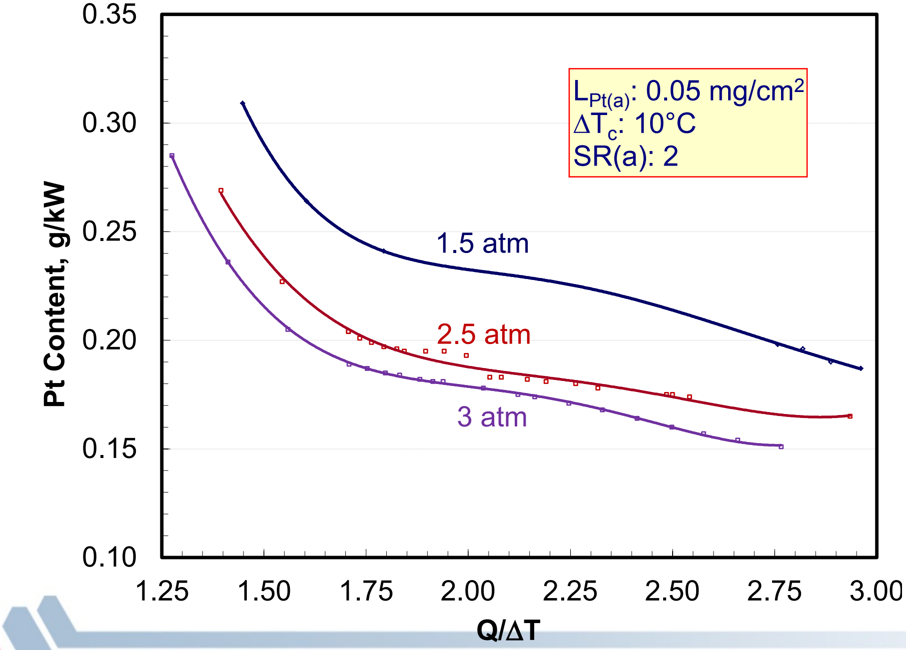


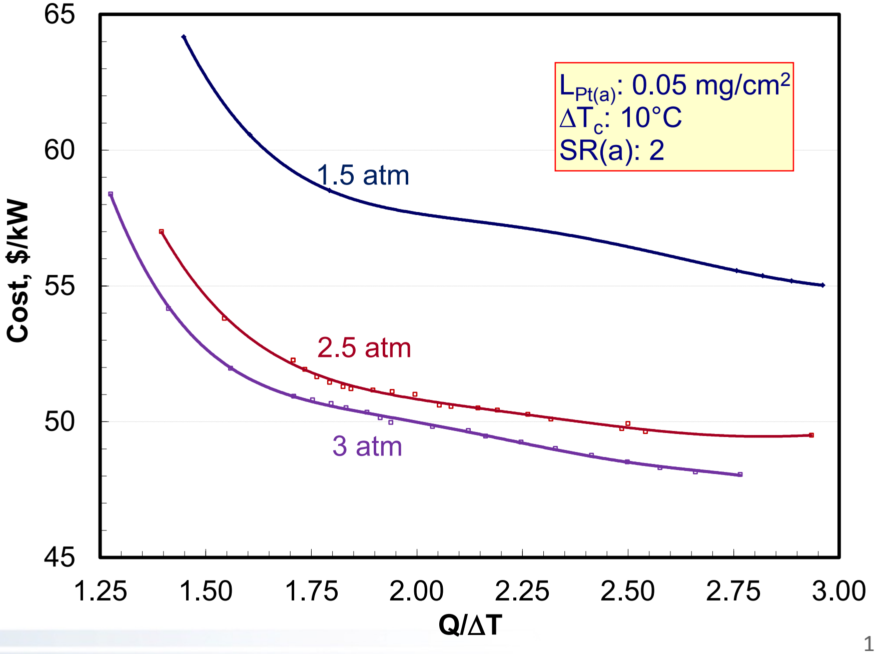
# Heat Rejection – Q/ΔT

Multi-variable optimization study for lowest system cost

- Raising stack T to 95°C to meet Q/ΔT constraint results in higher costs (2.5 atm inlet pressure, 40°C ambient temperature)

| Minimum cost subject to Q/ΔT constraint, 95°C maximum stack temperature, 40°C ambient temperature ($T_{amb}$) | | | | | Minimum cost, given system efficiency, $T_{amb}$ = 27°C | |
|---|---|---|---|---|---|---|
| Q/ΔT | System | Cell V | Pt Content | Cost | Pt Content | Cost |
| kW/K | Eff.,% | mV | g/kW | \$/kW | g/kW | \$/kW |
| 3.0 | 40 | 563 | 0.19 | 54.9 | 0.16 | 46.8 |
| 1.7 | 45 | 640 | 0.20 | 52.3 | 0.18 | 47.9 |
| 1.5 | 47.5 | 670 | 0.23 | 53.8 | 0.20 | 49.2 |
| 1.4 | 50 | 700 | 0.27 | 57.0 | 0.23 | 52.3 |

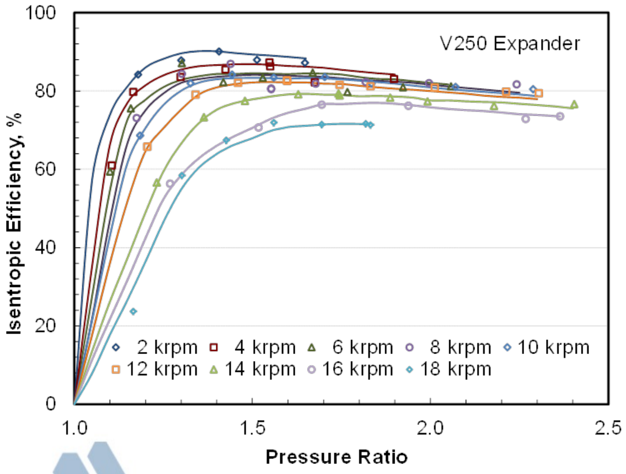


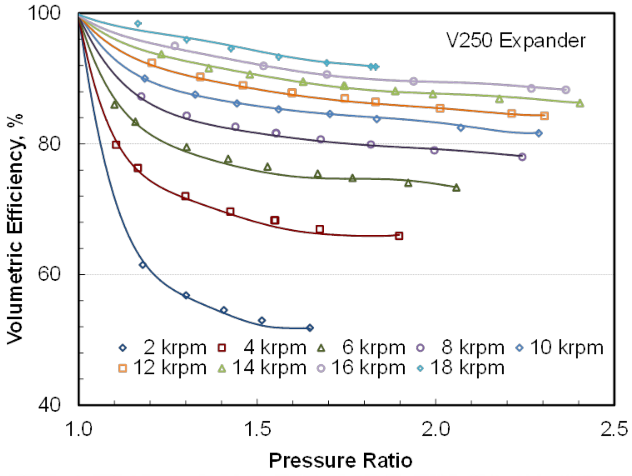


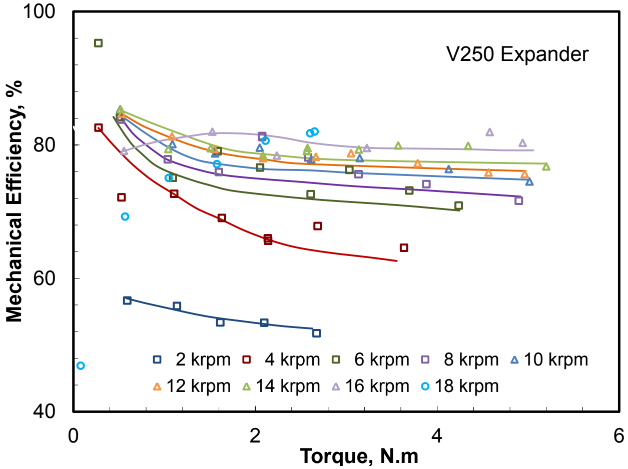
# Air Management System: Roots Compressor and Expander

Collaborating with and providing modeling and system analysis support to Eaton’s project. Eaton is still designing the components for fuel cells, but has provided data to help ANL in preparing models.

- Formulated thermodynamic models for Roots blowers and expanders
- Developed performance maps for off-the-shelf Roots compressors: isentropic efficiency, volumetric efficiency, and mechanical efficiency
- Developed performance maps for the first-generation Roots expander: isentropic efficiency, volumetric efficiency, and mechanical efficiency
- Developed performance map for a commercial motor and motor-controller





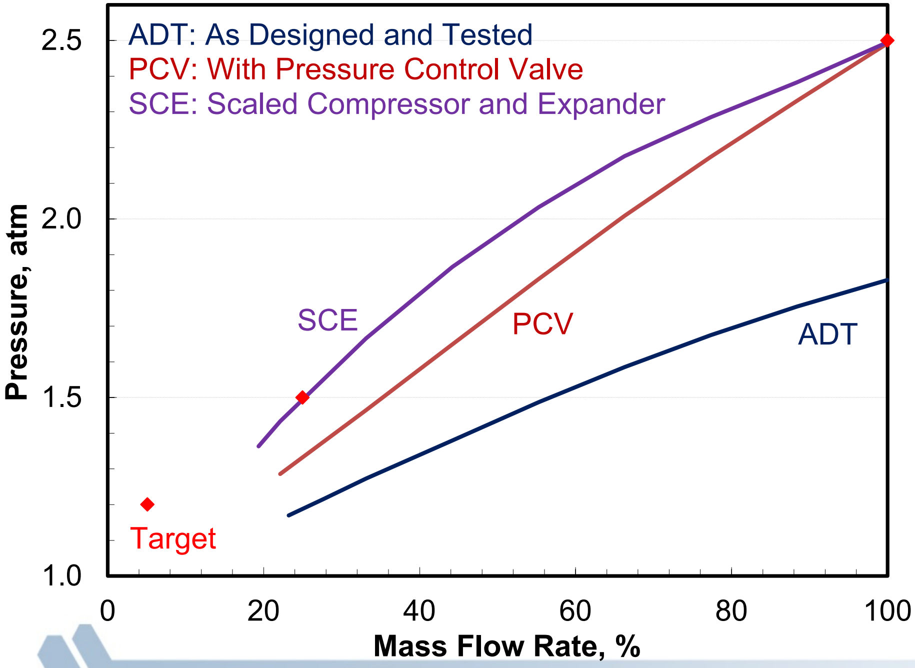


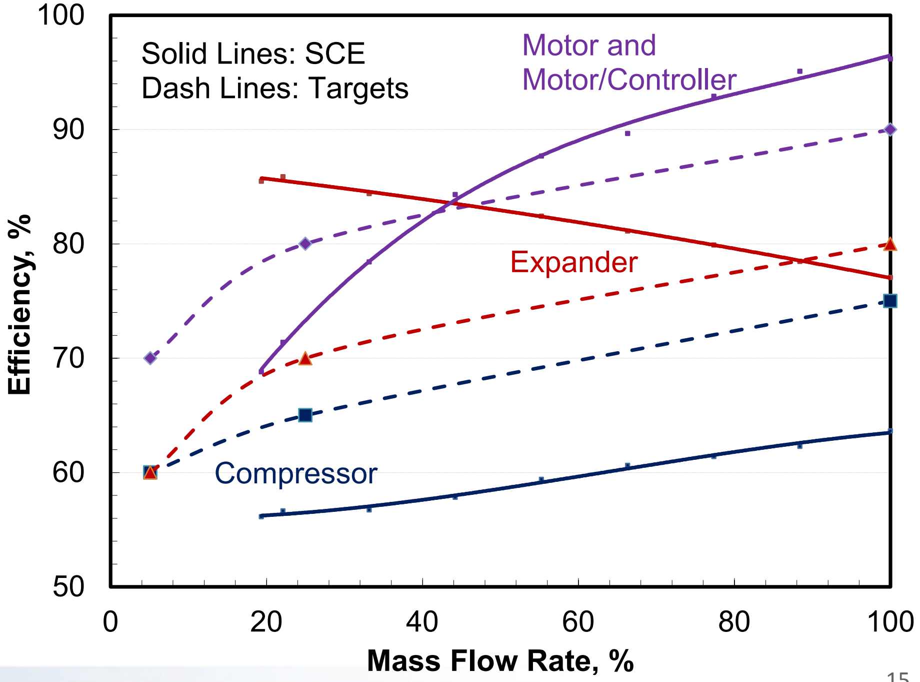
# Air Management System – Preliminary Performance

Preliminary assessment of a compressor-expander module* using model and available maps of components, all mounted on a single shaft

- ANL Configuration ADT: As tested Roots compressor, expander, and motor and motor-controller
- ANL Configuration PCV: PCV upstream of expander
- ANL Configuration SCE: Scaled compressor and expander

| | Parasitic Power (kW) | | |
|---|---|---|---|
| Flow Rate | 100% | 25% | Idle |
| Status: Centrifugal | 11.0 | 2.3 | 0.6 |
| Status: Modeled Roots | 11.4 | 2.0 | |
| DOE Target | 8.0 | 1.0 | 0.2 |



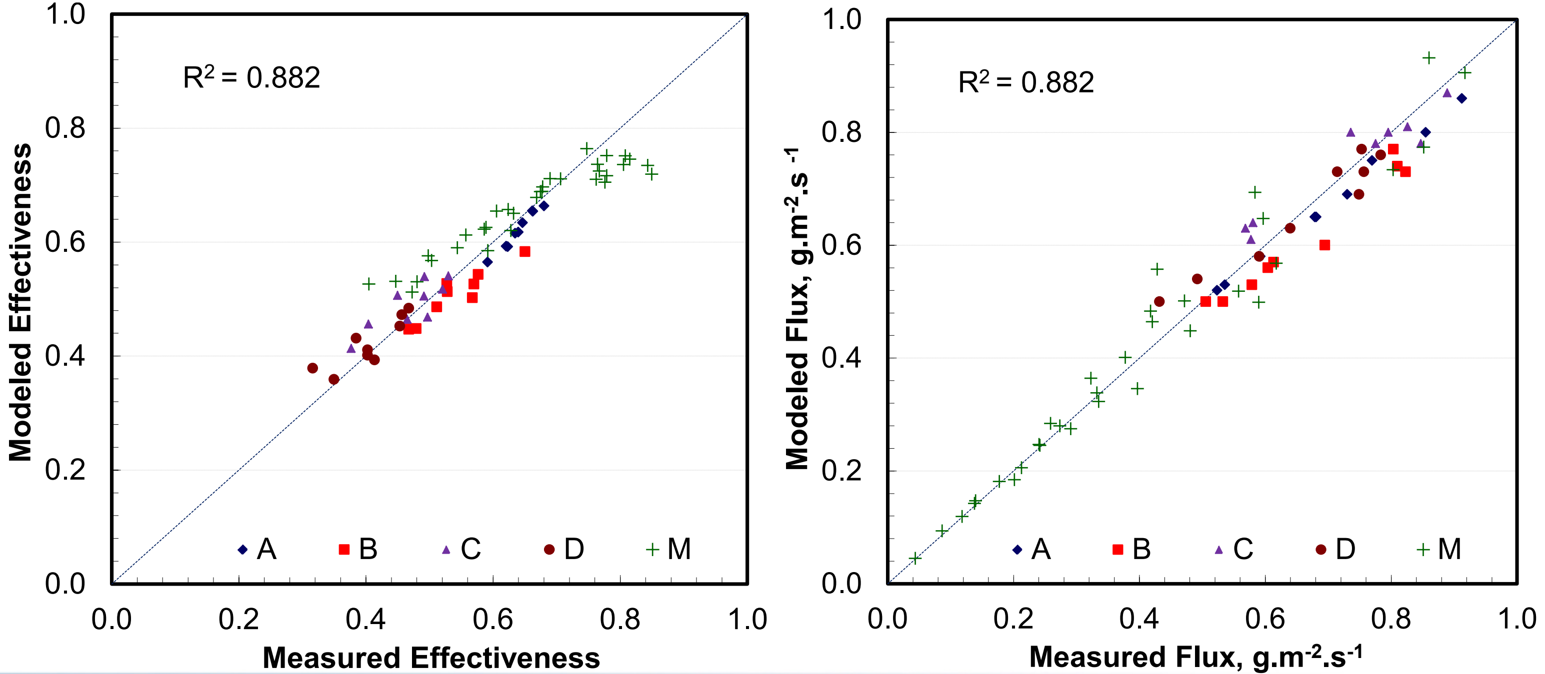


***Eaton is assessing other design and integration options**

# Water Management System

Collaboration with Gore, Ford and dPoint to develop and validate a model for a cross-flow (or counter-flow) humidifier with Gore 311.05 membrane

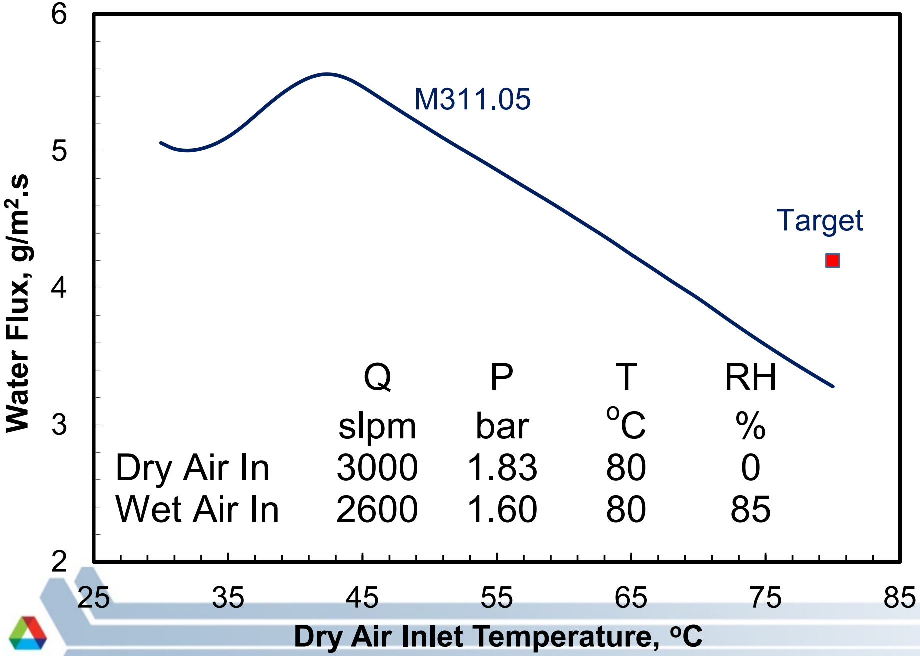
- 2-D finite-difference model for heat and mass transfer with $\Delta P$
- Literature data for water uptake and water diffusivity in the ionomer
- Gas phase, interfacial and ePTFE resistances derived from static and dynamic permeation tests (W.B. Johnson, FC067)
- Validated against Ford data for a full-scale unit, 10-100% flow rates, 1.2-2.3 atm, 30-70°C temperature range, 40-90% RH



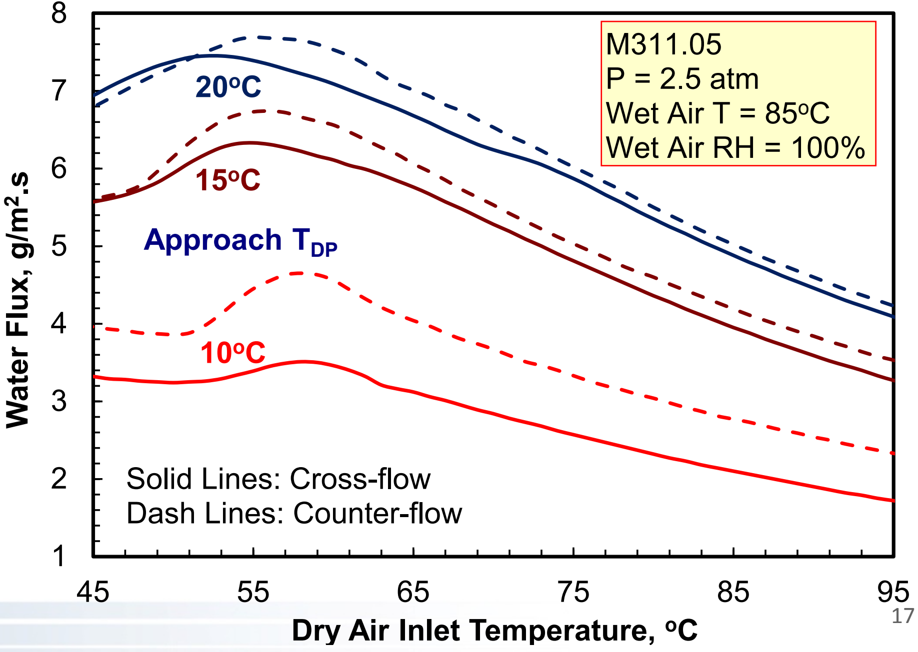
**Effectiveness: Fraction of water in wet stream that is transferred to dry stream**

# Assessment of Humidifier Performance

- The cross-flow humidifier with M311.05 membrane meets the DOE target of 4.2 g.m$^{-2}$.s$^{-1}$ at stipulated conditions (including 11$^{o}$C approach dew point temperature) if the inlet dry air is cooled below 65$^{o}$C.
  - ➢ Additional targets for cost, weight, volume, maximum operating T and pressure differential, pressure drop, air leakage and durability
- Depending on approach $T_{dp}$, water flux can be 10-30% higher with counter-flow than cross-flow
- With dry air pre-cooled to < 73$^{0}$C, water flux exceeds 5 g.m$^{-2}$.s$^{-1}$ at 2.5 atm and 15$^{o}$C approach dew-point temperature



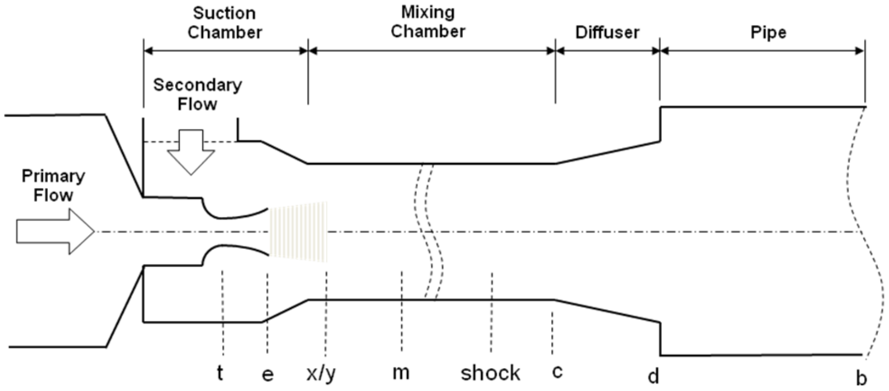
| | Q | P | T | RH |
|---|---|---|---|---|
| | slpm | bar | °C | % |
| Dry Air In | 3000 | 1.83 | 80 | 0 |
| Wet Air In | 2600 | 1.60 | 80 | 85 |

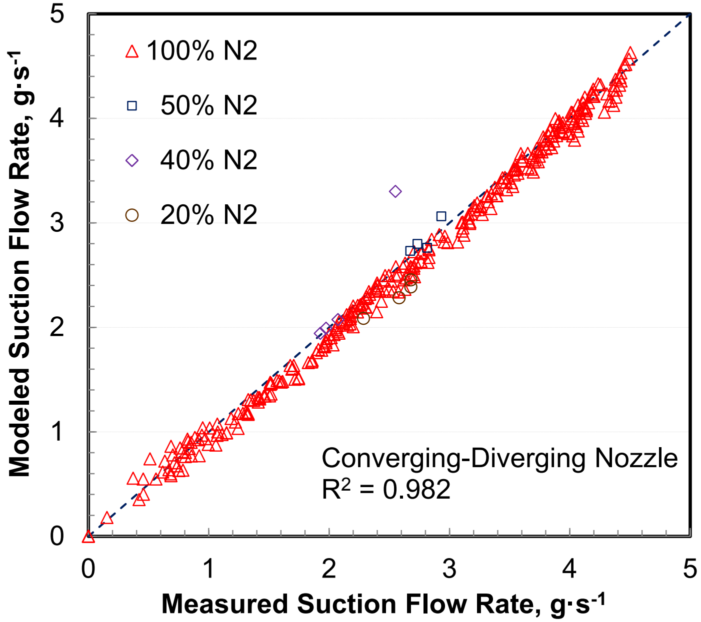


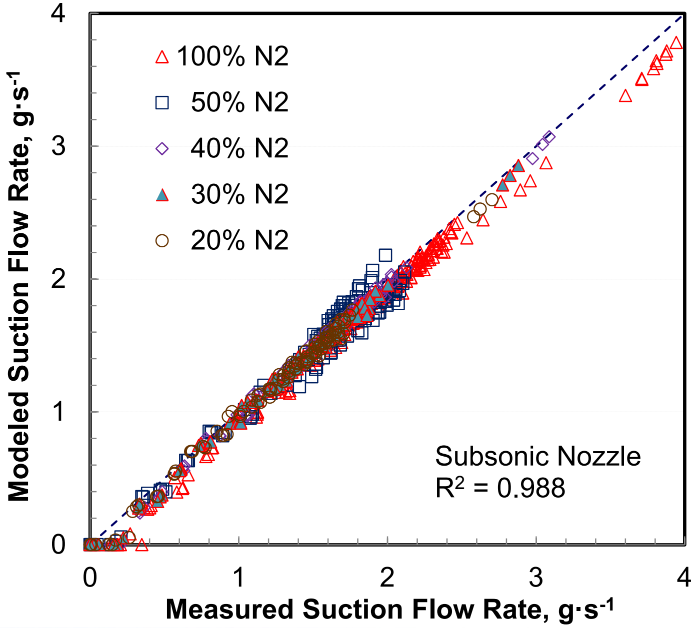
# Fuel Management

Collaborated with Ford to develop and validate a model for $H_2$ ejectors with converging-diverging and subsonic nozzles

- Flow choked at nozzle throat, supersonic flow at nozzle exit; oblique shock at inlet to mixing section
- Flow choked at nozzle throat, normal shock inside nozzle
- Subsonic flow in nozzle







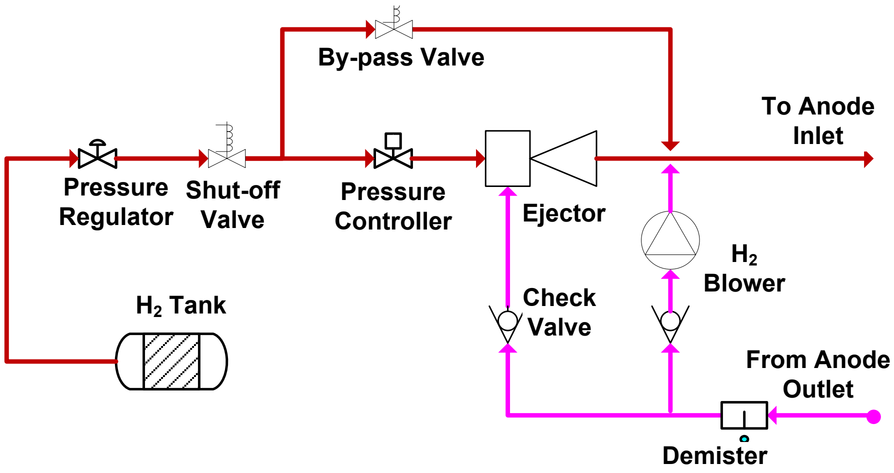
# Performance of Fuel Management System

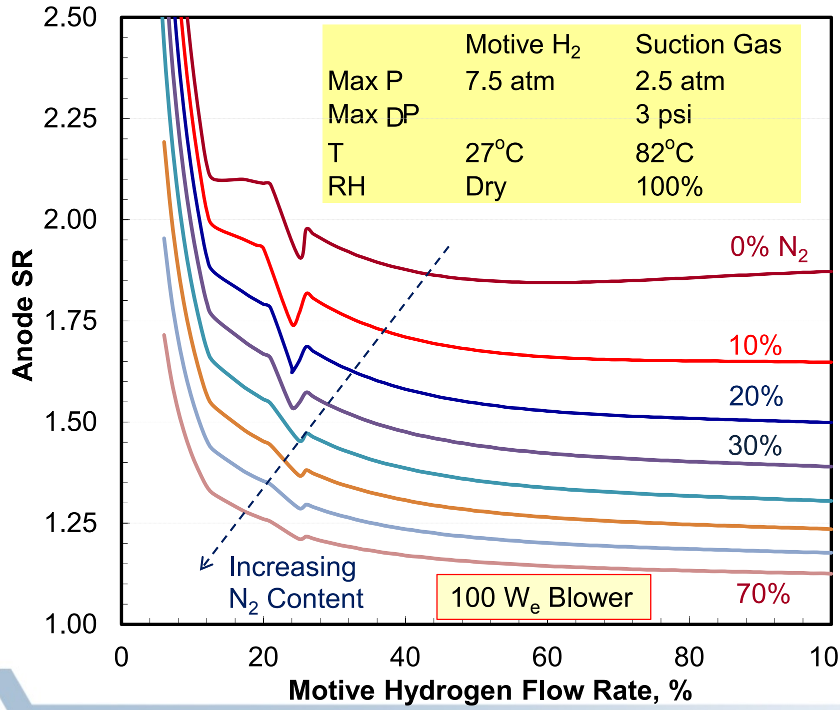
1. Hybrid ejector-blower system

- Variable inlet pressure with bypass valve to admit additional hydrogen during anode purge

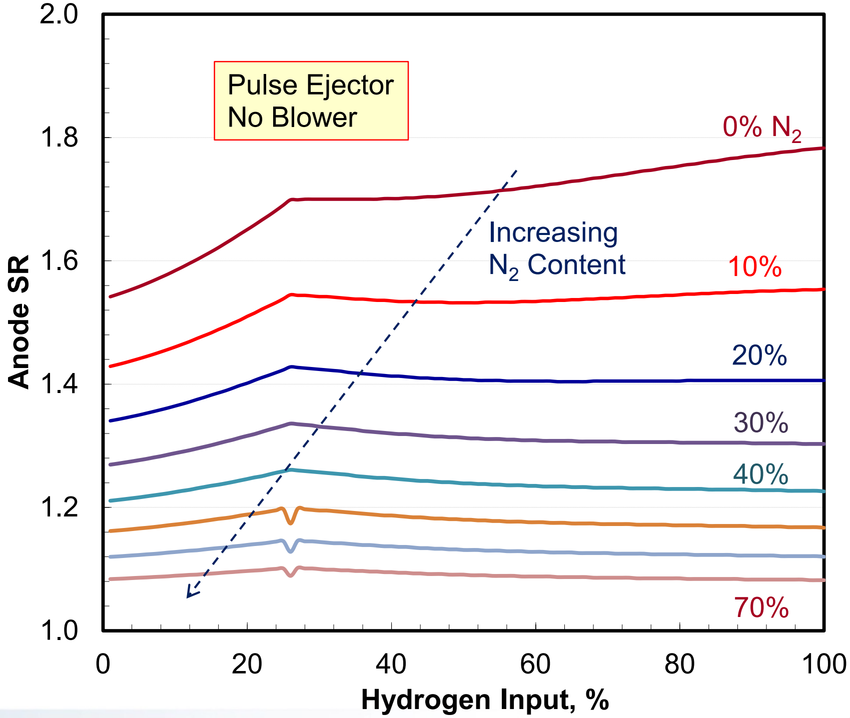
2. Anode system without a blower

- Variable pulse frequency and pulse width*





| | Motive $H_2$ | Suction Gas |
|---|---|---|
| Max P | 7.5 atm | 2.5 atm |
| Max DP | | 3 psi |
| T | 27°C | 82°C |
| RH | Dry | 100% |



*R. Senner, D. C. Di Flore, Injector Control for Fuel Cell Systems, Patent US 8,389,168, March 5, 2013

# Collaborations

| | |
|---|---|
| Air Management | Eaton |
| Stack | 3M, Nuvera |
| Water Management | Gore, Ford, dPoint |
| Thermal Management | Honeywell Thermal Systems |
| Fuel Management | 3M, Ford |
| Fuel Economy | ANL (Autonomie) |
| $H_2$ Impurities | 3M, ISO-TC-192 WG |
| System Cost | SA |
| Dissemination | IEA Annex 22 and 26, Transport Modeling Working Group |

- Argonne develops the fuel cell system configuration, determines performance, identifies and sizes components, and provides this information to SA for high-volume manufacturing cost estimation
- Conducting joint life-cycle cost studies with SA

# Future Work

1. Support DOE development effort at system, component, and phenomenological levels
2. Support SA in high-volume manufacturing cost projections, collaborate in life-cycle cost studies
3. Alternate MEAs with advanced alloy catalysts
    - De-alloyed PtNi on NSTF (3M collaboration)
    - De-alloyed PtNi on corrosion-resistant carbon support (ANL catalyst project with JM and UTRC as partners)
4. Balance-of-plant components
    - Air management system with Roots compressors and expanders (Eaton collaboration)
    - Elevated temperature operation for heat rejection, Q/ΔT target (collaboration with OEM)
    - Simplified anode system, pulsed ejectors/purge (OEM collaboration)
5. Incorporate durability considerations in system analysis
6. System optimization for cost, performance, and durability
    - Drive cycle simulations for durability enhancement

# Project Summary

| | |
|---|---|
| Relevance: | Independent analysis to assess design-point, part-load and dynamic performance of automotive and stationary FCS |
| Approach: | Develop and validate versatile system design and analysis tools<br>Apply models to issues of current interest<br>Collaborate with other organizations to obtain data and apply models |
| Progress: | Extended the NSFC stack model to 3 atm; validated the earlier conclusion that Pt content and FCS cost can be reduced to less than 0.2 g/kW and \$50/kW<br>Modeled Roots compressors and expanders; established base-line performance of integrated unit with different configurations<br>Validated the humidifier model against data for a full-size unit to show that Gore M311.05 membrane can achieve >4.2 $g/m^2/s$ water flux with pre-cooling<br>Obtained initial results on the effect of $Q/\Delta T$ on Pt content and system cost<br>Extended and validated the model for hydrogen ejectors |
| Collaborations: | 3M, dPoint, Eaton, Ford, Gore, SA, ANL (Autonomie) |
| Future Work: | Fuel cell systems with emerging de-alloyed catalysts<br>Alternate balance-of-plant components<br>System analysis with durability considerations on drive cycles |

# Technical Backup Slides

# Cell Averaged PtCoMn/NSTF ORR Kinetics

- Series A data for low current densities, < 0.5 A.cm$^{-2}$, small mass transfer effects
  - Challenges: more than 1 parameter varying at a time, finite utilization, variability in data
  - Two step approach for determining Tafel equation parameters: cell-averaged kinetics, local kinetics

$$i + i_x = i_0 A_{Pt} L_{Pt} P_{O_2}^{\gamma} \Phi^{\beta} \exp(\frac{\alpha n F}{RT}\eta) \qquad i_0 = i_{or} \exp[-\frac{E_{O_2}}{R}(\frac{1}{T}-\frac{1}{T_r})]$$

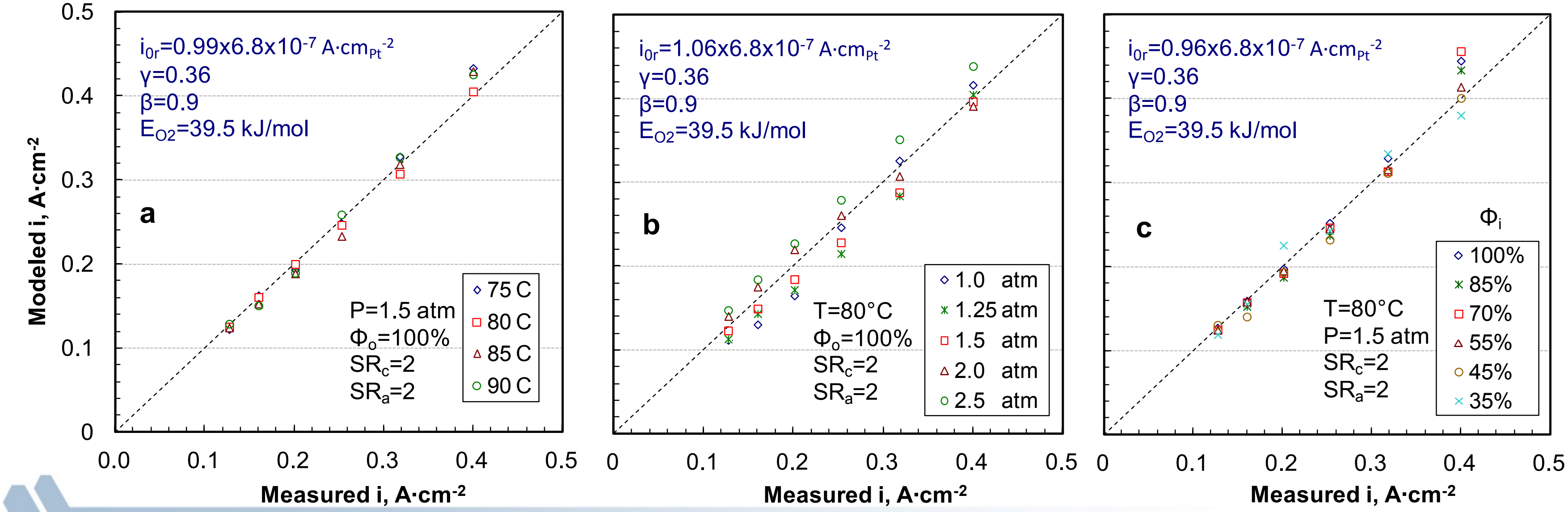
- Stepwise procedure for determining cell-averaged kinetic parameters
  - Dependence on average $P_{O_2}$ from series 2 data at 80°C, 50% $O_2$ utilization, 100% RH at cell exit ($\gamma$ = 0.36)
  - Dependence on T from Series 1 (and 2) data at 75-90°C, 50% $O_2$ utilization, 100% RH at cell exit ($E_{O_2}$ = 57.7 kJ/mol)
  - Dependence on RH from Series 3 (and 1) data for different exit RH ($\beta$ = 1.3), $\alpha = 0.4665/(1+0.0926\Phi)$

# Local PtCoMn/NSTF ORR Kinetics

- Formulated 1-D model for local values of *i*, $P_{O_2}$, $P_{H_2}$ and $\Phi$ from the measured polarization curves, JPS 215 (2012) 77-88
- Optimizer to determine $i_0$, $E_{O_2}$ and $\beta$
  - Unable to improve $\gamma$ because overpotentials not as sensitive to P
  - Unable to change $\alpha$ because of convergence issues (too sensitive)

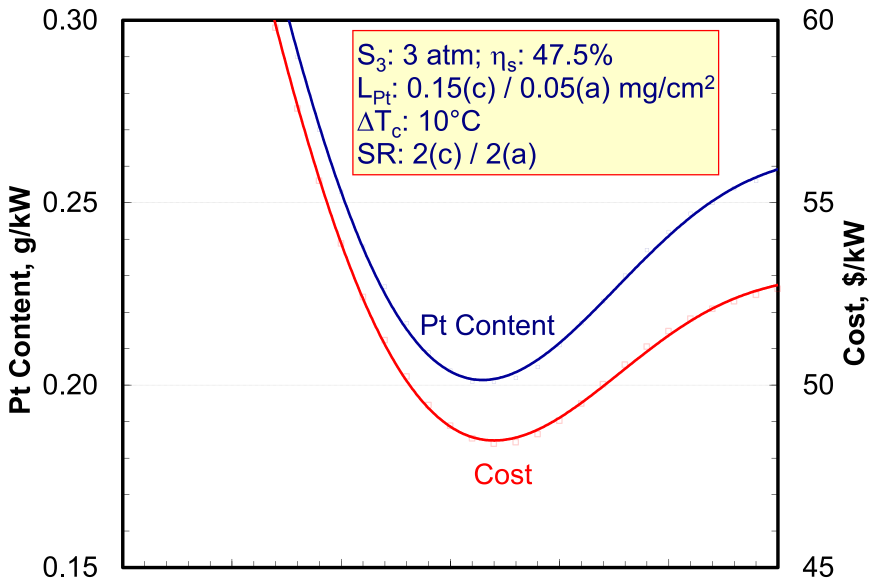
$i_{0r}$= 6.8x10$^{-7}$ A.cm$_{Pt}^{-2}$, $E_{O_2}$= 39.5 kJ.mol$^{-1}$

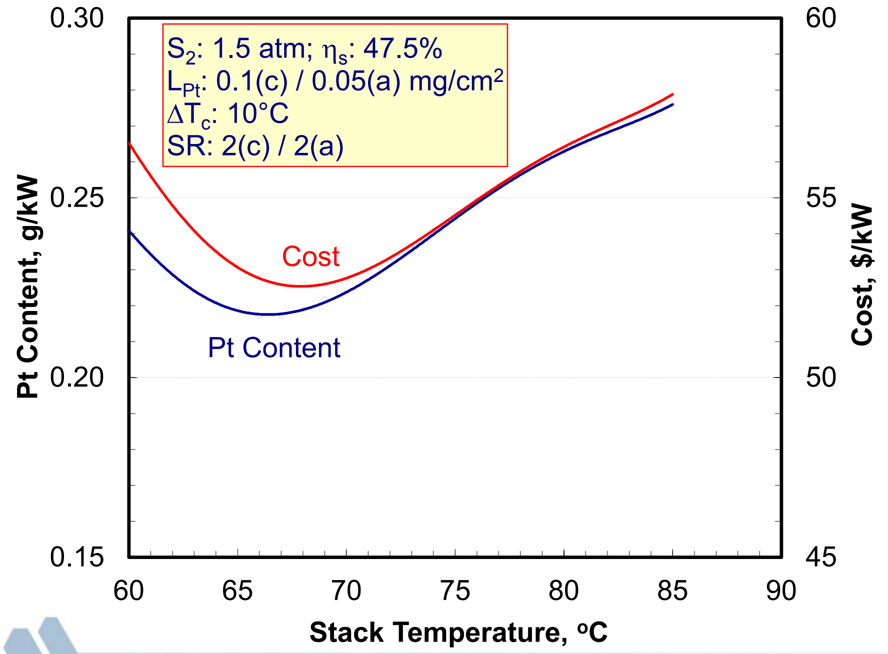
$$\beta = \begin{cases} 0.9 + 1.5(0.65 - \Phi) & \Phi < 0.65 \\ 0.9 & \Phi \geq 0.65 \end{cases}$$

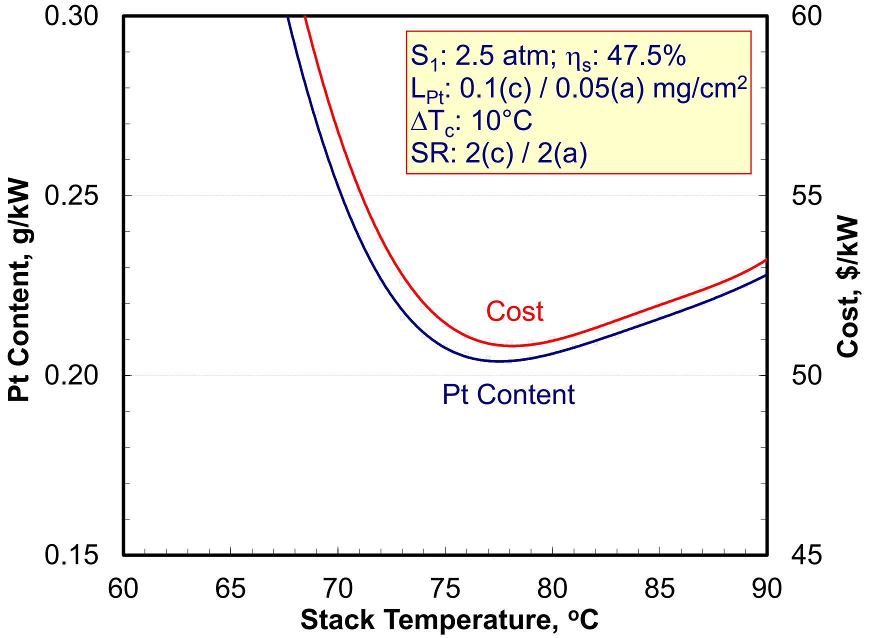


# Pt Content and System Cost

- Optimum stack T (exit coolant exit T) and inlet $RH_c$ at which the Pt content and the system cost* are lowest depend on the operating P
- At optimum stack T, Pt content and system cost are lower at 2.5 and 3 atm operating P



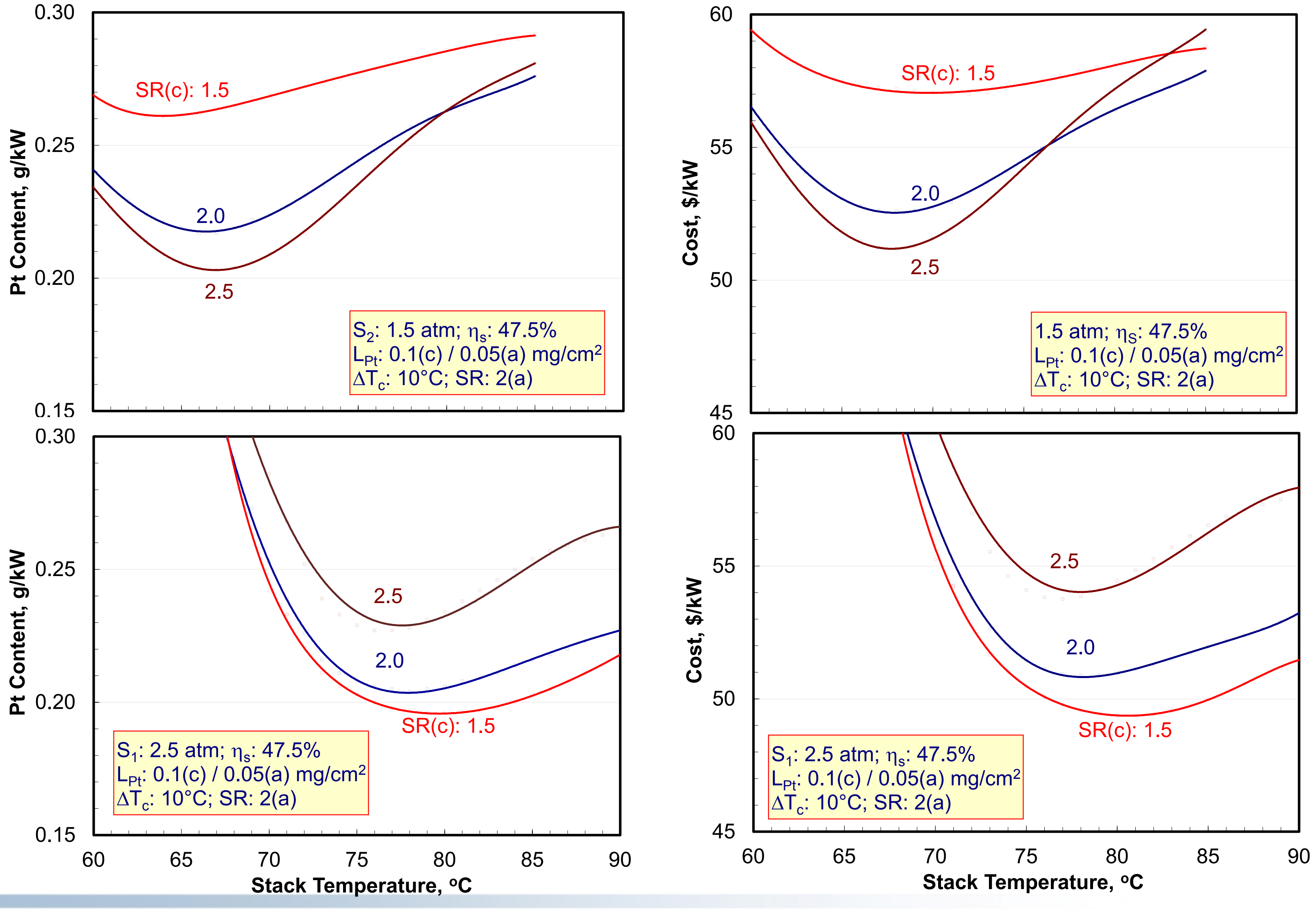




***Cost estimates from SA correlations for high volume manufacturing**

# Optimum Cathode Stoichiometry

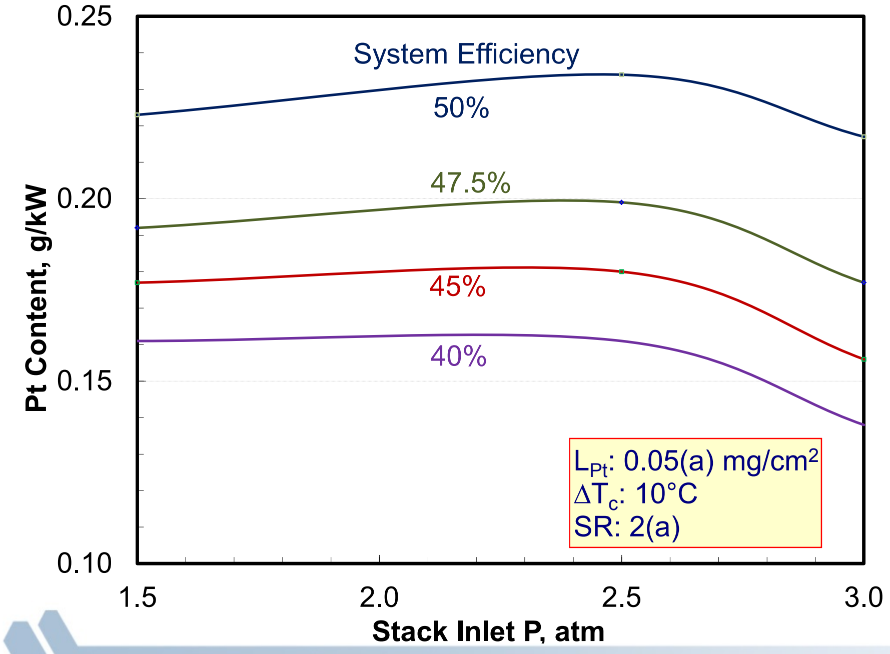
Optimum stoichiometry and is smaller at higher operating pressures: 1.5 at 2.5-3 atm and 2.5 at 1.5 atm

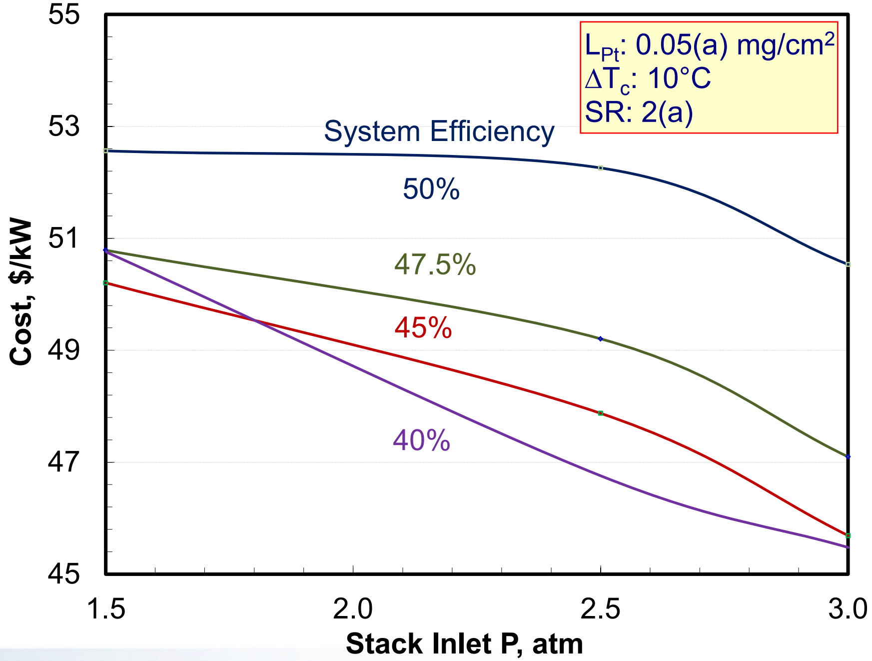


# System Cost vs. System Efficiency Trade-Off

Four-variable optimization study to determine stack T, inlet $RH_c$, $SR_c$ and $L_{Pt}(c)$ for lowest system cost for specified system efficiency*

| System | $L_{Pt}(c)$ | Cell V | Power Density | Pt Content | Cost ($/kW) | | |
|---|---|---|---|---|---|---|---|
| Efficiency, % | mg/cm$^2$ | mV | mW/cm$^2$ | g/kW | Pt | Stack | System |
| Stack Inlet P = 2.5 atm; SRc = 1.5-1.6 | | | | | | | |
| 40.0 | 0.112 | 579 | 1134 | 0.16 | 5.7 | 20.7 | 47.0 |
| 45.0 | 0.108 | 634 | 971 | 0.18 | 6.4 | 22.9 | 48.0 |
| 47.5 | 0.110 | 661 | 882 | 0.20 | 7.0 | 27.8 | 49.4 |
| 50.0 | 0.111 | 695 | 753 | 0.23 | 8.3 | 28.2 | 52.5 |
| Stack Inlet P = 1.5 atm; $SR_c$ = 2.4-2.5 | | | | | | | |
| 40.0 | 0.074 | 569 | 860 | 0.16 | 5.7 | 23.7 | 50.9 |
| 45.0 | 0.086 | 633 | 849 | 0.18 | 6.3 | 24.4 | 50.4 |
| 47.5 | 0.093 | 665 | 817 | 0.19 | 6.8 | 25.5 | 50.9 |
| 50.0 | 0.104 | 696 | 755 | 0.22 | 7.9 | 27.8 | 52.7 |



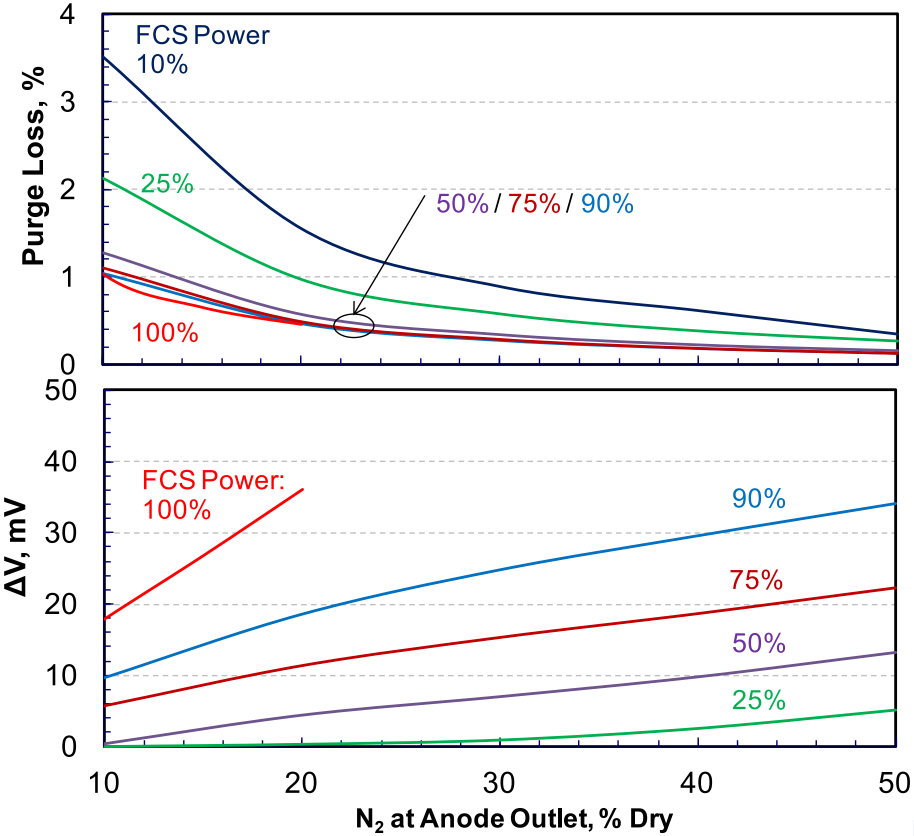


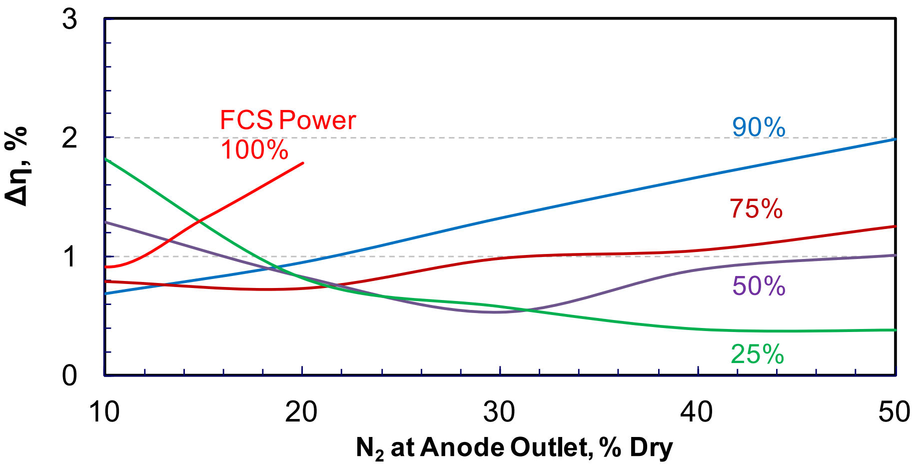
***Possible heat rejection issues in systems with low efficiencies**

# Nitrogen Buildup and Performance Losses

Dynamic simulations (system S1, variable P, 85$^o$C); ISO $H_2$ quality

- Single purge, additional $H_2$ at rated flow rate, 2x anode system volume
- Smaller purge losses, but larger decrease in cell voltage, at higher power or greater allowable $N_2$ buildup
- For optimum efficiency, allowable $N_2$ buildup is a compromise between purge loss and decrease in cell voltage

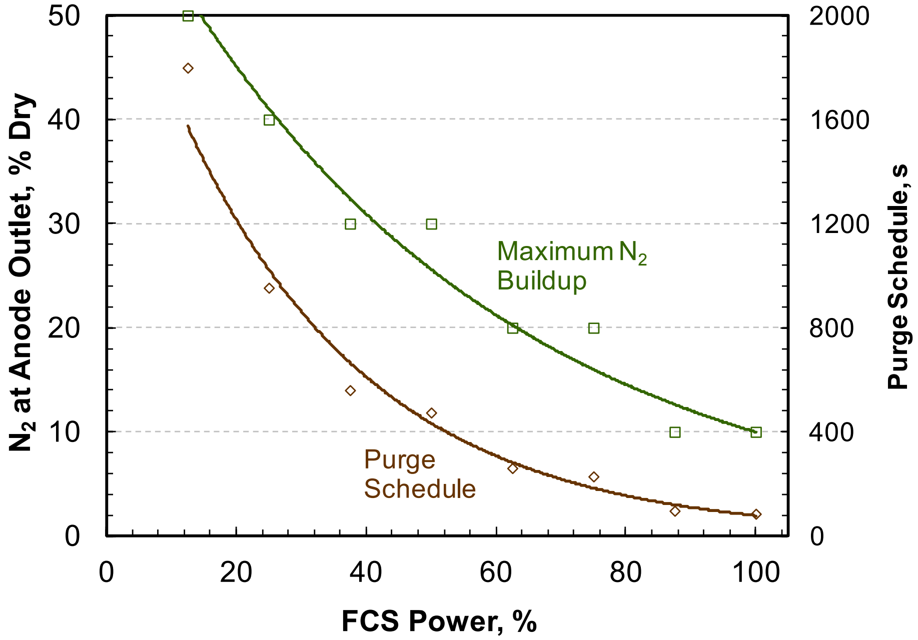


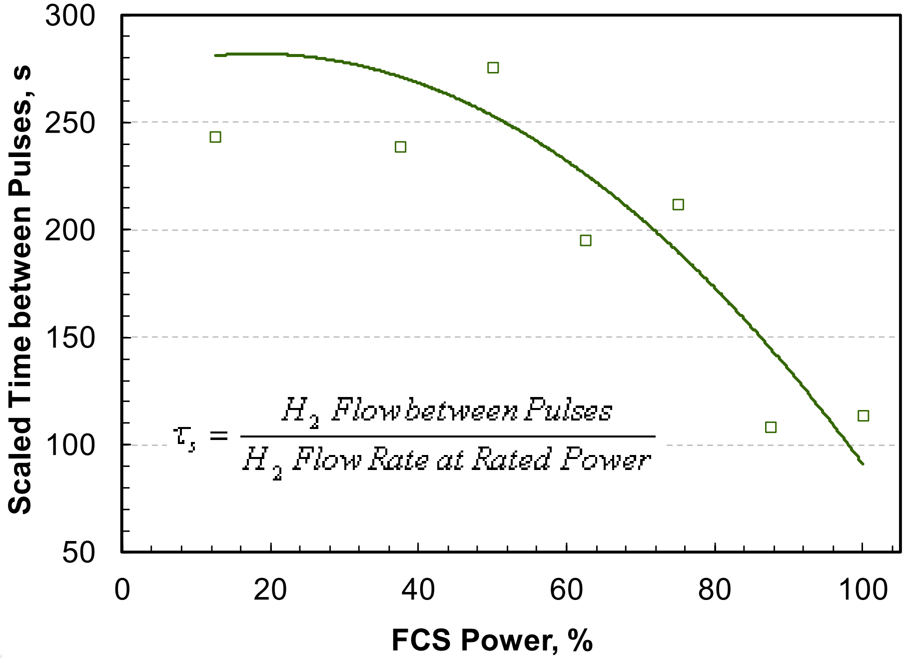


# Optimum Purge Schedule

Conducted dynamic simulations at constant power to determine the optimum purge schedule and the allowable $N_2$ buildup

- Shorter purge schedule and smaller allowable $N_2$ concentration at higher power
- Developed criterion for purging anode without relying on a $H_2$ sensor
- Running drive-cycle simulations to verify and improve dynamic optimum purge criterion

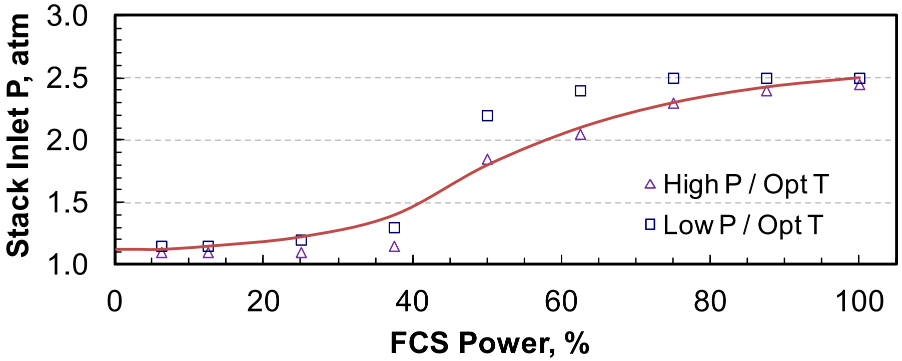


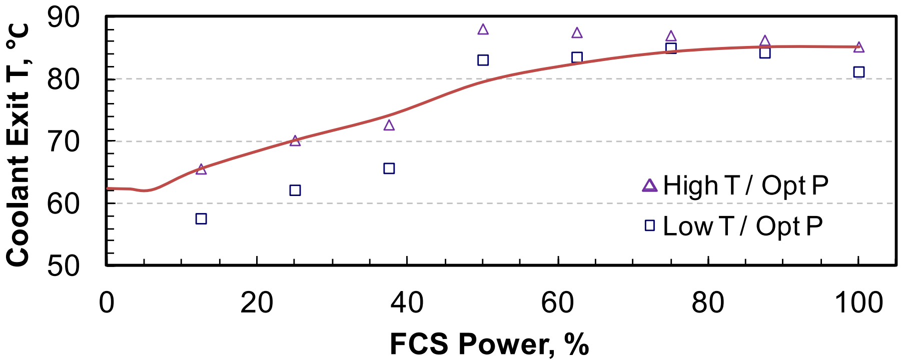


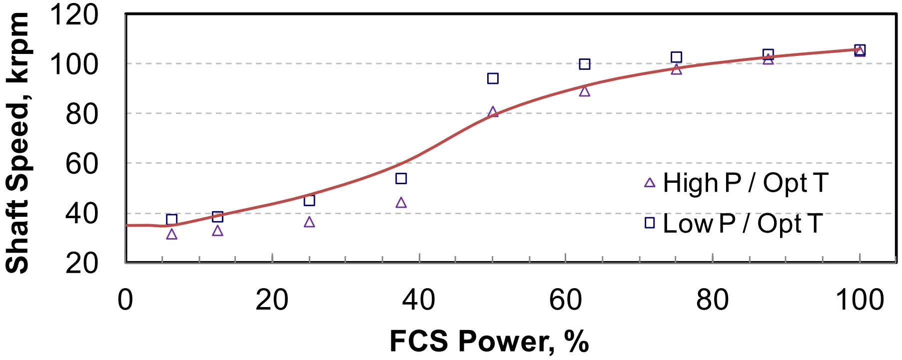
# CEM Operating Conditions Part Load

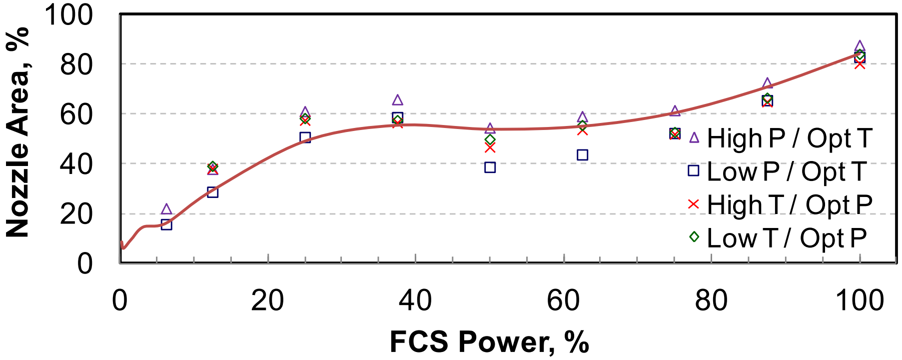
Optimum operating conditions for maximum FCS efficiency at part load*

- CEM variables: expander nozzle area and CEM shaft speed, as a function of FCS net power (fixed SR(c))
- Simulations to map range of stack inlet P and coolant exit T for FCS efficiency within 0.25 percentage points of the optimum







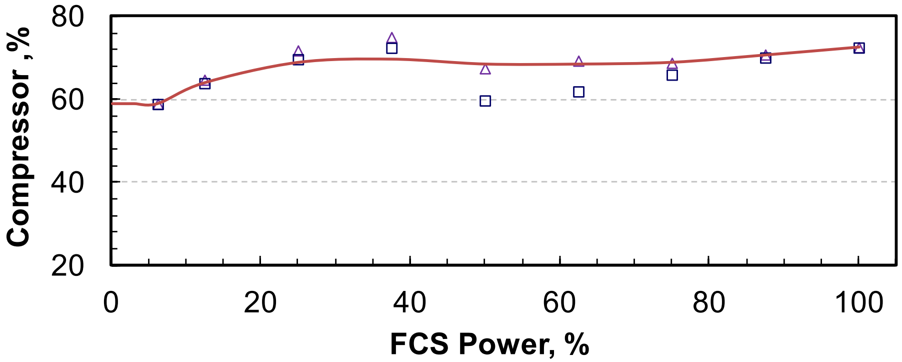


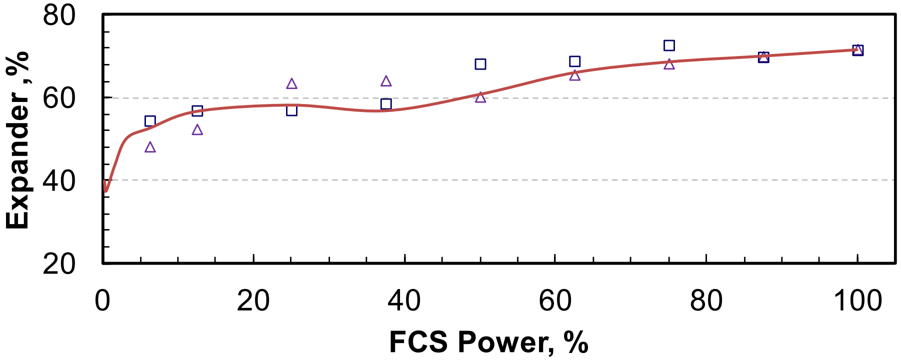
***S1 system with Honeywell's compressor-expander module (CEM)**

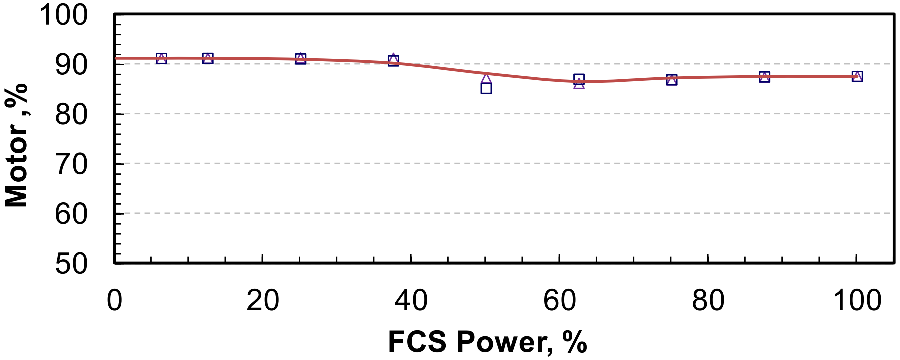
# CEM Component Efficiencies at Part Load

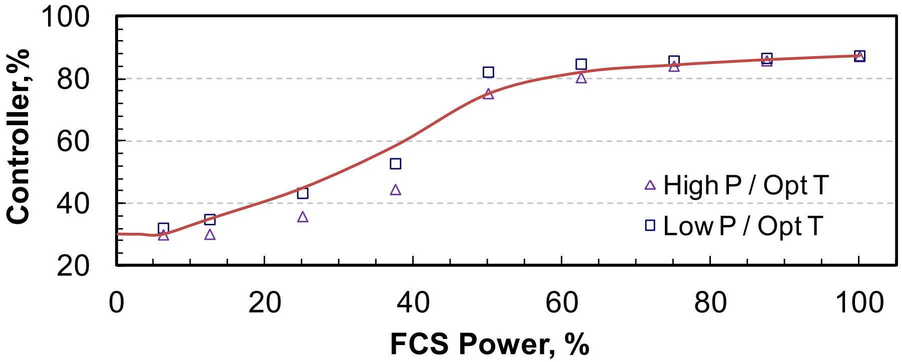
Scaled CEM maps

- 71 - 60% compressor efficiency, 20 maximum turndown
- 73 - 50% expander efficiency with variable nozzle inlet area
- 87 - 92% motor efficiency
- Poor controller efficiency at low loads



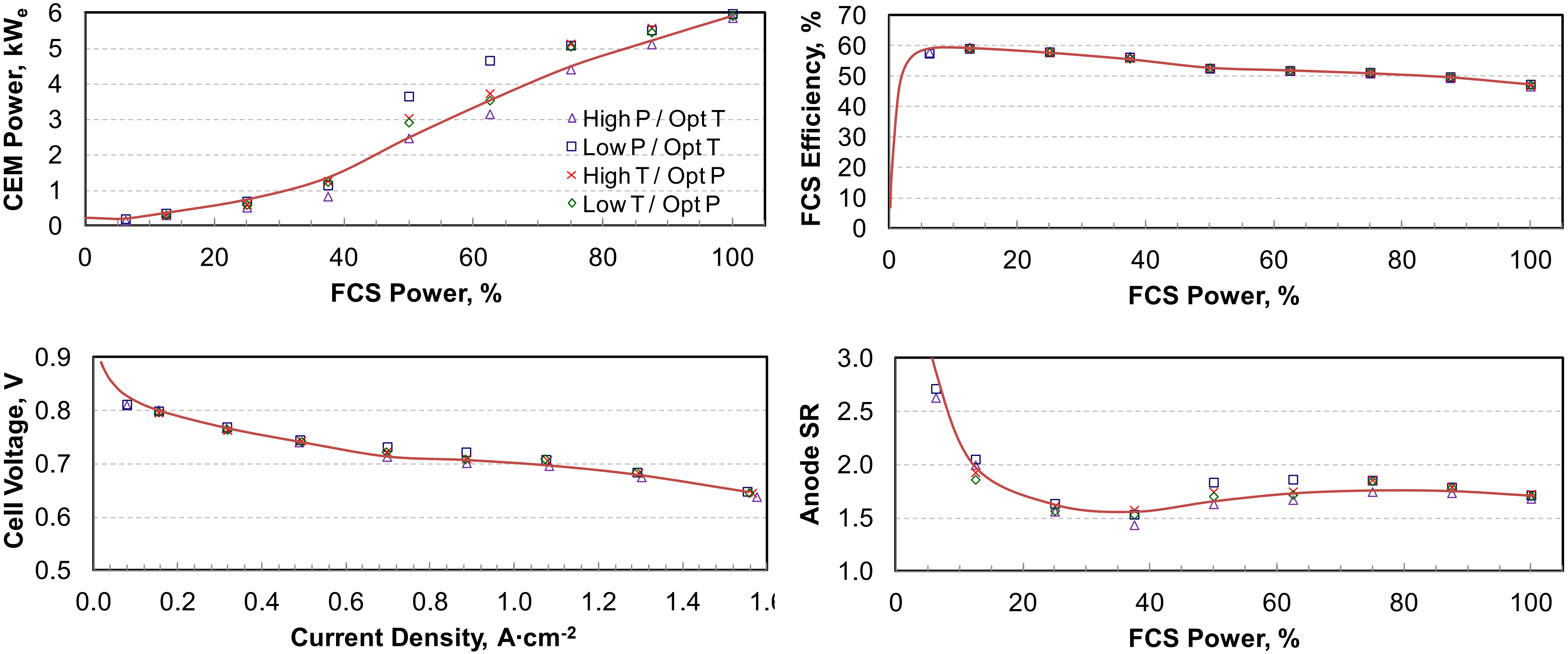






# FCS Performance at Part Load

- 6 kW$_e$ CEM parasitic power at SR(c) = 1.5, 27$^o$C ambient T; system power derated at 40$^o$C ambient T
- 210 W$_e$ CEM parasitic power at idling: turndown of 20, 30% minimum controller efficiency
- 60% peak efficiency target reached at ~10% power



***S1 system with Honeywell's compressor-expander module (CEM)**

# Peak Efficiency Sensitivity Study

| | FCS Efficiency[1] % | System Cost[2] $/kW | Comments |
|---|---|---|---|
| 2012 ANL Status[3] | 57.7 | 45.2 | 3M ternary NSTF catalyst with 0.185 mg/cm$^2$ Pt loading, Honeywell CEM, 1.5 cathode stoichiometry, 47.5% system efficiency at rated power |
| Thinner Membrane | 57.9 | 43.1 | Reinforced membrane; thickness reduced from 24 to 12 μm |
| Improved Air Management System | 59.0 | 42.9 | New Eaton project to develop efficient Roots blowers and expanders |
| Passive Anode System | 59.3 | 42.8 | Hybrid hydrogen blower-ejector replaced with a pulse ejector |
| 2X Catalyst Activity | 61.0 | 41.8 | New 3M project to develop dealloyed $Pt_3Ni_7$/NSTF catalyst |
| 5X Catalyst Activity | 63.4 | 40.7 | |

[1] FCS efficiency refers to system efficiency at 25% power. System efficiency can be higher at lower loads.

[2] Cost of 80-kW$_e$ fuel cell systems estimated using SA correlations for high-volume manufacturing (500,000 units/year). All systems have 47.5% efficiency at rated power.

[3] RK Ahluwalia, X Wang, R Kumar, "Fuel Cells Systems Analysis," Fuel Cell Tech Team Meeting, Southfield MI, July 18, 2012

# Sources of Inefficiencies

| | Cell Voltage mV | Stack Efficiency % | Parasitic Power[1] % | FCS Efficiency[2] % | Comments<br>Metrics at 25% power |
|---|---|---|---|---|---|
| 2012 ANL Status[3] | 767 | 60.9 | 5.3 | 57.7 | 3M ternary NSTF catalyst with 0.185 mg/cm$^2$ Pt loading, Honeywell CEM, 1.5 cathode stoichiometry, 47.5% system efficiency at rated power |
| Thinner Membrane | 769 | 61.0 | 5.3 | 57.9 | HFR affects system cost more than it affects efficiency at 25% power. |
| Improved Air Management System | 769 | 61.1 | 3.6 | 59.0 | Parasitic power is small since the compressor discharge pressure is only 1.25 atm at 25% power. |
| Passive Anode System | 769 | 61.1 | 3.1 | 59.3 | Hybrid hydrogen blower-ejector replaced with a pulse ejector |
| 2X Catalyst Activity | 790 | 62.8 | 2.9 | 61.0 | Peak efficiency is most sensitive to catalyst activity for ORR or Pt loading for dispersed catalysts. |
| 5X Catalyst Activity | 820 | 65.1 | 2.7 | 63.4 | |

[1] Parasitic power as percent of power produced by stack

[2] FCS efficiency refers to system efficiency at 25% power

[3] RK Ahluwalia, X Wang, R Kumar, "Fuel Cells Systems Analysis," Fuel Cell Tech Team Meeting, Southfield MI, July 18, 2012

# dPoint Humidifier with Gore M311.05 Membrane

- Single channel, steady or transient, counter-flow or cross-flow with heat and mass transfer
- 2-D finite-difference model, variable number of nodes
- Literature data for water uptake and water diffusivity in the ionomer
- Gas phase, interfacial and ePTFE resistances derived from static and dynamic permeation tests (W.B. Johnson, FC067)
- Pressure drop correlation from the unit experimental data
- Cross-over of $N_2$ and $O_2$

| | |
|---|---|
| Flow Rate | 27 $g.s^{-1}$ |
| P | 1.2 bar |
| Dry Inlet T | 65 $^oC$ |
| Wet Inlet T | 60 $^oC$ |
| RH | 85% |