Fuel Cell System Modeling and Analysis

R. K. Ahluwalia, X. Wang, and J-K Peng

U.S. DOE Hydrogen and Fuel Cells Program

2018 Annual Merit Review and Peer Evaluation Meeting

Washington, D.C.

June 13-15, 2018

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

- FY17 DOE Funding: $500 K
- Planned DOE FY18 Funding: $250 K
- Total DOE Project Value: $250 K

Partners/Interactions

- Eaton, Ford, Honeywell, UDEL/Sonijector
- SA, Aalto University (Finland)
- 3M, Ballard, Johnson-Matthey Fuel Cells (JMFC), UTRC, FC-PAD, GM
- IEA Annex 34
- Transport Modeling Working Group
- Durability 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 (primary objective) and stationary (secondary objective) fuel cell systems (FCS)

- 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

Impact of FY2018 work

- Projected 46.0* ± 0.7 $/kW$_e$ FCS cost at 500,000 units/year and 8.5 ± 0.4 kW$_e$/g$_{Pt}$ FCS Pt utilization with SOA d-PtCo/C cathode catalyst, reinforced 14-μm 850 EW membrane, and $Q/\Delta T$ = 1.45 kW/^{o}C constraint
- Verified that the SOA catalyst system can achieve 1180 ± 55 mW/cm^2 stack power density exceeding the target at low Pt loading (0.125 mg-Pt/cm^2 total)
- Projected <5% penalty in power density if the cathode humidifier is removed, and ~15% penalty if stack inlet pressure is lowered to 2 atm from 2.5 atm
- Showed that parasitic power approaches 25 kW$_e$ if the compressor discharge pressure is raised to 4 atm
- Modified the reference system configuration to include valves and controls for protected shutdown, safe startup from sub-freezing temperatures, and limiting cell voltage to 0.85-0.875 V during idle

***51 $/kW$_e$ at 100,000 units/year; Q: Stack heat load; ΔT: Stack coolant exit T – Ambient T**

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

1	Evaluate the advantages of operating PEMFC stack at elevated pressures up to 4 atm using 2-stage centrifugal compressors.	12/17
2	Determine the comparative performance of PEMFC stacks with and without cathode humidifier.	03/18
3	Evaluate the performance and durability of MEAs with de-alloyed PtCo cathode catalyst on high surface area carbon with tailored pore size distribution relative to the targets of 0.44 A/mg-PGM mass activity, 1000 mW/cm^2 at rated power, 300 mA/cm^2 at 800 mV, and 5000 h lifetime.	06/18
4	Update the performance and cost of an automotive fuel cell system with an advanced low-PGM catalyst relative to 2020 targets of 65% peak efficiency, Q/ΔT of 1.45 kW/K, and \$40/kW cost.	09/18

Technical Accomplishments: Summary

Stack: Collaboration with FC-PAD and GM in obtaining data to develop and validate model for pressures up to 3 atm

- State-of-the-art (SOA) dispersed de-alloyed PtCo/C catalyst systems
- De-alloyed PtCo/C catalyst system: durability on drive cycles

Air Management: Investigating integrated air management system with high speed centrifugal compressors and expanders including cooling requirements of motor and airfoil bearings (AFB) and two-stage compressors (Honeywell patent)

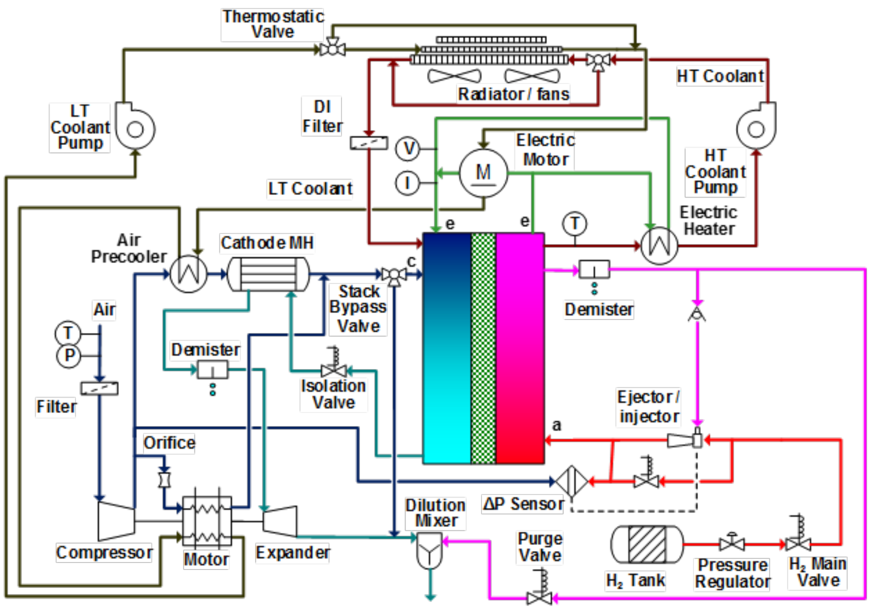
Water Management: Optimizing cost of integrated PEFC stack and cross-flow humidifier

- Investigating FCS performance without cathode humidifier (dispersed catalyst electrodes)

Fuel Management: Evaluating the performance of anode system with a pulse injector in lieu of H_2 recirculation blower (collaboration with Ford & UDEL)

Thermal Management: Optimizing system performance and cost subject to Q/ΔT constraint

System startup and shutdown: Modified reference system to incorporate controls for protected shutdown, safe startup from sub-freeze temperatures, and limiting cell voltage at idle



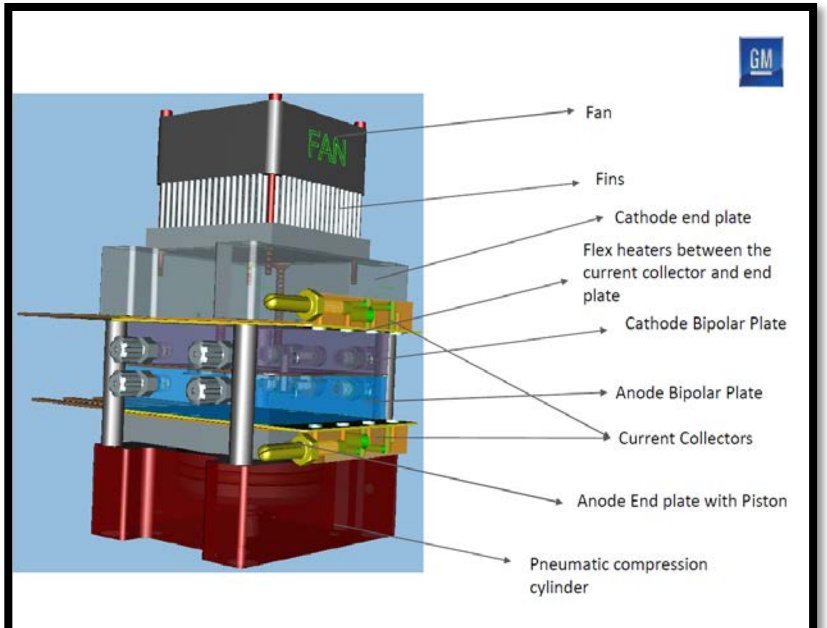
Argonne 2018 FCS Configuration

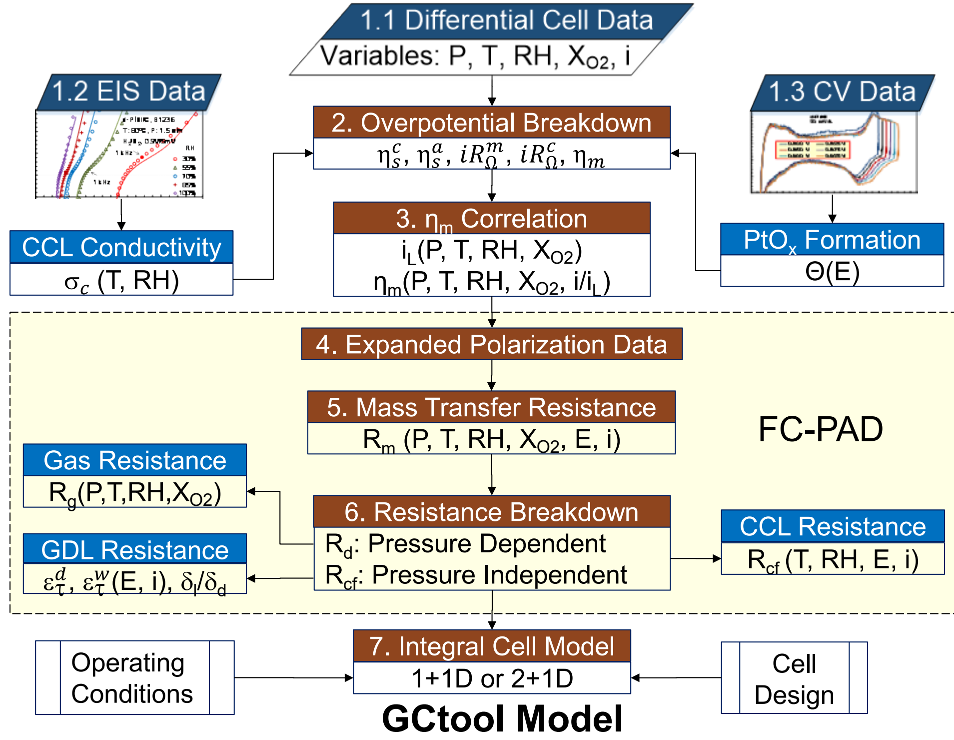
ΔT: Stack coolant exit T – Ambient T

Model Framework and Single Cell Hardware

US-EU Differential Cell Hardware*

- P: 1-3 atm; T: 45-95°C,
- RH: 30-150%; $X(O_2)$: 1-21%
- **Random Tests**: Semi-statistical randomized with multiple variables, forward scans, 3-min hold at each cell voltage
- **Controlled Tests**: Model guided single-variable with some two-variable tests, forward scans, 3-min hold at each cell voltage





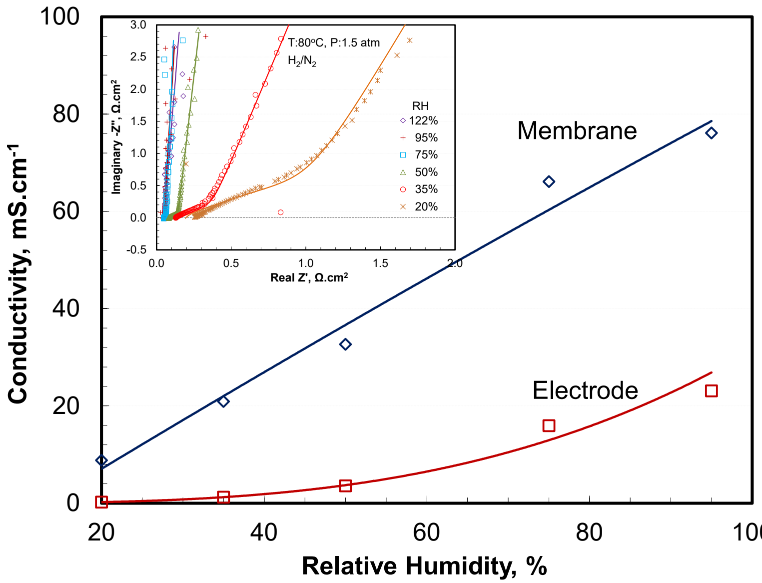
Representative State-of-the-Art Low-PGM MEA		
	Cathode	Anode
Catalyst	d-Pt_3Co/C	Pt/C
Catalyst Support	HSAC	Vulcan
Ionomer Equivalent Weight	950	950
Pt Loading	0.1 mg/cm^2	0.025 mg/cm^2
ECSA	45 m^2/g	60 m^2/g
Electrode Thickness	7 μm	5 μm
Diffusion Medium Thickness	200 μm	200 μm
Membrane	18 μm Reinforced	

***All tests conducted at GM (S. Arisetty Lead), FCPAD-FC156 collaboration (S. Kumaraguru PI)**

Kinetics of ORR on d-PtCo/C Catalyst

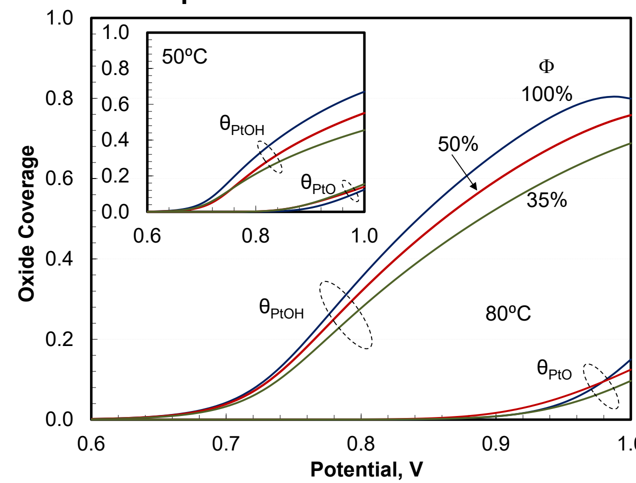
Electrode Resistance

- Electrode (σ_c) / membrane conductivities (σ_m) from Galvanostatic impedance data in H_2/N_2



PtO_x Formation on d-PtCo/C Catalyst

- Transient solid solution model from measured CV reduction charge after hold for 12 s to 2 h at constant potential[1]



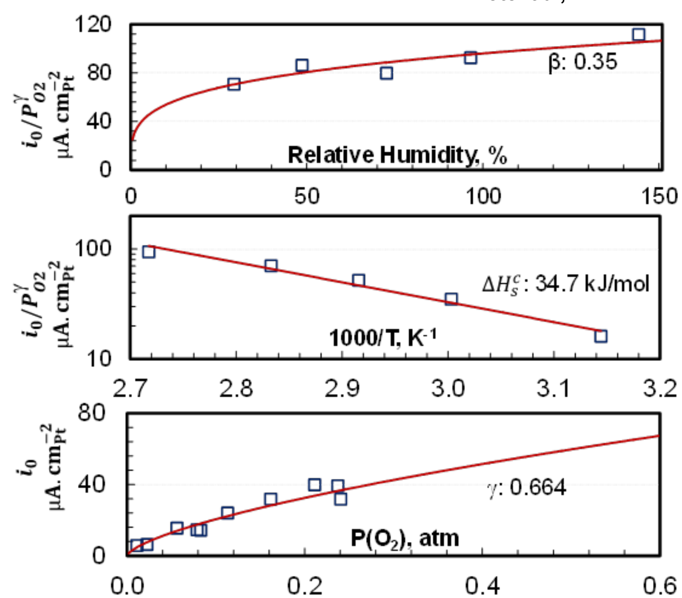
Distributed ORR Kinetic Model

- For Tafel kinetics, the ORR and CCL Ohmic overpotentials are separable

$$\eta_c = \eta_s^c + iR_\Omega^c\left(\frac{i\delta_c}{b\sigma_c}\right)$$

$$i + i_x = i_0 S_{Pt}(1-\theta)e^{-\frac{\omega\theta}{RT}}e^{\frac{\alpha nF}{RT}\eta_s^c}$$

$$i_0 = i_{0r}e^{-\frac{\Delta H_S^C}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)}P_{O_2}^{\gamma}\Phi^{\beta}$$



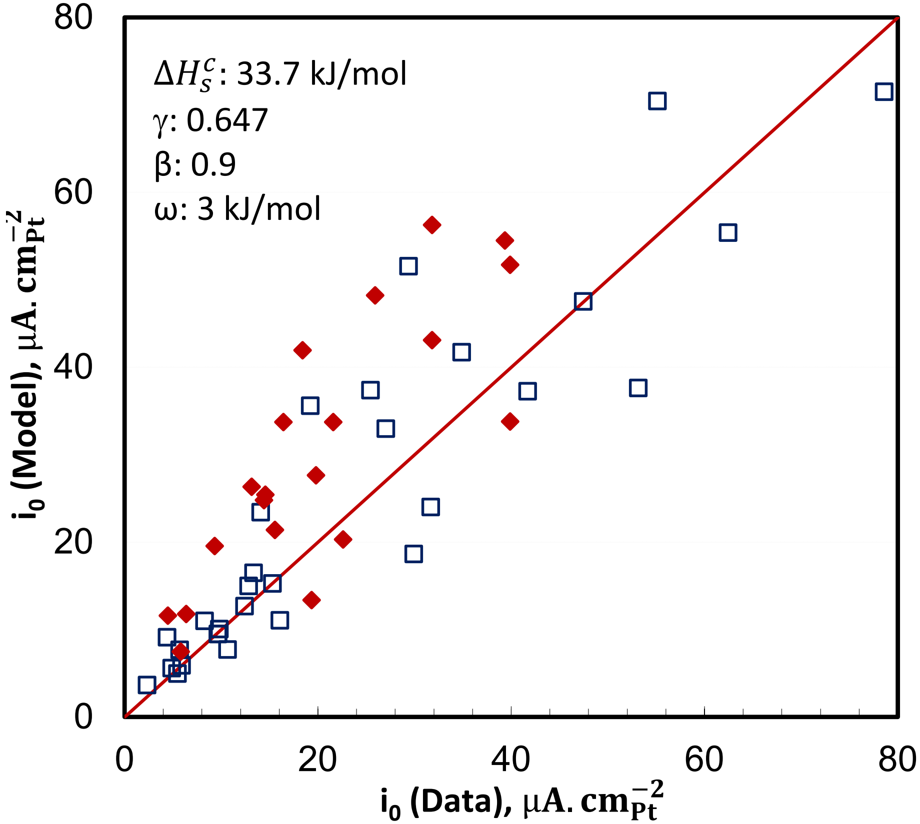
Kinetic data from controlled tests

[1] Arisetty et. al. (2015), ECS Transactions, 69, 273-289

Calibration of ORR Kinetic Model*

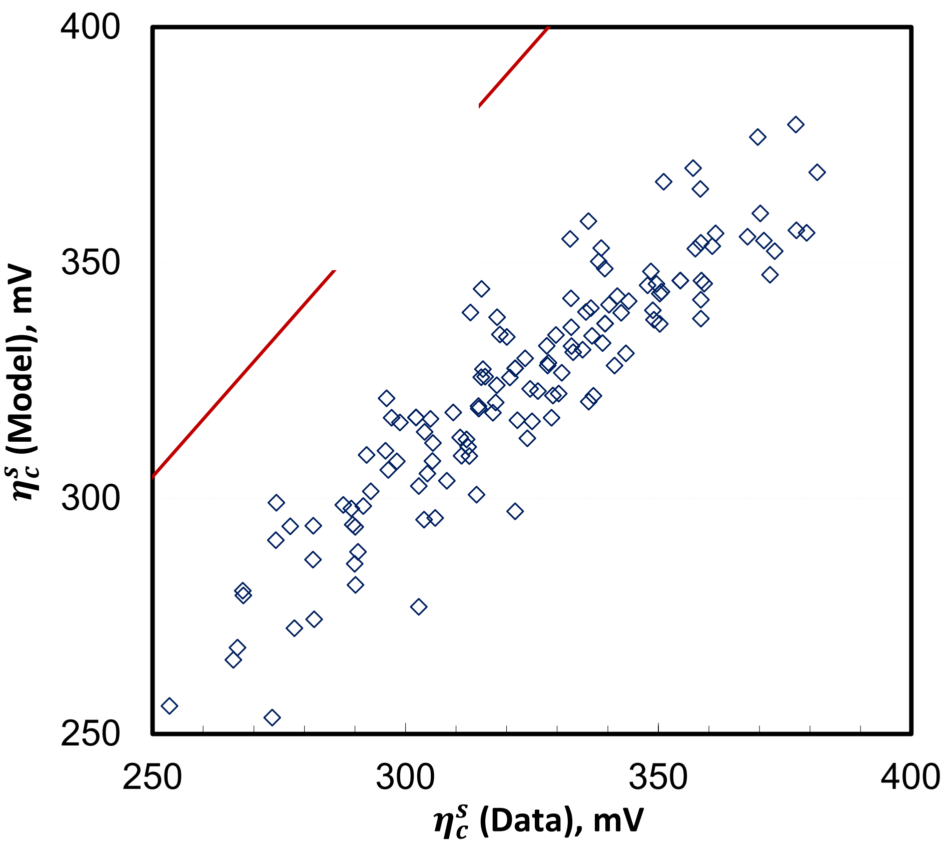
i_0 calibration: 1 data point per pol curve

- Data: $i + i_x = i_0 S_{Pt}(1-\theta)e^{-\frac{\omega\theta}{RT}}e^{\frac{\alpha n F}{RT}\eta_S^c}$
- Model: $i_0 = i_{0r}e^{-\frac{\Delta H_S^C}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)}P_{O_2}^{\gamma}\Phi^{\beta}$



η_S^c calibration: all data in kinetic region

- Data: $\eta_S^c = E_N - E - iR_\Omega^m - iR_\Omega^c$
- Model: $\eta_S^c = b\left[\ln\left(\frac{i+i_x}{i_0 S_{Pt}}\right) - \ln(1-\theta) + \frac{\omega\theta}{RT}\right]$

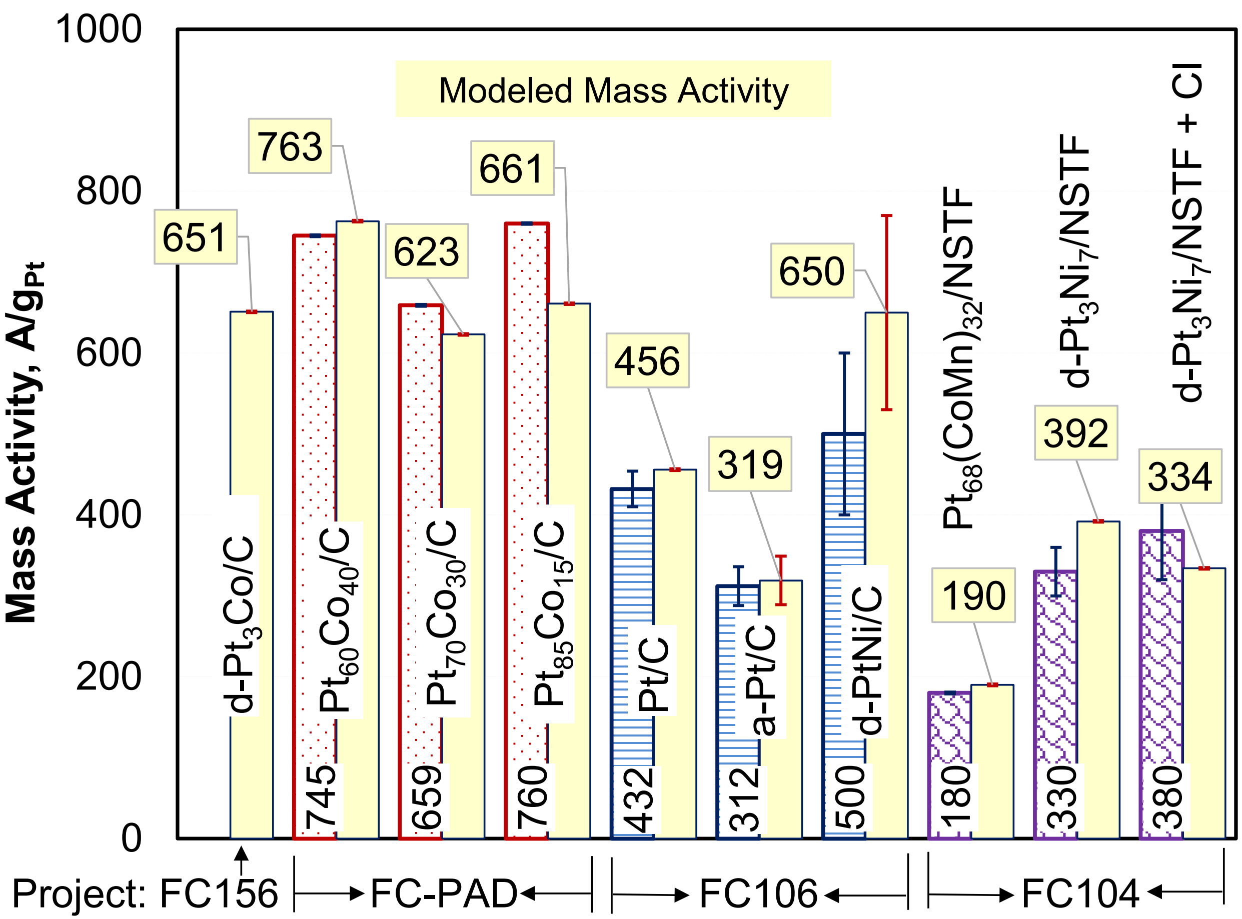


Open symbols: Random tests (BOT); Closed symbols: Controlled tests (EOT: end of test)

***Kinetic model based on random test data; BOT: Beginning of tests; EOT: End of tests**

Mass Activity for ORR on d-PtCo/C Catalysts

- d-PtCo/C has 2X modeled mass activity of a-Pt/C that has nearly the same particle size
- d-PtCo/C and d-PtNi/C alloy have comparable mass activities
- Both low-PGM alloy catalysts (d-PtNi/C and d-PtCo/C) meet the mass activity targets of 440 A/g_{Pt}



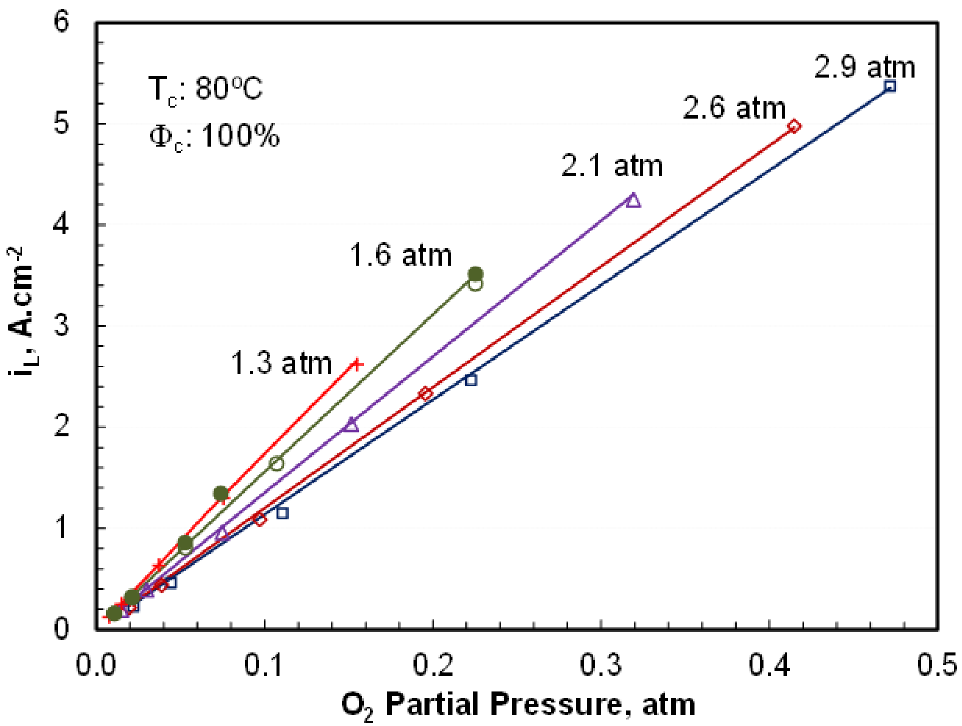
Solid Fill: Modeled mass activity from ORR kinetic model

Pattern Fill: Measured mass activity in H_2/O_2

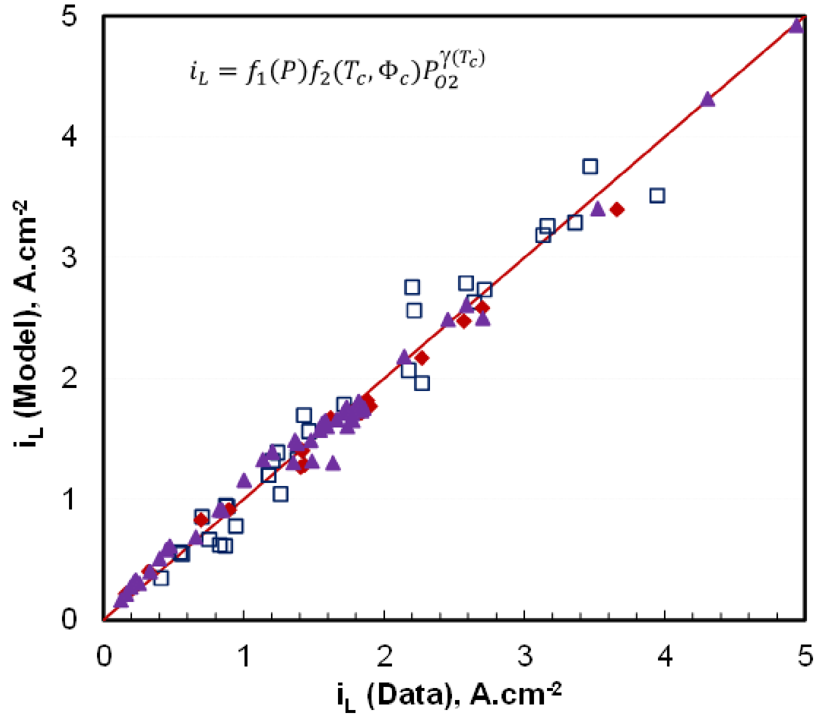
Oxygen Mass Transfer: Limiting Current Density

Determined limiting current density (i_L) and correlated mass transfer overpotential (η_m) with reduced current density (i/i_L)

- $\eta_m = E_N - E - iR_\Omega^m - \eta_c - \eta_a$
- i_L defined as current density at which η_m equals 400 mV



Symbols
T: Bipolar plate temperature; T_c: CCL temperature
Φ: Gas channel RH; Φ_c: CCL RH



Model Variables

- P: Pressure
- P_{O_2}: O_2 partial pressure in gas channel
- T_c : CCL temperature, function of T, E_N, E, and i
- Φ_c : CCL RH, function of Φ, i, and water transport across membrane

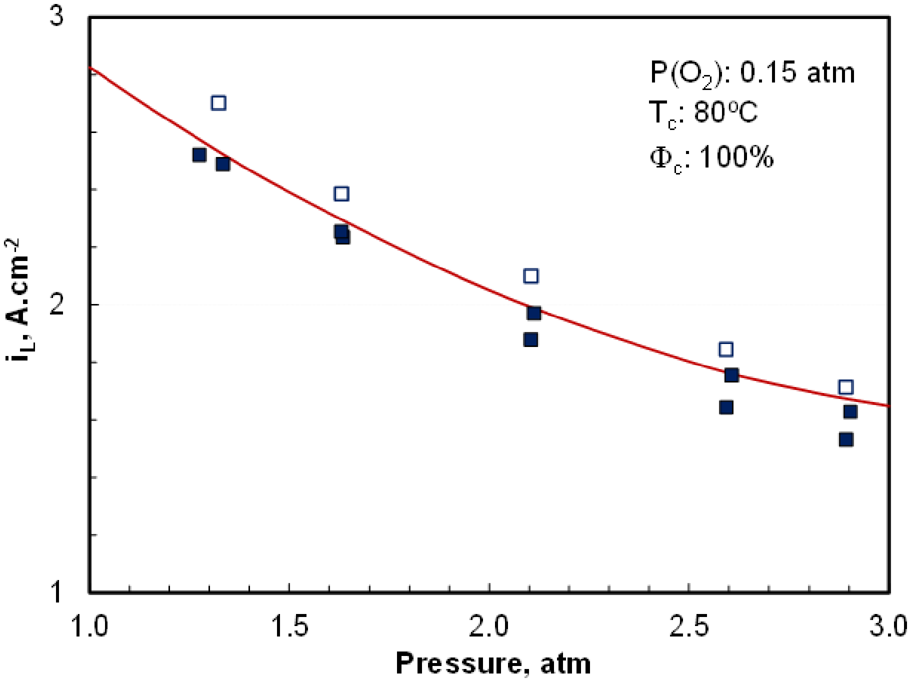
Limiting Current Density: Effect of Pressure

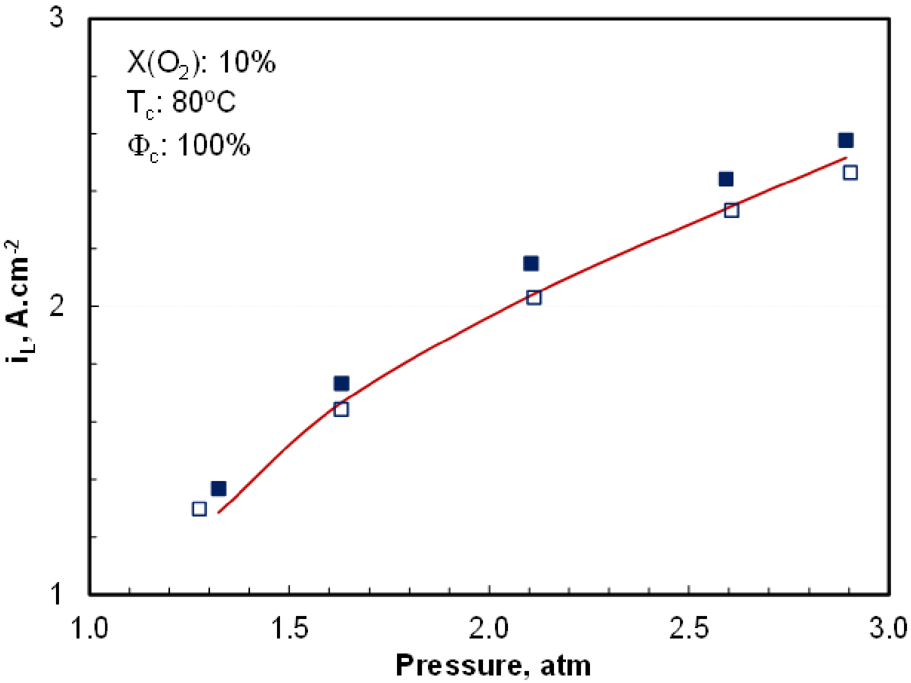
At constant P(O_2), i_L decreases with increase in P because of the inverse dependence of O_2 gas phase diffusivity on P.

- The decrease in i_L is less than proportional to 1/P, implying that non-Fickian diffusion controls mass transport resistance

At constant X(O_2), i_L increases with increase in P because of higher P(O_2).

- The increase in i_L is somewhat less than proportional to P(O_2), implying that mass transport resistance also increases with P(O_2).





The plots include the experimental data for i_L at different P, X(O_2), T=80°C, and Φ=100%. For comparison, the model was used to rescale the i_L data to P(O_2)=0.15 atm or X(O_2)=10%, T_c=80°C, and ϕ_c=100%.

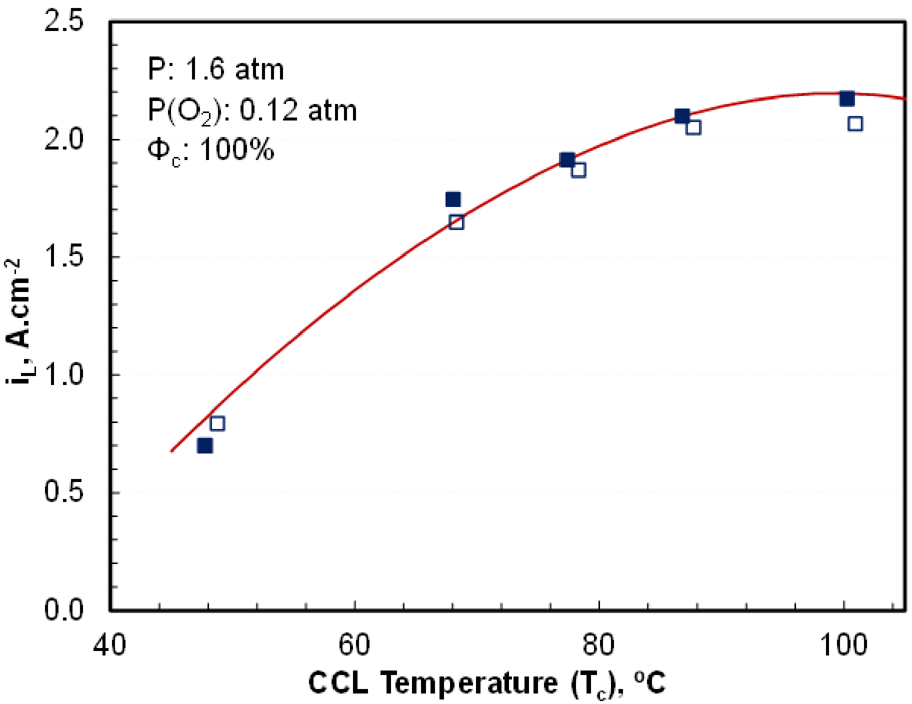
Limiting Current Density: Effect of Temperature and RH

Dependence of i_L on T_c >> $T^{3/2}$, confirming that processes other than Fickian diffusion are rate controlling.

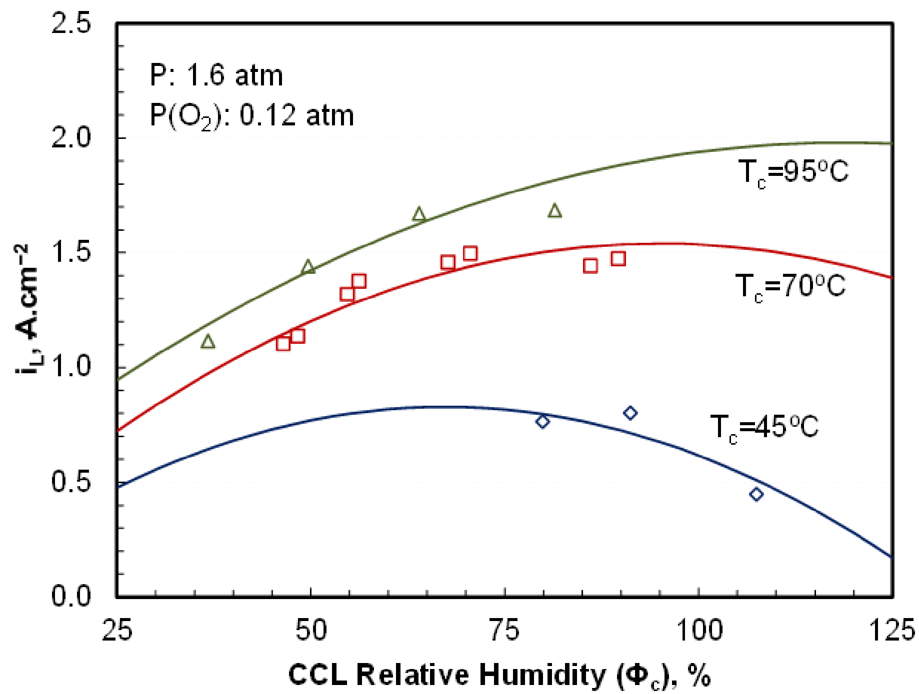
- O_2 permeability through the ionomer film on the catalyst particles

For given T_c, i_L is highest at an intermediate RH in CCL (ϕ_c^*).

- CCL flooding for $\phi_c > \phi_c^*$
- ϕ_c^* Increases at higher T_c



The plot includes all the experimental data for i_L at different T, P=1.6 atm, X(O_2)=10%, and Φ=100%. For comparison, the model was used to rescale the i_L data to P(O_2)=0.12 atm, and ϕ_c=100%.



The plot includes all the experimental data for i_L at different Φ, T=45, 70 and 95°C, P=1.6 atm and X(O_2)=10%. For comparison, the model was used to rescale the i_L data to P(O_2)=0.12 atm and different T_c=45, 70 and 95°C.

Performance of Automotive FCS with SOA d-PtCo/C Cathode Catalyst

Modeled optimal beginning of life (BOL) performance of automotive FCS subject to Q/ΔT=1.45 kW/°C constraint: 0.125 mg/cm² total Pt loading; 850 EW, 14-µm chemically-stabilized, reinforced membrane

FY2018 model based on differential cell data supports FY2017 landmark result

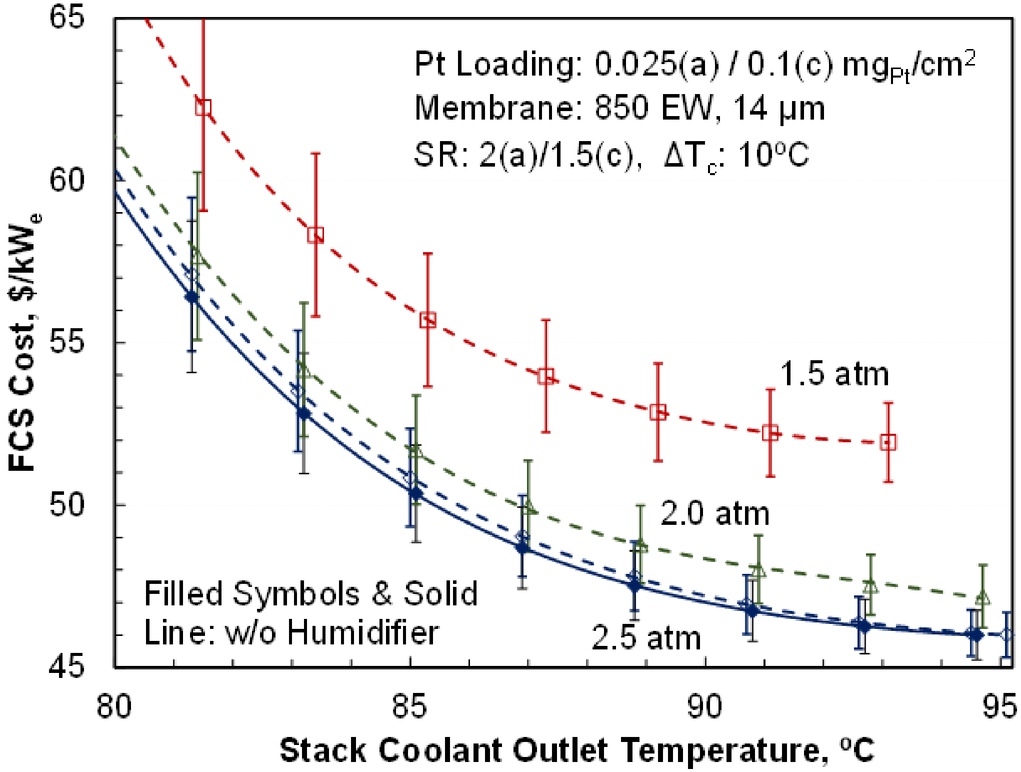
- 46.0 ± 0.7 $/kW$_e$ projected cost* at 2.5 atm stack inlet pressure and 95°C stack coolant outlet temperature for high volume manufacturing
- Removing membrane humidifier slightly lowers the system cost at 2.5 atm stack inlet pressure

Results are preliminary pending model validation using data from 50-cm² integral cell

- Error bars reflect variance of kinetic data in random and controlled tests and include degradation between the two series of tests

Effect of manufacturing volume on projected cost (SA)

- 500,000 units/year: 46 $/kW$_e$
- 100,000 units/year: 51 $/kW$_e$
- 10,000 units/year: 88 $/kW$_e$



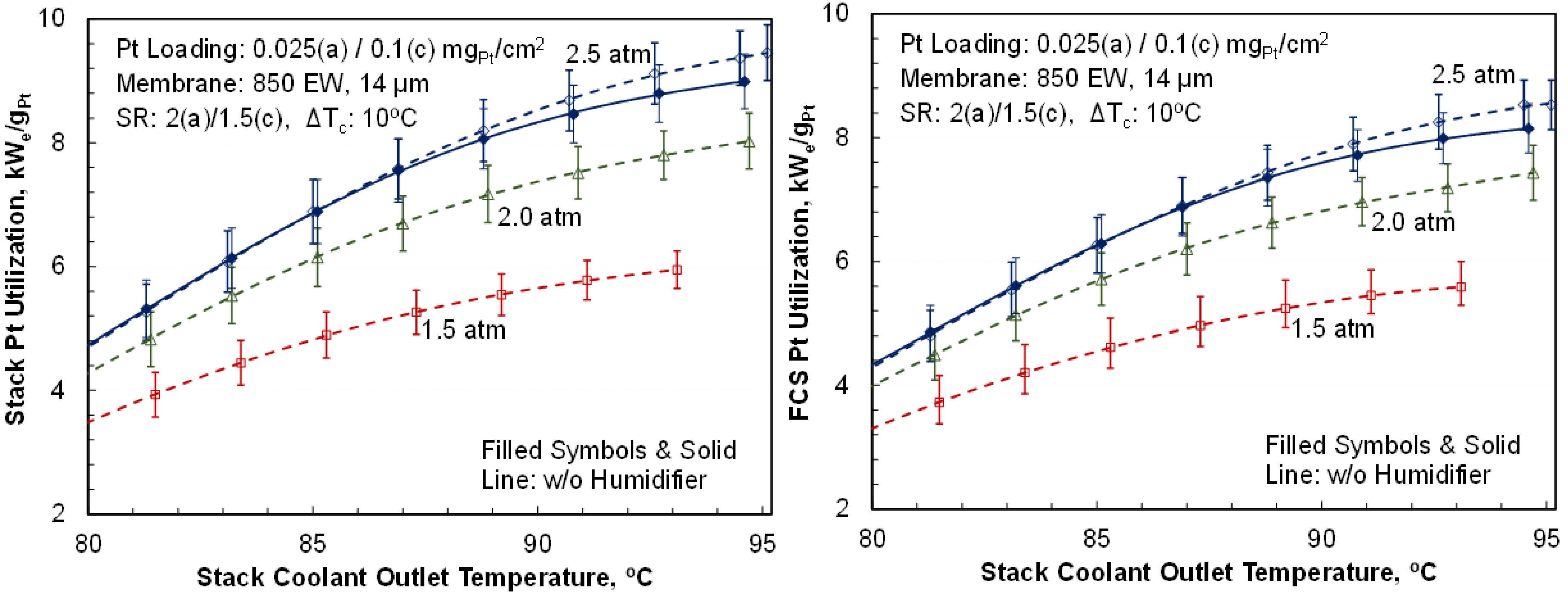
***Using 2018 cost correlations from Strategic Analysis (SA), 500,000 units/year, no H_2 blower. Includes $2.01 cost increase in 2018 for manufacturing bipolar plates and MEAs, added controls, and CEMM price inflation.**

FCS with SOA d-PtCo/C Cathode Catalyst: Pt Utilization

Modeled optimal beginning of life (BOL) performance of automotive FCS subject to $Q/\Delta T$=1.45 kW/^{o}C constraint: 0.125 mg/cm^2 total Pt loading; 850 EW, 14-µm chemically-stabilized, reinforced membrane

FY2018 model based on differential cell data supports FY2017 landmark result

- Modeled stack Pt utilization (9.5 ± 0.5 kW_e/g_{Pt}) exceeds the target (8.0 kW_e/g_{Pt})
- Modeled FCS Pt utilization (8.5 ± 0.4 kW_e/g_{Pt}) also exceeds the target
- Stack inlet pressure ≥ 2.0 atm needed to meet the Pt utilization target

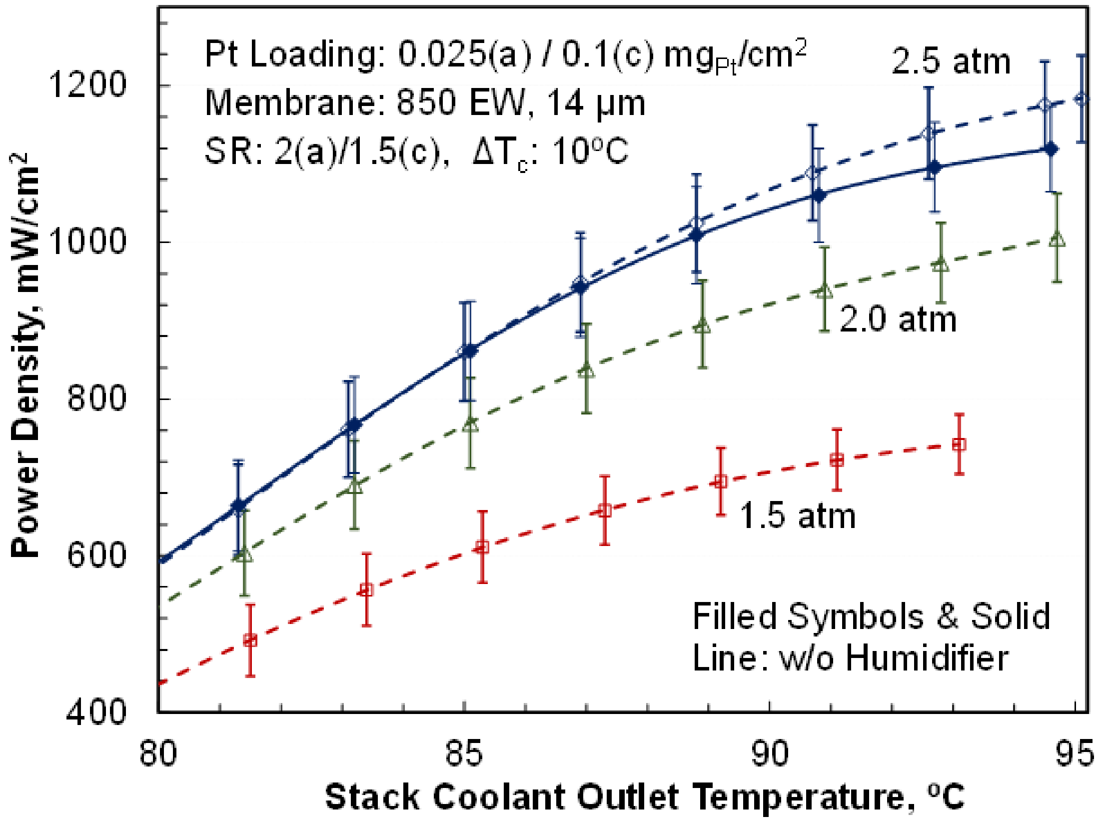


FCS with SOA d-PtCo/C Cathode Catalyst: Power Density

Modeled optimal beginning of life (BOL) performance of automotive FCS subject to Q/ΔT=1.45 kW/°C constraint: 0.125 mg/cm^2 total Pt loading; 850 EW, 14-μm chemically-stabilized, reinforced membrane

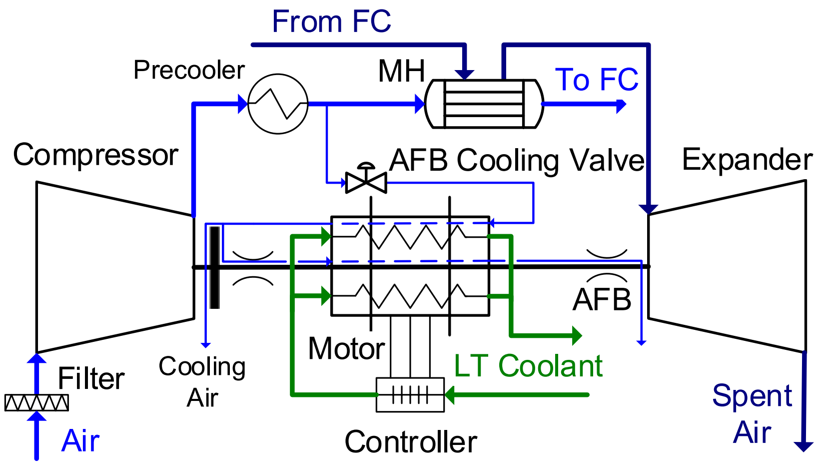
FY2018 model based on differential cell data supports FY2017 landmark result

- Modeled gross stack power density (1180 ± 55 mW/cm^2) exceeds the target (1000 mW/cm^2) at low Pt loading (0.125 mg-Pt/cm^2 total)
- Stack inlet pressure ≥ 2.0 atm needed to meet the power density target

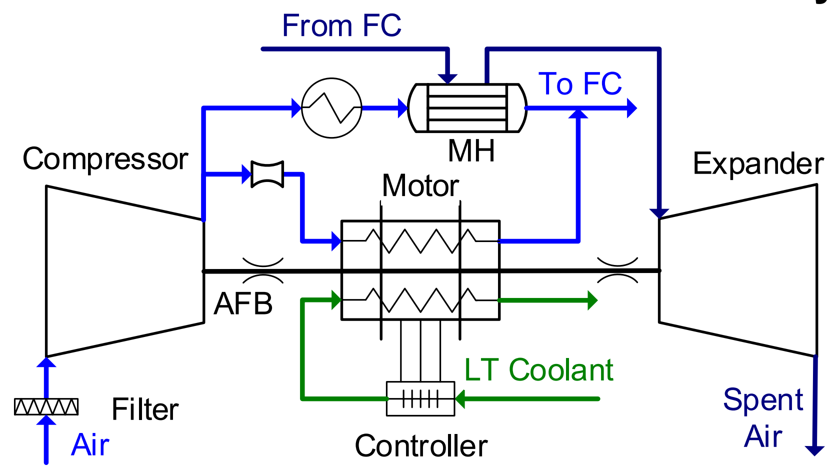


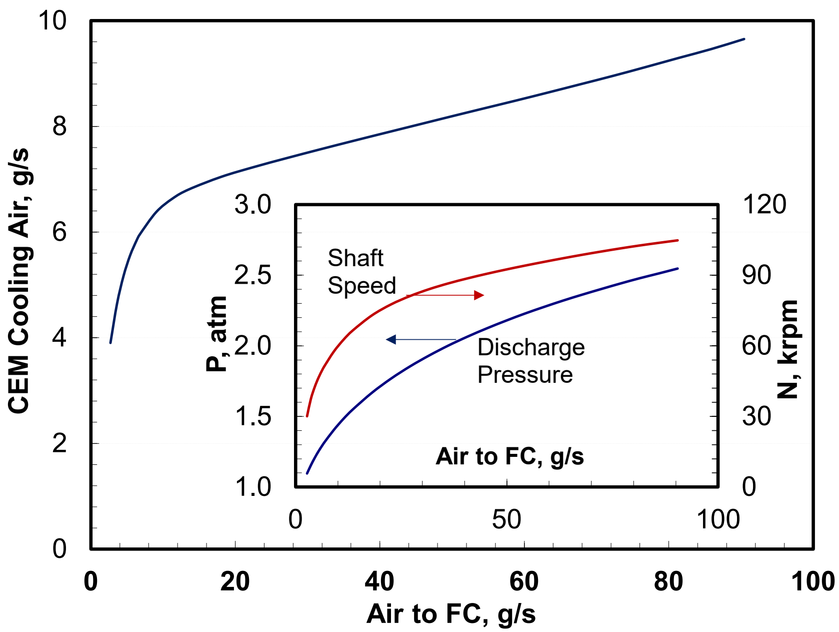
Air Management System

CEMM w/o Bleed Air Recovery

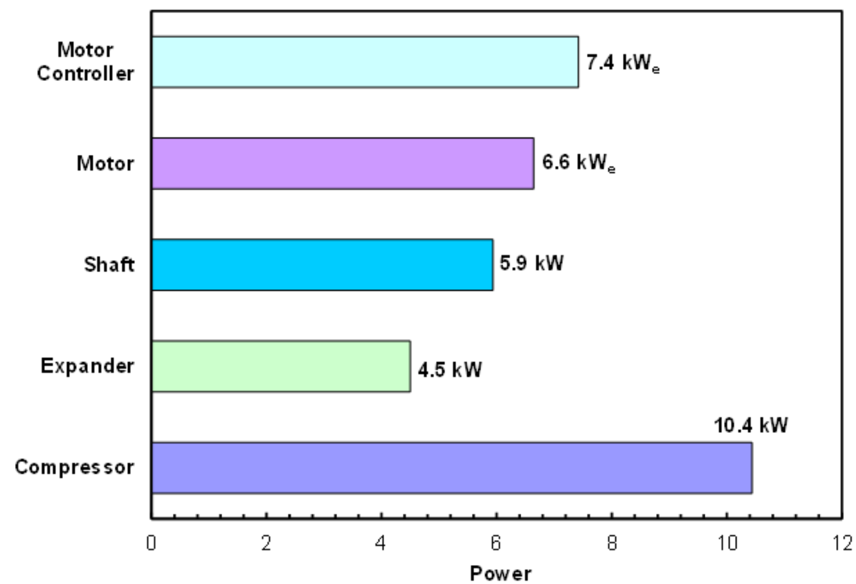


Modeled CEMM with Bleed Air Recovery





Projected cooling air loss using Honeywell data for CEMM



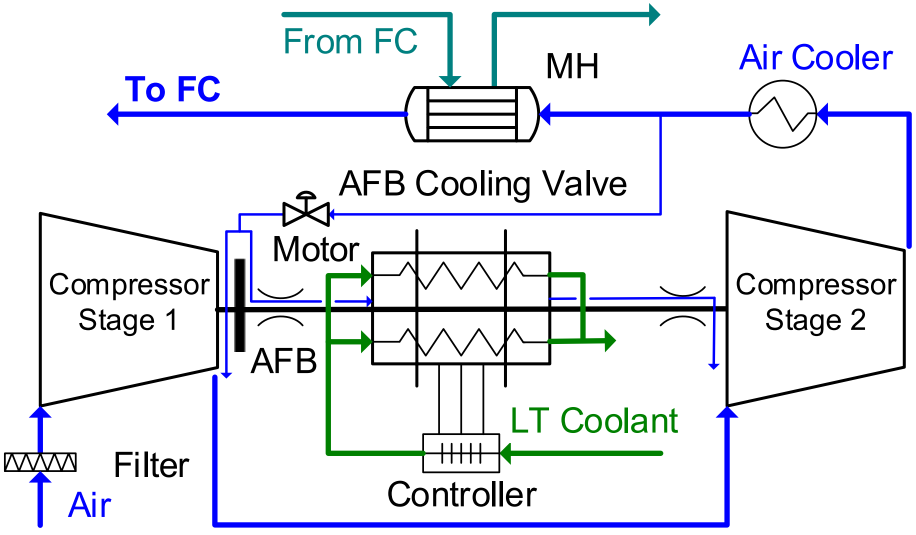
Simulation results: 73 g/s air flow rate, and 2.5 atm compressor discharge P; 2.3 atm expander inlet P, 85^{o}C inlet T, fully saturated; 40^{o}C ambient T

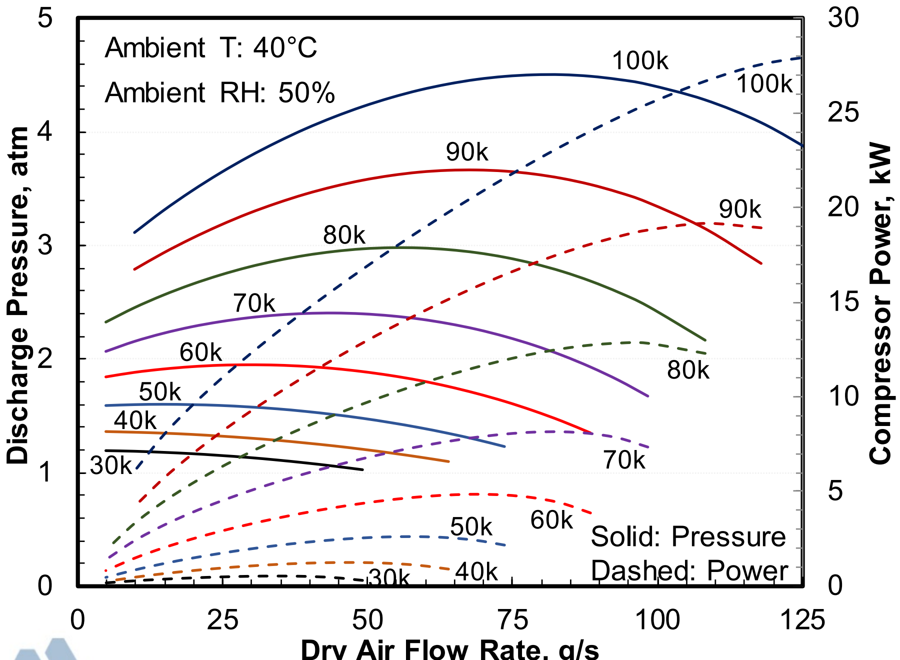
*AFB: Air foil bearing

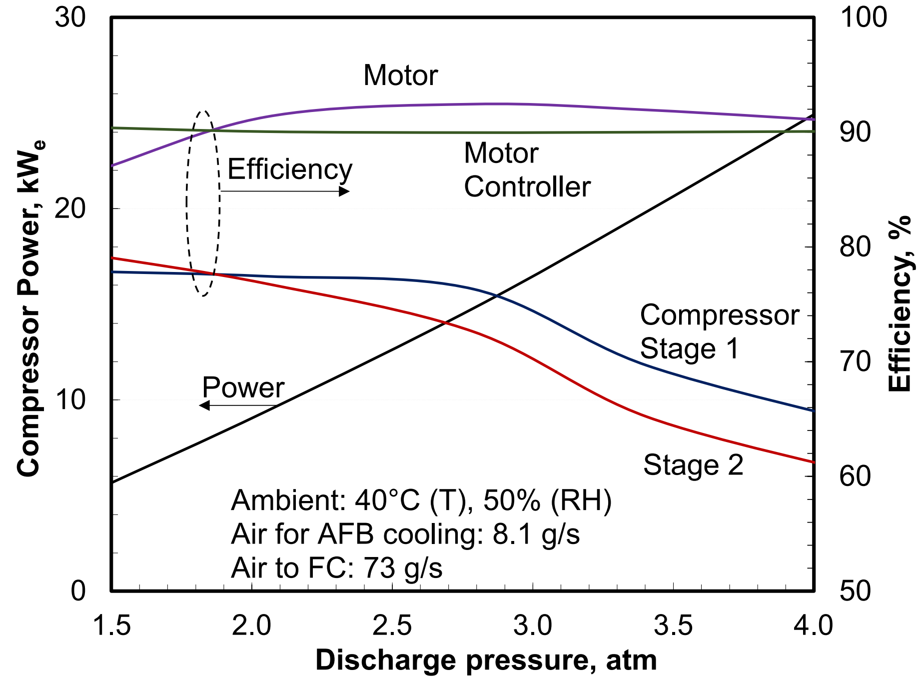
Performance of Two-Stage Centrifugal Compressor

Mixed axial and radial flow compressors on a common shaft with AFBs and 3-phase brushless DC motor; Honeywell US Patent 2015/0308456

- AFB*/motor cooling air extracted downstream of the pre-cooler and is not recovered
- Compressor power ~25 kW_e at 4-atm discharge pressure
- Results for existing compressor but resized motor and motor controller



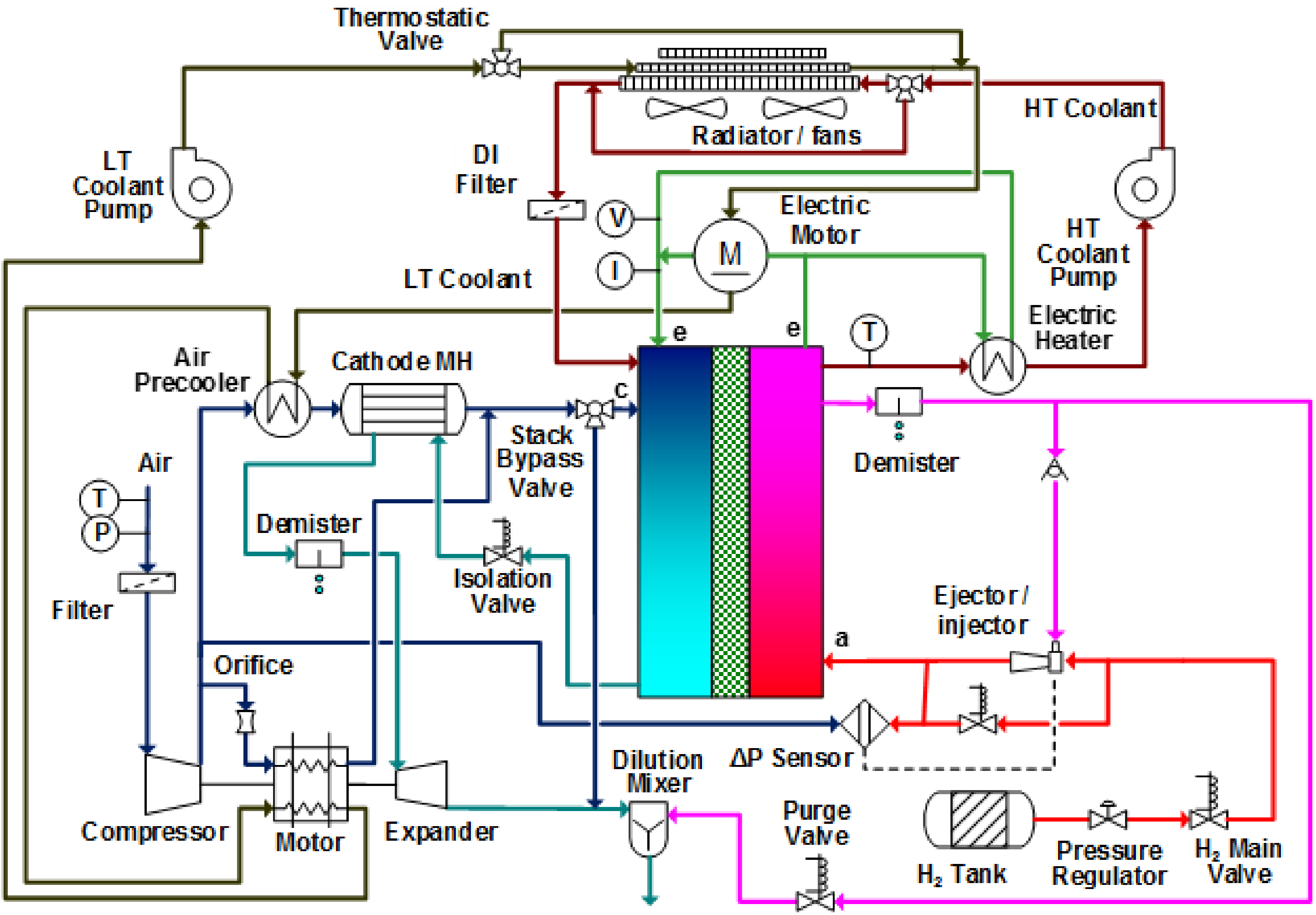




*AFB: Air foil bearing

Proposed Argonne 2018 FCS Configuration with Controls

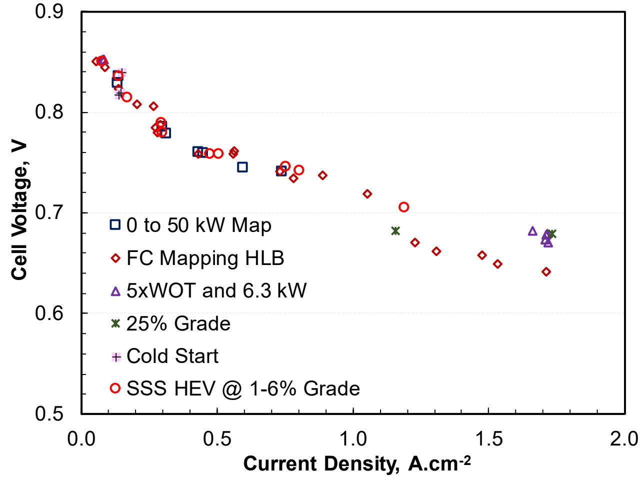
- **Stack idling: Limit cell voltage by operating at low SR(c) and low O_2 concentration**
- **Stack shutdown: Avoid H_2-air front during subsequent start-up by depleting oxygen**
- **Sub-freeze start: Prevent icing by maximizing in-stack heat production***



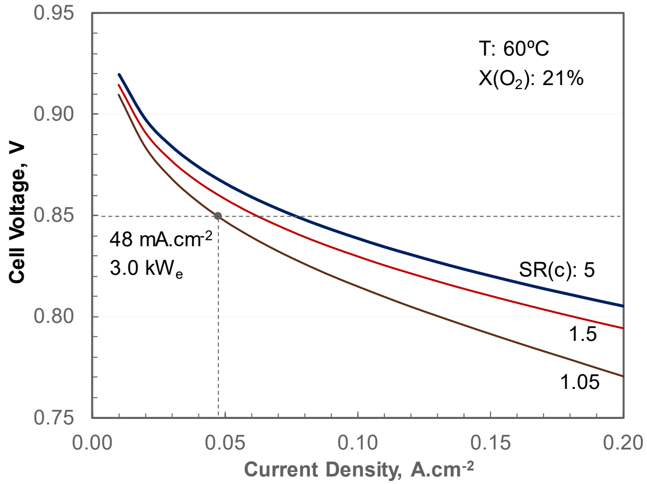
*M. Toida, Y. Naganuma, and T. Ogawa, "Fuel Cell System and Method for Discharging the System," US 2016/0141672 A1, May 19, 2016.

Mitigation of High Cell Voltages

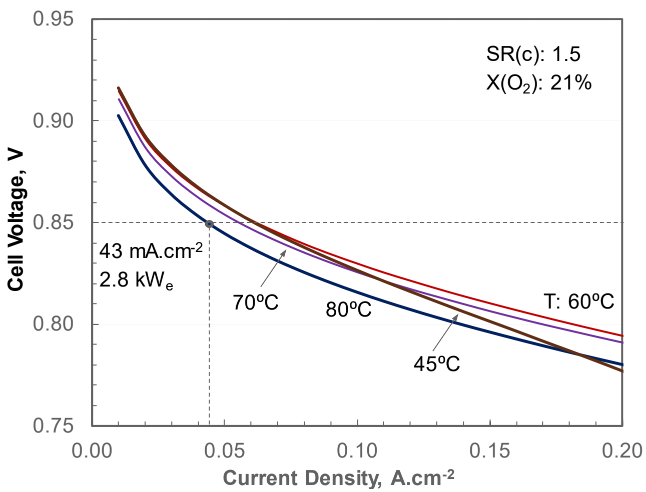
SOA stack limits cell voltage to 0.85 V during idle



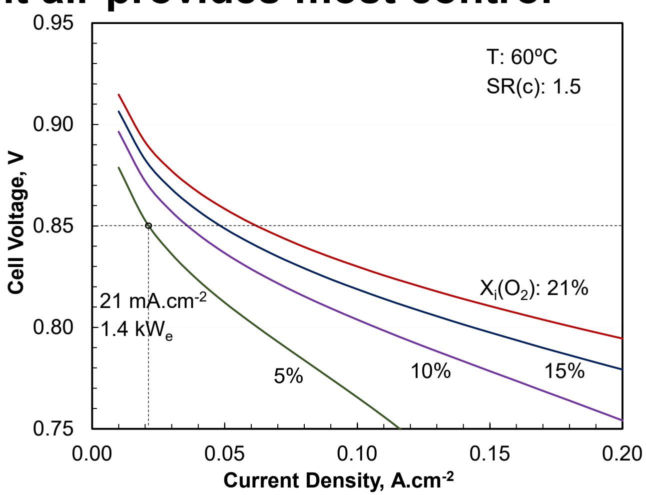
Reducing cathode stoichiometry may not provide adequate control of cell voltage



Lowering stack temperature may also be inadequate and has thermal inertia



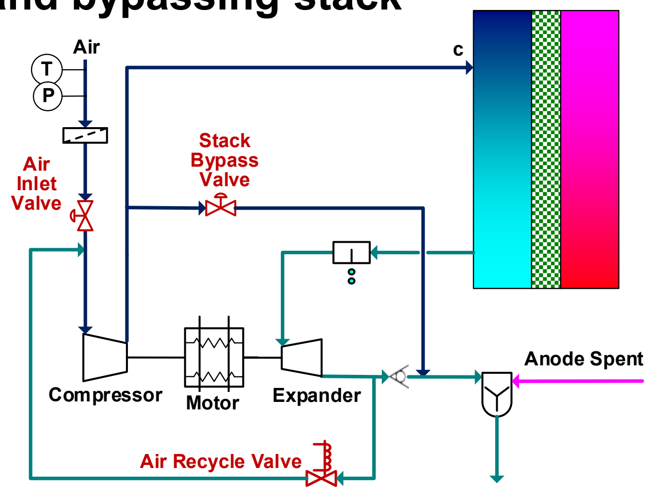
Reducing O_2 concentration by recycling spent air provides most control



M. Sato, "Fuel cell System and method of Controlling the Same," US 2017/0047602 A1, Feb. 16, 2017.
S. Kawahara, K. Suematsu, M. Toida, and R. Akaboshi, "Fuel Cell System and Control Method Thereof," US 9,531,022 B2, Dec. 27, 2016.

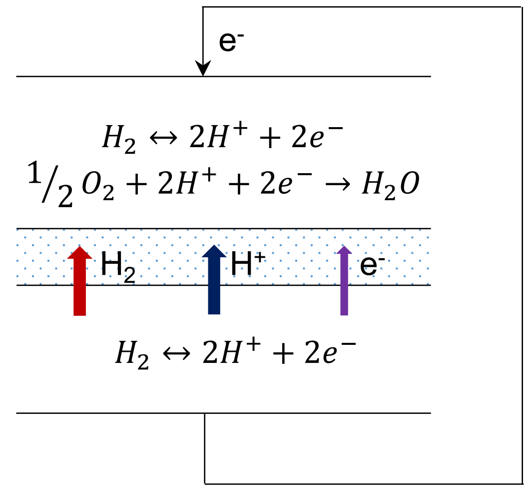
Controlling O_2 Concentration at Stack Inlet

Controlling O_2 concentration at stack inlet by recycling cathode spent air and bypassing stack*

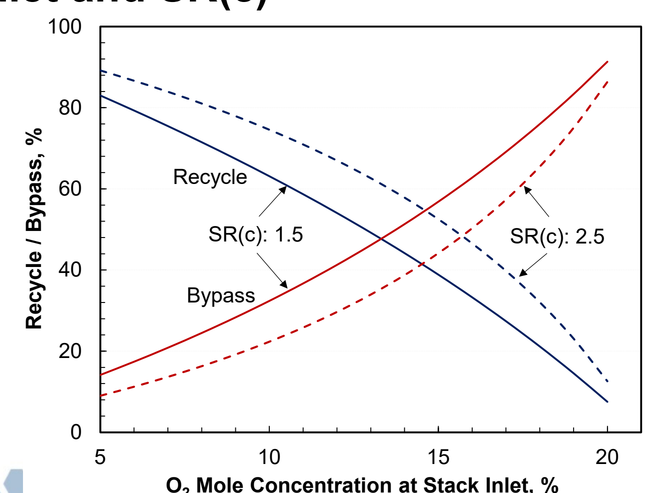


Air inlet and recycle valves not included in Argonne 2018 FCS configuration

Model for mixed cathode potential at low cathode stoichiometry



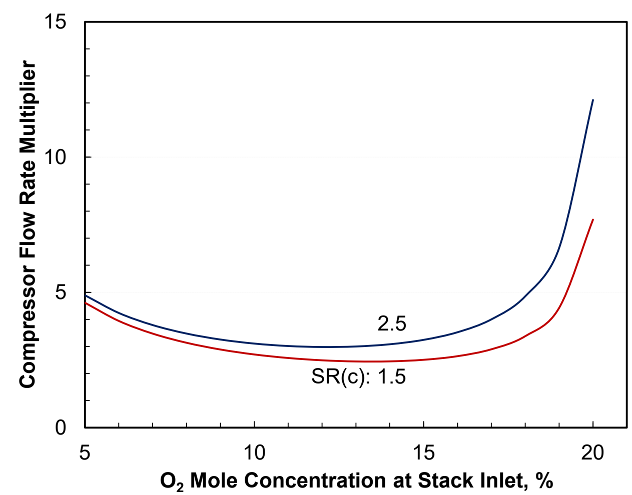
Recycle and bypass depend on desired reduction in O_2 concentration at stack inlet and SR(c)



$$R = \dot{m}_R / \dot{m}_c$$

$$B = \dot{m}_B / \dot{m}_c$$

Increase in compressor flow rate to reduce inlet O_2 concentration below 21%



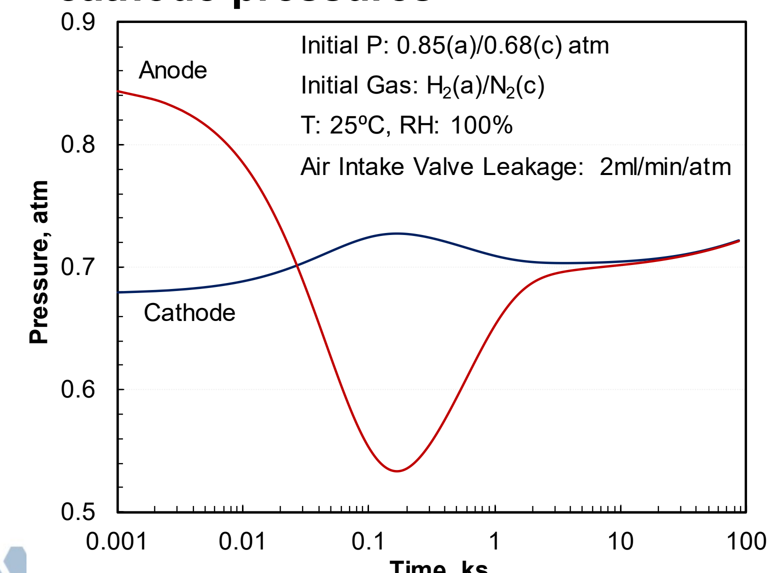
*M. P. Wilson, V. Yadha and C. A. Reiser, "Low Power Control of Fuel Cell Open Circuit Voltage," US 8,808,934 B2, Aug. 19, 2014.

Protected Shutdown

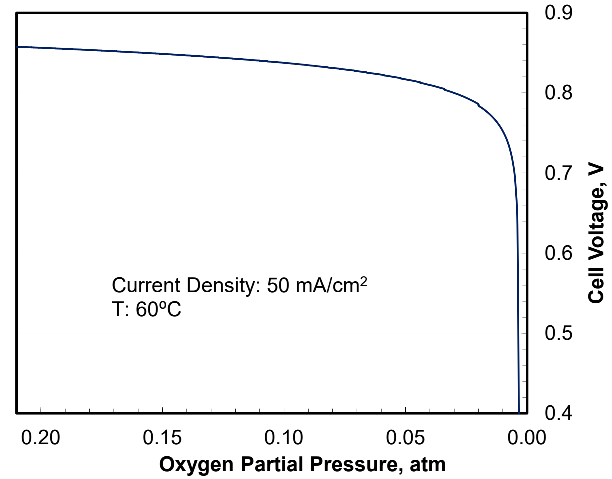
Protected shutdown algorithm

- **Step 1: Isolate the cathode circuit by closing the air intake valve and opening the air recycle valve**
- **Step 2: Deplete oxygen by applying load while supplying hydrogen**
- **Step 3: Shut the compressor (if on) and isolate H_2 circuit by closing the H_2 main valve**
- **Step 4: Allow H_2 and N_2 in anode and cathode circuits to equilibrate**

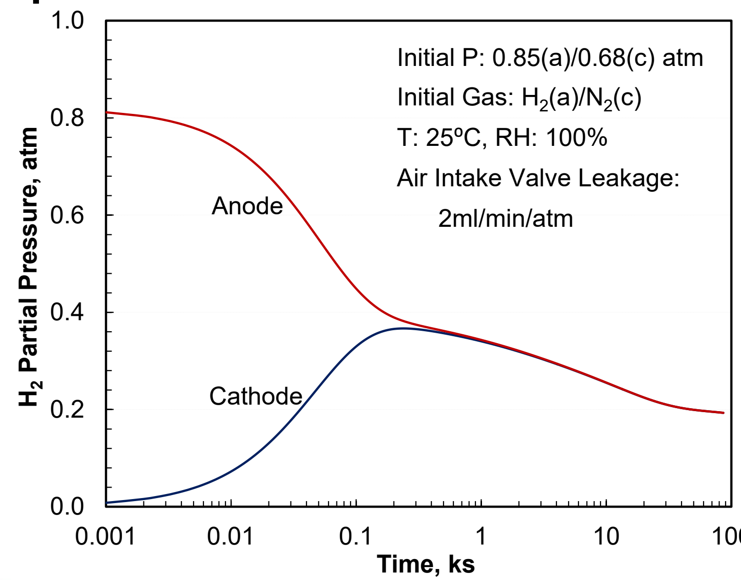
Step 4: Equilibration of anode and cathode pressures



Step 2: Depletion of oxygen with cathode air recycled by compressor



Step 4: Equilibration of H_2 partial pressures in anode and cathode circuits



S. U Kwon, S. H. Choi, N. W. Lee, S. P. Ryu, and S. S. Park, "Idle Stop-Start Control Method of Fuel Cell Hybrid Vehicle," US 2010/0009219 A1, Jan. 14, 2010.

Collaborations

Air Management	Honeywell: Cost and Performance Enhancements for a PEM Fuel Cell Turbocompressor (FC27)
	Eaton: Roots Air Management System with Integrated Expander (FC103)
Stack	3M: High Performance, Durable, Low Cost Membrane Electrode Assemblies for Transportation (FC104)
	Ballard/Eaton: Roots Air Management System with Integrated Expander (FC103)
	JMFC and UTRC: Rationally Designed Catalyst Layers for PEMFC Performance Optimization (FC106)
	FC-PAD: Fuel Cell Performance and Durability Consortium (FC135, FC136, FC137, FC138, FC139)
	GM: Highly-Accessible Catalysts for Durable High-Power Performance (FC144)
	GM: Durable High-Power Membrane Electrode Assemblies with Low Pt Loadings (FC156)
Water Management	Gore, Ford, dPoint: Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers (FC067)
Thermal Management	3M, Honeywell Thermal Systems
Fuel Management	3M, University of Delaware (Sonijector)
Fuel Economy	ANL-Autonomie (SA044), Aalto University (Fuel Cell Buses)
H_2 Impurities	3M
System Cost	SA: Manufacturing Cost Analysis of Fuel Cell Systems and Transportation Fuel Cell System Cost Assessment (FC163)
Dissemination	IEA Annex 34, Transport Modeling Working Group, Durability Working Group, Catalysis 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

Proposed Future Work

1. Continue to support DOE development effort at system, component, and phenomenological levels
2. Continue to support SA in high-volume manufacturing cost projections, collaborate in life-cycle cost studies
   - Optimize system parameters considering costs at low-volume manufacturing
   - Life cycle cost study for medium and heavy duty vehicles (Ballard, Eaton, SA)
3. Alternate MEAs with advanced alloy catalysts
   - State-of-the-art low PGM Pt and Pt alloys (FC-PAD collaboration)
   - Alternate electrode structures (FC-PAD FOA projects collaboration)
   - Durability models (FC-PAD and GM collaboration)
4. System architecture and balance-of-plant components
   - Air management system with centrifugal and Roots compressors and expanders (Honeywell/Eaton collaboration)
   - Fuel and water management systems: anode gas recirculation, internal/external humidification
   - Bipolar plates and flow fields for low pressure drops and uniform air/fuel distribution, cell to stack performance differentials
   - Strategies and controls for stack idling, startup and shutdown, subfreezing temperatures
5. Incorporate durability considerations in system analysis
   - System optimization for cost, performance, and durability on drive cycles (Advanced alloy catalyst systems)

Any proposed future work is subject to change based on funding levels.

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 Apply models to issues of current interest Collaborate with other organizations to obtain data and apply models
Progress:	Projected 46.0 ± 0.7 $/kW_e$ FCS cost at high volume manufacturing and 8.5 ± 0.4 kW_e/g_{Pt} FCS Pt utilization with SOA d-PtCo/C cathode catalyst, reinforced 14-μm 850 EW membrane, and $Q/\Delta T$ = 1.45 kW/^oC constraint Verified that the stack can achieve 1180 ± 55 mW/cm^2 power density exceeding the target at low Pt loading (0.125 mg-Pt/cm^2) Projected <5% penalty in power density if the cathode humidifier is removed, and ~15% penalty if stack inlet pressure is lowered to 2 atm from 2.5 atm Showed that parasitic power approaches 25 kW_e if the compressor discharge pressure is raised to 4 atm Modified the reference system configuration to include valves and controls for protected shutdown, safe startup from sub-freezing temperatures, and limiting cell voltage to 0.85 V during idle
Collaborations:	3M, Eaton, GM, Gore, JMFC, SA, UTRC, UDEL/Sonijector
Future Work:	Fuel cell systems with emerging high activity catalysts Alternate balance-of-plant components System analysis with durability considerations on drive cycles

Reviewers' Comments

Sample comments and feedback

- ANL employs sound approach in forecasting performance but need more validation
- Impressive range of accomplishments, excellent study of catalyst systems, but needs more focus on Ni loss and other degradation mechanisms
- Excellent collaborations, but needs better definition of engagement with FC-PAD.
- Closer collaboration with OEMs to obtain stack and system data
- The project addresses multiple barriers including cost, performance, thermal/water/air subsystems, but more validation needed.
- Future work appears to be appropriate. More emphasis on durability in future.

Work scope consistent with above recommendations

√ On-going work on differential cell data for PtCo/C dispersed catalysts in collaboration with FC-PAD and an industrial partner. Initial results on performance and durability are included in FC-PAD presentations. The PI is FC-PAD coordinator for modeling and validation thrust area.

√ Examining durability during idling, startup/shutdown and sub-freeze start. Added valves and controls to mitigate catalyst degradation.

√ Analyzing system simplification (compressor air bleed), component elimination (humidifier, H_2 recirculation blower) and alternative operating conditions (higher pressures)

√ Expanded collaboration with an OEM on model validation using 10-50 cm^2 cells. Analyzing data from a SOA automotive stack and fuel cell system.

√ ANL is a subcontractor to SA on FC-163 project, responsible for supplying performance and design data. Plans and recent results are discussed in bi-weekly calls.

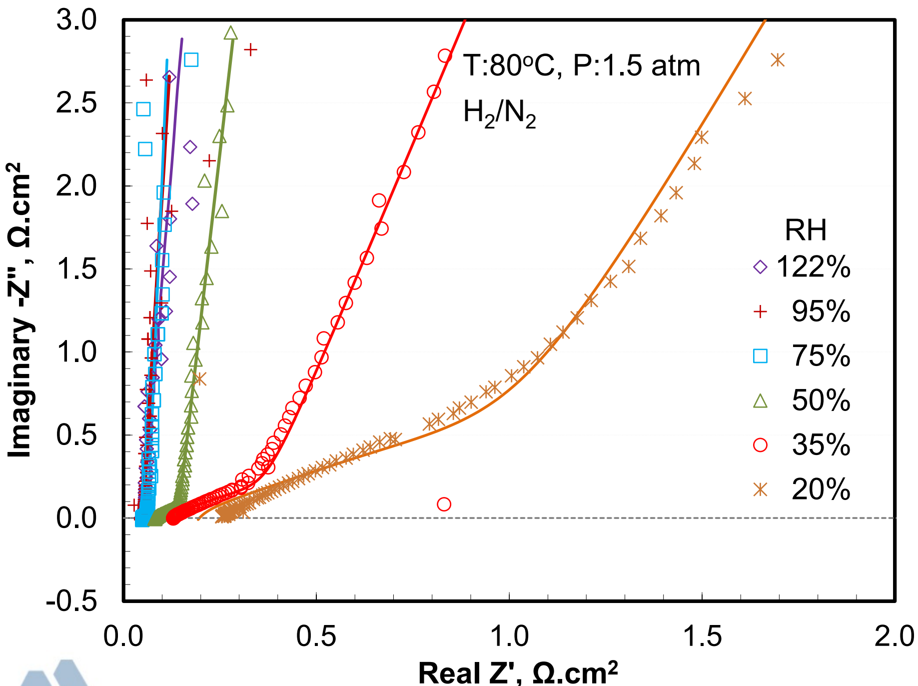
Technical Back-Up Slides

Electrode Resistance

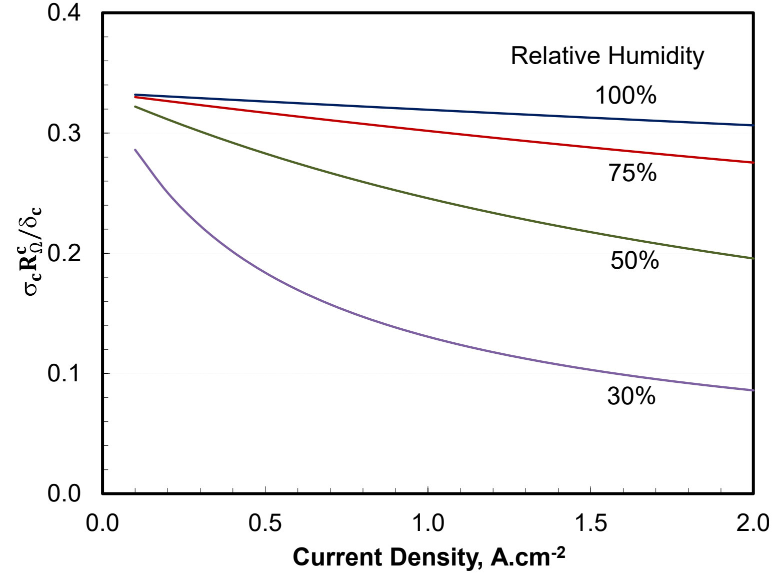
Electrode (σ_c) and membrane conductivities (σ_m) from Galvanostatic impedance data in H_2/N_2 at 0.4 V with 5 mV perturbation

- ZVIEW transmission line model (100 repeat units)

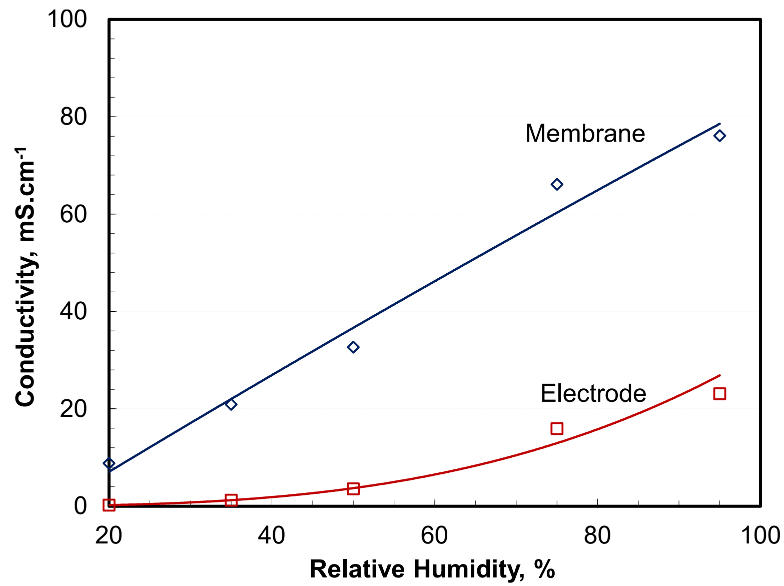
Nyquist plot consistent with RC circuit



Effective electrode resistance



Electrode and membrane conductivities



Oxide Formation on d-PtCo/C Catalyst

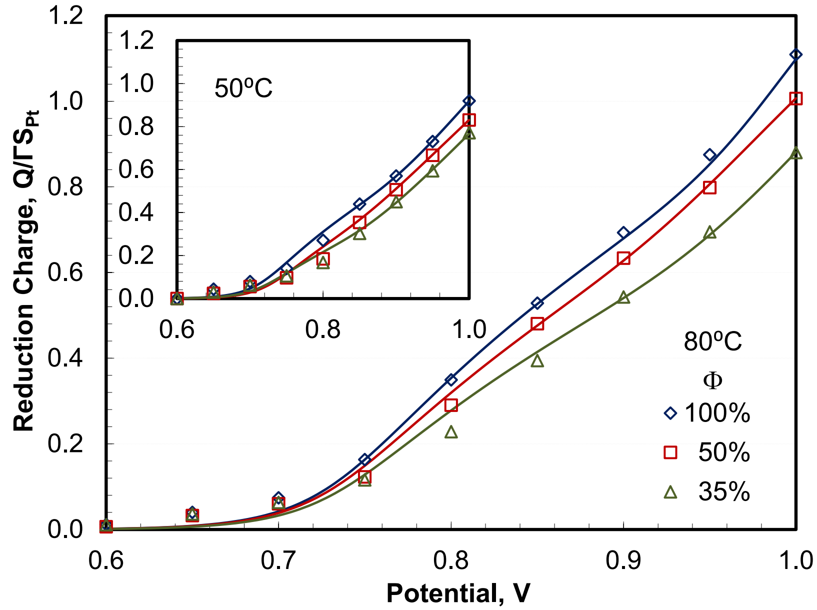
- Solid solution model for PtO_x formation developed from measured CV reduction charge after 45-min hold at constant potential[1]

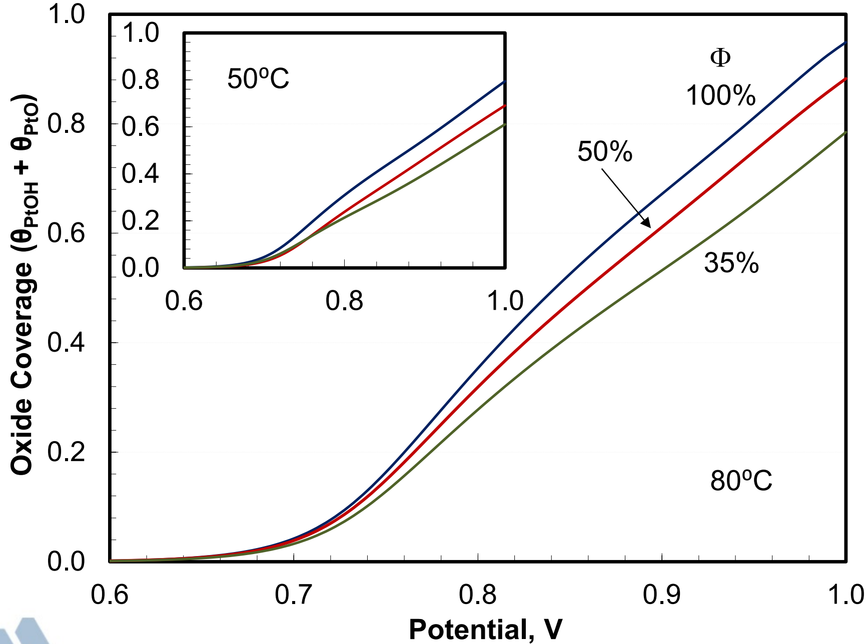
$$Pt + H_2O = PtOH + H^+ + e^-$$

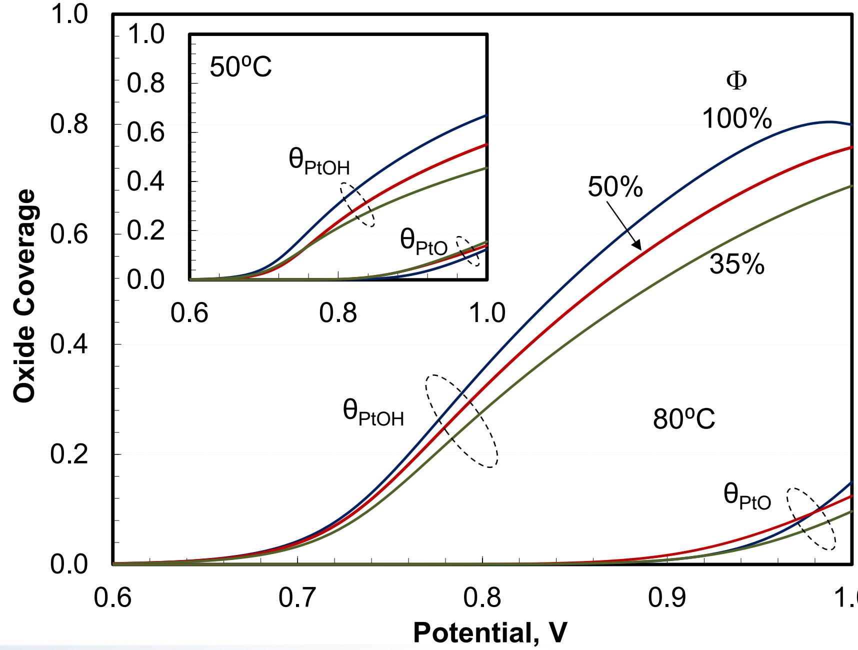
$$PtOH = PtO + H^+ + e^-$$

$$\theta = \theta_{PtOH} + \theta_{PtO}$$

$$K_i = c_{H^+}\left(\frac{\theta_i}{\theta_{i+1}}\right) e^{-\frac{F}{RT}[E-E_{0i}]} = K_{i0} e^{-\frac{\omega_i}{RT}\theta_i^{x_i}}$$







[1] Arisetty et. al. (2015), ECS Transactions, 69, 273-289

Model Validation

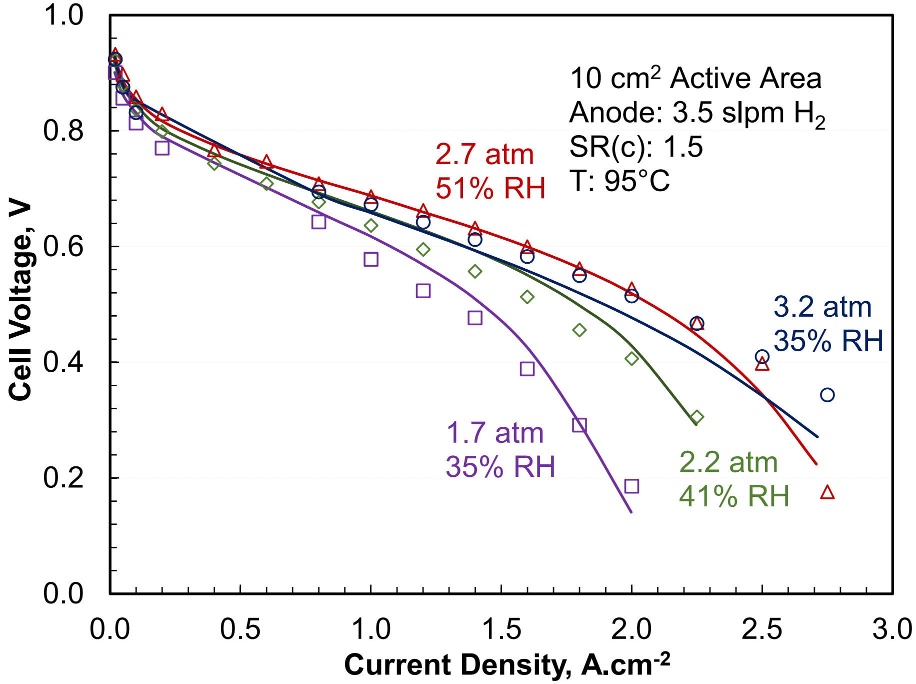
Work in Progress

- Validation tests on 50-cm^2 integral cell with controlled SR(c) and SR(a)
- Differential cell tests with 0.05 and 0.2 mg/cm^2 Pt loadings in cathode
- Extracting resistances for O_2 transport in GDL, CCL pores and ionomer

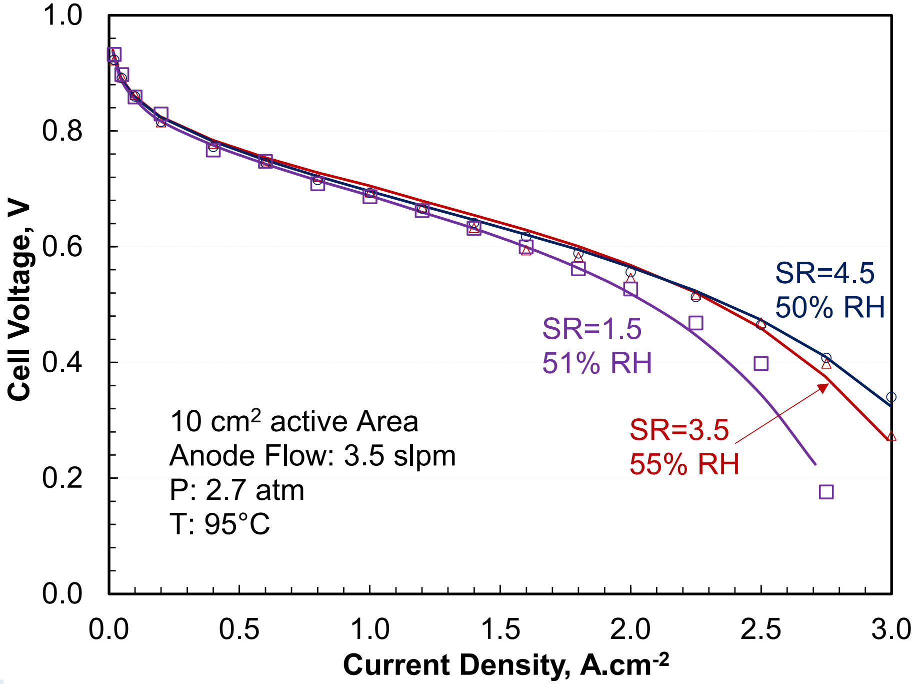
Future Work

- Catalyst accelerated cell tests to model durability

Differential cell operated in integral mode: Constant SR(c), variable P



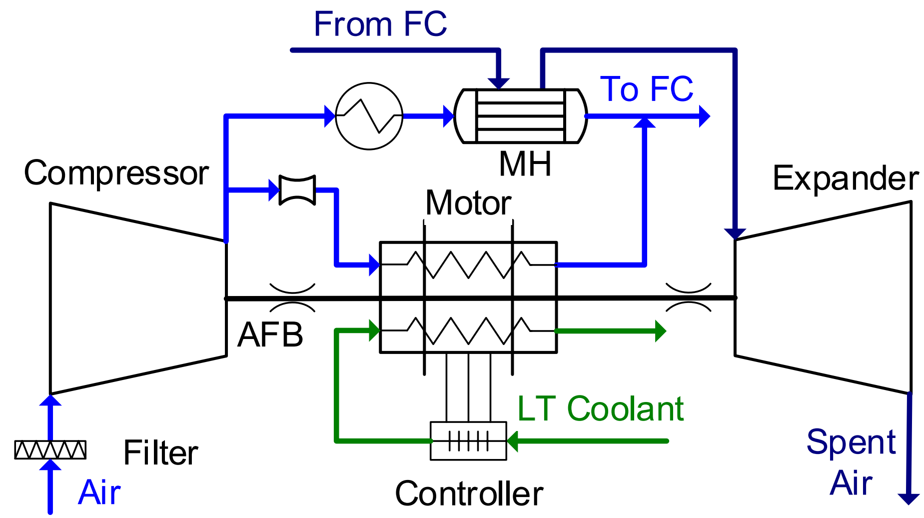
Differential cell operated in integral mode: Variable SR(c), constant P

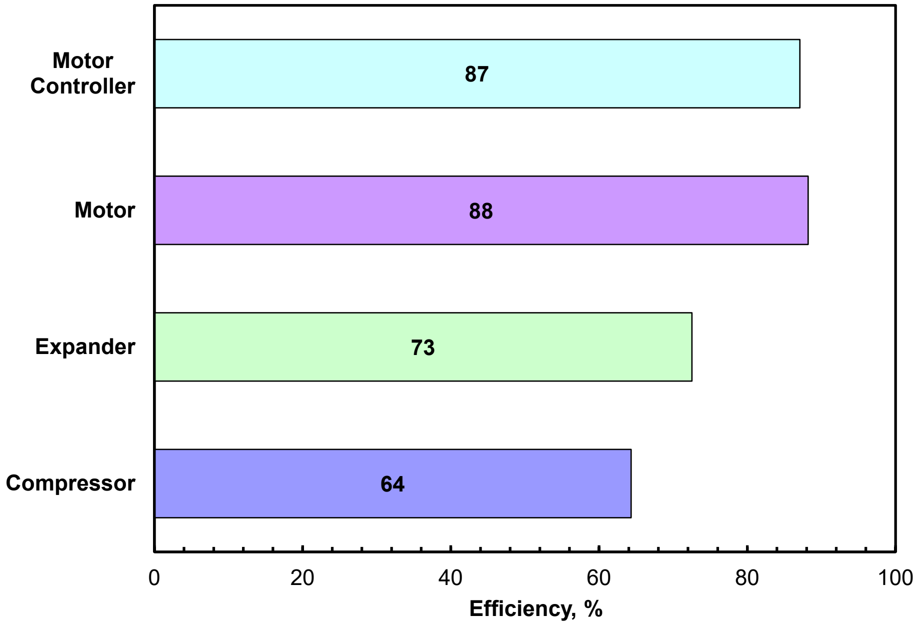


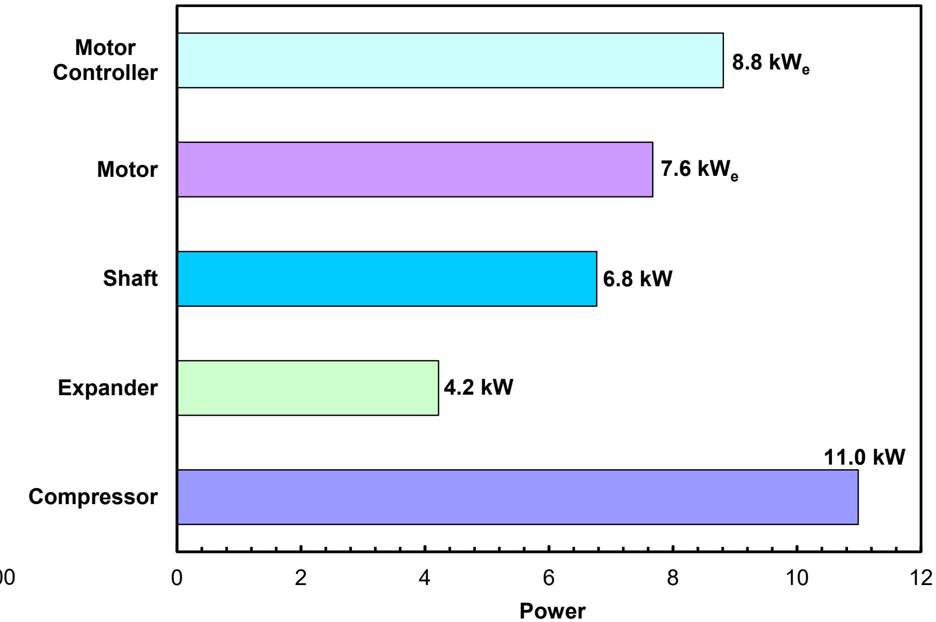
Projected Performance of CEMM with Bleed Air Recovery

Assumption: CEM cooling air can be recovered and combined with humidified air upstream of the PEFC stack

- **Data are for as-built components. Efficiencies and performance can be improved by resizing the components to match the actual operating conditions**





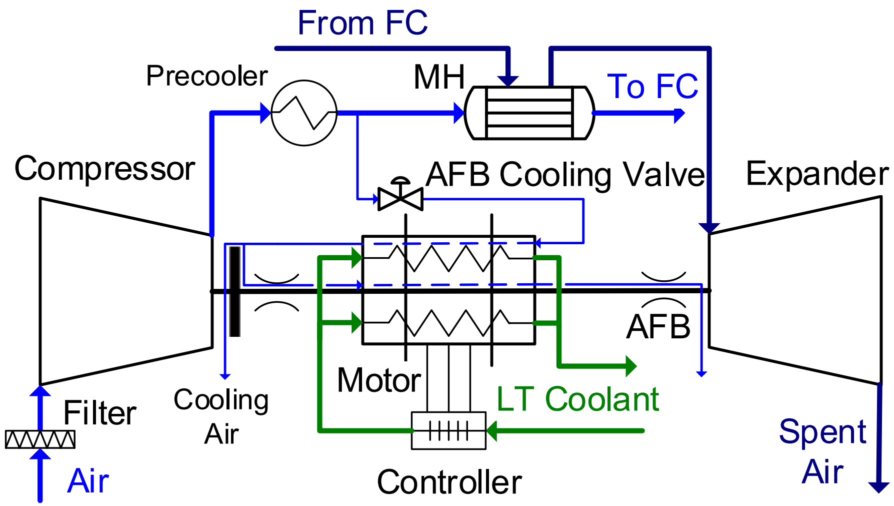


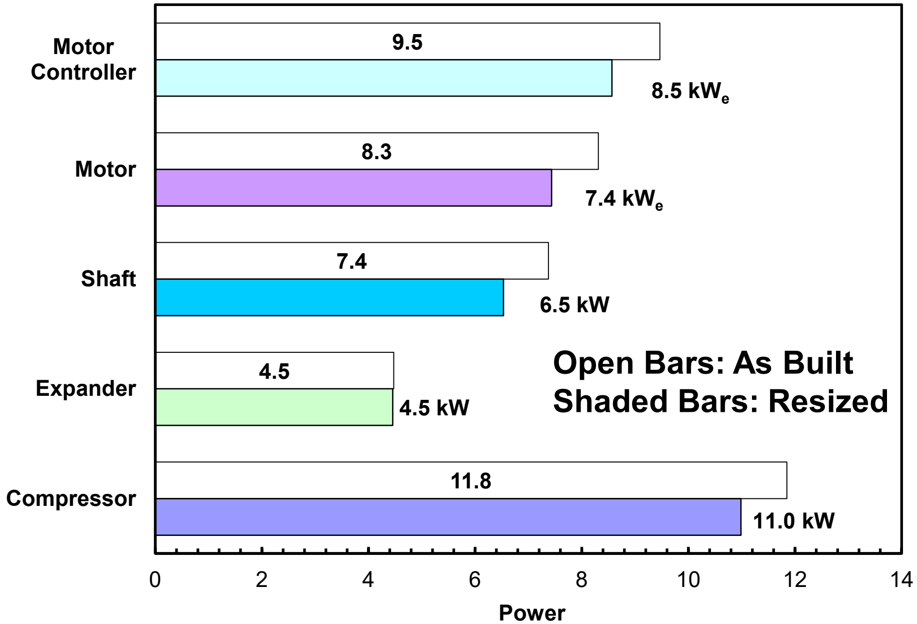
Simulation results for 73 g/s air flow rate and 2.5 atm compressor discharge P; 2.3 atm expander inlet P, 85°C inlet T, fully saturated; 40°C ambient T

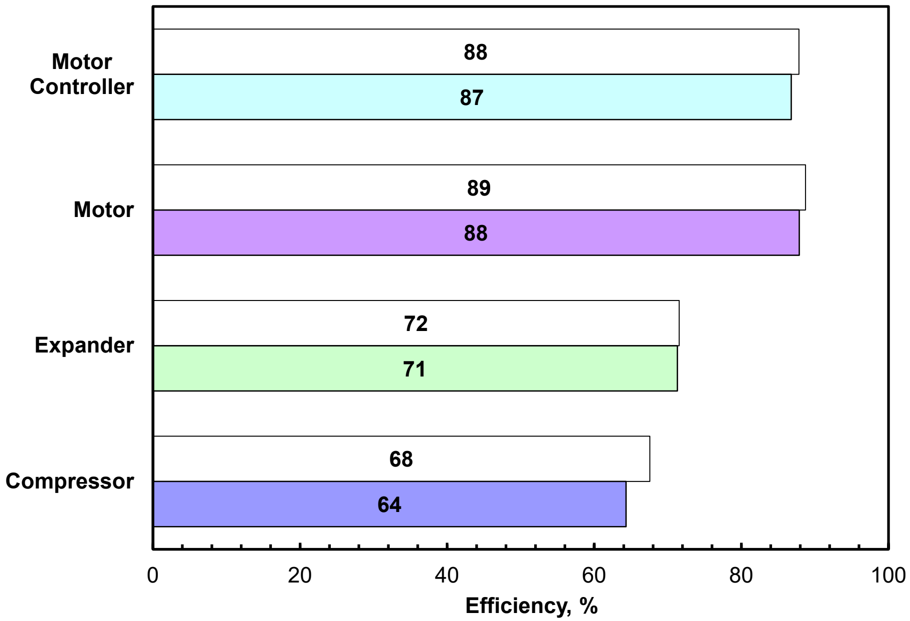
Comparative Performance of CEMM w/o Bleed Air Recovery

A control valve used to split pre-determined amount of air downstream of the pre-cooler to cool AFB and motor; this cooling air is lost irrecoverably.

- **Data are for as-built components. With resizing, the parasitic power can be reduced to 7.0 kW_e with bleed air recovery and 8.1 kW_e w/o bleed air recovery.**







Simulation results for 73 g/s air flow rate and 2.5 atm compressor discharge P; 2.3 atm expander inlet P, 85°C inlet T, fully saturated; 40°C ambient T