Fuel Cell System Modeling and Analysis

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U.S. DOE Hydrogen and Fuel Cells Program

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Project ID: FC017

Overview

Timeline

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

Budget

- FY19 DOE Funding: $300 K
- Planned DOE FY20 Funding: $200 K
- Total DOE Project Value: $200 K

Barriers

B. Cost

C. Performance

E. System Thermal and Water Management

F. Air Management

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

Partners/Interactions

- Eaton, Ford, Honeywell, UDEL/Sonijector
- SA, Aalto University (Finland)
- 3M, Ballard, Johnson-Matthey Fuel Cells (JMFC), UTRC, FC-PAD, GM, ElectroCat
- IEA Annex 34
- ANL-Autonomie, 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 FY2020 work

- In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs)
- Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3%
- Determined the operating conditions for 55.3% ECSA loss: CEM* turndown = 12 (10), coolant exit temperature = 66°C/70°C for 5000 h/8000 h electrode durability
- Proposed initial metrics for heat rejection in FCS for Class-8 heavy duty trucks: 0.7 V at rated power (275 kW net), 87°C coolant exit temperature
- Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm^2 power density at 0.7 V.
- Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, specifying time spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles

***CEM: compressor-expander module**

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	In collaboration with GM, analyze methods of extending the durability of MEAs with SOA d-PtCo cathode catalyst relative to reach the target of 8000 h lifetime.	12/19
2	In collaboration with FC-PAD, establish an initial benchmark for performance and durability of MEAs for medium and heavy-duty trucks.	03/20
3	In collaboration with SA, update the performance and cost of an automotive FCS with an advanced low-PGM catalyst relative to 2020 targets of 65% peak efficiency, $Q/\Delta T$ = 1.45 kW/K, and \$40/kW cost.	06/20
4	In collaboration with SA, determine the performance and cost of truck fuel cell systems relative to the FCTO targets.	09/20

Technical Accomplishments: Summary

1. Durability of LDV Fuel Cell Systems with State-of-the-Art (SOA), Low-PGM Pt Alloy Cathode Catalyst

- In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs)
- Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3%
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2. Fuel Cell Systems for Heavy-Duty Vehicles

- Proposed initial metrics for heat rejection in FCS for Class-8 heavy duty trucks: 0.7 V at rated power (275 kW net), 87^{o}C coolant exit temperature
- Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm^2 power density at 0.7 V.
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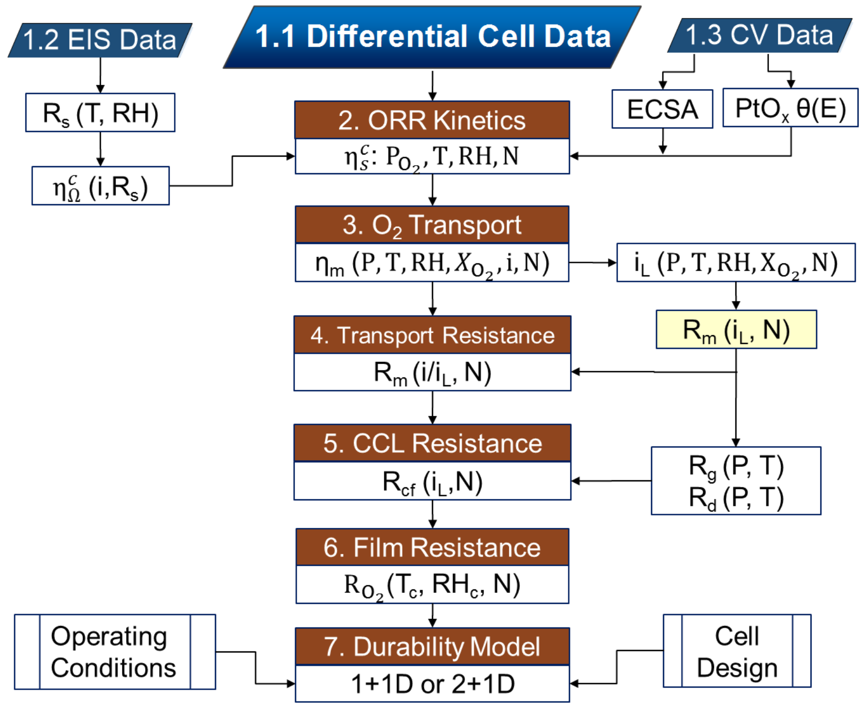
[1]d-PtCo/C: de-alloyed PtCo catalyst on high surface area carbon (HSAC) support

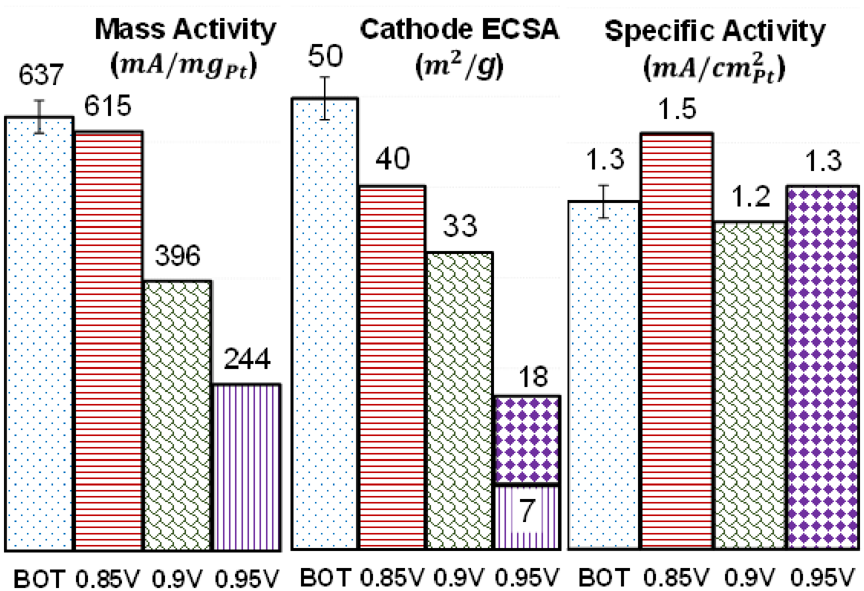
1. Fuel Cell Durability Model Framework using Single Cell Hardware

Degradation Model for ORR Kinetics and O_2 Transport Resistance*

- Degrade cells using catalyst AST protocol for 15k, 30k and 50k cycles
- Vary UPL: 0.95, 0.90, 0.85 V, 0.8 V
- Vary RH: 40%, 100%
- Vary temperature: 95°C, 80°C, 60°C
- Measure cell performance and H_2/N_2 EIS at BOT and EOT for 12 operating conditions; 1-2.5 atm; 60-95°C; 30-100% RH; 5-21% $X(O_2)$
- Measure and model Pt and Co dissolution using online ICP-MS



GCtool Model



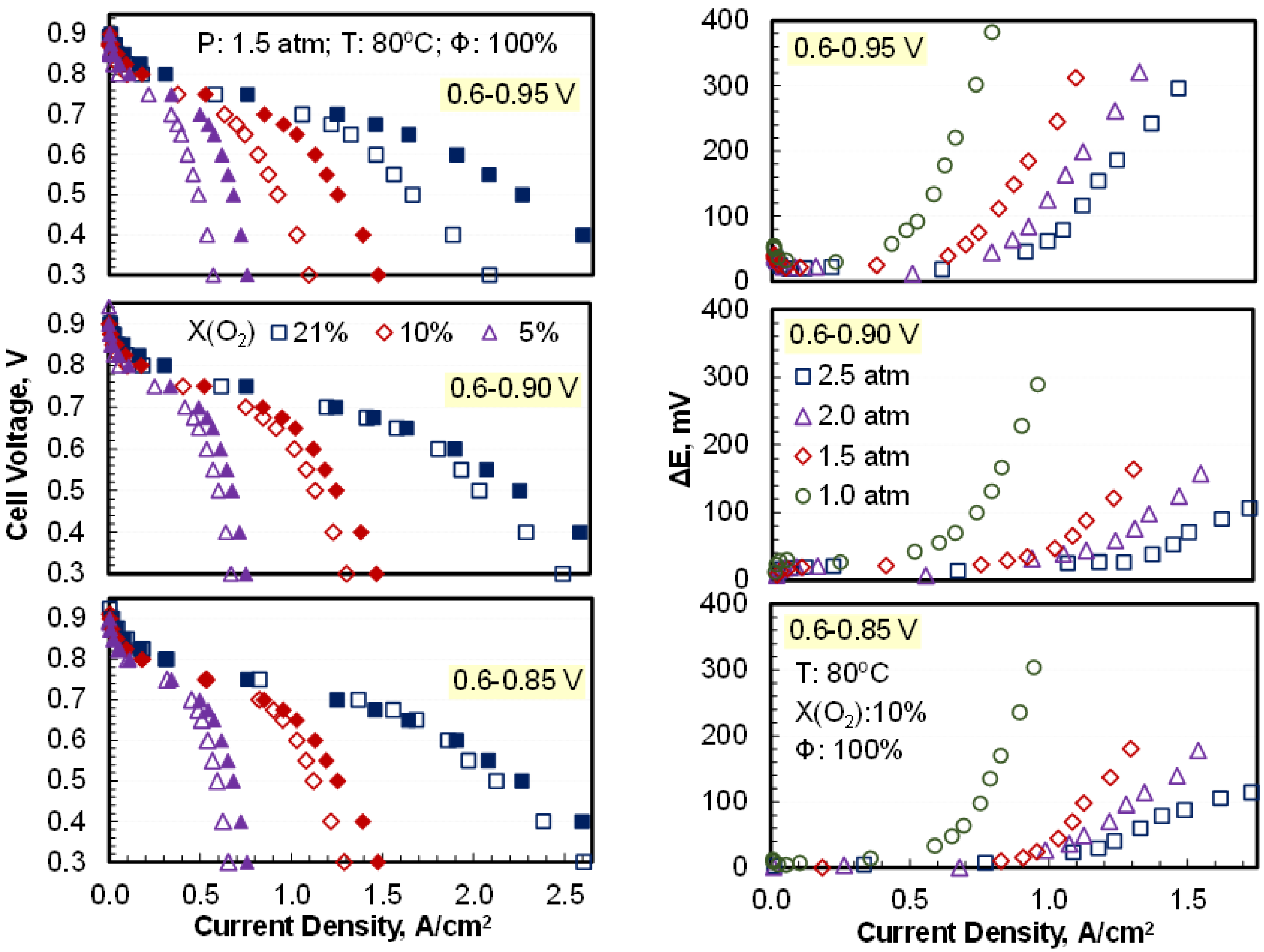
Representative State-of-the-Art Low-PGM MEA		
	Cathode	Anode
Catalyst	d-Pt_3Co/C	Pt/C
Catalyst Support	HSAC-a	Vulcan
Ionomer Equivalent Weight	825	950
Pt Loading	0.1 mg/cm^2	0.025 mg/cm^2
ECSA	45 m^2/g	60 m^2/g
Electrode Thickness	7 μm	5 μm
Diffusion Medium Thickness	200 μm	200 μm
Membrane	12 μm Reinforced	

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

Controlling Voltage Degradation by Voltage Clipping

Degradation can be controlled by clipping cell voltage

- After 30k AST cycles: ΔV(0.85V UPL) < ΔV(0.9V UPL) << ΔV(0.95V UPL)
- Smaller voltage losses at higher operating pressures: advantage of pressurized system



Solid symbols: data at BOT
Open symbols: data at EOT for different $X(O_2)$

ΔE: E(BOT) – E(EOT)
Open symbols: ΔE for different P

Polarization curves in a differential cell at 80°C, 100% RH

ORR Kinetics on Degraded d-PtCo/C Catalyst

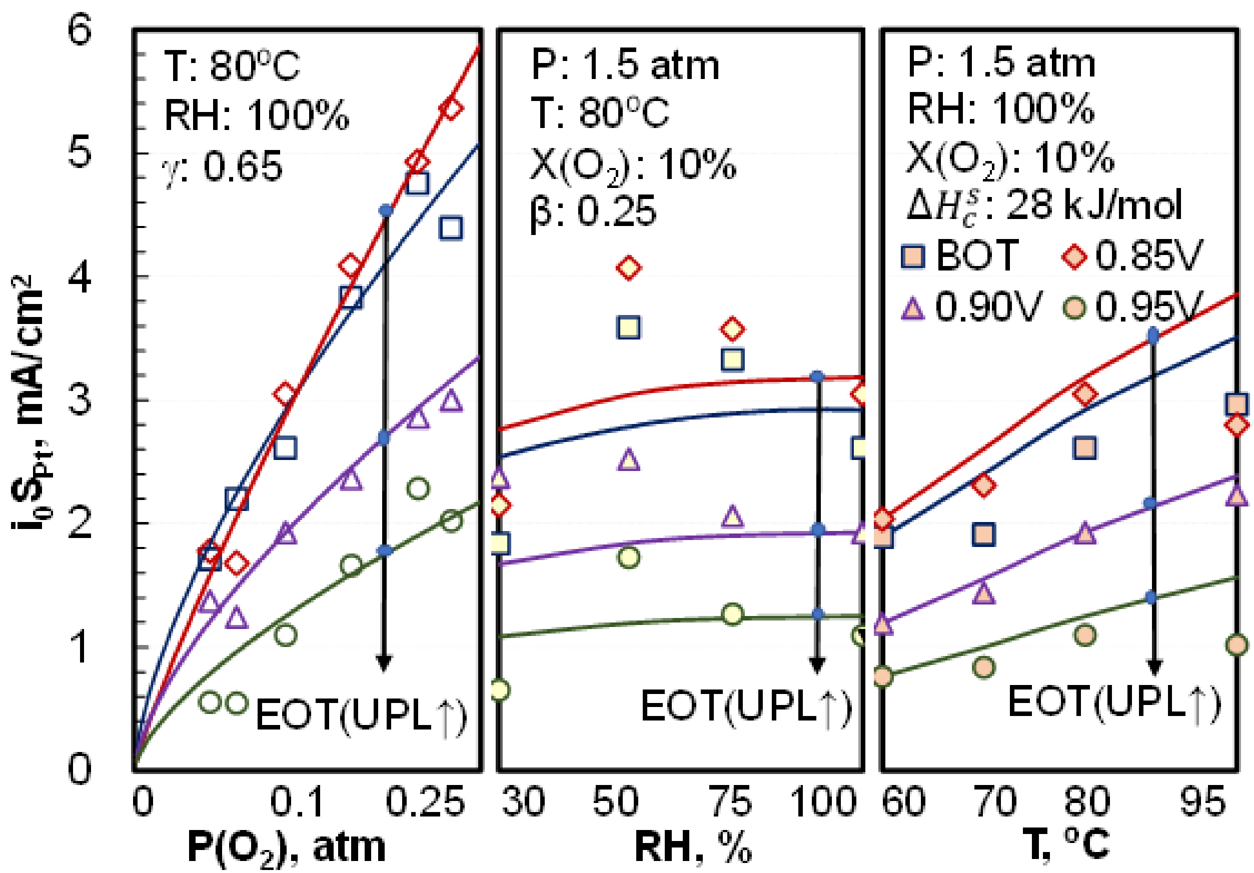
- Negligible changes in kinetic parameters denoting reaction order (γ), activation energy (ΔH_S^c), and RH dependence (β)
- Kinetic losses are nearly proportional to ECSA loss (S_{Pt})

Distributed ORR Kinetic Model

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

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

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



Effect of Ageing on O_2 Transport Resistance (d-PtCo/C Catalyst)

Smaller increase in R_{cf} at lower UPL after 30k cycles

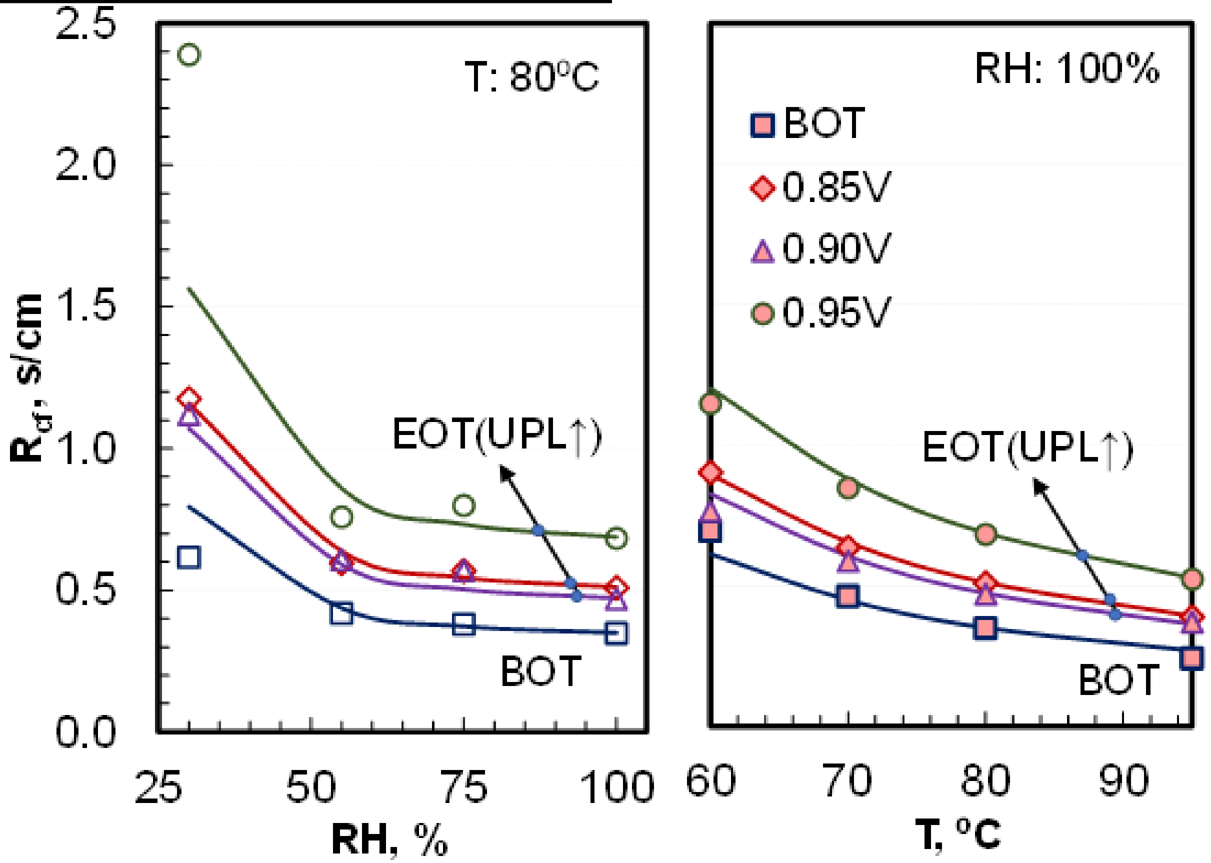
UPL	ΔS_{Pt}	ΔR_{cf}
0.95 V	-65%	100%
0.90 V	-35%	40%
0.85 V	-20%	50%

O_2 Transport Model

$R_m = R_g + R_d + R_{Kn} + R_{cf}$

R_g and R_d are P dependent

R_{Kn} and R_{cf} are P independent



Effect of Ageing on R_{O_2} (d-PtCo/C Catalyst)

R_{O_2} decreases after ageing – ionomer conditioning

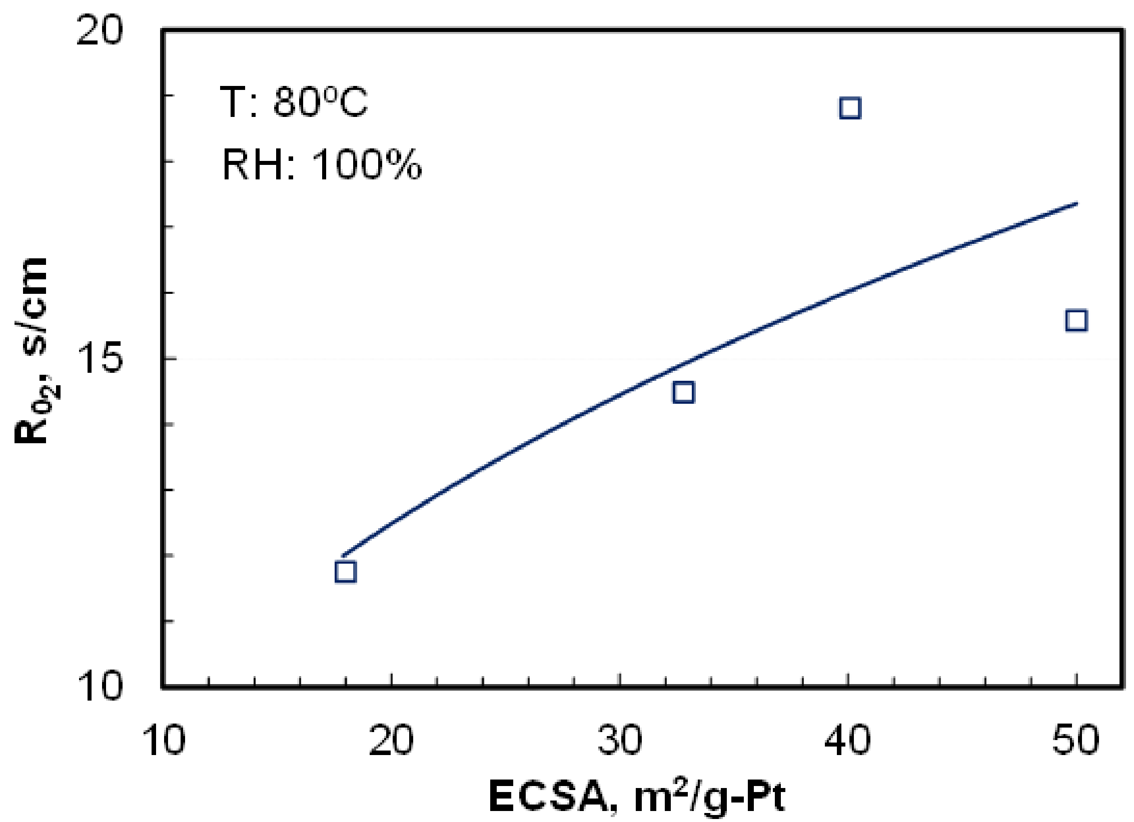
UPL	ΔS_{Pt}	ΔR_{O2}
0.95 V	-65%	-30%
0.90 V	-35%	-15%
0.85 V	-20%	-8%

O_2 Transport Model

$$R_m = R_g + R_d + R_{Kn} + R_{cf}$$

$$R_{cf} = \frac{R_{O_2}}{S_{Pt}}$$

$$R_{O_2} = R_{O_2}(T_c, \Phi_c, N)$$

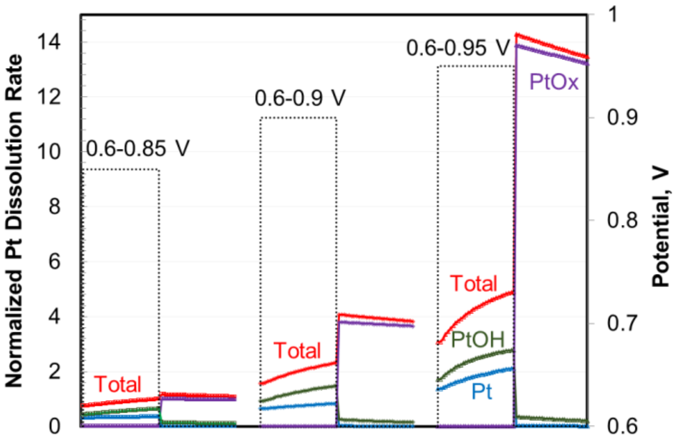


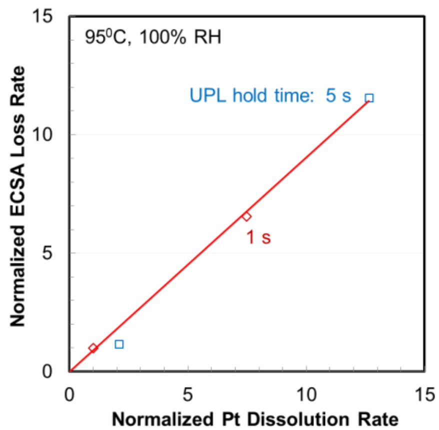
Catalyst Durability Model

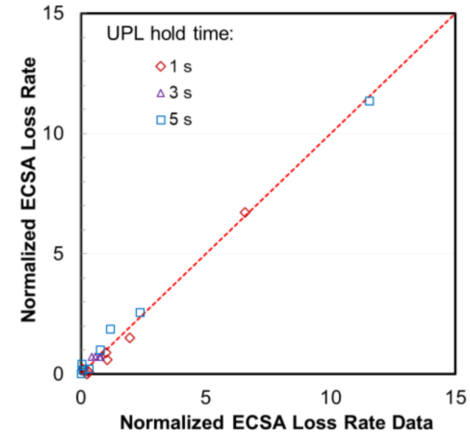
Pt dissolution model from on-line ICP-MS data in aqueous media at room temperature (RT): R.K. Ahluwalia et al, JECS 165(6) F3024-F3035 (2018)

ECSA (S) loss on catalyst AST

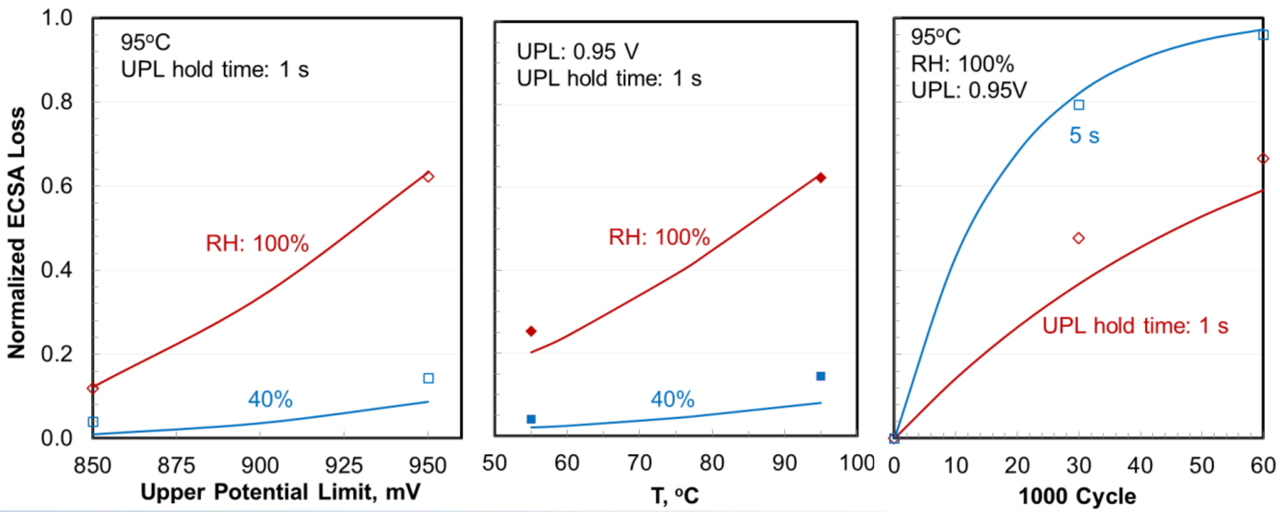
$$\frac{dS}{dt} = -k(S - S_0), \qquad \frac{k}{k_0} = a_k\left(\frac{\dot{r}_d}{\dot{r}_{d,0}}\right)\Phi^{\alpha} e^{-\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)}$$







Data from FCPAD-FC156 collaboration (S. Kumaraguru PI): 50-cm² cell, Trapezoidal wave: 0.6 V LPL, 0.85-0.95 V UPL, 350 mV/s scan rate, 60,000 cycles; 55-95ºC; 1-5 s hold time at UPV; 40-100% RH.



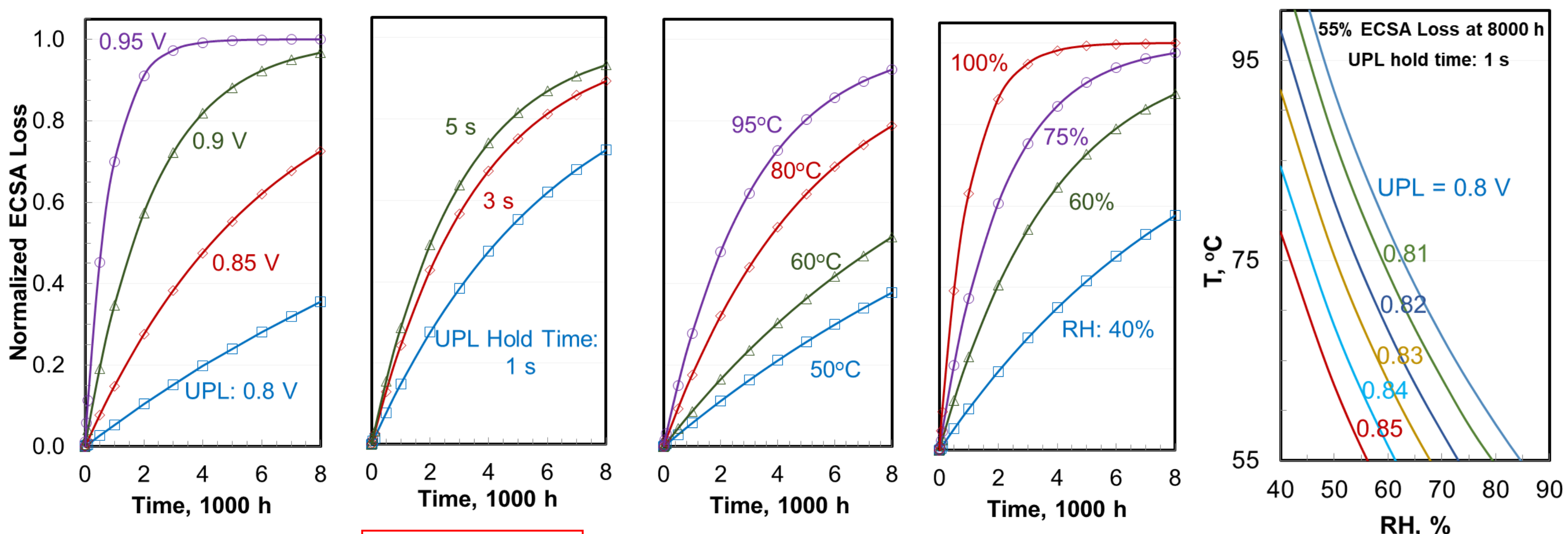
Catalyst Durability Study

Default conditions

- Trapezoidal potential: 0.6 (LPL) - 85 V (UPL), 1-s holds at UPL & LPL, 75^{o}C, 50% RH

Main conclusions from parametric and acceptability map analyses

- Limit UPL below 0.85 V (Frame 1)
- Avoid extended holds at UPL (Frame 2)
- Long operation above 80^{o}C is extremely damaging (37.3 kJ/mol) (Frame 3)
- Low RH is preferable but may compromise in membrane stability (Frame 4)
- UPL-T-RH map for 8000-h life with 55% ECSA loss, 1-s holds at UPL & LPL (Frame 5)



Frame 1
UPL Study

Frame 2
UPL Hold Time

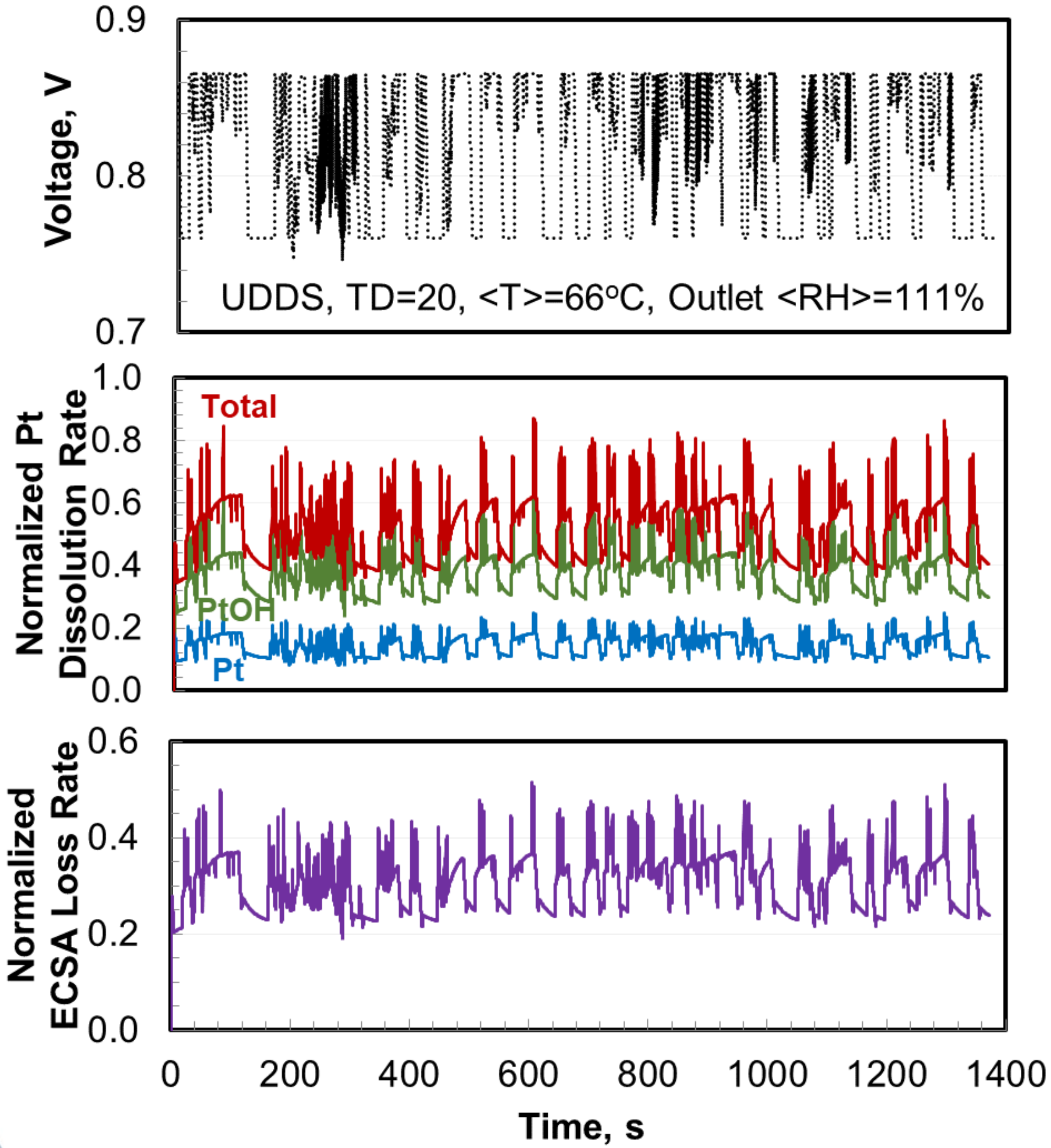
Frame 3
T Study

Frame 4
RH Study

Frame 5
Acceptability Study

***A. Kneer and N. Wagner, JECS 186(2) F130-F137 (2019)**

Catalyst Degradation on Drive Cycles



UDDS Drive Cycle*

- **Average FCS power: 10 kW**
- **CEM turndown: 20**
- **Minimum FCS power: 4 kW**
- **Average T: 66°C**
- **Average outlet RH: 111%**
- **Cell voltage: 760-866 mV**

Pt Dissolution

- **Pt dissolves more as PtOH than as Pt**
- **PtO_x does not form on UDS**

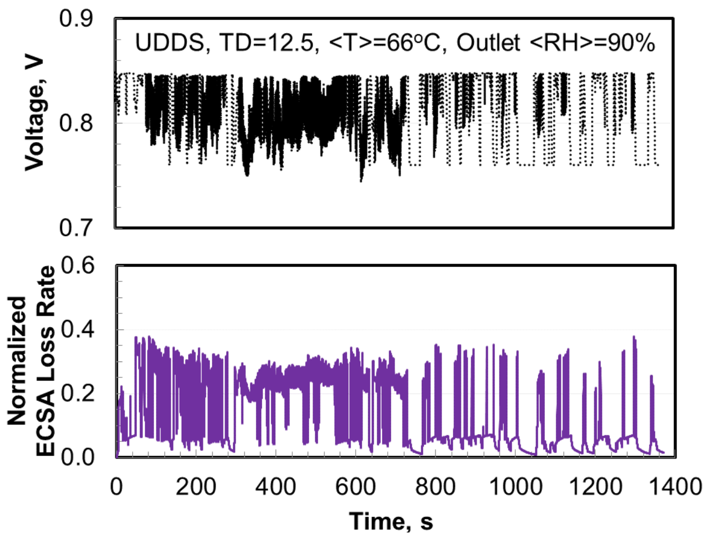
ECSA loss rate ~8X faster than the target for 8,000 h durability

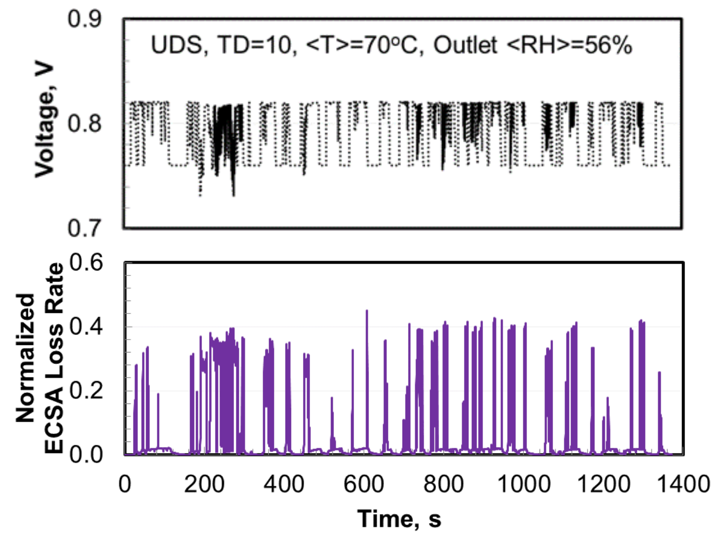
***Vehicle demand from Autonomie simulations by Ram Vijayagopal, ANL**

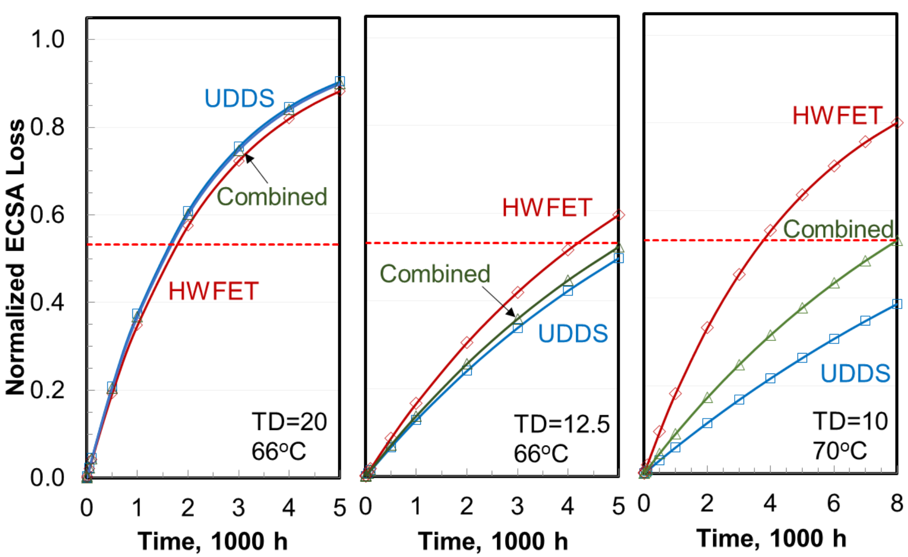
Pathways for Reaching 5000-h and 8000-h Electrode Lifetime

Turndown=12.5: 849 – 760 mV on UDDS; outlet <RH>: 90%; ~six-fold lower ECSA loss rate

70^{o}C <T>: 825 – 760 mV on UDDS; outlet <RH>: 56% UDDS, 52% HWFET; 26% lower ECSA loss rate







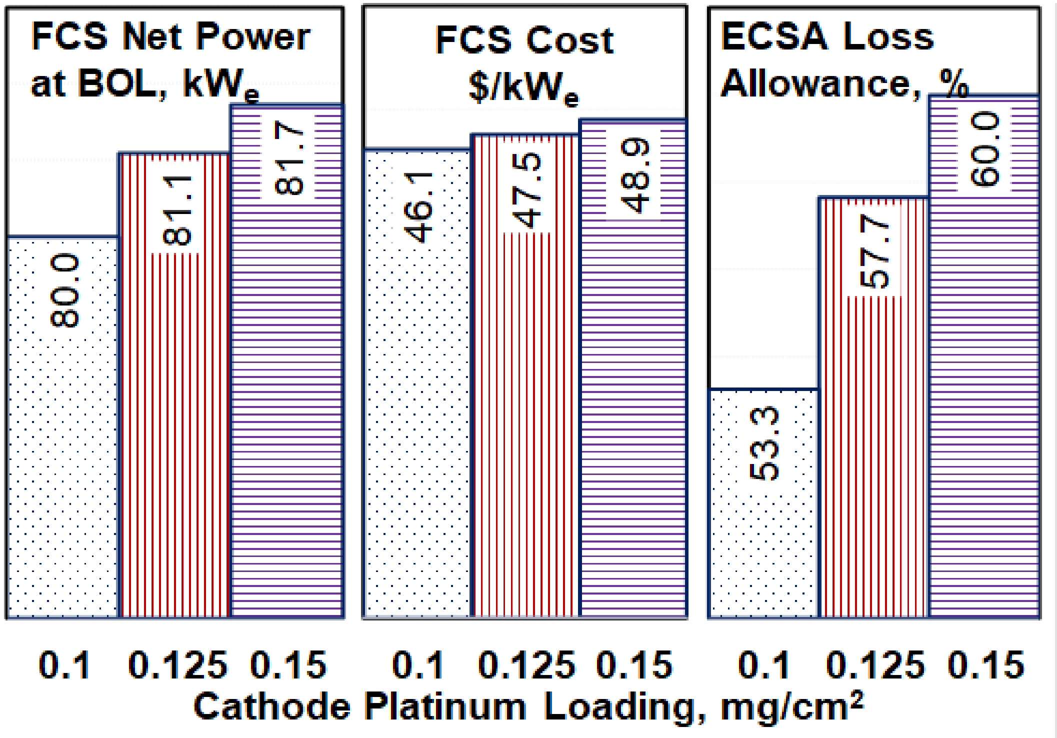
Conditions for 5,000-h and 8000-h durability on combined EPA UDDS and HWFET cycles. The combined cycles include 76% time on UDDS and 24% time on HWFET.

	Durability on Combined UDDS & HWTET Cycles			
Durability	5000 h		8000 h	
Load Cycles	UDDS	HWFET	UDDS	HWFET
CEM Turndown	12.5		10	
Average Outlet T	66^{o}C		70^{o}C	
Average Outlet RH	90%	102%	56%	83%
Cell Voltage	760-850 mV		760-825 mV	
ECSA Loss	50.0%	60.0%	40.0%	80.0%
Combined ECSA Loss	55.3%		55.3%	

Effect of Cathode Pt Loading on Cost and Allowable ECSA Loss

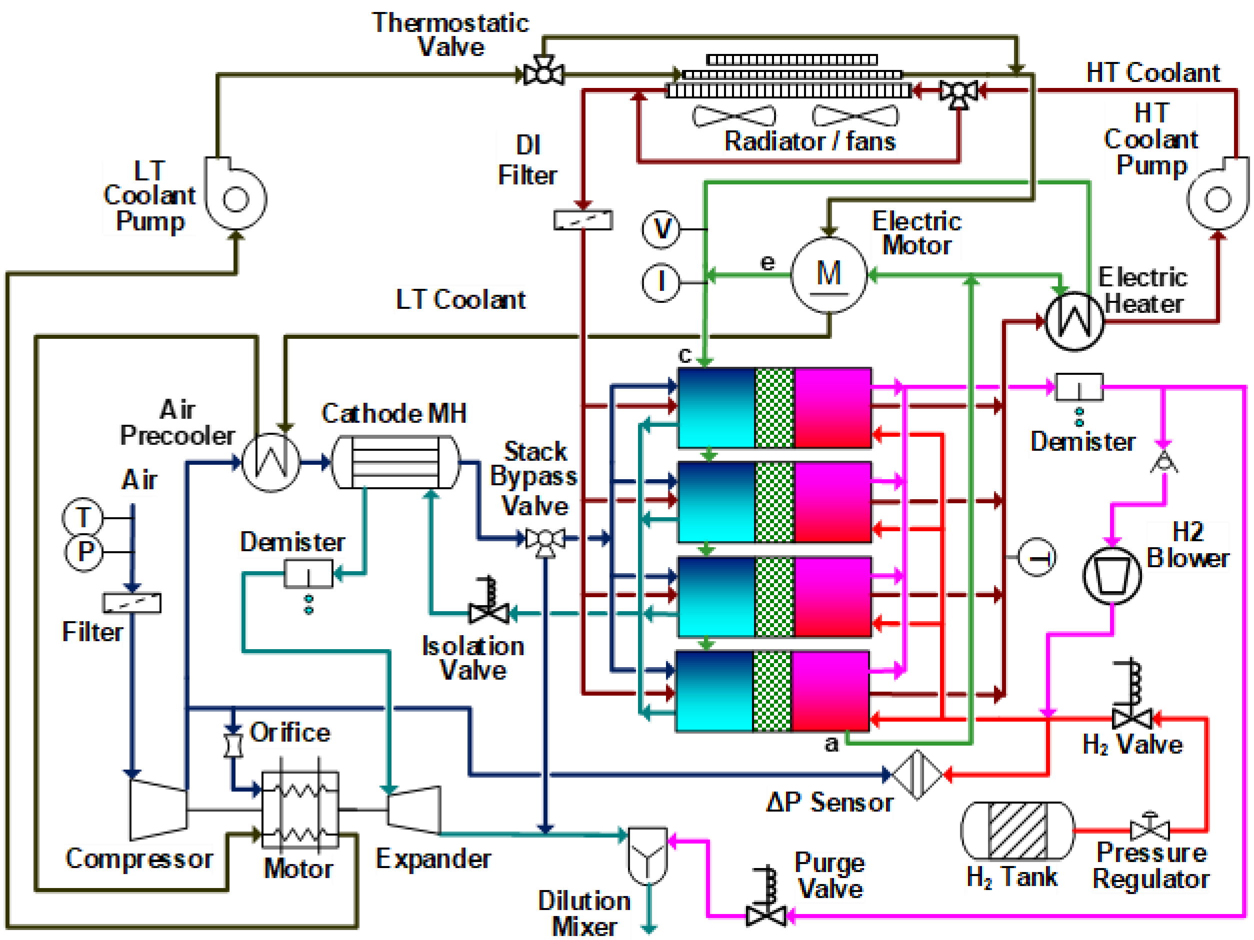
Simulations to determine FCS cost with different Pt loadings in cathode

- Constraint 1: Fixed active membrane area as determined for electrode with 0.1 mg/cm^2 Pt loading in the alloy catalyst
- Constraint 2: FCS produces 72 kW at EOL (5000 or 8000 h) on the EPA combined cycle
- Constraint 3: FCS satisfies the Q/ΔT constraint at BOL and at EOL for 40^{o}C ambient temperature



	Pt Loading	ECSA	Cell Voltage	Power Density	Current Density	FCS Power	FCS Efficiency
	mg/cm^2	m^2/g	mV	mW/cm^2	A/cm^2	kW$_e$	%
BOL	0.1	48	682	1024	1501	80.0	49.7
	0.125	48	686	1037	1511	81.1	50.0
	0.15	48	688	1045	1518	81.7	50.2
EOL	0.1	22	652	930	1426	72.0	47.1

2. Fuel Cell Systems for Medium- and Heavy-Duty Trucks



Salient Features

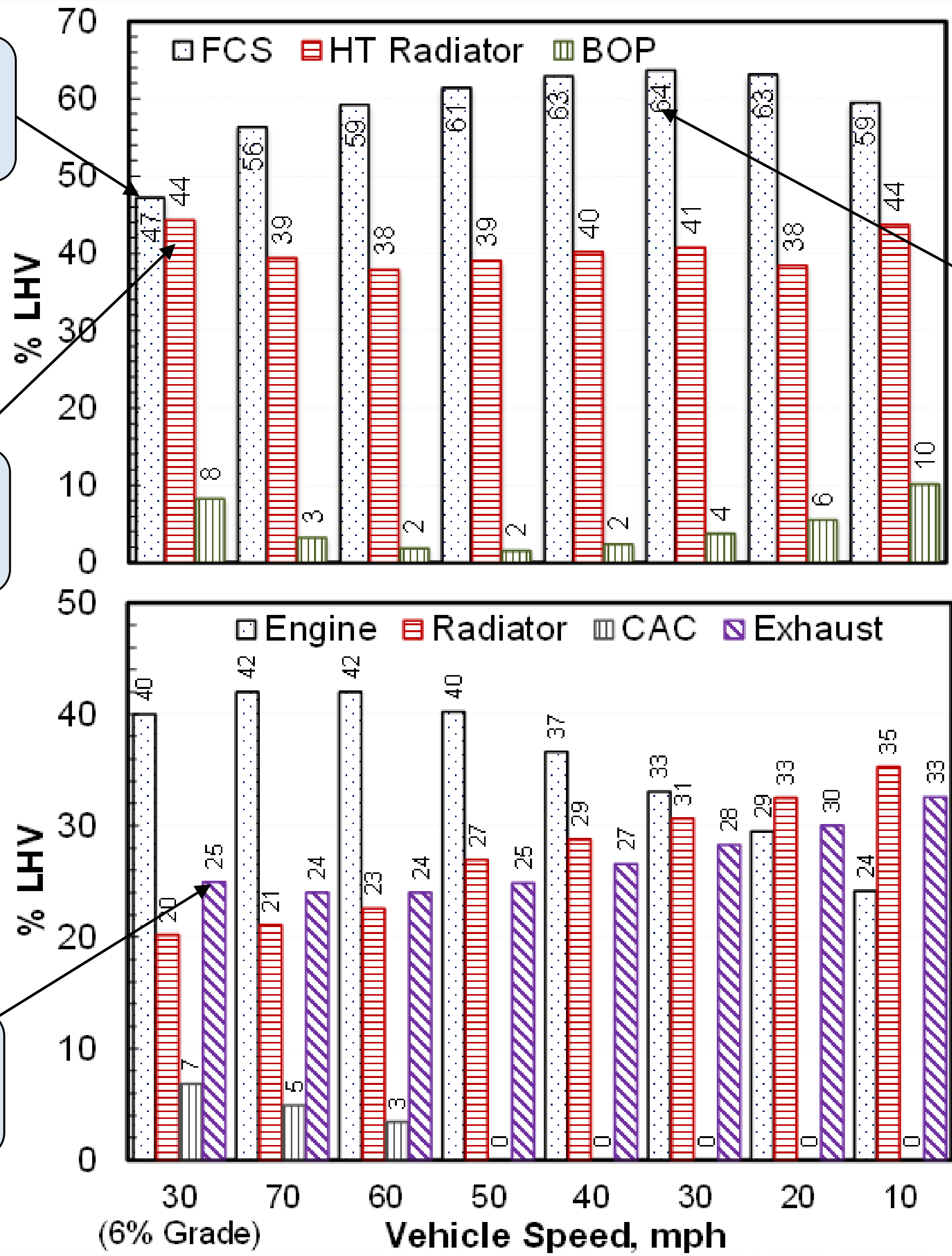
- **Multiple stacks 2, 3 or 4**
- **Pt loading Cathode: 0.2 mg/cm^2 Anode: TBD**
- **Membrane thickness: TBD**
- **Single air system with expander**
- **Single anode system with recirculation blower**
- **No cathode humidification**
- **Rated power: 2.5 atm, 87^{o}C, 0.7 V**
- **Control valves for startup/shutdown, cold start and OCV**

Class 8, Linehaul Heavy-Duty Trucks: Diesel vs. Fuel Cells

FCS 20% more efficient than diesel at rated power

Higher radiator heat load (Q) even though FCS is more efficient

More heat rejected in the tail pipe than the radiator



275-kW FCS, 0.7 V cell voltage at rated power

Double the diesel efficiency at low speeds

450-hp turbocharged diesel engine

Heat rejection in FCS can be an issue

- Compared to diesel engines, higher Q and smaller ΔT

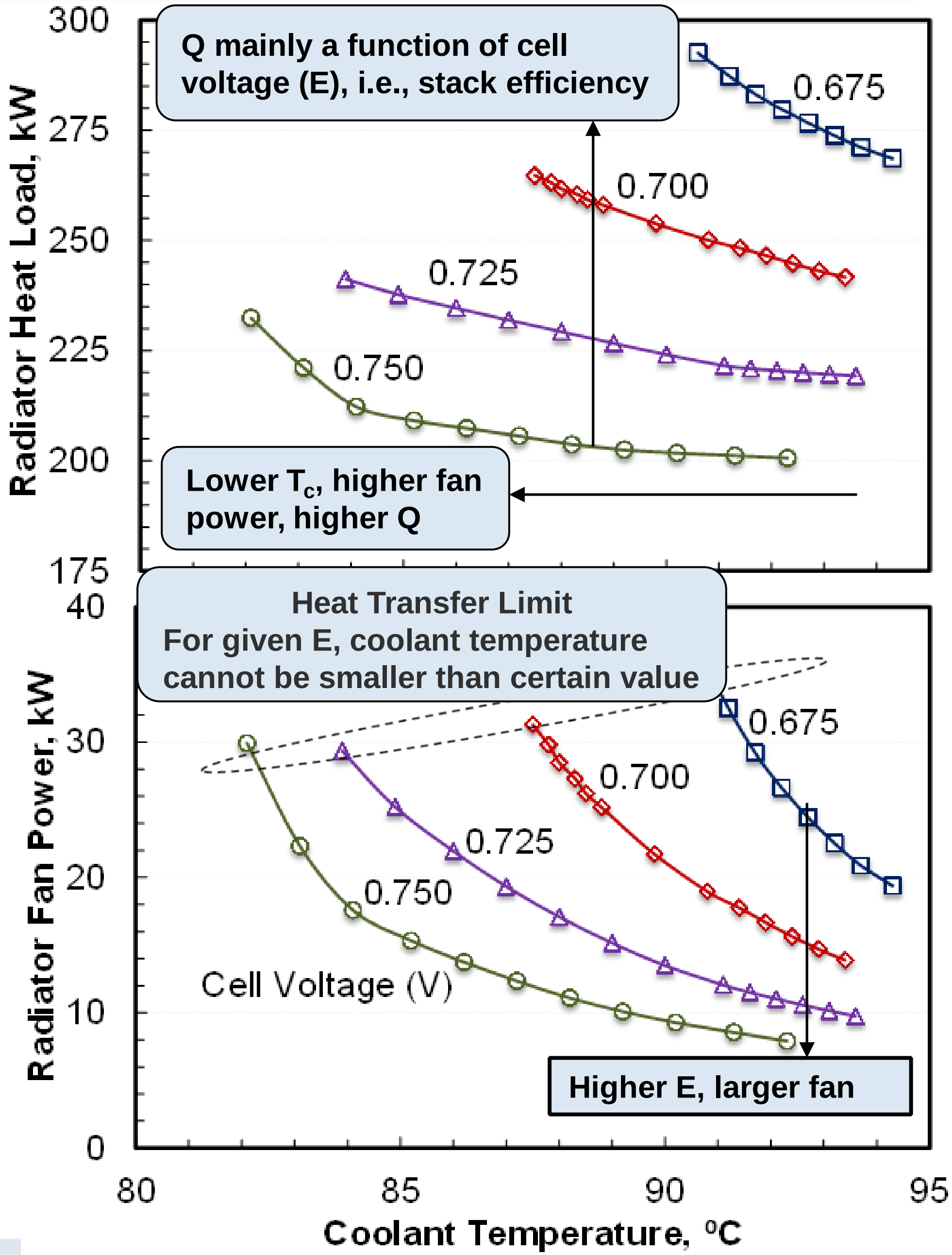
FCS Heat Rejection

Fuel cell dominant propulsion system rated at 275-kW$_e$ net, 35-kWh ESS

- Hill climb at 30 mph, 6% grade, 20-min duration
- 25°C ambient temperature

Cell Voltage (E)	Coolant T (T_c)	Radiator Heat Load (Q)	Fan Power
V	°C	kW	kW$_e$
0.675	91 - 94	295 - 275	40 - 20
0.700	87 - 93	265 - 240	30 - 15
0.725	84 - 94	240 - 220	30 - 10
0.750	82 - 93	240 - 220	30 - 8

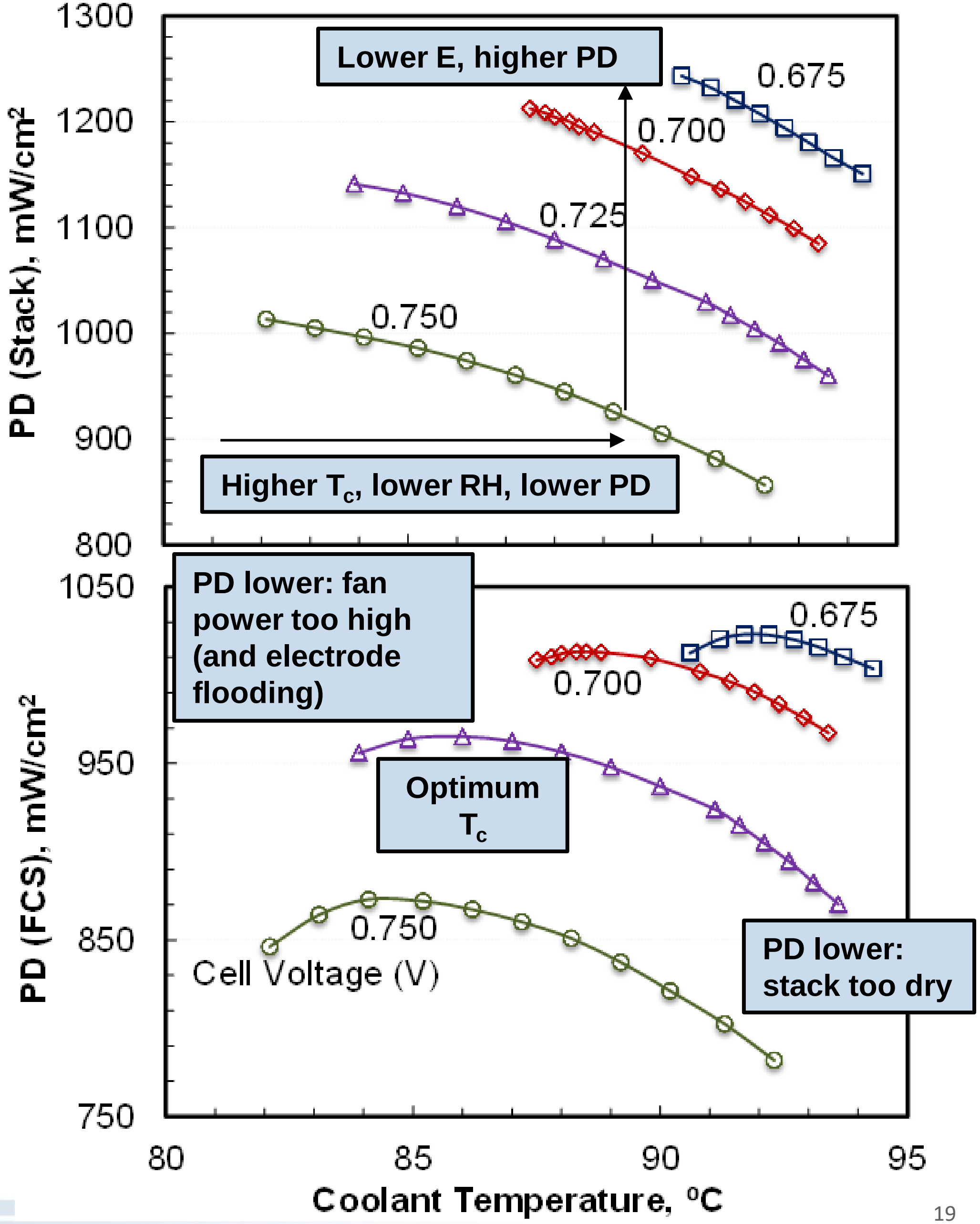
Cell voltage > 0.750 V at rated power needed for stacks that operate below 80°C



Stack Power Density (PD): No Cathode Humidification

Optimum T_c for highest FCS PD as function of E

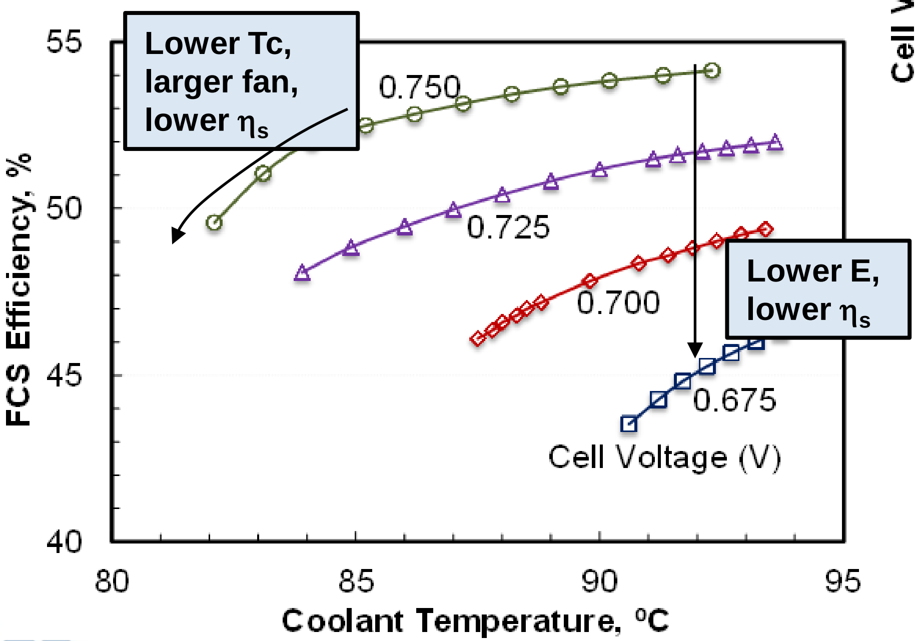
Cell Voltage (E)	Optimum Coolant T (T_c)	Stack Power Density	Stack Net PD
V	°C	mW/cm^2	mW/cm^2
0.675	92	1220	1025
0.700	88	1200	1015
0.725	86	1120	965
0.750	84	1000	875

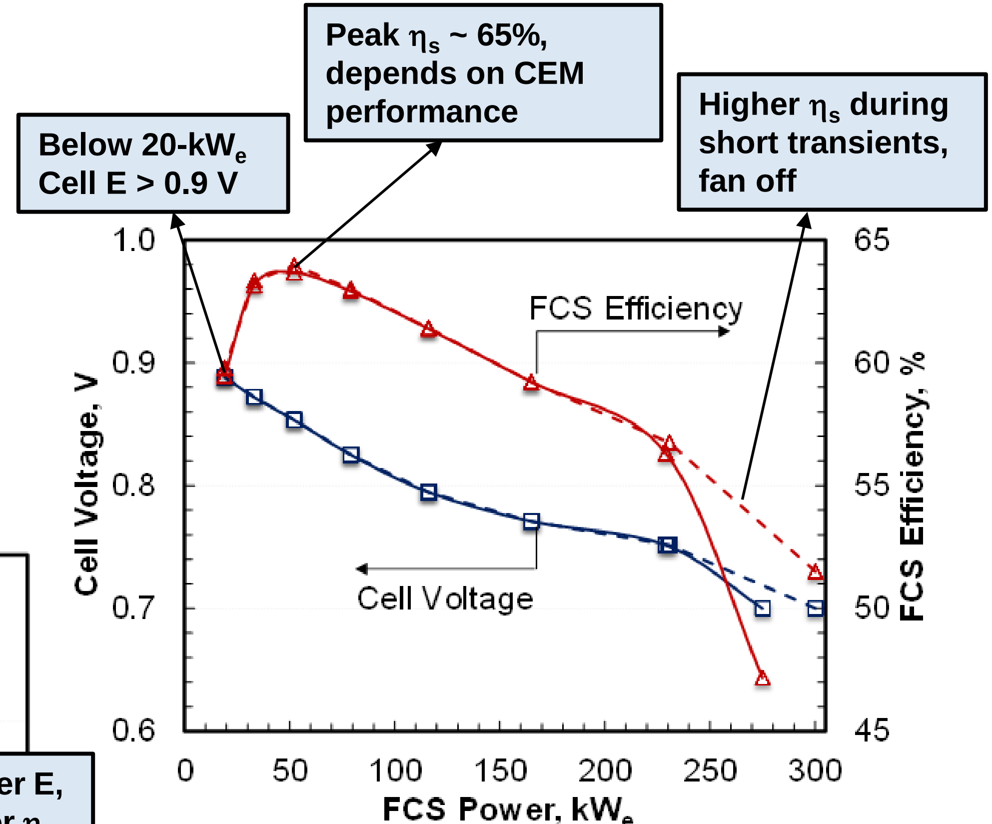


FCS Performance at Steady State

Rated-Power FCS Efficiency at Highest Net Stack Power Density

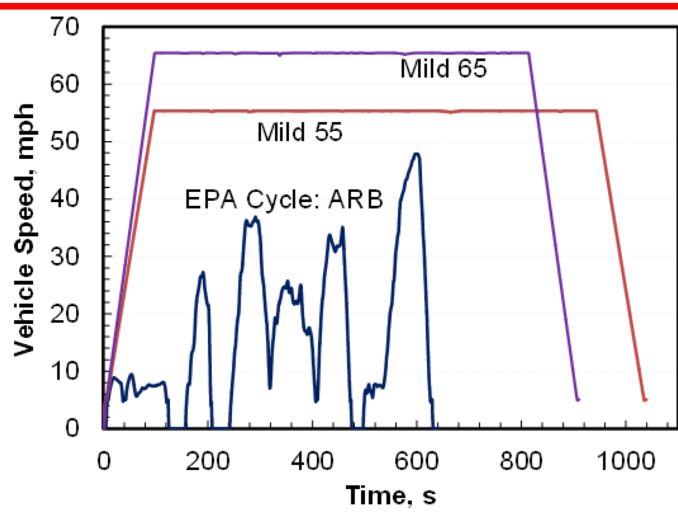
Cell Voltage (E)	Optimum Coolant T (T_c)	FCS Efficiency
V	°C	%
0.675	92	45
0.700	88	47
0.725	86	49
0.750	84	52

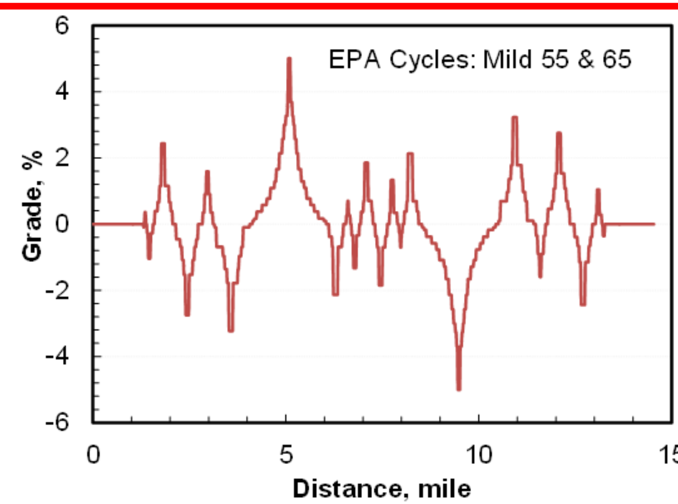


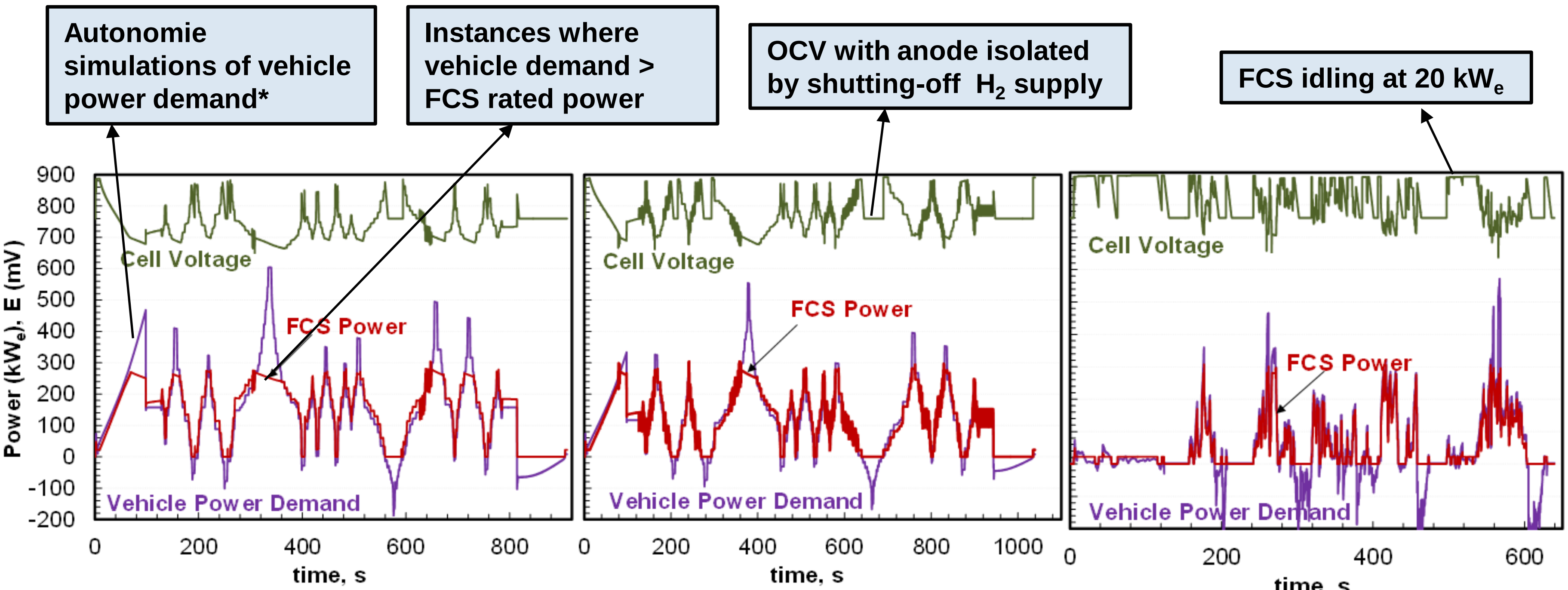


FCS Efficiency Map at Steady State
Cell Voltage 0.7 V at Rated Power

FCS Performance on EPA Drive Cycles







Mild 65

Mild 55

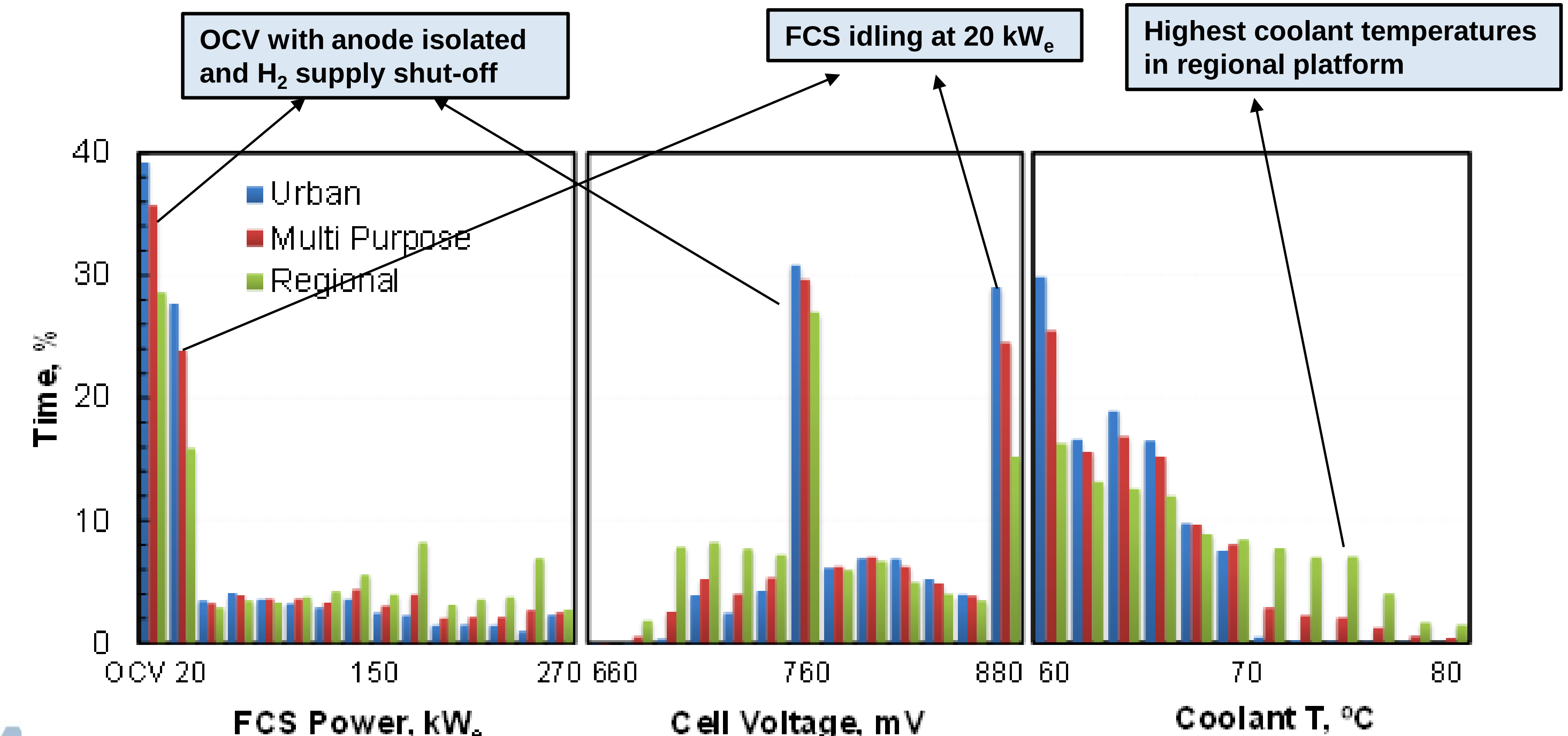
ARB

*Results from Ram Vijayagopal, ANL

FCS Duty Cycle

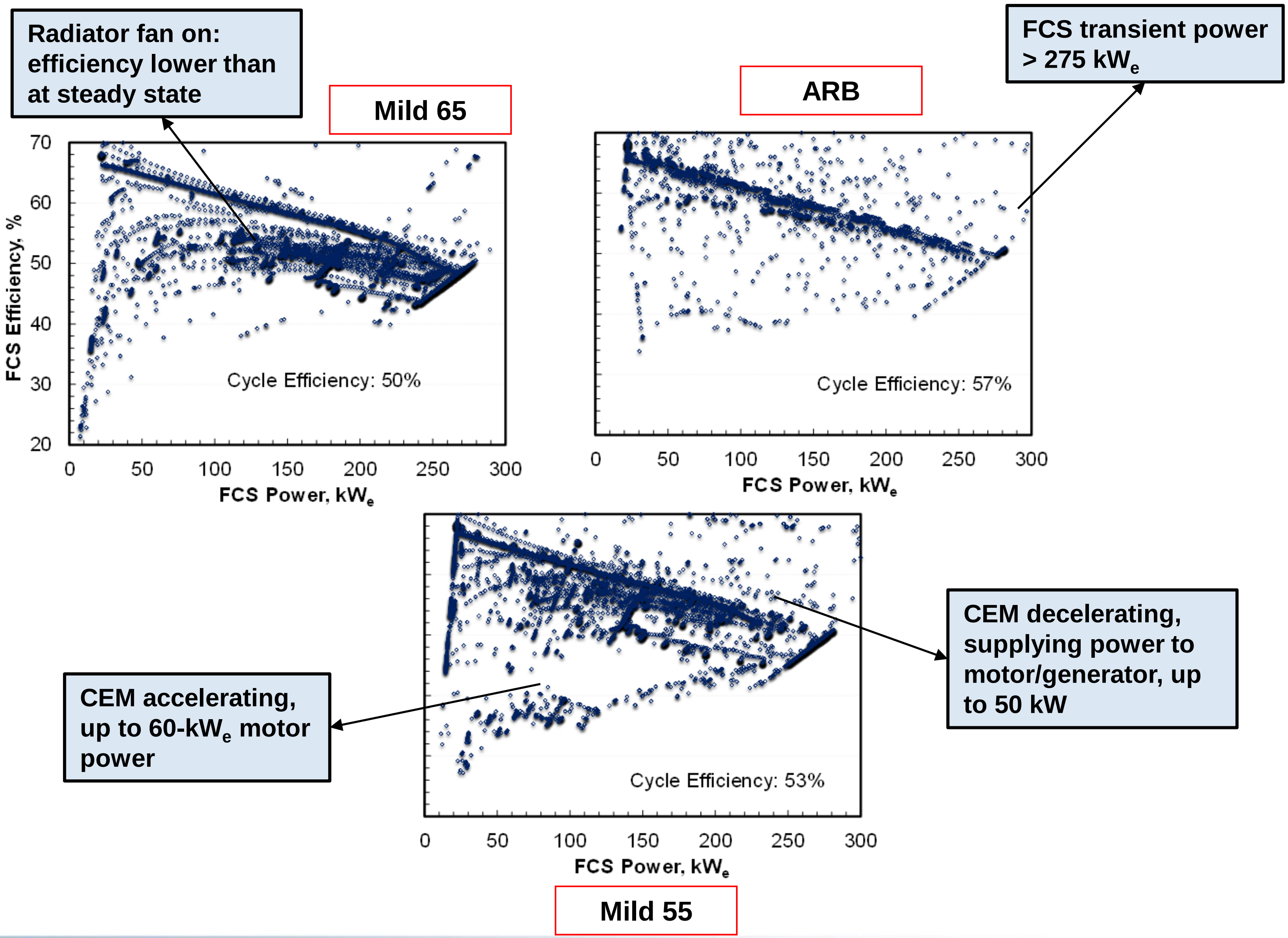
Simulation methodology

- Fuel cell dominant power train, battery for regenerative braking, hill climb and SOC balance
- Limit high potentials by restricting FCS idle power (20 kW_e)
- Control OCV by shutting off H_2 supply during deceleration and parked idle
- Attempt to limit high temperatures by operating the fan when coolant exit T exceeds the set target (65°C)



Dynamic FCS Performance

- Dynamic cycle efficiency: ARB > Mild 55 > Mild 65



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)
	ElectroCat: Electrocatalysis Consortium (FC156)
Water Management	Gore, Ford, dPoint: Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers (FC067)
Thermal Management	ANL-Autonomie, 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 (FC-PAD, SA)
3. Fuel cell systems for medium and heavy-duty vehicles and locomotives
   - Heat rejection considerations and impact
   - Low and high-PGM catalysts and MEAs for >1,000,000-mile durability
   - Bipolar plates and flow fields for large stacks (300 kW)
   - Configuring systems with multiple stacks
4. 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.

Remaining Barriers and Challenges

1. Even with recent advances in catalysts and MEAs, \$40/kW$_e$ DOE target for 2020 FCS cost has not been achieved.
   - Recent emphasis on PGM-free catalysts
2. Breakthroughs are needed to achieve \$30/kW$_e$ ultimate DOE target for FCS cost.
   - Higher activity catalysts
   - Alternate electrode structures to control mass transfer losses at high current densities
   - More fundamental understanding of voltage losses, transport resistances and degradation mechanisms
   - Cheaper bipolar plate substrates and coatings
3. Air management system cost and performance, particularly with an expander
4. Durability of catalysts with low Pt loadings and thin membranes
   - Current generation of fuel cell vehicles on road use high Pt loadings and cannot meet the heat rejection requirement ($Q/\Delta T = 1.45\ kW/^oC$)
5. Durability models to guide mitigation strategies and system controls
6. System and component simplification for cost reduction

Technology Transfer Activities

Not applicable to this Fuel Cell System Modeling and Analysis Project. However, we are

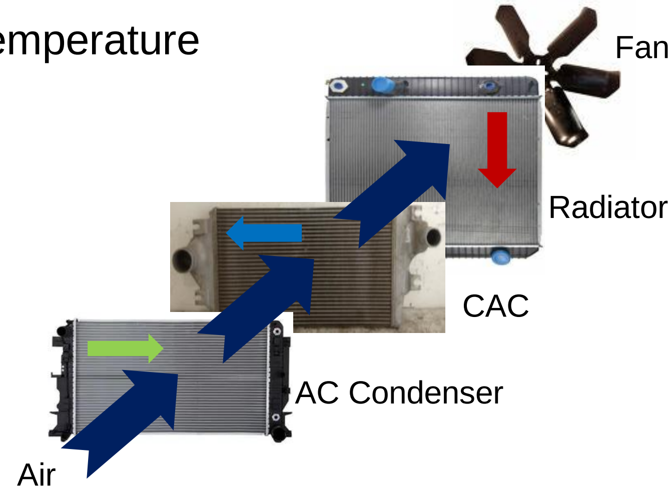
1. Working closely with FCPAD project partner to jointly develop test protocols to rapidly obtain data on differential cells (goal: 2-3 days testing) that is critical for development of models for performance and durability.
2. Working jointly with partners to develop method to project the performance of integral cells using the model developed for differential cells, determine optimum operating conditions, and control performance degradation.

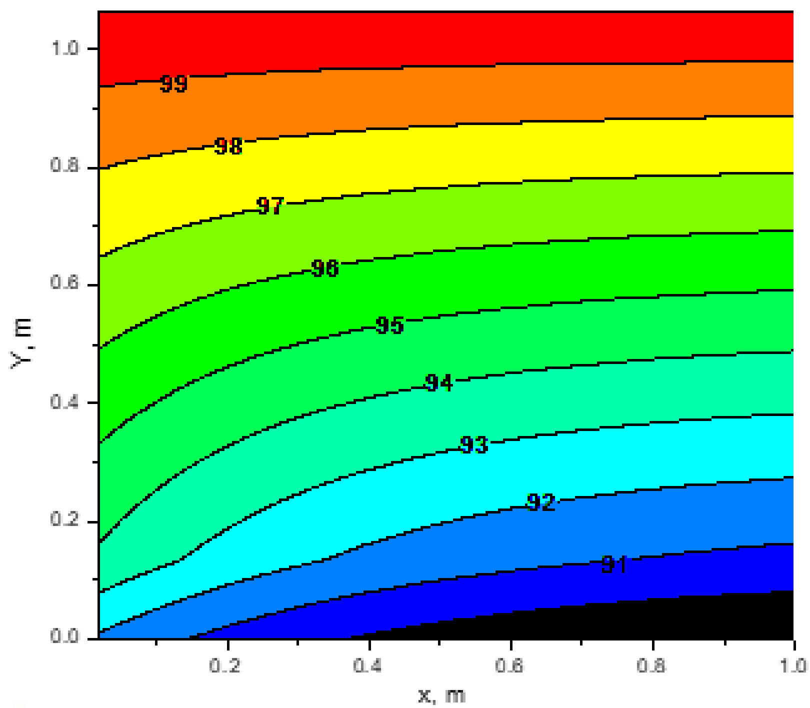
Backup Slides

Diesel Heat Rejection System

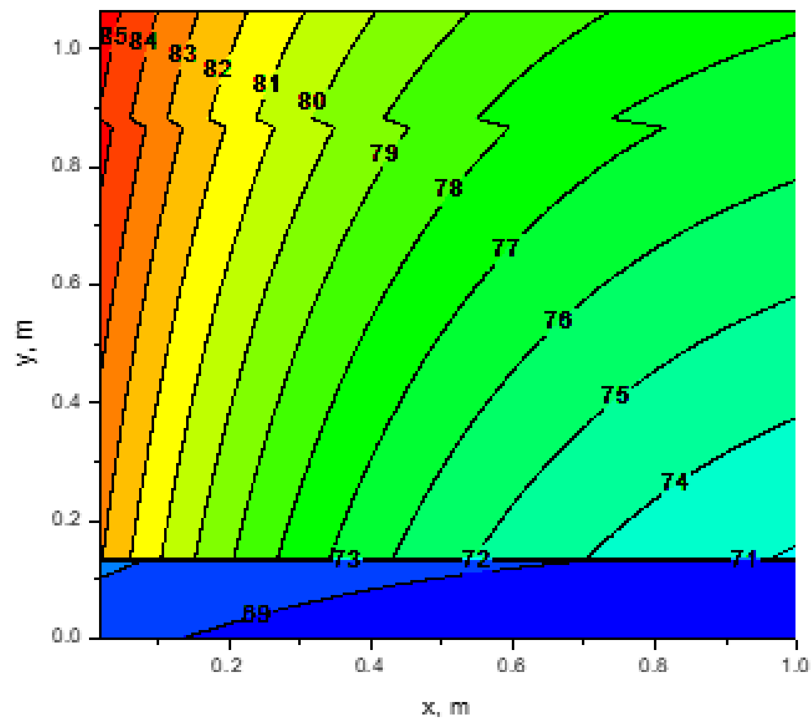
Radiator fan for 450-hp diesel engine, 52ºC air-to-boil temperature

Heat Exchangers	Dimensions and Details	Heat Loads	Radiator Fan 31 kW
Radiator	40″ (W) x 42″(H) x 2″ (D) Fins: louvered, 12-fpi, 10-mm height Tubes: 2-mm height	174 kW	Vehicle Speed: 38 mph
CAC	40″ (W) x 35″ (H) x 2.5″ (D) Fins: louvered, 8-fpi, 20-mm height Tubes: 10-mm height	59 kW	Ambient T: 52ºC
AC Condenser	40″ (W) x 28″ (H) x 0.75″ (D) Fins: plain, 12-fpi, 10-mm height Tubes: 2-mm height	12 kW	Air Flow Rate: 8.5 kg/s





Coolant Temperature (ºC)



Air Temperature (ºC)

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:	In collaboration with GM and FC-PAD, demonstrated that d-PtCo catalyst supported on high surface area carbon (HSC) can be stabilized by limiting the high potential limit to 0.80-0.85 V in catalyst accelerated stress tests (ASTs) Demonstrated that the target of 10% loss in power can be achieved by limiting the electrochemically active surface area (ECSA) loss to 55.3% Determined the operating conditions for 55.3% ECSA loss: CEM* turndown = 12 (10), coolant exit temperature = 66^{o}C/70^{o}C for 5000 h/8000 h electrode durability Proposed initial metrics for heat rejection in FCS for Class-8 heavy duty trucks: 0.7 V at rated power (275 kW net), 87^{o}C coolant exit temperature Showed the relationship between cell voltage, optimum operating temperature and stack power density as determined by heat rejection: 1200 mW/cm^{2} power density at 0.7 V. Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, specifying time spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles
Collaborations:	3M, Eaton, GM, Gore, JMFC, SA, UTRC, UDEL/Sonijector
Future Work:	Extending durability of low-PGM FCS for light-duty vehicles Fuel cell systems for heavy-duty vehicles and locomotives System analysis with durability considerations on drive cycles

Reviewers' Comments

Sample comments and feedback

- The project is progressing well towards the set objectives and the diversity of its studied aspects. It also progresses well towards the DOE goals. The modeling methodology and procedures are highly developed.
- ANL's accomplishments are relevant, and the team provides excellent data
- Additional details on the methodology for reaching DOE targets in performance and cost would be helpful
- The addition of HDVs to the analysis framework is interesting and needed.
- A complete system dynamic model would be valuable for explaining barriers related to system thermal management and transient operation.
- Evaluating the impact of different materials, designs, and some operations is needed to achieve the overall objectives of the project. Increased emphasis on Pt dissolution/impact on ECSA would be beneficial.

Work scope consistent with above recommendations

√ On-going work on performance and durability of PtCo/C catalysts in collaboration with FC-PAD and an industrial partner.

√ In collaboration with GM and FC-PAD, evaluated the durability of d-PtCo catalyst supported on high surface area carbon (HSC).

√ Determined the operating conditions for LDVs to reach 10% rated power loss for 5000 h / 8000 h electrode durability, Demonstrated the concept of managing CEM turndown and coolant exit temperature for meeting the durability target.

√ Initial metrics for heat rejection in FCS for Class-8 heavy duty trucks

√ Established FCS duty cycles for Class-8 trucks for regional, multi purpose and urban vocations, determined time and energy spent at different voltages and temperatures on ARB, mild-55 and mild-65 drive cycles

FCS with d-PtCo/C Cathode Catalyst: Critical Assumptions

PEFC Stack

- Membrane: 12-µm, 850 EW, PFSA Mechanically reinforced, with chemical additive
- Cathode Electrode: GM d-Pt_3Co/C catalyst, 0.1 mg_{Pt}/cm^2, high surface-area carbon support, 825 EW ionomer, I/C=1.0
- Anode Electrode: Pt/C catalyst, 0.025 mg_{Pt}/cm^2, Vulcan carbon support
- Cathode/Anode GDL: Non-woven carbon paper with microporous layer (MPL), SGL 25BC, 235 µm nominal uncompressed thickness
- Seals/Frames: PET subgasket (3M patent)
- Bipolar Plates: 3-mil (0.075 mm) 316 SS substrate with Treadstone coating, 0.5 mm land, 0.7 mm channel, 0.4 mm depth. 62.5% active area, 15 $m\Omega.cm^2$ 2X ICR*

Fuel Management System

- Hybrid ejector-recirculation pump
- 35% pump efficiency, 1% H_2 purge
- 3 psi pressure drop at rated power

Air Management System

- Integrated centrifugal compressor-expander-motor module (Honeywell), air foil bearings (AFB)
- Mixed axial flow compressor
- Inflow radial expander, variable area nozzle
- 3-phase brushless DC motor, liquid and air cooled; liquid-cooled motor controller
- Efficiencies at rated power: 71% compressor, 73% expander, 89.5% motor, 89.5% controller
- Turn-down: 20
- 5 psi ΔP between compressor discharge and expander inlet at rated power

Heat Rejection System

- Two circuits: 75-95^{o}C HT, 10°C ΔT 65^{o}C LT coolant, 5°C ΔT
- 55% pump + 92% motor efficiency
- 45% blower + 92% motor efficiency
- 10 psi ΔP in stack and 5 psi in radiator

Water Management System

- Planar cross-flow humidifier with Gore's M311.05 membrane

***2X ICR: two-sided interfacial contact resistance**

Publications and Presentations

Journal Publications

F. C. Cetinbas, R. K. Ahluwalia, N. N. Kariuki, V. D. Andrade, and D. J. Myers, "Effects of Porous Carbon Morphology, Agglomerate Structure and Relative Humidity on Local Oxygen Transport Resistance," JECS, 167(1) 013508), 2020.

R. K. Ahluwalia, X. Wang, and J.-K. Peng, "Performance and Durability of Advanced Automotive Fuel Cell Stacks and Systems with State-of-the-Art d-PtCo/C Cathode Catalyst in Membrane Electrode Assemblies," FY 2019 Annual Progress Report, DOE Hydrogen and Fuel Cells Program, 2020.

R. Ahluwalia, X. Wang, L. Osmieri, J-K Peng, H. T. Chung and K.C. Neyerlin, "Performance of Polymer Electrolyte Fuel Cell Electrodes with Atomically Dispersed (AD) Fe-C-N ORR Catalyst," Journal of the Electrochemical Society 166 (14) F1096-F1104, 2019.

F. C. Cetinbas, R. K. Ahluwalia1, A. D. Shum, and I. V. Zenyuk, "Direct Simulations of Pore-Scale Water Transport through Diffusion Media," JECS, 166 (7) F3001-F3008, 2019.

L. Osmieri, R. Ahluwalia, X. Wang, H. Chung, X. Yin, A. Kropf, J. Park, et al, "Elucidation of Fe-N-C Electrocatalyst Active Site Functionality via in-situ X-ray Absorption and Operando Determination of Oxygen Reduction Reaction Kinetics in a PEFC," Applied Catalysis. B, Environmental 257 (117929), 2019.

Conference Presentations

R. Ahluwalia, X. Wang, F. C. Cetinbas, N. Macauley, D. Langlois, R. Mukundan, and R. Borup. "Oxygen Transport in Electrodes with Degraded d-PtCo/C Cathode Catalyst," 236th Electrochemical Society Meeting, Atlanta, GA, October 13-17, 2019.

R. Ahluwalia,, X. Wang, J-K Peng, S. Arisetty, S. Kumaraguru, and N. Ramaswamy. "Performance and Durability of Automotive Fuel Cell Stacks and Systems with Low-Loaded d-PtCo/C Cathode Catalyst in Membrane Electrode Assemblies," 236th Electrochemical Society Meeting, Atlanta, GA, October 13-17, 2019.

R. Ahluwalia, X. Wang, L. Osmieri, K.C. Neyerlin, and H. T. Chung. "Activity and Stability of Atomically Dispersed (AD)Fe-N-C Catalyst in Polymer Electrolyte Fuel Cell Environment," 236th Electrochemical Society Meeting, Atlanta, GA, October 13-17, 2019.

R. K. Ahluwalia, X. Wang, and J.-K. Peng, "Fuel Cell System Modeling and Analysis," US Drive Fuel Cell Tech Team Meeting, Southfield, MI, February 12, 2020.

R. Ahluwalia, R., X. Wang and J-K Peng. "Fuel Cell System Modeling and Analysis," 2019 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Arlington, VA US, April 29 - May 1, 2019.

Nomenclature

a	annealed
A_c	BET surface area
A_{Pt}	electrochemically active surface area
b	Tafel slope
d	de-alloyed
E	cell voltage
E_c	cathode potential
E_N	Nernst potential
E_{0R}	Redox potential
i	current density
i_0	exchange current density
i_0^m	mass activity
i_{0r}	reference exchange current density
i_L	limiting current density
L_c	PGM-free catalyst loading
L_{Pt}	Pt loading
n	no of electrons
N	number of potential cycles
P	pressure
P_r	reference pressure, 1 atm
R	gas constant
R_{cf}	CCL O_2 transport resistance
R_d	GDL O_2 transport resistance
R_f	film resistance
R_g	gas channel O_2 transport resistance
R_{Kn}	Knudsen O_2 transport resistance
R_m	O_2 transport resistance
R_s	CCL sheet resistance
R_Ω^c	cathode ionic resistance
R_Ω^m	high-frequency resistance (HFR)
RH	relative humidity
S_{Pt}	Pt surface roughness
SR	stoichiometry
T	temperature
T_c	CCL temperature
T_r	reference temperature, 353 K
X	mole fraction
ΔH_s^c	ORR activation energy
Φ_c	CCL relative humidity
Φ_i	inlet relative humidity
α	symmetry factor
β	RH dependence
γ	O_2 partial pressure dependence
δ_c	cathode electrode thickness
η_c	cathode overpotential
η_m	mass transfer overpotential
η_s^a	HOR kinetic overpotential
η_s^c	ORR kinetic overpotential
θ	PGM-free catalyst available sites
σ_c	cathode ionic conductivity