Fuel Cells Systems Analysis

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Project ID: FC017

Overview

Timeline

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

Budget

- FY11 funding: $650K
  DOE share: 100%
- FY10 funding: $650K

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

- Honeywell CEM+TWM projects
- DTI, TIAX
- 3M, Gore, NJIT
- ISO-TC192 WG12, HNEI, JARI, LANL
- IEA Annexes 22 and 25
- FreedomCAR 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 laboratory and at Argonne's Fuel Cell Test Facility.

- Collaborate with external organizations

Apply models to issues of current interest.

- Work with FreedomCAR Technical Teams
- Work with DOE contractors as requested by DOE

Collaborations

Air Management	Honeywell Turbo Technologies
Stack	3M, Nuvera
Water Management	Honeywell Aerospace, Gore, NJIT
Thermal Management	Honeywell Thermal Systems
Fuel Economy	ANL (Autonomie)
H_2 Impurities	JARI, LANL, ISO-TC-192 WG
System Cost	DTI, TIAX
Dissemination	IEA Annex 22 and 25

- Argonne develops the fuel cell system configuration, determines performance, identifies and sizes components, and provides this information to TIAX for high-volume manufacturing cost estimation
- Establishing closer ties with DTI, conducting joint life-cycle cost studies

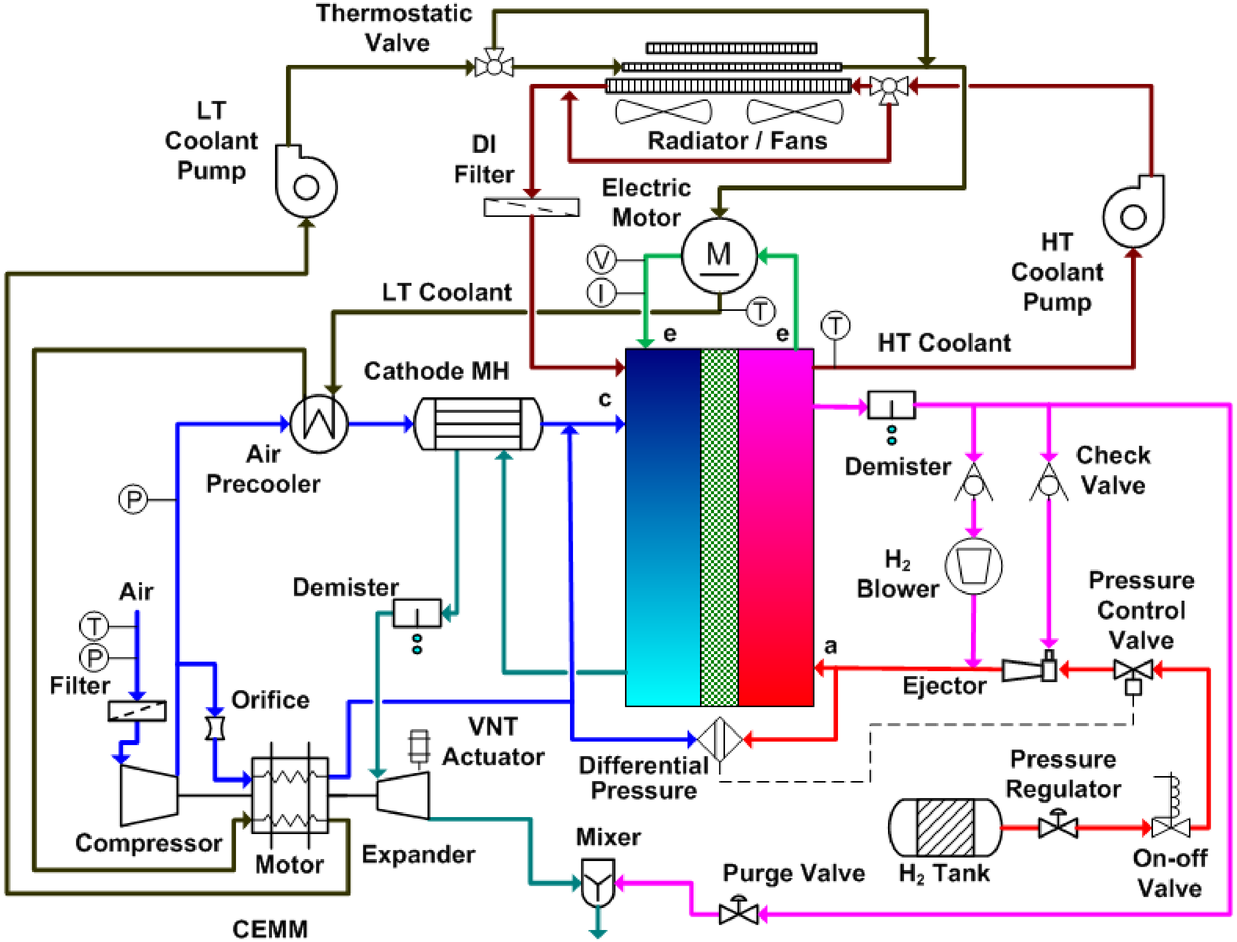
Summary: Technical Accomplishments

System analysis to update the status of technology

- **Stack:** Determined the performance of NSTF stacks at low temperatures and on drive cycles
- **Air Management:** Evaluated the dynamic performance of Honeywell's compressor-expander-motor (CEM) and compressor-expander-motor/generator (CEMG) modules
- **Fuel Management:** Evaluated the dynamic performance of parallel ejector-pump hybrids
- **Water Management:** Analyzed the dynamic performance of planar and supported liquid membrane (SLM) humidifiers
- **Thermal Management:** Analyzed the dynamic performance of microchannel automotive radiators and PEFC stack during cold start on drive cycles
- **Drive Cycle Simulations:** GCtool-Autonomie simulations for fuel economy, ownership cost, and optimum FCS operating parameters
- **Cost:** Collaborated with DTI in projecting system cost for different sizes and efficiencies and estimating the life cycle costs

Argonne 2011 FCS Configuration

- S1 – Pressurized FCS, 2.5 atm stack inlet pressure at rated power
- S2 – Low-pressure FCS, 1.5 atm stack inlet pressure at rated power
- Dynamic performance of the components and the system



2011 FCS

MEA

- **3M NSTFC MEA**
- **20-µm 3M membrane**
- **0.05(a)/0.1(c) mg/cm² Pt**
- **Metal bipolar plates**

Air Management System

- **Honeywell CEMM**
- **Air-cooled motor/AFB**

Water Management System

- **Cathode MH with precooler**

Thermal Management System

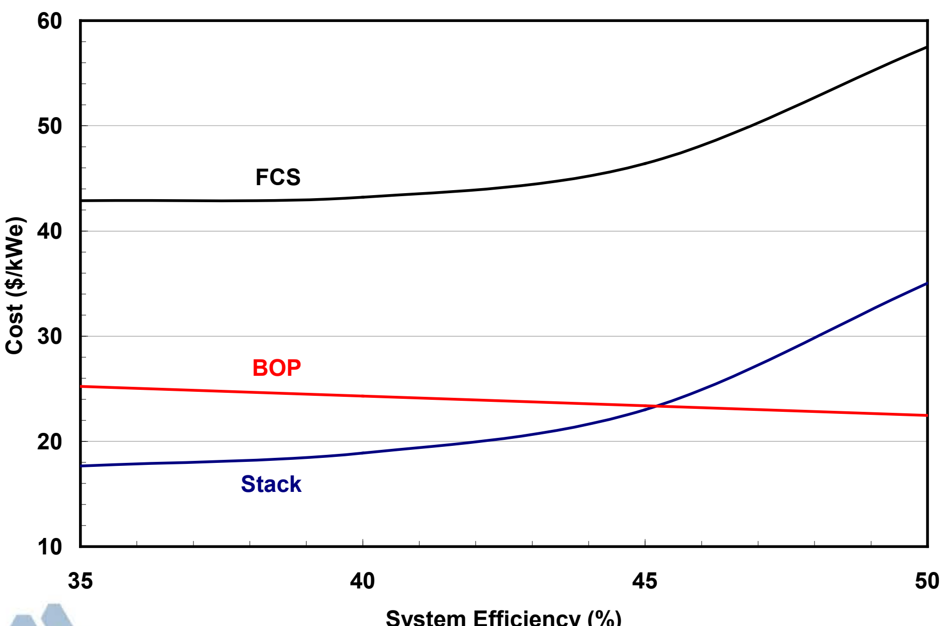
- **Advanced 40-fpi microchannel fins**

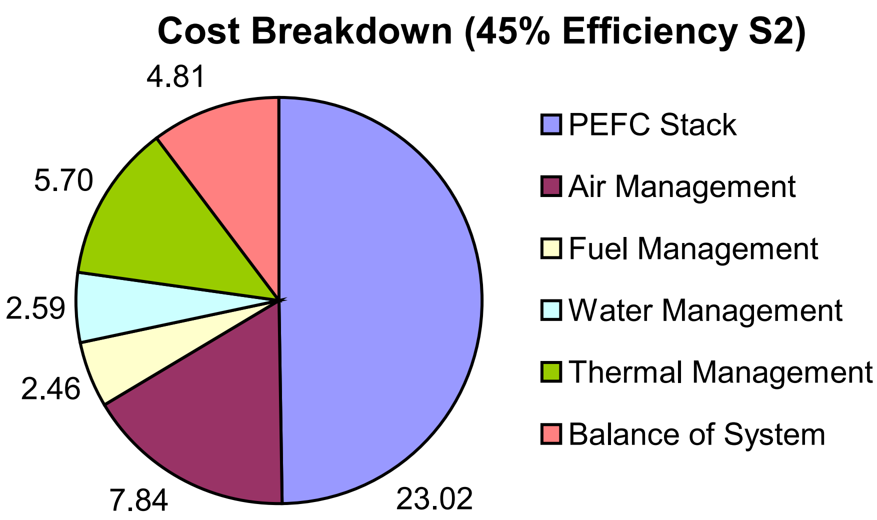
Fuel Management System

- **Parallel ejector-pump hybrid**

Cost vs. Performance Trade-off Study

- Saving in Pt by accepting rated-power efficiency <50% (system S2): 45% at η=45%, 59% at η=40%, 62% at η=35%
- Cost estimates from DTI correlations with Argonne data for components and subsystems
- Projected saving in stack cost by accepting rated-power efficiency <50%: 34% at η=45%, 46% at η=40%, 50% at η=35%
- Projected saving in system cost by accepting rated-power efficiency <50%: 19% at η=45%, 25% at η=40%, 26% at η=35%

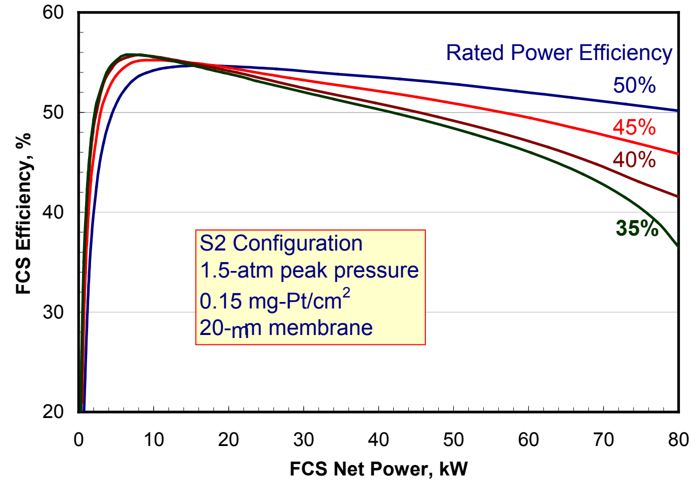




Cell Voltage to Reach 60% Peak Efficiency

Parasitic losses: 7.1% of net power at peak efficiency point

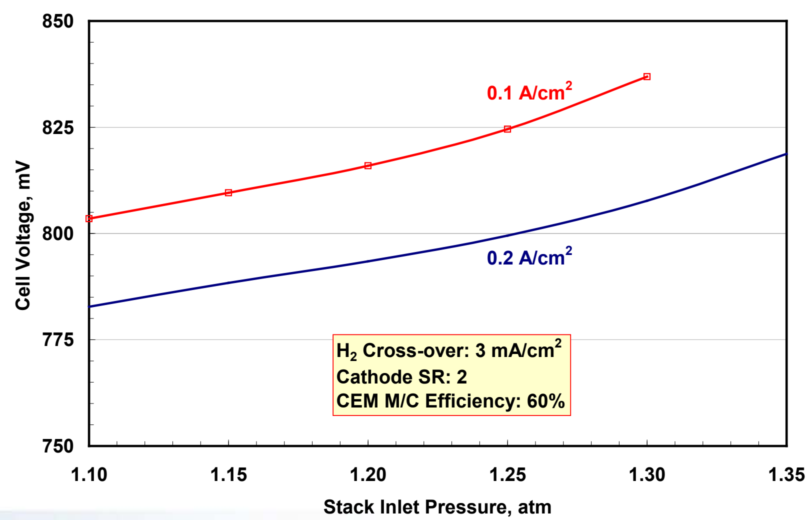
- 37% CEM M/C efficiency near idle
- H_2 losses to crossover & purge
- Target not met with improved M/C efficiency alone



Pressure	Temperature	Current Density	Cell Voltage	Stack Efficiency	CEM M/C Efficiency	Peak FCS Efficiency
(atm)	(^{o}C)	(A/cm^2)	(mV)	(%)	(%)	(%)
1.2	75	0.1	784	60.2	37	56
1.2	75	0.1	784	60.2	60	57.4

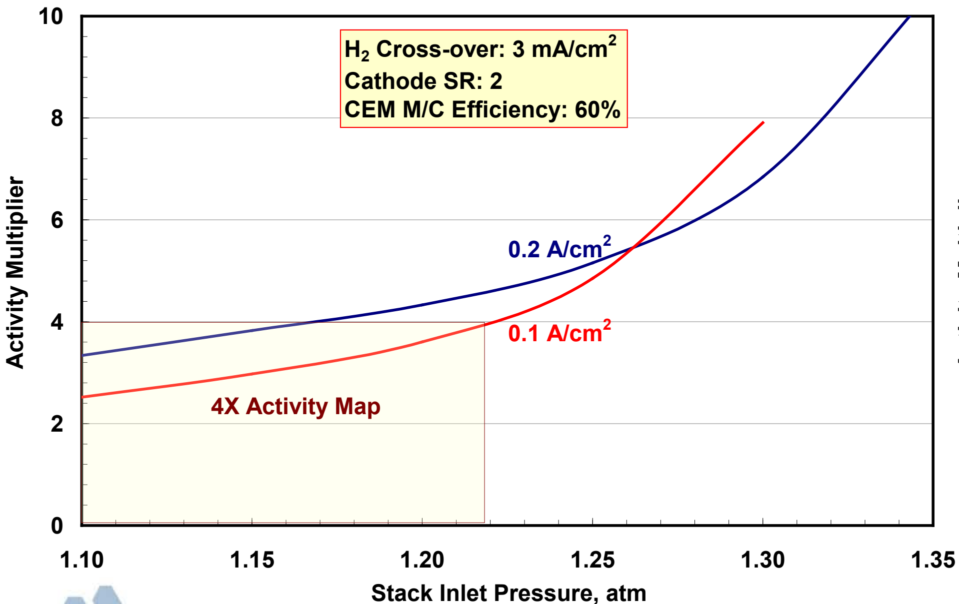
Cell V to reach 60% peak efficiency

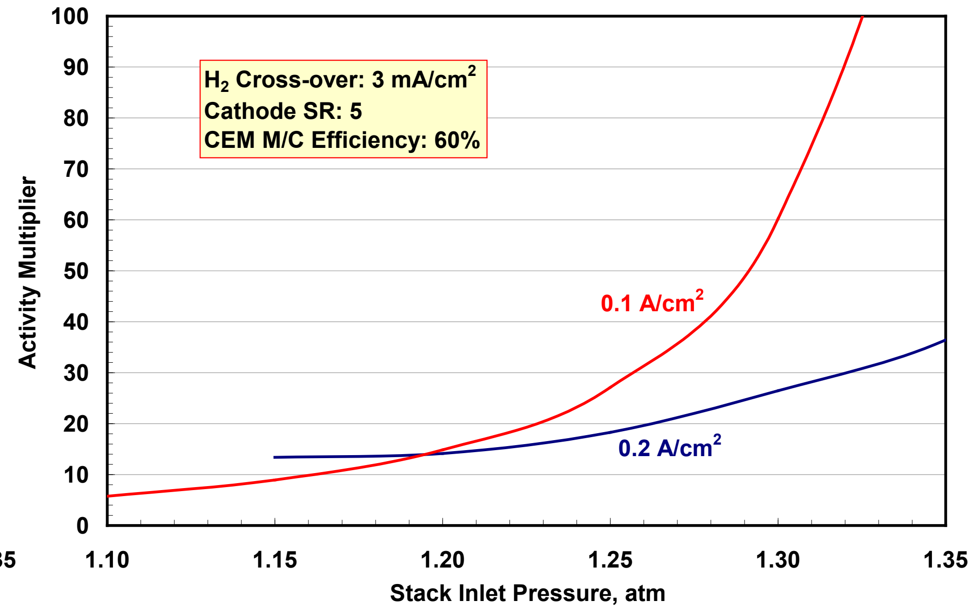
- 32 mV ΔV at 0.1 A/cm^2, 1.1 atm, SR = 2
- Needed cell V lower at 0.2 A/cm^2
- Required cell V higher at higher P
- Required cell V even higher at SR = 5



Catalyst Activity to Reach Target Cell Voltages

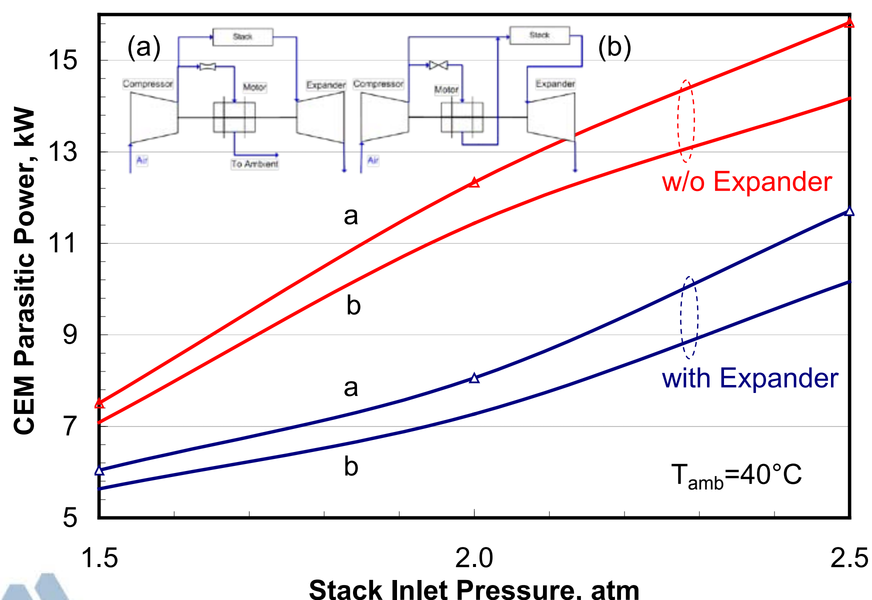
- Reference activity is for ternary $Pt_{68}(CoMn)_{32}$ catalyst with 0.1 mg/cm^2 Pt loading
  - Reaching 60% peak efficiency is very difficult if the cell has to operate at >2 SR or >1.25 atm at low current densities
  - Easier to reach the peak efficiency target at 0.1 A/cm^2 than at 0.2 A/cm^2 for P < 1.3 atm, SR = 2
  - Inset for 4X absolute activity which can be reached with higher Pt loading, or higher mass activity, or combination of the two

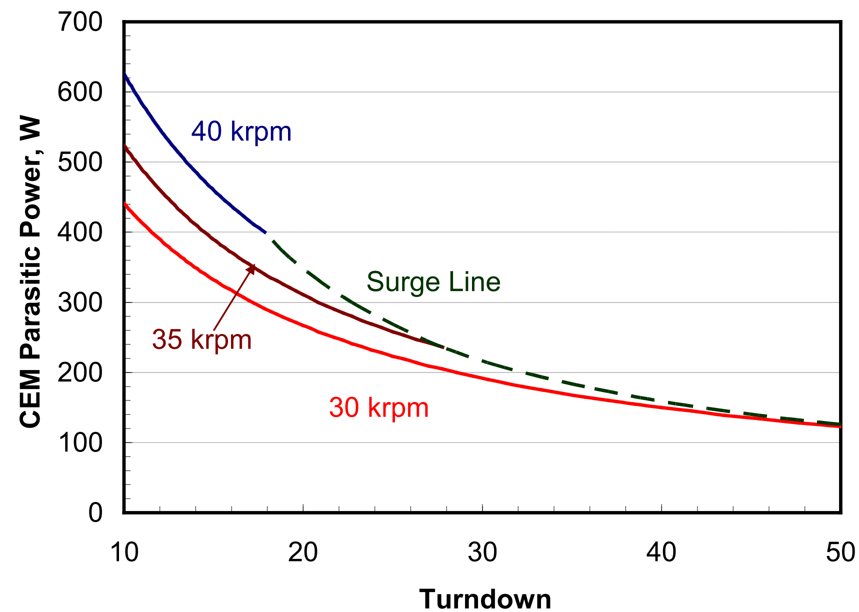




Air Management System

- Determined the performance of Honeywell's CEMM in S1 and S2 systems for two modes of cooling the motor
  - GCtool model, performance maps from component data
- Expander reduces CEM parasitic power by 4 kW in S1, 1.5 kW in S2
  - Recovering cooling air reduces CEM power by 0.4-1.6 kW
- Turndown is a function of the minimum rpm and may be limited by the surge line
  - Turndown >10 and minimum rpm <35k desirable else parasitic power at Idle >500 W



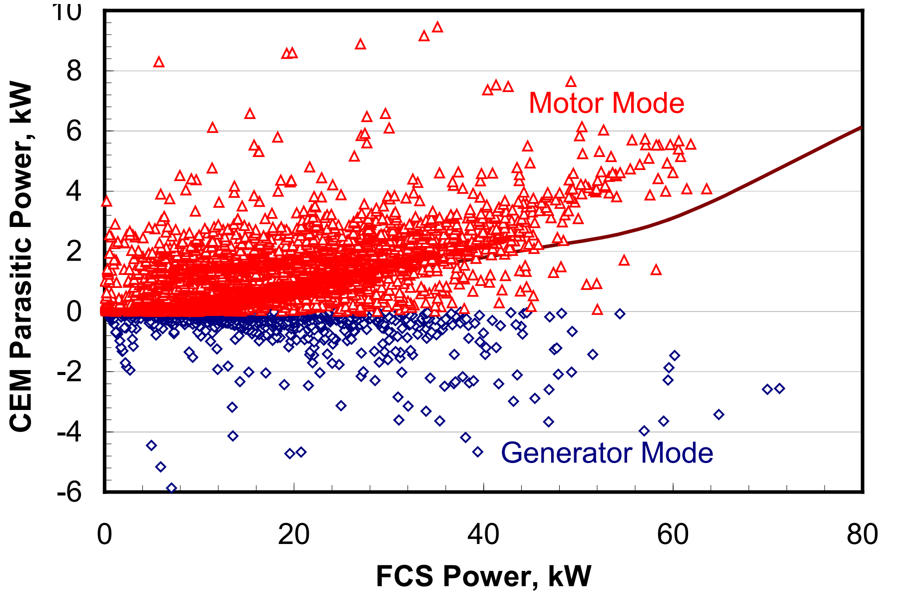


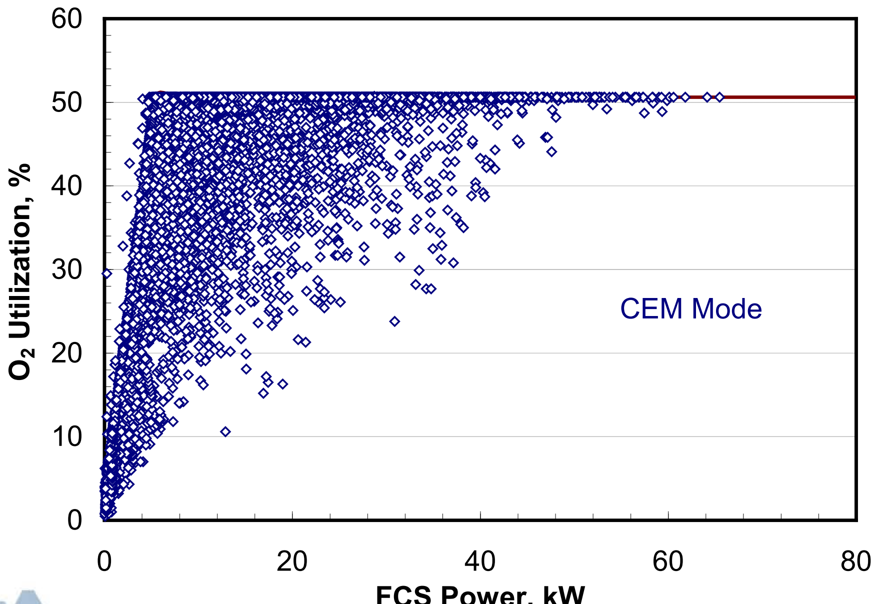
Dynamic Performance of Integrated CEM Module

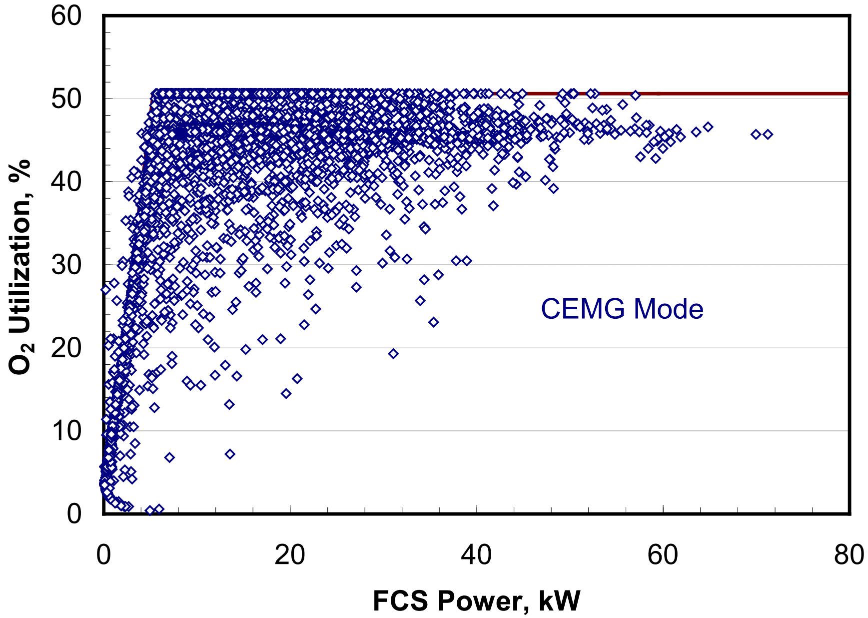
Dynamic simulations on hybrid UDDS and HWFET cycles

Operation as motor/generator (CEMG)

- Faster response during deceleration
- SR >2 in deceleration, >>5 at low power
- Parasitic power >> steady-state values during acceleration, lower or even negative during deceleration





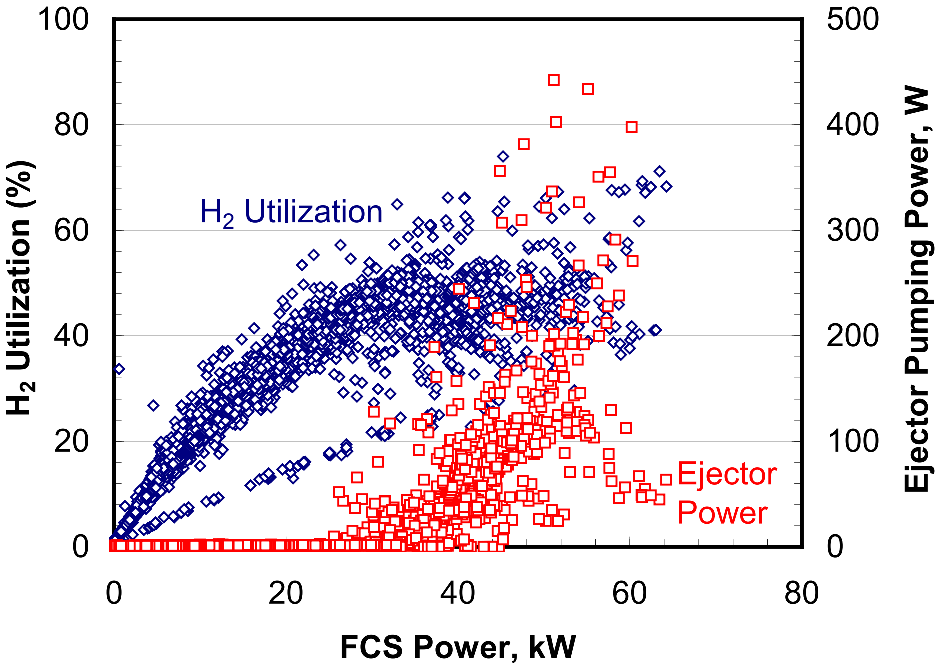


Solid lines indicate results from steady-state simulations

Fuel Management System

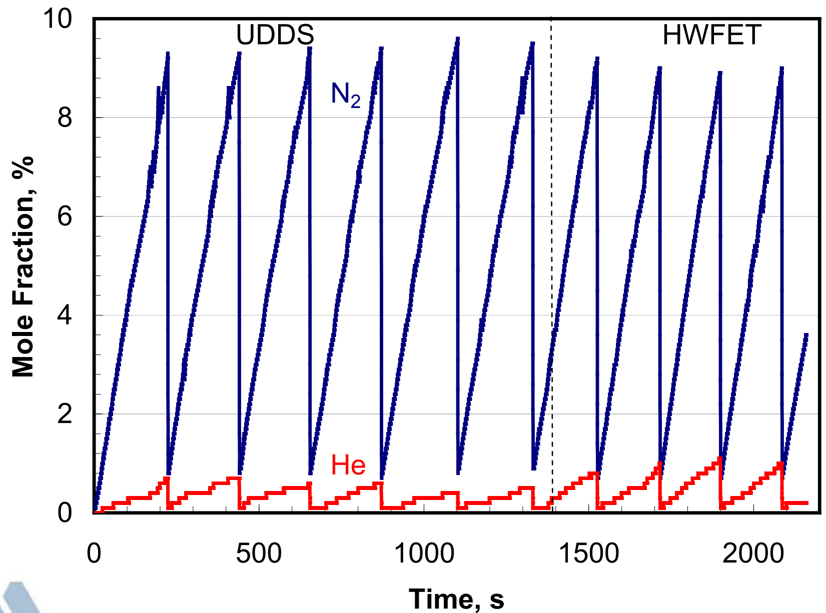
- Parallel ejector-pump hybrid
  - Ejector for >45% power (zone I), blower for <30% power (zone II), hybrid for intermediate power (zone III)
  - Motive gas pressure regulated to <8 atm
- Dynamic simulations with single-speed blower (always on)
  - Ejector pumping power up to 400 W (parasitic reduced by 1 kW_e)
  - H_2 utilization maintained around 50% in zone I, << 50% in zone II

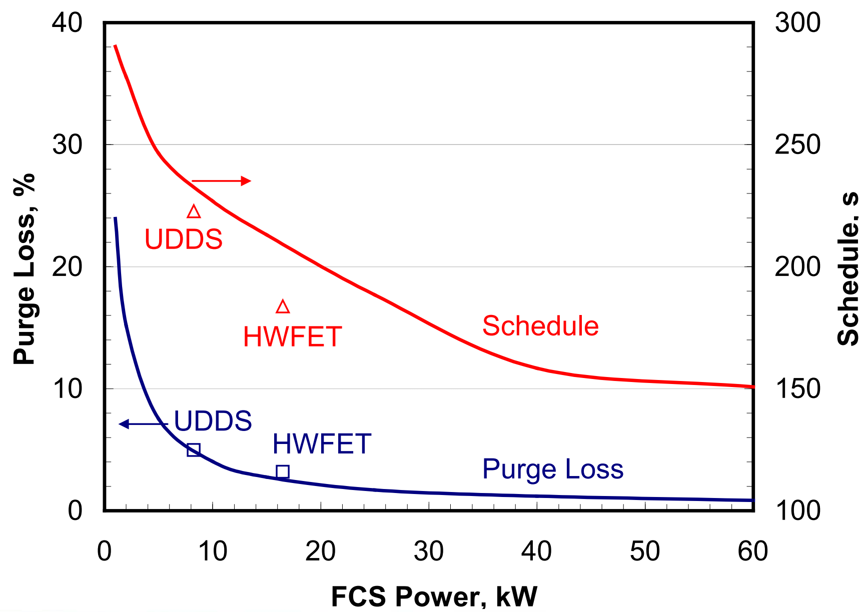
- H_2 feed rate proportional to pressure differential between cathode and anode
  - >60% H_2 utilization during depressurization
  - H_2 utilization affected by impurity buildup that reduces ejector entrainment



Purge Losses

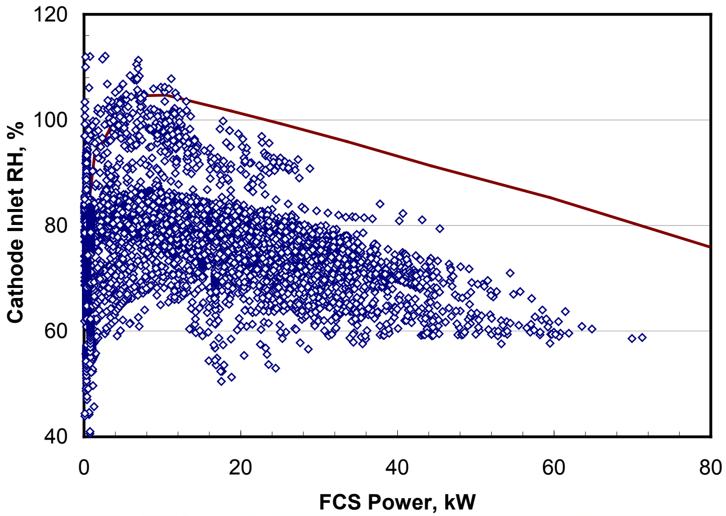
- Dynamic simulations on UDDS and HWFET cycles, hybrid mode
- ISO-TC 192 specs for N_2 (100 ppm) and He (200 ppm) impurities
  - Purge schedule determined by N_2 buildup due to crossover from air
  - Cyclic buildup of reactive hydrocarbon impurities
  - NH_3 does not accumulate due to significant crossover to cathode
  - Cumulative degradation due to H_2S
  - Anode purged (15 sl) when inerts (N_2 + He) build up to 10 mol%
  - H_2 loss and purge schedule depend on duty cycles and allowable inert concentration (maximum)

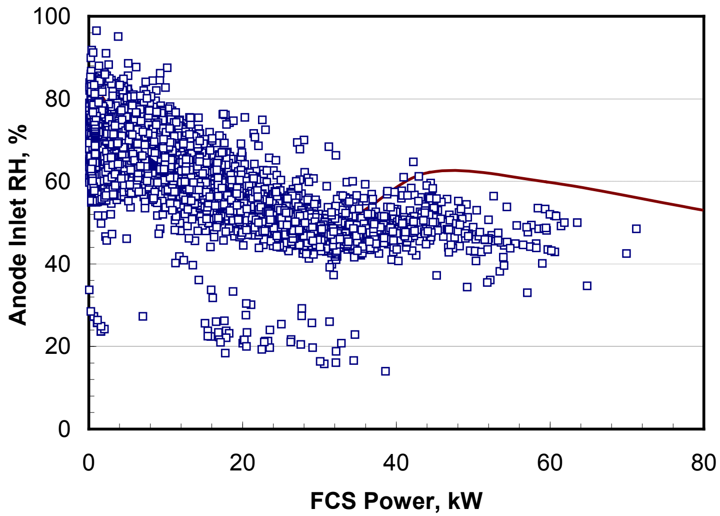




Water Management System (Humidifier)

- Completed analysis of Honeywell data for full-scale, half-scale, and 1/10th sub-scale membrane humidifiers
  - Data received for planar humidifier with a composite membrane
- Summary of model results
  - Optimum dry-air inlet temperature for maximum flux (last year)
  - Thinner membrane: higher water flux, but lower optimum T and mechanical support may be needed
  - Lower P: Higher flux, but required water transfer rate also greater
  - Cathode RH reported at stack inlet T (air concurrent with coolant)
  - Anode RH reported at stack outlet T (air countercurrent with fuel)





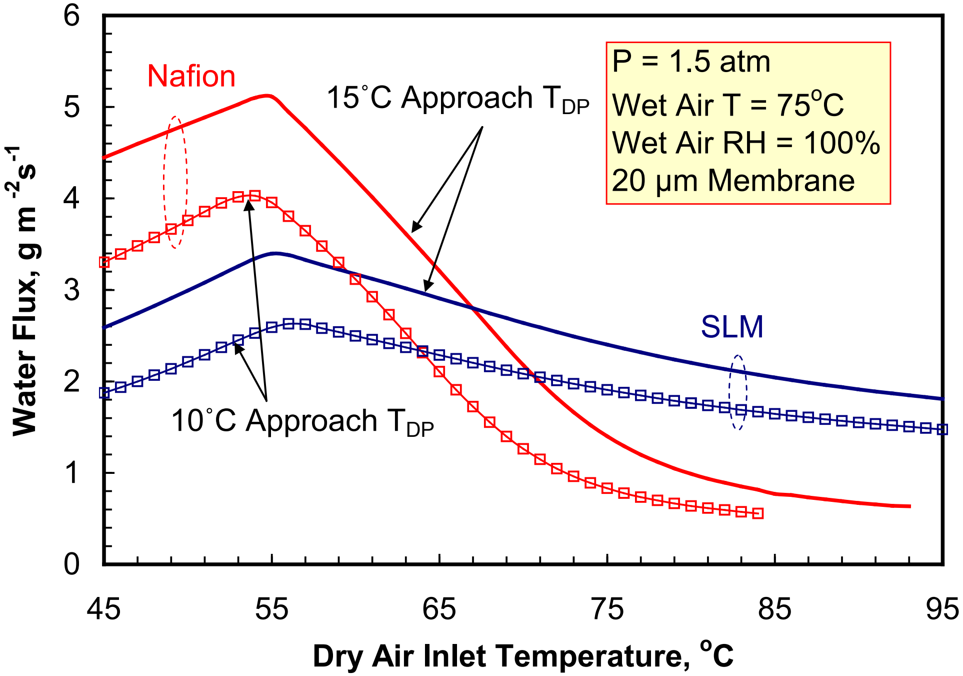
Anode humidification is due to recycle (no anode humidifier in the system)

Supported Liquid Membrane (SLM)

- Moisture diffusion coefficient higher in liquid membranes than in solid membranes
- Composite SLM by Zhang, J. Membrane Science 276 (2006) 91-100
  - LiCl solution immobilized in hydrophilic cellulose acetate (CA) membrane, 50-70 μm thick, 0.22 μm pores
  - Hydrophobic PVDF membranes as protective layers, 45 μm thick, 0.15 μm pores
  - Composite SLM considered experimental, not optimal

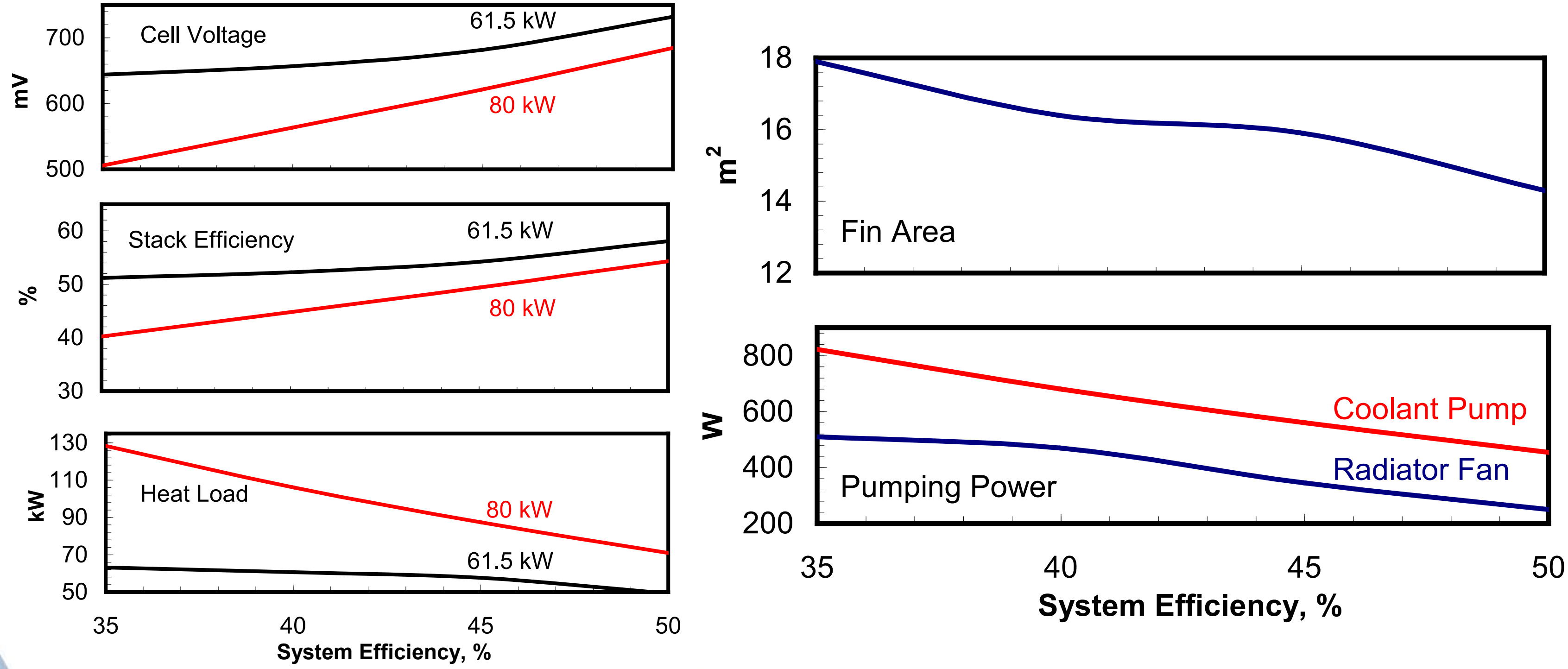
Modeled Performance

- For same membrane thickness higher flux at high T
- Flux limited by resistance in the protective layers
- Many SLM configurations reported in literature
  - Higher flux
  - Eliminate pre-cooler



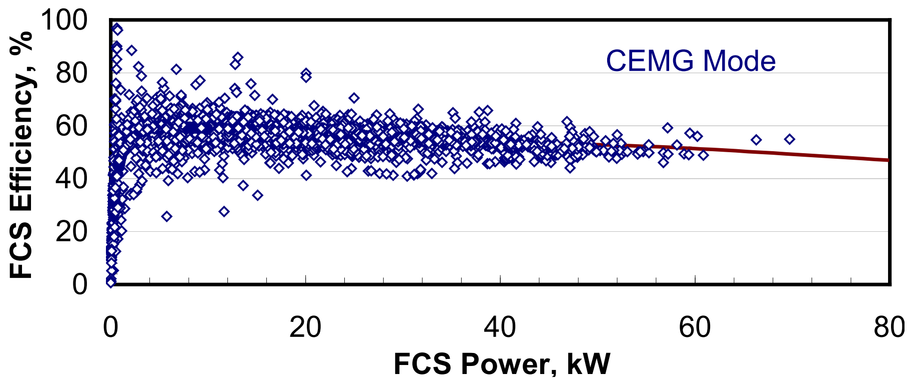
Thermal Management System – Heat Loads

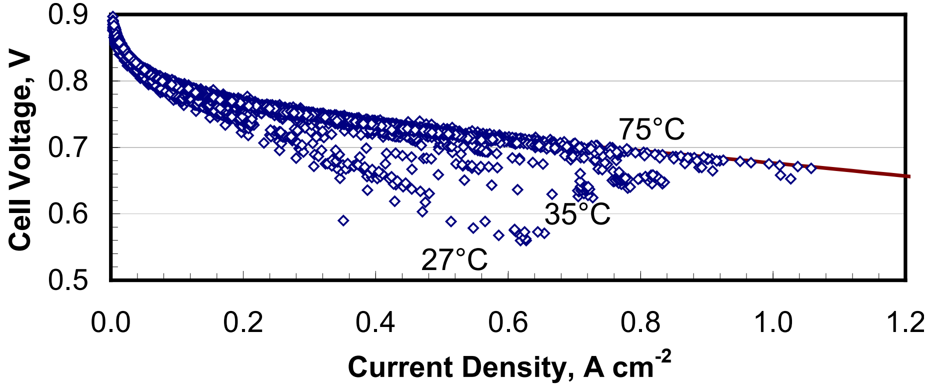
- Heat loads at rated power and on 6.5%-grade at 55 mph
  - Stack heat load proportional to $P_{PEFC}(1-\eta_{PEFC})/\eta_{PEFC}$
- Stacked HT radiator, LT radiator and AC condenser, 40-fpi MC fins
  - On grade, stack T allowed to rise to 95^{o}C, P to 2.3-2.4 atm
  - Expander needed even in S2
  - Depending on vehicle platform and FCS rated power, 35-40% efficiency at rated power may be acceptable

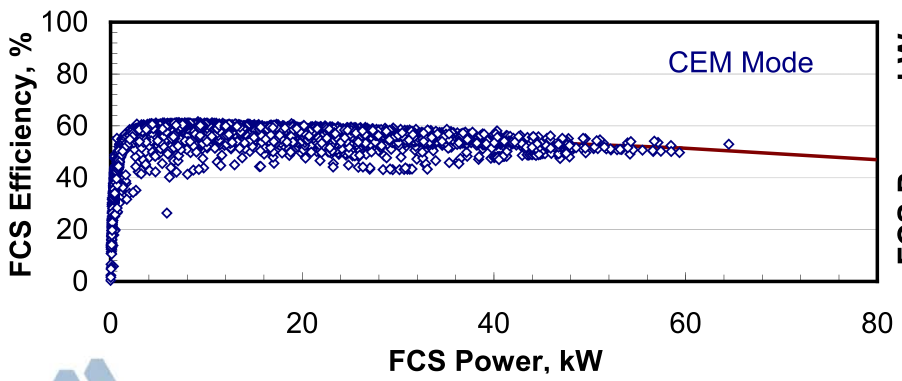


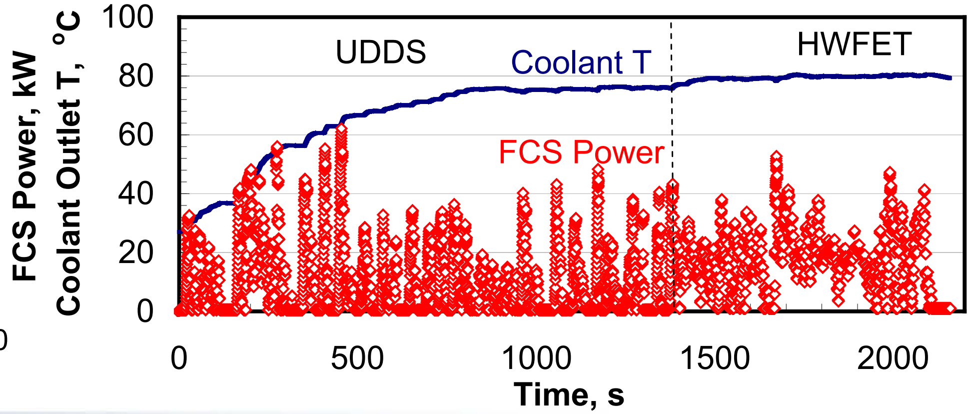
Dynamics of Cold Start

- Improving water transport model using 3M's polarization and water balance data at 30-80°C and data without anode MPL
- Cold-start simulation on 1 UDDS and 1 HWFET starting at 27°C
  - Flooding limits stack power to 32 kW at 30°C, 50 kW at 45°C
  - Stack heat-up time and temperature depend on the drive cycle
  - FCS efficiency is a function of stack temperature and drive cycle



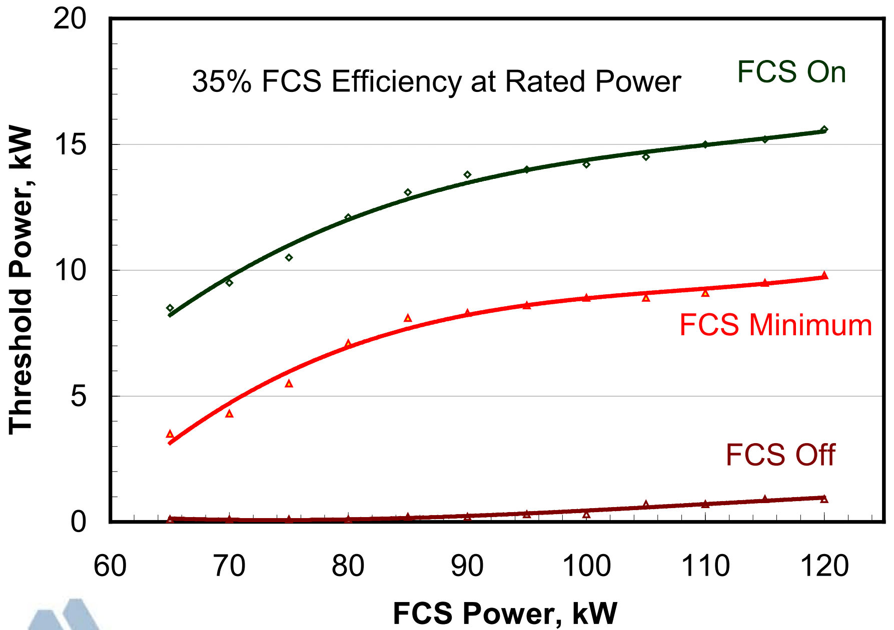


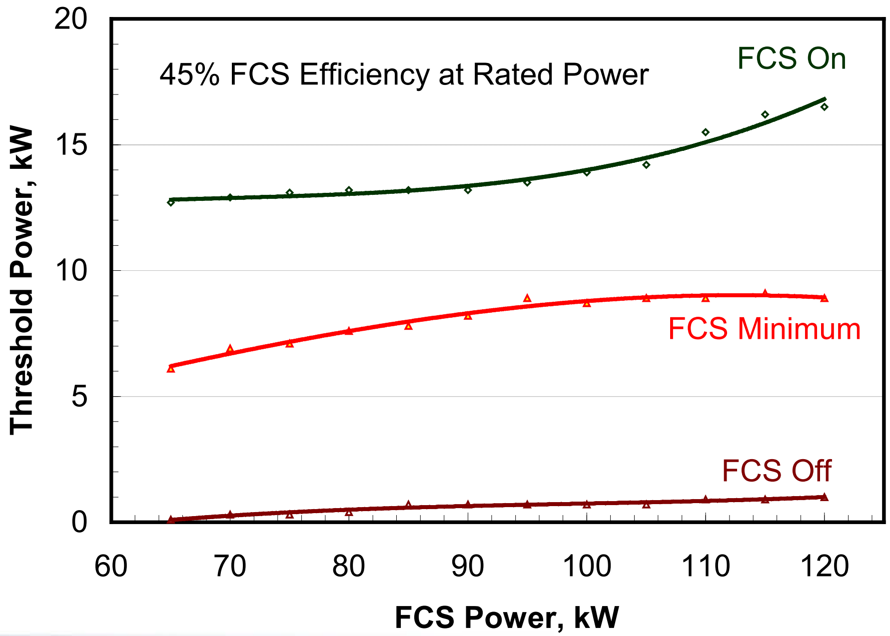




Optimum FCS Control Parameters

- Drive cycle simulations for 35-50% rated-power efficiency and 65-120 kW FCS rated power
  - Mid-size hybrid vehicle, Kansas City drive cycles
  - FCS provides the hotel loads, 250-W idle power
- Determined optimum control parameters: power threshold for turning FCS on, threshold for idling FCS, minimum FCS power, battery power
- Minimum FCS power and traction power (at motor) for turning on the FCS is a function of the rated power and the rated-power efficiency
  - Depending on battery SOC, FCS operates at low traction power

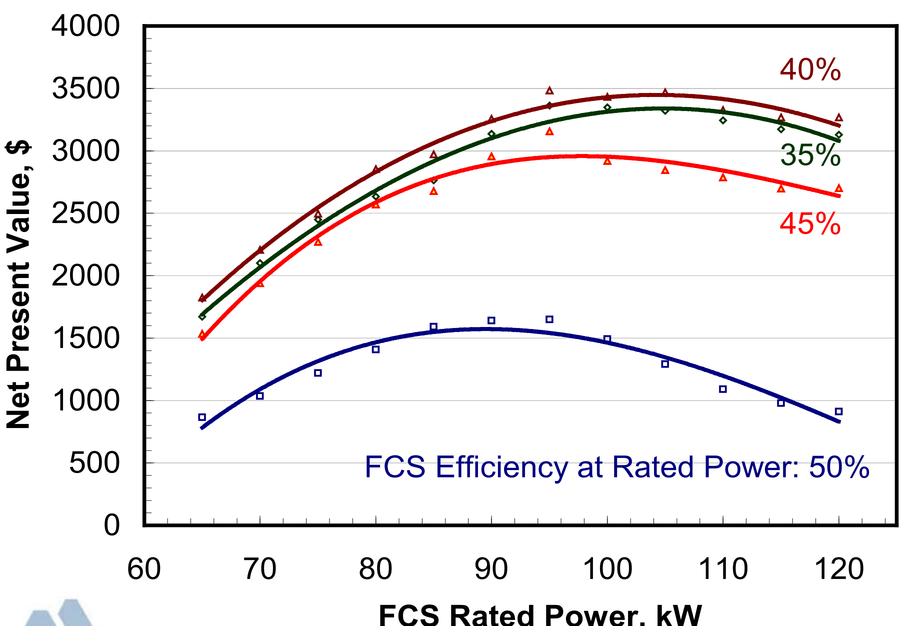


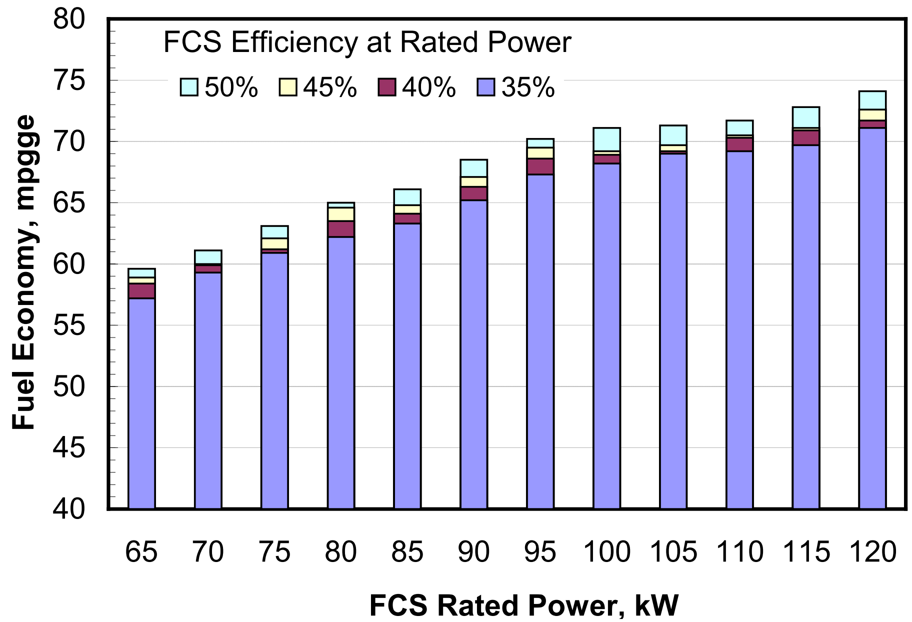


Preliminary results, control strategy will depend on stack/battery durability considerations

Summary: System Performance on Drive Cycles

- Relationship between rated-power efficiency, FCS rated power, FCS cost (DTI input), fuel economy, ownership cost
  - Optimum FCS control parameters
- Net present value (NPV) shows that 85-kW FCS with 40% rated-power efficiency offers the best solution (3.70/5 \$/gge gasoline/H_2)
  - NPV: present value of investments and future savings, compared to reference ICEV
- Fuel economy higher with the largest FCS, small dependence on rated power efficiency





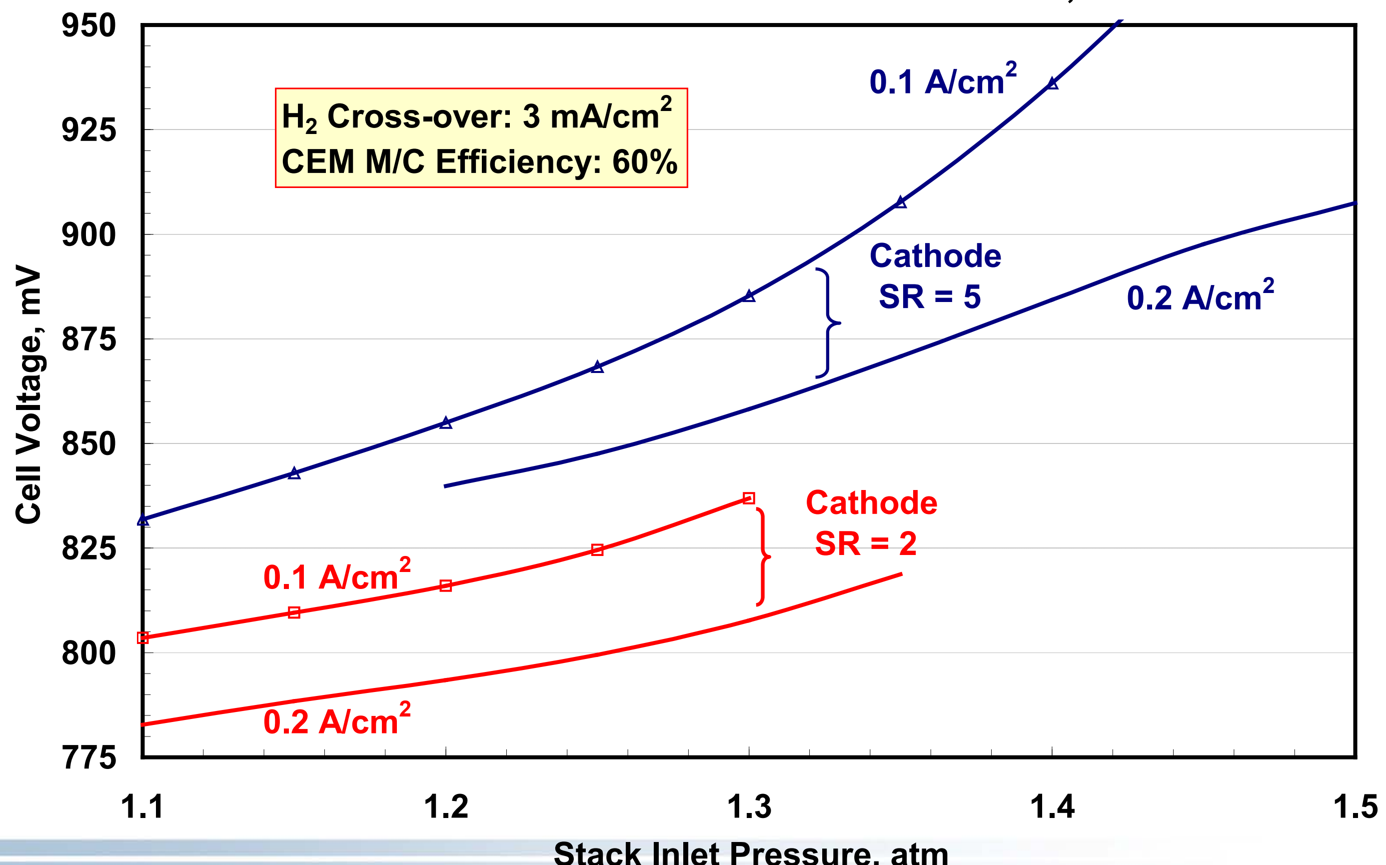
Future Work

- Support DOE/FreedomCAR development effort at system, component, and phenomenological levels
- Continue collaboration with 3M to validate, calibrate and document the stack model
  - Alternate membranes, catalyst structures, and system configurations
- Continue cooperation with partners to validate air, fuel, thermal, and water management models
  - Establish closer collaborations with the OEMs
- Support DTI and TIAX in high-volume manufacturing cost projections, collaborate in life-cycle cost studies
- Collaborate with 3M to develop durability models for NSTFC electrode structures
  - System optimization for cost, performance, and durability
  - Drive cycle simulations for durability enhancement
- GCtool model of PEFC systems for fork-lift applications
- Performance of PEFC systems for stationary applications

Supplemental Slides

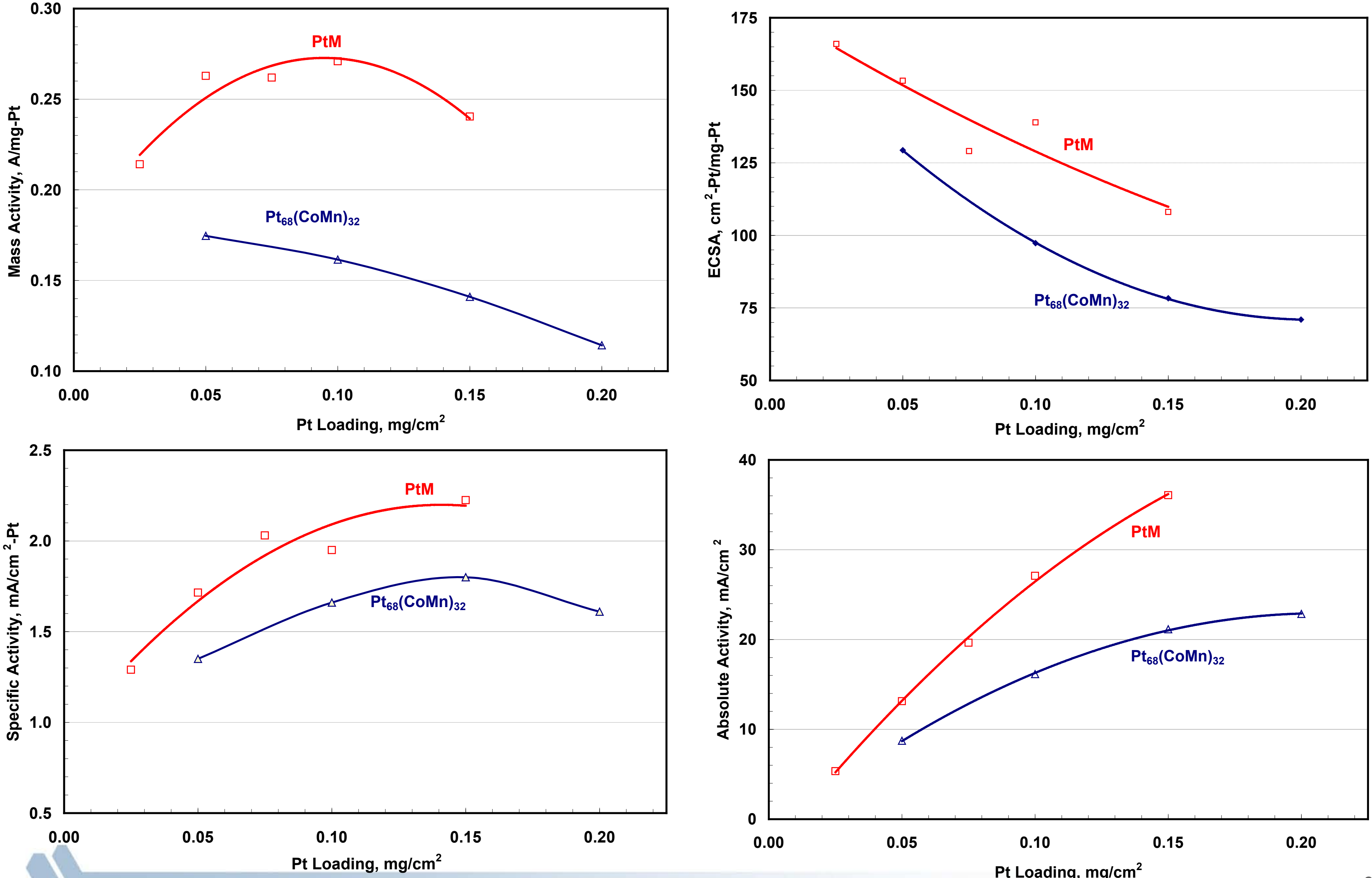
Effect of Stoichiometry and Operating Pressure

- At low current densities, cells are sometimes operated at higher SR because of limited CEM turndown or catalyst flooding issues
  - Cell voltage for 60% peak efficiency is ~50 mV higher if the cathode SR is 5 instead of 2 at 0.2 A/cm², 1.2 atm
  - Needed cell voltage is ~17 mV higher if the pressure is increased from 1.2 to 1.3 atm at 0.2 A/cm², SR = 2



Advanced Binary vs. Ternary Catalyst

For same Pt loading, PtM has 1.5-1.7 times the absolute activity of PtCoMn



Approach to Reach 60% Peak FCS Efficiency

- Redesign the CEMM controller
  - Improve M/C efficiency at low power from 35% to >60%
- AND operate at low SR (<2) and low pressures (<1.2 atm)
- AND increase Pt loading in PtCoMn
  - 40% improvement in absolute activity by increasing Pt loading from 0.1 mg/cm^2 to 0.2 mg/cm^2
- OR use more active binary PtM catalyst (still under development, mass transfer issues at high current densities, durability yet to be demonstrated)
  - Compared to 0.1-mg-Pt/cm^2 ternary catalyst, the activity of binary catalyst is 70% higher for same Pt loading and 120% higher at 0.15 mg-Pt/cm^2 loading

Water Management System

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