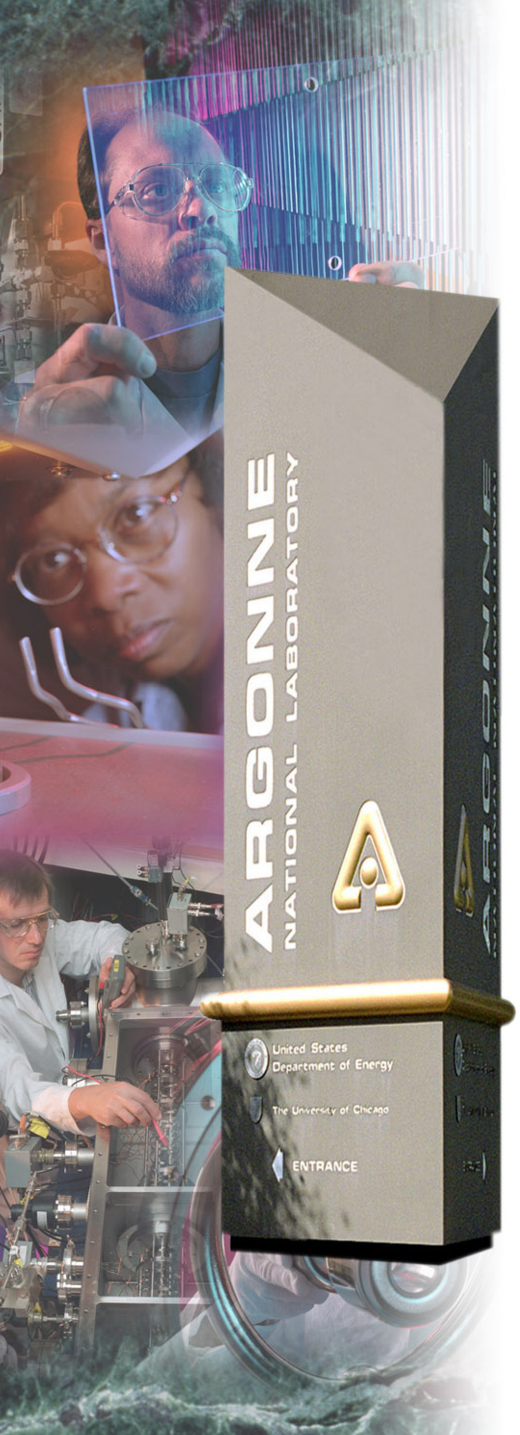

Fuel Cell Systems Analysis

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This presentation does not contain any proprietary or confidential information

Argonne National Laboratory *Project ID# FC35*

Office of Science
U.S. Department of Energy

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Overview

Timeline

- Start date: Oct 2003
- End date: Open
- Percent complete: 30%

Barriers

A. Compressors/Expanders

C. Fuel Cell Power System Benchmarking

D. Heat Utilization

H. Start-up Time

R. Thermal and Water Mgmt

Budget

- Total funding: $400K
  - DOE share: 100%
- FY04 funding: $400K
- FY05 funding: $400K

Partners

- Honeywell CEM+TWM projects
- IEA Annexes 17 and 20
- FreedomCAR fuel cell tech team
- HTM working group

Objectives

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

- Support DOE in setting R&D goals and research directions
- Establish metrics for gauging progress of R&D plans

Approach

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

- GCtool: Stand-alone code on PC platform
- GCtool_ENG: Coupled to PSAT (MATLAB/SIMULINK)

Validate the models against data obtained in laboratory and at Argonne's Fuel Cell Test Facility.

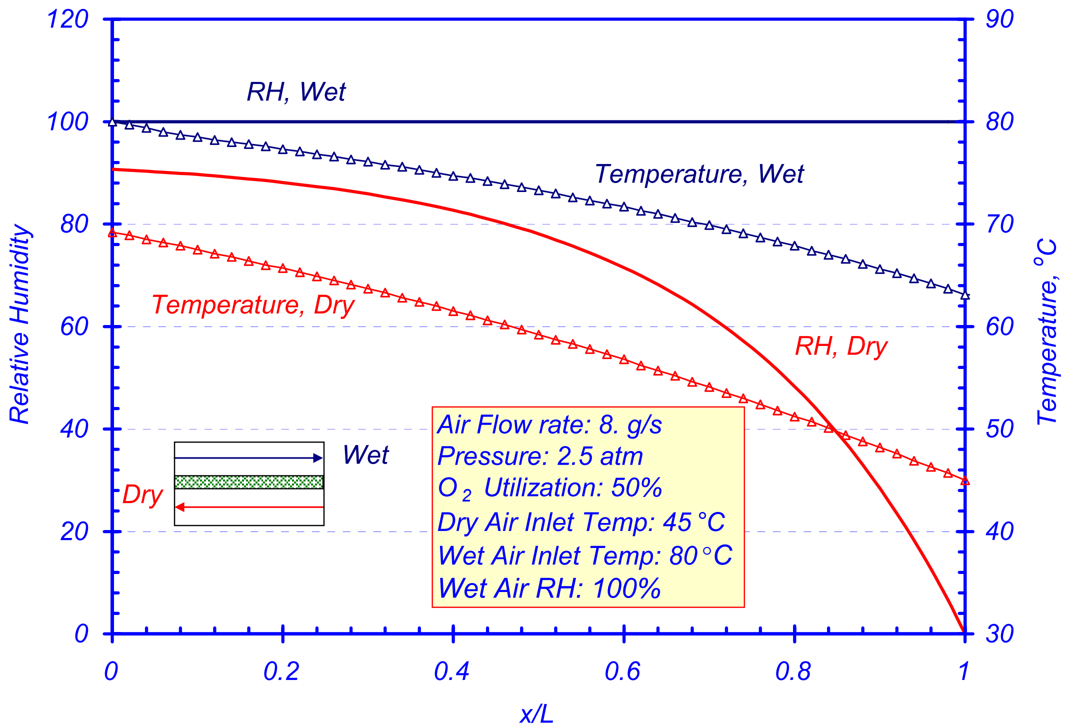
Apply models to issues of current interest.

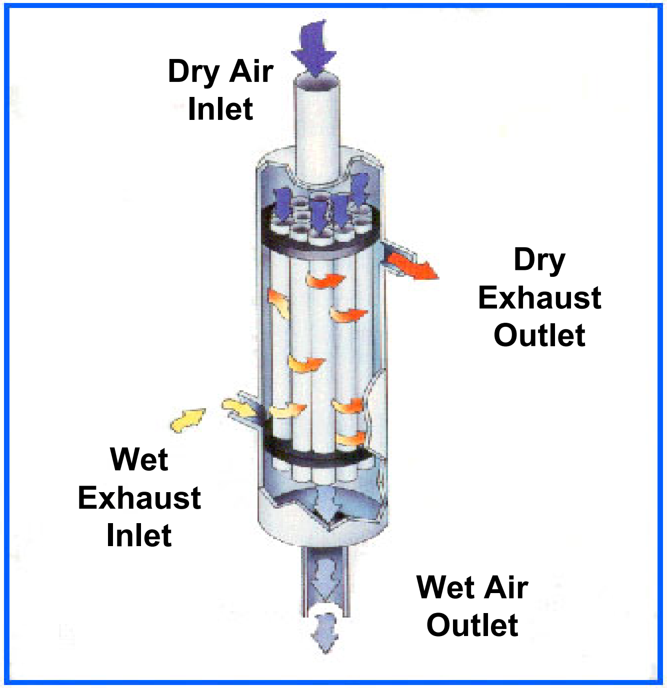
- Work with FreedomCAR Technical Teams.
- Work with DOE contractors as requested by DOE.

Membrane Humidifier Model

Counterflow shell and tube configuration (Perma Pure)

- Mass transfer determined from gradient of membrane water content (λ) and diffusivity D(λ,T)
- Coupled heat and mass transfer

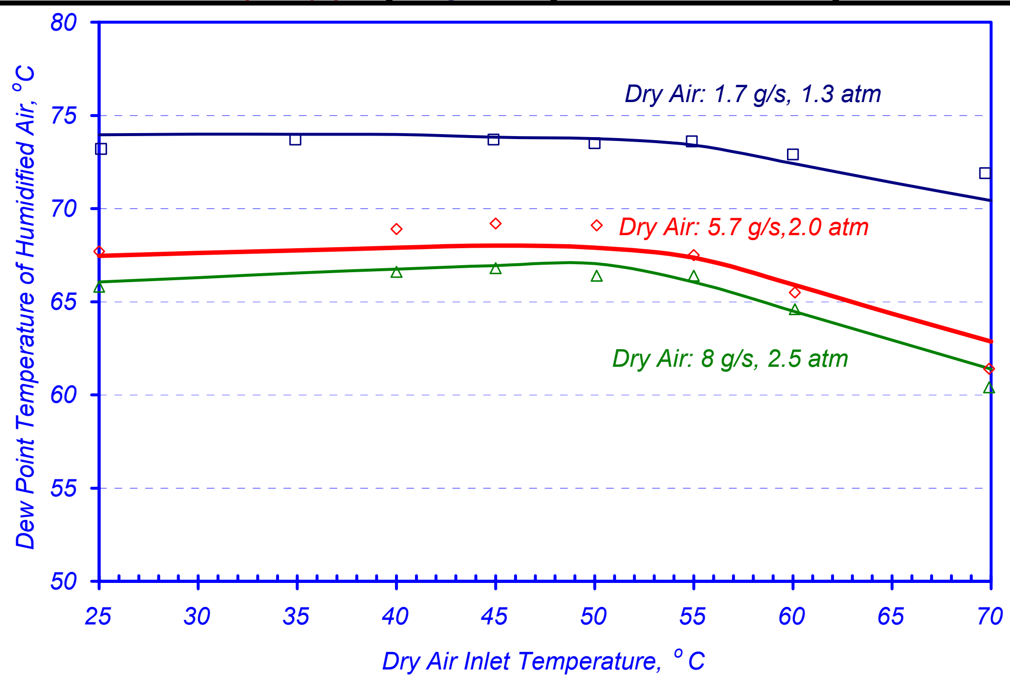




Membrane Humidifier Model Validation (Data from Honeywell / Perma Pure)

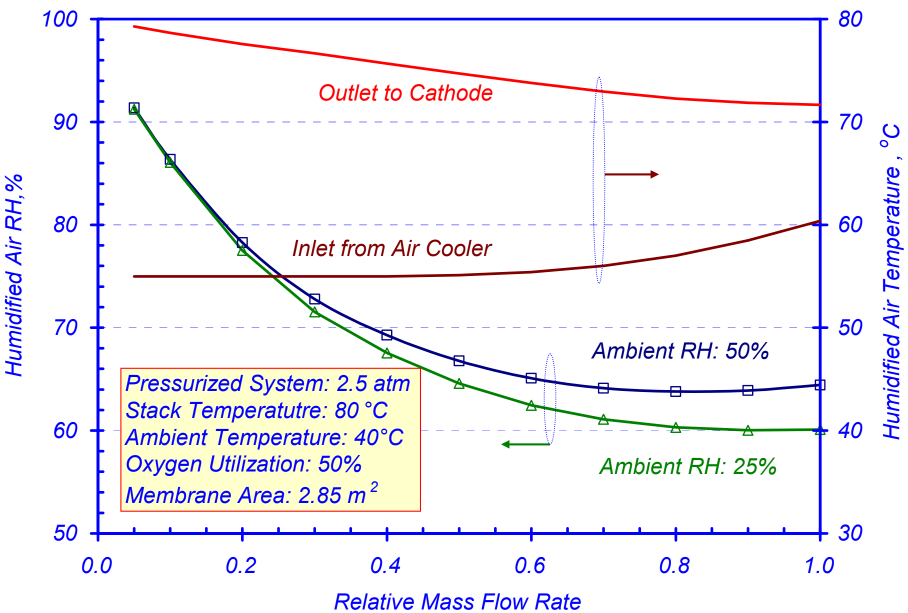
Mass transfer decreases above 50°C inlet dry air temperature

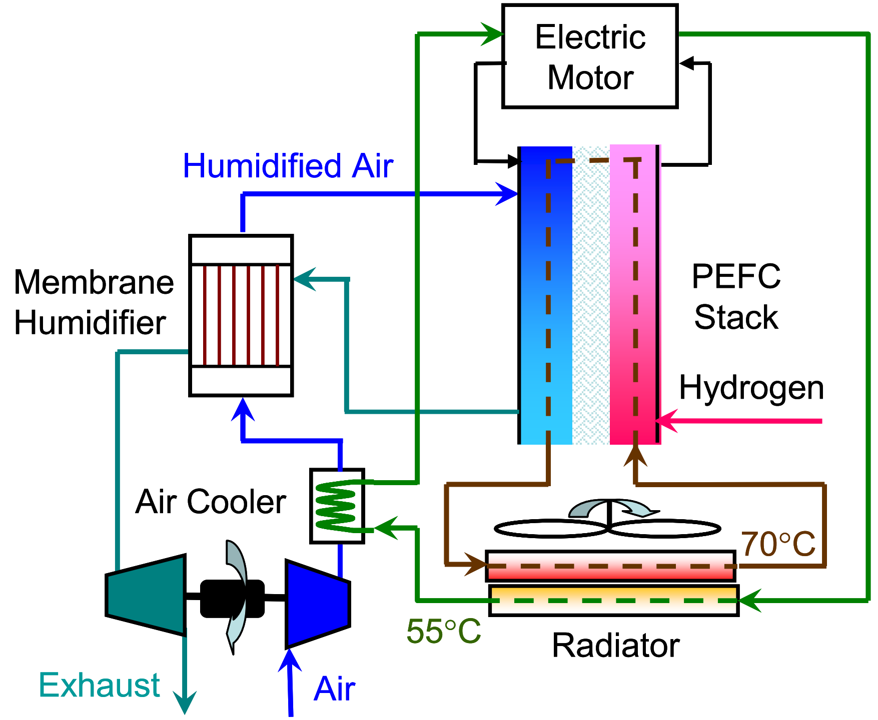
		Dry Air	Wet Air
Temperature	°C	25 - 70	80
Relative Humidity	%	Dry	100
Pressure	atm	1.3 - 2.5	1.3 - 2.3
Air Flow Rate (Dry)	g/s	1.7 - 8	1.5 - 7.2



Pressurized FCS with Membrane Humidifier

- Demister between stack and humidifier not required
- Compressor discharge cooled with low-T stack coolant or air
- Possible to maintain stack at 80°C at all loads
- 60-85% outlet RH @ 25-50% ambient RH

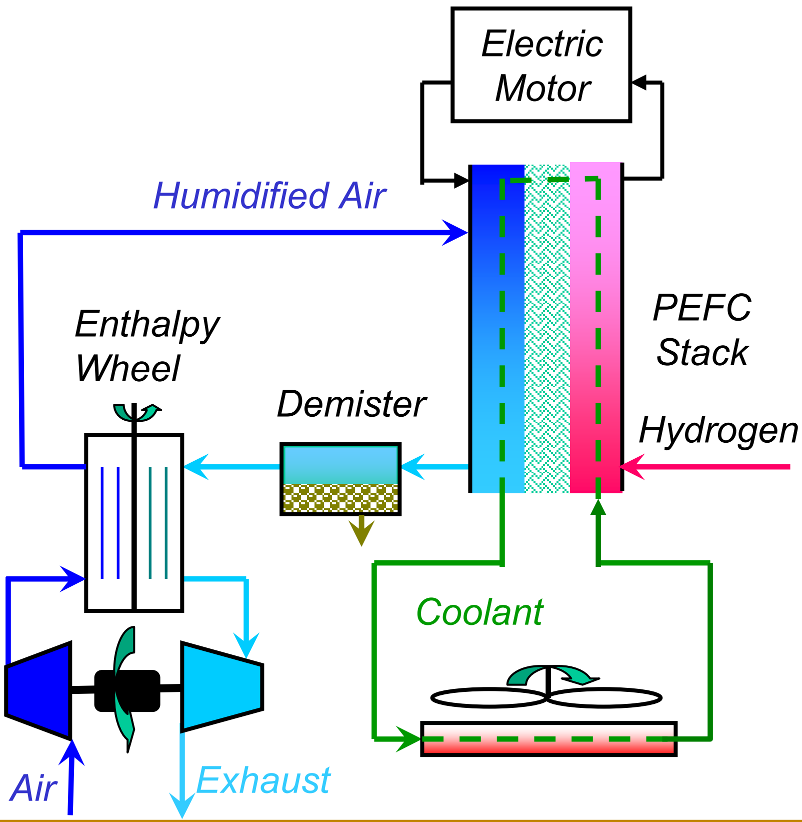


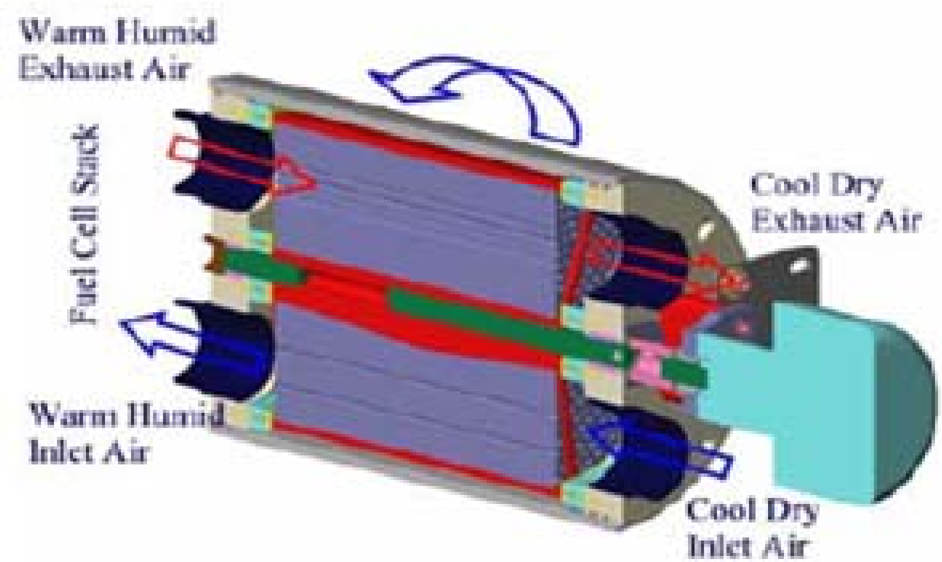


Pressurized FCS with Enthalpy Wheel Humidifier

Model developed in FY04, validated with Honeywell/Emprise data

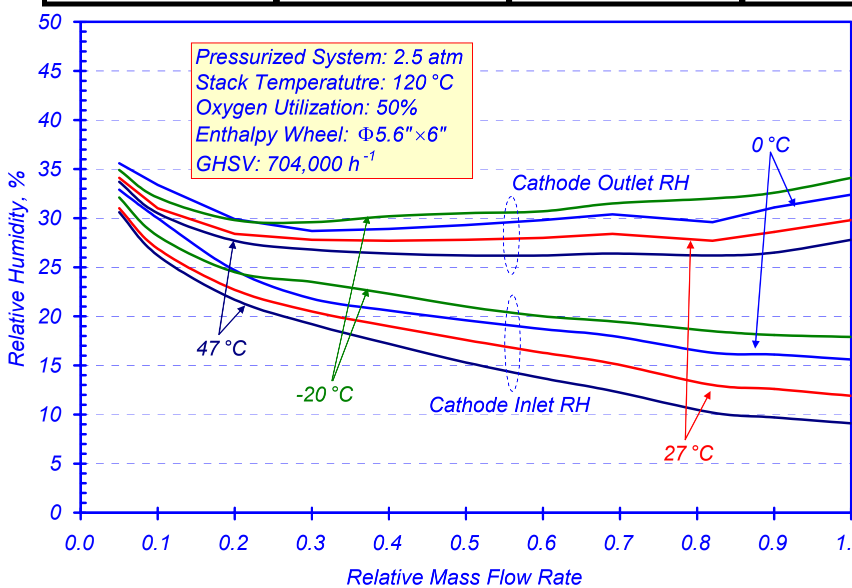
- EW model used in FY05 to support TWM Honeywell program
- Evaluated EW for high-temperature membranes at 120°C

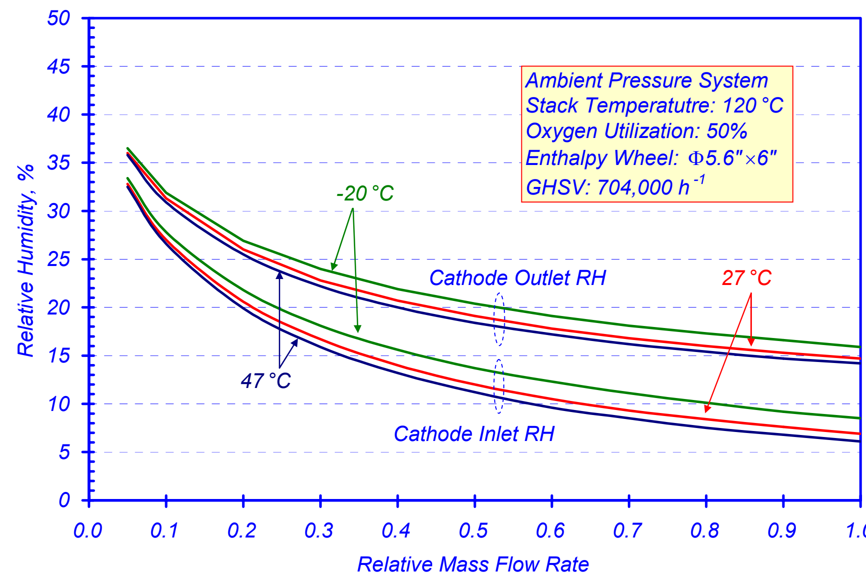




With EW in HTM-FCS, cathode air at 120^{o}C can be humidified to 10-30% RH at 2.5 atm and <15% RH at 1 atm

	Pressuized System			Ambient Pressure System		
% Flow	% RH In	% RH	η_{MT} (%)	% RH In	% RH	η_{MT} (%)
EW Space Velocity = 700,000/h						
100	9-17	27-34	25-45	6-9	15-16	35-45
10	31-34	33-35	80-85	33	36	80-85
EW Space Velocity = 350,000/h						
100	20-30	35-42	40-60	10-13	17-19	50-60
10	35	38	80-85	37	40	80-85





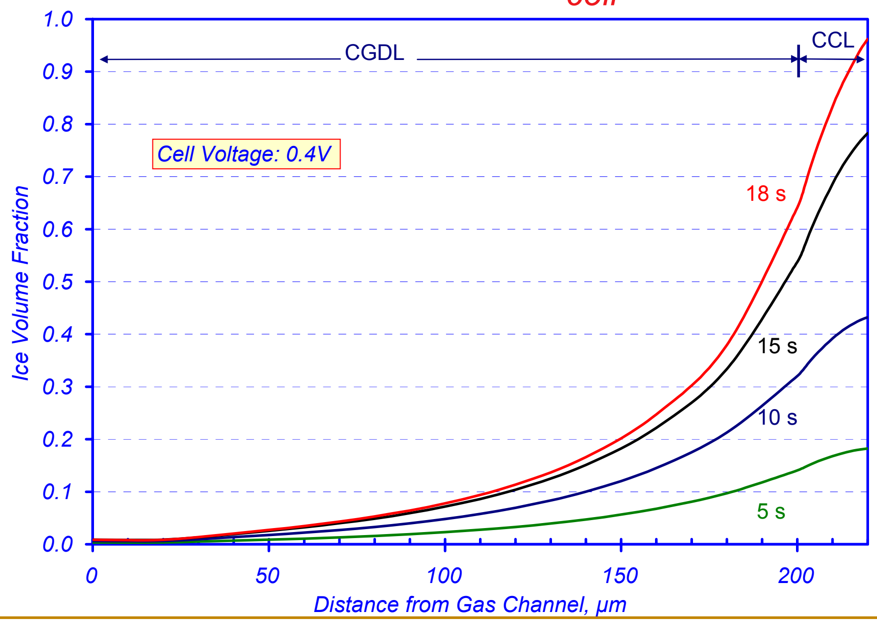
Self-Start of PEFC Stacks from Sub-Freezing Temperatures

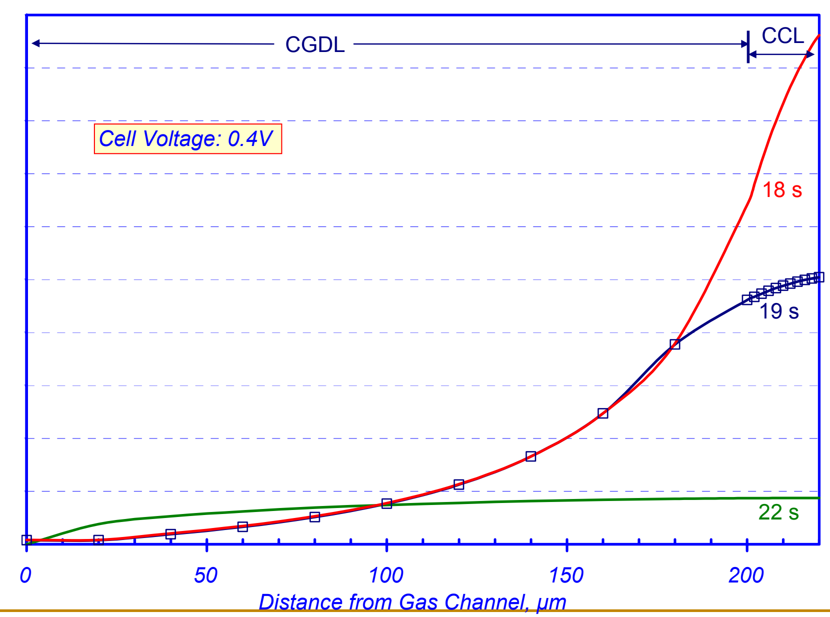
2-D Dynamic Simulation Model

- ✓ Reactions with species transport in five-layer MEA
- ✓ Formation and melting of ice
- ✓ Effect of ice on ECSA & transport
- ✓ Capillary transport of water in GDL & porous catalysts
- ✓ T distribution in bipolar plate, flow channels and MEA

Simulation under conditions for which self-start is possible at -20°C

P = 1 atm, V_{cell} = 0.4 V, SG_{ice} = 0.5, 50-μm membrane

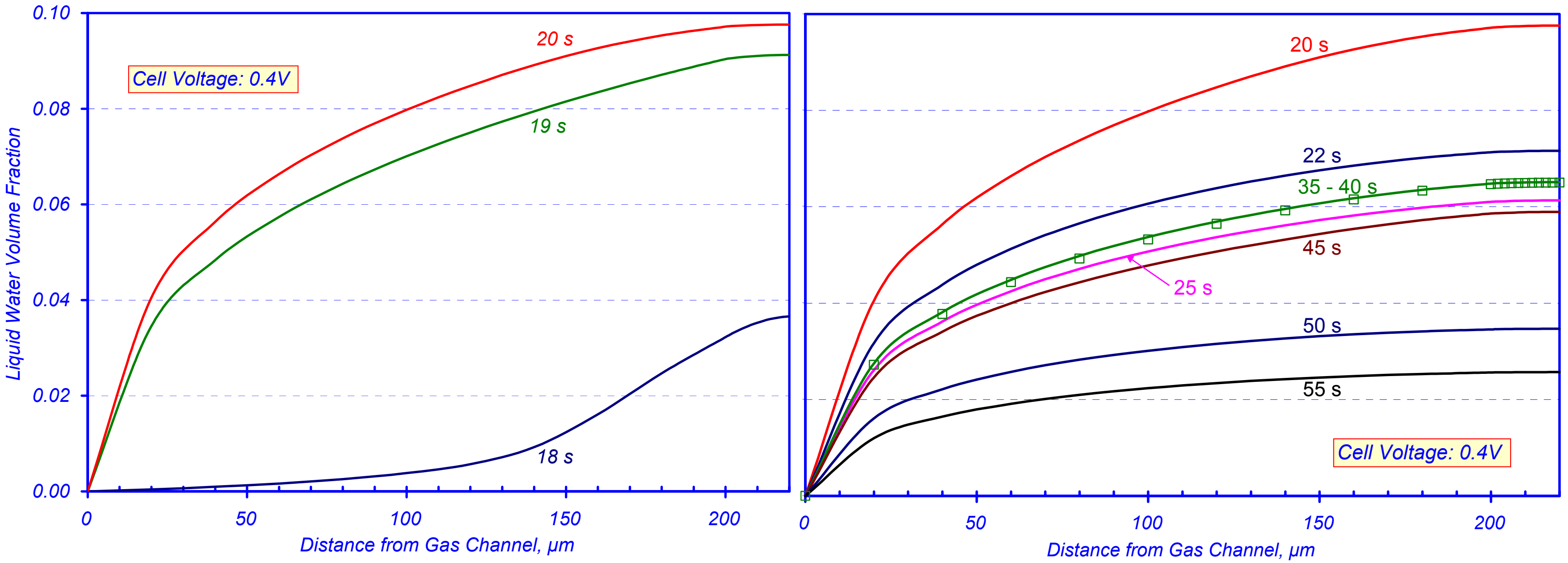




Simulation Result: Liquid Water Formation

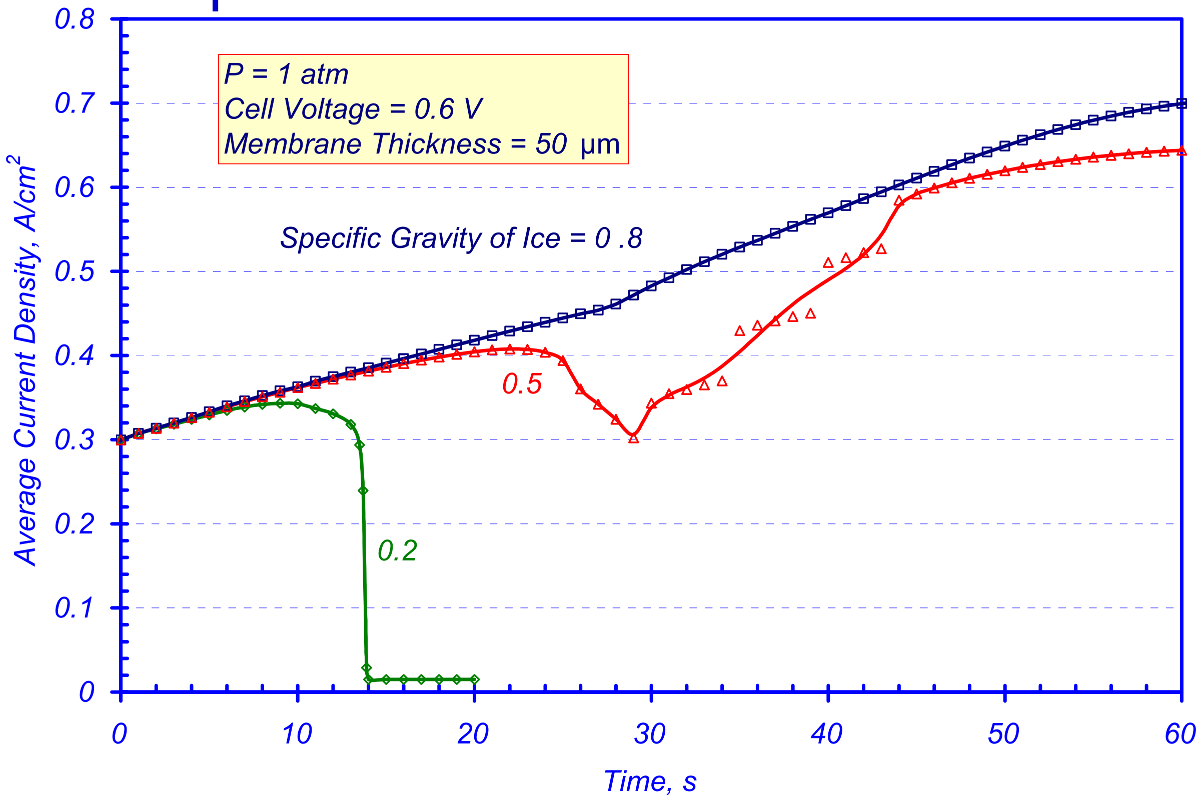
Simulation under conditions for which self-start is possible

- Ice and liquid water coexist between 18 and 22 s
- Liquid water volume decreases for t > 20 s
- May need to humidify air because stack heats up to 70^{o}C at 55 s



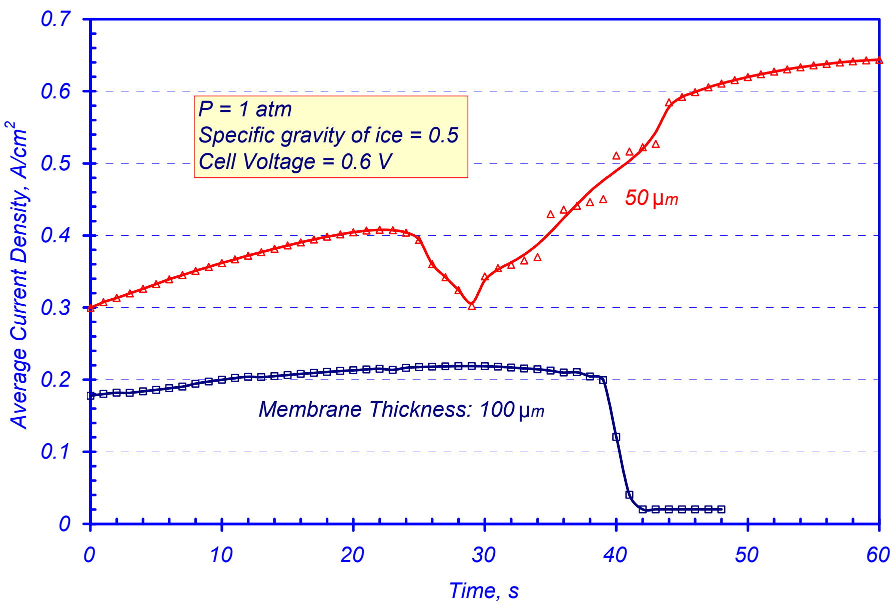
Simulation results are sensitive to the assumed bulk density of ice

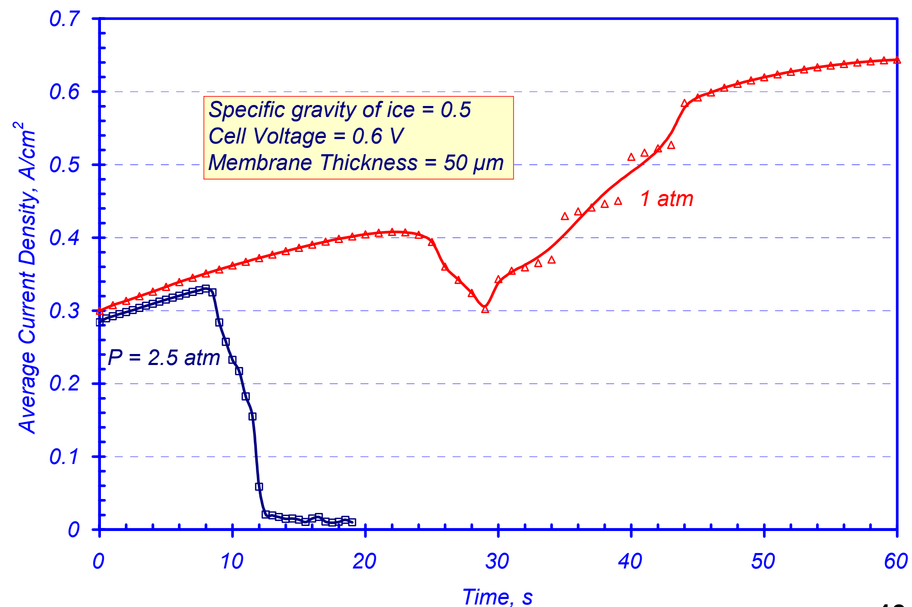
- P = 1 atm, V_{cell} = 0.6 V, 50-μm membrane, T_i = -20°C
- At SG = 0.2, cathode is completely covered with ice and stack temperature equilibrates below the melting point.
- Self start is possible for SG > 0.5.



Simulated Effects of Membrane Thickness and Pressure

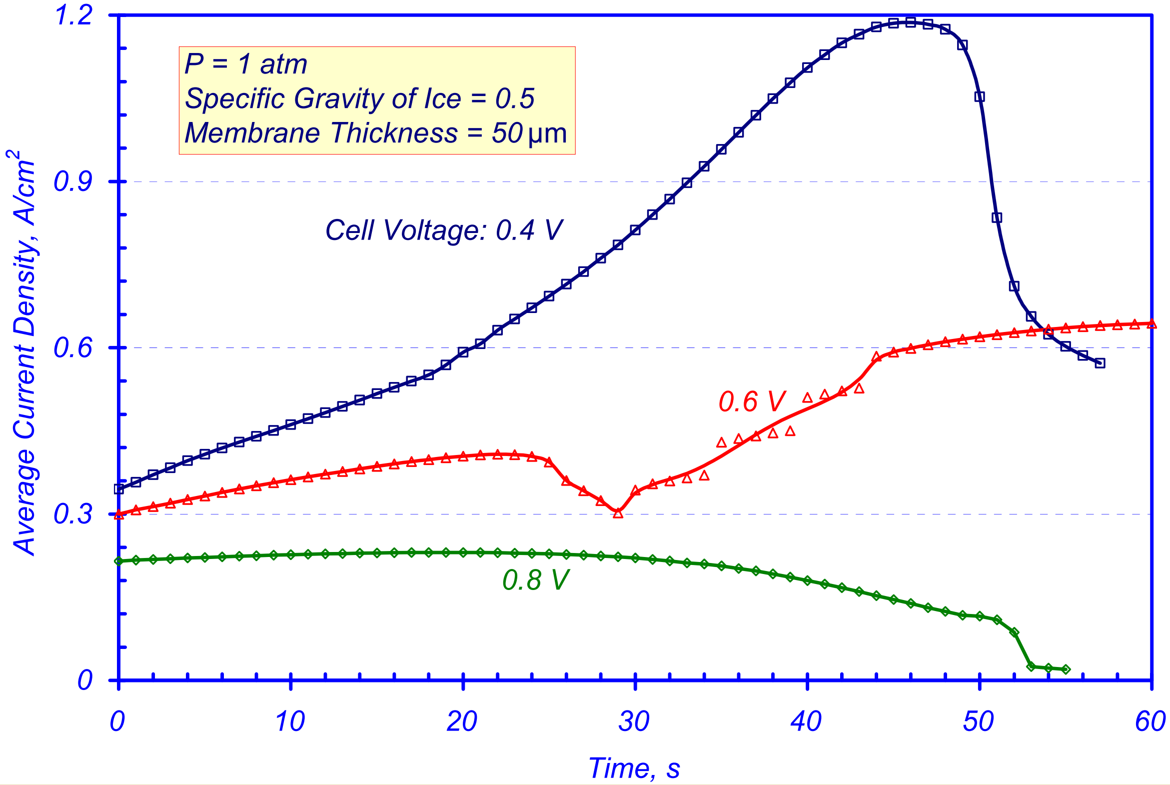
- More rapid build-up of ice on cathode catalyst in a pressurized stack
- Lower current density at pressure and with thicker membranes because of larger Ohmic overpotential across membrane





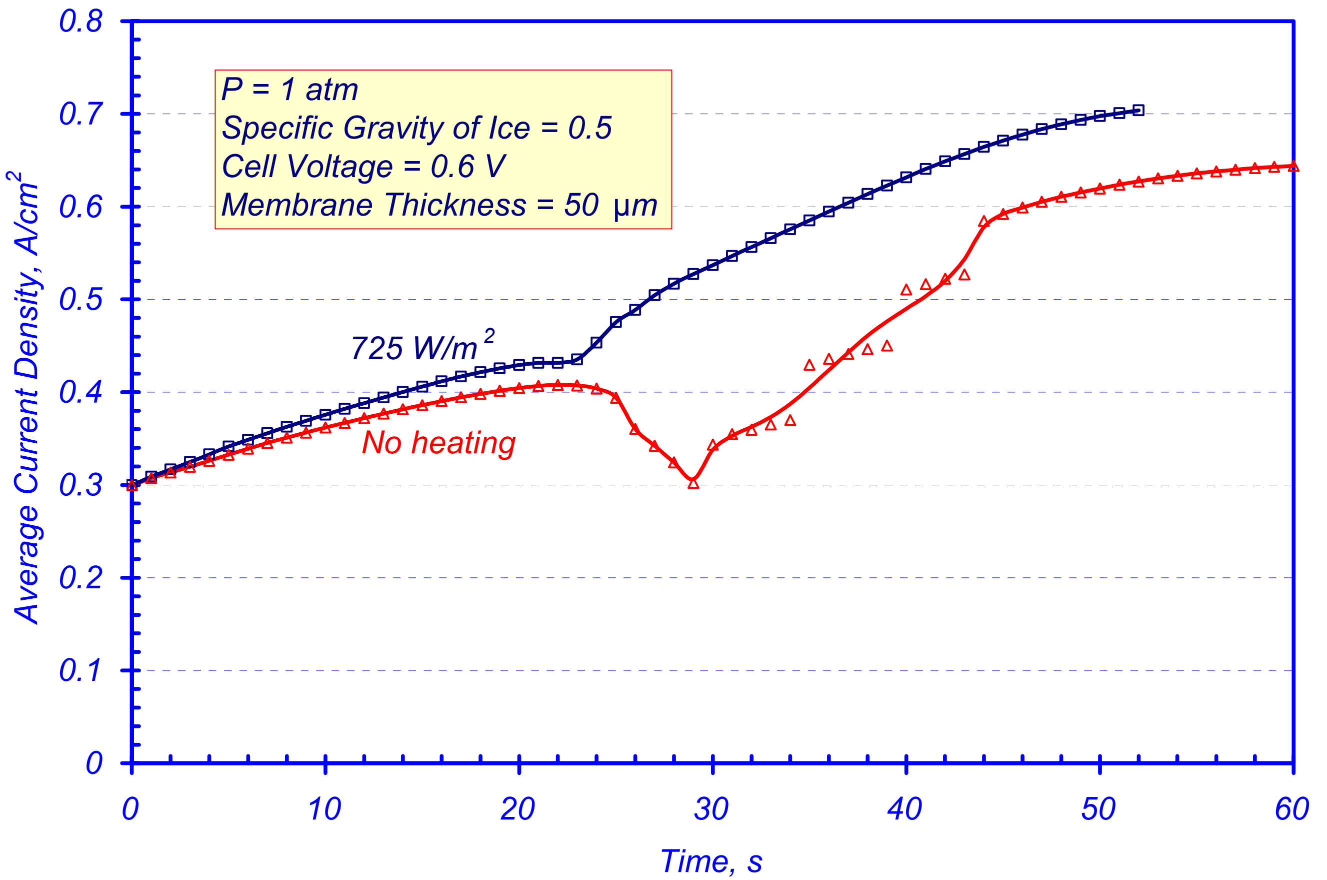
Self start is generally easier at lower cell voltages

- Self start is not possible at 0.8 V
- Self start is possible at 0.6 V but there is an intermediate period (25-30 s) over which the power decreases.
- Start up is robust at 0.4 V.



Simulated Effect of Stack Heating

- Start-up from -20°C is more robust and faster if the bipolar plate can be electrically heated.



Alternate Methods of Start-up from Subfreezing Temperatures

Start-up Time: Time to place the FCS in a state where it is capable of producing 90% of rated power on demand.

Start-up Energy Consumption: Additional fuel energy consumed on FUDS w.r.t FCS at normal operating T.

Alternate methods evaluated

1. Internal oxidation of hydrogen on MEA catalyst
   - Constrained by flammability limits
2. External combustion of hydrogen
   - Ineffective: 5.6 MJ of fuel energy needed to transfer 1.4 MJ needed to heat the stack to 0^oC from -20^oC
3. Insulated coolant tank with electrical heating
4. Insulated stack with electrical heating
   - Maintain stack at threshold temperature
   - Self-start stack at threshold T: < 10 s, 1 MJ of fuel energy

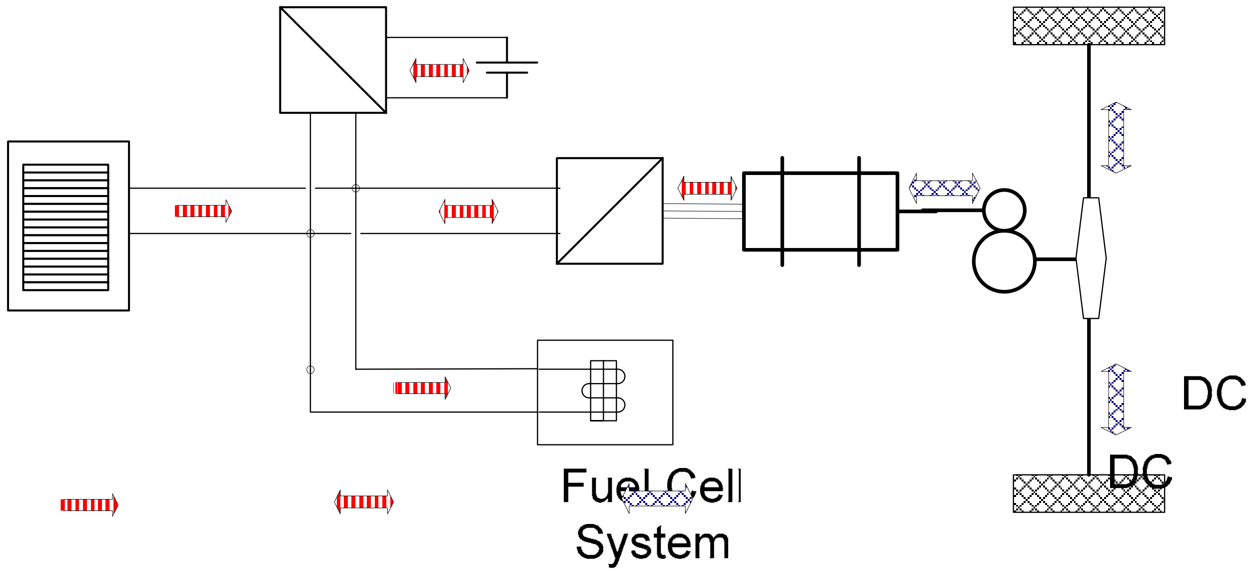
Stack Heating to Threshold Temperature Insulated Stack with Electrical Heating

- 1” insulation, 0.05 W/m.K
- Stack cools from 80^{o}C to 0^{o}C in 13-25 h
- A 40-kW hybrid battery maintains stack at 0^{o}C for 6-24 h

Ambient Temperature	Cool-Down Time to 0^{o}C	Heat Loss at 0^{o}C
-10^{o}C	25 h	20 W
-20^{o}C	19 h	40 W
-40^{o}C	13 h	80 W

- Periodically operate FCS for ~4 min at 25% power
  - ✓ Recharge the battery (480 W.h)
  - ✓ Excess power (60%) to electrical heaters
  - ✓ Heat the stack from 0 to 80^{o}C
  - ✓ 5.3 MJ/day fuel energy consumption at -20^{o}C ambient

Completed study on fuel economy of hybrid load-following fuel cell vehicles



Issues addressed in the study

- How much gain in fuel economy can we expect if FCEVs are hybridized with energy storage systems?
- How does the gain compare with ICE hybrids?
- How is the gain affected by North American, European and Japanese drive cycles?

Vehicle
Accessor

Reviewers' Comments

Generally favorable reviews with recommendations to

- Redirect away from fuel processing options
- Study effect of sub-zero ^{o}C startup and operation
- Place more emphasis on model development
- Keep engaged in thermal and water management
- Maintain close communications with fuel cell tech team

FY05 work scope consistent with above recommendations

- Focusing on direct hydrogen fuel cell systems
- Working on start-up from sub-freezing temperatures
- Developing models for enthalpy wheels, membrane humidifiers, ice formation……..
- Working with Honeywell and TIAX
- Member of fuel cell tech team

Proposed Future Work

- Continue work on freeze-start of fuel cell systems
- Continue collaboration with Honeywell on thermal and water management system
- Continue to support DOE/FreedomCAR development efforts
- Participate in validation effort
- Explore CHP applications of FCS
- Support HFCIT program on system analysis

Publications and Presentations

Journal Publications

R. K. Ahluwalia, X. Wang, and A. Rousseau, "Fuel Economy of Hybrid Fuel Cell Vehicles," *Journal of Power Sources,* (in print), 2005.

R. K. Ahluwalia and X. Wang, "Direct Hydrogen Fuel Cell Systems for Hybrid Vehicles," Journal of Power Sources, 139, 152-164, 2005.

R. K. Ahluwalia, X. Wang A. Rousseau and R. Kumar, "Fuel Economy of Hydrogen Fuel Cell Vehicles," *Journal of Power Sources,* 130, 192-201, 2004.

Conferences

R. K. Ahluwalia, X. Wang, and A. Rousseau, "Fuel Economy of Fuel Cell Hybrid Vehicles," *2004 Fuel Cell Seminar,* San Antonio, TX, November 1-5, 2004.

R. K. Ahluwalia, X. Wang, R. Kumar, "Fuel Cell Systems for Hybrid vehicles," *2004 International PEM Fuel Cell Conference, Hsinchu,* Taiwan, October 14-15, 2004.

R. K. Ahluwalia and X. Wang , "Performance of Hybrid Fuel Cell Vehicles," *Annex XX Meeting,* Stuttgart, Germany, September 28, 2004.

R. K. Ahluwalia and X. Wang, "Systems Level Perspective on Humidification in Direct Hydrogen Fuel Cell Systems with a High-Temperature Membrane," *USDOE High Temperature Membrane Working Group Meeting*, Philadelphia, PA, May 27, 2004.

Presentations

R. K. Ahluwalia and X. Wang, "Startup of PEFC Stacks From Sub-Freezing Temperatures," *DOE Workshop on Fuel Cell Operations at Sub-Freezing Temperatures,* Phoenix, AZ, February 1-2, 2005.

R. K. Ahluwalia and X. Wang, "Fuel Cell Systems for Hybrid Vehicles," DaimlerChrysler Research and Technology, Ulm, Germany, September 27, 2004.

Hydrogen Safety

- This is an analytical and computer modeling project. There are no hydrogen safety issues involved.