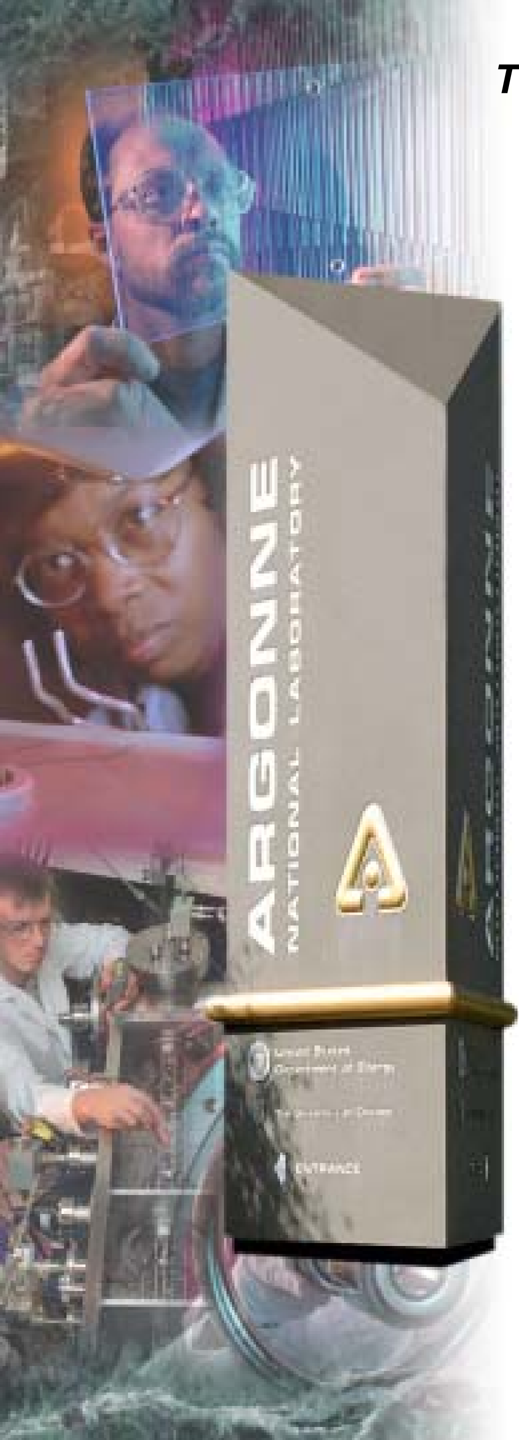

Fuel Cell Systems Analysis

2004 USDOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Philadelphia, PA

May 24-27, 2004

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Operated by The University of Chicago

Objective

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 activities

Technical Barriers Addressed

A. Compressors/Expanders

C. Fuel Cell Power System Benchmarking

D. Heat Utilization

H. Start-up Time

I. Fuel Processor Start-up and Transient Operation

M. Fuel Processor System Integration and Efficiency

R. Thermal and Water Mgmt

FY 2004 Budget: $400 K

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

Project milestones

Milestone	Date	
Build models for components and systems	12/03	✓
Analyze data taken at ANL's Fuel Cell Test Facility	01/04	✓
Establish efficiency targets for membrane based fuel processors	03/04	✓
Evaluate thermal and water management requirements and subsystem	07/04	
Assess the effect of humidity on high-temperature membrane FC systems	05/04	✓
Evaluate performance of PEFC systems for combined heat and power	08/04	
Analyze FC systems for hybrid vehicles	09/04	

Reviewers' comments

Focus on hydrogen fuel-cell systems

- Focus on hydrogen storage options (working with TIAX)
- Resolve benefits of high temperature membranes with regard to efficiency, performance and BOP (presentations to Tech Team and HTMWG)
- Plan verification with subsystem and component data from contractors (Honeywell/Emprise)

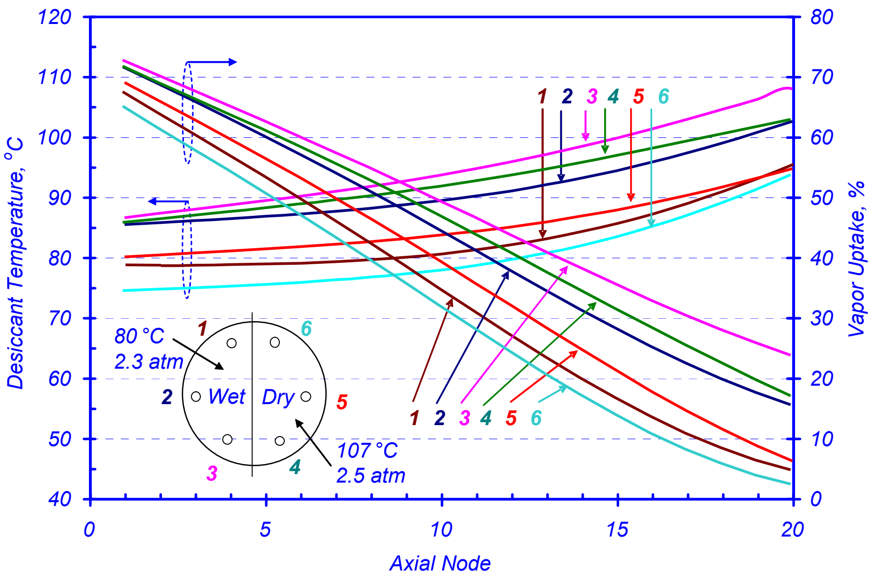
Closer communications with FreedomCAR Fuel Cell and Vehicle Teams

- Member of Fuel Cell Tech Team
- Participating in hybridization study with Joint Team
- Seek OEM validation of model results and proposed targets (presentation on Start-up Energy Consumption)

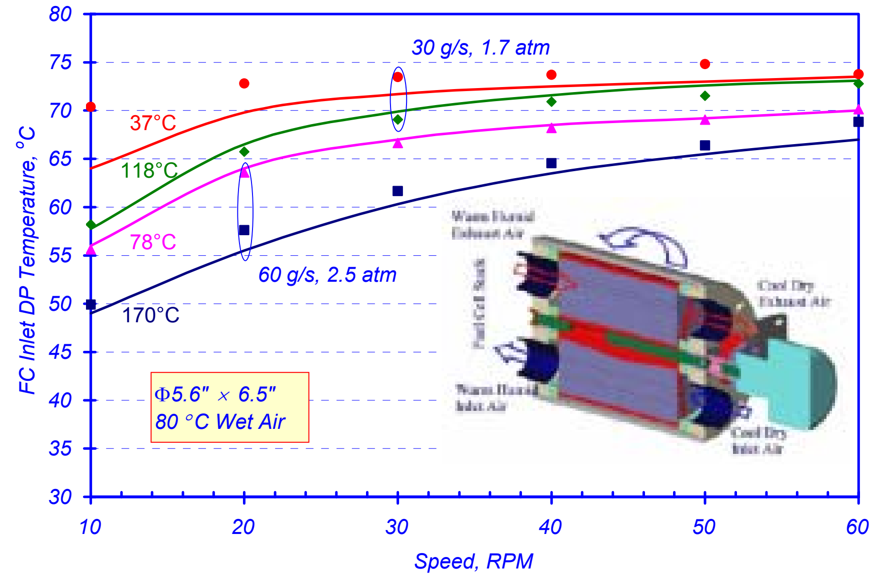
Code development in FY 2004

- Dynamic model of enthalpy wheel humidifier
- Membrane humidifier model
- Dynamic models of catalytic auto-thermal, shift and PrOx reactors

Enthalpy Wheel Model Simulation



Model Validation



Validated models against data taken at ANL's Fuel Cell Test Facility

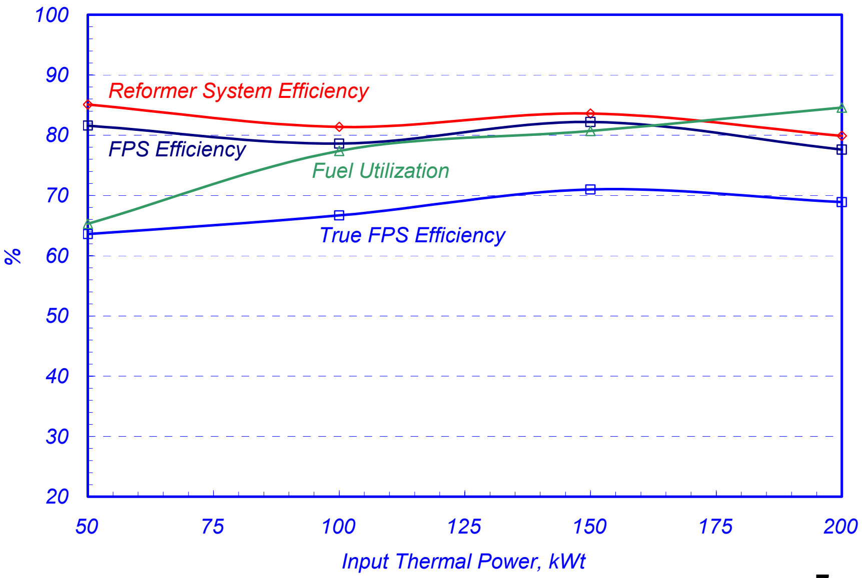
Analyzed test data for two systems from Nuvera

- Series SFAA 1A Fuel Cell System: 10 kWe, gasoline powered fuel cell system
- STAR System: 200 kWt

Major conclusions

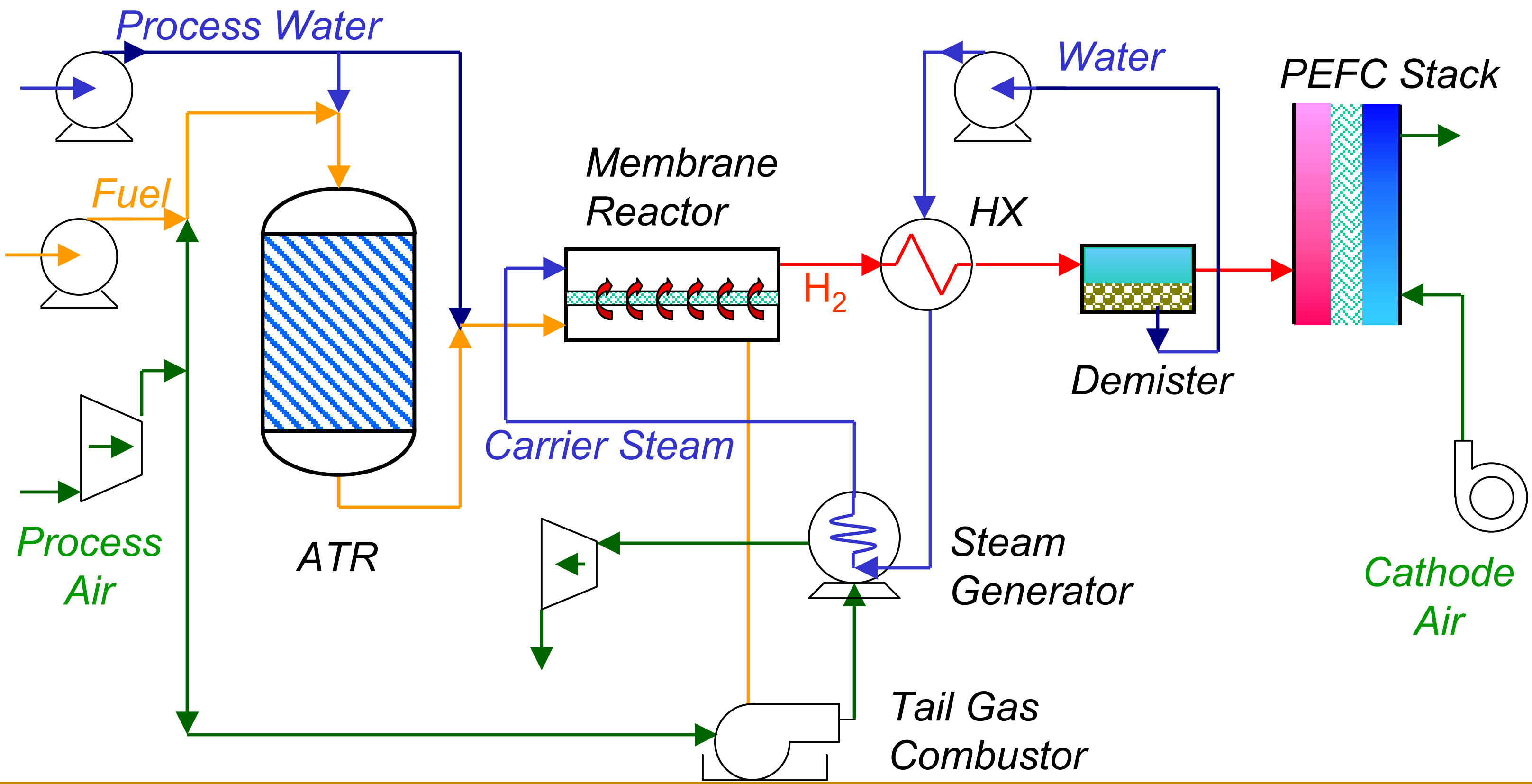
- Possible to characterize FPS performance in terms of S/C, O/C and COx selectivity
- True efficiency, which includes LHV of fuel burned in TGC, is a better measure of FPS performance

STAR Performance



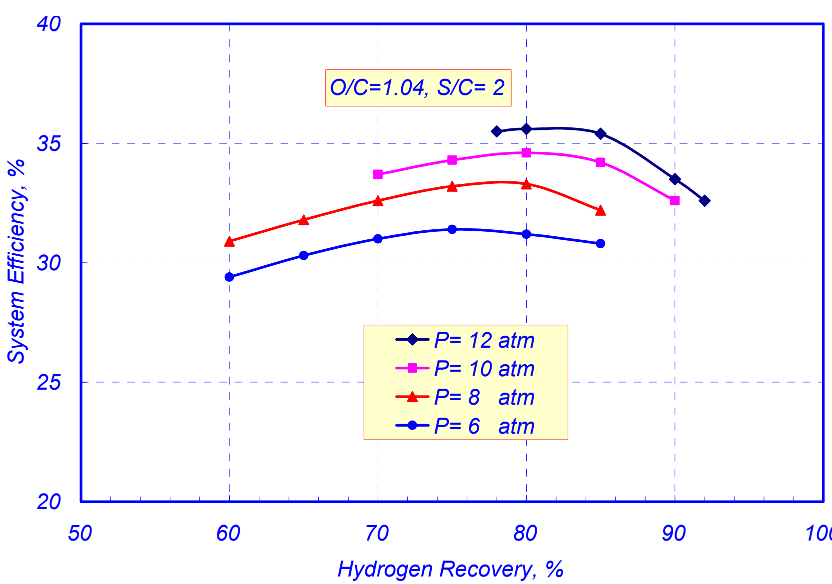
Efficiency of membrane reactor-based fuel processors

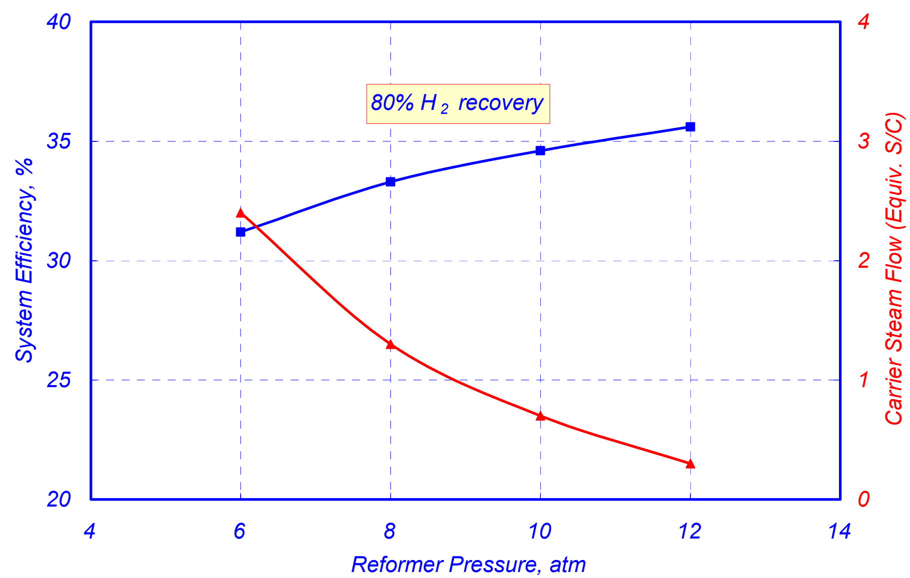
- Why membrane reactors for WGS?
  - Eliminate difficult-to-control PrOx reactors
  - Shrink WGS reactor, simplify lay-out, remove HXs
  - Not having to deal with CO in PEFC stack is a plus



Target efficiency needed for H_2 membrane reactor based FPS can be reduced to 68%

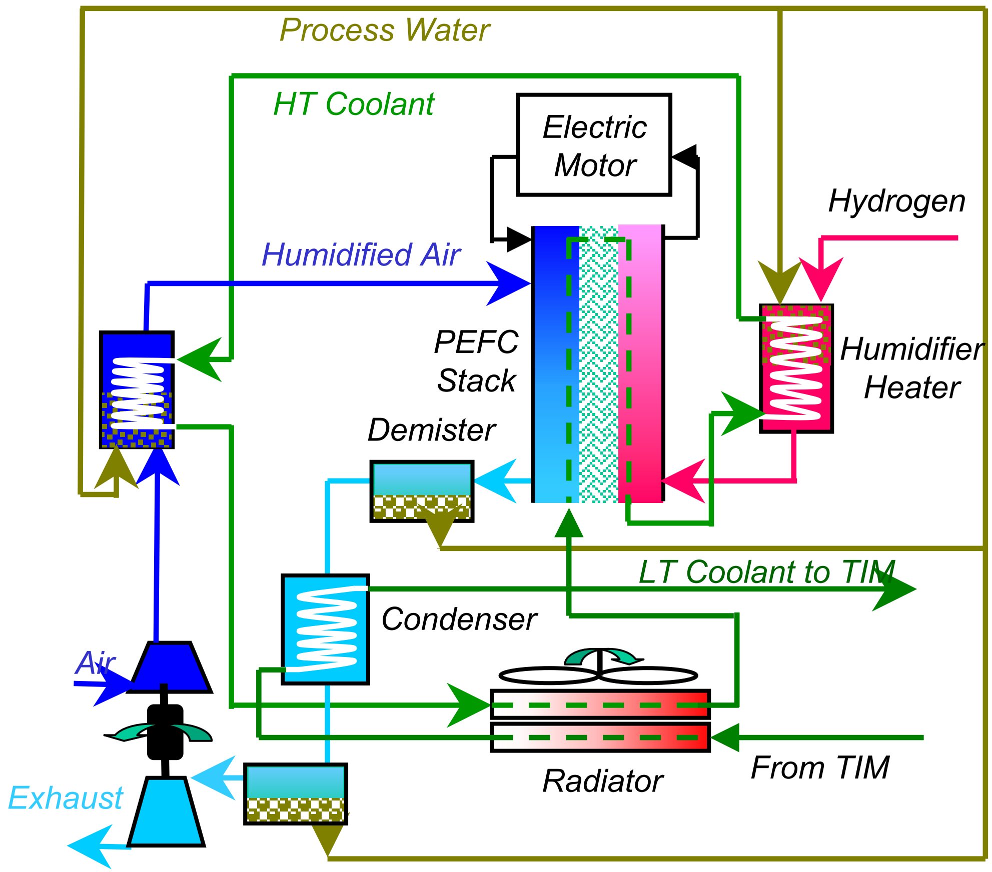
- 100% H_2 recovery not required
- FPS will have to operate at elevated pressure
- Development of new compressor/expander module
- Maintaining efficiency at part load may be a challenge



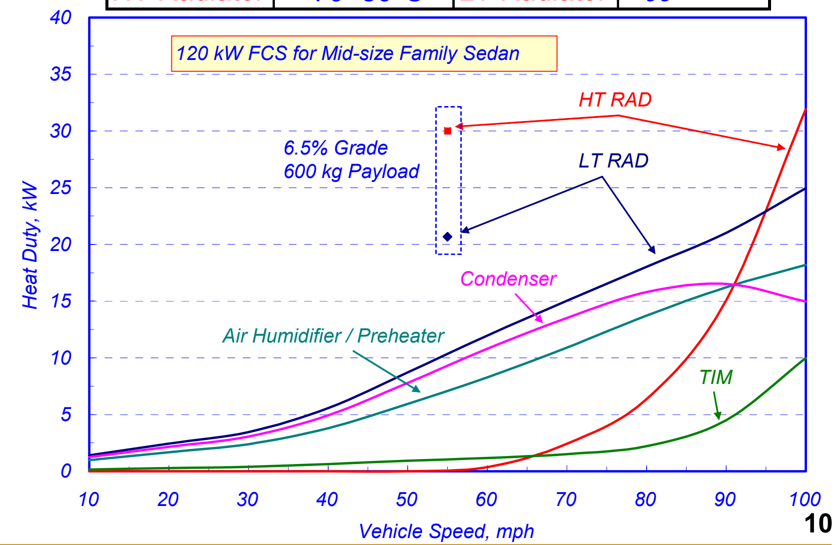


Thermal & Water Management
Pressurized FCS with condenser and two coolant circuits

- Large radiator (30 kg, 13.6 cm depth) and fan (700 W)
- Large heat duty on air pre-heater (20 kW, 90% RH)
- Difficult to maintain stack at 80°C at low loads

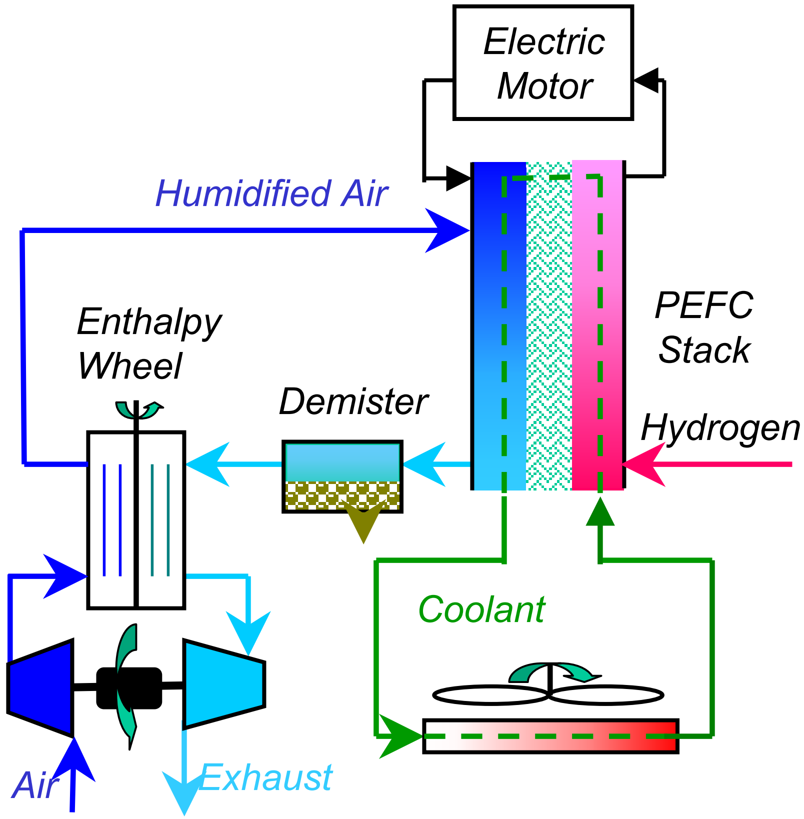


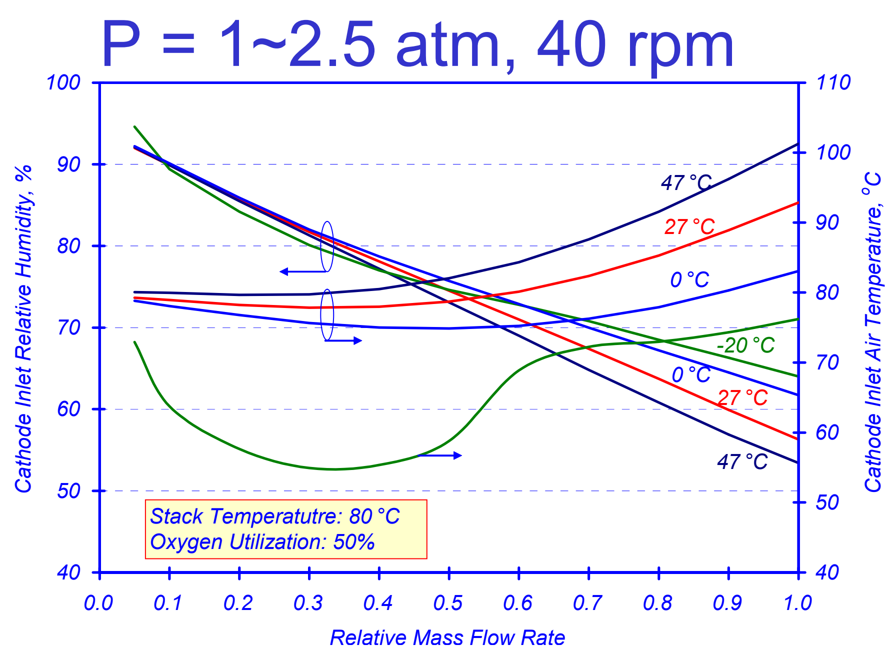
FCS Rated Power	Radiator Depth (cm)		Weight (kg)
	High Temp.	Low Temp.	
120 kW	5.4	4.5	21.9
65 kW	12	1.6	30.0
Front Area	$0.6 \times 0.5\ m^2$	Pitch	1.25 mm
Radiator Fan			
Power	700 W	Head	380 Pa
Coolant Inlet Temperature			
HT Radiator	70~80°C	LT Radiator	55~70°C



Thermal & Water Management
Pressurized FCS with enthalpy wheel humidifier

- 5.6”Φ x 6” enthalpy wheel can supply air at 50-70% RH
- Only HT coolant loop needed
- Can maintain stack at 80°C at all loads





Direct H_2 fuel cell system with high-temperature polymer membrane

Stack issues

- Faster ORR kinetics
- Reduced PGM loading
- Higher power density

BOP issues

- Air management system
- Heat rejection system
- Water recovery system

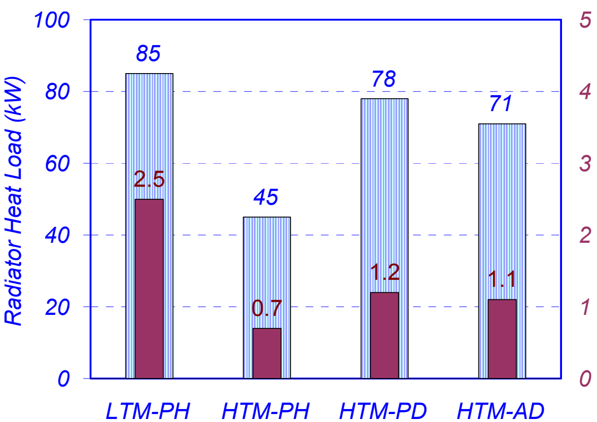
Effect of humidity on system architecture and size

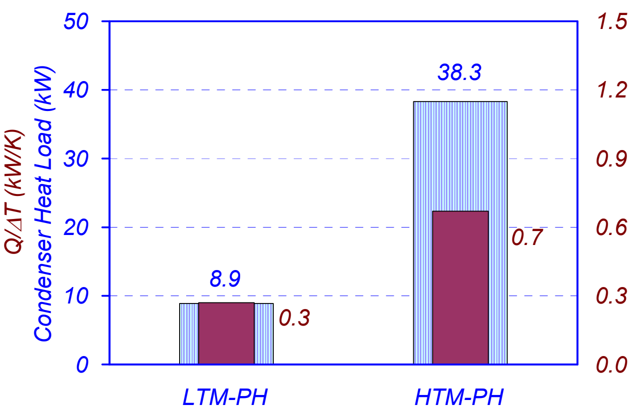
- Analyzed four systems

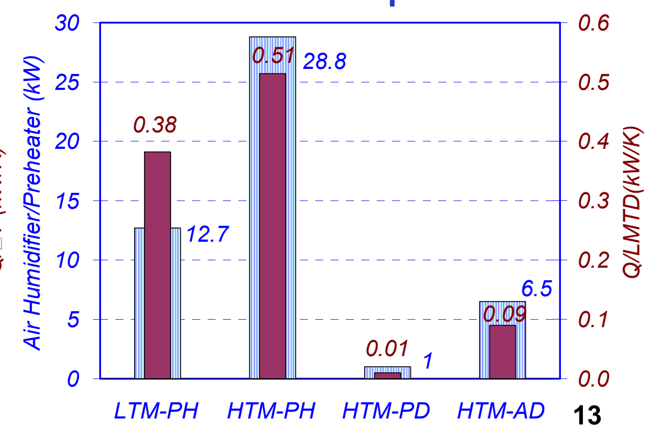
System	Membrane	Air Management	Humidification
LTM-PH	LTM (80^{o}C)	CEM (2.5 atm)	90% RH
HTM-PH	HTM (120^{o}C)	CEM (2.5 atm)	25% RH
HTM-PD	HTM (120^{o}C)	CEM (2.5 atm)	Dry
HTM-AD	HTM (120^{o}C)	Blower	Dry

High temperature membrane system BOP is unattractive if membrane must be humidified

- Why operate dry?
  - Water recovery is difficult at 120°C stack temperature.
  - Stack cannot be maintained at 120°C below 50% of rated power
- Incentive to develop membrane whose ionic conductivity does not depend on moisture
  - Elimination of air and fuel humidifiers, pre-heaters become compact
  - Stack can operate at 120°C at all loads
- HTM option is attractive if FCS is operated at near ambient pressure
  - Replace compressor/expander with blower
  - Stack more compact than in pressurized systems w/o an expander

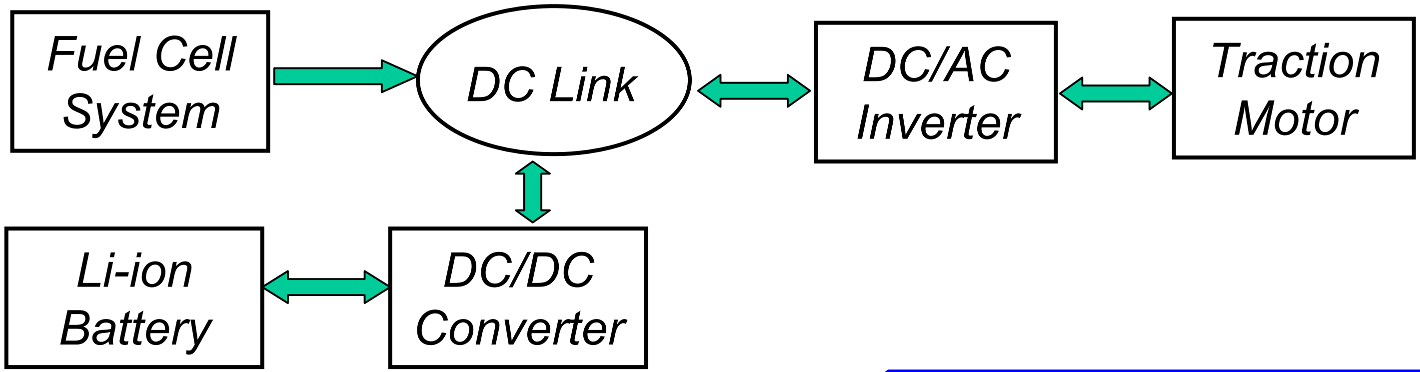






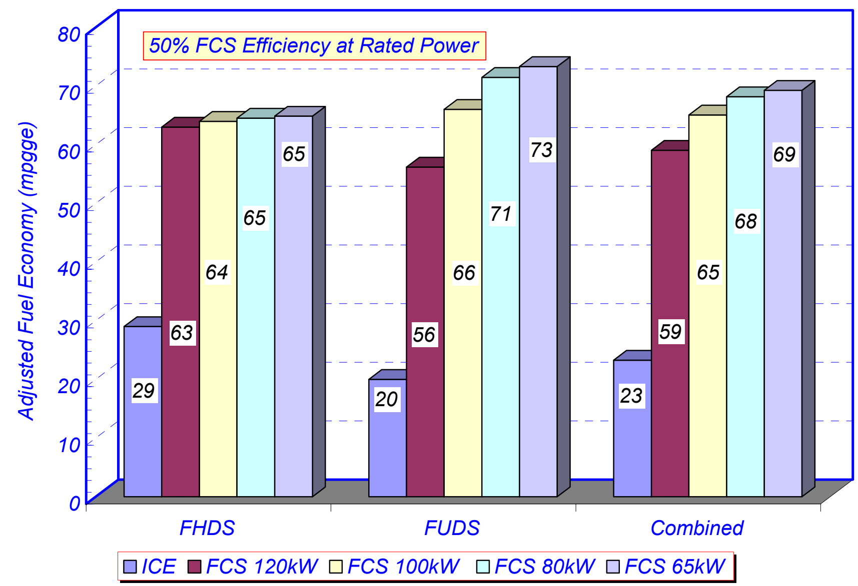
Fuel economy of hybrid fuel cell vehicles

GCtool-PSAT model of load-following fuel cell vehicles



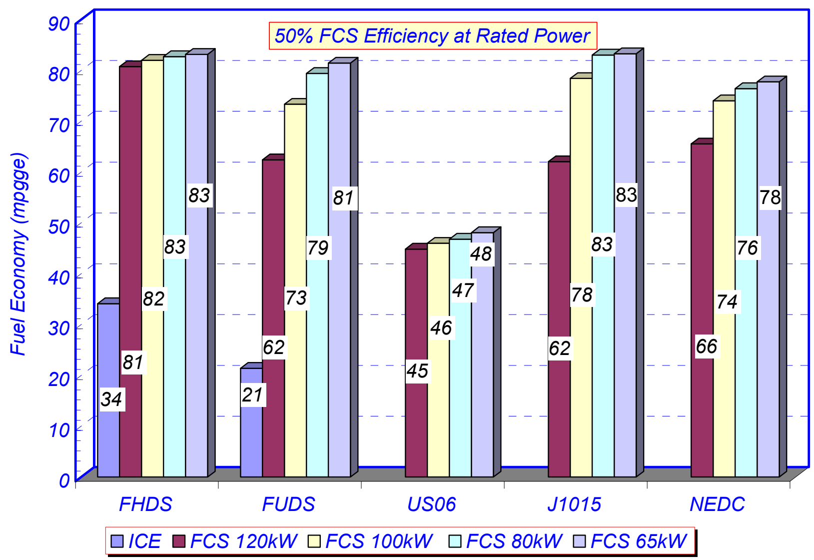
Results for mid-size family sedan

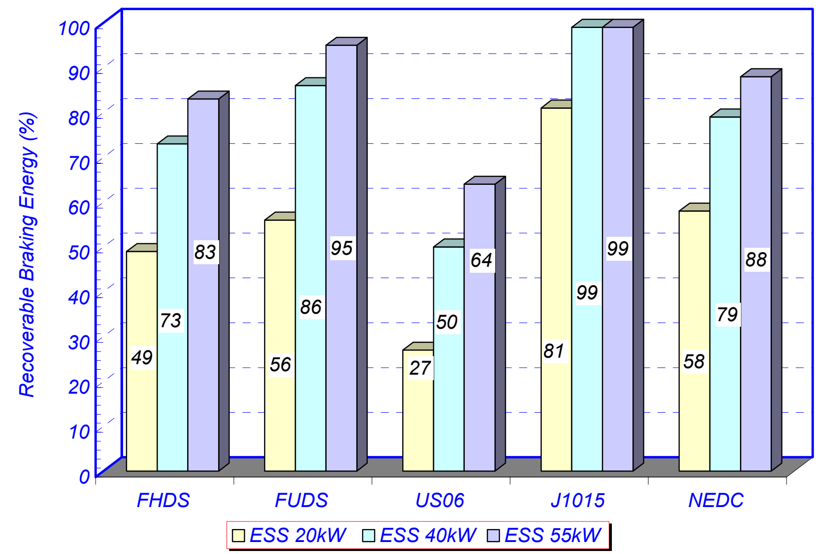
- 65-kW sustained at 100 mph
  120-kW peak for Z-60 in 10s
- FCS/ICE FE multiplier
  3.0 with 55 kW ESS vs. 2.5 with stand-alone FCS



Drive cycles affect improvement in fuel economy with hybridization

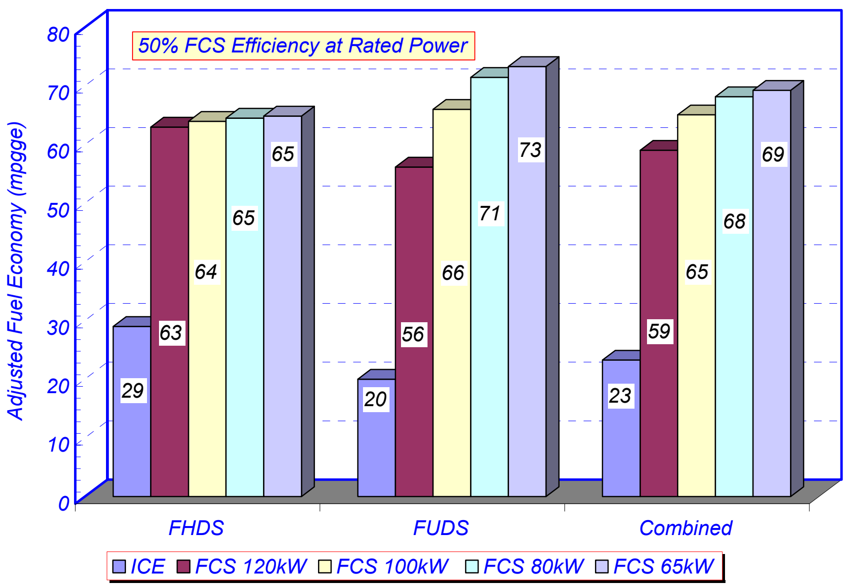
Change in fuel economy		Braking energy/traction energy	
FHDS:	3%	FHDS:	13%
FUDS:	30%	FUDS:	50%
US06:	7%	US06:	34%
J1015:	34%	J1015:	53%
NEDC:	19%	NEDC:	35%

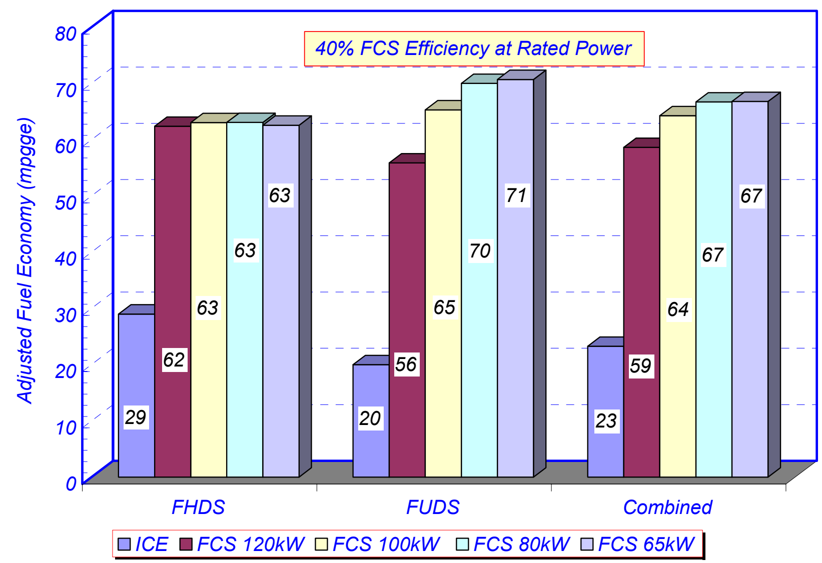




Fuel cell system efficiency at rated power has only a small effect on overall fuel economy

- FCS-1: 50% efficiency (680 mV, 780 W/kg) at rated power
- FCS-2: 40% efficiency (560 mV, 1150 W/kg) at rated power
- Less than 2 mpgge difference in FE on combined cycles
- Differences in fuel economy are even smaller with larger fuel cell systems

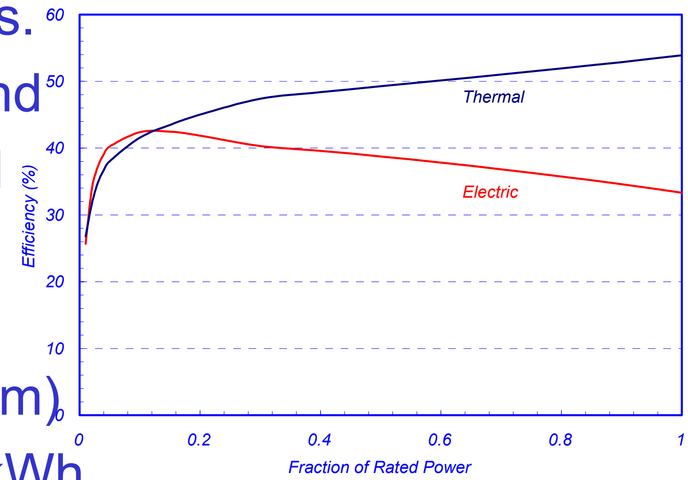




Fuel cell systems for combined heat and power

Mismatch between thermal and electric demands.

- Summer: High electric but low thermal demand
- Winter: Low electric but high thermal demand



Why heat pump with FC-CHP makes sense?

- Natural gas (NG) furnace, ¢2/kWh ($0.60/therm)
- Heat pump (HP) with central power (CP), ¢8/kWh
- Heat pump coupled with fuel cell system (FCS)

Ambient Temp		**Thermal Efficiency**			**Relative Energy Cost**		
	HP	NG	CP+HP	FCS+HP	NG	CP+HP	FCS+HP
°C	COP	%	%	%	$	$	$
10	3.6	80	119	171	100	86	47
0	3.0	80	100	152	**100**	**103**	53
-10	2.5	**80**	**81**	133	100	126	60
-20	2.2	80	71	123	100	145	65

Used DOE2.1-120 and GCtool for a 1200 ft^2 Chicago single family home

Baseline: FCS + NG Furnace

Low utilization: 1.6 kWe peak power

Peak FC thermal eff: 46.9%

Waste heat is insufficient even to meet DHW demand

SH provided by NG furnace

Overall energy efficiency ~80%

Alternative: FCS + HP

High utilization: 5.2 kW peak power

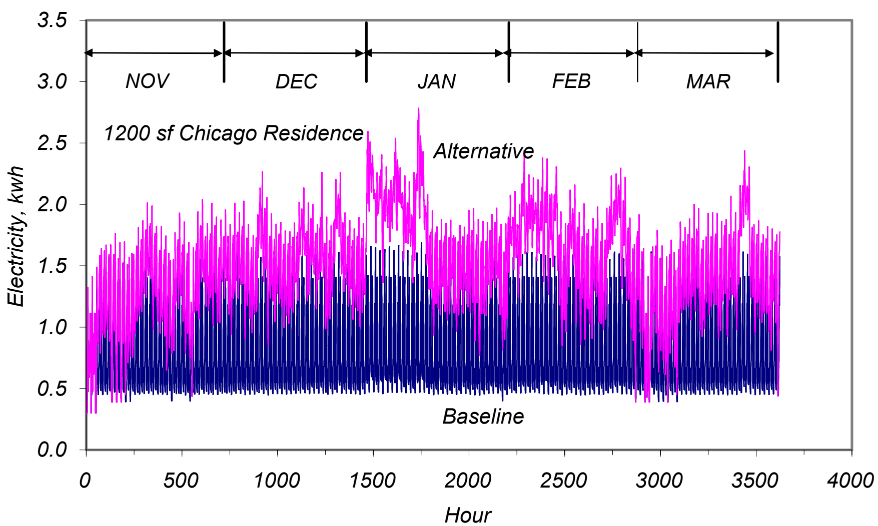
Peak FC thermal eff: 53.3%

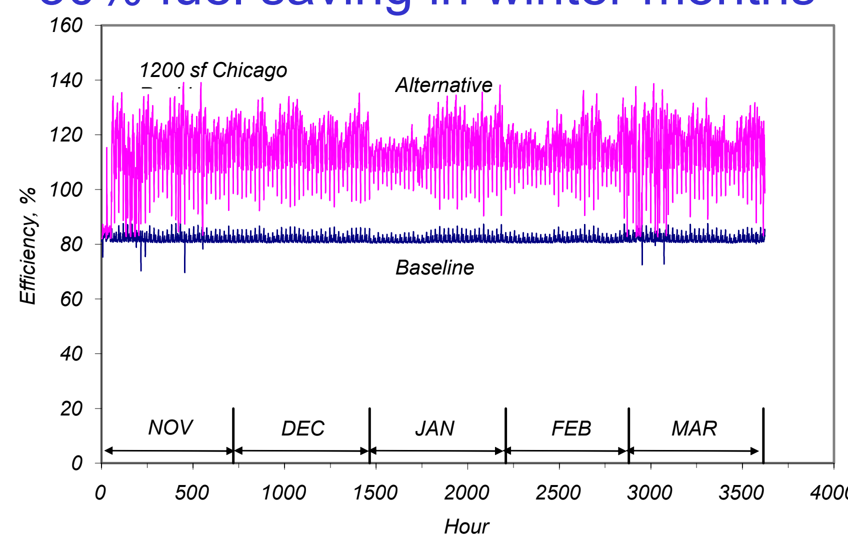
Waste heat used for DHW plus 37% of space heating (SH)

63% of SH provided by HP

Overall energy efficiency ~115%

30% fuel saving in winter months





Technology transfer and collaborations

Licensed GCtool to many domestic and international private enterprises, universities, national labs, and government affiliated organizations.

Collaborations and Interactions

- Enthalpy wheel humidifier: Emprise and Honeywell
- Thermal and water management: Honeywell
- Hydrogen storage: TIAX
- Hybrid vehicles: ANL-PSAT, Joint Battery, Fuel Cell and SEAT Tech Team
- High Temperature Membrane FC Systems: FreedomCAR Fuel Cell Tech Team and HTMWG
- Validation: ANL Fuel Cell Test Facility, Nuvera

Future work

- Fuel Cell – Battery Hybridization study with Joint Tech Team
- Initiate joint work with UTRC on ambient-pressure fuel cell systems
- Participate in validation effort
- Initiate study on cold start of fuel cell systems
- Fuel cell systems for combined heat and power
- Support fuel processor engineering projects at ANL
- Continue to support DOE/FreedomCAR development efforts