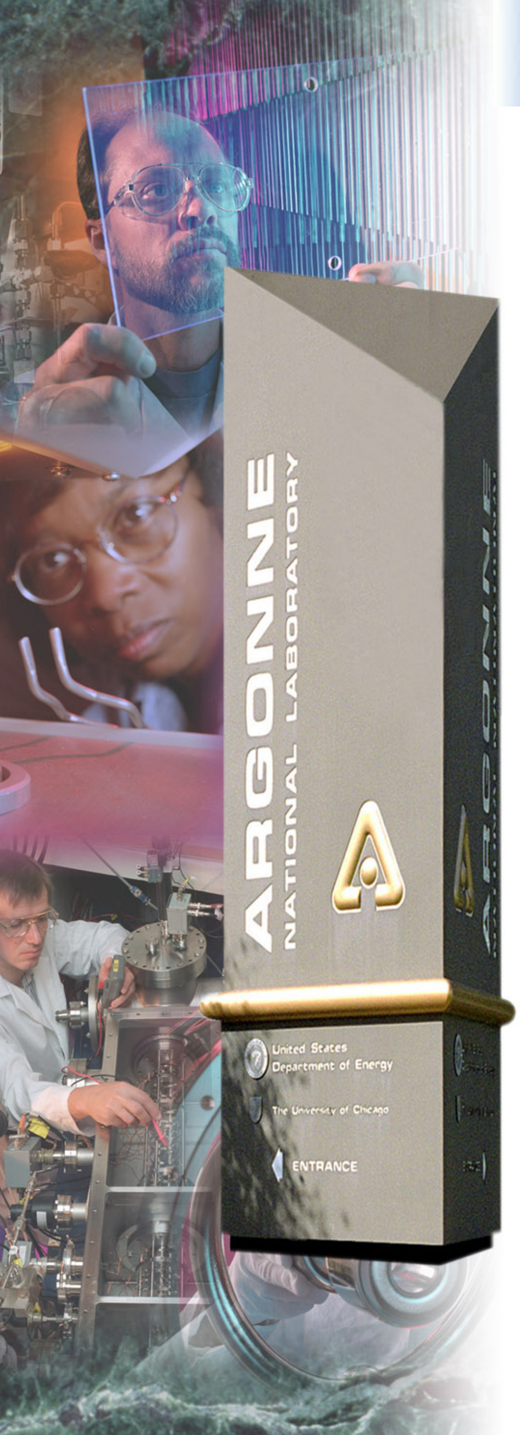

Fuel Cell Systems Analysis

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This presentation does not contain any proprietary or confidential information.

Project ID: FC23

THE UNIVERSITY OF CHICAGO

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Overview

Timeline

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

Barriers

A. Durability
D. Thermal, Air & Water Management
E. Compressors/Expanders
F. Fuel Cell Power System Integration
J. Startup Time/Transient Integration

Budget

- Total funding: $450K
  DOE share: 100%
- FY05 funding: $400K
- FY06 funding: $450K

Partners

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

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 and evaluating R&D goals and research directions
- Establish metrics for gauging progress of R&D projects

Approach

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

- 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

FY2006 Technical Accomplishments

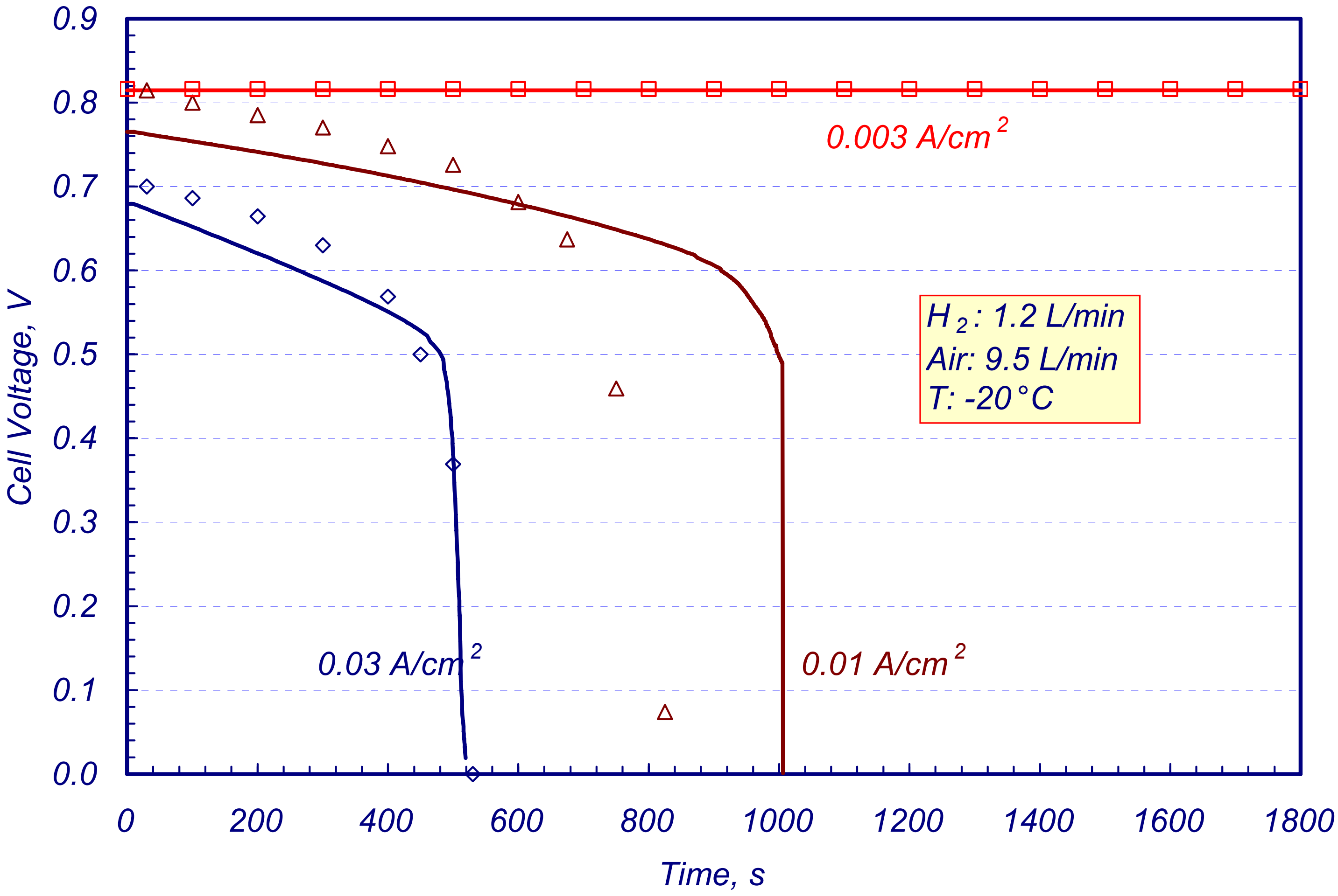
- Self-start from subfreezing temperatures
- Effect of fuel impurities and air contaminants
- Update of FCS attributes
  - Stack performance
  - Anode subsystem
  - Heat rejection
  - Water management
- Validation and Calibration
  - Stack data from ANL Fuel Cell Test Facility
  - Enthalpy wheel data from Honeywell/Emprise
  - Membrane humidifier data from Honeywell/Perma Pure
  - Radiator model calibrated against Honeywell results
  - Vendors’ data on ejectors, and vane & centrifugal pumps
  - Cold start data from literature

Startup from Subfreezing Temperatures

- Fuel cells for transportation must be able to start unassisted below -20°C and produce 50% of rated power within 30 s (DOE 2010 target).
- At subfreezing temperatures, the water produced from the electrochemical reaction coats the cathode catalyst with ice that reduces ECSA and may terminate the reaction.
- Ice formation may be prevented by operating at low currents and using dry feeds at high flow rates but the startup times are unacceptably long.
- Fast start from subfreezing temperatures will invariably involve formation of ice. The challenge is to manage the build-up of ice.

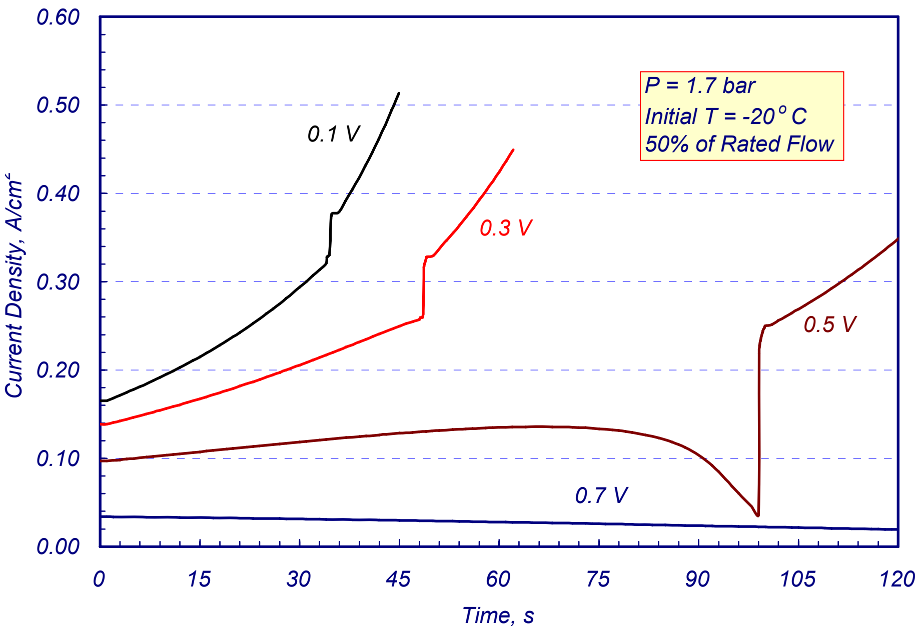
Model Validation: Isothermal Cell at -20°C

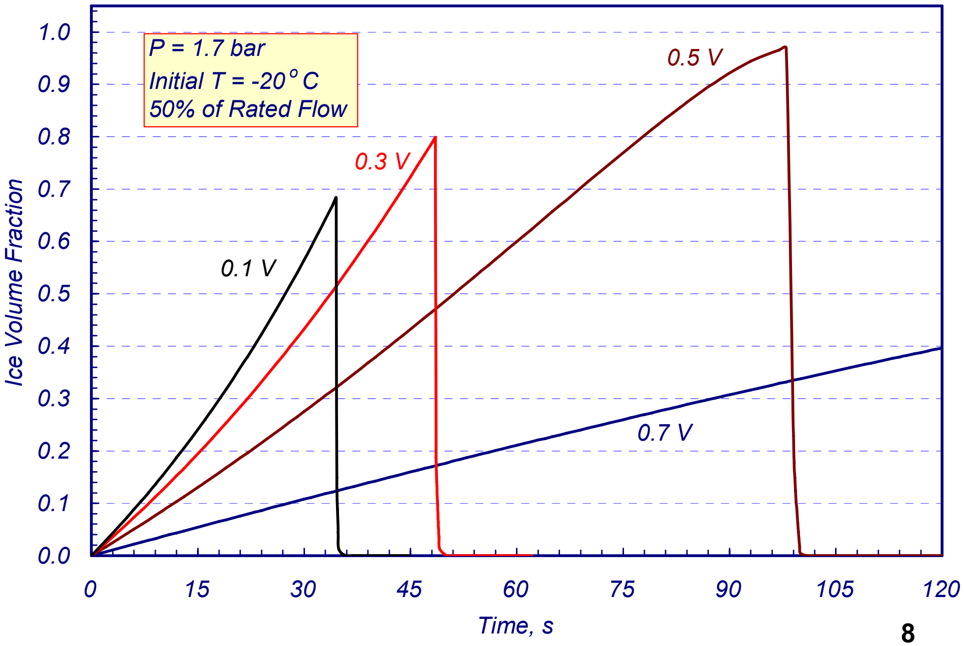
- Data reported by Hishinuma, Chikahisa, Kagami and Ogawa in JSME International Journal, Series B, Vol. 47, No. 2, 2004.
- Single 104-cm^2 cell, 30-μm Gore membrane, graphite plate, dry gases



Self-Start of PEFC Stacks: Critical Voltage

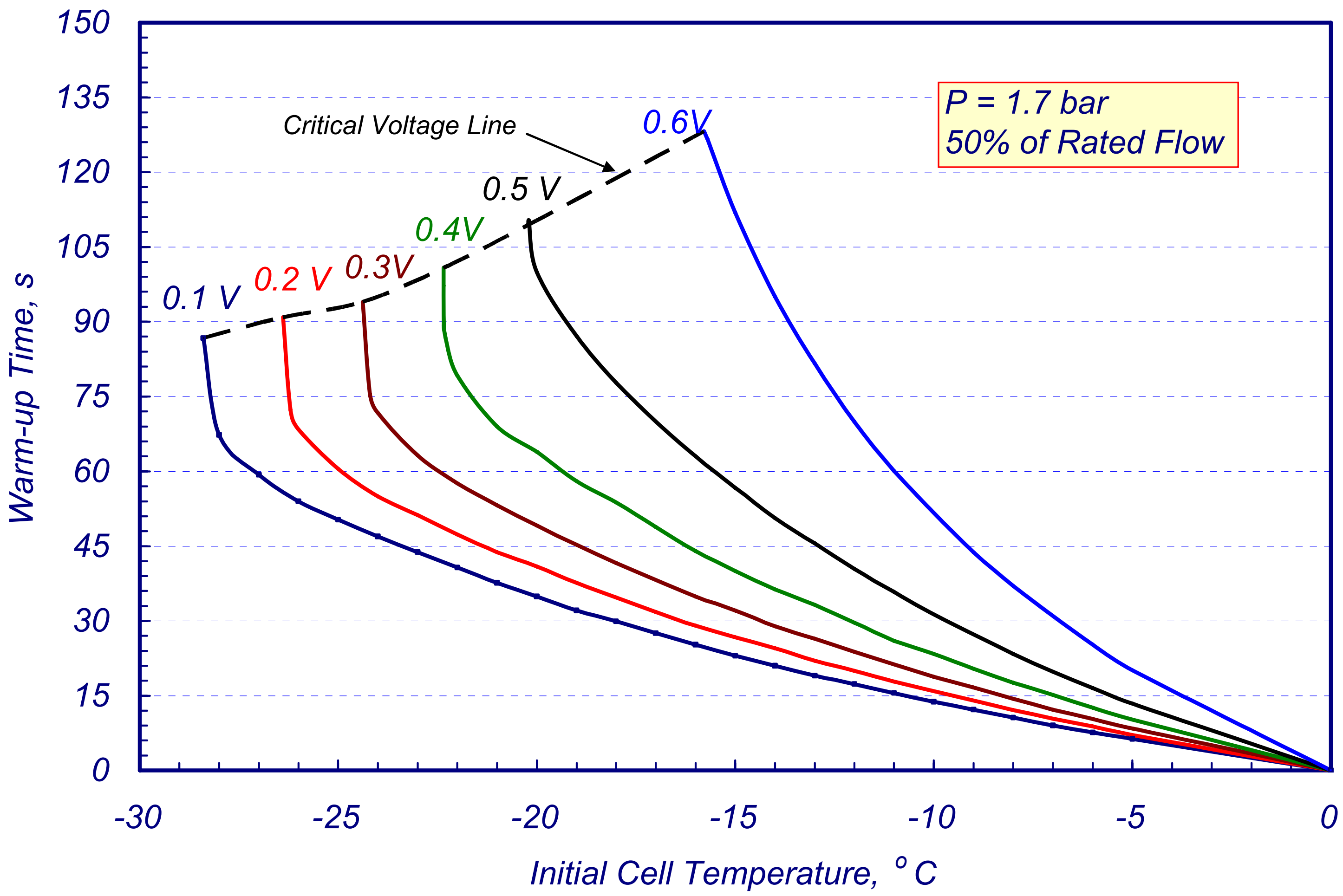
- Stack with graphite bipolar plates, 820 W_e/kg specific power
- Stack cannot be started without assistance above a critical cell voltage which is a function of temperature and thermal inertia.
- Ice is always formed during startup from subfreezing temperatures. Self start is possible only if the stack can be heated to 0°C before ice completely covers the cathode catalyst and shuts down the electrochemical reaction.





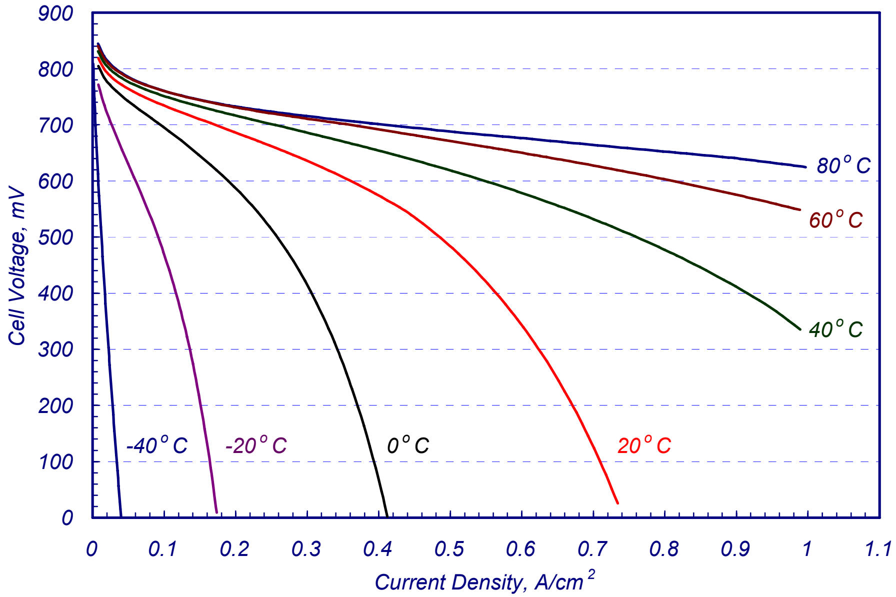
Time to Warm-up Stack to 0^oC

- Critical voltage for self start is a function of initial temperature
- To minimize the time spent near short circuit, follow the critical voltage line to raise cell voltage as the stack warms up.



Can PEFC stacks be self-started below subfreezing temperatures?

- Fuel cells can be started, without assistance, from below -20°C by managing the build-up of ice.
- There is a critical cell voltage (function of P, T, specific power) above which a PEFC stack cannot be self-started.
- Preheating feed streams has only a small effect on ability to startup from subfreezing temperatures.
- Startup of ambient pressure stacks is easier but not much faster.
- Startup is more difficult if ice is present initially.



Behavior of N_2 in PEM Fuel Cell Stack

How much N_2 crosses over from cathode to anode streams?

- Depends on power level, N_2 in feed, purge, membrane thickness.
- 0.008-0.024% at rated power with optimal purge.

How does N_2 build-up in anode gas channel depend on purge rate?

- With pure H_2, 50-70% at low purge, 5-20% at 2% purge

What is the effect of N_2 build-up on cell voltage?

- With pure H_2, 10-18 mV lower at 25-60% N_2, <5 mV at 2-25% N_2

What are the impacts of purge and N_2 build-up on efficiency?

- Both decrease efficiency but purge also limits N_2 build-up.

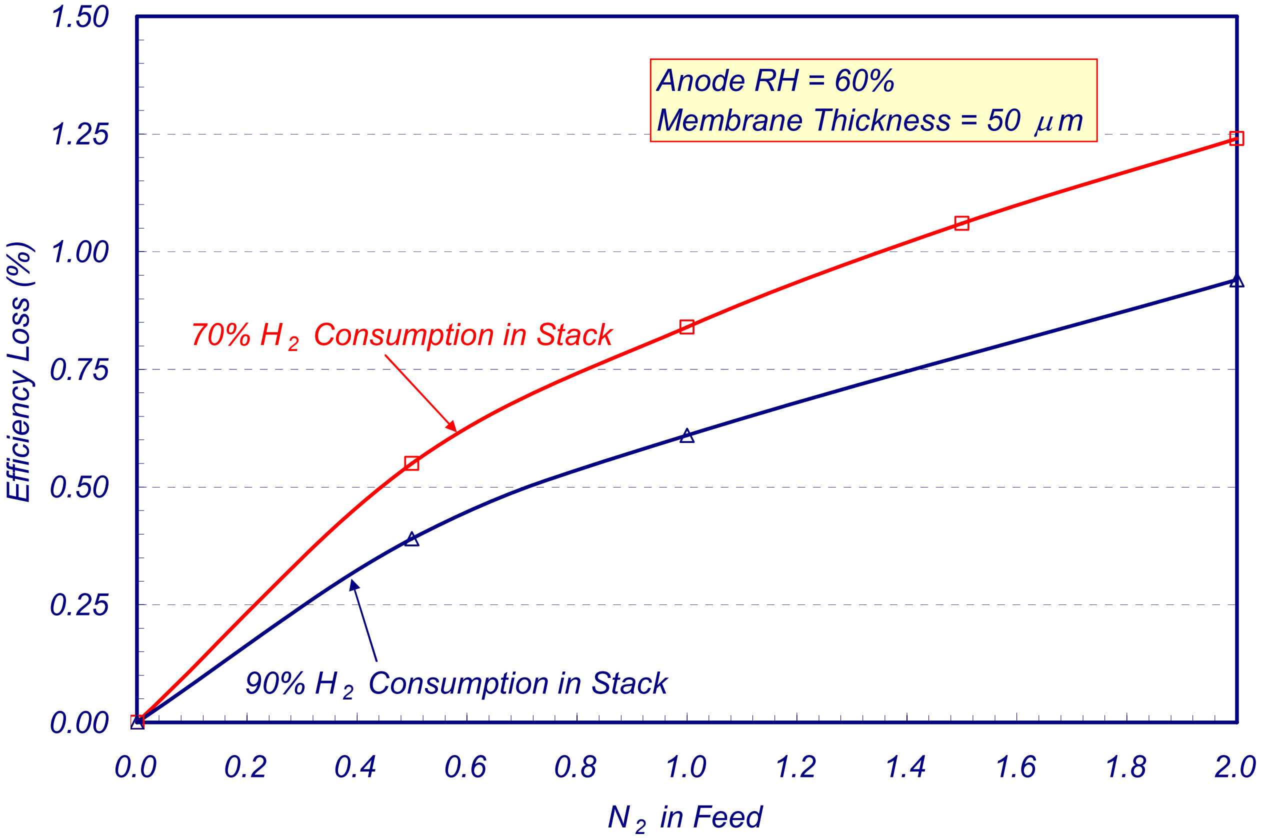
What are acceptable levels of N_2 impurity in feed?

- For 25-µm membrane, 70% H_2 consumption per pass

Target Efficiency Loss (%)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Allowable N_2 in Feed (%)	0.08	0.17	0.27	0.38	0.50	0.63	0.79	0.98	1.20	1.47

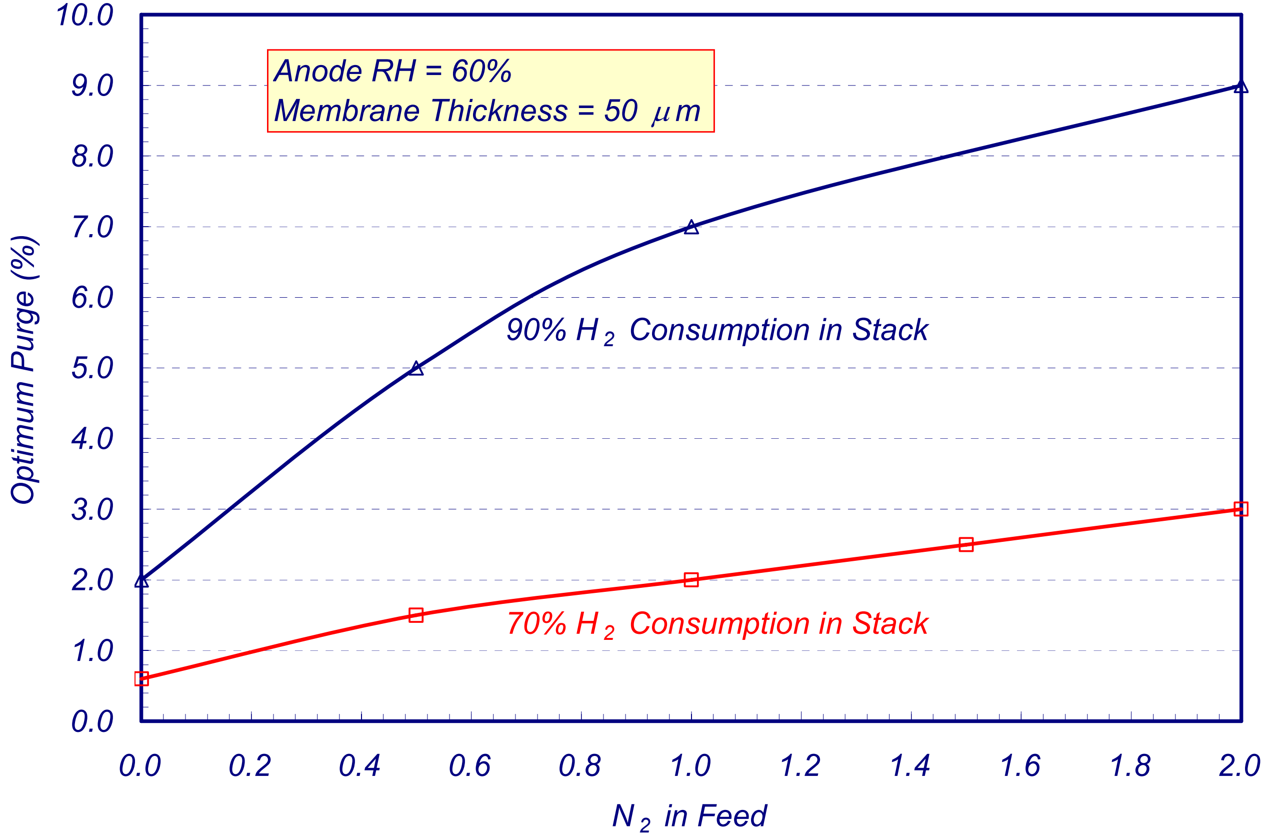
Effect of H_2 Consumption on Acceptable N_2 Impurity Levels

- Tighter specifications for 70% H_2 consumption in stack than for 90% H_2 consumption in stack
- At 70% H_2 consumption per pass, 1.3% inerts in feed may be acceptable for 1 percentage-point loss in efficiency



Effect of H_2 Consumption on Optimum Purge

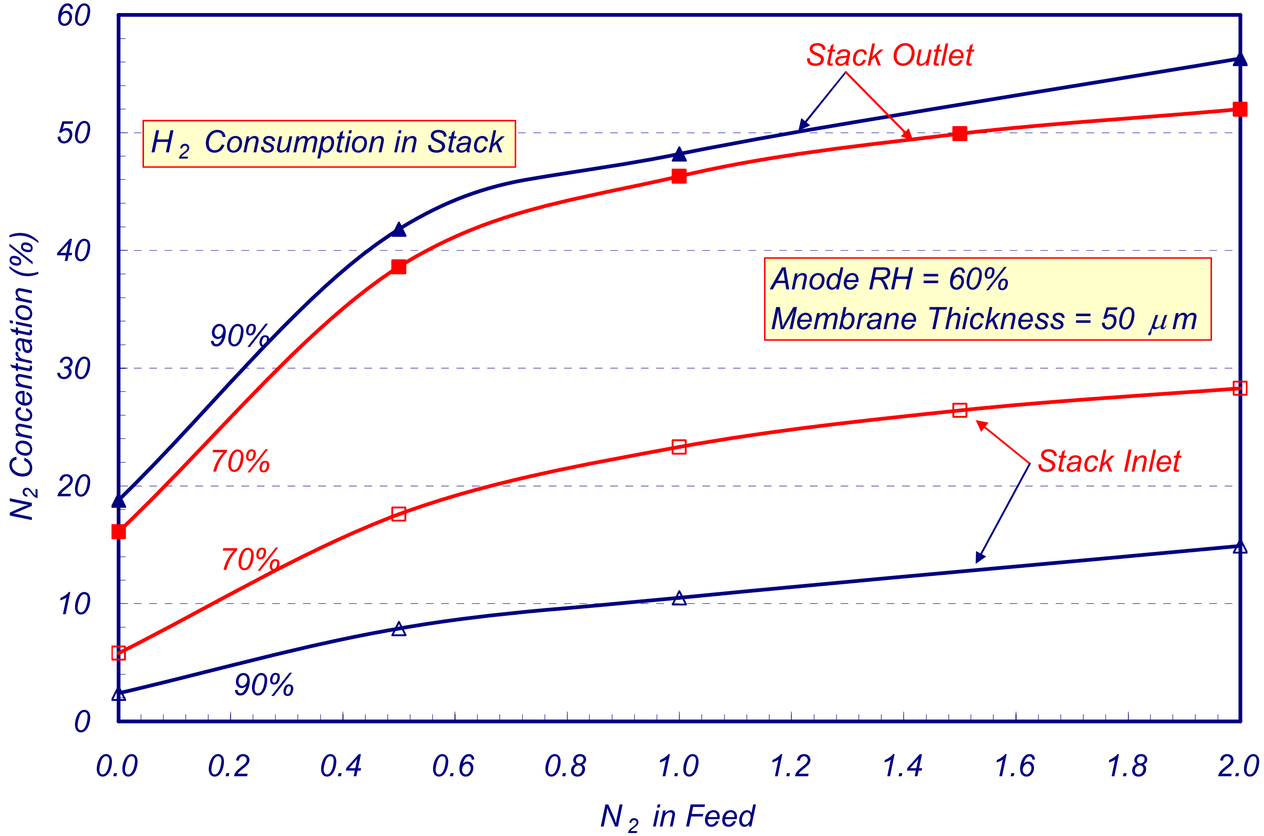
- For given N_2 impurity in feed, the smaller the H_2 consumption per pass the lower the optimum purge.
- Optimum purge : 0.6-2% with pure feed, ~9% with 2% N_2 in feed



*C. Mittelsteadt and M. Umbrell, "Gas Permeability in Perfluorinated Sulfonic Acid Polymer Membranes," 207th Electrochemical Society Meeting, Toronto, Canada, May 15-20, 2005.

Effect of H_2 Consumption on N_2 Buildup

- Under optimum operating conditions, N_2 concentrations at stack outlet are similar at 1.1 and 1.4 stoichs.
- Even with pure feed, N_2 concentration can reach 2-6% at stack inlet and 16-18% at stack exit.
- N_2 concentration at stack exit can exceed 50% with >1.2% N_2 in feed.

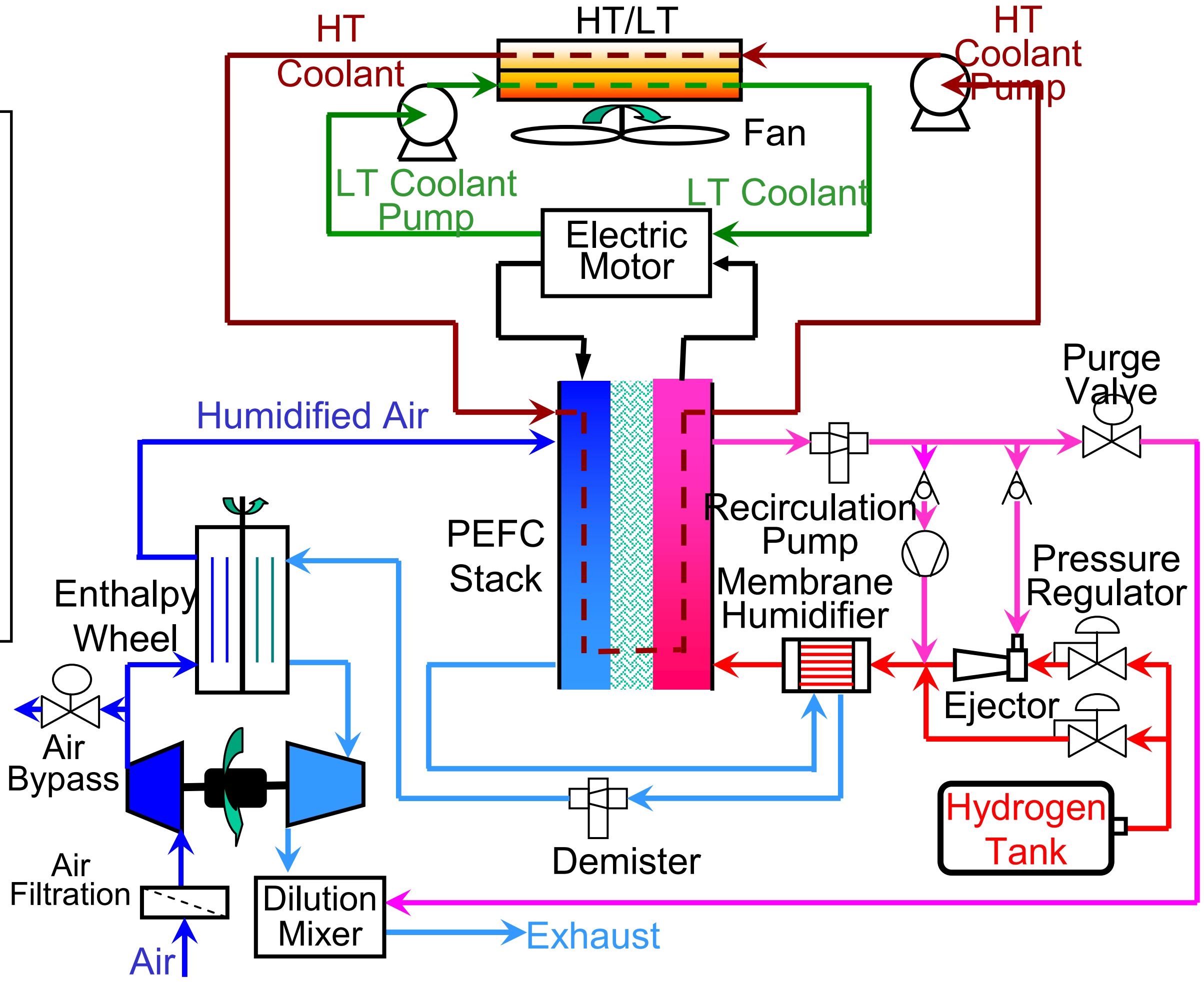


Automotive Hydrogen Fuel Cell System

- Update FCS performance by incorporating recent results on catalyst loading, crossover of gases, heat rejection and water management.

Anode Gas Systems Considered

- **Ejector bank**
- **Centrifugal pump**
- **Vane recirculation pump**
- **Compound ejector-recirculation pump**



Stack Performance

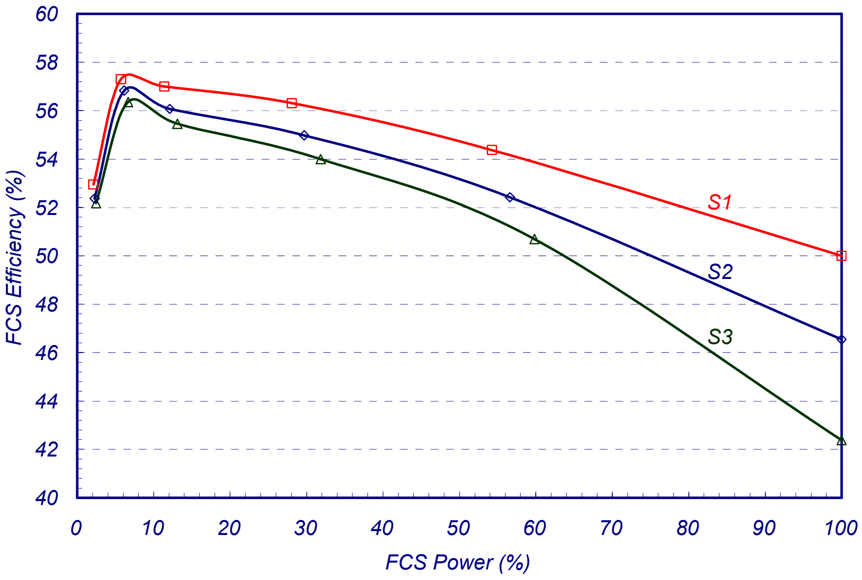
- 2.5 atm at rated power
- 50% O_2 utilization, 70% H_2 consumption per pass
- Cell voltage at rated power: 0.7, 0.65 or 0.6 V
- 50-mm Nafion membrane at 80^{o}C
- Pt loading: 0.50/0.25 mg/cm^2 Pt loading on C/A
- GDL: 275-mm woven carbon cloth
- 2-mm expanded graphite plates, each with cooling channels, 9.6 cpi

- S1 does not meet DOE's 2005 targets of 1500 W/L, 1500 W/kg
- Stack efficiency of S2 & S3 < target of 55% at rated power
- S1 & S2 meet 2005 PGM target of 1 g/kW

		S1	S2	S3
Cell voltage at rated power		0.70 V	0.65 V	0.60 V
Stack power	kW	89.7	90.6	91.5
Active membrane area	m^2	19.6	13.6	10.9
Pt loading	g/kW	1.64	1.12	0.90
Power density	mW/cm^2	458	666	839
Stack specific power	W/kg	1241	1726	2080
Stack power density	W/L	1260	1860	2358
N_2 crossover	%	0.017	0.012	0.009
H_2 crossover	%	0.302	0.202	0.152
O_2 crossover	%	0.028	0.017	0.011
Purge fraction	%	1.0	1.0	1.0
H_2 utilization	%	99.2	99.3	99.4
Stack efficiency	%	55.5	51.7	47.6

System Efficiency

- S2 & S3 do not meet the 50% efficiency target at rated power
- CEMM & radiator fan are main sources of parasitic power
- Systems do not meet 60% efficiency target at 25% rated power
- At low loads, H_2 utilization is 95% (S1) - 97.5% (S3)



Air Management System

- Compressor-expander module
- Liquid-cooled motor
- Efficiencies at rated power: 78% (C), 82% (E), 92% (M), 92% (M/C)
- Turn-down: 20
- 5 psi pressure drop at rated power

		S1	S2	S3
Cell voltage at rated power		0.70 V	0.65 V	0.60 V
PEFC Stack	kWe	89.7	90.6	91.5
CEM motor	kWe	6.1	6.6	7.3
Enthalpy wheel motor	We	30	30	30
Radiator fan	kWe	2.7	2.7	2.7
Coolant pump	kWe	0.8	1.0	1.1
H_2 recirculation pump	We	252	271	269
FCS efficiency	%	49.5	45.7	41.7

FCS Specific Power and Power Density

- S1, S2 & S3 meet 2005 specific power target of 500 W/kg and power density target of 500 W/L
- LTR and A/C condenser weight & volume not included but affect weight, volume & parasitic power
- Allowing stack to operate at >80^{o}C on 6.5% grade (with tow) will help reduce the frontal area of the main radiator

	S1		S2		S3	
	W (kg)	V (L)	W (kg)	V (L)	W (kg)	V (L)
PEFC stack	72	71	52	49	44	39
Air management system	18	15	19	16	21	18
Fuel management system	6	7	6	7	6	8
Heat rejection system	12	35	14	41	17	47
Water management system	9	8	10	9	11	10
Miscellaneous	12	14	10	12	10	12
Total	128	150	112	135	109	133
FCS specific power (We/kg)	623		715		736	
FCS power density (We/L)	533		594		600	

Advanced Radiator Configurations

Fan power for fixed radiator frontal area (70 cm x 54 cm) & depth (3.2 cm)

- Coolant in at 75°C, out at 70°C, 3 kg/s; ambient air at 40°C
- Specific heat transfer (*Q/ṁ*)
  Microchannel > advanced automotive ≈ Al foam > standard automotive
- Specific pressure drop (*ΔP/ṁ*)
  Standard automotive < microchannel < advanced automotive < Al foam
- Fan power (kW)
  Microchannel < advanced automotive < standard automotive < Al foam

Parameters	Units	Standard Automotive	Advanced Automotive	Microchannel	Al Foam
Fin Type		Louver	Louver	Plain	Foam
Fin Pitch	mm	1.7	1.0	0.6	40 PPI
Fin Density	1/inch	15	25	40	$\varepsilon = 0.92$
Fin Thickness	μm	75	50	50	
Heat Transfer	**kW**	**65**	**65**	**65**	**65**
Air Outlet Temperature	°C	51.4	59.5	60.3	59.3
Air Flow Rate	kg/s	5.4	3.2	3.0	3.2
Air Pressure Drop	Pa	213	230	138	919
Fan Pumping Power	**kW**	**1.04**	**0.65**	**0.38**	**2.65**

Proposed Future Work

- Continue to support DOE/FreedomCAR development efforts at system, component and phenomenological levels
- Participate in validation effort
- Validate freeze-start model with ANL data
- Continue collaboration with Honeywell on air, thermal and water management systems
- Expand work on impurity effects
- Incorporate ANL's data on Pt dissolution to project EOL stack performance (durability issues)
- Continue work on anode gas system
- Examine additional loss mechanisms: high stoichiometry at part load, purge, shutdown, etc

BACKUP MATERIAL

Publications and Presentations

Journal Publications

S. Ahmed, R. Ahluwalia, S. H. D. Lee, and S. Lottes, “A Gasoline Fuel Processor Designed to Study Quick-Start Performance,” *Journal of Power Sources*, 154, 214-222, 2006.

R. K. Ahluwalia, Q. Zhang, D. J. Chmielewski, K. C. Lauzze, and M. A. Inbody, “Performance of CO Preferential Oxidation Reactor with Noble-Metal Catalyst Coated on Ceramic Monolith for On-Board Fuel Processing Applications,” *Catalysis Today*, 99, 271-283, 2005.

R. K. Ahluwalia, X. Wang, A. Rousseau, and R. Kumar, “Fuel Economy of Hybrid Fuel Cell Vehicles,” *Journal of Power Sources*, 152, 233-244, 2005.

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

Conferences

R. K. Ahluwalia and X. Wang, “Rapid Self-Start of Fuel Cells from Subfreezing Temperatures,” *2005 Fuel Cell Seminar,* Palm Springs, CA, November 14-18, 2005.

Presentations

R. K. Ahluwalia and X. Wang, “Startup of Fuel Cells from Subfreezing Temperatures,” *IEA PEFC Annex XVII Meeting*, Loughborough, U.K., November 30 – December 1, 2005

Reviewers' Comments

Generally favorable reviews with recommendations to

- Validate models
- Calibrate models
- Work more closely with OEMs and system integrators
- Keep engaged in thermal and water management
- Maintain close communications with fuel cell tech team

FY06 work scope consistent with above recommendations

- Calibrated stack model with experimental data
- Compared stack assumptions with practice
- Validated water management models with data
- Compared thermal management results with Honeywell modeling results
- Results discussed with OEMs and system integrators
- Member of fuel cell tech team

Modeling Approach for N_2 Effects Study

For purpose of comparison, define reference systems with 50% efficiency at rated power.

- Pure H_2 feed
- 90% (stoich=1.1) or 70% (stoich=1.4) H_2 consumed in stack in single pass
- 60% RH of anode and cathode streams at stack inlet
- MEA parameters: 0.4 mg/cm^2 Pt on cathode, 0.2 mg/cm^2 Pt on anode, 50-μm or 25-μm membrane, 200-μm GDL
- 100% of H_2 in spent anode gas recycled

Use the reference PEMFC stack to analyze the effects of

- N_2 in feed
- N_2 crossover from cathode to anode

Fuel Cell System Parameters

PEFC Stack

- 2.5 atm at rated power
- 50% O_2 utilization
- 70% H_2 consumption per pass
- Cell voltage at rated power: 0.7, 0.65 or 0.6 V
- 50-µm Nafion membrane at 80°C
- Pt loading: 0.50/0.25 mg/cm^2 on cathode/anode
- GDL: 275-µm woven carbon cloth
- 2-mm expanded graphite bipolar plates, each with cooling channels
- 9.6 cells/inch

Fuel Management System

- Hybrid ejector-recirculation pump
- 25% pump efficiency
- 3 psi pressure drop at rated power

Air Management System

- Compressor-expander module
- Liquid-cooled motor
- Efficiencies at rated power: 78% compressor, 82% expander, 92% motor, 92% controller
- Turn-down: 20
- 5 psi pressure drop at rated power

Heat Rejection System

- Two circuits: 70°C HT coolant, 55°C LT coolant
- 75% pump + 92% motor efficiency
- 60% blower + 92% motor efficiency
- 10 psi pressure drop each in stack and radiator

Water Management System

- EW humidifier for cathode air, 60% RH at rated power
- Membrane humidifier for H_2, 60% RH at rated power