Highly Efficient, 5kW CHP Fuel Cells Demonstrating Durability and Economic Value in Residential and Light Commercial Applications

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May 16, 2012
H2RA003

plug power®

Today's Fuel Cells for proven, reliable power.

OVERVIEW

Timeline

- Project start – October 2009
- Project end – September 2013
- 85% complete

Barriers

- Barriers addressed:
  - A. Durability
  - B. Cost
  - C. Performance

Budget

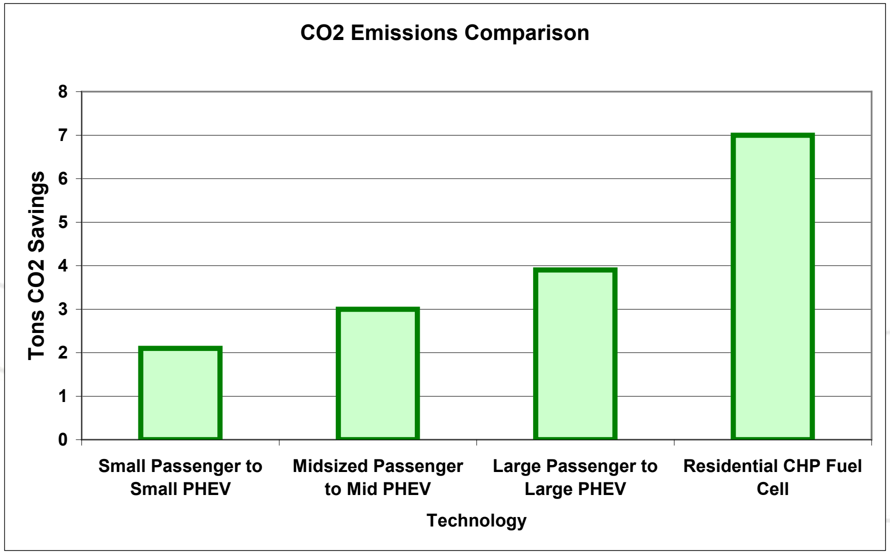
- Total project funding - $6.7M
  - DOE - $3.35M
  - Plug Power - $3.35M
- Funding in FY09 - $1.3M
- Funding in FY10 - $1.2M
- Funding in FY11 - $0.4M
- Planned in FY12 - $0.4M

Partners

- Interactions/collaborations
  - University of California Irvine
  - Southern California Gas
- Project Leads
  - Dr. Jack Brouwer
  - Randy Brown

Relevance

- Program: Highly Efficient, 5-kW CHP Fuel Cells Demonstrating Durability and Economic Value in Residential and Light Commercial Applications
- Purpose:
  - Substantiate durability through reliability fleet operation
  - Verify the technology and commercial readiness
  - Develop engineering models and train graduate students
  - Create new products, jobs and market



Partners:
- University of California Irvine ($50,836 cost share)
- Southern California Gas ($180,000 cost share)

CHP FUEL CELL DURABILITY DEMONSTRATION - Approach

- Task 1: Internal Durability/ Reliability Fleet Testing
  - ☑ Task 1.1: System Design
  - ☑ Task 1.2: System Modeling
  - ☑ Task 1.3: Site Identification and Selection
  - ☑ Task 1.4: Procure Parts and Build Systems
  - ☑ Task 1.5: Long Term Tests
    - ☑ *1st GO/NO GO Decision*

- Task 2: External Customer Demonstration and Testing
  - ☑ Task 2.1: Communication, Education and Outreach
  - ☑ Task 2.2: Site Preparation, Natural Gas and Grid Interconnection
  - ☑ Task 2.3: Build and Installation
  - Task 2.4: Demonstration Testing and Maintenance
    - *2nd GO/NO GO Decision*
  - Task 2.5: Decommissioning

UCI operational
MEA Supply issues
Stop home installs

- Task 3: Project Management
  - Task 3.1: Cost Analysis

TASK 1.1: SYSTEM DESIGN - COMPLETE

Product Characteristics	
Minimum Continuous Output	0.5 kW
Maximum Continuous Output	2.5 kW to 5.0 kW
Operating Fuel	Natural Gas
Dimensions	101cm x 71cm x 122cm
Weight	250kG
Nominal Voltage	120Vac 60Hz or 230Vac 50Hz
Efficiency (Electric/CHP)	30% / 85% LHV
Integrated Burner	Variable Output (7kW / 25kW)
Operating Conditions	
Location	Indoors
Ambient Temperature Range	0°C - 40°C

Plug Power design initiatives:

- **Controls and efficiency improvements**
  - Start-up, thermal response and heat modulation improvements, improved thermal recovery
  - From 89% peak total efficiency to 94%
- **Manufacturability improvements**
  - Enclosure, piping, insulation and wiring
  - Reduced build time from > 120 hours to < 50
- **Design for certification**
  - Integrated with commercial automatic burner control system
  - Reduced exhaust temperature
- **Reduction in material cost**
  - From ~$90k to $53k in volumes < 20

The low cost, reliable, simple to install design with a compelling value proposition yields an energy efficient green product that delivers value to the customer.

TASK 1.2: SYSTEM MODELING

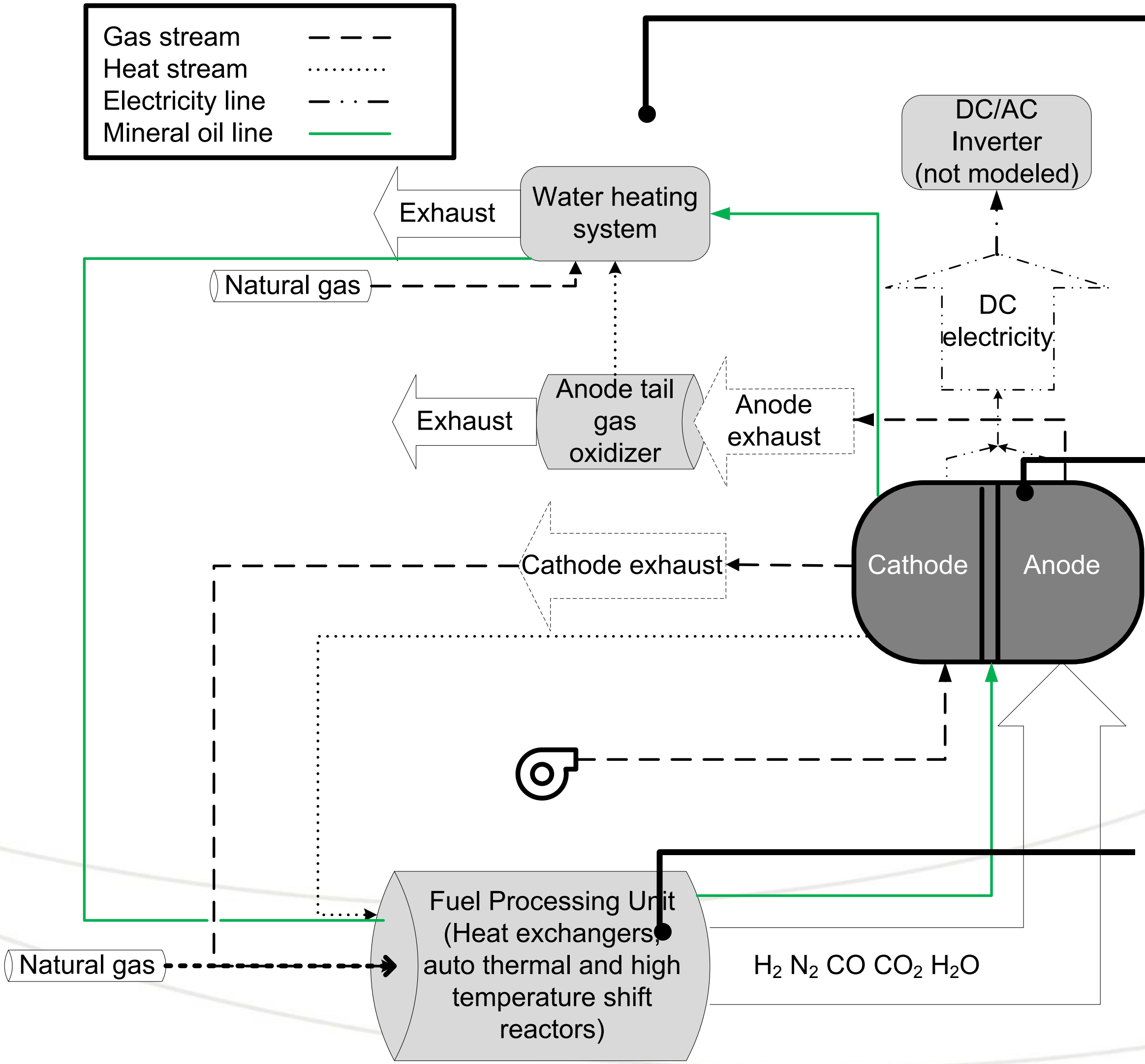
- **Objective:** Using Matlab-Simulink, develop a dynamic model and simulation of the ***GenSys Blue*** fuel cell system, correlate with data from the reliability fleet and use the model to further understand and improve the design.

- **Approach:** Develop independent models of the stack, fuel processor and burner then integrate these into a system model; demonstrating initially steady-state capability and then dynamic.

- **Status:** Sub-system models, system integration and steady-state capability complete. Dynamic development ongoing.

UCI is leading the system modeling effort. The team is correlating data generated by the model with data from the reliability fleet.

Model structure & theory



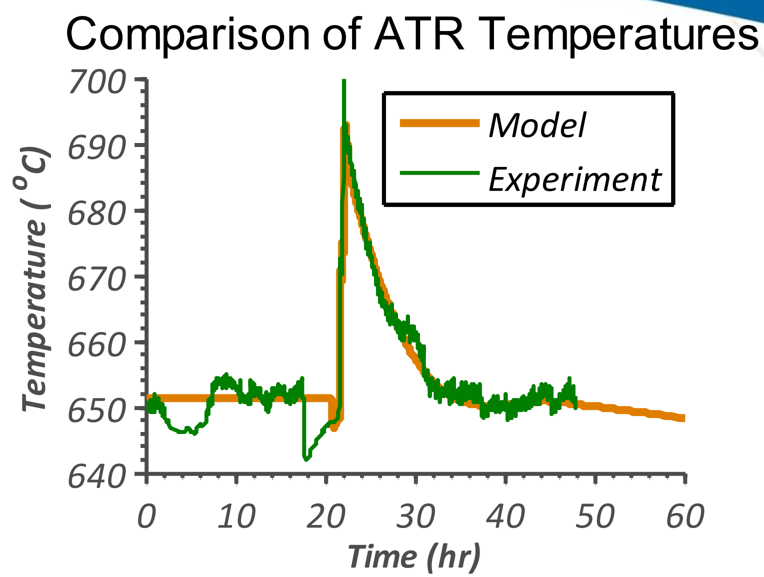
Networked of heat exchangers and combustion reactors. Modeled with conservation of mass and energy first principles.

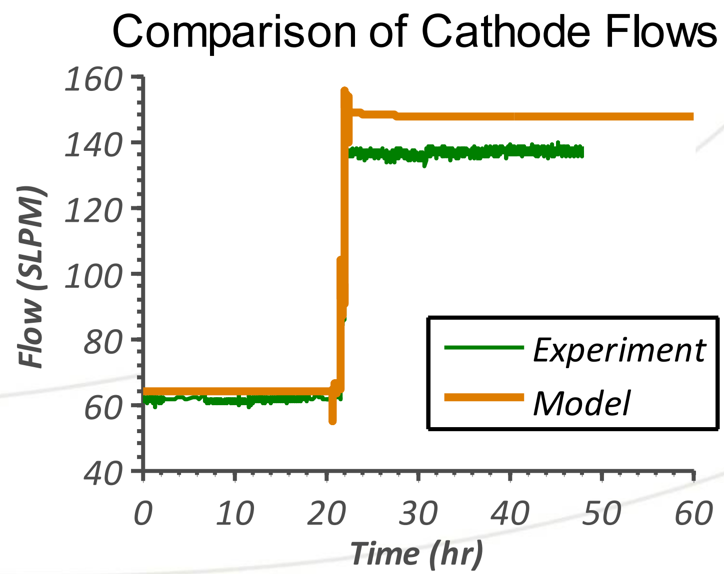
Discretized fuel cell model (perpendicular to the flow direction)(Mueller 2007)

Dynamic models of
- ATR (Yuan 2004)
- Heat exchangers (Roberts 2006)

Recent model results

- Power transient 1.5 kW – 3 kW
- ATR temperature rose 50°C within 30 minutes, decreased gradually to the normal operating temperature
- Model comparison to experimental data allowed:
  - Improvement on controller model
  - Understanding of flow meter uncertainties
  - To get the experimental ATR temperature profile, 10% of air needs to be added at the high power set point.





TASK 1.3: SITE IDENTIFICATION AND SELECTION

- UCI Installation Completed
  - Systems installation completed
  - CHP rig interfaced with each system
  - Heat rejection loop installed
  - Started up and running 2 systems in CHP and 1 system in heat only

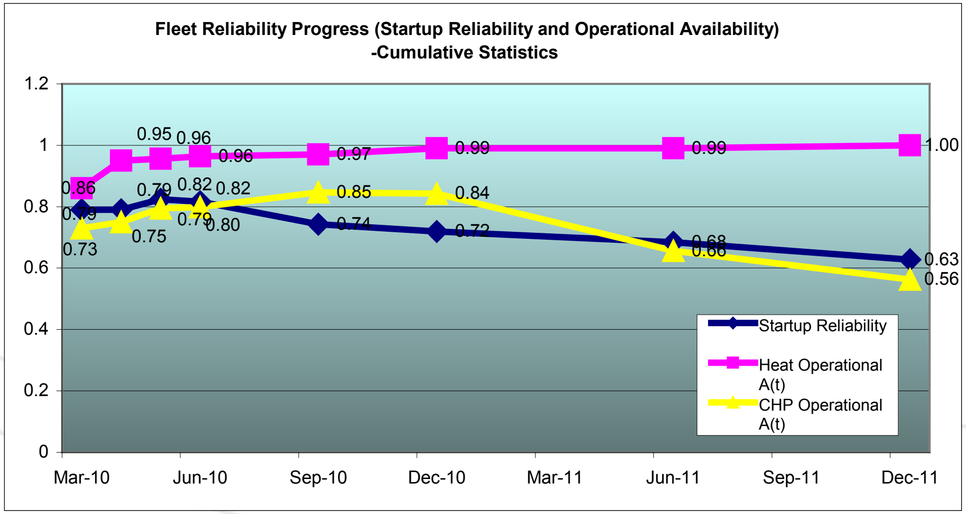
Installation started	February 2011
2 Stacks delivered	June 2011
Systems started	July 2011
Running period	July- present

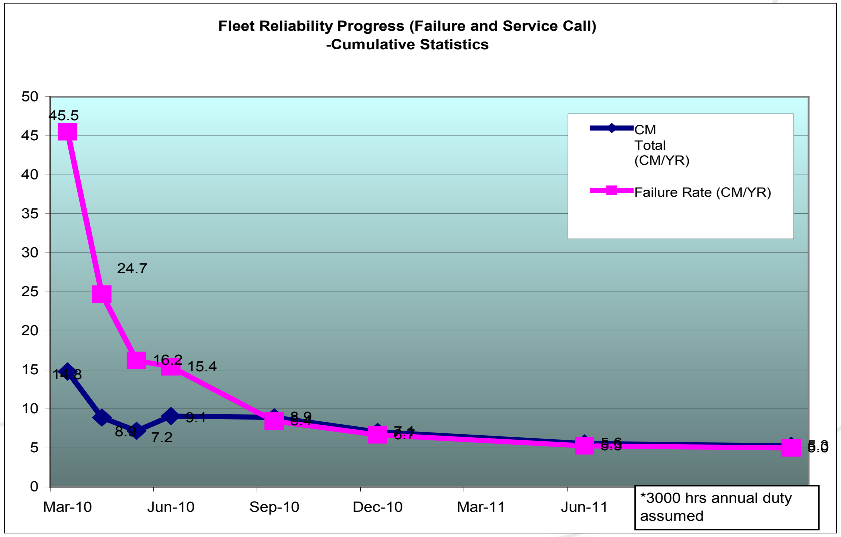
UCI came online at the same time we were seeing MEA issues

TASK 1.5: LONG TERM TESTING

Internal fleet dashboard metrics:

- **6** systems commissioned in Plug Power labs
- Over **31,000** run hours
- **53 MWhrs** of electricity and **633 MWhrs** of heat produced
- Unadjusted heat availability of **99%**
- Unadjusted CHP availability of **56%**



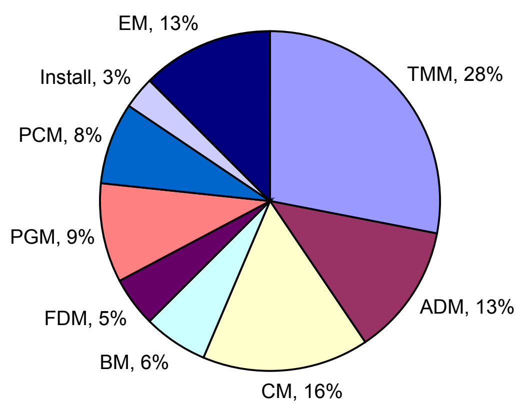


TASK 1.5: LONG TERM TESTING

HT GenSys Reliability Fleet Stats Through 12/31/2011 0:00

System S/N	Commissioned Date	System Runtime (Hours)	Current Stack Runtime	Burner Runtime	Electrical kWh	Thermal kWh	Startup Reliability	Heat Operational A(t)	CHP Operational A(t)
EpsilonPlus8	1/8/2010 14:50	7823	6058	11443	15247	117862	0.60	1.00	0.72
EpsilonPlus9	1/11/2010 15:14	4381	3802	9910	7349	101859	0.70	1.00	0.39
EpsilonPlus10	4/9/2010 8:55	1777	1777	8344	2520	95252	0.71	0.99	0.56
Foxtrot2	1/8/2010 14:59	8977	1651	7958	15109	112070	0.64	1.00	0.70
Foxtrot3	3/2/2010 10:47	5011	3098	11191	6679	122348	0.56	1.00	0.54
Foxtrot4	6/11/2010 14:45	3249	3249	8264	6002	83607	0.55	0.99	0.47
Totals	-	31219	19635	57109	52905	632998	-		-
Average	-	5203	3273	9518	8818	105500	0.63	1.00	0.56

Reliability Fleet Failure-Module Allocation (31219 cumulative system hours) as of 12/31/11



Module Acronyms

TMM	Thermal Managment
ADM	Air Delivery
CM	Controls
BM	Burner
FDM	Fuel Delivery
PGM	Power Generation
PCM	Power Controls
Install	Installation
EM	Electronics

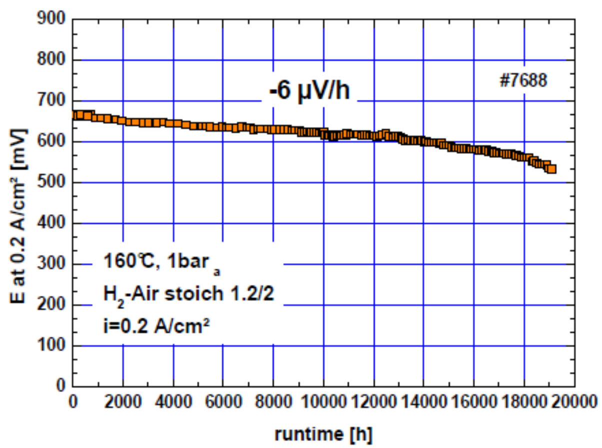
TASK 1.5: LONG TERM TESTING

- Current stack life in system is:
  - 3000-5000 h (6-12 months)

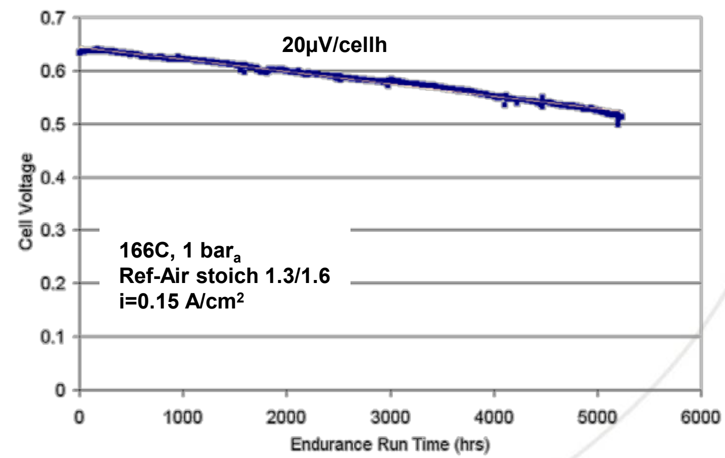
	Before April 2010		After April 2010
	Hrs		Hrs
Epsilon 8	1045		4073
Epsilon 9	580		3801
Epsilon 10	1778		
Foxtrot 2	2068		4742
Foxtrot 3	1913		3098
Foxtrot 4	#N/A		3206
Avg	1476.8		3784

6050

- BASF Laboratory Data:
  - 20,000 h



- Current stack life on test station is:
  - >5400h (12+ months) and running
  - Projected 10,000h (18-24 months) at current rate



Last Year We Saw Encouraging Results: Stack Lifetimes Were Approaching Commercial Launch Requirements

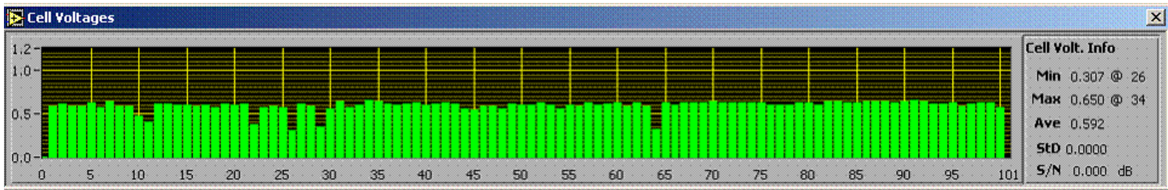
MEA Supply & Stack Began to Show Inconsistent Performance

- Individual testing of MEA's showed reduction in holes and early failures
- Edge leaks also diminished
- Previously, we would see failures in ~ %10-%20 of tested MEA's
- Recently saw improvement to 1%-2% failure rate.

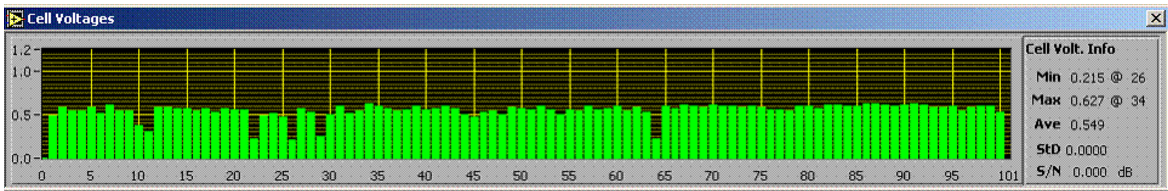
Stack Cell Profile

- Cell profile indicates stack would have performance issues
- Even high stoich conditions did not help
- Several troubleshooting sessions
  - Catalyst issues
  - Over compression
  - Phos. acid blinding of catalyst
  - Prototype consistency
  - Raw material questions
  - Stack assembly concerns

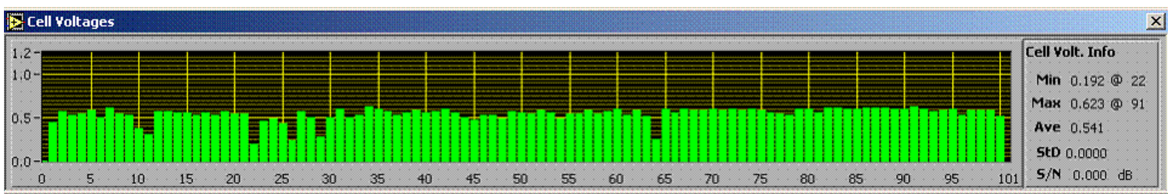
1.91 Anode Stoichs 30A on Reformate



1.63 Anode Stoichs 35A on Reformate



1.58 Anode Stoichs 36A on Reformate



Stack tests indicated high variability in cell-to-cell performance

MEA Supply, Performance and Stack Risk

- Discussions held with BASF
- Recognized issues and lack of resources to solve
- BASF offered a standard format MEA design to substitute Plug Power's custom configuration
  - This would require prohibitive stack redesign
  - Plug Power did not want home customers to experience early stack failures
  - Plug Power decided risk was too great to move forward
- Plug Power decided to engage ClearEdge Power to provide home systems
- Agreement is being developed between Plug Power, ClearEdge Power and DOE.

Discussions with BASF are very collaborative, but no quick solutions were found and BASF and Plug Power are not resourced for this level of challenge

2.2: SITE PREPARATION, NATURAL GAS AND GRID INTERCONNECTION

Site	Site Survey	NEPA Form	Application Engineering	Permits	Interconnect Application	Installation	Interconnect Approval	Commissioning
University of California, Irvine, California								
Installation 1	13-Sep	n/a	1Q11	1Q11	n/a	2Q11	n/a	2Q11
Installation 2	13-Sep	n/a	1Q11	1Q11	n/a	2Q11	n/a	2Q11
Installation 3	13-Sep	n/a	1Q11	1Q11	n/a	2Q11	n/a	2Q11
Sempra Energy Sites, California								
Woodbury Lagoon	14-Sep	n/a	2Q11	3Q11	2Q11	3Q11	3Q11	4Q11
Anthony Residence	14-Sep	n/a	2Q11	3Q11	2Q11	3Q11	3Q11	4Q11
Hentschel Residence	15-Sep	n/a	2Q11	3Q11	2Q11	3Q11	3Q11	4Q11
Huie Residence	14-Feb	n/a	2Q11	2Q11	2Q11	3Q11	3Q11	4Q11

Operate UCI as much as possible

On Hold After No-Go

Sites are on hold until we gain clarity around the ClearEdge discussions

Where We Are

Fleet Performance

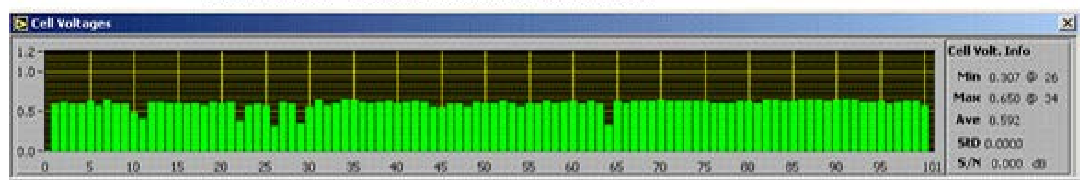
- Plug Power: 6 units running
    - 5 in heat only mode
    - 1 in CHP mode
    - **2 full years of run time**
- UC-Irvine: 1 unit running
    - Down units waiting for component replacement

6A Target Performance and Go/No-Go Decision Chart					
Characteristic	**Units**	**Goal**	**1st GO - 2Q10**	**1st GO Actual**	**2nd GO - 2Q11**
Electrical efficiency at rated power	%	40	>30	32%	>30
CHP efficiency at rated power	%	90	>80	90%	>80
Cost (qnty < 15)	$/kWe	10,000	20,000	10,400	20,000
Durability at < 10% rated power degradation	hr	10,000	2,000	3,000	8,700
Noise	dB(A)	<55 at 10m	<55 at 10m	55 at 1m	<55 at 10m
Emissions (combined NOx, CO, SOx, hydrocarbon, particulates)	g/MWhr	< 1.5	< 1.5	< 1.5	< 1.5
				GO	**NO GO**

Primary Issue: Stack continuity of supply, quality issues

- Voltage suppression, cell to cell variability
- BASF MEA supply stretched thin

1.91 Anode Stoichs 30A on Reformate



Lack of continuity of supply for the stack component prevents further testing with electrical power output. Systems are currently being run in “heat only” mode.

Lessons Learned

- Stack reliability is key
- Stack manufacturing
  - Raw materials consistency & pre-qualification
  - Stack testing
- Stack re-work
  - Stack repair & maintenance
  - Cell jumper
  - Pt recycling for MEA's
- High temperature oil
  - Pushes material limits
  - Seals and gaskets
  - Avoid leaks into anode/cathode
- Still need low cost components
  - Pumps, blowers, boards
  - Air manifold
  - TMM valve
  - ADM valve
  - Enclosure
- Problem list is addressable given time and resources

Continued assertion that fuel cell CHP market is real

COLLABORATIONS

- **University of California Irvine – National Fuel Cell Research Center**
  - –University, cost sharing partner within the program
  - –NFCRC develops a system model for product development, refining controls and improving operation
- **Southern California Gas**
  - –Industry, non-cost sharing partner within the program
  - –Providing sites for testing and will assist in interconnection and fleet evaluation
- **California Air Quality Management District (AQMD)**
  - –State agency, non-cost sharing partner outside of the program
  - –AQMD will evaluate fleet data against California air quality standards
- **National Renewable Energy Laboratory (NREL)**
  - –National lab, non-cost sharing partner outside of the program
  - –NREL will assist in fleet data analysis

Future Work

- Steps to Program Completion

6A CHP Reliability Testing Remaining Tasks		
Task	Reference	Completion Date
Continue running 6 systems at Plug Power in heat only mode, including service and reporting	1.5	-
Continue running 3 systems at UCI in heat only mode, including service and reporting	2.4	-
Continue modeling with UCI	1.2	-
Complete arrangement and purchase order with ClearEdge for 2 turn-key units with service and	2.4	1-Apr-12
Quarterly Report - Q1 2012	3.0	10-Apr-12
Install ClearEdge units and begin 1 year of data	2.4	1-Jun-12
Quarterly Report - Q2 2012	3.0	10-Jul-12
Decommission 6 systems at Plug Power	2.5	1-Sep-12
Decommission 3 systems at UCI	2.5	1-Sep-12
Quarterly Report - Q3 2012	3.0	10-Oct-12
Quarterly Report - Q4 2012	3.0	10-Jan-13
Quarterly Report - Q1 2013	3.0	10-Apr-13
Quarterly Report - Q2 2013	3.0	10-Jul-13
Cost Analysis	3.1	12-Jun-13
Program Management Conclusion	3.0	12-Jun-13

- Further enabling the industry
  - 2 CHP units in real customer application in California

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Backup Slides

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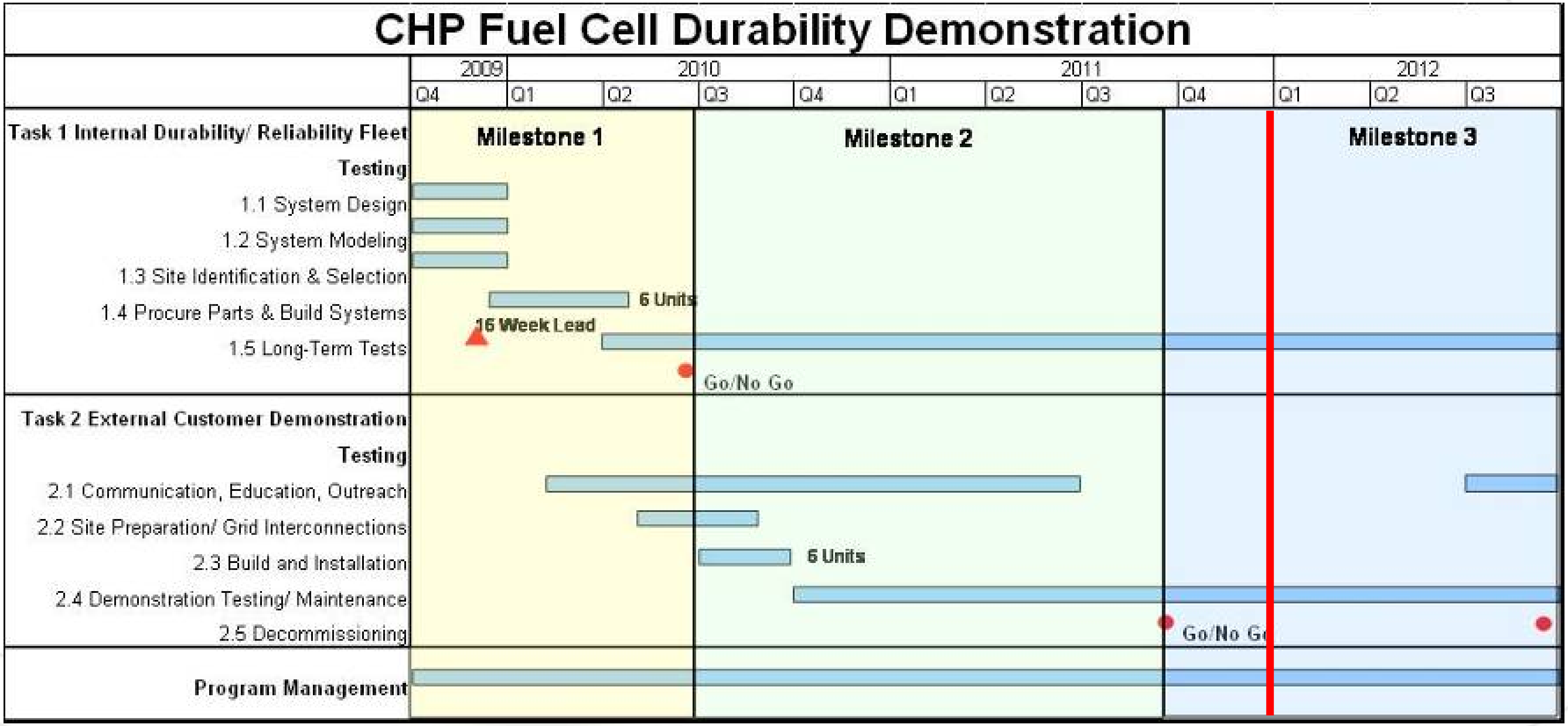
MILESTONES


CHP Fuel Cell Durability Demonstration
2009
2010
2011
2012
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Task 1 Internal Durability/ Reliability Fleet Testing
1.1 System Design
1.2 System Modeling
1.3 Site Identification & Selection
1.4 Procure Parts & Build Systems
1.5 Long-Term Tests
Milestone 1
Milestone 2
Milestone 3
6 Units
16 Week Lead
Go/No Go
Task 2 External Customer Demonstration Testing
2.1 Communication, Education, Outreach
2.2 Site Preparation/ Grid Interconnections
2.3 Build and Installation
2.4 Demonstration Testing/ Maintenance
2.5 Decommissioning
6 Units
Program Management

Accomplishments

- Fleet of 6 systems located at Plug Power

Plug Power CHP System Performance Metrics (Through December 2011)								
System S/N	E8	E9	E10	F2	F3	F4	Totals	Average
Commissioned Date	Jan-10	Jan-10	Apr-10	Jan-10	Mar-10	Jun-10		
System Runtime (Hours)	7,823	4,381	1,777	8,977	5,011	3,249	31,219	5,203
Current Stack Runtime	6,058	3,802	1,777	1,651	3,098	3,249	19,635	3,273
Burner Runtime	11,443	9,910	8,344	7,958	11,191	8,264	57,109	9,518
Electrical kWh	15,247	7,349	2,520	15,109	6,679	6,002	52,905	8,818
Thermal kWh	117,862	101,859	95,252	112,070	122,348	83,607	632,998	105,500
Startup Reliability	60.0%	70.0%	71.4%	64.0%	56.3%	54.5%		62.7%
Heat Operational	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%		100.0%
CHP Operational	71.9%	39.2%	55.7%	70.4%	53.8%	46.9%		56.3%


Plug Power Systems Lab

- Fleet of 3 systems located at UC-Irvine

- Design Improvements
  - Performance optimization through modeling
  - Efficiency: enhanced thermal recovery
  - Controls: start-up, thermal response
  - Efficiency: 89% total peak to 94%
  - Manuf: Build reduced from >120 to <50 hr
  - DMC Reduction: ~$90k to $53k in volumes < 20


University of California - Irvine

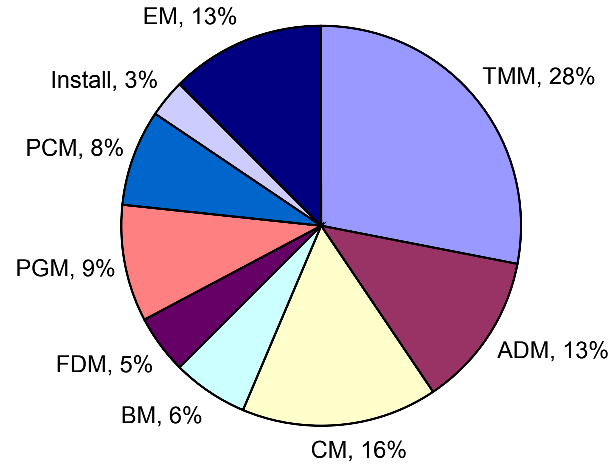
Top Problems

- PGM: Stack life less than 8000 hours
- PGM: Stack early mortality due to cell variability
- TMM: Oil pump failures due to seal loss, seizing, electronics failure
- TMM: Oil leaks due to stack gasket leaks
- TMM valve seizing and coupling failure
- ADM: manifold material warping
- ADM: valve seizing, controls
- BM: Igniter failure due to materials/ temperature
- CM: Sola failure due to voltage
- CM: valve position drift/loss
- FDM: Reformer temperature too high

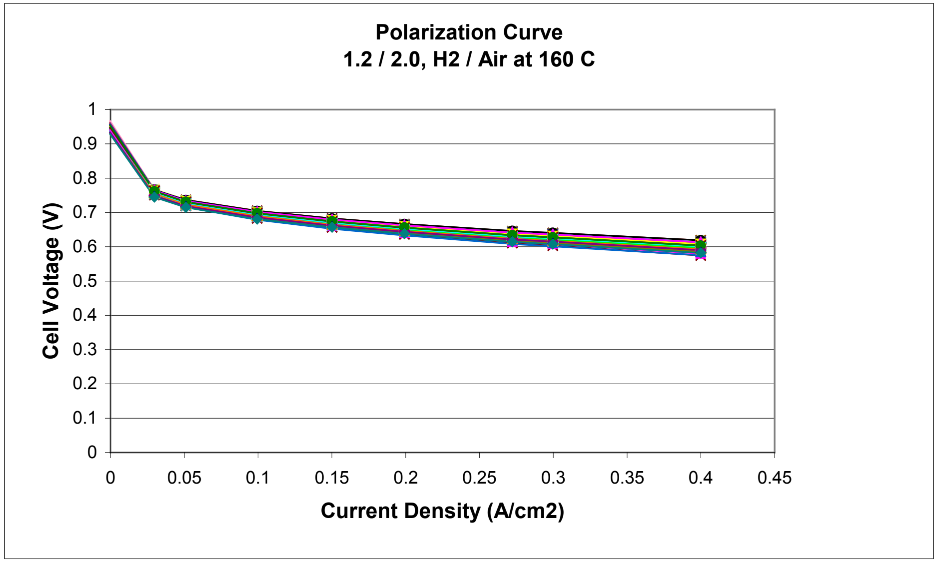
Module Acronyms

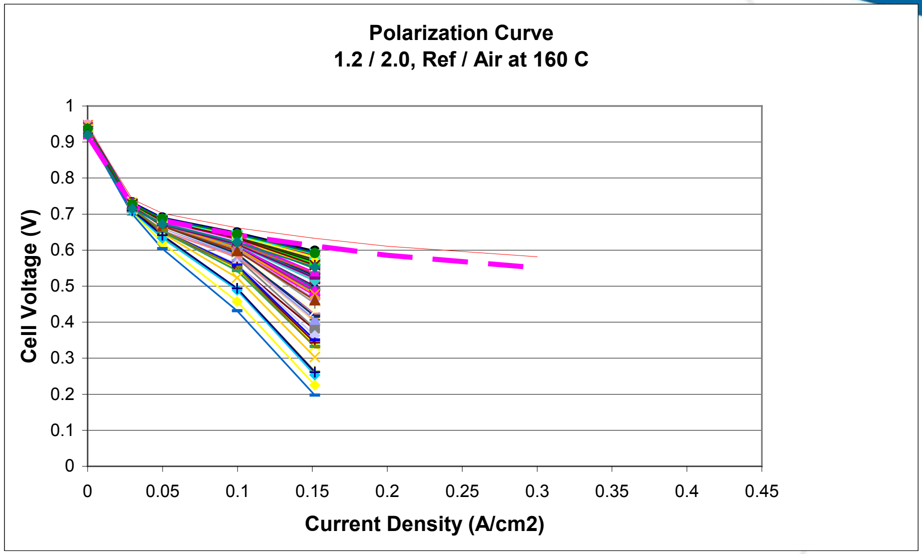
TMM	Thermal Managment
ADM	Air Delivery
CM	Controls
BM	Burner
FDM	Fuel Delivery
PGM	Power Generation
PCM	Power Controls
Install	Installation
EM	Electronics

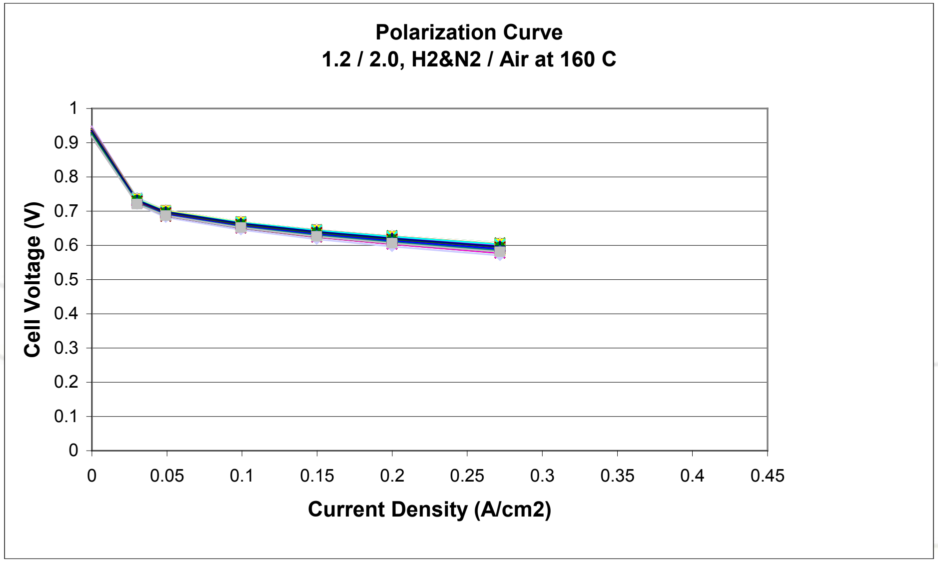
Reliability Fleet Failure-Module Allocation (31219 cumulative system hours) as of 12/31/11



Assembled Stack Tests Showed New Challenges





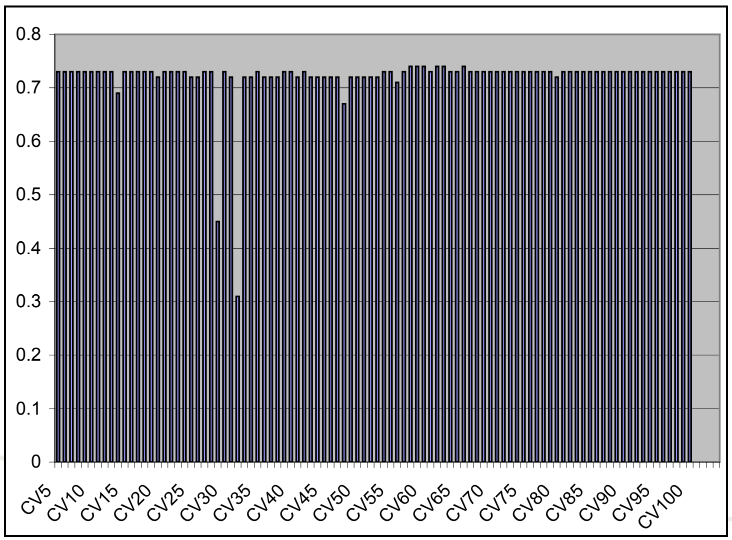


- H2 Air tests looked good
- Diluted H2/N2-Air looked good
- Reformate testing showed much cell-to-cell variability
- Stacks would have multiple weak cells

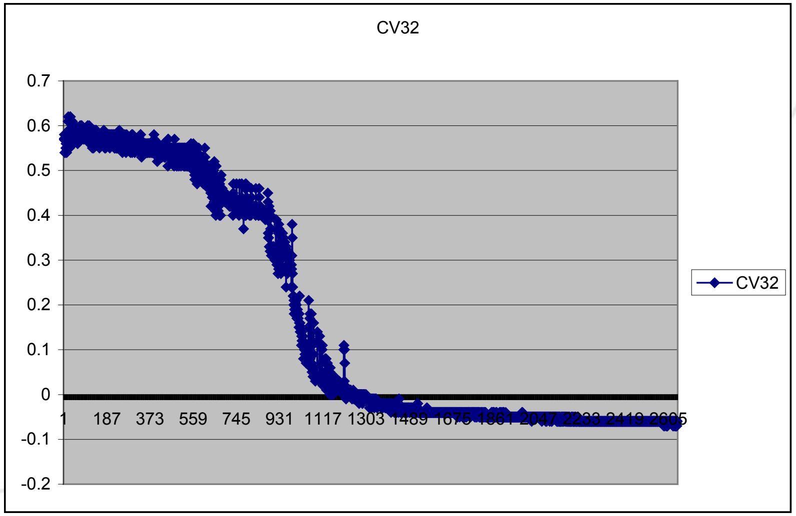
Early Stack Mortality

- Observed one stack that degraded significantly after 1 week of operation
- Cell looked weak, but then dropped off rapidly
- Cell went negative and had to shut down the stack

Stack Cell Profile



Cell Death Profile



2.1: COMMUNICATION, EDUCATION AND OUTREACH

Events to date:

- Ribbon cutting ceremony for *GenSys Blue* installation at Union College in NY
- Alumni Day at Union College
- New York State Science, Technology, Engineering and Mathematics (STEM) Educational Collaborative at Ballston Spa High School in Ballston Spa, NY
- United States Fuel Cell Seminar in Palm Springs, California. *GenSys Blue: Fuel Cell Heating Appliance*
- Ballston Spa High School technology field trip
- Plans for system on display at the Schenectady Museum
- UCI installs GenSys systems in California
- Co-taught Fuel Cell Seminar Course with UCI NFCRC

NYS Assemblyman Jim Tedisco with Union College faculty, Plug Power and National Grid employees at ribbon cutting ceremony (DOE 7C)