Diesel Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power DE-FC36-04GO14318

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Cummins Power Generation

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FC43

- Cummins Power Generation
  - Balance of Plant (blower, fuel supply, plumbing)
  - Controls & power electronics
  - System integration
  - Sub and system testing

Minneapolis, MN

- Protonex LLC
  - "Hot Box" – SOFC modules, heat exchange, high temperature insulation
  - CPOX diesel fuel reformer
  - Sub-system testing

Broomfield, CO

- International Truck & Engine Corp.
  - Vehicle Requirements, Systems, Interface
  - On-vehicle test & evaluation

Fort Wayne, IN

Why Solid Oxide Fuel Cells (SOFC's)?

- Advantages
  - Greatly simplified fuel reformation for HC fuels (thermally matched, CO is fuel constituent, some Sulfur tolerance)
  - No water management in stacks
  - Potential for low / no precious metals (cost)
  - No external cooling required
  - High quality (high temperature) single waste heat stream
  - Good efficiency
- Challenges
  - Thermal management (start up, shut down, transients) – startup time
  - Degradation
  - Zero net water diesel fuel reforming
  - Cost, cost, cost ("chickens'n'eggs")

Overview

Timeline

- Project start: 9/1/2004
- Placed on hold FY 2006; restarted Aug 2007
- Project end: 6/15/2009
- Percent complete: 40%

Barriers

- Waterless reforming of Ultra Low Sulfur Diesel (ULSD) fuel
- Transient operation of solid oxide fuel cell (SOFC) system
- Power density, specific power (W/L, W/kg)
- Shock and vibration tolerance

Budget

- Project funding
  - DOE share = $3,225,611
  - Contractor share = $1,732,938
- Funding received
  - FY07: $800K
  - FY08: $750K (to date)

Partners

- Cummins Power Generation (project lead)
- Protonex LLC (SOFC power module)
- International Truck and Engine (vehicle and installation)

Objectives

- On-vehicle demonstration and evaluation of a SOFC APU with integrated on board reformation of diesel fuel
- Develop transparent method of water management for diesel fuel (ULSD) reformation
- Develop controls to seamlessly start, operate and shutdown SOFC APU
- Evaluate hardening the SOFC APU to enable it to operate reliably in the on-highway environment
- Develop overall system for performance, size, cost and reliability targets

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Milestones

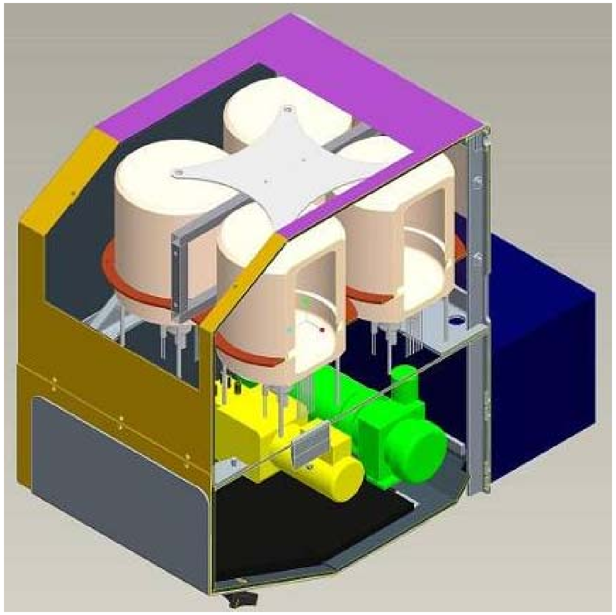
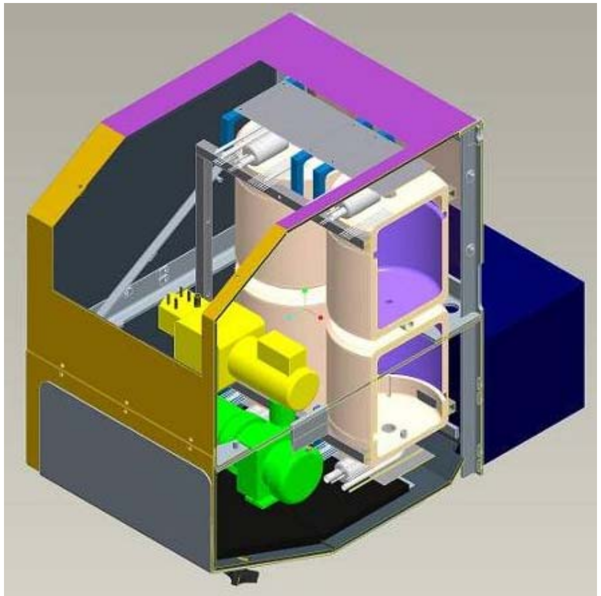
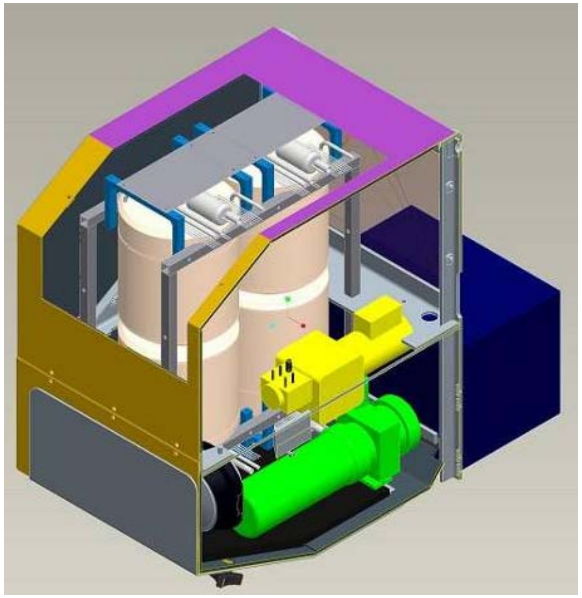
FY	Qtr	Milestone
FY07	Q4	**Program re-start --** ***Protonex replaces SOFCo hot section***
FY08	Q1	**Specifications finalized --** ***reviewed and adjusted to match PTX hot section***
FY08	Q2	**Protonex delivery of Module 1 --** ***Q3 delivery can be managed***
FY08	Q4	**System BOP design complete**
FY09	Q1	**Protonex delivery of SOFC sub-assembly (4-pack)**
FY09	Q2	**System ship from CPG to International Truck & Engine**
FY09	Q3	**Vehicle Tests Complete**

Approach

	Analysis and design	Sub-system test and development	Laboratory testing
Balance of Plant	Supply and Regulation: Cathode air Anode air Fuel	Cathode air Anode air supply Fuel supply	BOP Assembled Wired Checked
Controls & Power Electronics	Control Fluid flows Load response Power Electronics DC Link Load management	Bench testing Control loop responses System simulation	Integrate MCU and control software Simulated system testing Demonstration of system operation
SOFC, Hot Box Fuel Reformer	Module scale-up Thermal analysis CPOX chemistry	Module operational bench testing	Stack simulators utilized for initial checkout Functional SOFC stacks assembled tested in hot box
System Integration & Packaging	General arrangement Shock & Vibration attenuation	Solid modeling (CAD) Stereolithography Vibration testing at module level	Validate system performance Operation across load range Transient response Efficiency
Vehicle Integration	Systems integration 12V DC bus 120V AC bus Fuel supply Coolant loop Mount & Connect	N/A	In-vehicle evaluation 12V and 120VAC load testing EMI / RFI testing Vehicle-level thermal testing Operation at extreme temperatures Power and efficiency Cab climate performance

System mechanical design

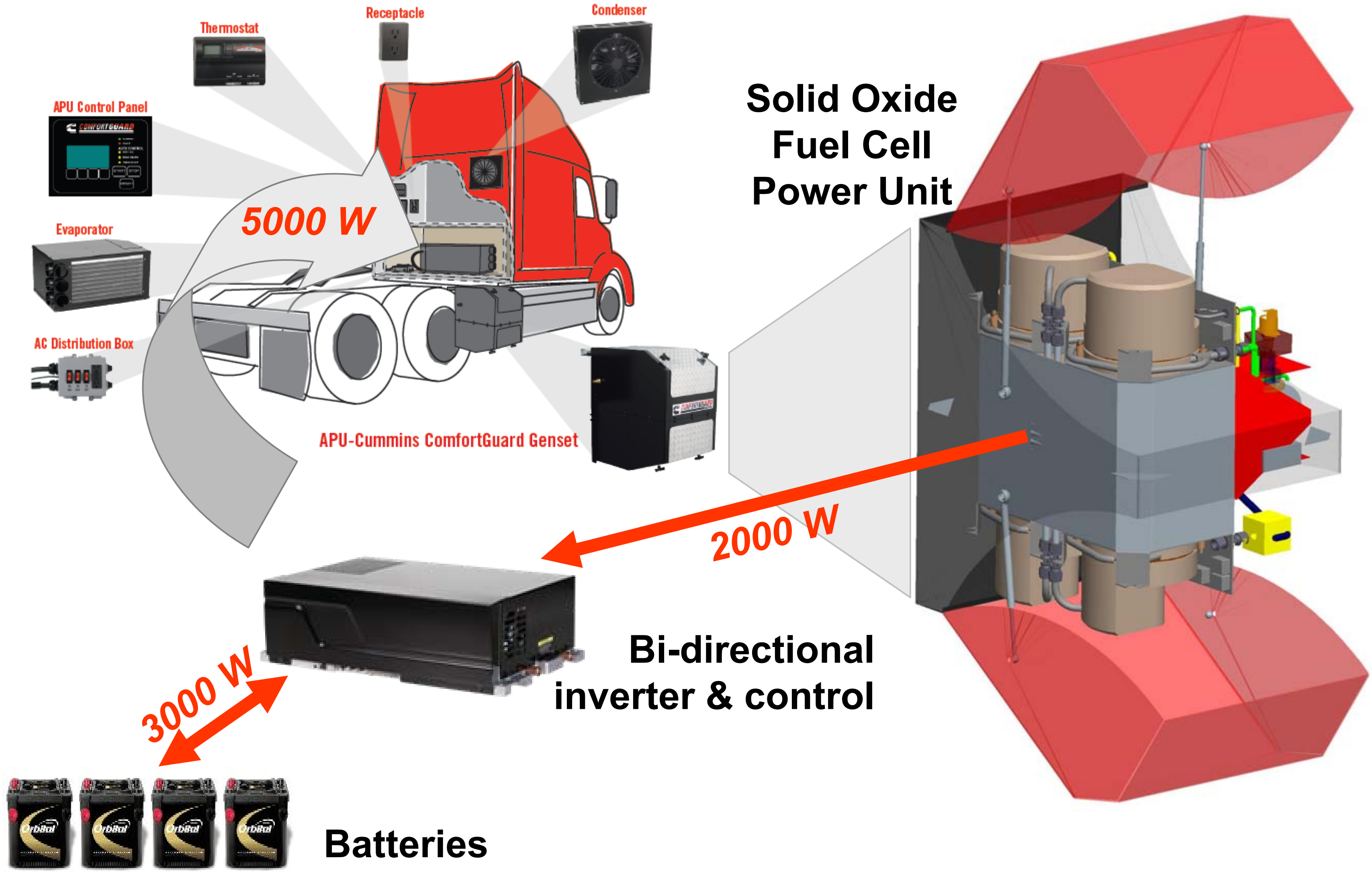
- Evaluated multiple module arrangements
- Selected system provides easy connection between Hot zones and cold balance of plant
- SOFC package size and weight based on successful commercial APU

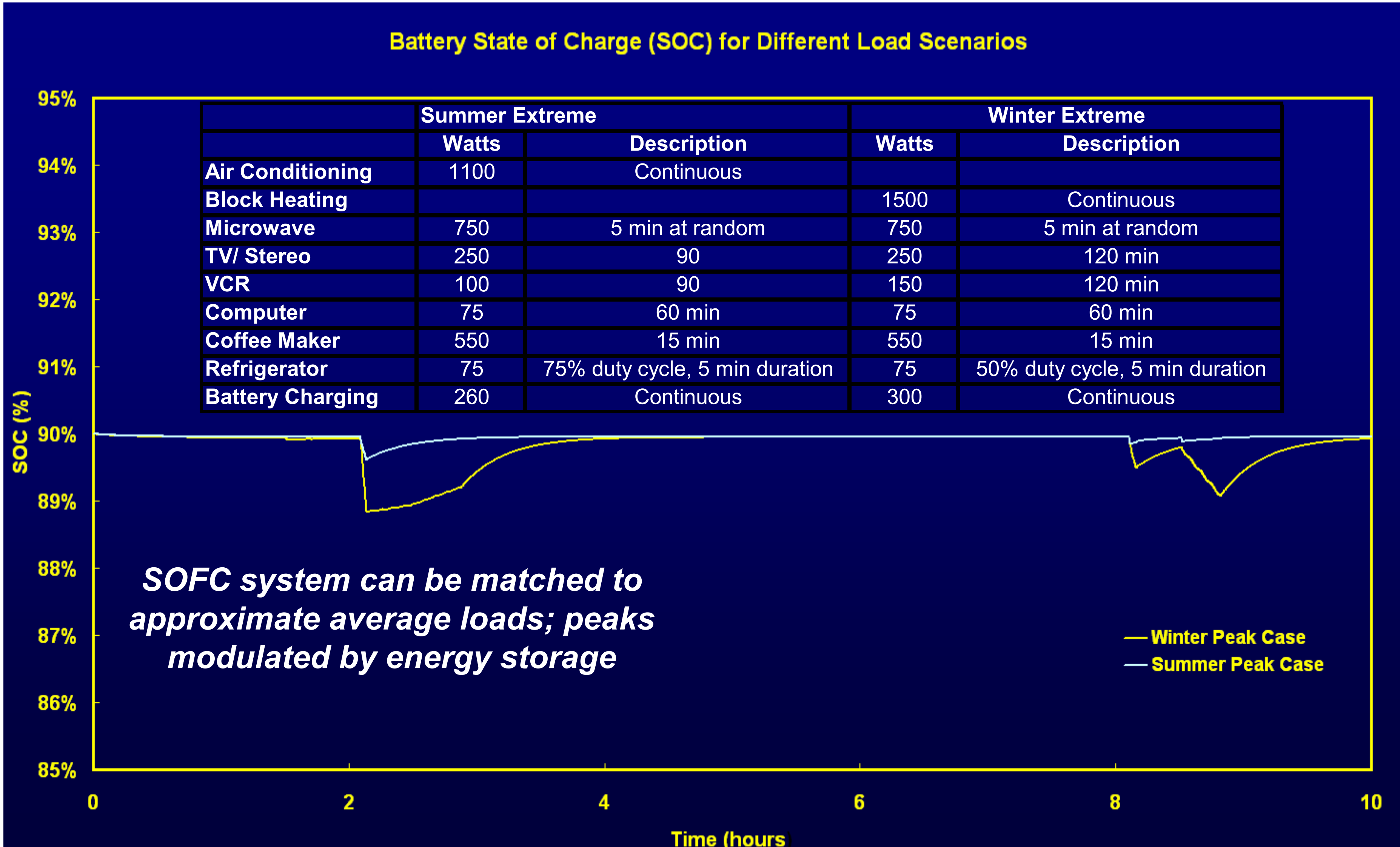
Power Generation

COMFORTGUARD

System Arrangement



System Modeling Example

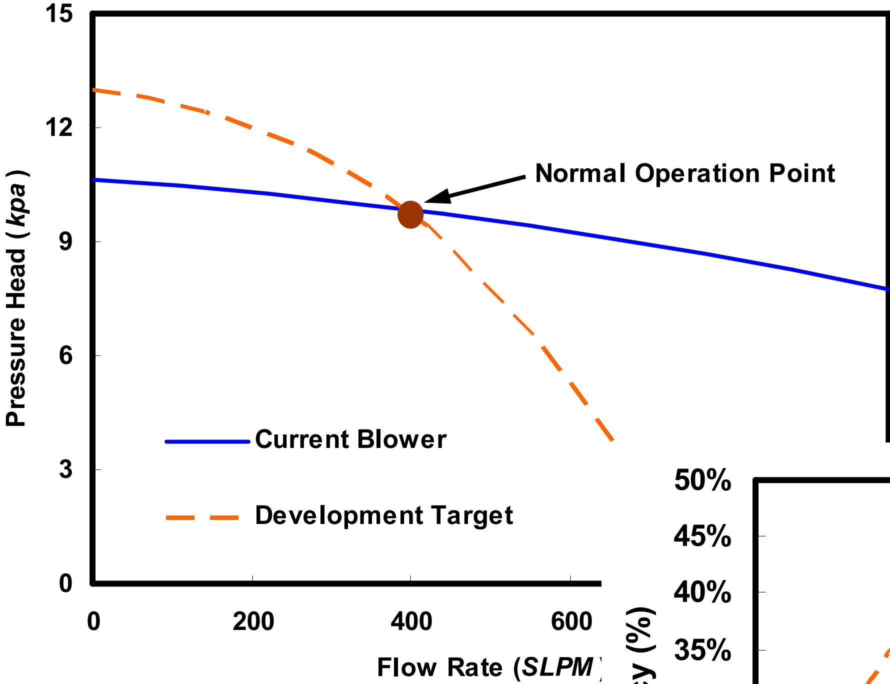


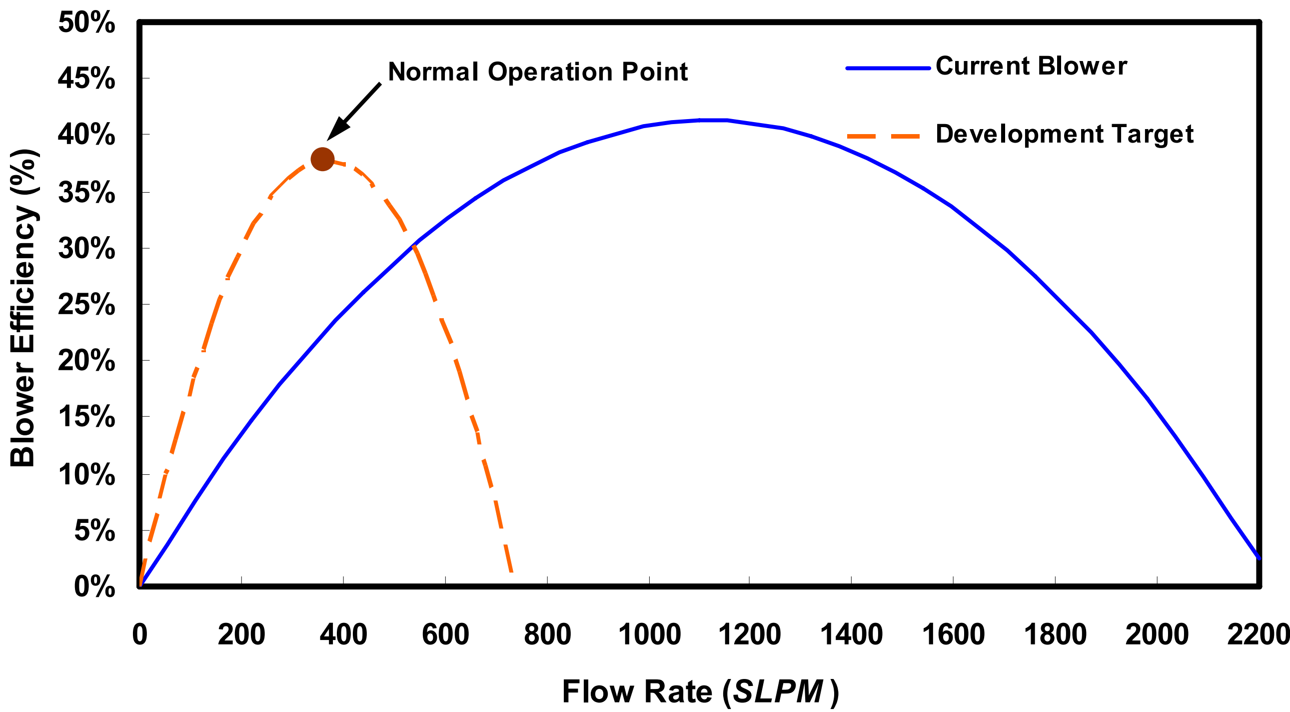
	Summer Extreme		Winter Extreme	
	Watts	Description	Watts	Description
Air Conditioning	1100	Continuous		
Block Heating			1500	Continuous
Microwave	750	5 min at random	750	5 min at random
TV/ Stereo	250	90	250	120 min
VCR	100	90	150	120 min
Computer	75	60 min	75	60 min
Coffee Maker	550	15 min	550	15 min
Refrigerator	75	75% duty cycle, 5 min duration	75	50% duty cycle, 5 min duration
Battery Charging	260	Continuous	300	Continuous

SOFC system can be matched to approximate average loads; peaks modulated by energy storage

Cathode Air Supply Development

- **Cost effective single-stage centrifugal blowers identified to provide design flows**





- ***Future work will examine potential for improving matches for higher efficiency***

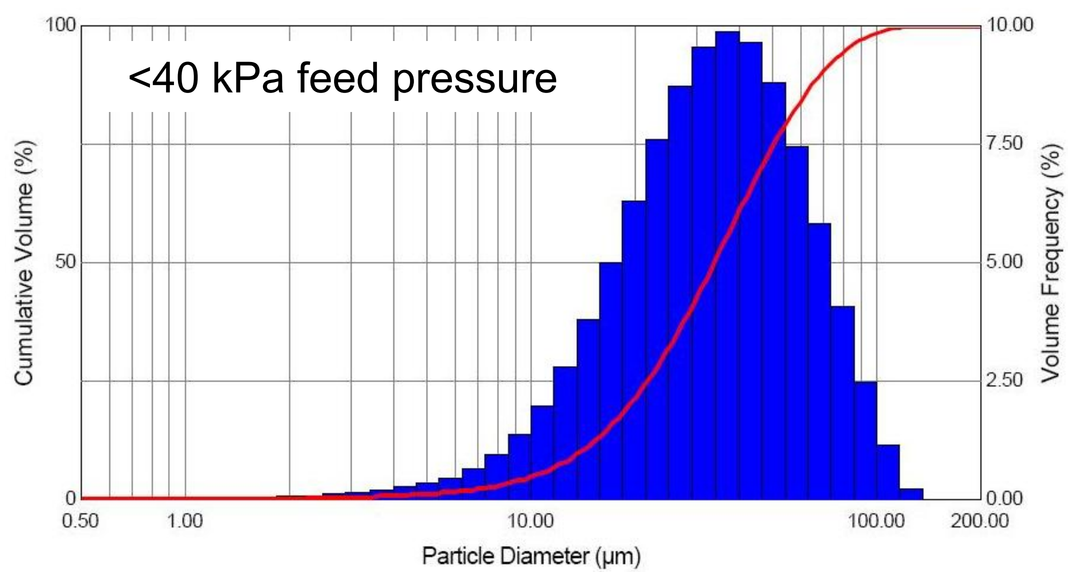
Stack design

- Selected modular design
  - 4 modules, 66 cells/module
- Target performance for complete APU (4 modules)

parameter	*value*	*notes*
power	14.3 A @ 185 V = 2640 W Gross Power	
OCV	264–276 V	4 modules in series
fuel flow at full load	18 ml/min	0.285 gal/hr ULSD
CPOX air flow	60 slpm @ 11 kPa	
cathode air flow	280 slpm @ 5.3 kPa	
hot zone thermal management air flow	<200 slpm @ <2 kPa	Provided by cathode blower
system efficiency	21% gross (2640 W) 17% net (2000 W)	DC/LHV

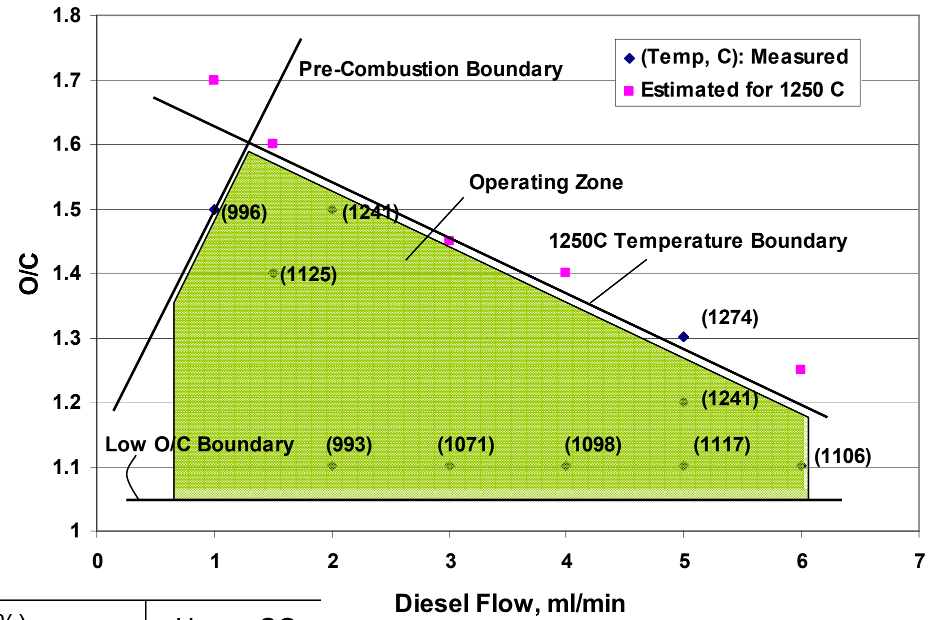
Fuel feed system

- Demonstrated both atomization and vaporization of ULSD
  - <40 µm droplets at low feed pressure
  - Demonstrated with CPOX reactor and ULSD
- Stable operation for hundreds of hours
- Vaporizer for initial units, atomizer has long-term advantages
  - Atomizer requires less start-up energy
  - Extended maintenance intervals (>500 hours)



Catalyst Selection

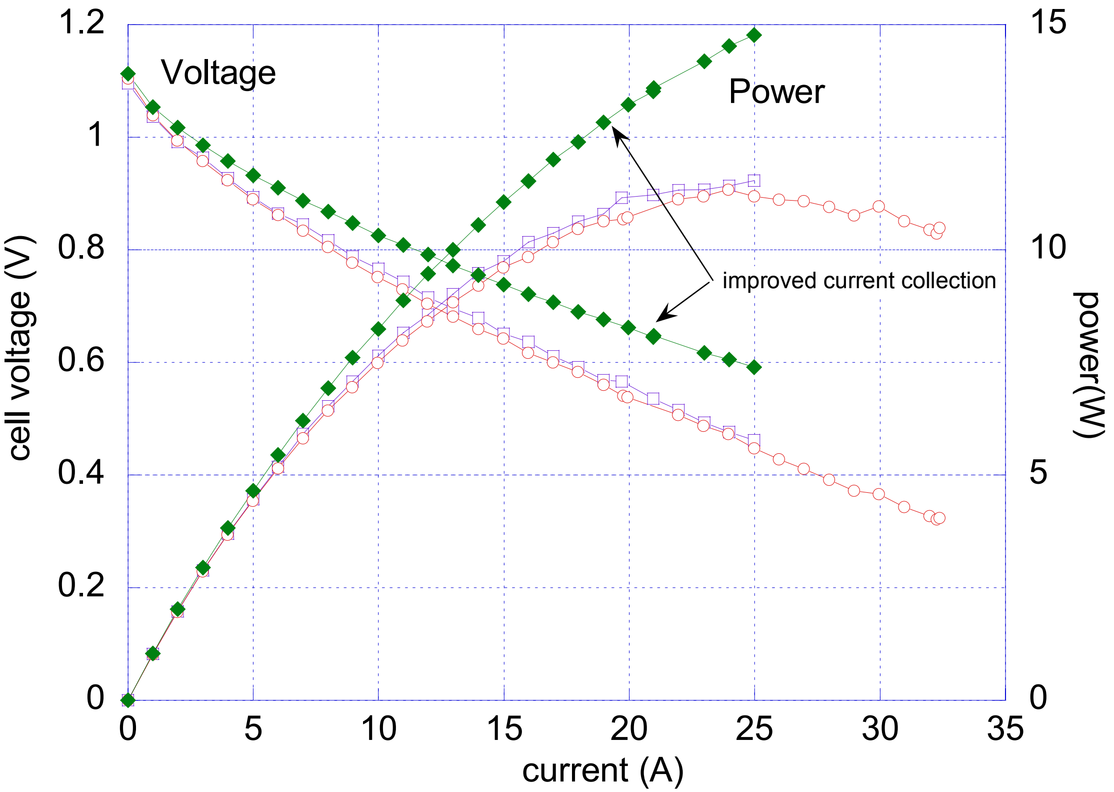
- **Screened four catalysts**
- **Selected catalyst is capable of >93% carbon and H_2 selectivity at design flow rates without added water**
- **Stable performance**
- **Wide operating range in flow and O/C ratio**



Diesel ml/min	O/C	Wet Reformate Composition (%)							H_2 Yield	CO Yield
		N_2	H_2	CO	CO_2	CH_4	Ar	H_2O		
6.0	1.1	50.6	21.9	23.9	0.50	0.24	0.61	2.2	0.93	0.97
5.0	1.1	50.8	21.5	23.8	0.49	0.40	0.61	2.5	0.91	0.96
1.0	1.5	57.0	15.9	16.9	4.2	0.05	0.68	5.4	0.82	0.83

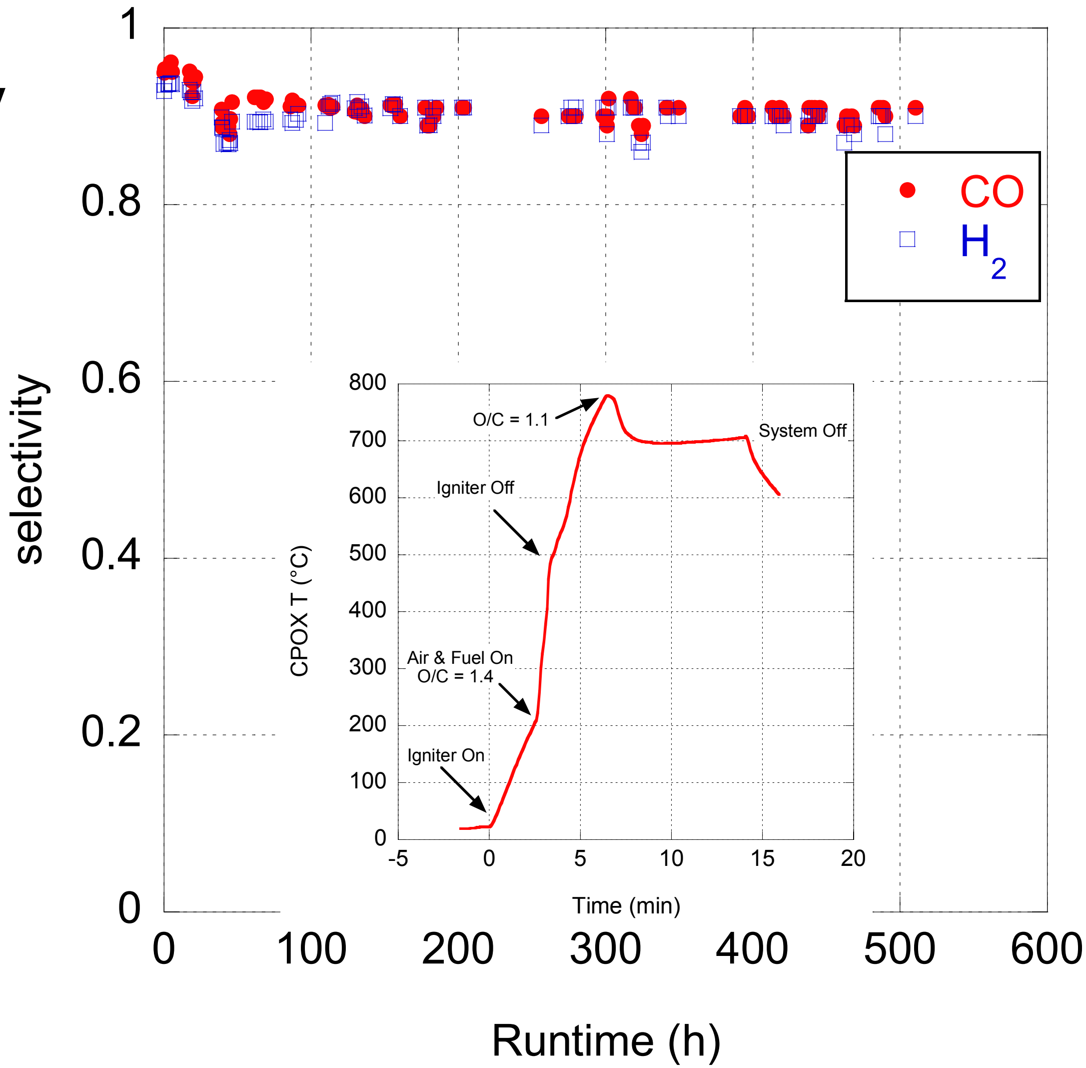
SOFC cell performance

- **Demonstrated improved performance with improved current collection**
- **Achieved 12.8 W / tube at design conditions, exceeds 10 W / tube target for initial design**



Reformer life testing

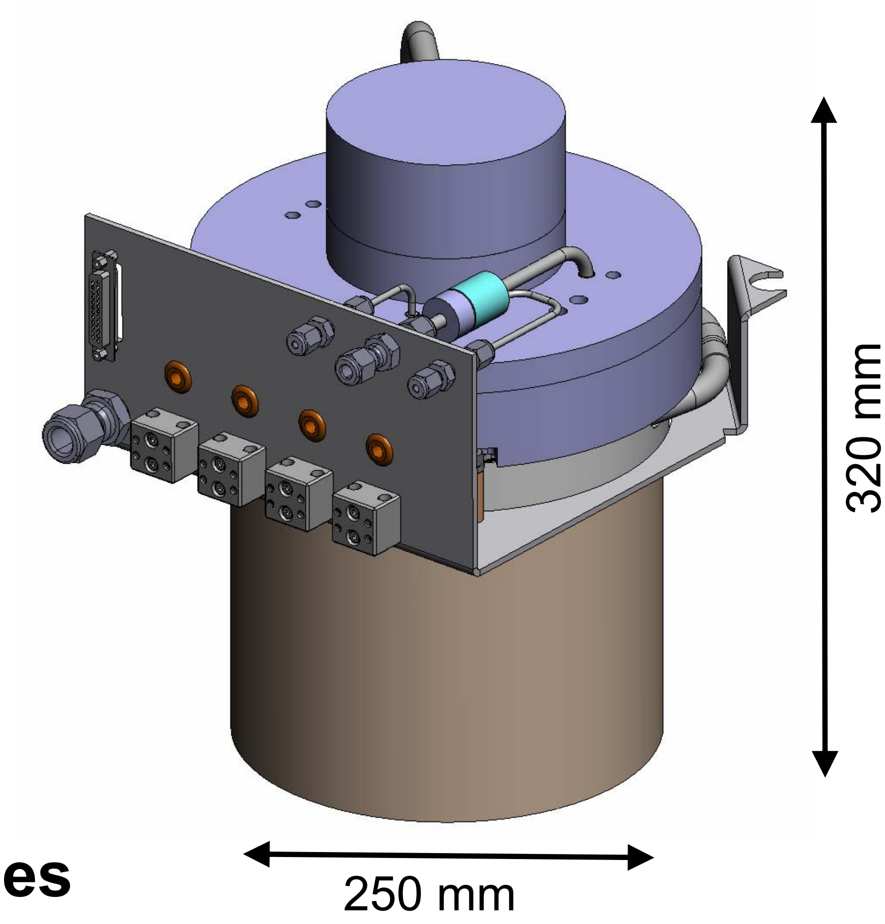
- **Demonstrated steady operation over 500+ hours with selected catalyst**
- **No carbon formation**
- **CO and H_2 selectivity's stable and >90% over test**
- **Integrated igniters allow startup in < 5 minutes with either vaporizer or atomizer**



Protonex™

Hot zone design

- Developed tightly integrated hot zone design
- Hot module includes:
  - Reformer
  - Stack
  - Recuperator
  - Tail-gas combustor
  - Mechanical structure
  - Insulation
- Design complete, first modules to be built Q3 2008



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Future work

- Fabricate & test hot zones (Q3-Q4 2008)
  - Build single modules and 4-module sets
  - Test modules in furnace and in insulation packages
- Optimize bundle performance (Q4 2008)
  - Select current collection approach
  - Develop techniques to improve temperature uniformity
- Fuel feed system improvements (Q4’08, Q1’09)
  - Test CPOX with atomizer
  - Explore limits of atomizer operation
  - Develop maintenance procedure for vaporizer

Future work

- Reformer optimization
  - Investigate performance at part-load
  - Develop optimized start-up protocol
- Stack fabrication improvements
  - Demonstrate automation of key assembly steps
  - Demonstrate near-net-shape fabrication of key stack parts

Future Work

- Evaluate potential for improved blower match(es) and implement if feasible
- Complete structural evaluation and shock / vibration attenuation system design
- Complete the system BOP design (FY08 Q4)
- Assemble system at CPG and begin qualification and final tuning (FY09 Q1)
- Ship system ship to International Truck & Engine (FY09 Q2)
- Vehicle Tests Complete (FY09 Q3)

Summary

- Project successfully re-constituted following interruption, change of hot section partner
- Significant progress at Protonex on CPOX reformer, upscale of hot section module
- CPG system integration progressing consistent with contemporary commercial APU packaging
- On track to demonstrate a viable SOFC solution to anti-idling
- Future DOE support can accelerate production viability

Acknowledgements

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