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

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Outline

- Team
- Solid Oxide Fuel Cells
- Overview and Objectives
- APU Efficiency Perspectives
- Approach
- Milestones
- System
- Stack
- Fuel Processor
- SOFC Module
- Future Directions
- Summary

Terminology

- "Snapshot"

Status of project design, development, performance as of March 2009

- "Demo Plan"

Anticipated performance at the demonstration phase of the project

- "Design 1"

Original objectives and targets for the APU design

- "Design 2"

Projected performance and characteristics of the next generation APU design

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Team

- Cummins Power Generation
  - Balance of Plant (blower, fuel supply, plumbing)
  - Controls & power electronics
  - System integration
  - Sub and system testing
  - On-vehicle demonstration
- Protonex LLC
  - "Hot Box" – SOFC modules, heat exchange, high temperature insulation
  - CPOX diesel fuel reformer
  - Sub-system testing
- International Truck & Engine Corp.
  - Vehicle Requirements, Systems, Interface
  - No longer active in project

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Minneapolis, MN

Protonex™

Broomfield, CO

International ®

Fort Wayne, IN

Power Generation

Solid Oxide Fuel Cells

for Truck APU's

- Advantages
  - Relatively simple fuel reformation for diesel fuel
  - No water management in stacks
  - Potential for low / no precious metals (cost)
  - No external cooling required
  - High quality (high temperature) single waste heat stream for CHP
- Barriers
  - Thermal management: start up, shut down, transients, cycling
  - Degradation
  - Zero net water diesel fuel reforming
  - Mechanical robustness
  - Cost – the "chicken-n-egg" problem
    - SOFC's will be cost effective at production volumes
    - Making the first ones affordable is a challenge

Power Generation

Overview and Objectives

Timeline

- Project start: 9/1/2004
- Placed on hold FY 2006; restarted Aug 2007
- Planned project end: 6/15/2009
- Percent complete: 75%

Budget

- Project funding
  - DOE share = $3,225,611
  - Contractor share = $1,732,938
- Funding received
  - Previous: $800K
  - FY07: $800K
  - FY08: $750K
  - FY09: $500K (to date)

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

Partners

- Cummins Power Generation (project lead, demonstration)
- Protonex LLC (SOFC power module)
- International Truck and Engine (now inactive)

Overview and 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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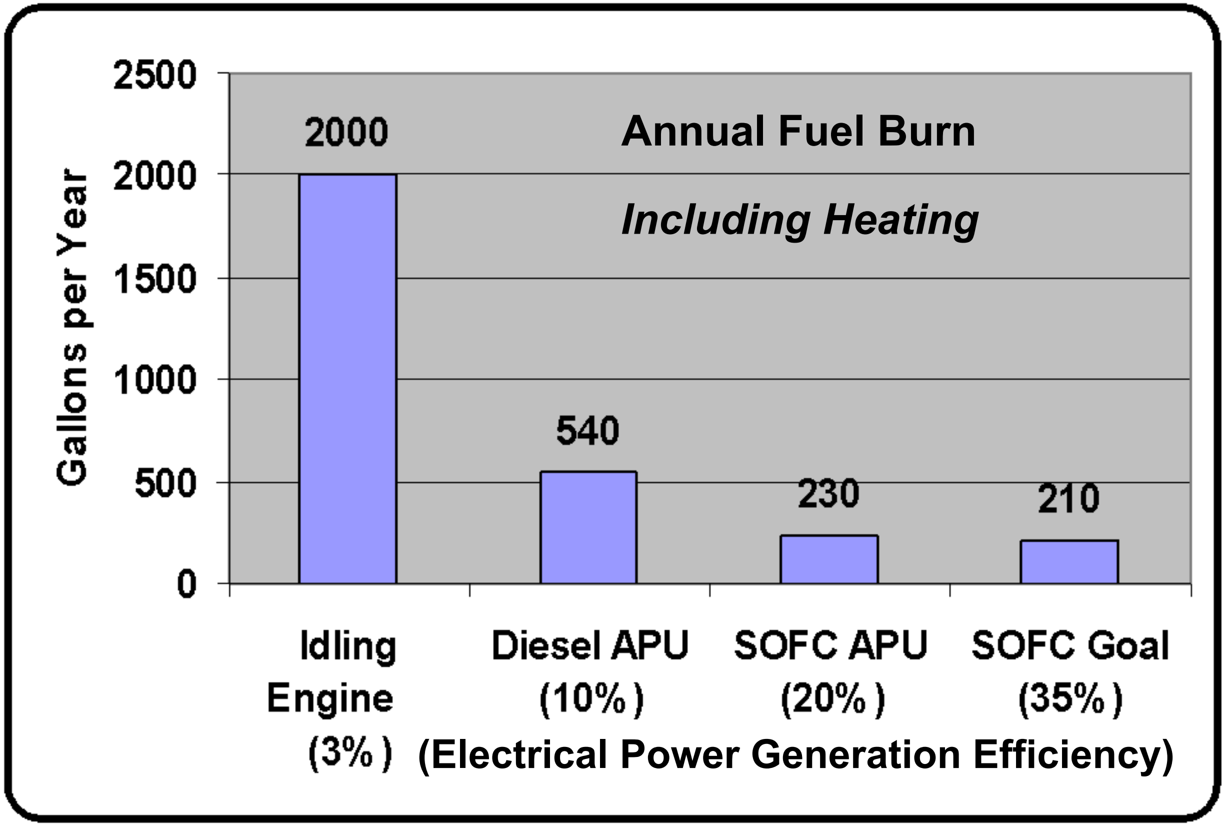
APU Efficiency Perspectives

- The biggest efficiency gain is in shutting off the main engine
- The law of diminishing returns decreases the incremental economic value of increasing efficiency gains



- Incremental gains in efficiency must be balanced against cost, complexity, reliability
- Dry CPOX reduces overall system efficiency, but offers benefits in initial cost, simplicity, reliability

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Approach

	Analysis and design 95% Complete	Sub-system test and development 90% Complete	Laboratory system testing 40% Complete
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	On-vehicle demonstration 12V and 120VAC load testing Vehicle-level thermal testing Power and efficiency Cab climate performance Noise

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Milestones

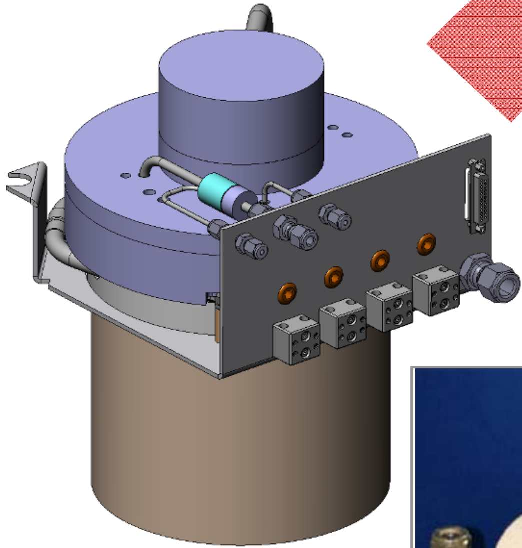
Original Plan

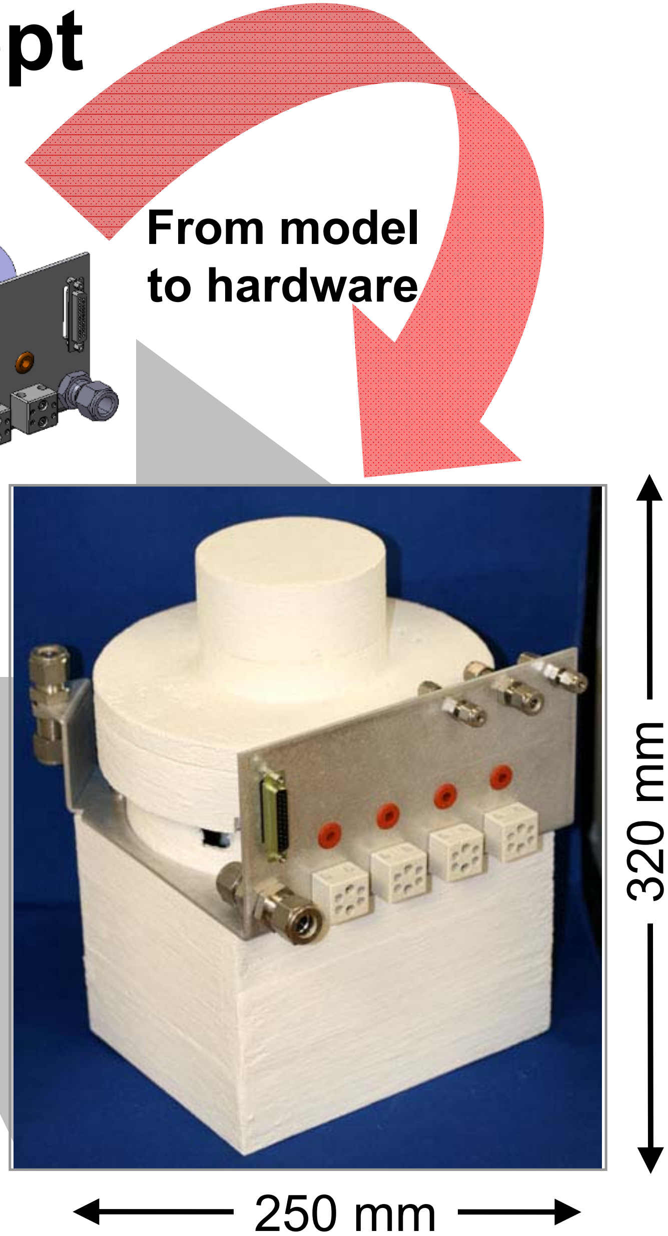
Current Plan

Qtr FY (Original Plan)	Qtr FY (Current Plan)	Milestone
Q4 FY07	Q4 FY07	Program re-start
Q1 FY08	Q1 FY08	Specifications finalized
Q2 FY08	Q3 FY08	Protonex delivery of Module 1 (Delivered 9/8/2008)
Q4 FY08	Q2 FY09	System BOP design complete
Q1 FY09	Q3 FY09	Protonex delivery of SOFC sub-assemblies
Q2 FY09	Q4 FY09	System checkout ready for vehicle install
Q3 FY09	Q1 FY10	Vehicle Tests Complete

System Design
Module Concept

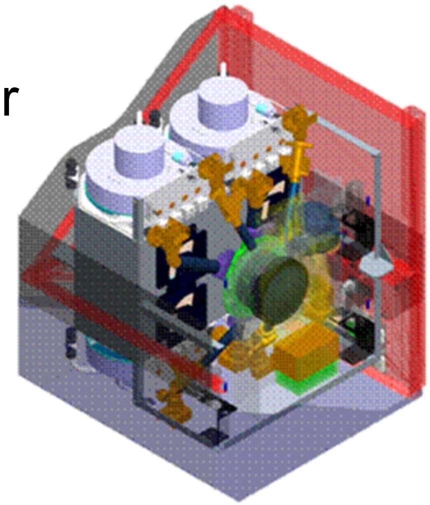
- PTX- developed tightly integrated hot module design
- Hot module includes:
  - Thermally integrated dry CPOX fuel processor
  - Stack
  - Recuperator
  - Tail-gas combustor
  - Mechanical structure
  - Insulation
- Initial design complete, first modules built Q3 2008



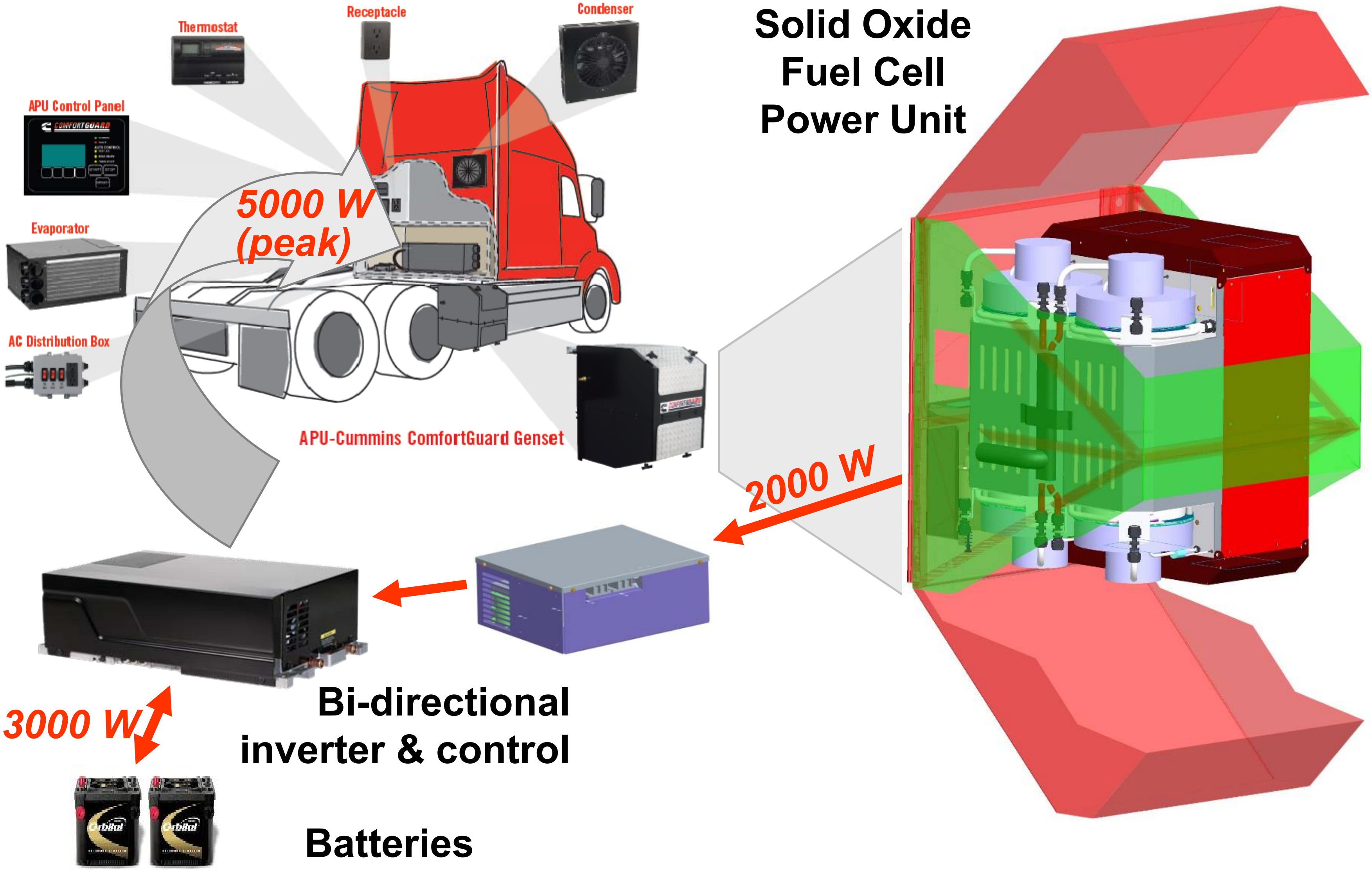


System Design 1

- Initial decision on “4-pack” module arrangement for Design 1
- Replicated module concept met initial program objectives for achievable module scale-up, projected power requirement
- Existing PTX 250 W module scaled to 650 W gross
- “4-pack” projected to yield > 2000 W net system power
- Master control with CAN Bus connected replication of control elements
- System packaging provides simple connection between hot zone modules, cold balance of plant, controls, power electronics
- SOFC assembly locates to truck frame rail
- Batteries and power electronics located separately on vehicle



System Arrangement Design 1



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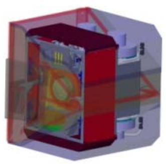
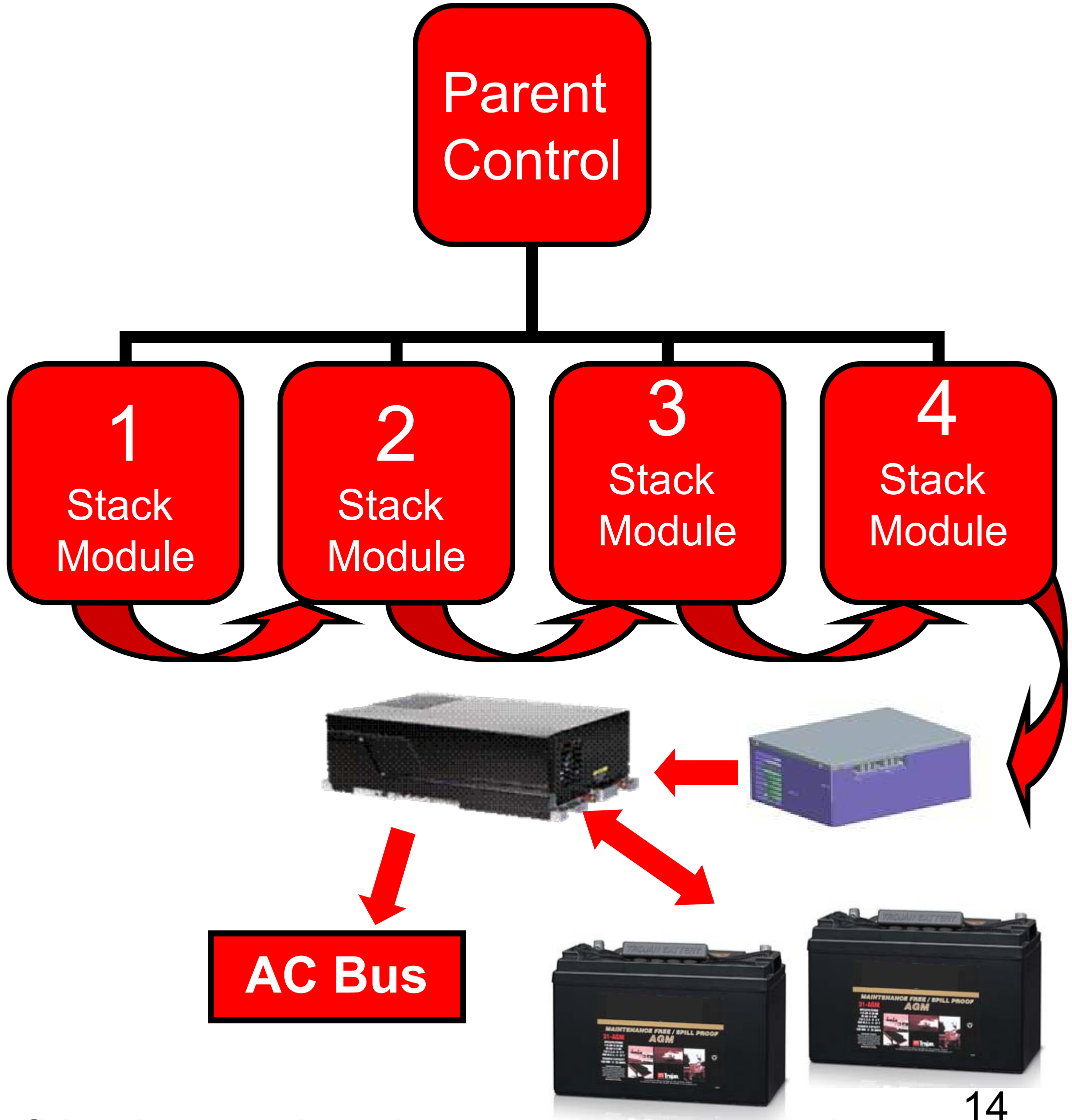
System Snapshot Status

	Power Watts	Weight Kg	Volume L	Fuel Consumption gph avg	Noise dB(A) @ 3m
 Diesel APU	4000 Continuous	170	235	0.27	75dB(A)
SOFC System Total	4500 Peak 1500 Continuous	197 Total	391 Total	0.18	55 dB(A) (est.)
 SOFC Unit		96	304	N/A	N/A
DC-DC Boost, Control, Inverter 		53	62	N/A	N/A
Batteries 2 x Group 24 		48	25	N/A	N/A

System Balance of Plant Controls & Power Electronics Snapshot vs.Targets

- **Modular Control Architecture**
  - **Independent operation and regulation of four stack modules**
  - **Shared air source**
  - **Adaptable to changes in system feature scope and scale**
- **Power Electronics (output stage)**
  - **High Efficiency DC-DC Boost**
  - **Modified commercial (CPG) DC-AC inverter**
  - **Tested with simulated fuel cell source**
  - **Interfaced over common CAN bus for current mode control of stack modules**



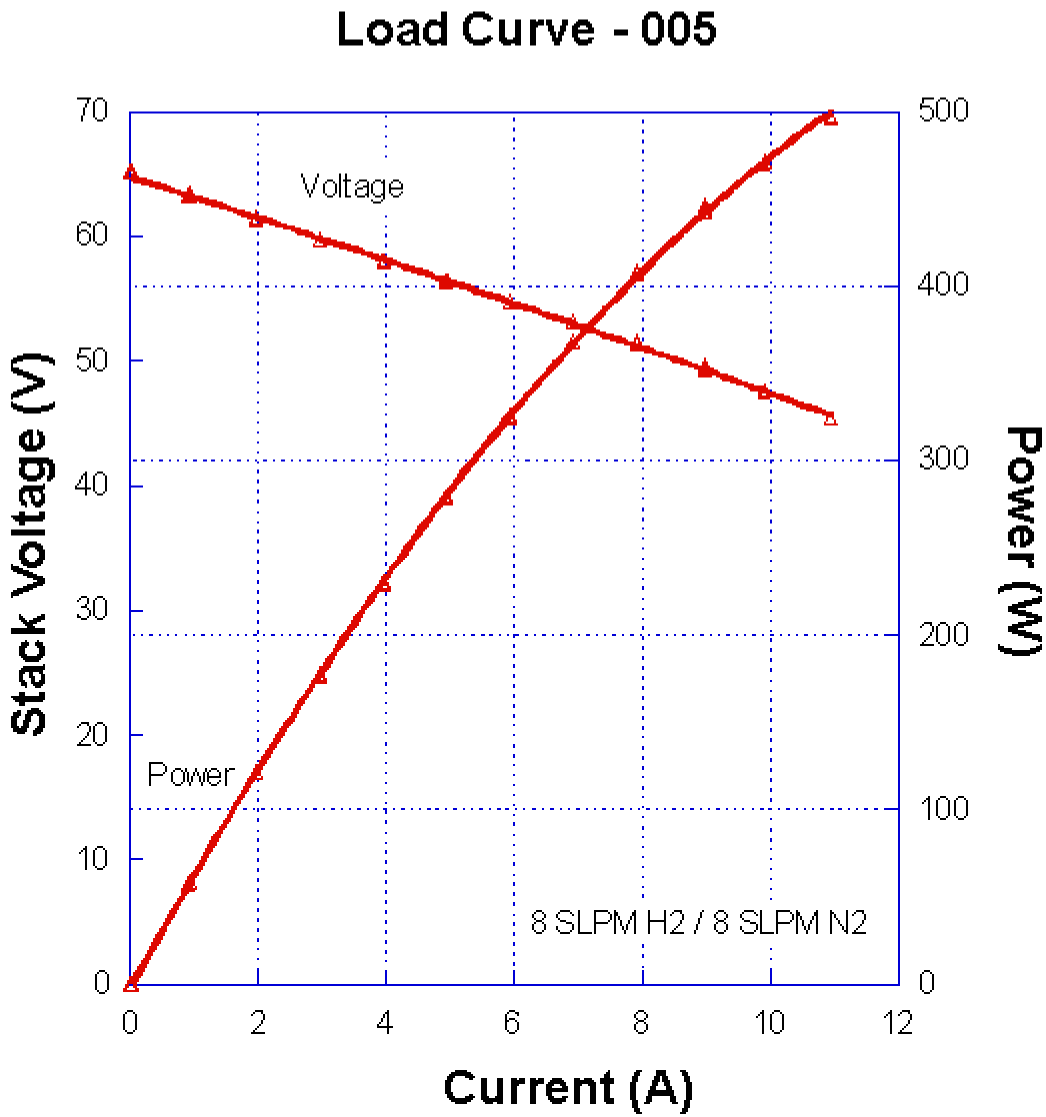
Stack Design

- 4 modules, 66 cells/module, series connection
- Target performance for 4-module assembly

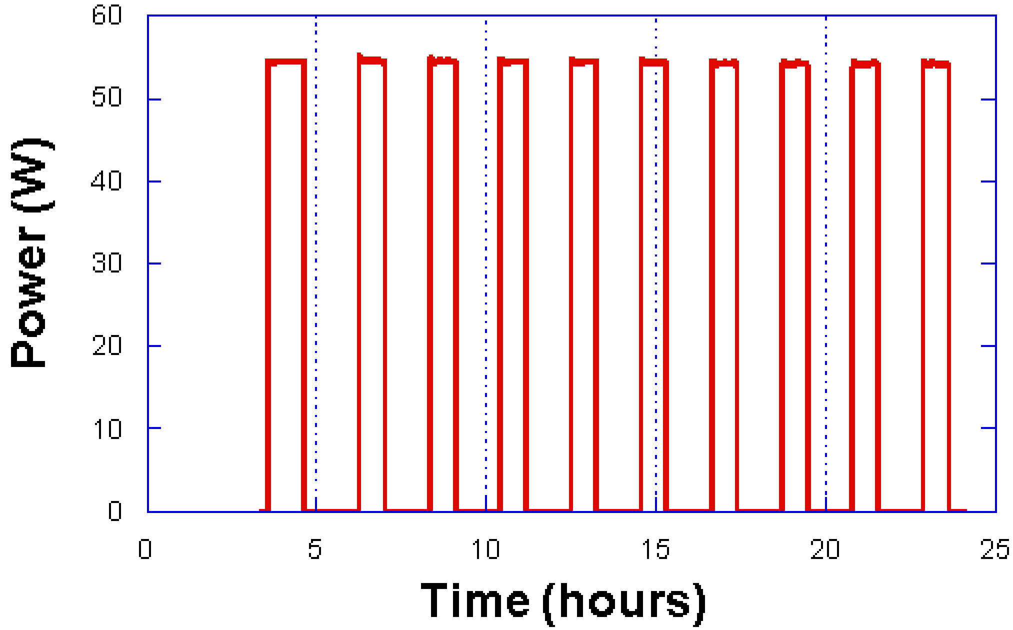
parameter	*Design 1 target*	*Snapshot status or estimate*
Gross power	15.3 A @ 171 V = 2600 W (650 W / module)	10.9 A @ 183 V = 2000 W (500 W / module)
OCV 4 modules in series	264–276 V (>65V / module)	264–276 V (64-66v / module)
BOP parasitic Power	200 W	500 W
System Efficiency DC/LHV	21% net (2400 W net)	18% net (1500 W net)
Fuel utilization	70%	63%

Stack load curve

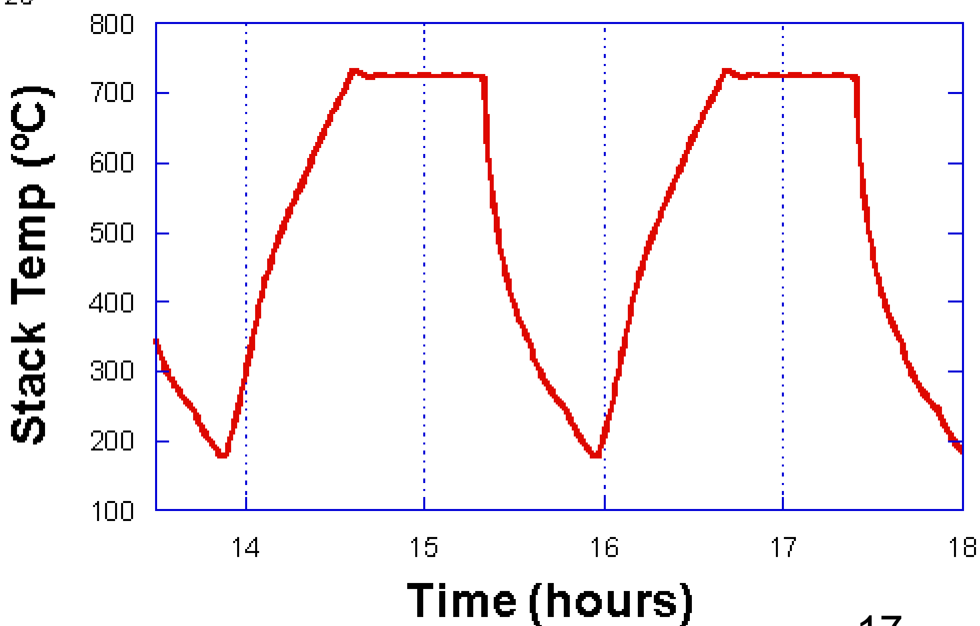
- Integrated fuel processor / stack / HX / tailgas-combustor
  - Single insulation package, one thermal zone
  - Low-cost (simple geometry, no exotic alloys)
- Power density below target
  - Tube limitations (lifetime/power density trades)
  - Anode/cathode flow distributions and temperature



Sub-scale Stack thermal cycling



<1% degradation in 10 thermal cycles



Stack heating and cooling
40 minutes heatup
40 minutes cooldown

Fuel Processor Status vs. Targets

	Design 1 Target	Demo Plan	Notes
Water requirement	None	None	Dry CPOX
Vaporizer startup energy	None	470 kJ	130 Wh
Minimum carbon-free O:C ratio	1.3	1.3	
Maintenance interval	>500 hrs	> 150 hr: vaporizer (> 500 hr: atomizer)	Vaporizer selected for initial demonstration
Vaporizer power requirement in steady state	0 W	0 W	Driven with stack waste heat

Fuel Processor Accomplishments and Progress

- Simplest possible fuel processor—extremely compact and inexpensive design
- Demonstrated stable operation of SOFC stack on ULSD with no added or recovered water
- Higher O/C ratio required to avoid carbon formation with ULSD
  - Boundary is sensitive to fuel composition and reactor thermal integration
  - Reformer capable of 1.1 O/C operation; carbon deposition in stack drives 1.3 O/C at this time

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Module
Accomplishments and progress

- **Integrated fuel processor / stack / HX / tailgas-combustor**
  - Simple geometry
  - Single insulation package, one thermal zone
  - Low-cost, simple geometry, no exotic alloy parts
- **Demonstrated thermally-self-sustaining operation**
  - Overall balance good
  - Working to improve axial temperature gradients
- **Experienced tube failures during initial stack reduction**
  - Better seals
  - Higher cathode flow
  - Less instrumentation (possible electrical shorting)

Future Directions Design 2 Evolution

Design 1

- 5000 W Peak
- 2000 W Continuous

Parent Control

1 Stack Module | 2 Stack Module | 3 Stack Module | 4 Stack Module

2 x Group 24
160 Amp-Hours

Design 2

- 4000 W Peak
- 1000 W Continuous

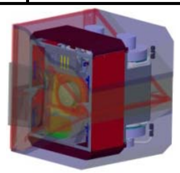
- Smaller prime mover
  - Single SOFC module
  - Nominal 1 kW
- Increased storage
- Simplified system
  - Lower cost
  - Higher reliability

Parent Control

1 Stack Module

2 x Group 31
220 Amp-Hours

Future Directions Design 2

	Power Watts	Weight Kg	Volume L	Fuel Consumption gph avg	Noise dB(A) @ 3m
 Diesel APU	4000 Continuous	170	235	0.27	75dB(A)
SOFC System Total	4000 Peak 1000 Continuous	159 Total	198 Total	0.14	55 dB(A) (est.)
 SOFC Unit		64	140	N/A	N/A
Integrated DC-DC Boost, Control, Inverter 		29	31	N/A	N/A
Batteries 2 X Group 31 		66	27	N/A	N/A

Summary
Work to Complete Project (as of March 2009)

- Fabrication of completed design for demonstration unit
  - BOP sub-systems completed
  - Controls and power electronics hardware completed
  - Stack modules 90% complete
  - Housing ready for fabrication
- Controls tuning of operational SOFC modules
  - Ready to start upon delivery of module(s)
- Upfit of SOFC APU and Power electronics to test vehicle
- On-vehicle demonstration

Summary

- 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 and continuing DOE support could accelerate production viability

Acknowledgements

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