

# **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*

## ■ Cummins Power Generation

- Balance of Plant (blower, fuel supply, plumbing)
- Controls & power electronics
- System integration
- Sub and system testing
- On-vehicle demonstration



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
- No longer active in project



Fort Wayne, IN

# 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

# 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)

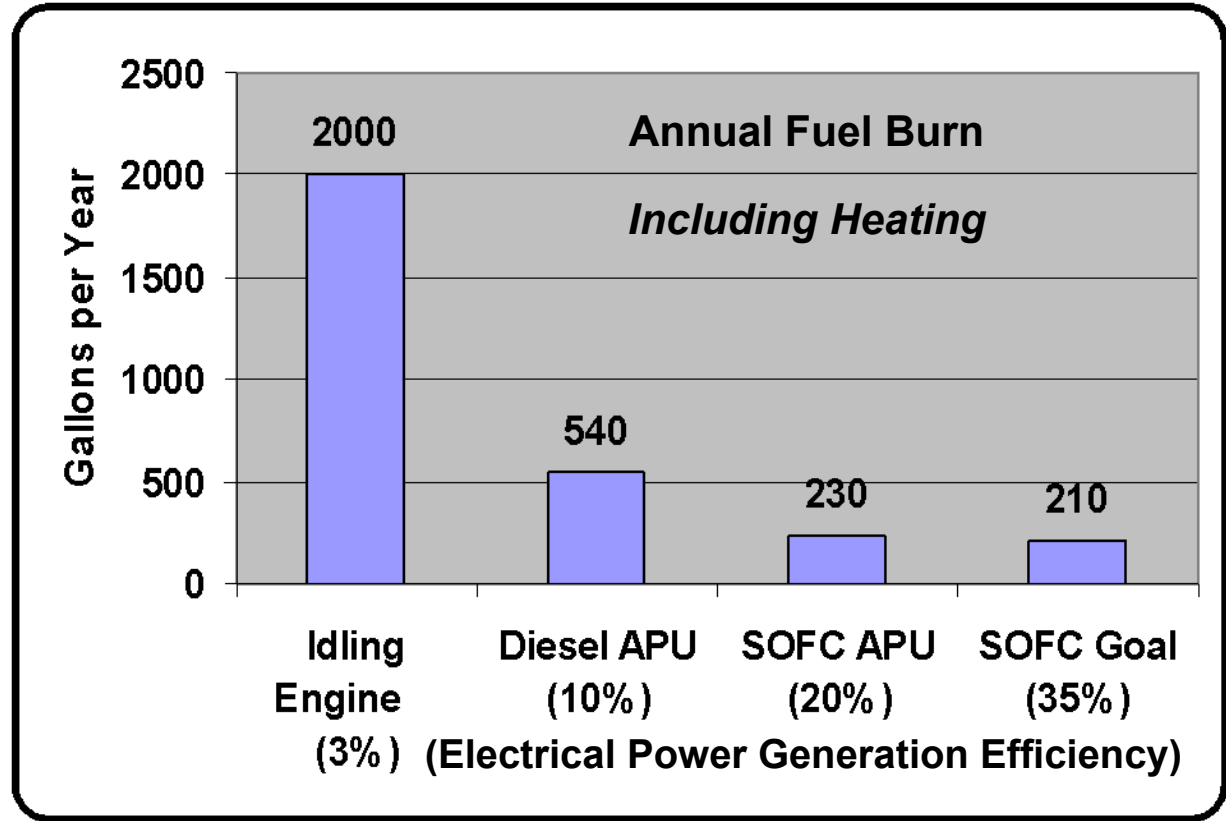
# Overview and Objectives



- **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**

# 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



# Approach



**Analysis and design**  
95% Complete

**Sub-system test and development**  
90% Complete

**Laboratory system testing**  
40% Complete

<b>Balance of Plant</b>	Supply and Regulation: ● Cathode air Anode air Fuel	Cathode air ● Anode air supply Fuel supply	BOP Assembled Wired Checked
<b>Controls &amp; Power Electronics</b>	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
<b>SOFC, Hot Box Fuel Reformer</b>	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 ●
<b>System Integration &amp; Packaging</b>	General arrangement ● Shock & Vibration attenuation ●	Solid modeling (CAD) ● Stereolithography ● Vibration testing at module level ●	Validate system performance Operation across load range Transient response Efficiency
<b>Vehicle Integration</b>	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



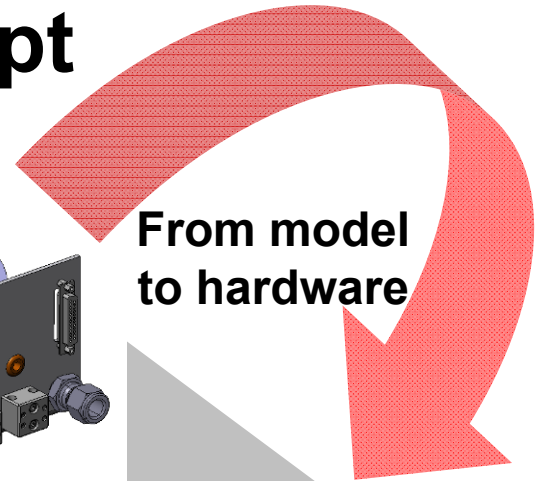
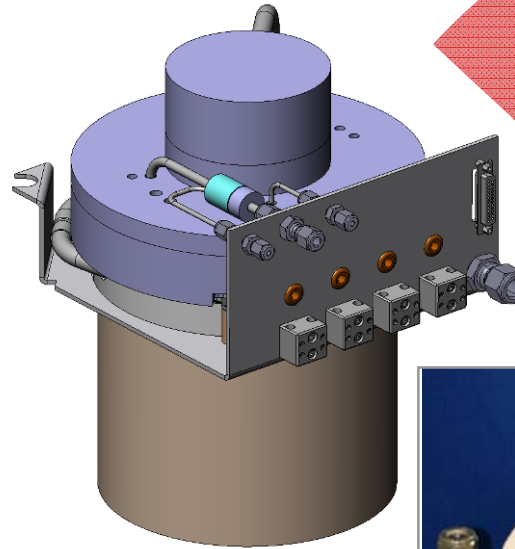
# Milestones

Original Plan  
Current Plan

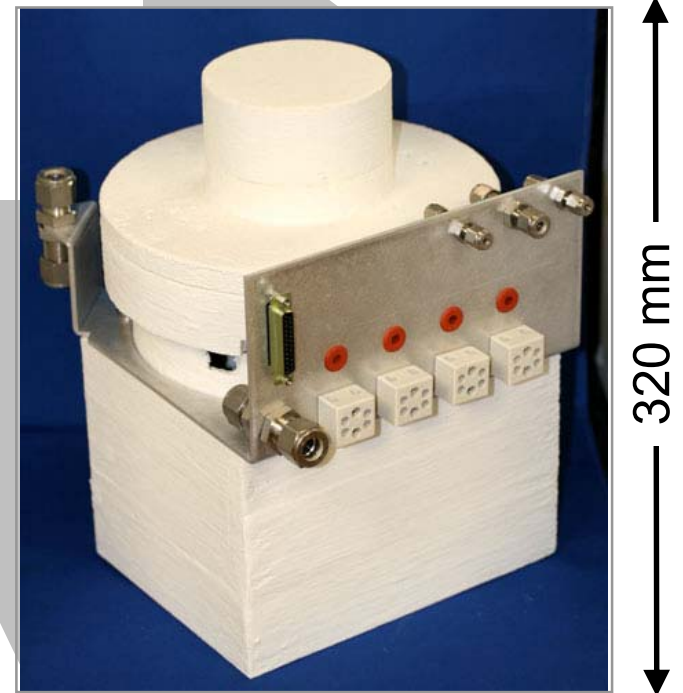
Qtr FY	Qtr FY	Milestone
Q4 FY07	Q4 FY07	Program re-start
Q1 FY08	Q1 FY08	Specifications finalized
Q2 FY08	Q3 FY08	Protonex delivery of Module 1 (Delivered 9/8/2008)
Q4 FY08	Q2 FY09	System BOP design complete
Q1 FY09	Q3 FY09	Protonex delivery of SOFC sub-assemblies
Q2 FY09	Q4 FY09	System checkout ready 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



**From model  
to hardware**

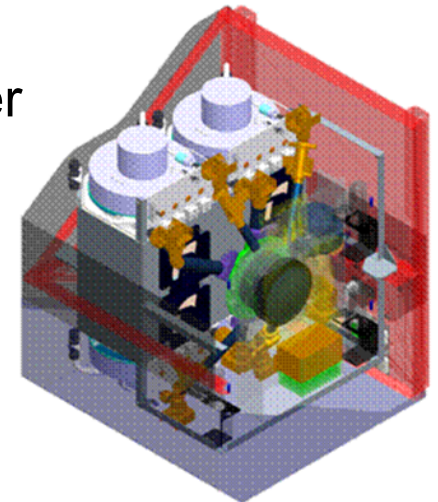


← 250 mm →

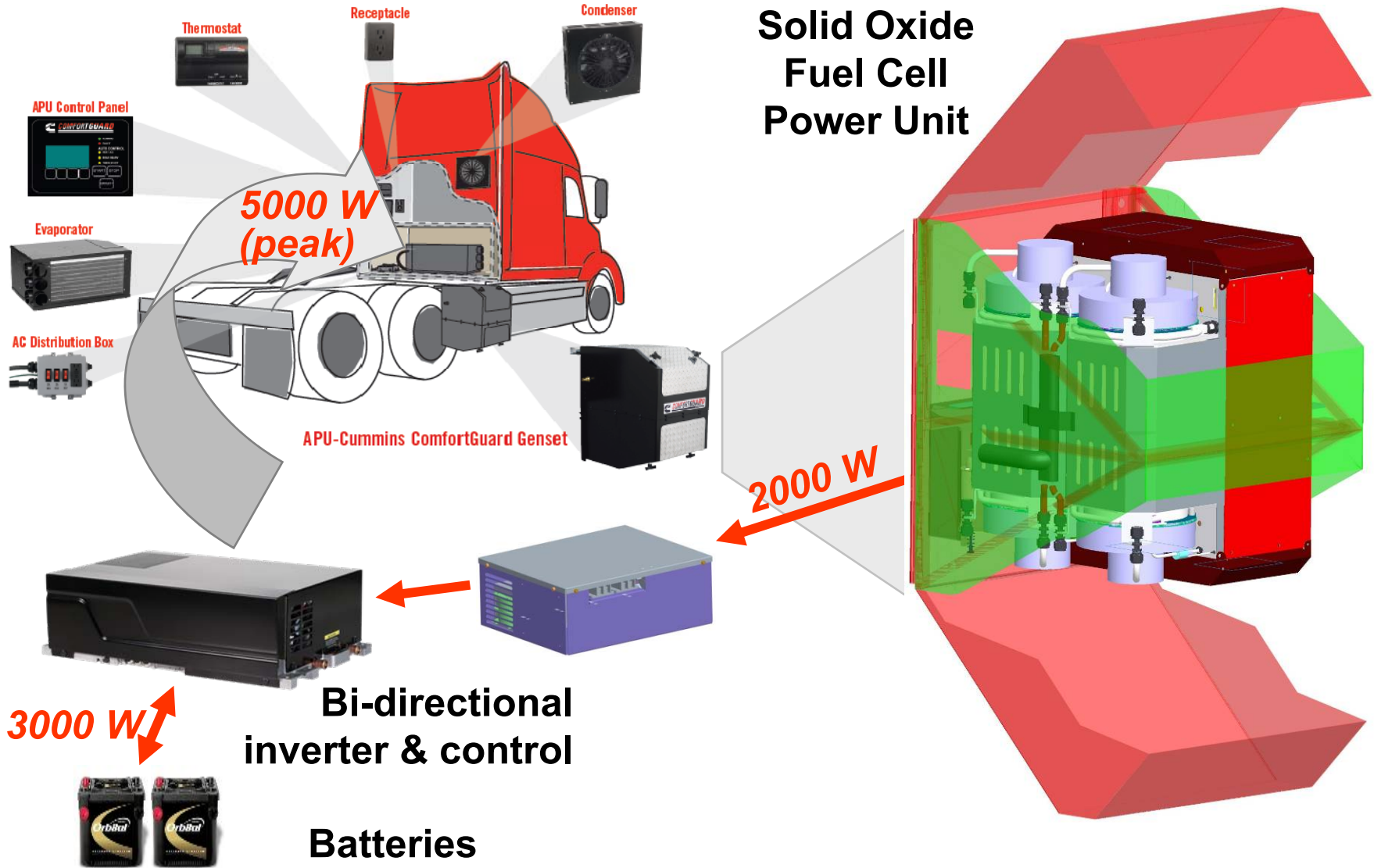
320 mm

# System Design 1


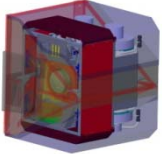


- Initial decision on “4-pack” module arrangement for Design 1
- Replicated module concept met initial program objectives for achievable module scale-up, projected power requirement
- Existing PTX 250 W module scaled to 650 W gross
- “4-pack” projected to yield > 2000 W net system power
- Master control 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



# 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

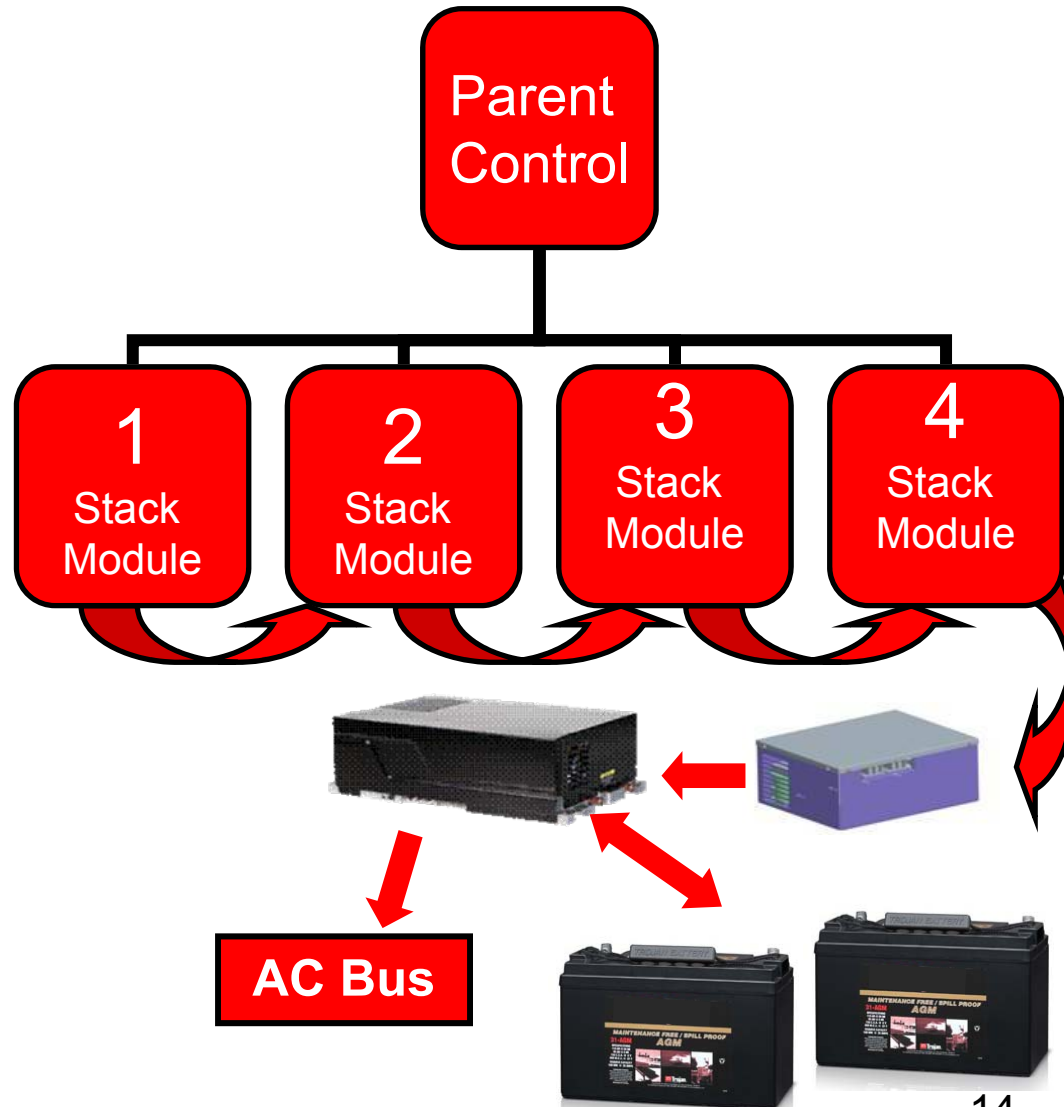
- **Power Electronics (output stage)**

- ↳ 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





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

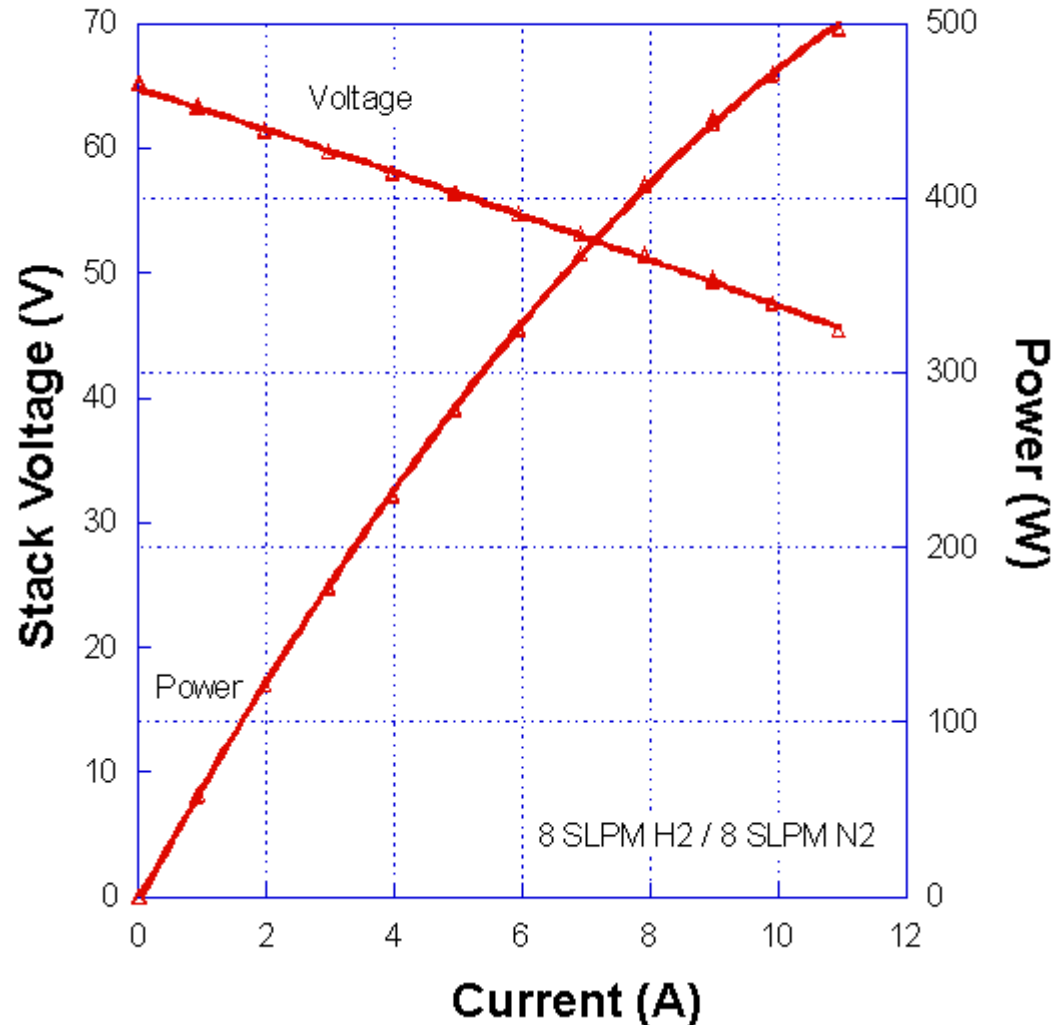
<i>parameter</i>	<i>Design 1 target</i>	<i>Snapshot status or estimate</i>
● Gross power	15.3 A @ 171 V = 2600 W (650 W / module)	10.9 A @ 183 V = 2000 W (500 W / module)
● OCV 4 modules in series	264–276 V (>65V / module)	264–276 V (64-66v / module)
● BOP parasitic Power	200 W	500 W
● System Efficiency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



# Stack load curve

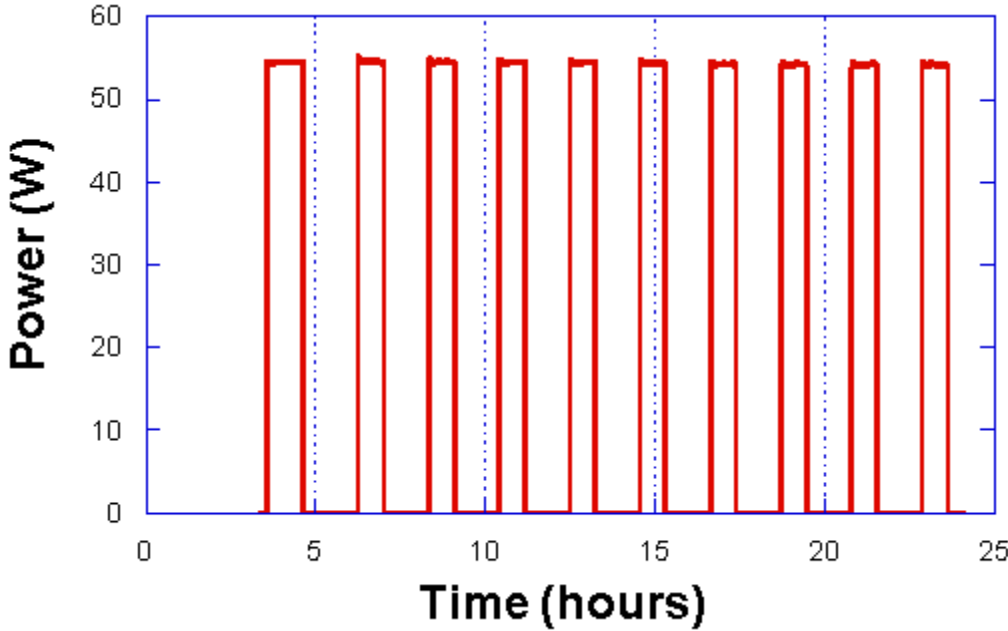
Load Curve - 005

- **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**



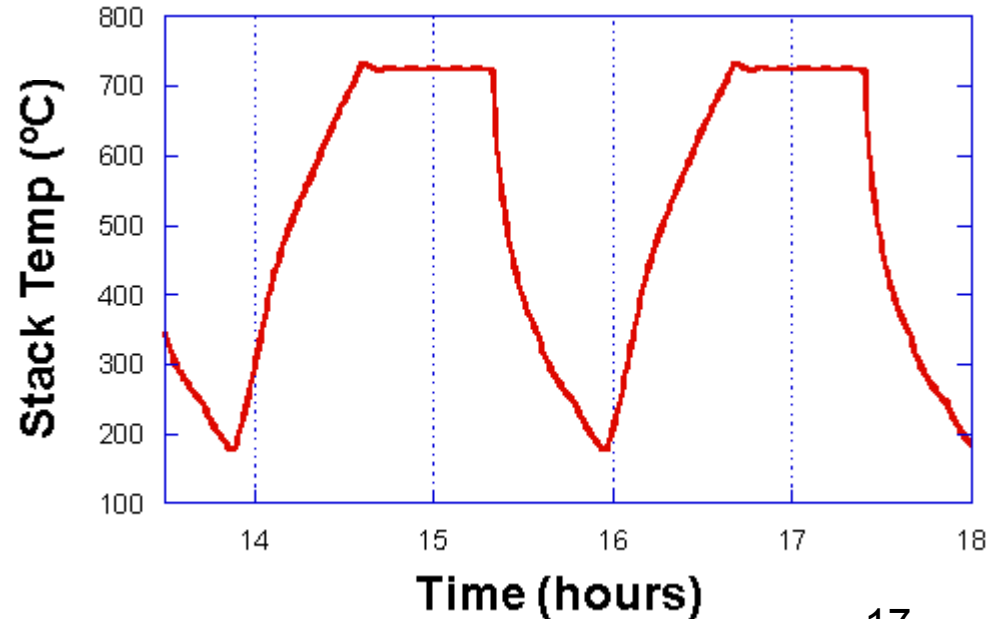
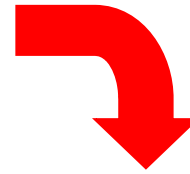


# Sub-scale Stack thermal cycling







**Stack heating and cooling  
40 minutes heatup  
40 minutes cooldown**

**<1% degradation  
in 10 thermal cycles**



# 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

# 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

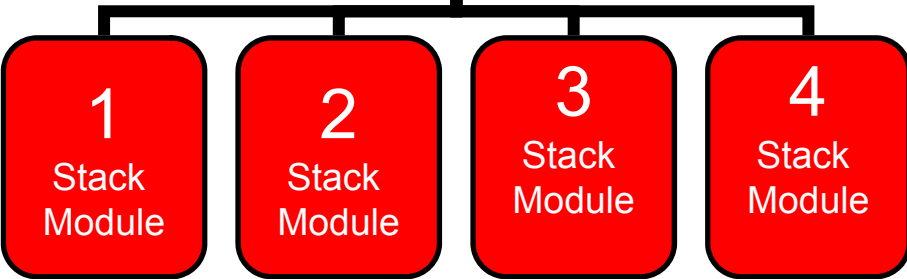
- 5000 W Peak
- 2000 W Continuous



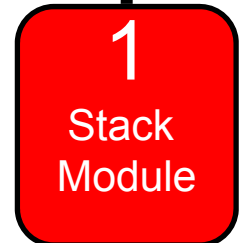
## Design 2

- 4000 W Peak
- 1000 W Continuous

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


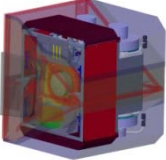


2 x Group 24  
160 Amp-Hours



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	<b>159 Total</b>	<b>198 Total</b>	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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