Power Generation

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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FC061

Collaborations

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

Fort Wayne, IN

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Relevance
Truck APU's

- Studies indicate that approximately 500,000 class 7/8 trucks currently travel more than 500 miles from base on their daily trips
- It is estimated that these trucks may spend up to 300 days per year idling for 8 hours per day at overnight rest stops to provide heat and power for the sleeper cab
- Under these conditions idling trucks consume, at 0.8 gals of fuel per idling hour, 960 million gallons of diesel fuel
- Significant amounts of NOx, CO_2 and PM are produced under these engine idling conditions
- Elimination of truck engine idling by providing heat and power in a more efficient manner, (such as a truck mounted APU), has the potential to conserve large amounts of diesel fuel and significantly reduce exhaust emissions

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Solid Oxide Fuel Cells

for Truck APU's

Relevance

✓ Addressed
⇘ To be addressed

- Advantages
  - ✓ High efficiency, flat efficiency characteristic vs load
  - ✓ Extremely low emissions
  - ✓ 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 full production volumes
    - Making initial production affordable is a challenge

Overview and Objectives

Timeline

- Project start: 9/1/2004
- Placed on hold FY 2006; restarted Aug 2007
- Contract end: 12/31/2009
- Completed: 2/26/2010

Budget

- Project funding (complete)
  - DOE = $3,225,611
  - Contractor = $1,765,678

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 (vehicle requirements, systems, interface)

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Objectives and Results

Objective		Result
On-vehicle demonstration and evaluation of a SOFC APU with integrated on board reformation of diesel fuel	⟺	Simulated vehicle demonstration with loads including air conditioner, battery charging
Develop transparent method of water management for diesel fuel (ULSD) reformation	⟺	Operated dry CPOX on pump ULSD without water supply or recycle
Develop controls to seamlessly start, operate and shutdown SOFC APU	⟺	Some manual intervention required during transients
Evaluate hardening the SOFC APU to enable it to operate reliably in the on-highway environment	⟺	System designed to provide isolation to road vibration and shock, not tested
Develop overall system for performance, size, cost and reliability targets	⟺	System form factor consistent with commercially available anti-idle solutions

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Approach

	Analysis and design	Sub-system test and development	Laboratory system 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 Demo of system operation including Automated stack temperature control Fueling and O/C ratio control
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		12V and 120VAC Load Testing Operated truck air conditioner Battery charging Lighting Waste Heat Recovery (CHP)

Shock & Vibration attenuation system designed and incorporated in prototype but not tested

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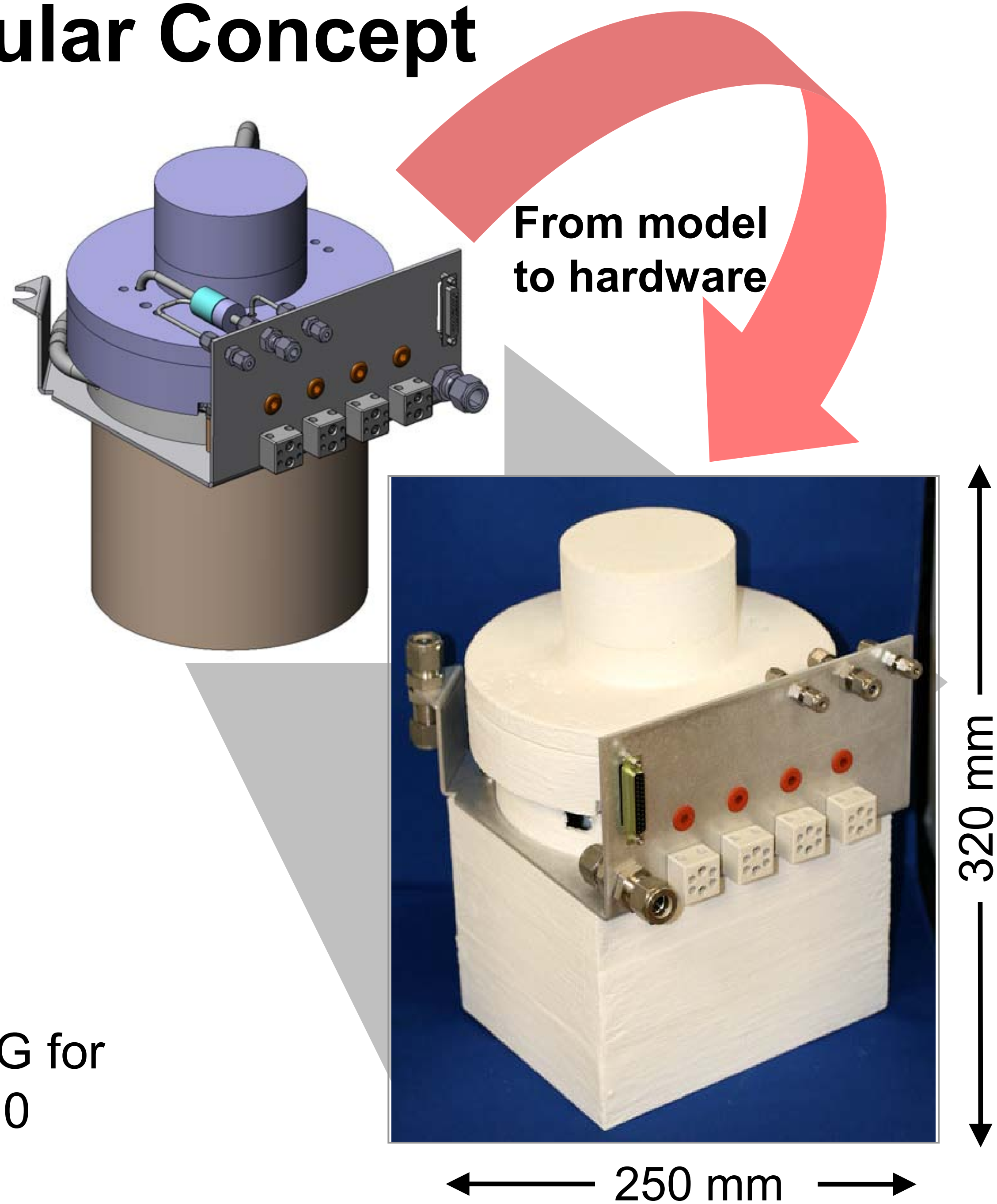
Technical Accomplishments and Progress
Milestones

Qtr FY	Milestone
Q4 FY07	Program re-start
Q1 FY08	Specifications finalized
Q4 FY08	Protonex delivery of Module 1
Q2 FY09	System BOP design complete
Q1 FY10	System checkout ready for testing
Q2 FY10	Protonex delivery of SOFC sub-assemblies
Q2 FY10	Demonstration Testing Complete

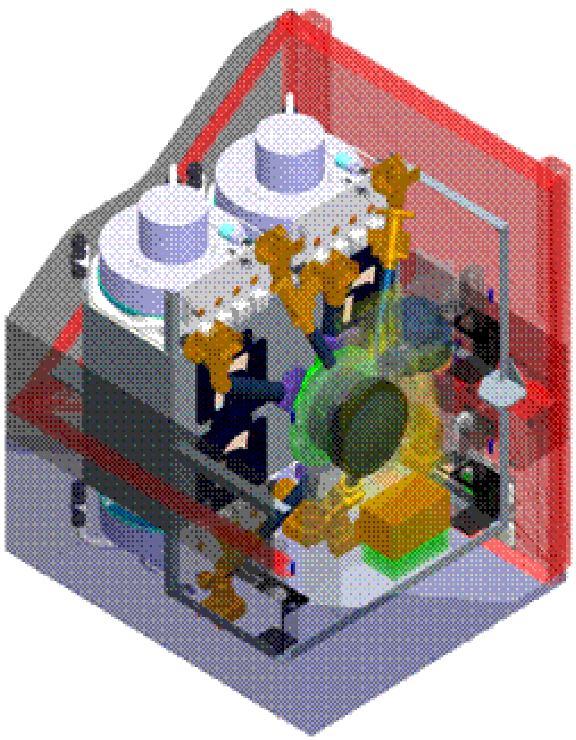
Approach
Modular Concept

- PTX- developed tightly integrated hot module design
- Hot module includes:
  - Thermally integrated dry CPOX fuel processor
  - Stack
  - Recuperator
  - Tail-gas combustor
  - Mechanical structure
  - Insulation
- Final modules delivered to CPG for demonstration testing Feb 2010

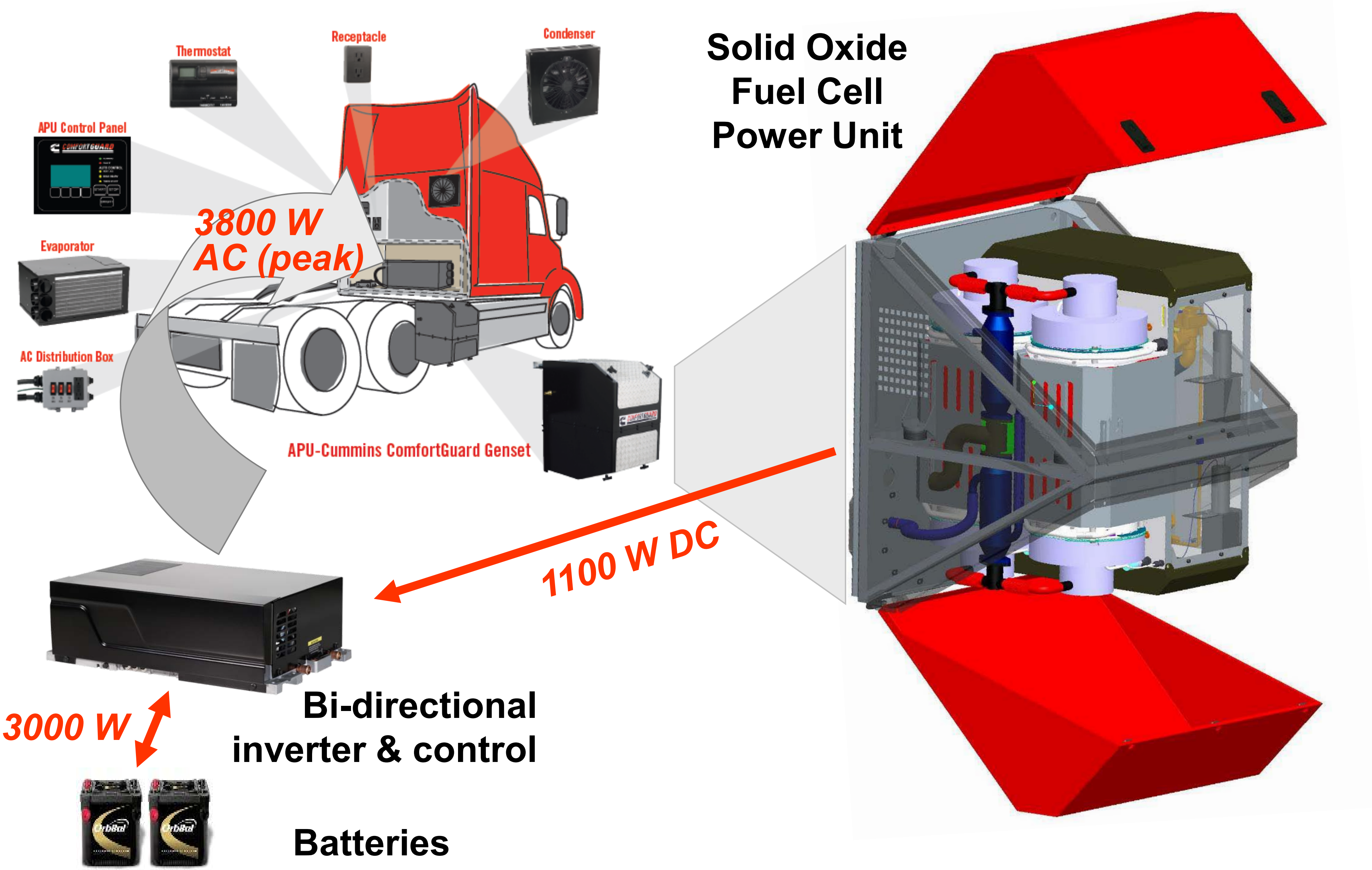


Approach
SOFC System Design

- Initial decision on “4-pack” module arrangement
- Replicated module concept met initial program objectives for achievable module scale-up, projected power requirement
- Existing PTX 250 W module scaled to 450 W gross
- “4-pack” of SOFC modules yields > 1100 W DC net system power, enough to simultaneously run air conditioning and lighting
- Master control with CAN Bus connected replication of control elements
  - 1 “parent” board
  - 4 “child” boards, one per module
- 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

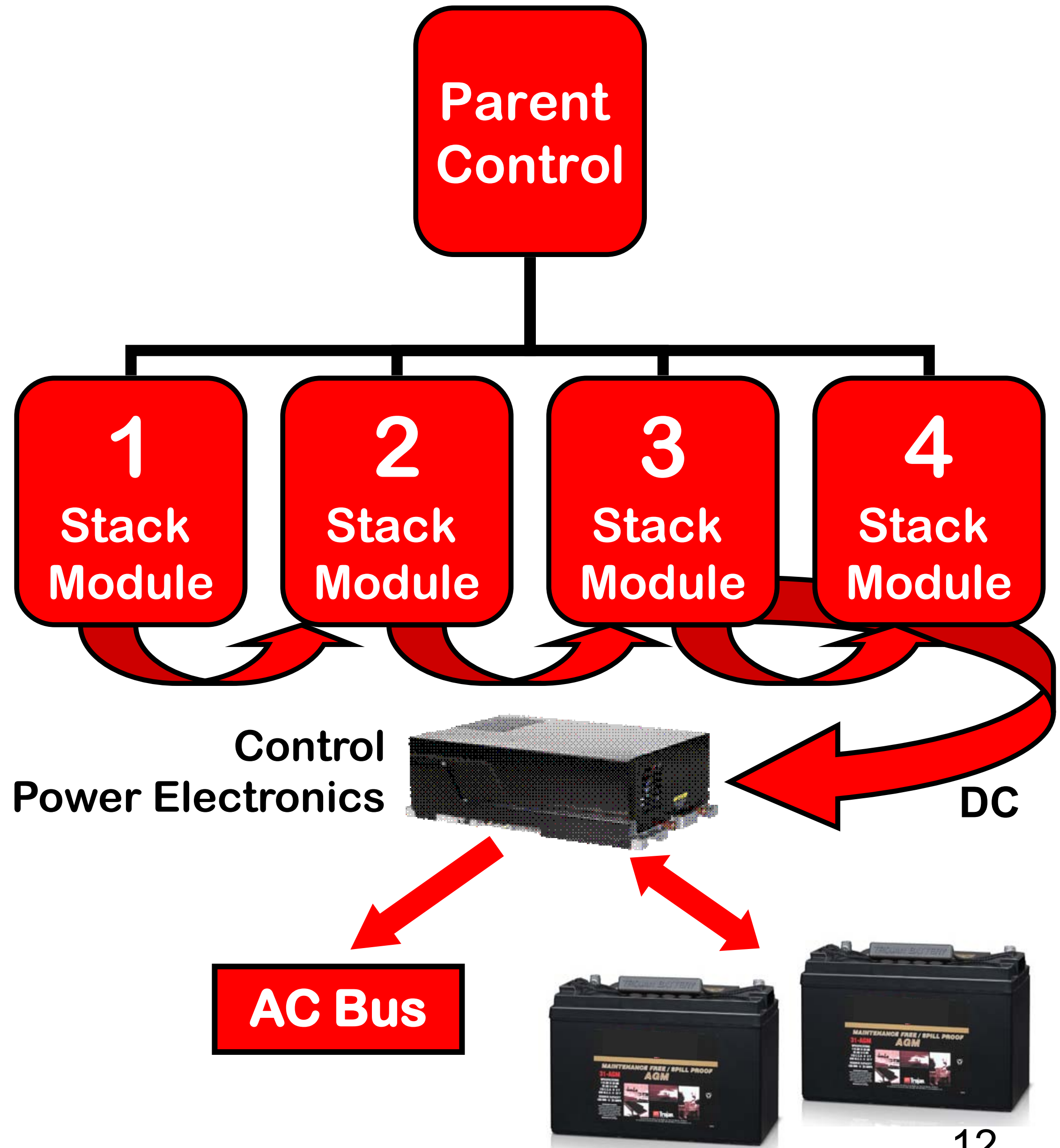


Approach
System Arrangement



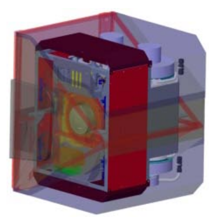
Approach
System Balance of Plant Controls & Power Electronics

- **Modular Control Architecture**
  - **Independent operation and regulation of four stack modules**
  - **Common cathode air source**
  - **Anode air boosted from cathode, module by module flow regulation**
  - **Independent fuel supplies**
  - **Adaptable to changes in system feature scope and scale**
- **Power Electronics (output stage)**
  - **High Efficiency DC-DC Boost**
  - **Modified commercial (CPG) DC-AC inverter**
  - **Interfaced over common CAN bus for current mode control of stack modules**



Technical Accomplishments and Progress

System Status

	Rated Power (Watts)	Weight Kg	Volume L	Fuel Consumption gph avg	Noise dB(A) @ 3m
 Diesel APU	4000 Available	170	235	0.27 @ 1500 W	75dB(A)
SOFC System Total	3800 Peak AC 1100 Net DC 820 Net AC	197 Total	360 Total	0.24 @ 1100 W	55 dB(A) (est.)
 SOFC Unit		120	304	N/A	N/A
Control Power Electronics 		29	31	N/A	N/A
Batteries 2 x Group 24 		48	25	N/A	N/A

Technical Accomplishments and Progress

Stack Design

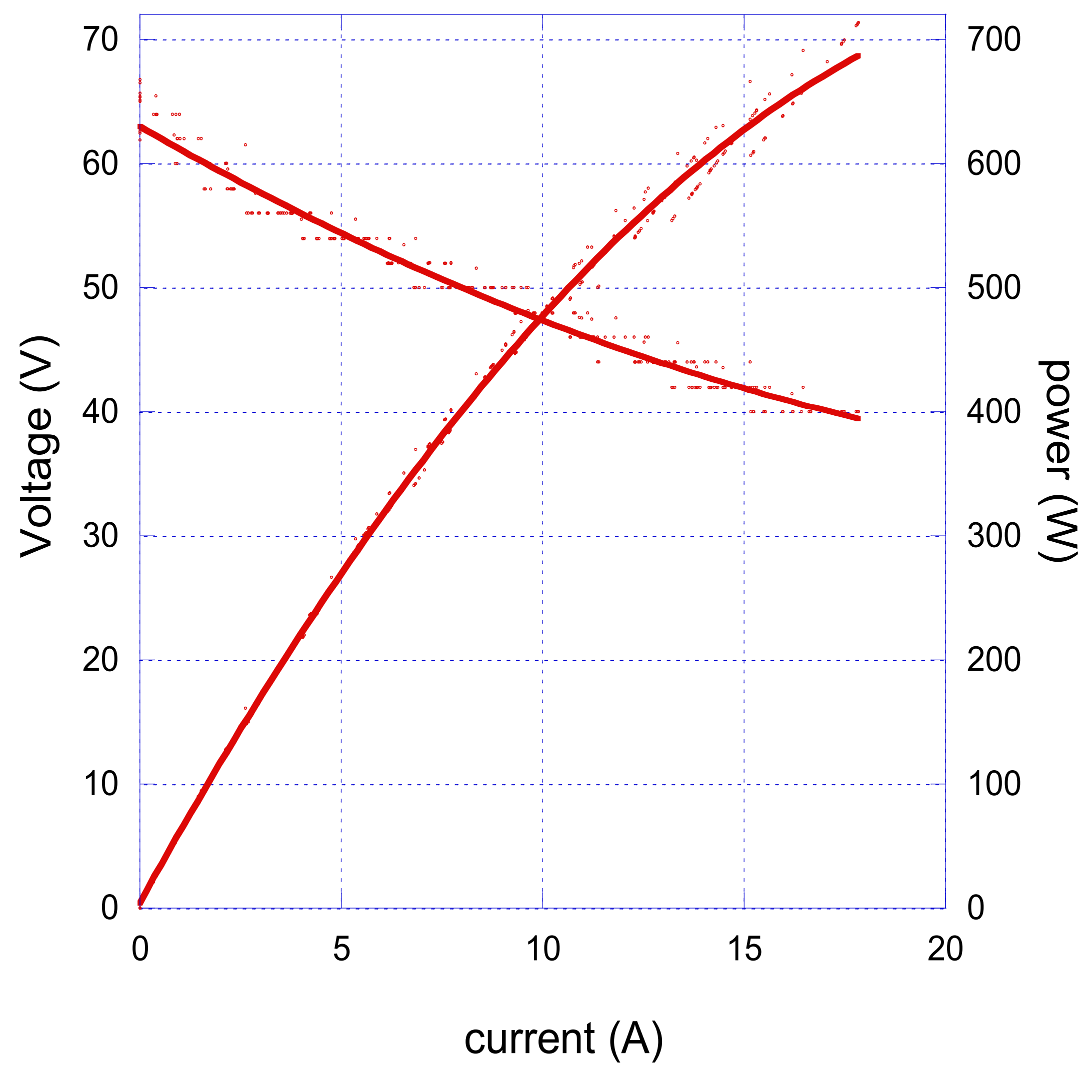
- 4 modules, 66 cells/module, series connection
- Target performance for 4-module assembly

parameter	*Design 1 target*	*Demonstration*
Gross power 4 modules in series	15.3 A @ 171 V = 2600 W (650 W / module)	10.0 A @ 168 V = 1680 W (420 W / module)
OCV 4 modules in series	264–276 V (>65V / module)	264–276 V (64-66v / module)
BOP parasitic power (system)	200 W	< 450 W
System Efficiency DC/LHV	21% net @ (2400 W net)	11% net @ (1100 W net)
Fuel utilization	70%	45%

Technical Accomplishments and Progress

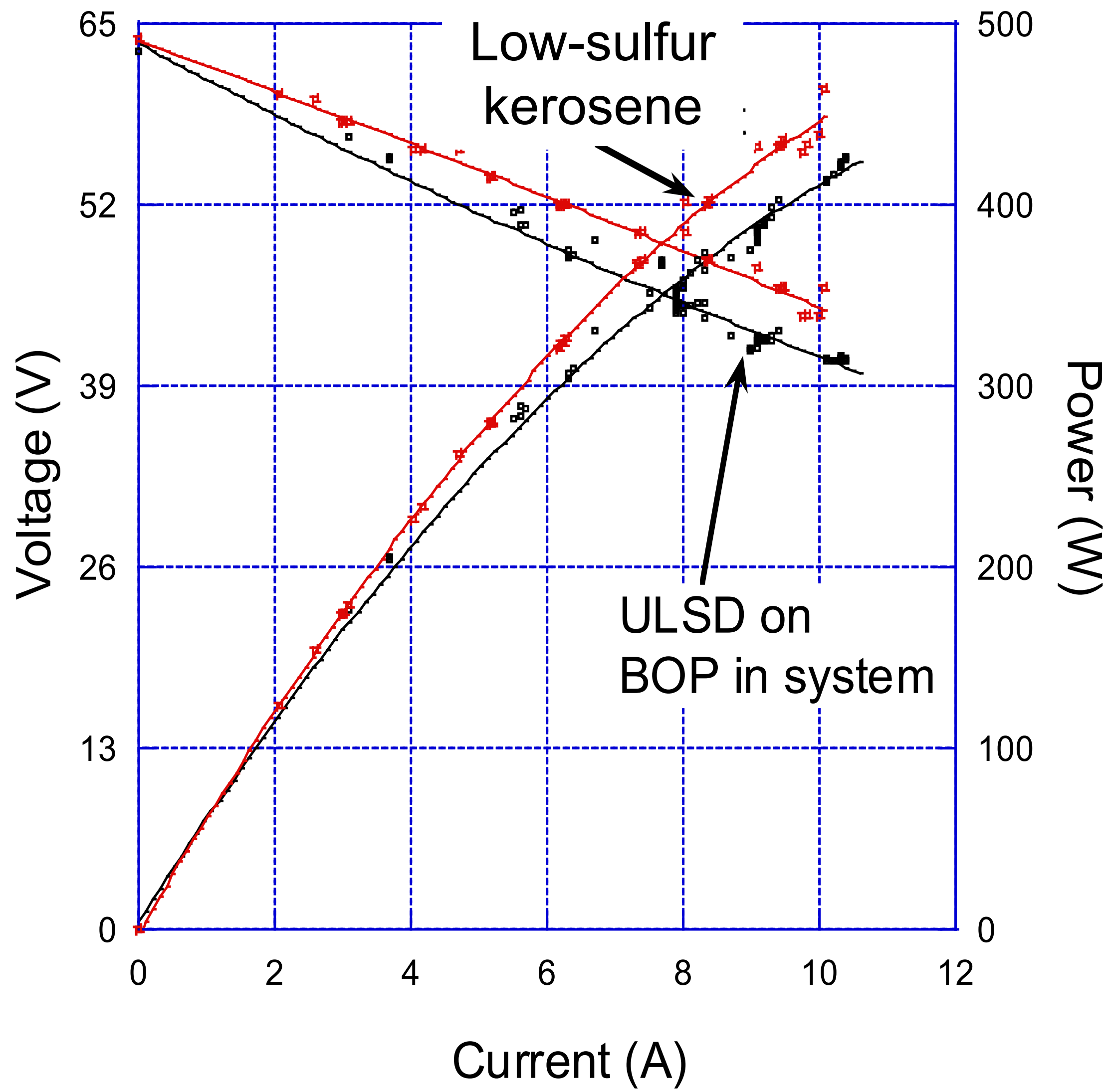
Performance – Full Scale Stacks

- Integrated fuel processor / stack / HX / tailgas-combustor
- Single insulation package, one thermal zone
- Low-cost (simple geometry, no exotic alloys)
- H2/N2 operation in furnace
- Peak power
  - >600 W per stack
  - 713 W highest recorded
- Power at nominal operating conditions 520-570 W
- Low cost fabrication/ assembly methods developed
- Multiple stacks built -- good stack-to-stack consistency



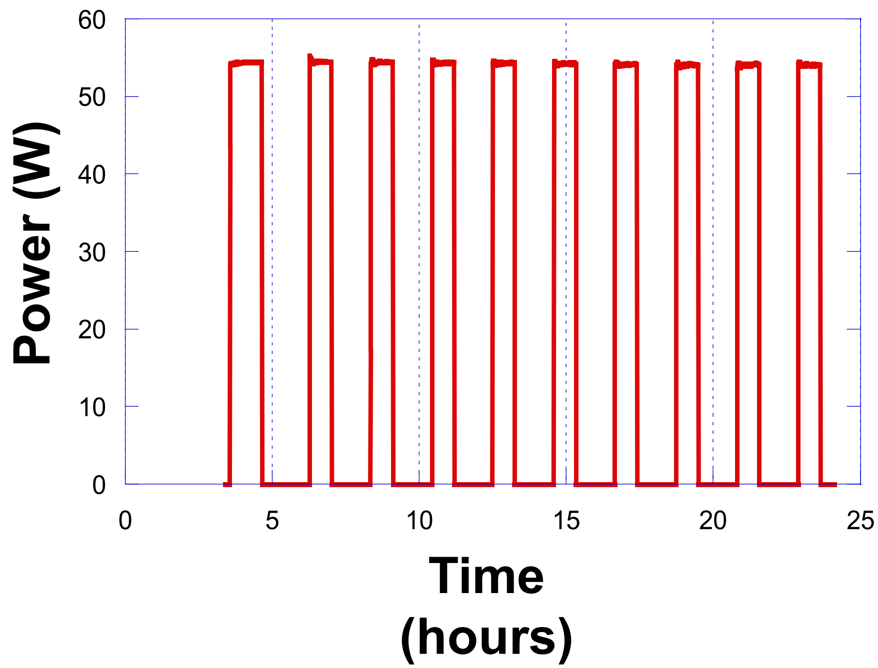
Technical Accomplishments and Progress
Performance – Liquid Fuel

- **Operation on low-sulfur kerosene with mass flow controllers in laboratory**
  - **Identical test facility with ULSD showed results within 2%**
- **Performance on BOP in final system test showed 8% difference with low-sulfur kerosene results in laboratory at 10A**
- **410 - 450 W at nominal operating conditions**
- **Difference with H_2/N_2 performance is thermal limitation on fuel flow and O/C**
- **Optimizing insulation with tube configuration could significantly increase performance**



Technical Accomplishments and Progress

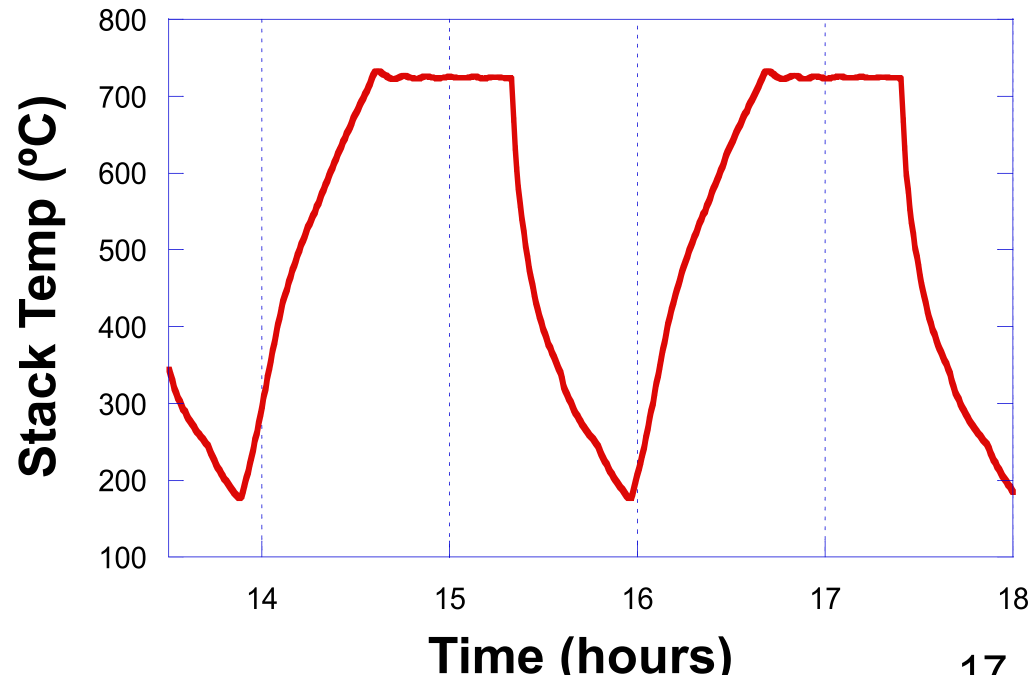
Sub-scale Stack thermal cycling



<1% degradation in 10 thermal cycles

Stack heating and cooling
- **40 minutes heat-up**
- **40 minutes cool-down**

Sub-scale stack operating on low-sulfur kerosene



Technical Accomplishments and Progress

Fuel Processor

- Simple fuel processor—extremely compact and inexpensive CPOX 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 drove 1.3 O/C for demo

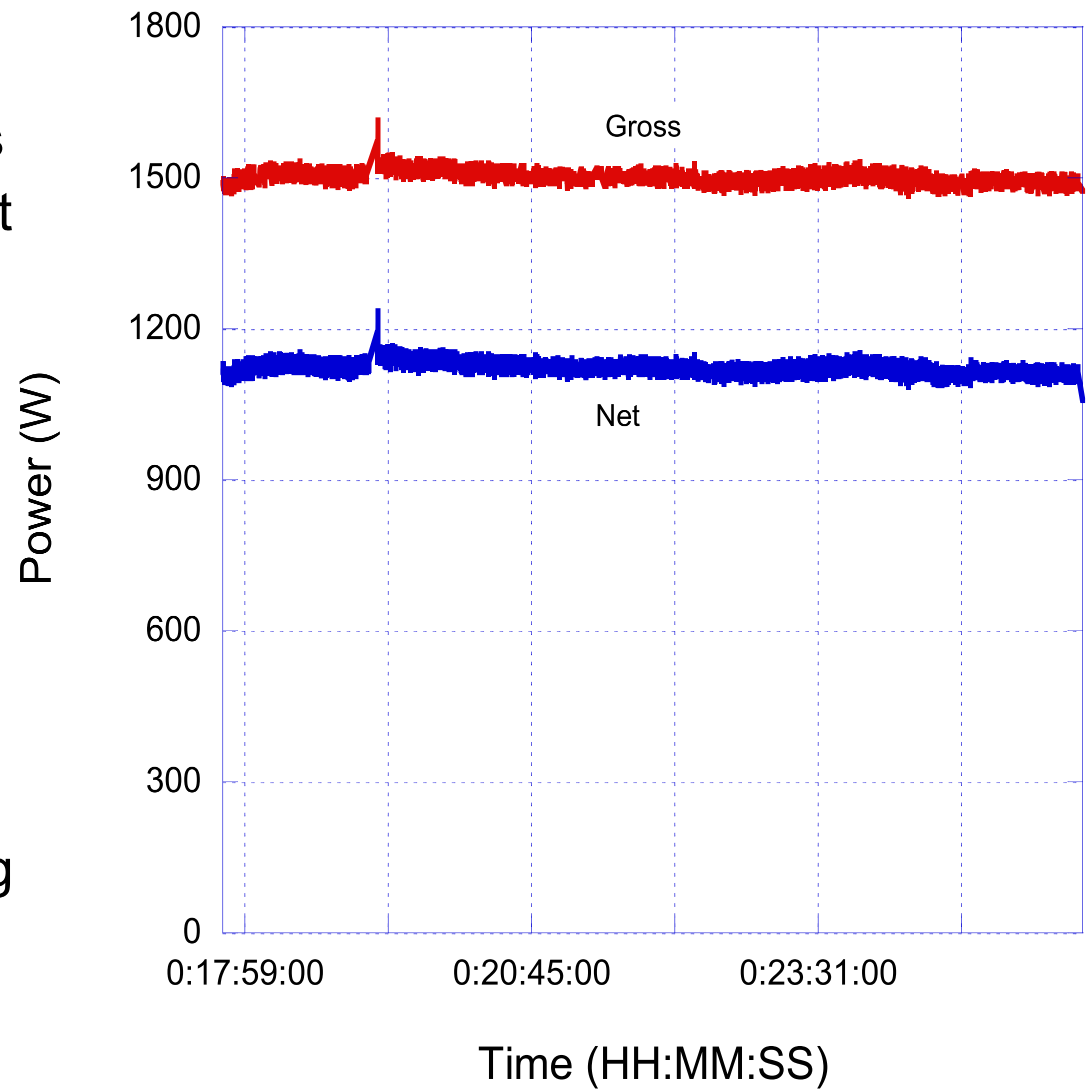
Technical Accomplishments and Progress

SOFC Module

- **Integrated fuel processor / stack / HX / tail-gas 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
- **Power production**
  - >600 W per stack on H_2/N_2
  - 16% reduction moving from H_2/N_2 to liquid fuel
  - Liquid fuel operation
    - thermally limited due to cell performance
    - minor upgrades can significantly increase output
  - Demonstrated 14 cycles on liquid fuel (5 low-sulfur kerosene, 9 ULSD)

ULSD Operation At CPG

- Results are for 4 modules operating in system on ULSD
- All BOP, controls, and system integration performed by Cummins
- ULSD from the pump for entire test
- Simultaneous operation
  - Air conditioning
  - Simulated cab lighting
  - Additional DC loading
  - Combined heat and power (CHP) generation
- Fully hybridized system
- Chassis and power conditioning based on production hardware
- 11 hours DC, 1.5 hours AC loading
  - > 1520 W **DC** (>1100 W net)
  - > 1460 W **AC** (>820 W net)
- Peak power ~1680 W DC (1230 W DC net)



Technical Accomplishments and Progress

Results vs.Targets

- **Tube Performance → power, efficiency**
  - Smaller (previous design) tubes used to estimate gross power target
  - Larger delivered tubes did not meet original specifications
    - Lower power production
    - Reduced performance at higher utilizations
    - Larger statistical performance distribution
- **Thermal limitations → power, efficiency**
  - Thermal integration design based on tubes with original performance resulted in reduced maximum fuel flow rate
  - Significant increases in performance are possible if thermal integration were re-designed to match current tube performance
- **CPOX → efficiency**
  - Further development needed to optimize carbon-free operation at target O/C ratio
- **System Integration (BOP) → efficiency**
  - BOP sized to original power target (650W / module)
  - Lower efficiency operating off design point
  - Heat transfer off larger modules required active cooling

Proposed Future Work
Design 2 Evolution

Design 1
- 3800 W Peak
- 820 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

Proposed Future Work Design 2

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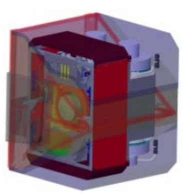
SOFC System Total	4000 Peak 1000 Continuous	159 Total	198 Total	0.14 @ 1000W	55 dB(A) (est.)
 SOFC Unit		64	140	N/A	N/A
Integrated DC-DC Boost, Control, Inverter 		29	31	N/A	N/A
Batteries 2 X Group 31 		66	27	N/A	N/A

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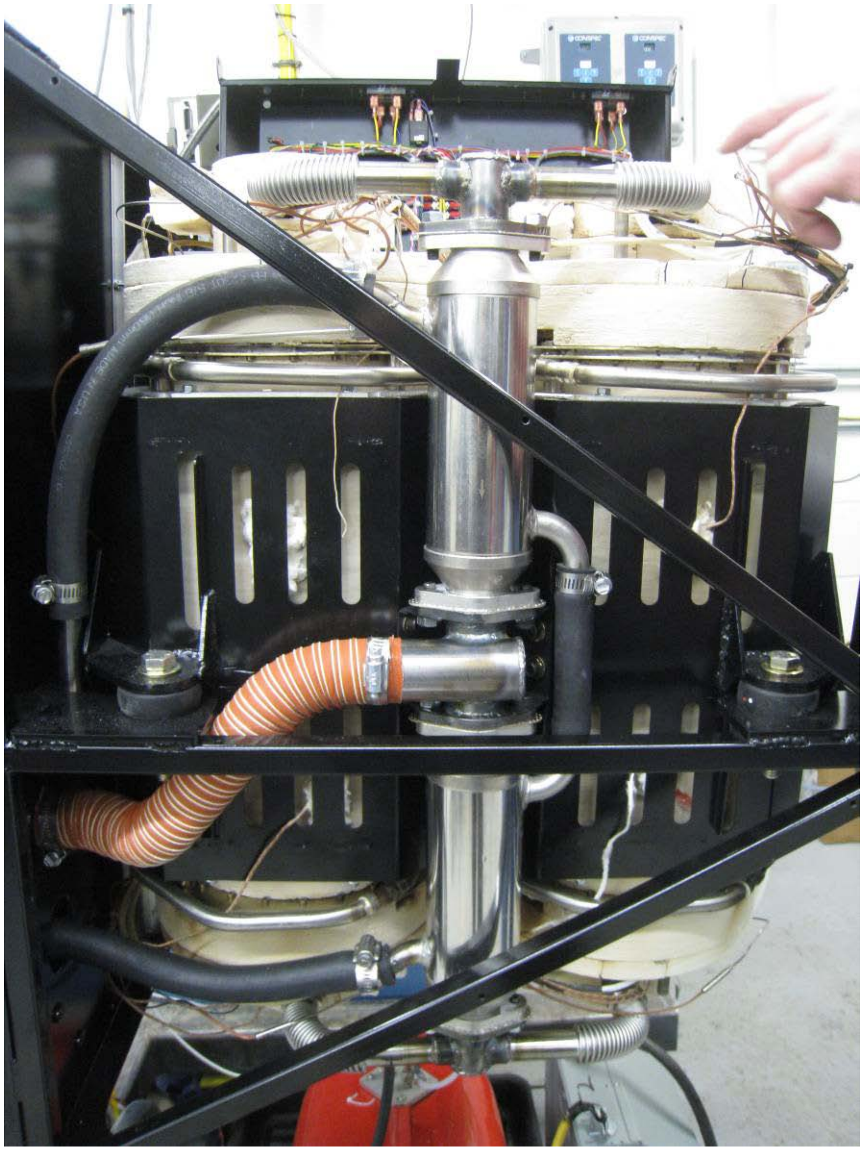
Technical Accomplishments and Progress

SOFC APU Prototype

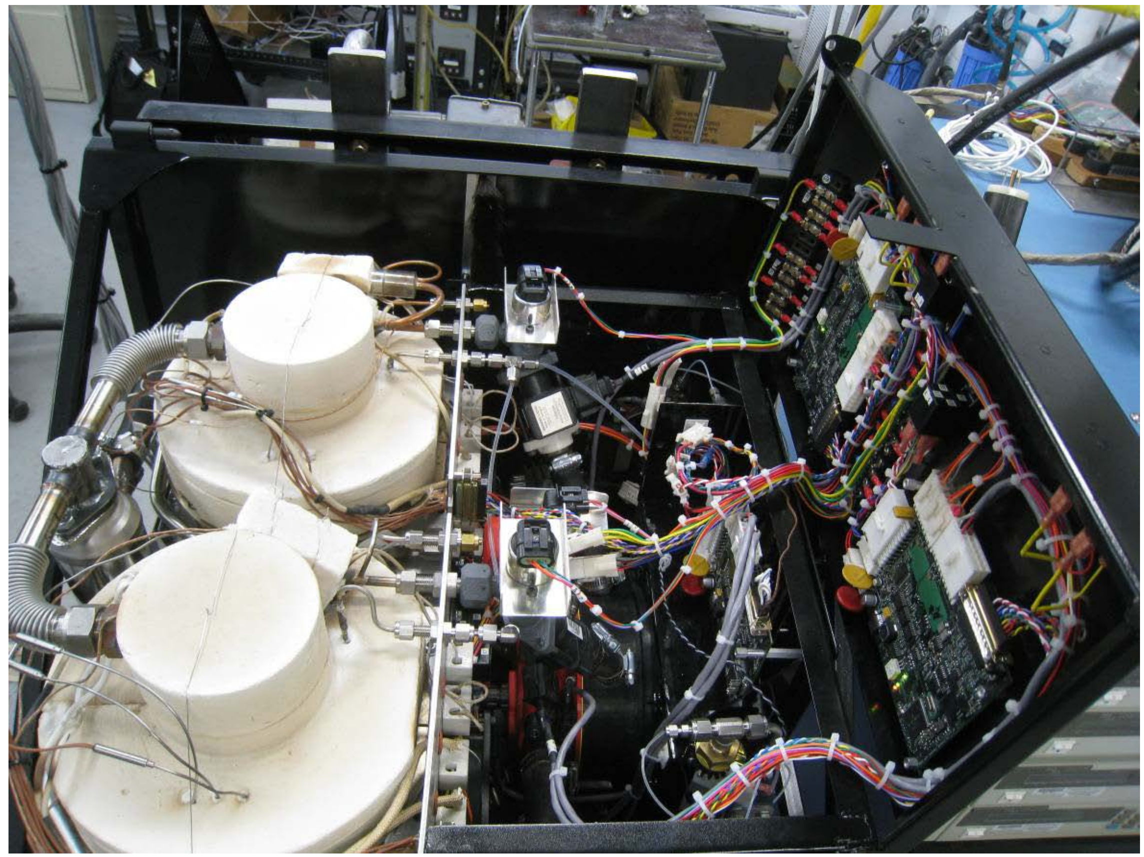
Technical Accomplishments and Progress

Exhaust heat recovery



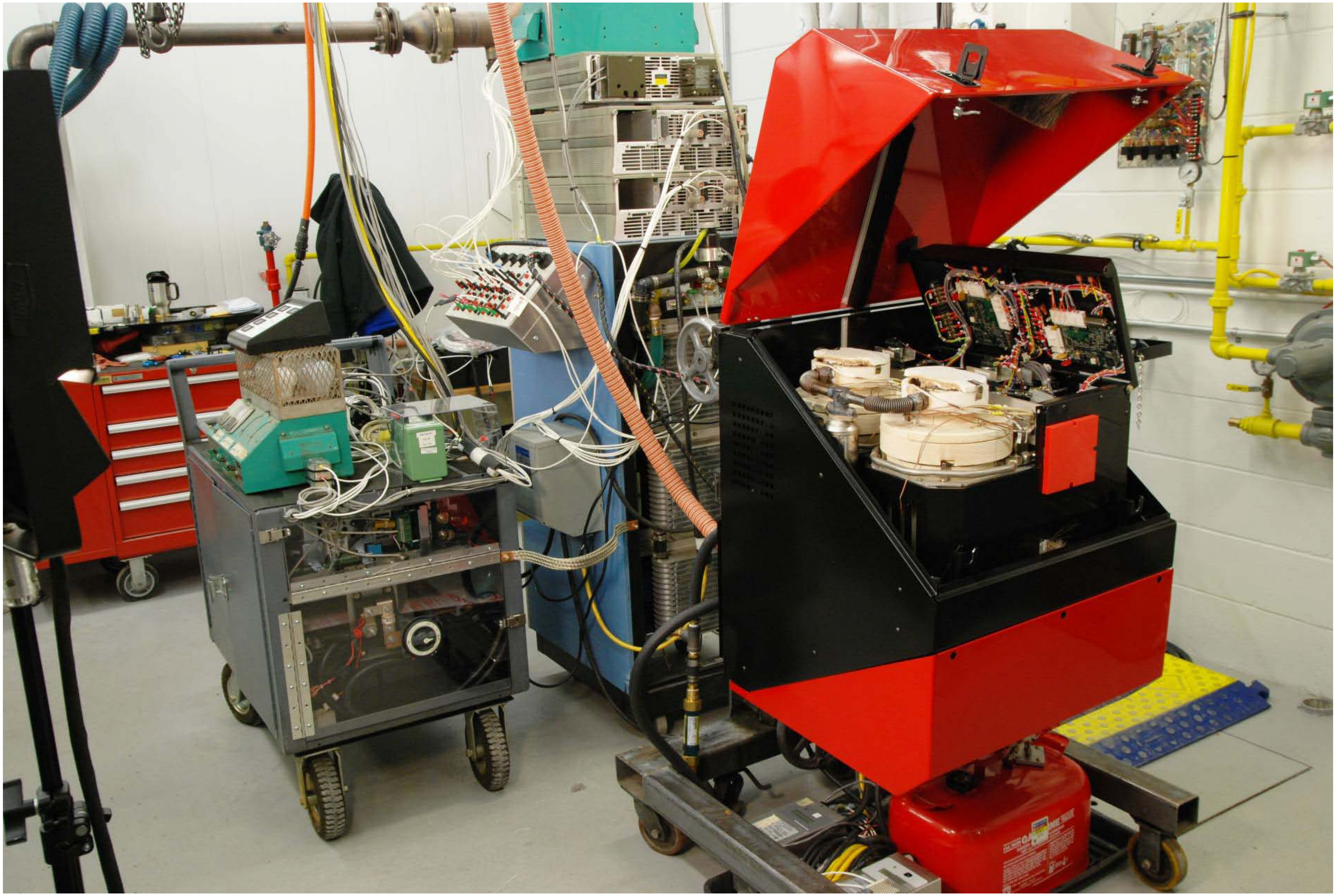
Upper two SOFC modules

CAN-linked controls



Technical Accomplishments and Progress

SOFC APU Test Setup



Technical Accomplishments and Progress

Summary

- Significant progress on waterless reforming of pump ULSD using CPOX
- 1:2 upscaling of thermally integrated tubular SOFC module
- System integration (packaging) consistent with contemporary commercial APU's, including shock and vibration isolation system
- Hybridization of SOFC with batteries utilizing commercially developed power electronics and controls
- Demonstration of an integrated SOFC solution to anti-idling providing DC and AC power plus waste heat recovery for cab and engine heating
- Future and continuing DOE support could accelerate production viability

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