10kWe SOFC Power System Commercialization Program Progress

April 20, 2005
Pacific Grove, CA

Dan Norrick
Manager Advanced Development
Cummins Power Generation

Acknowledgements

Cummins Power Generation	EFS SOFCo	DOE / NETL
Charles Vesely	Greg Rush	Don Collins
Brad Palmer	Rich Goettler	Joe Strakey
	Kurt Kneidel	Wayne Surdoval
	Milind Kantak	Mark Williams

Outline

- Cummins Power Generation
- CPG - SOFCo Team
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Power
Generation

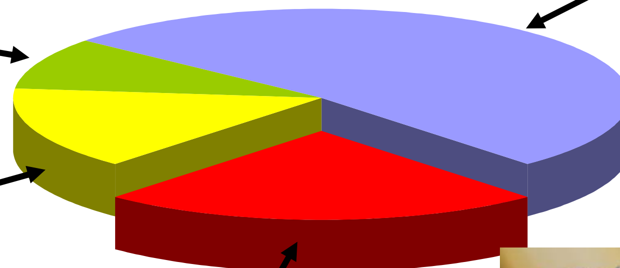
Cummins Power

Power Generation

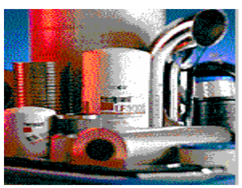
Cummins Business

Engine Business – $4.8 B

International Distributor Business $0.7 B



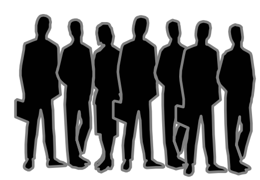
Filtration & Other Business - $1.3 B



Power Generation Business $1.6B (20%)

HQ in Columbus, Indiana since 1919

>50 manufacturing locations



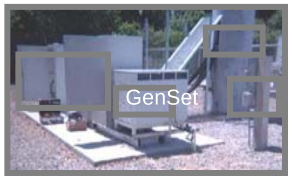
24,500 employees

R&D: $220 million

Cummins Power Generation Products and Markets

Stationary Power Markets


Residential



Telecommunications


Standby / Interruptible


Distributed Generation

Mobile Power Markets


Portables


Marine


Recreational Vehicle


Commercial Mobile

Rental

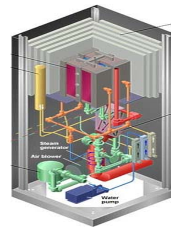
Technologies


Engine Gensets


Variable Speed Gensets

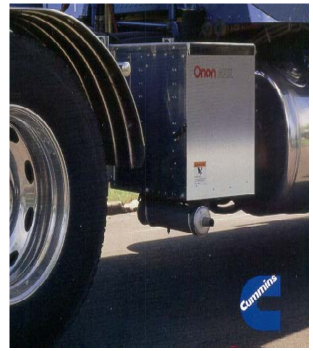

Controls, Switch Gear


Microturbines


Fuel Cell Program

Small Scale Fuel Cell Applications and Fuels

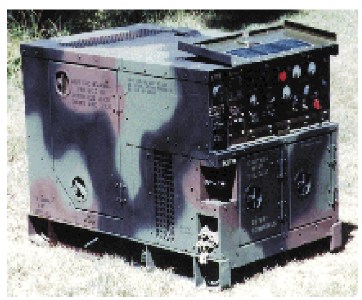
Recreational Vehicle
(Diesel)



Truck APU (Diesel)

Commercial Mobile
(Diesel)

Marine (Diesel)



Military
(Diesel)

Residential DG
(Natural Gas
or Propane)

Telecommunications
(Natural Gas
or Propane)

- Cummins Power Generation
- **CPG - SOFCo Team**
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Team Roles

Cummins Power Generation

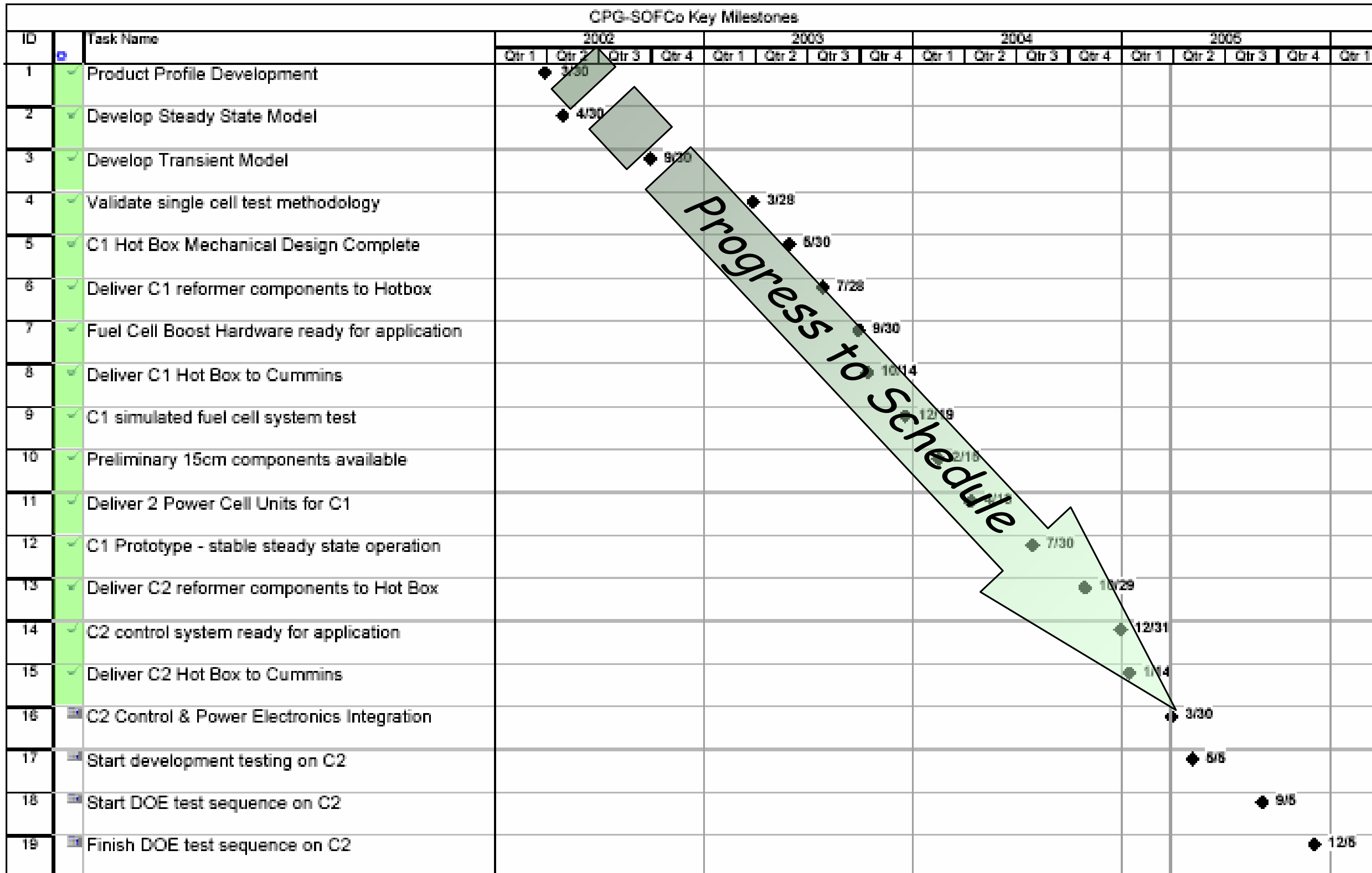
- Electronic controls
- Power electronics
- Fuel systems
- Air handling systems
- Noise and vibration
- System integration
- Manufacturing
- Marketing, sales, distribution

EFS SOFCo

- Planar SOFC technology
- Material science
- High temperature thermal integration
- Reformer technology
- Multilayer ceramic manufacturing

- Cummins Power Generation
- CPG - SOFCo Team
- **SECA Program Progress**
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Progress to Plan



Power Generation

Technical Challenges

- Achieving combination of
  - low ASR ($\leq$0.5 ohm-cm^2) and
  - low degradation ($\leq$2%/500 hours)
- Completion of low cost material substitutions
- Power Cell Unit (stack) / manifold / hot box design suitable for mobile product

Accomplishments

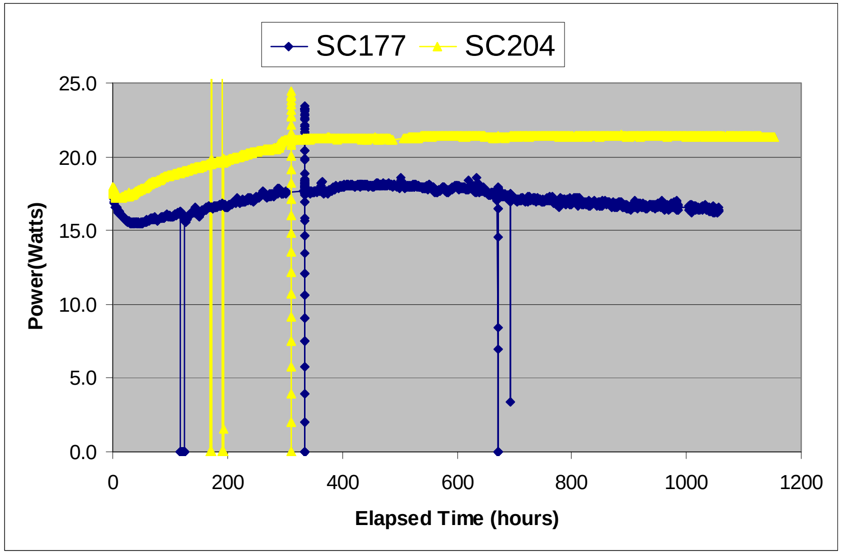
- ASR improvement
- Reduced degradation
- Waterless CPOX reformer performance
- Successful C1 operation & characterization
- Construction of C2 Power Module assembly & initial development
- System control algorithms validated and calibrated
- Progress with cost-effective BOP

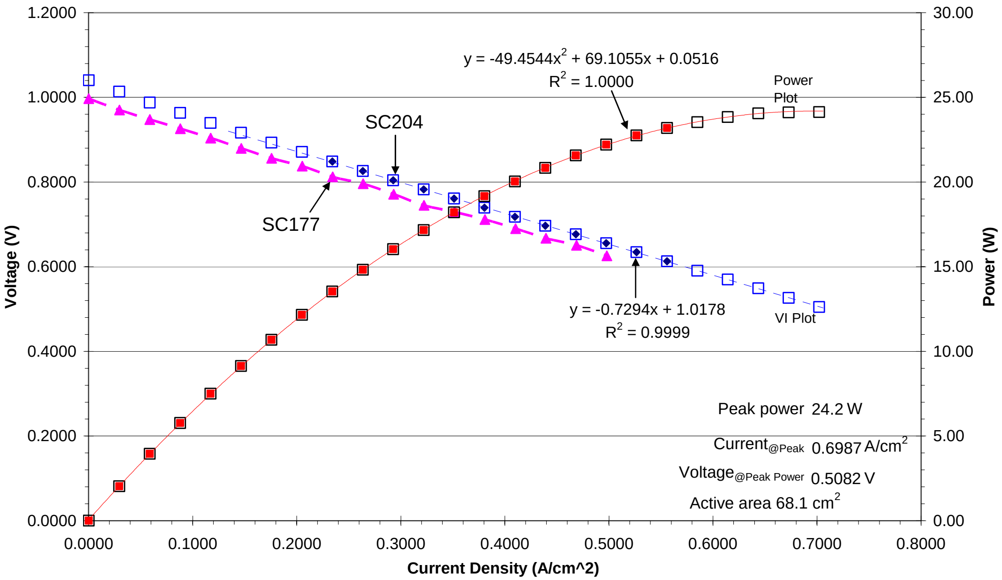
- Cummins Power Generation
- CPG - SOFCo Team
- **SECA Program Progress**
  - **Cell and Stack**
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Cell Evaluation and Selection

2004 Q3 ScSZ Test Results (825ºC)

(37% fuel utilization at 350 mA/cm², tested with humidified hydrogen)





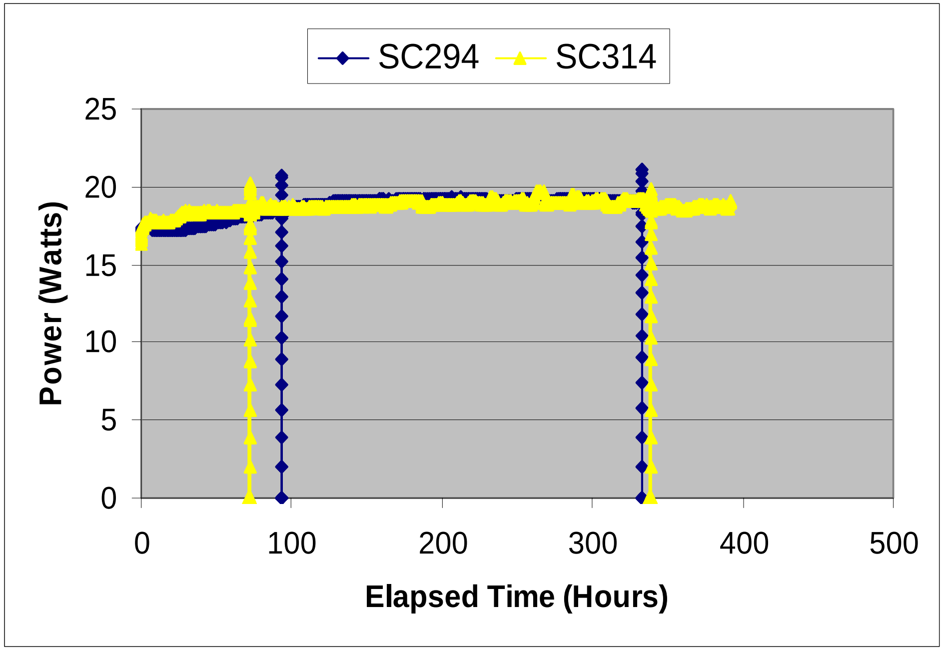
- **Initial ASR 0.71 – 0.76 ohm-cm²**
- **Ending ASR 0.72 - 0.73 ohm-cm²**
- **Relatively low degradation**
- **Variable performance**

- **V-I plot comparing SC177 to SC204**
- **Similar ASR**
- **355 mW / cm² peak power**

Recent Test Results – ScSZ (825°C)

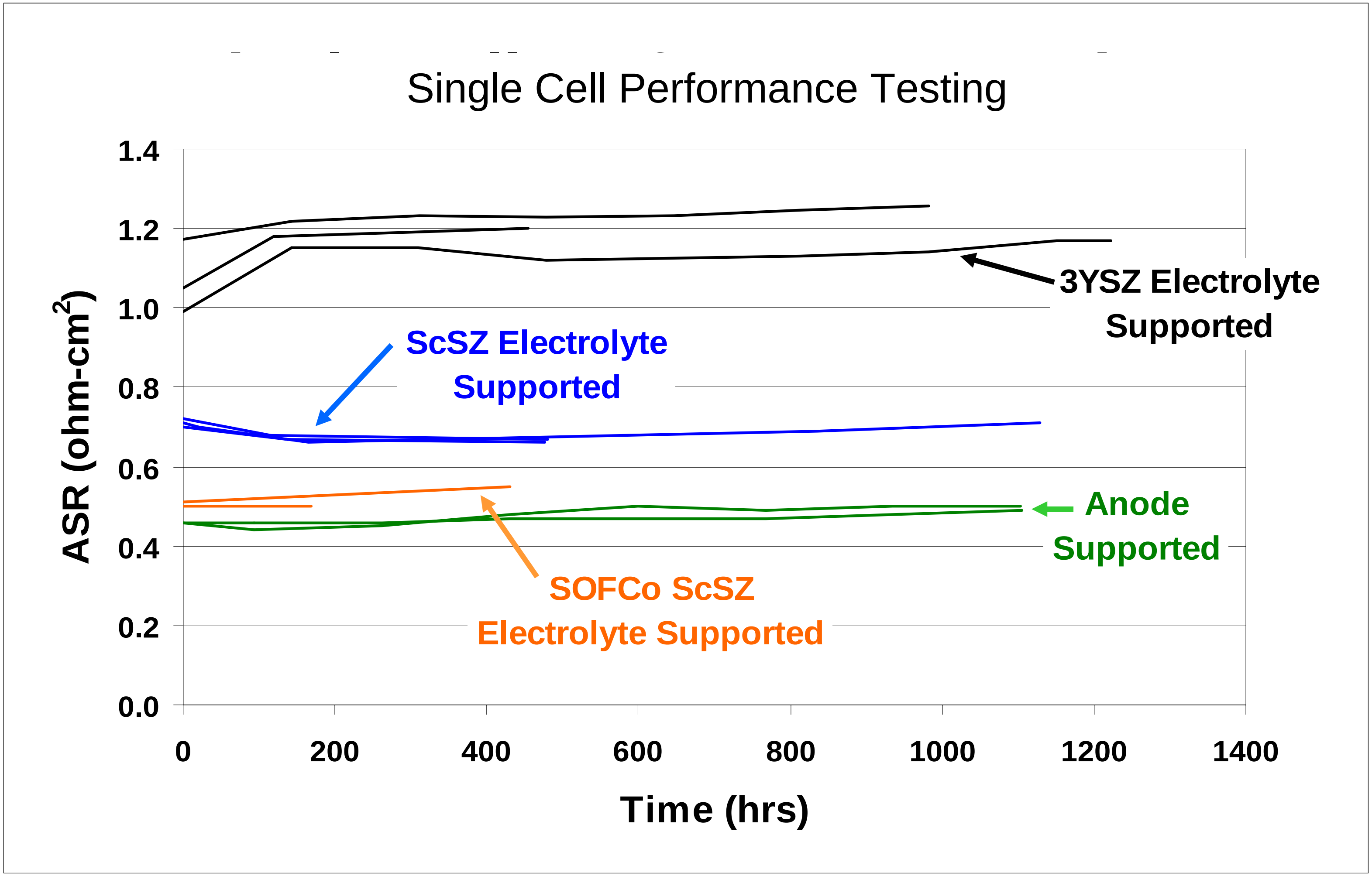
37% fuel utilization at 350 mA/cm^2, tested with humidified 50%H_2/50%N_2

- Normal test procedure (max cell temp – 825C)
- Initial performance close to Q3 data
  - SC314 – ASR 0.76 ohm-cm^2
  - SC294 – ASR 0.75 ohm-cm^2
- Low degradation
- Repeatable performance

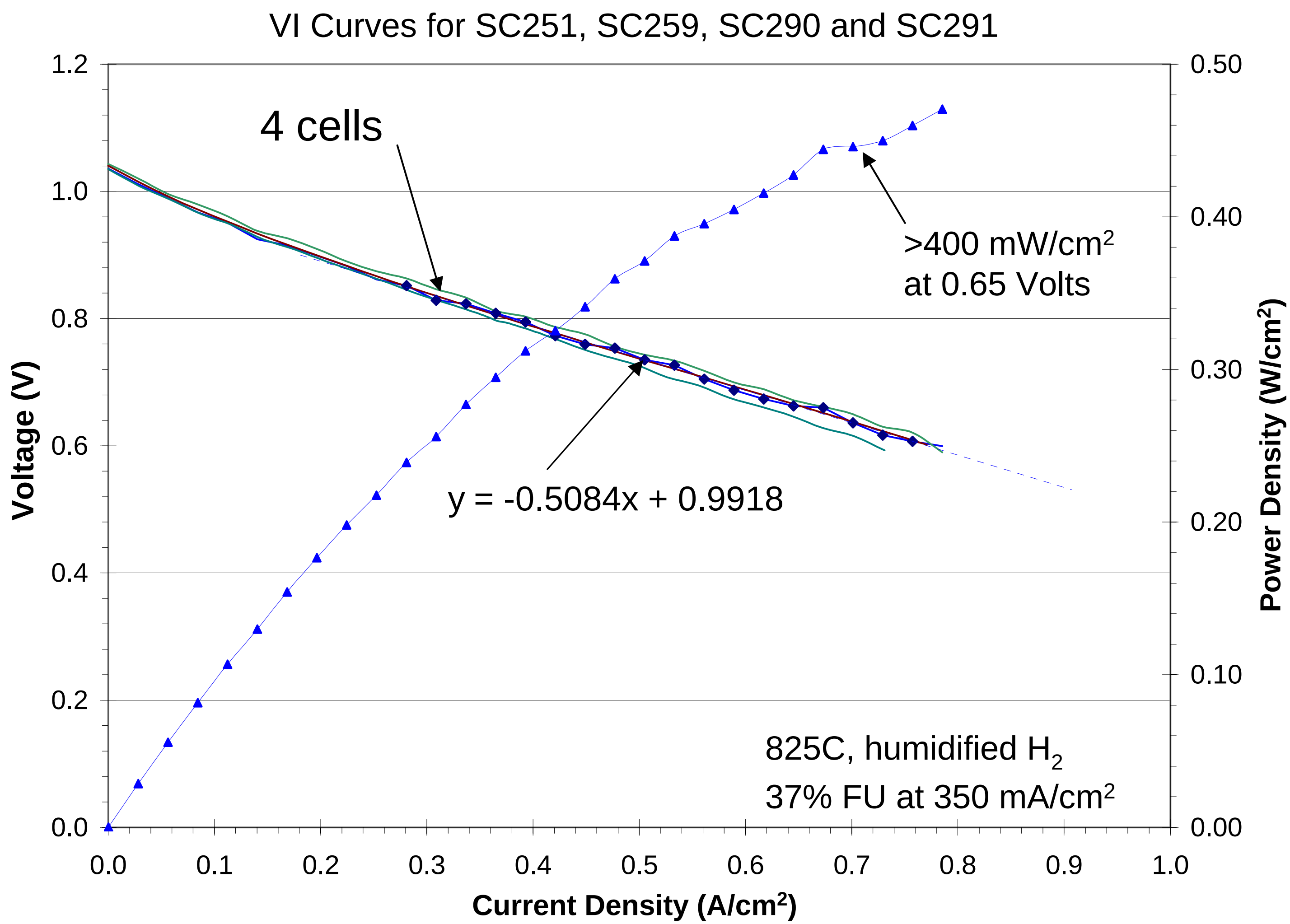


Power Generation

Cell ASR Reduction

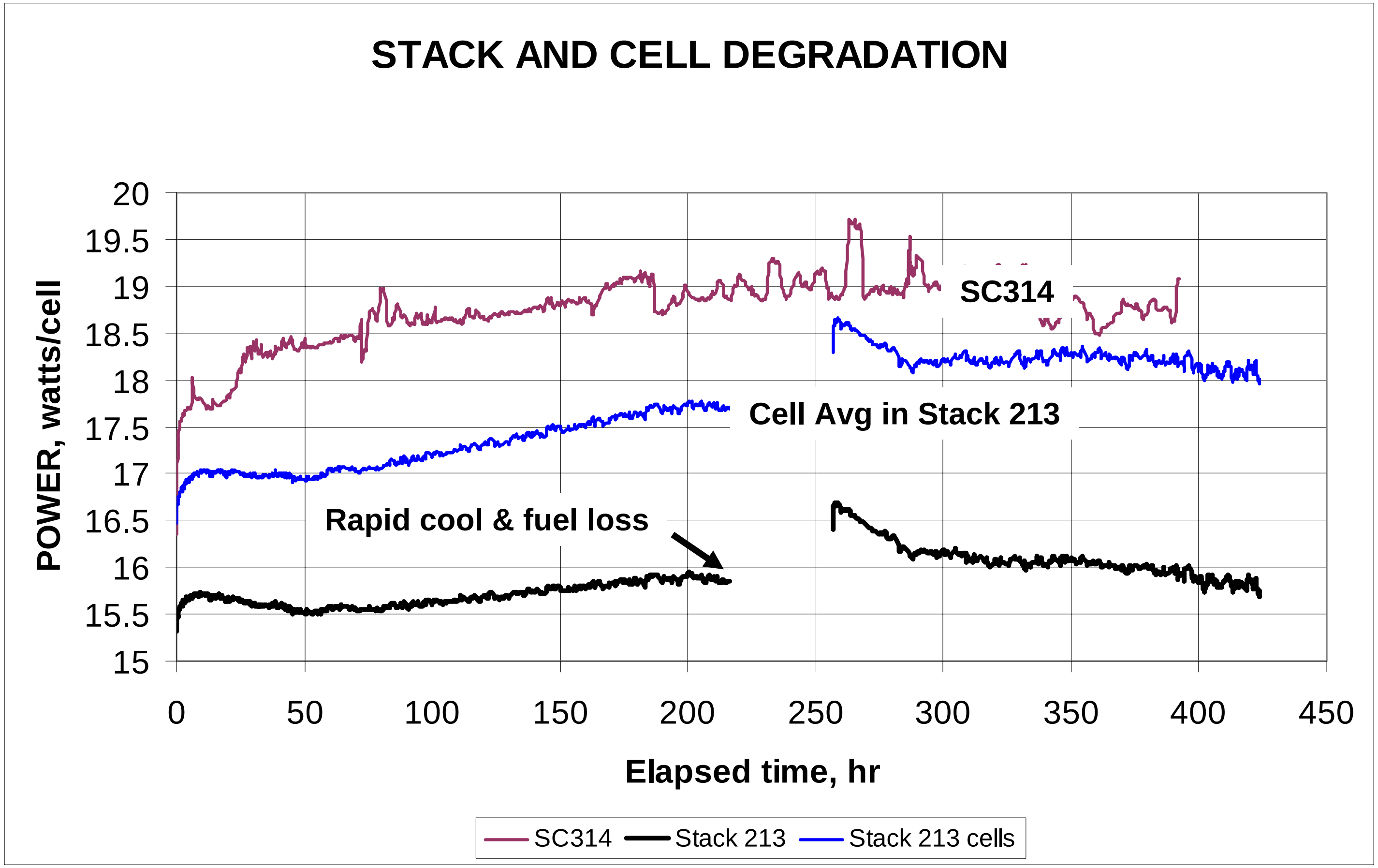


Current ScSZ Cell Performance



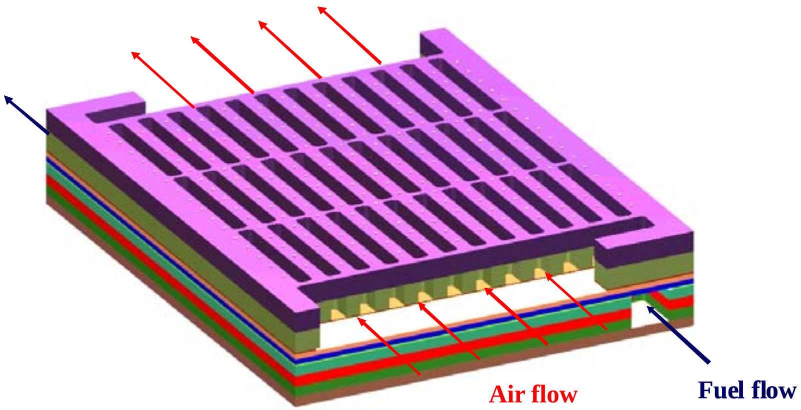
Cell Evaluation and Selection

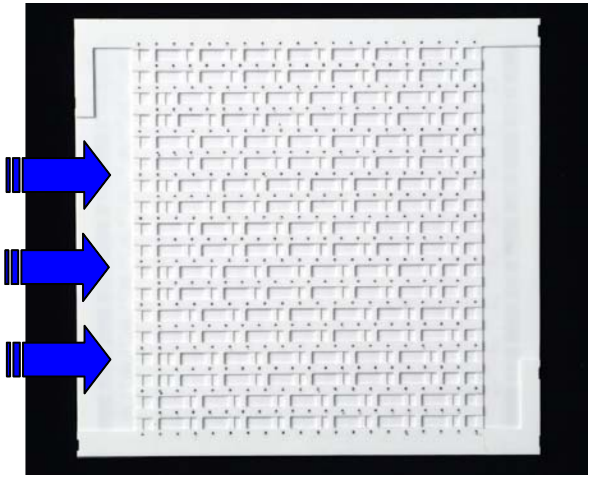
New ScSZ cells perform similarly
in single cell and stack tests



SOFCo Stack Technology

- "All-Ceramic" stack design
  - Cells and multi-layer interconnect are CTE matched
  - No ceramic-to-metal seal
  - Metal interconnect issues mitigated
  - Compatible with MLC manufacturing methods
- Co-flow design advantages
  - Improved temperature distribution reduces cell/interconnect stress
  - Simplified manifold and improved sealing
  - Improved reactant distribution

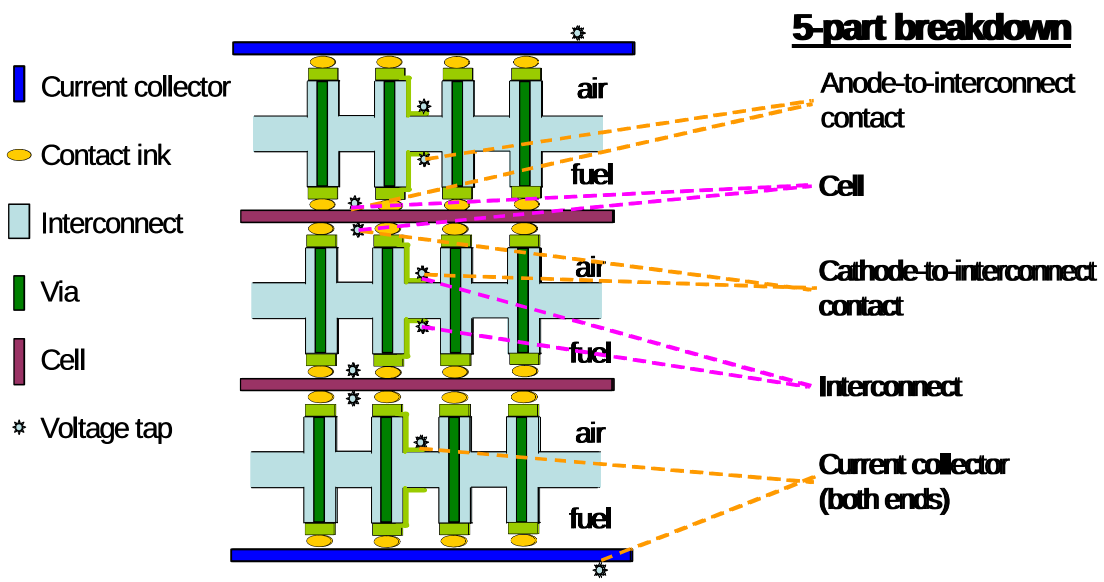




Co-Flow Multi-layer Ceramic (MLC) Interconnect

Stack Performance Improvement Development Test Tool

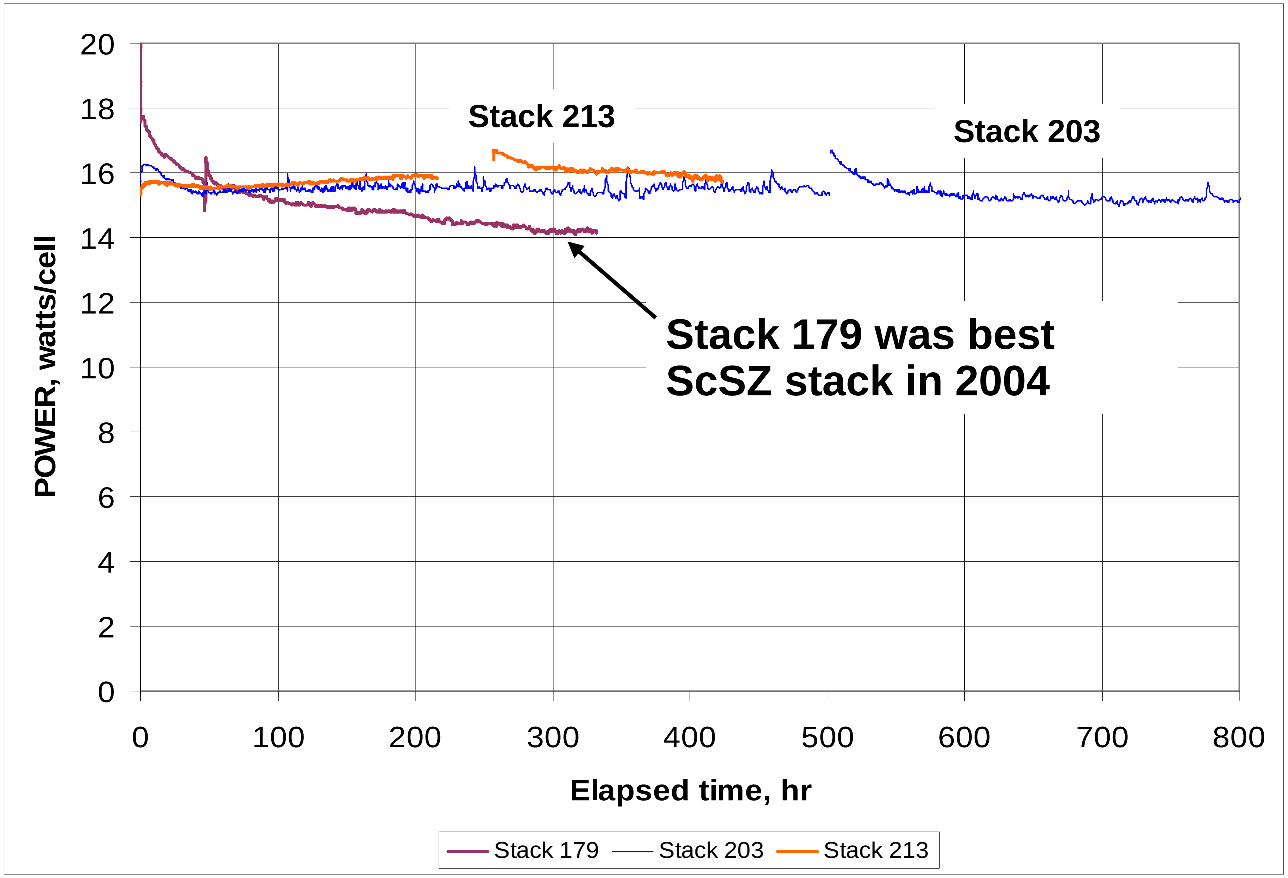
- Instrumented short stack allows isolation of contributions to stack resistance
- Significant non-cell contributions to stack ASR and power degradation eliminated
  - Non-cell ASR contribution reduced to < 0.2 ohm-cm^2
  - Short stack power degradation reduced to < 3% / 500 hrs



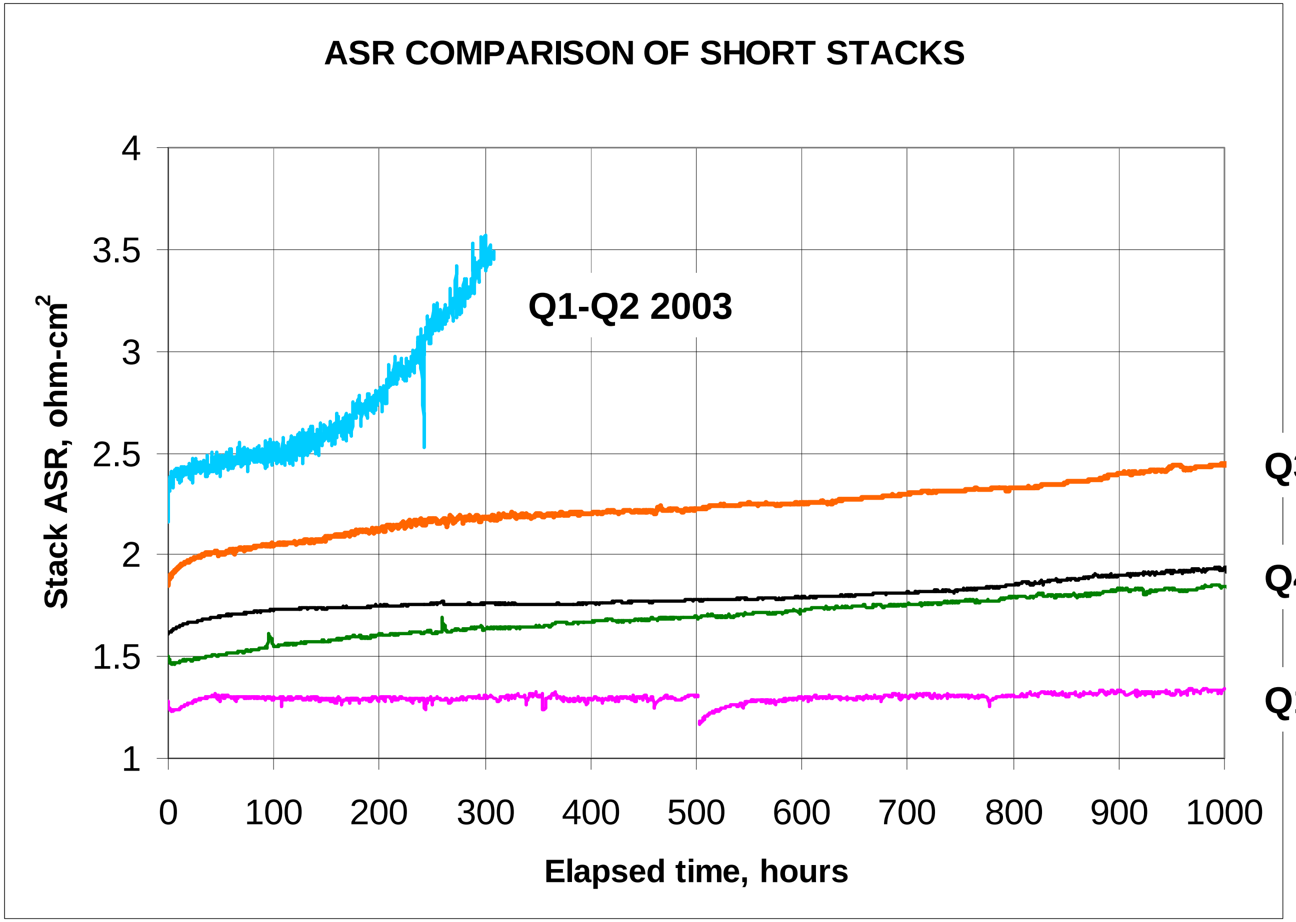
Cell Evaluation and Selection in Short Stacks

Short stacks show promising performance

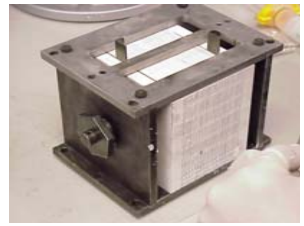
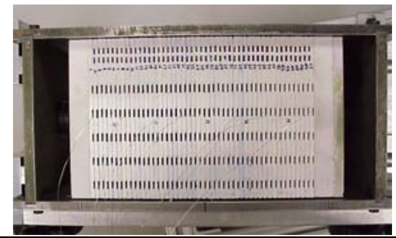
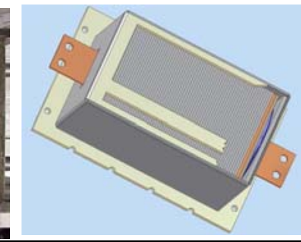
Degradation < 3% / 500 hours (@ constant voltage)



Progress in Stack ASR Reduction



SOFC Stack Development

Year	2002	2003	Q1 2004	Q2 2005 (Targets)
Configuration	Short Stacks	Medium Stacks	Tall Stacks	Power Cell Unit
Cells	2-5	20	45-50	50-70
ASR ohm-cm2	2.5	1.5	1.5	<0.75
Power Density mW/cm2	75	125	125	250
Power Deg % / 500 h	>20%	<4%	<4%	<2%
Fuel Utilization	> 70%	>75%	>75%	>80%

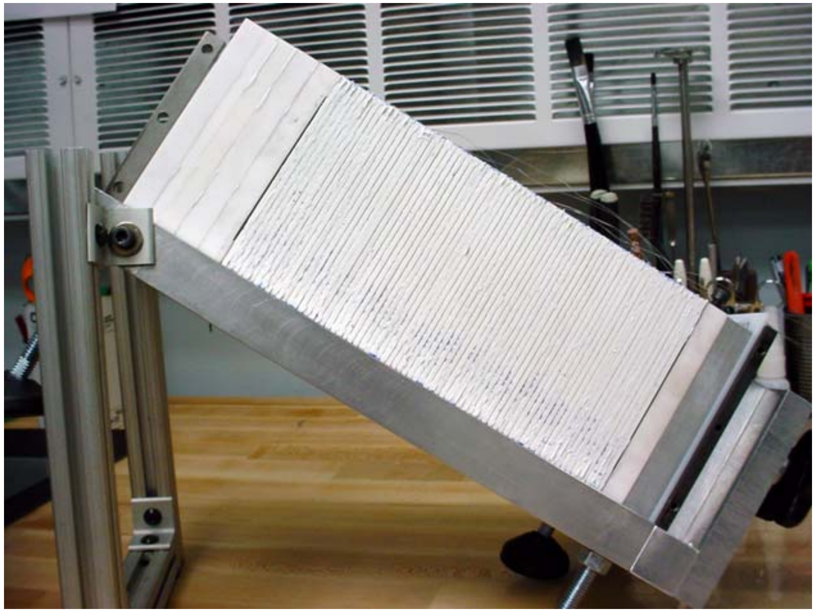
Cummins Power Generation

70-Cell PCU #1 – Assembly

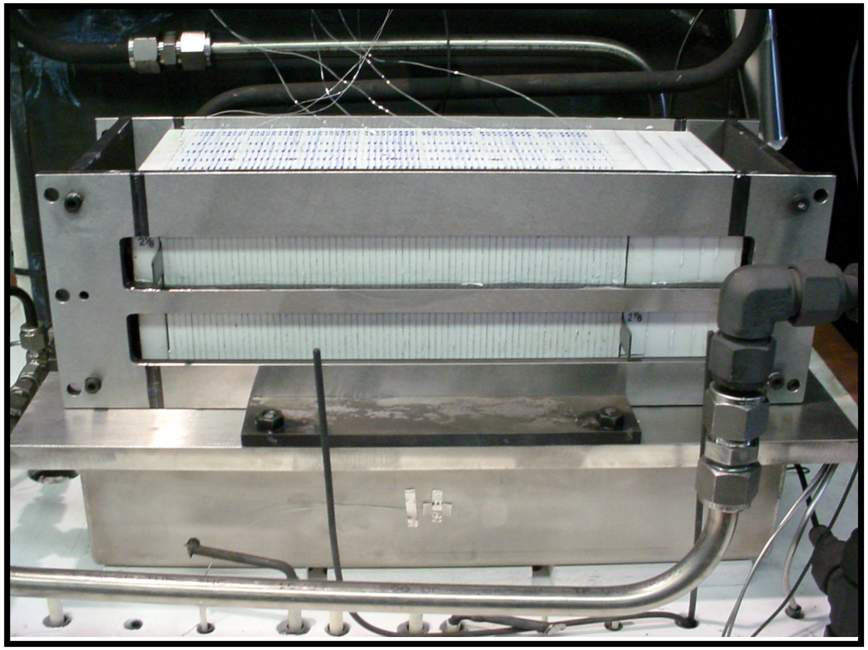
SOFCo EFS

Stack build progressing

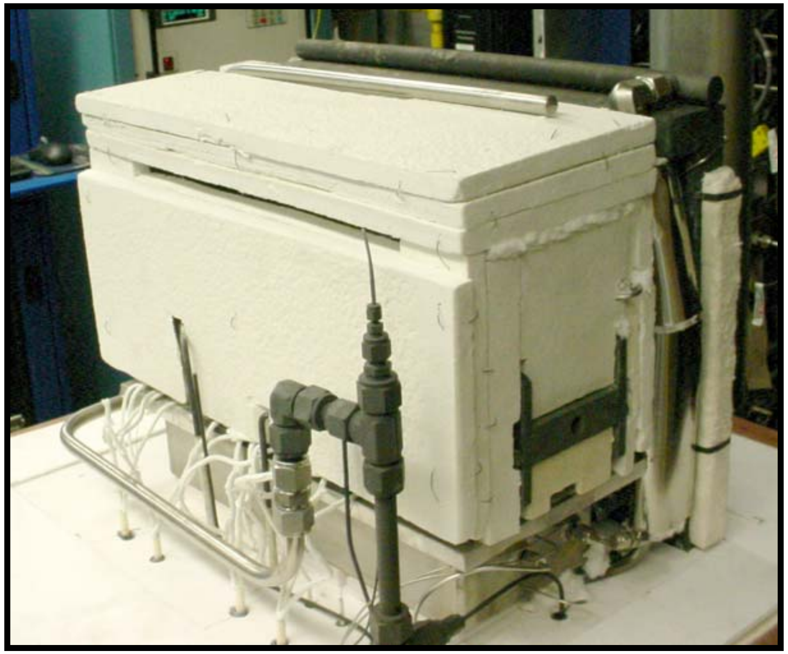
70-cell stack completed



70-Cell PCU#1 – Installation



Caged stack installed in Horizontal Stack Test (HST) Facility.



Power Generation

Stack Development Summary

- Stack Scale-up
  - Successful C1 (48 cell – Q3 2004)
  - On track for C2 (70-cell – Q2 2005)
- Performance and Cost
  - ScSZ cells exhibiting significant progress in ASR and degradation
  - Significant reduction in non-cell contributions to stack ASR and degradation
  - Projecting successful demonstration of Phase 1 performance targets
  - Achieving cost target = meeting performance targets + implementing low-cost materials

- Cummins Power Generation
- CPG - SOFCo Team
- **SECA Program Progress**
  - Cell and Stack
  - **Waterless CPOX fuel reformation**
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Power Generation

Fuel Flexible CPOX Design

Fuel	LP	Natural Gas [1]
Design/Size	25mm D x 150mm L	
Operation		
Feed Preheat	200 C	300 C
Turndown (% load)	100% to 20%	100% to 25%
Performance		
Fuel Conversion (%)	75 - 85	90 - 98
CPOX Efficiency (%)	65 - 72	75 - 85
H_2 + CO (Dry mole %)	40 - 45	47 - 50
H_2 / CO Ratio	1.2	2.0
Methane Slip (dry mole %)	0.5 - 2.0	0.4 - 4.0
C_2+ Slip (Dry mole %)	0 - 2.0	0 - 0.04

(1) Alliance, OH pipeline NG, ~5ppm S, 92-95% CH_4

Reformer Update

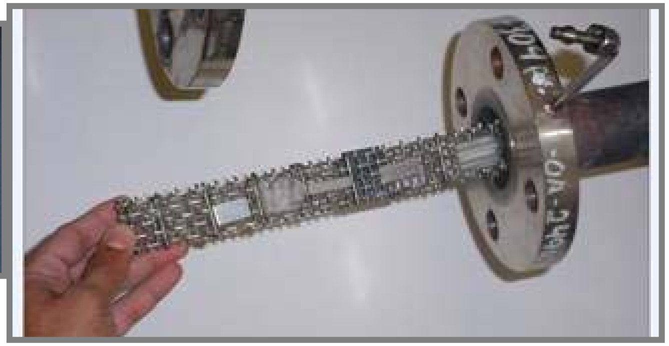
- Waterless 5 kWe CPOX reformer development completed and demonstrated for untreated (5 ppm S) natural gas
  - Performance
  - Durability
  - Rapid startup
  - Turndown
- Reformer installed in the C2 Power Module
- Carbon-free operation demonstrated for reformer and system hardware (2600 hrs)
  - >2000 hrs with stacks
  - Includes transients, start/stop cycles
- Established reformer design and operating conditions for Phase I tests

Reformer Update: Material Compatibility Tests

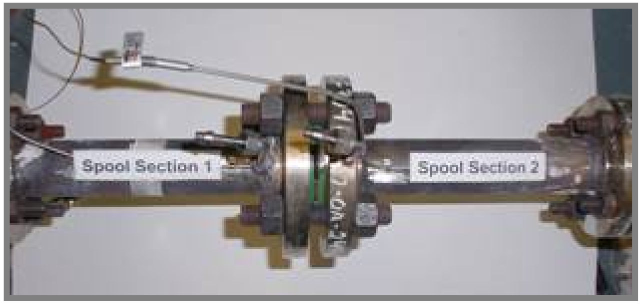
- SOFC stack and BOP materials tested:
  - Anode and cathode, Interconnect, via, Ni-screens, wires, meshes, felts, coated alloys
- Materials exposed to waterless NG CPOX reformate
- 100 hr duration at each test condition, representative contact times
- Normal and off-normal conditions: HC slips, temperatures
- Post-test visual inspection for carbon deposition
- Experimental understanding of the NG reformate thermodynamic stability
- *Material and operational tests showed carbon-free performance over the Phase I test operating range*

Observations
Material Compatibility

Coupon Tray Section



Tray Section Installation



Coupon Test Section

- Carbon-free at design operating conditions for temperature and slip
- Off-design conditions <u>are</u> carbon-prone
- High temp and excessive HC slip kinetically favor carbon (on Ni-rich surfaces)
- Short-term upset conditions are less likely to deposit carbon

NG CPOX Reformer Performance Summary

- Sulfur tolerant (no feed desulfurizer indicated for NG up to 20 ppm)
- Waterless operation
- Demonstrated durability:
  - 2900 hrs (1 kWe C1)
  - 2800 hrs (5 kWe C2)
- 2-4% performance drop for 1000 hrs of operation
- Flow turndown with stable performance: 20:1
- ~20% excess processing capacity for current design
- *No carbon issues anticipated for Phase I test conditions*

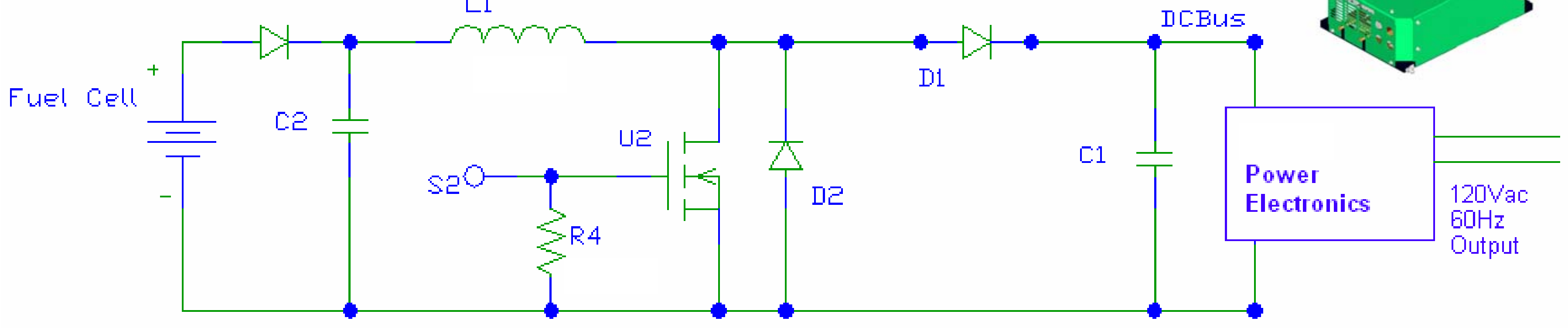
- Cummins Power Generation
- CPG - SOFCo Team
- **SECA Program Progress**
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - **Controls & Power Electronics**
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

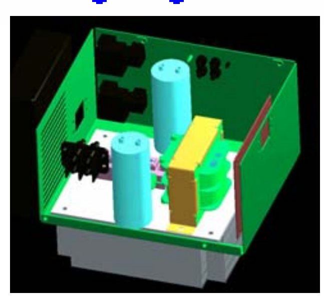
Purpose of Controls and Power Electronics

- Thermal and fluid management
  - Stack condition management
  - Control critical system temperatures
  - Control flows to match current demand and fuel utilization requirements
- Load management
  - Supply a buffer between required load power and fuel cell dynamics
    - Control stack loading to a safe rate
    - Maintain supplemental energy storage

SOFC Controls and Power Electronics

- Redesigned and packaged the fuel cell boost for operation with the C2 prototype system.
- Implemented new current limit control for use with power management interface.

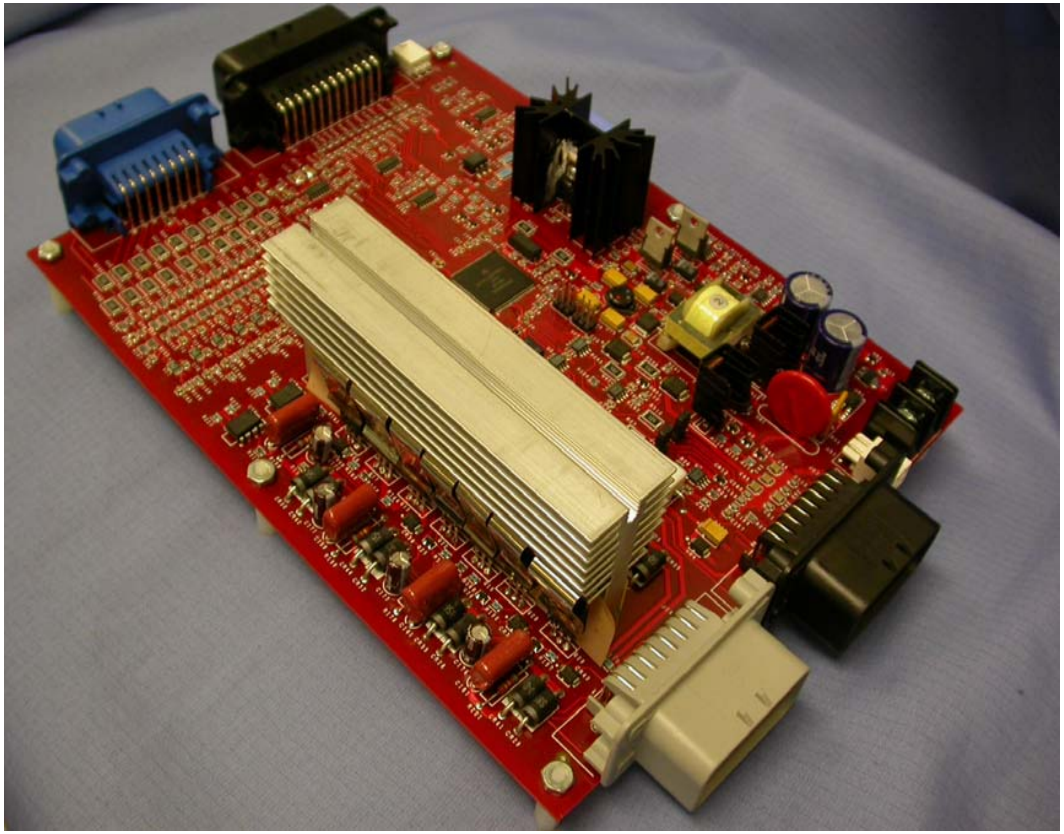




Controls and Power Electronics Summary

- Demonstrated control of our first live fuel cell system
- Demonstrated fuel cell stack temperature controls under transient conditions
- Control system algorithms redesigned to implement low cost mass flow control devices, and to capitalize on lessons learned from C1 prototype
- Redesigned and packaged fuel cell boost for operation with the C2 prototype system
- New C2 Single board control designed and constructed

New PCB integrates control circuitry



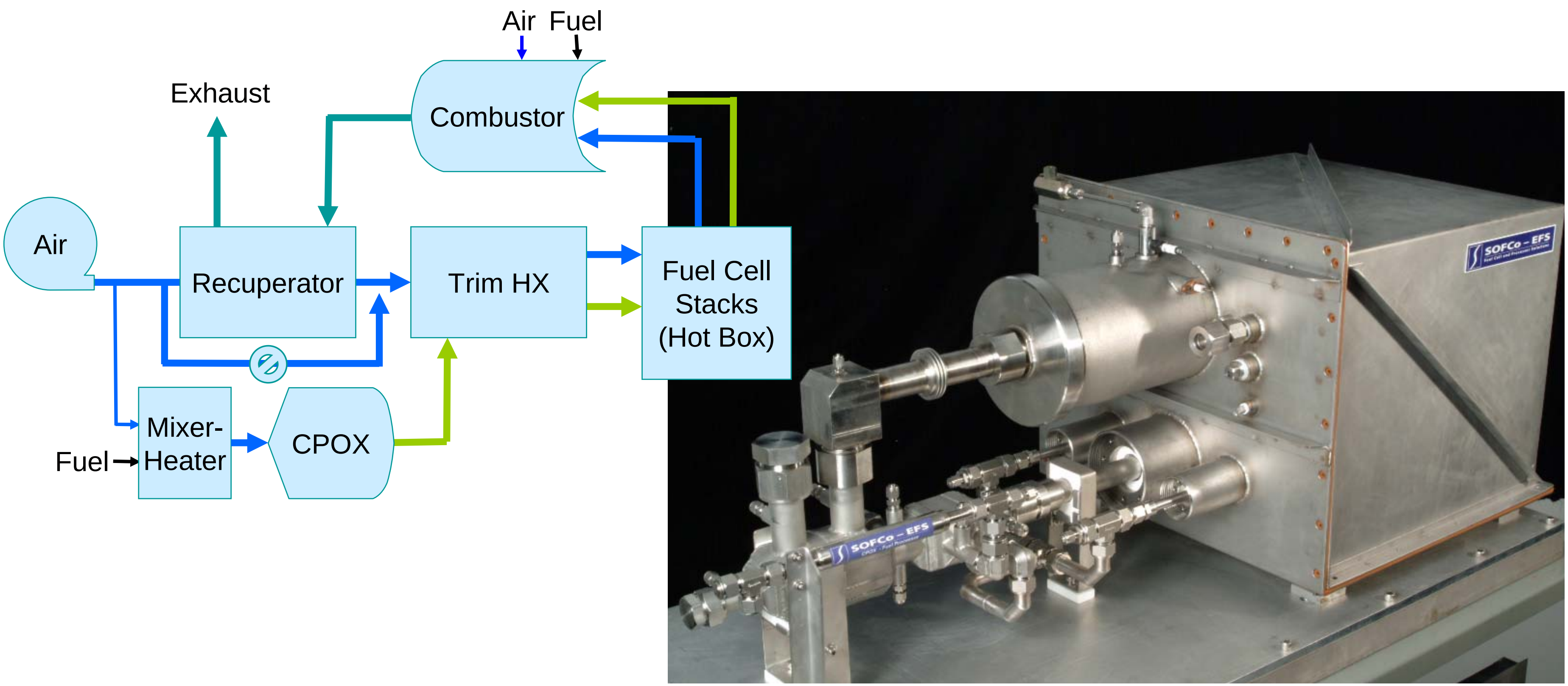
- Cummins Power Generation
- CPG - SOFCo Team
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- **Experience with C1 Prototype testing**
- Progress and plan for C2 Prototype
- Look ahead at C3
- SOFC APU Program

Staged prototyping C1 → C2 → C3

	C1	C2	C3
Objective	Development tool	Program deliverable	Development tool
Cell footprint	10cm x 10cm	10cm x 10cm	New footprint
Stack(s)	2 x 47 cell	4 x 70 cell	2 x NN cell
Integration Level	Not packaged	Integrated hot box assembly	Integrated hot box assembly
Electrical Output	DC output	Power conditioning • Load sharing • 120VAC output	Power conditioning • Load sharing • 120VAC output
Test Sequence	Characterization testing	SECA test plan	Operational performance development
Operating Hours	Approx 600	1500+	3000+
Operational	*July 2004*	*June 2005*	*Q1 2007*

C1 Development Unit

- Component and sub-system operation/control development
- Stack simulators utilized prior to stack installation



C1 Prototype in Cell 21 at CPG

Ignition Control

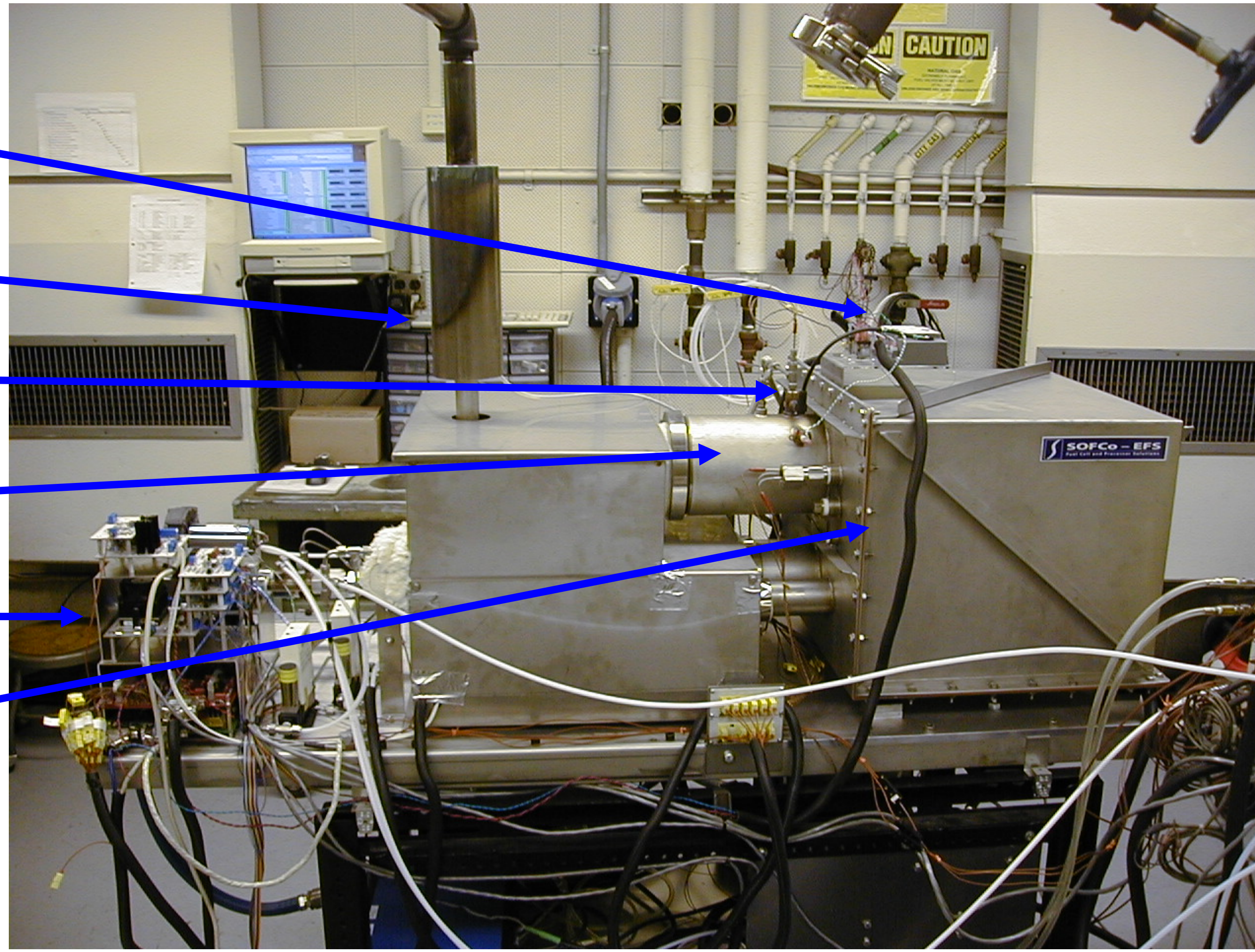
Exhaust

Startup Burner

Combustor

Controls

Hot Box



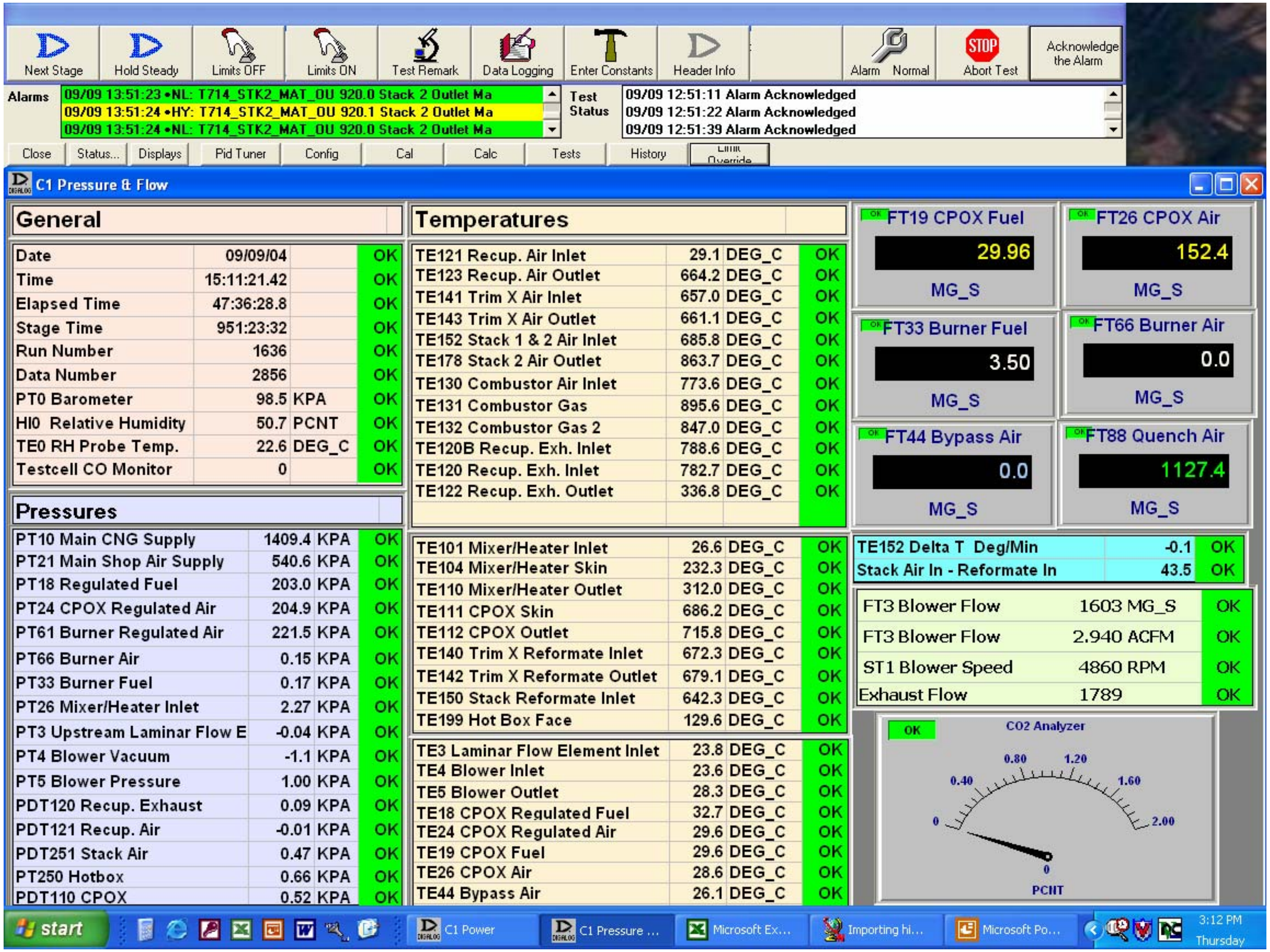
C1 Development Approach

- C1 prototype utilized to validate concepts and understanding of fuel cell system design and operation
- C1 configured as laboratory "breadboard"
  - Mass flow controllers and selected commercial components in BOP
  - Initial operation on stack simulators
  - Facilitated initial operation, base-lining, and system response characterization
  - Supported development of control algorithms
- C1 tested with live stacks Q3 2004
  - Steady state operation validated control software and hardware
  - Transient testing utilized to derive control parameters and validate software concepts
- C1 operational experiences provided important input to C2 design

C1 Experience

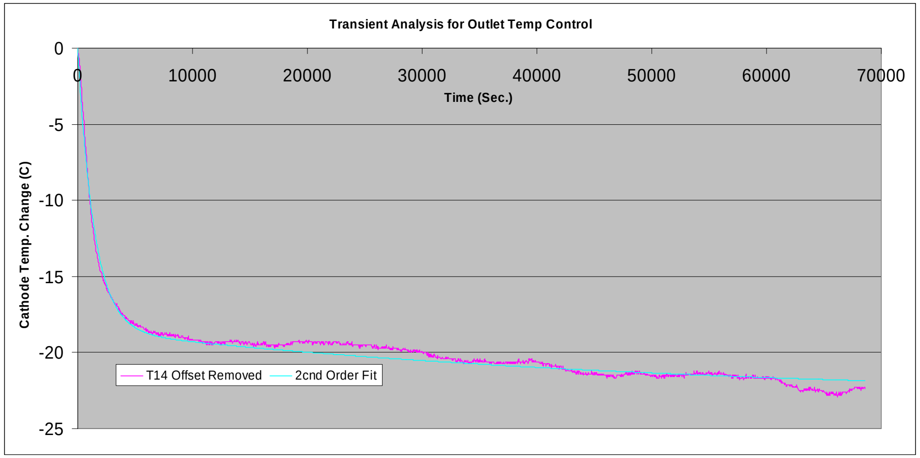
- C1 Prototype tested as functional system including BOP and controls
  - BOP components met functional requirements of C1 system.
  - 600 hours verification testing to C1 requirements including stacks, BOP anode air and fuel, cathode air, and bypass subsystems.
  - Steady state operation at loads from 300 to 500 W
  - C1 Testing:
    - provided improved understanding of overall system characteristics
    - revealed potential for extended operating limitations on transient fuel cell output capabilities
    - demonstrated importance of system thermal integration.
    - supported development of system operating procedures and systems including startup, shutdown, backup, and DAS system requirements.

Sample Data
Operational Development 09/2004

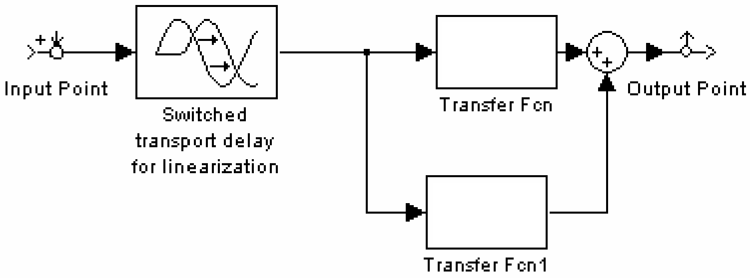


C1 System stack testing for controls development

- System identification for stack control
- Gain setting and sample rates
- Verified transient performance of closed loop thermal controls
- Aided in transient computer model development



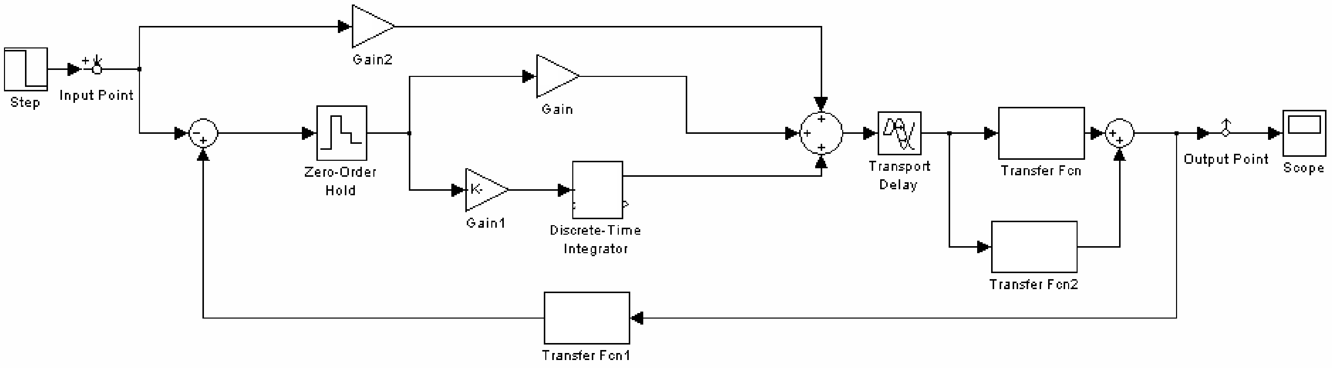
Stack outlet temperature response to step change in cathode air flow

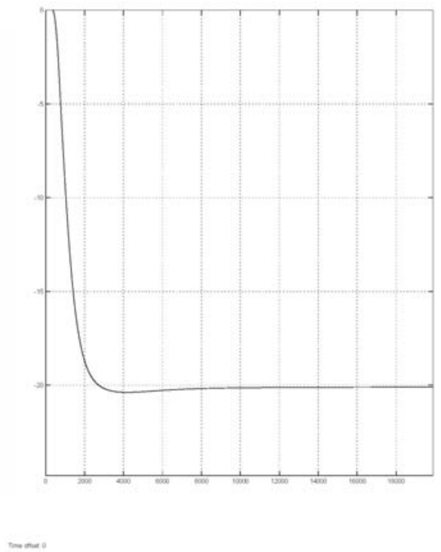


Simple transfer function of stack outlet temperature/cathode air flow

Thermal Fluid Control Loops

- Stack control is slow
  - Second Order System with Widely Spaced First Order Poles.
    - 1st Order Time Constants of approximately 1,500 and 50,000 seconds
  - Matlab Models Used to Simulate and Tune Controls
    - Step Transients Used for System ID





Closed loop model of stack outlet temperature control via cathode mass flow control, with command feed forward

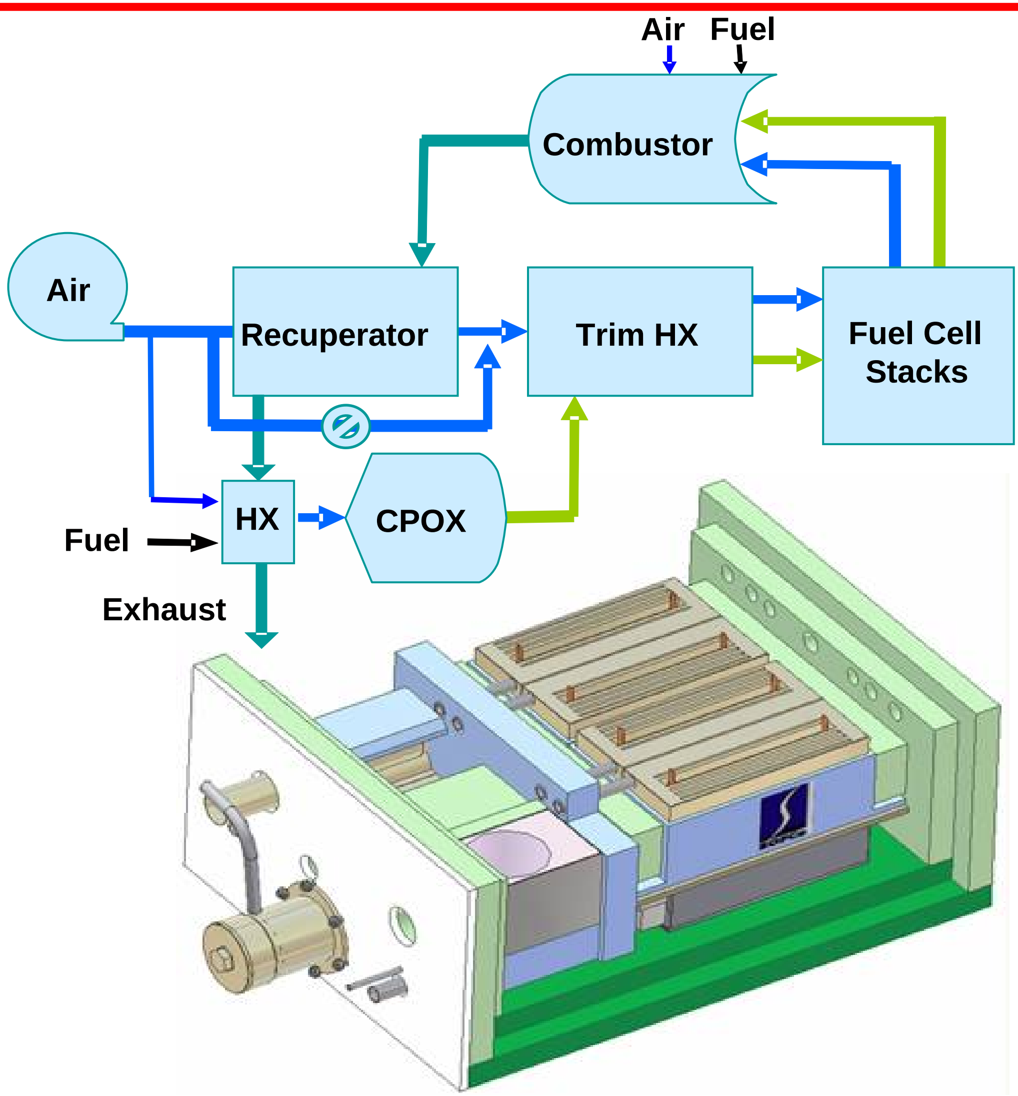
What did we learn from C1?

- Gain settings and time constants for system control
- Verified stability of various thermal control loops under transient load conditions
- Stack transient loads accepted faster than anticipated
- Stack simulators were an effective tool for system tuning and BOP development
- Restart from cold with very low degradation is possible

- Cummins Power Generation
- CPG - SOFCo Team
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- **Progress and plan for C2 Prototype**
- Look ahead at C3
- SOFC APU Program

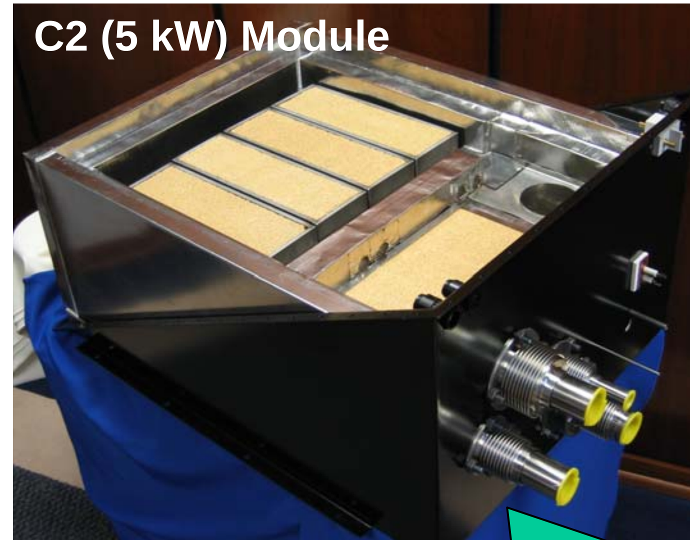
C2 Deliverable Unit

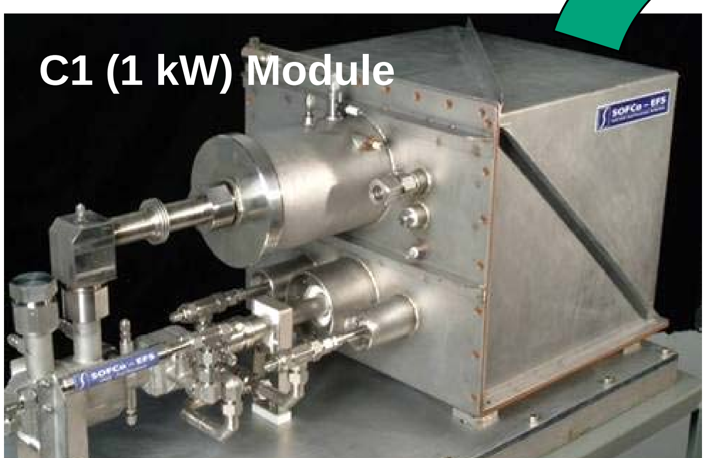
- Thermally integrated Power Module
- Increased system integration
- Production-like flow control and sensing hardware
- 4 x 70-cell (10 cm) stacks
- 5 kW

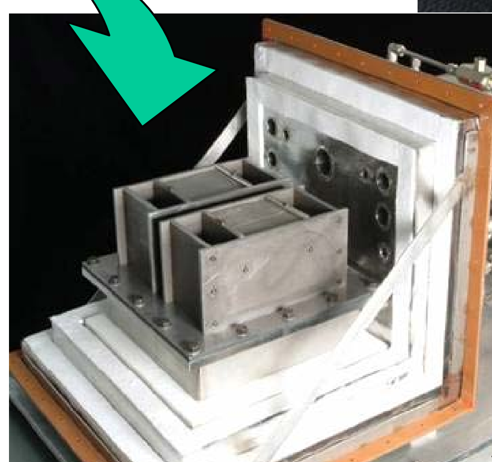


Power Module Update

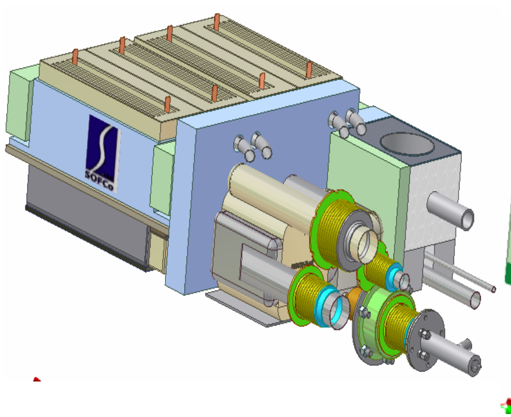
- C1 testing completed
- C2 Power Module design / fabrication completed
- Delivered in December
- First heat-up in January



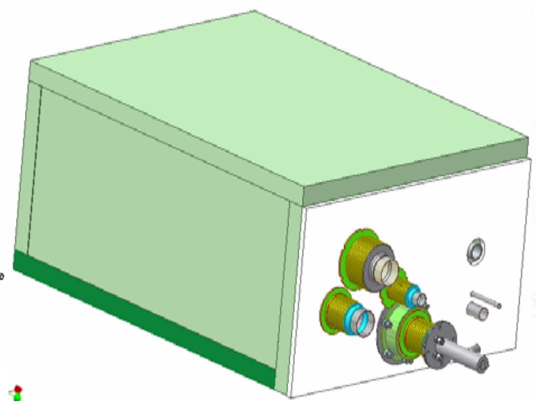




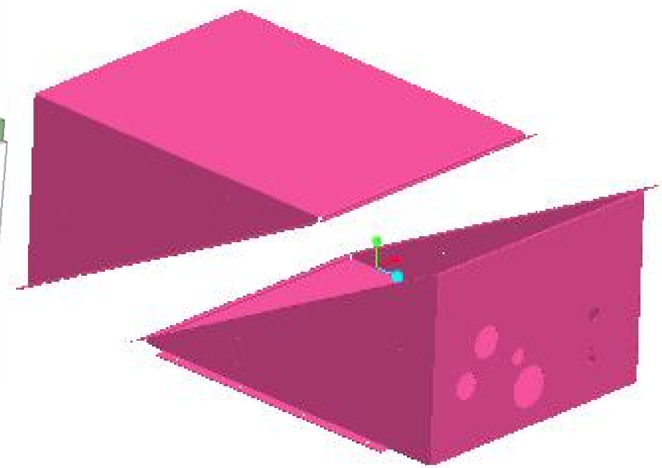
C2 Power Module Design



Stack and Hot Accessories Assembly



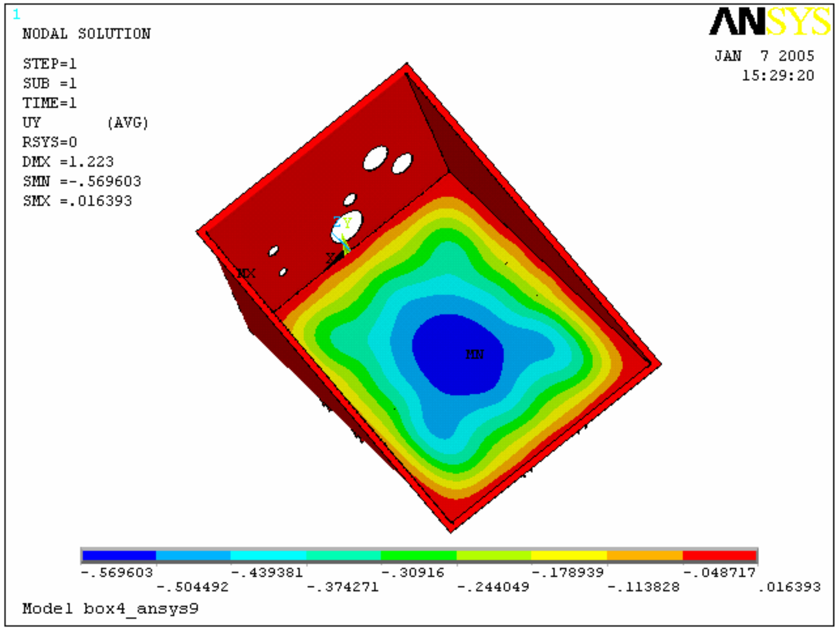
Insulation Enclosure

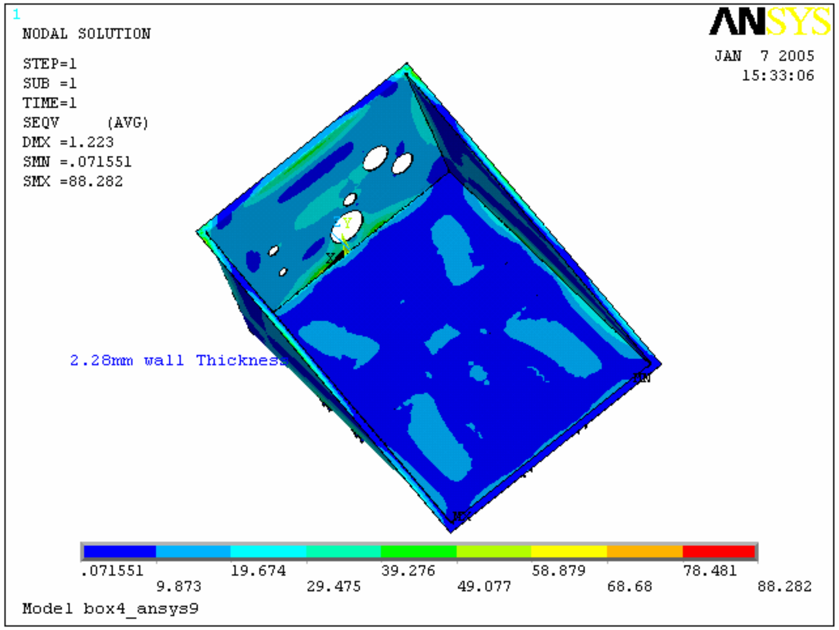


Hotbox Enclosure

- Diagonal split of enclosure enables pre-assembly of stacks, hot accessories, and insulation panels
- Single plane flange simplifies sealing design
- Flange stiffens enclosure walls

C2 Power Module Enclosure Structural Analysis



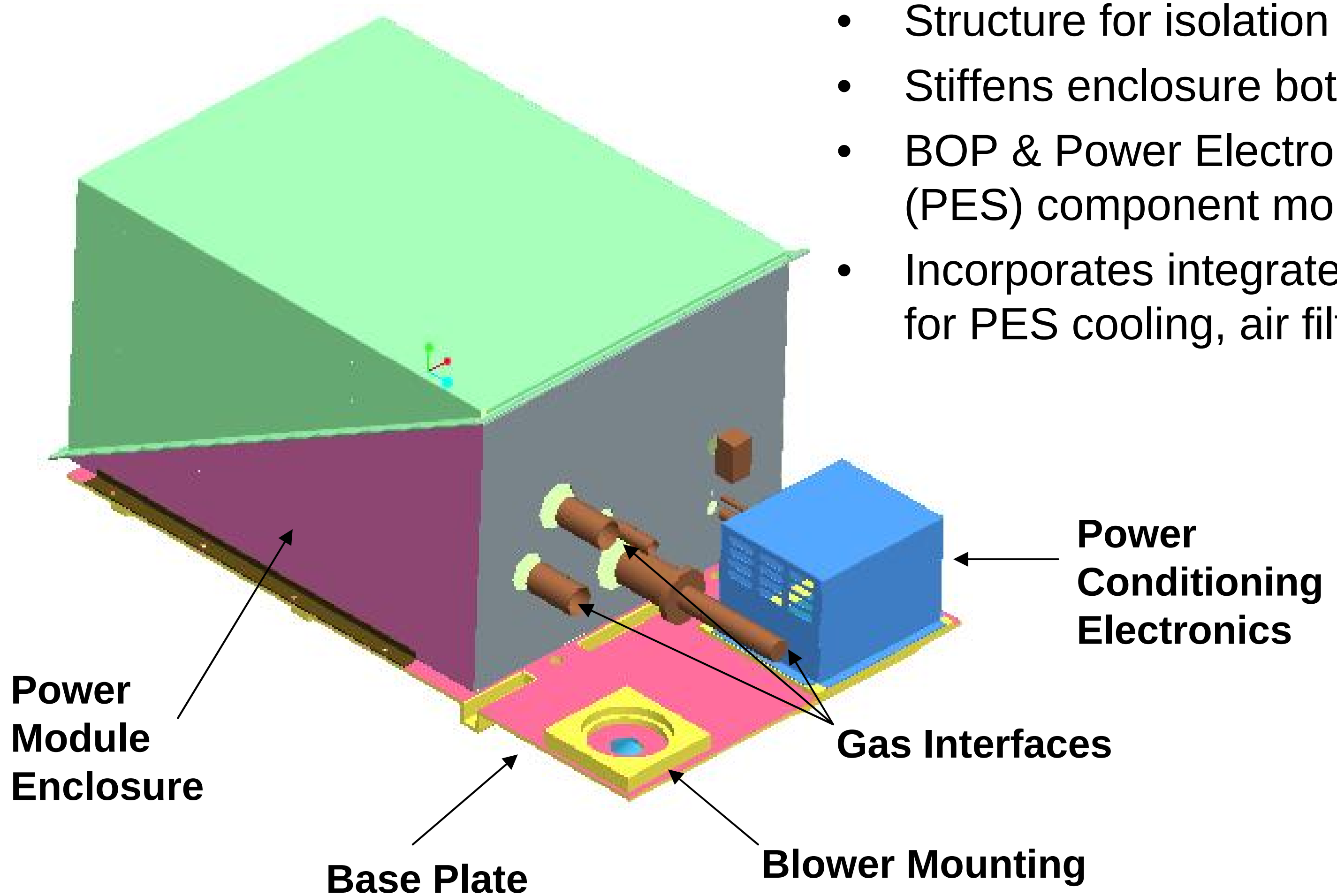


Enclosure Vertical Displacement Results under Pressure and Clamping Load (mm)

Enclosure Stress Results under Pressure and Clamping Load (MPa)

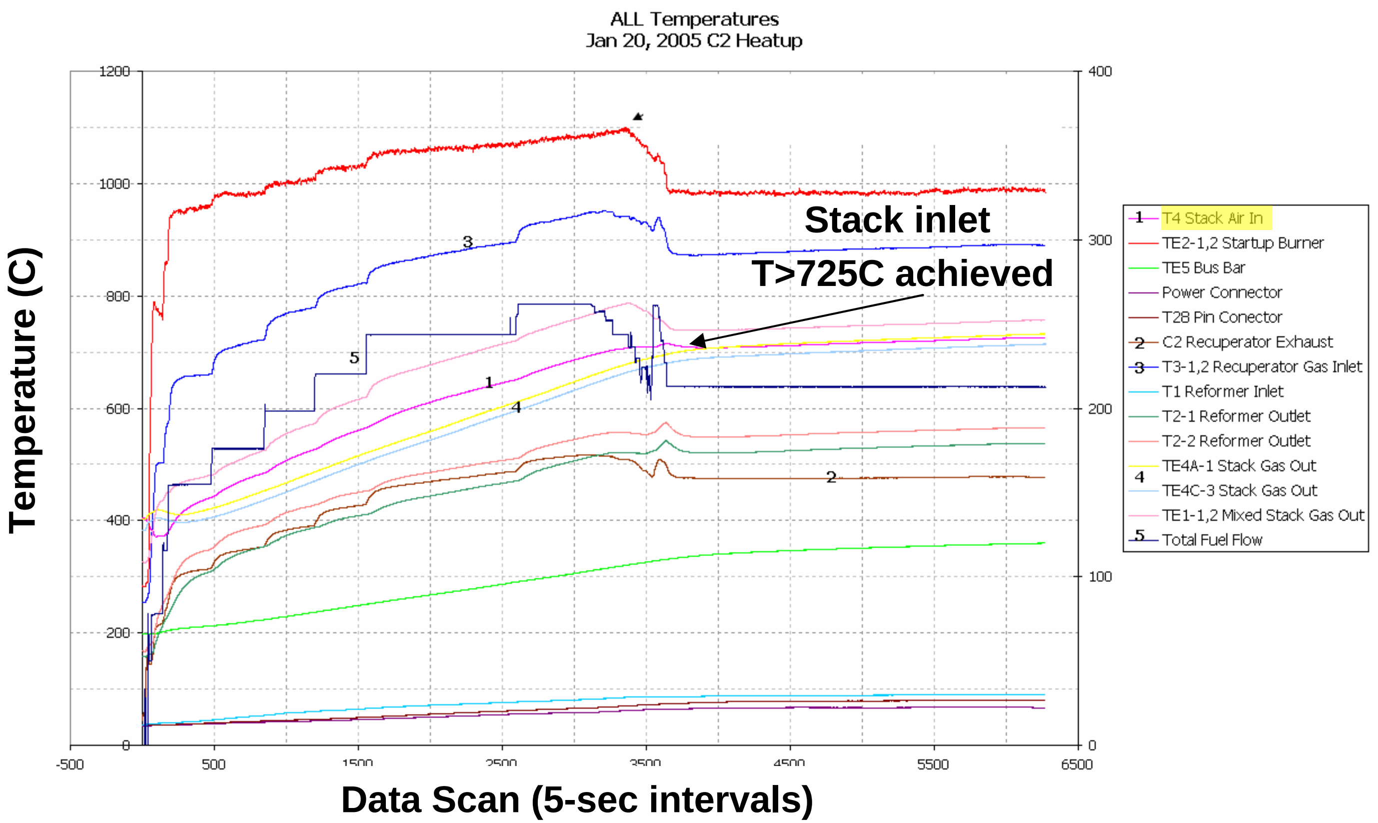
C2 Base Plate Design

- Structure for isolation mounts
- Stiffens enclosure bottom panel
- BOP & Power Electronics System (PES) component mounting
- Incorporates integrated air passages for PES cooling, air filtration

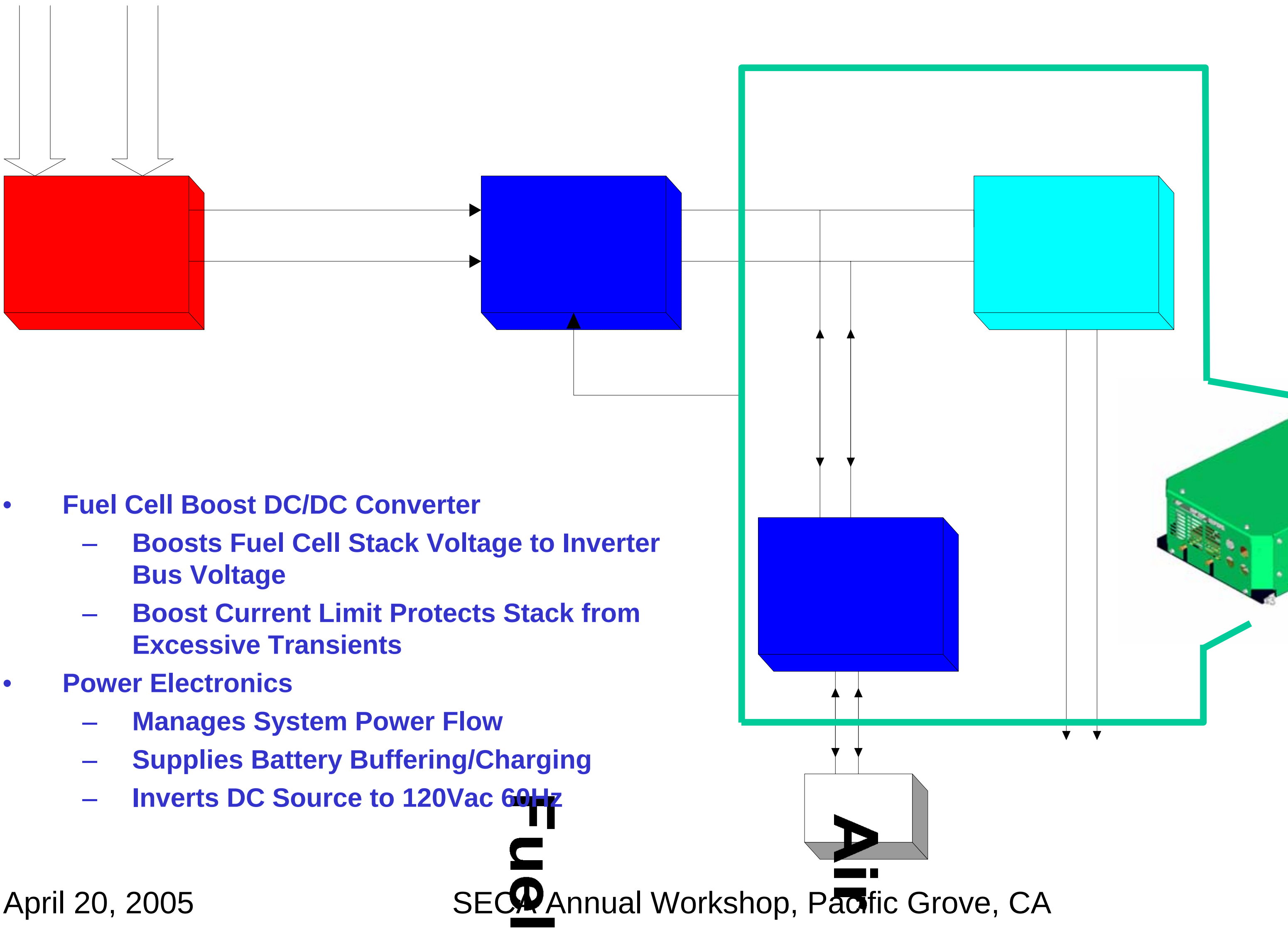


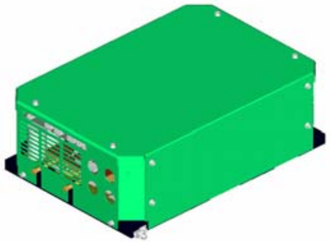
Systems Development: C2 Status

- Successfully demonstrated heat-up of Power Module
- Heat exchanger, insulation, seals, start-up burner OK



Power Electronics Architecture for C2 prototype

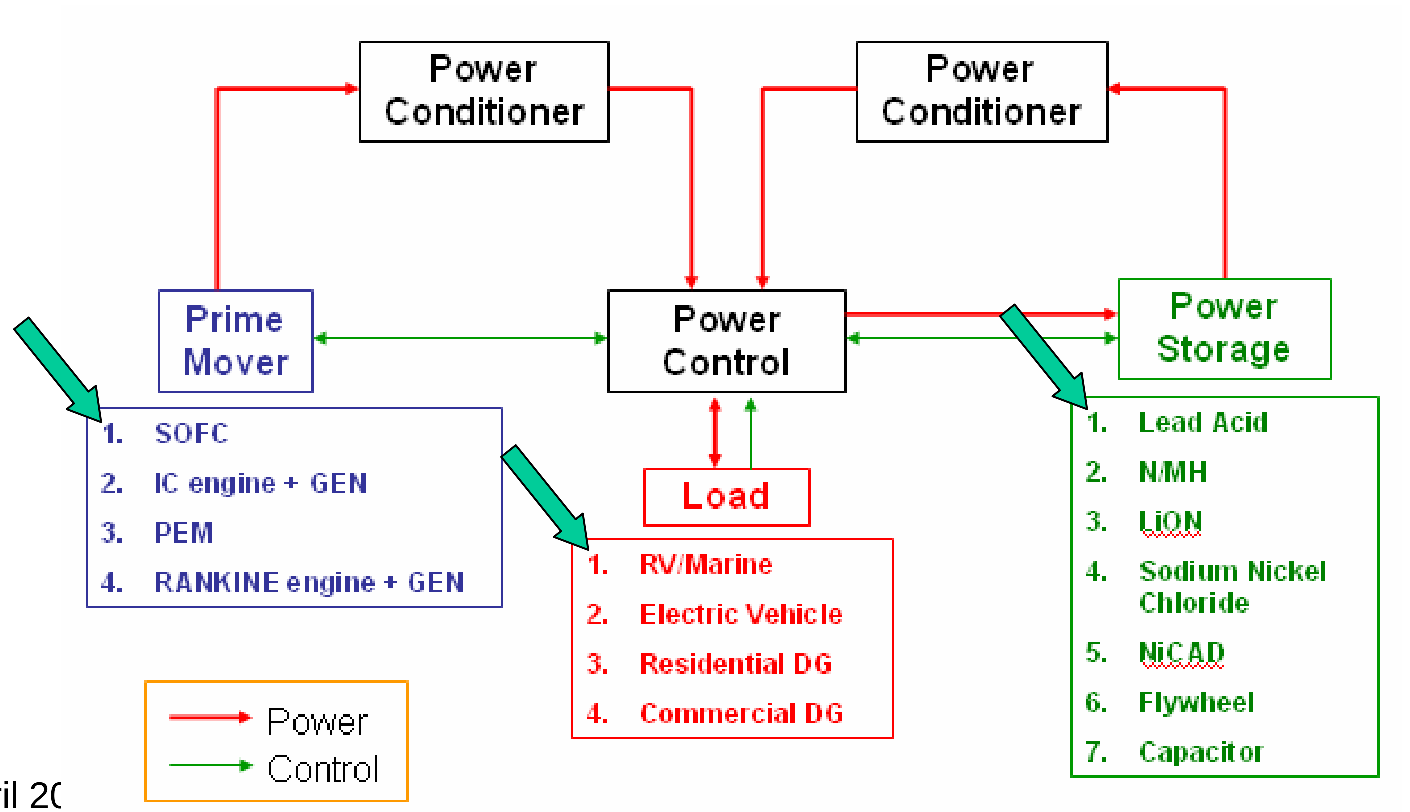




- Fuel Cell Boost DC/DC Converter
  - Boosts Fuel Cell Stack Voltage to Inverter Bus Voltage
  - Boost Current Limit Protects Stack from Excessive Transients
- Power Electronics
  - Manages System Power Flow
  - Supplies Battery Buffering/Charging
  - Inverts DC Source to 120Vac 60Hz

Simulink System Simulation

- Dynamic simulation to optimize fuel cell and power storage capacities
- Optimize stack power control strategy (transient modulation)
- Provide predictive values for tuning fuel cell control parameters



C2 Plan -- 2005

- Complete evaluation of C2 prototype with simulated stacks – May
- C2 development with functional stacks – June - July
- Complete test configuration buildup with deliverable stacks -- August
- Commence SECA 1500 hour test sequence – September 2005

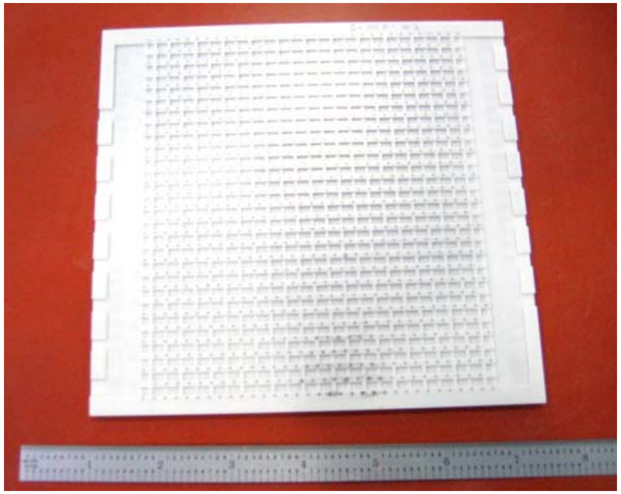
Power Generation

- Cummins Power Generation
- CPG - SOFCo Team
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- **Look ahead at C3**
- SOFC APU Program

Power Generation

Advanced Design: Interconnect

Interconnect Scale-up



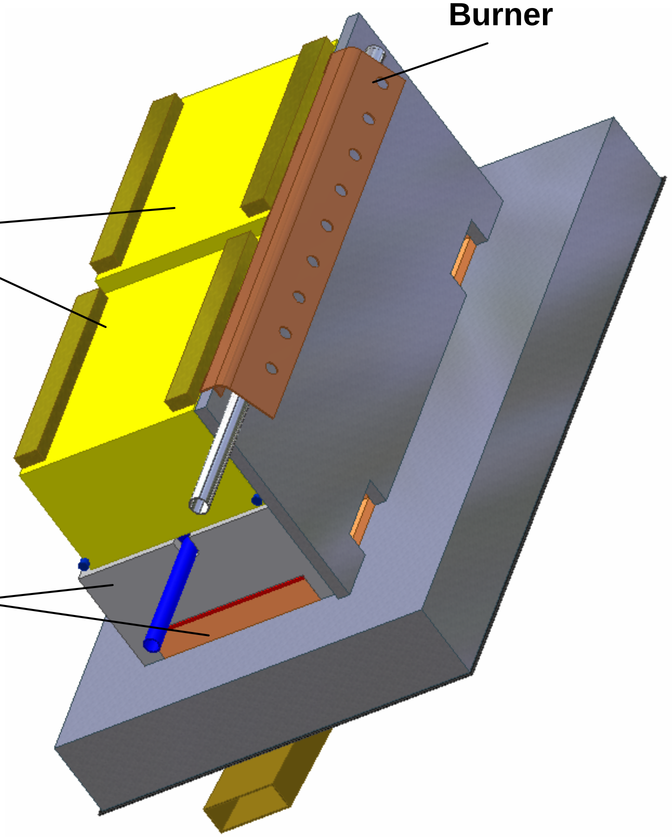
- Scale-up work began Q1 2003
- Design engineering
  - Flow / channel common to 10cm
  - Channel depth increased for delta P
  - Via density preserved
  - I/O manifolds scaled for flow
- Modeling
  - Parallel channel pressure modeled
  - Electro-chemical model being developed from 10 cm baseline
- First experimental 15 cm parts produced Dec 2003
- Parts completed to prove manufacturability Oct 2004
- Supports development of cost optimized cell/stack footprint

Advanced Design Concepts

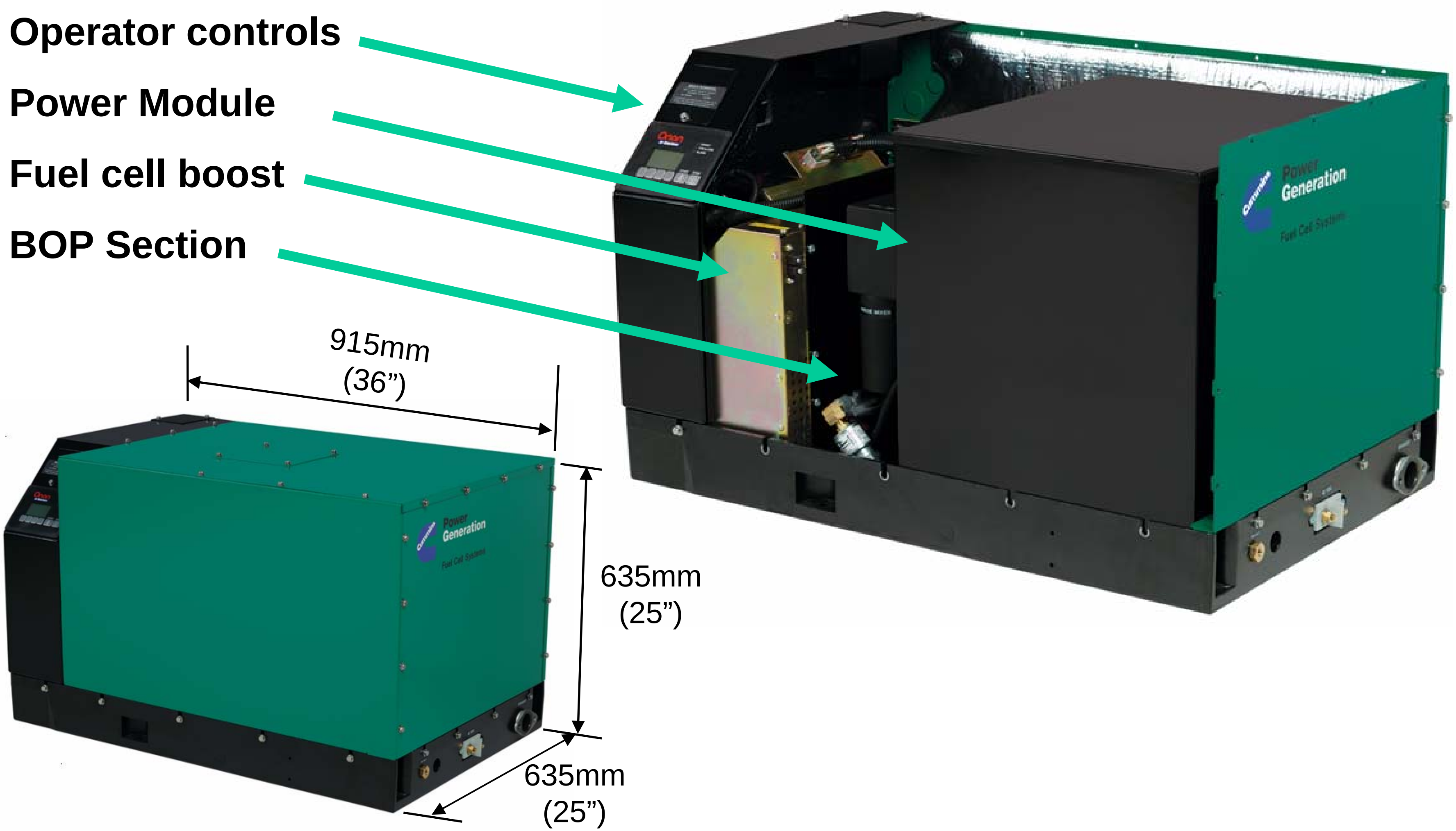
Features

- Optimized stack footprint
- 2-piece split manifold design incorporating HX collectors
- Heat exchanger with improved thermal integration and more compact packing
- Start-up burner with smaller footprint and improved integration

C3 Power Module Concept

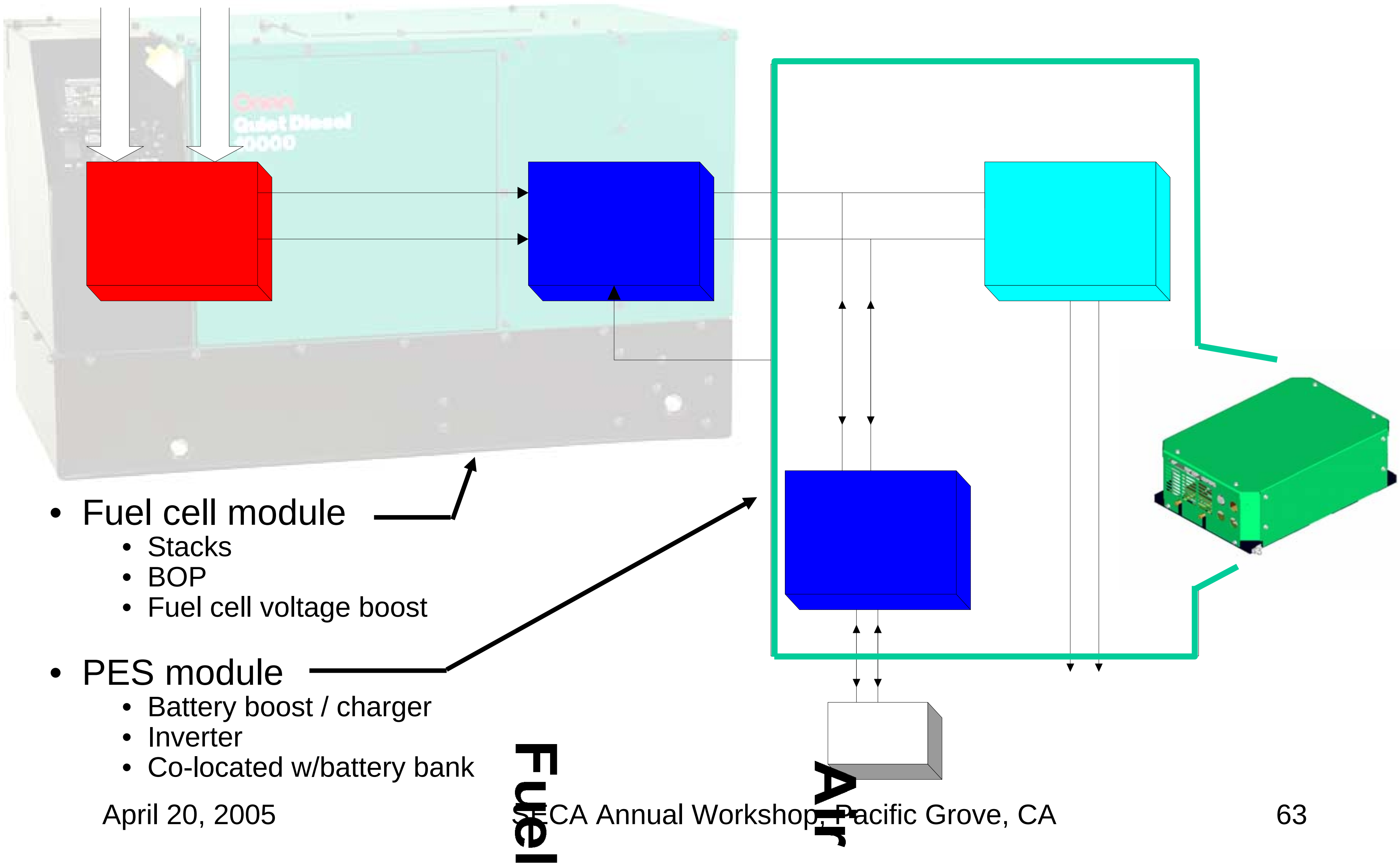


Fuel Cell System Mock-Up



Power Generation

C3 Prototype
System Physical Arrangement



- Fuel cell module
  - Stacks
  - BOP
  - Fuel cell voltage boost
- PES module
  - Battery boost / charger
  - Inverter
  - Co-located w/battery bank

- Cummins Power Generation
- CPG - SOFCo Team
- SECA Program Progress
  - Cell and Stack
  - Waterless CPOX fuel reformation
  - Balance of Plant
  - Controls & Power Electronics
- Experience with C1 Prototype testing
- Progress and plan for C2 Prototype
- Look ahead at C3
- **SOFC APU Program**

EERE SOFC APU

Mission: To design, develop, and fabricate a prototype SOFC APU that can be integrated with a Class 8 On-highway tractor, demonstrate providing the required heating, cooling, and electrical power operating from low-sulfur diesel fuel, drive it around, and bring it back alive by 2007.

- **International Truck & Engine Corp.**
  - **Vehicle Requirements, Systems, Interface**
  - **On-vehicle test & evaluation**
- **SOFCo-EFS Holdings LLC**
  - **Power Module – SOFC stacks, manifolds, recuperator, insulation, packaging**
  - **Diesel fuel reformer**
  - **Sub-system testing**
- **Cummins Power Generation**
  - **Balance of Plant (blower, fuel supply, plumbing)**
  - **Controls & power electronics**
  - **System integration**
  - **Sub and system testing**

Power Generation

Summary

- *Matrixed development of all-ceramic cells and interconnects demonstrating progress consistent with Phase 1 targets*
- *First generation prototype on schedule*
- *Parallel paths in place to evolve systems and components*
- *Demonstrated performance of CPOX reformer*
- *BOP, controls, and power electronics development on track to support system development*

SECA Program

Cummins Power Generation
10kWe SOFC Power System Commercialization Program
Pacific Grove, CA
April 20, 2005

This presentation was prepared with the support of the U.S. Department of Energy, under Award no. DE-FC26-01NT41244. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.