10kWe SOFC Power System Commercialization Program Progress

May 11, 2004

Boston, MA

Dan Norrick

Manager Advanced Development

Cummins Power Generation

- Cummins Power Generation
- Cummins - SOFCo Team
- SECA Program Progress
  - System Design & Application
  - Cell and Stack
  - Hot Box
  - Balance of Plant
  - Controls & Power Electronics

Power Generation

Cummins Inc.

Power Generation

Cummins Power Generation
World Headquarters and Manufacturing
Minneapolis, Minnesota

Cummins Power Generation

Micro-Turbine Gensets

Developing and manufacturing a wide range of power generation equipment ...

Diesel and Gas Engine Gensets, CHP Systems

Variable Speed Gensets

Diesel, Lean Burn and Stoichiometric Gas Engines

Controls, Power Electronics, Switches, Switchgear

Noise Attenuated Gensets

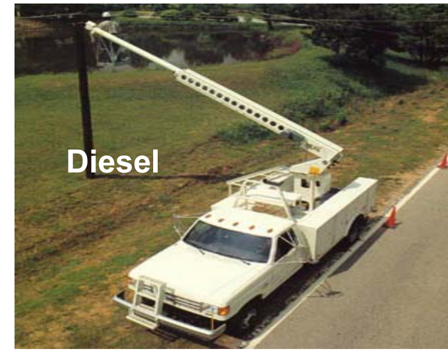
Power Generation

Energy Solutions

- **Containerised Diesel & Gas GenSets**
  - 1005 to 2000 kW
  - 50 & 60 Hz prime & standby rating
- **Projects mainly 2 to 30 MW**
  - prime mover sales
  - turnkey solutions
  - O&M contracts
  - equity-based full servicing
  - financing
- **Key Drivers**
  - power availability (mainly off-grid)
  - power reliability (high-quality or critical)
  - price insurance/arbitrage
  - energy optimization
- **Customer Types**
  - industrial end-users
  - commercial/public-sector end-users
  - utilities
  - developers
  - energy service companies (ESCOs)
  - regional authorities/government

Small Scale Fuel Cell Applications and Fuels

Recreational Vehicle



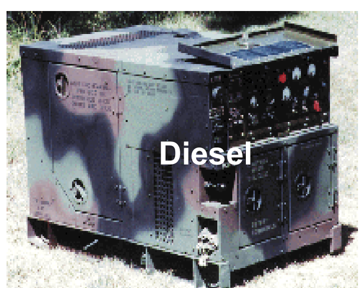
Commercial Mobile

Truck APU

Marine

Residential DG

Military



Telecommunications

Natural Gas or Propane

Cummins Power Generation

Clean energy for the world
SOFCo

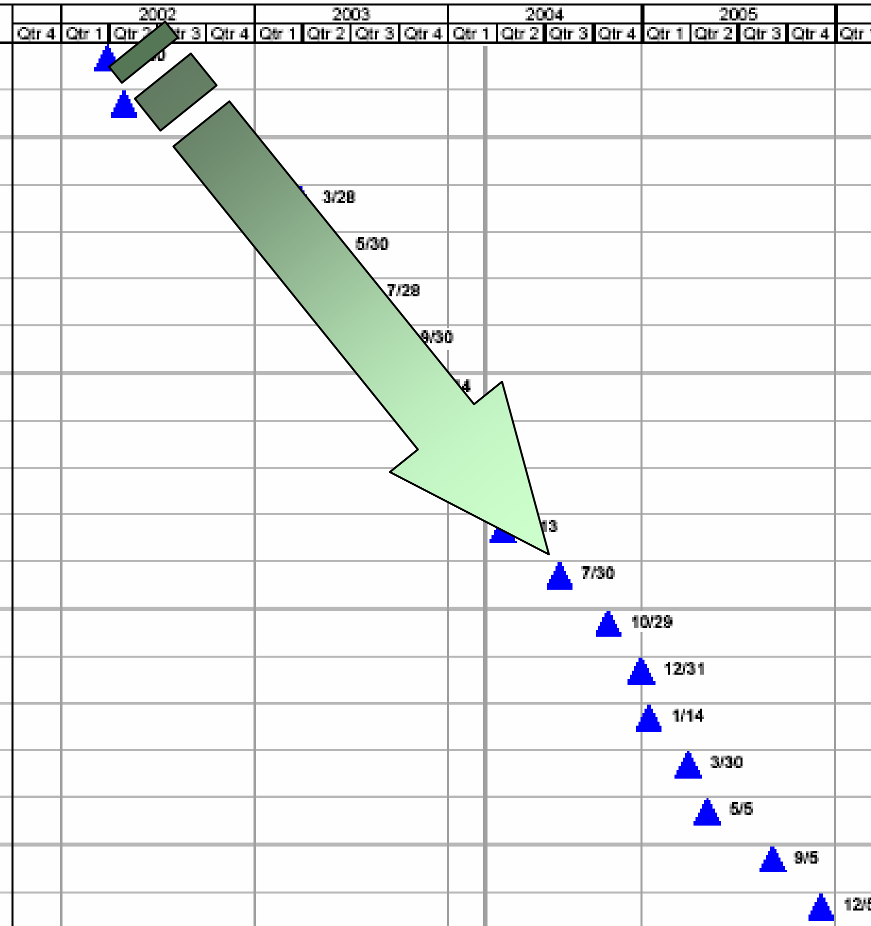
- Electronic controls
- Power electronics
- Fuel systems
- Air handling systems
- Noise and vibration
- System integration
- Manufacturing
- Marketing, sales, distribution

- Planar SOFC technology
- Reformer technology
- Material science
- Heat transfer
- Computational fluid dynamics
- Numerical modeling
- Multilayer ceramic manufacturing

Progress to Plan

CPG-SOFCo Key Milestones

ID	Task Name
1	Product Profile Development
2	Develop Steady State Model
3	Develop Transient Model
4	Validate single cell test methodology
5	C1 Hot Box Mechanical Design Complete
6	Deliver C1 reformer components to Hotbox
7	Fuel Cell Boost Hardware ready for application
8	Deliver C1 Hot Box to Cummins
9	C1 simulated fuel cell system test
10	Preliminary 15cm components available
11	Deliver 2 Power Cell Units for C1
12	C1 Prototype - stable steady state operation
13	Deliver C2 reformer components to Hot Box
14	C2 control system ready for application
15	Deliver C2 Hot Box to Cummins
16	C2 Control & Power Electronics Integration
17	Start development testing on C2
18	Start DOE test sequence on C2
19	Finish DOE test sequence on C2



Commercial target: same size envelope as Diesel RV Genset

0.49 m^3 (17.4 ft^3)

Fuel Cell System Mock-Up

Power Generation

Fuel Cell System Mock-Up

Staged prototyping -- C1 and C2

C1 Prototype

- Development tool
- 10cm x 10cm cells
- 2 x 47 cell stacks
- Not packaged
- DC output
- Characterization testing
- Limited operating hours

Operational June 2004

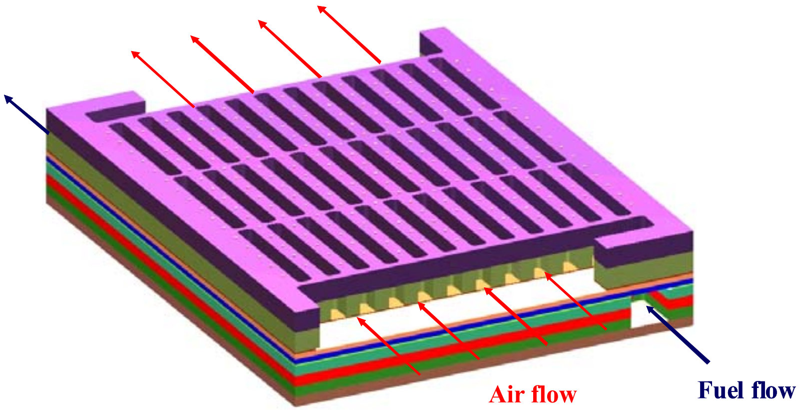
C2 Prototype

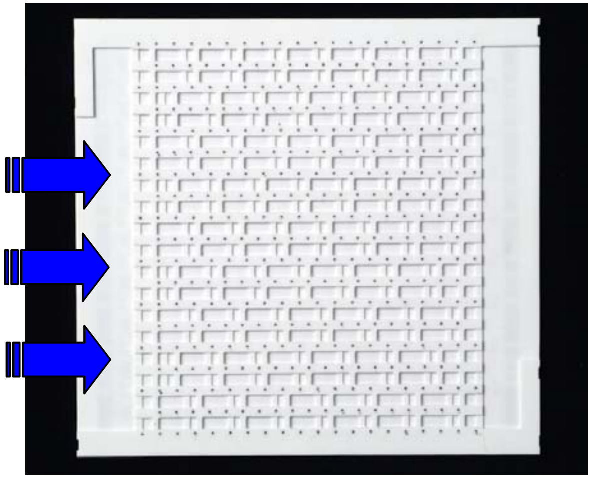
- Program deliverable
- 10cm x 10cm cells
- 4 x 70 cell stacks
- Integrated hot box assembly
- Power conditioning
  - Load sharing
  - 120VAC output
- Complete SECA test plan
- 1500+ operating hours

Operational June 2005

SOFC Stack Technology

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





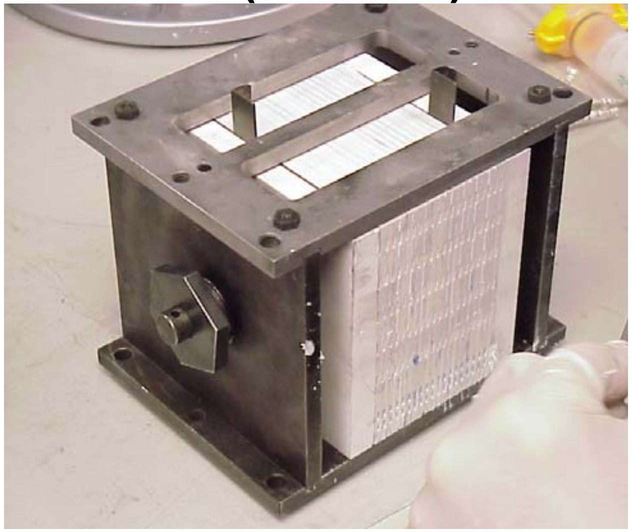
Co-Flow Multi-layer Ceramic (MLC) Interconnect

SOFC Stack Development

2002
Short Stacks
(2-5 cells)

- **ASR ~ 2.5 ohm-cm^2**
- **PD ~ 75 mW/cm^2**
- **Power Deg > 20% / 500 hrs**
- **Fuel Utilization > 70%**

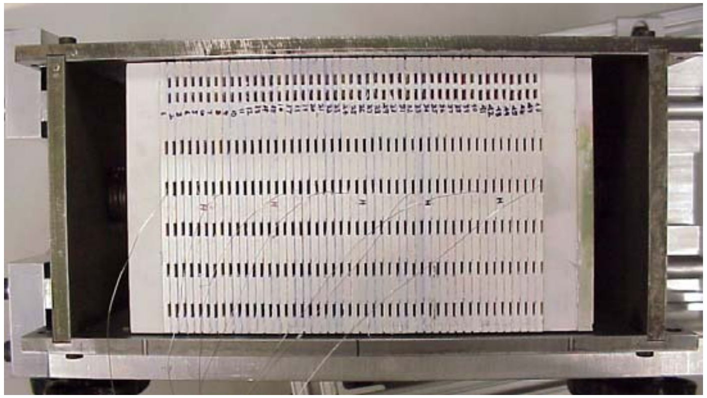
2003
Medium Stacks
(20 cells)



- **ASR ~ 1.5 ohm-cm^2**
- **PD ~ 125 mW/cm^2**
- **Power Deg < 4% / 500 hrs**
- **Fuel Utilization > 75%**

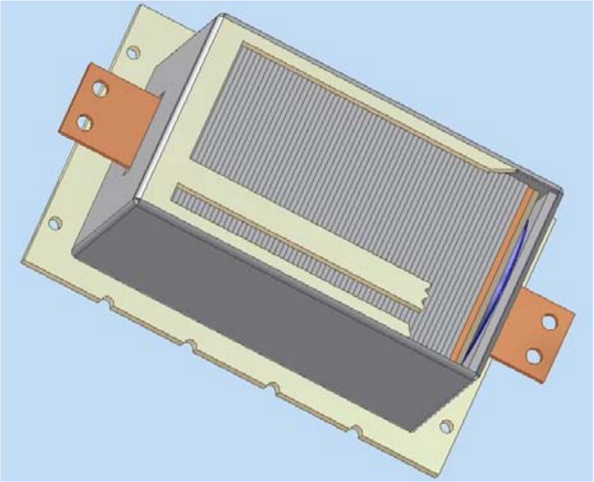
SOFC Stack Development

Q1 2004
Tall Stacks
(45-50 cells)



- ASR ~ 1.5 ohm-cm^2
- PD ~ 125 mW/cm^2
- Power Deg < 4% / 500 hrs
- Fuel Utilization > 75%

Q4 2004
PCU (50-70 Cells)

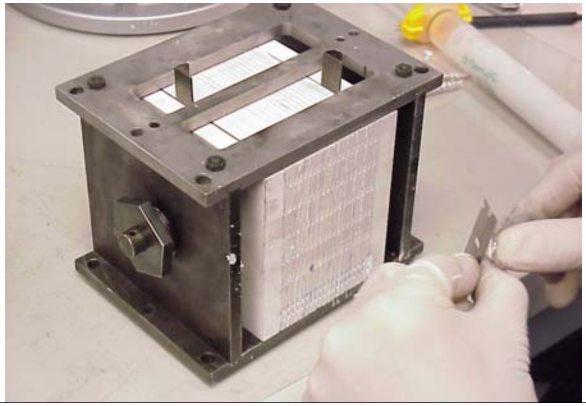


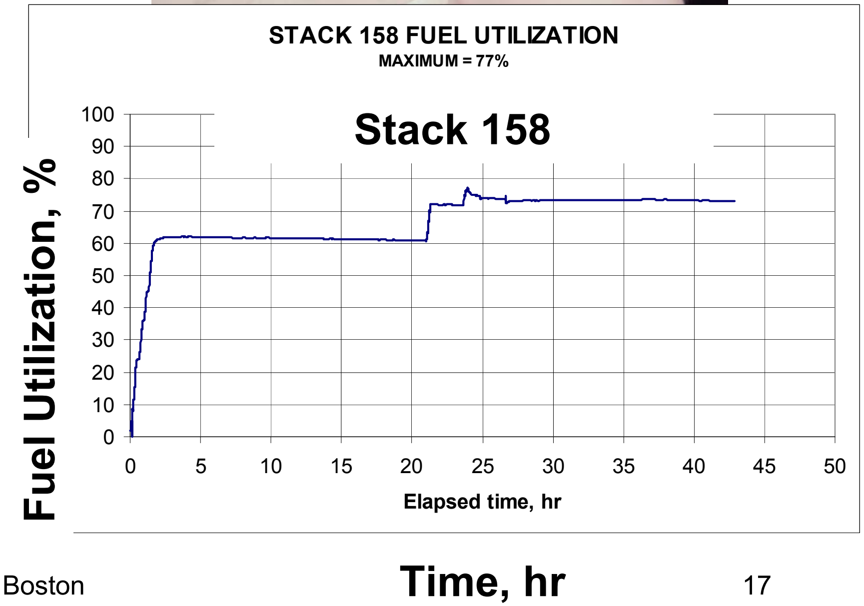
- ASR < 0.75 ohm-cm^2
- PD > 250 mW/cm^2
- Power Deg < 2% / 500 hrs
- Fuel Utilization ~ 80%

SOFC Stack Scale-up

- Achieved acceptable short stack performance Q3 2003
- Began transition to tall stacks
  - Horizontal orientation for assembly and operation
  - New manifold arrangement
  - No change to sealing materials, current collector, or cell-to-interconnect contact materials

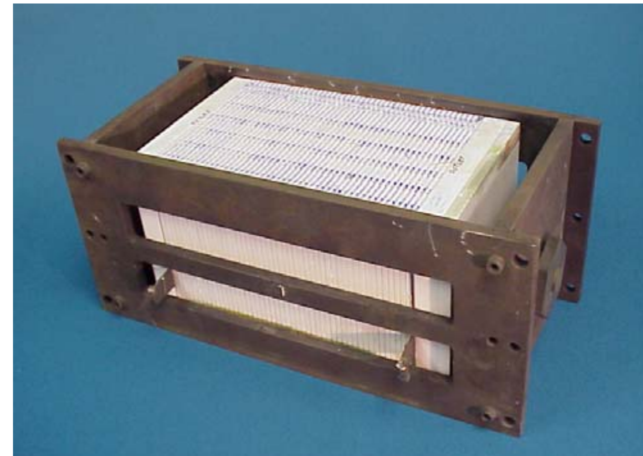
20-cell stack

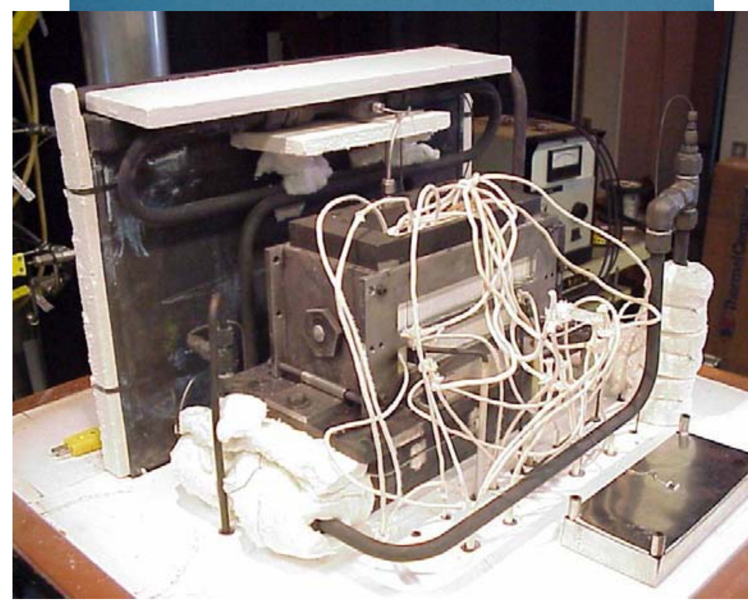




Tall Stack Development

- First build in early 2004
  - > 200 hrs operation on hydrogen with FU >70%
  - > 200 hrs operation with reformed natural gas with FU >75%
- Second test underway
  - Objective: Demonstrate C1 operating parameters (FU, air flow, etc)
- Two stacks for C1 prototype will be assembled in June



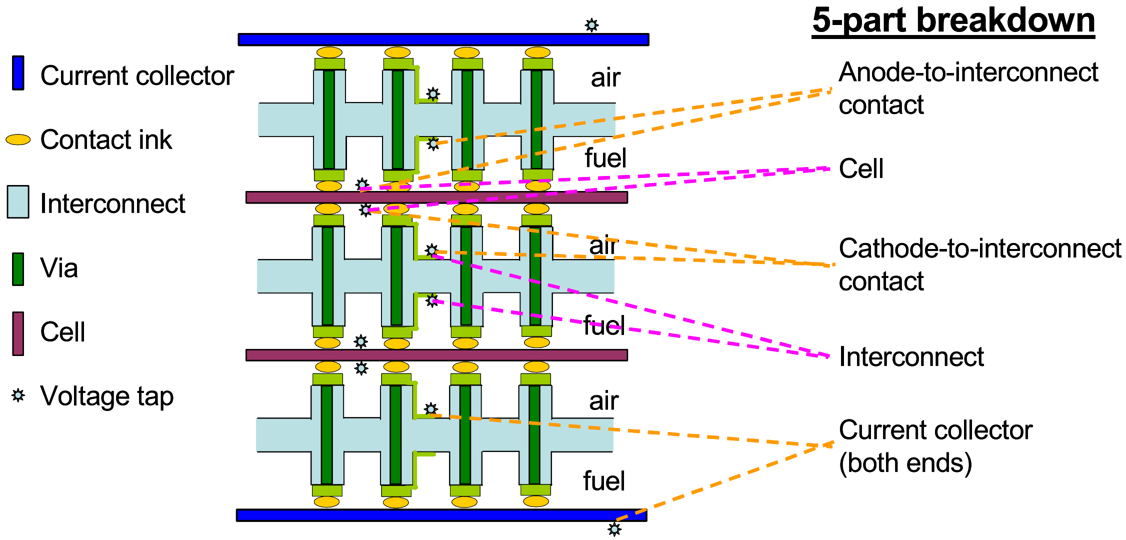


Performance Improvements

– Instrumented short stack allows isolation of contributions to stack resistance

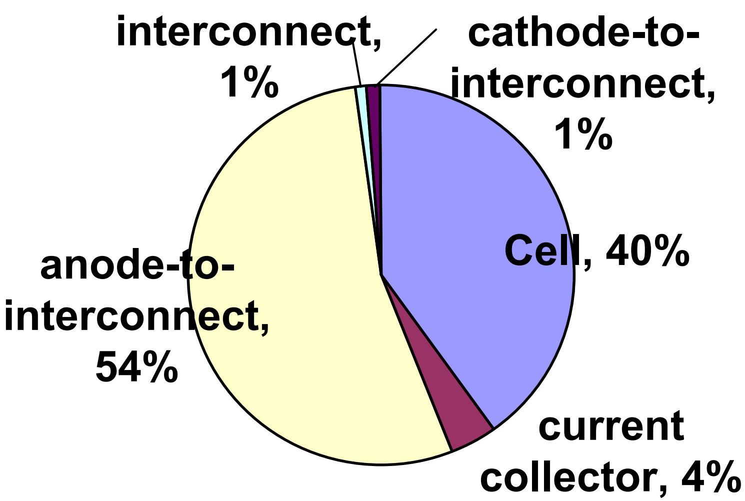
– Significant non-cell contributions to stack ASR and power degradation eliminated

- Non-cell ASR contribution reduced to < 0.2 ohm-cm^2
- Short stack power degradation reduced to < 3% / 500 hrs

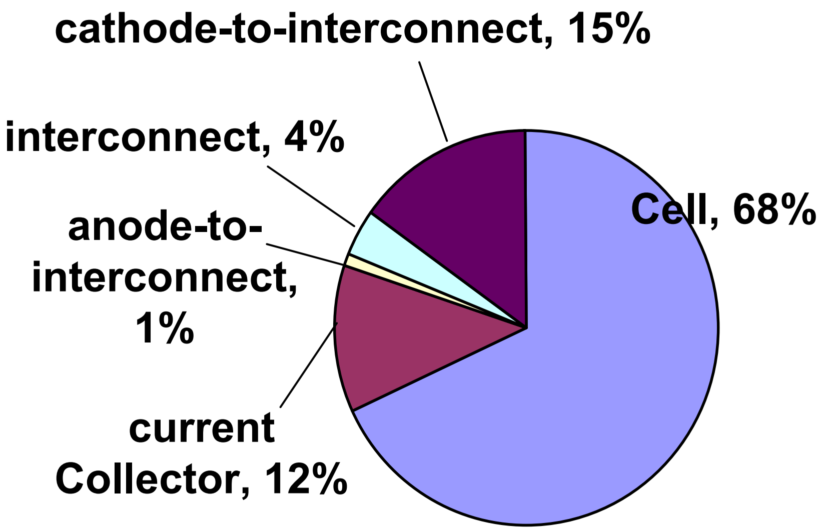


2002 Short Stacks –Degradation Reduced

- Anode-to-interconnect contact largest contributor
- Implemented new anode contact ink
- Significant reduction in degradation rate
- Major non-cell contributor to degradation is now the cathode-to interconnect contact

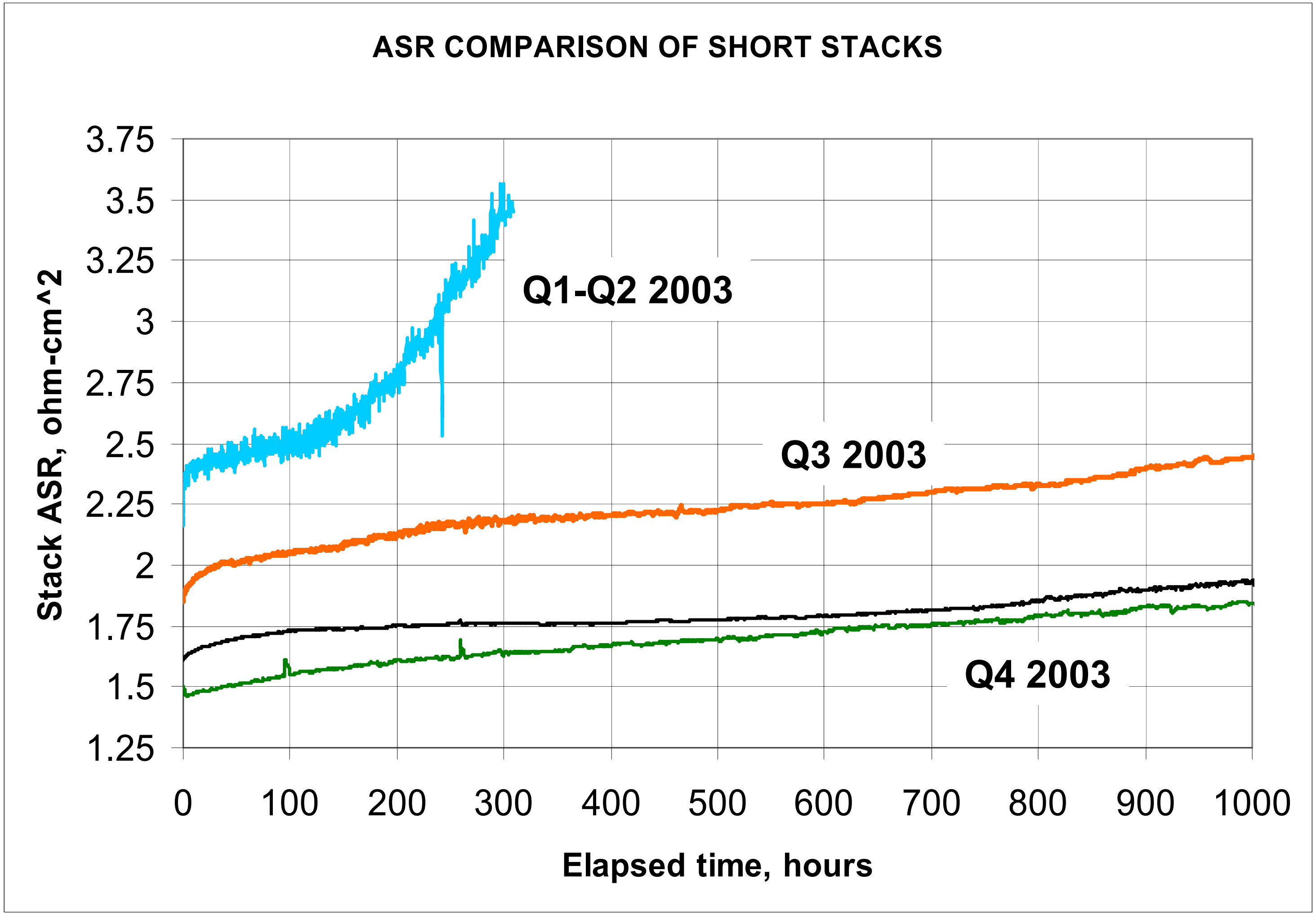


300 hr Relative Resistance

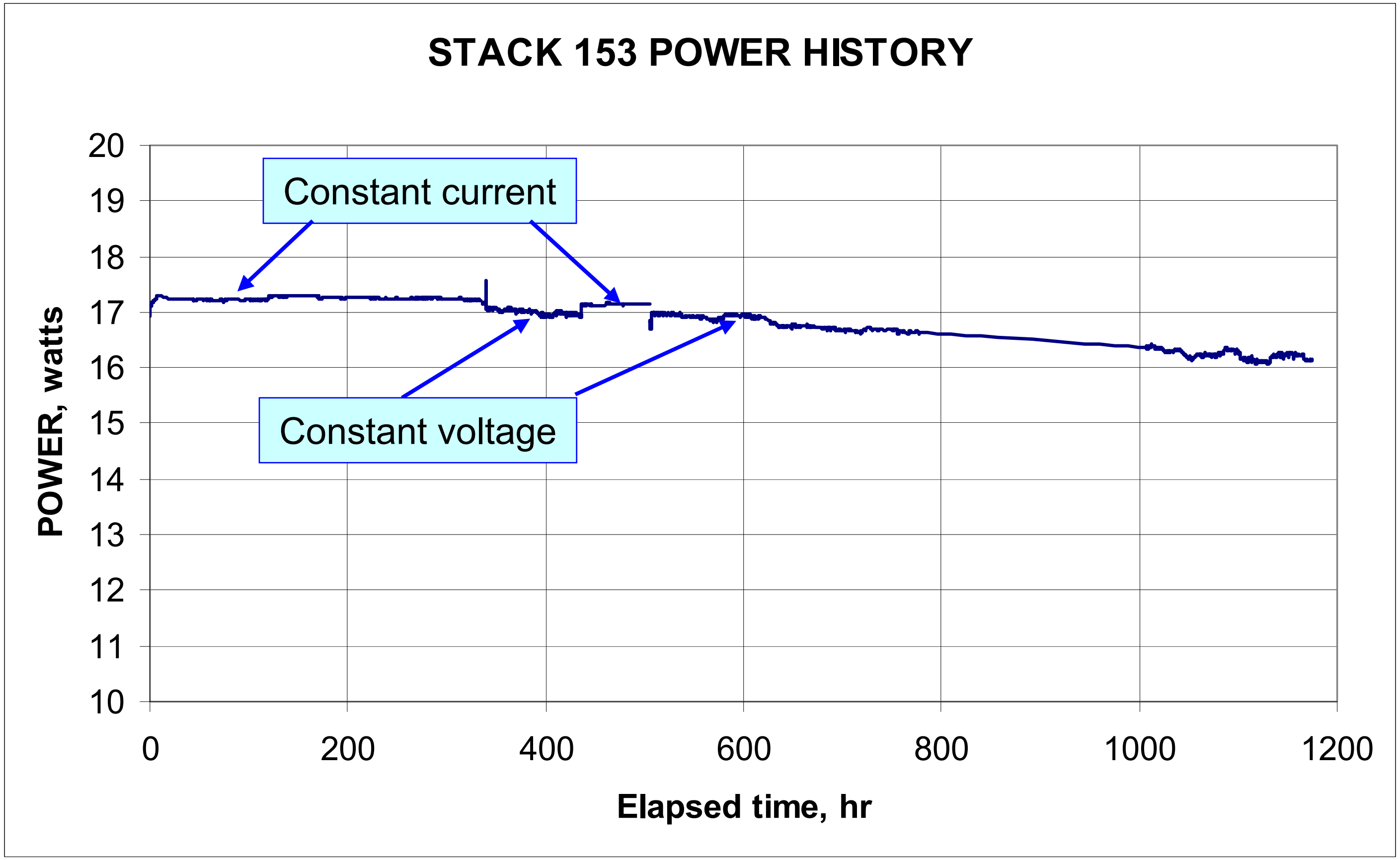


1000 hr Relative Resistance

SOFC Stack Technology



Improved Degradation



Calculated average degradation from 0 to 1175 hours = 2.9% per 500 hours, Initial ASR = 1.36 ohm-cm^2

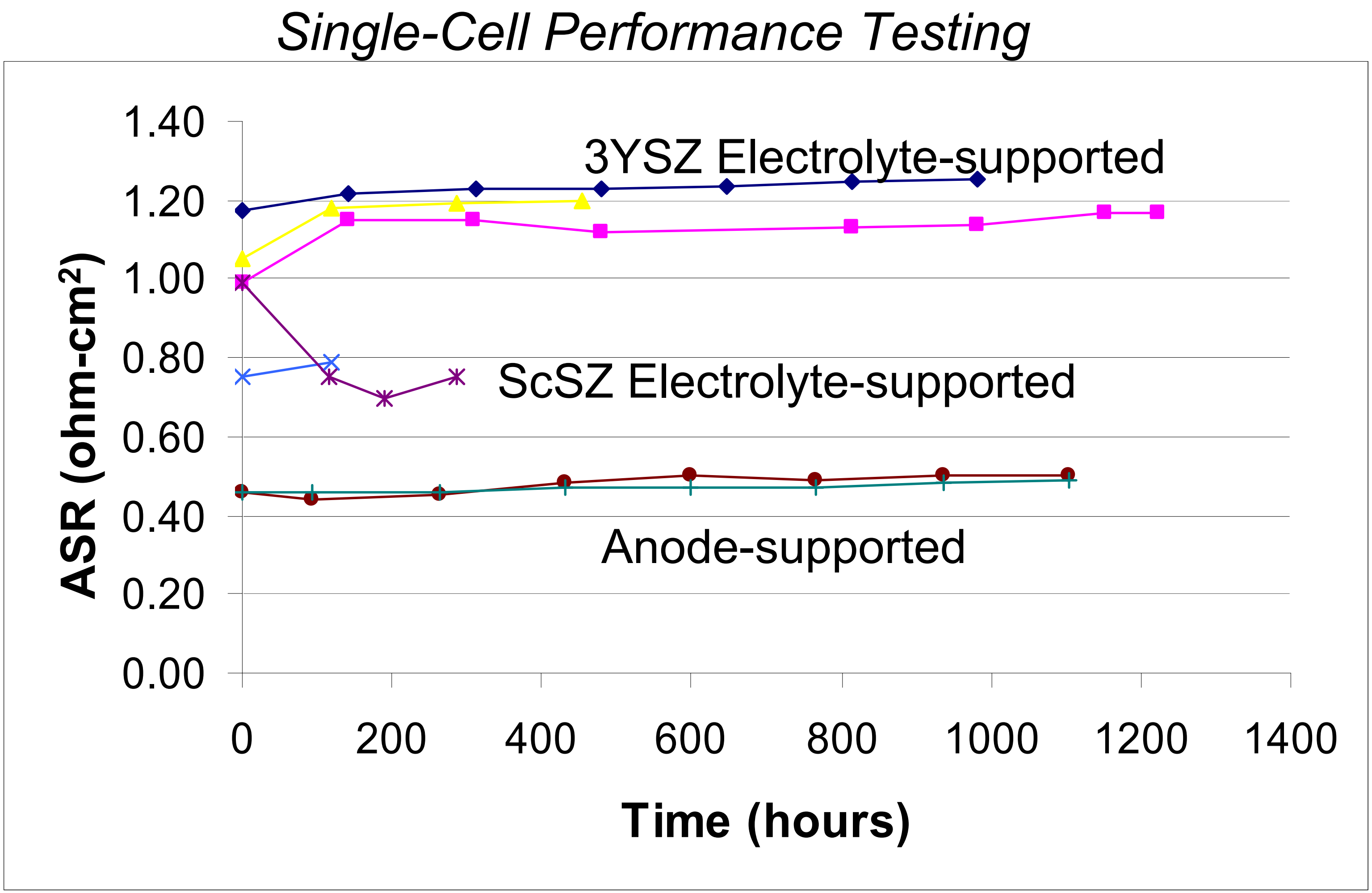
SOFC Cell Development

- 2002 cell development outcomes
  - Reached performance plateau with YSZ electrolyte-supported cells
  - Identified significant problem with integrity of co-fired cells
- 2003 cell development shifted to “dual path” approach
  - External sources for cells and cell technology
    - Baseline 3YSZ post-fired cell for stack development
    - Improved electrolyte-supported cell using ScSZ electrolyte
    - Anode-supported cells
  - Internal cell development focused on co-fired interconnect-supported cells

SOFC 2003 Cell Performance Progress

- Baseline 3YSZ electrolyte-supported cell for stack development
  - Stable, repeatable performance (ASR ~ 1.2 ohm-cm^2)
- Evaluated ScSZ electrolyte-supported cells produced by SOFCo and several external sources
  - ASR = 0.7 – 0.8 ohm-cm^2
  - Degradation exceeds target
- Evaluated anode-supported cells from external suppliers
  - ASR ~ 0.45 – 0.6 ohm-cm^2
  - Degradation exceeds target
  - Limited short stack testing
- Work planned for 2004
  - Cooperative development working with suppliers to improve cell performance
  - Aggressive insertion of new cells into stack development

Driving ASR down



Manufacturing Status - Background

Interconnects

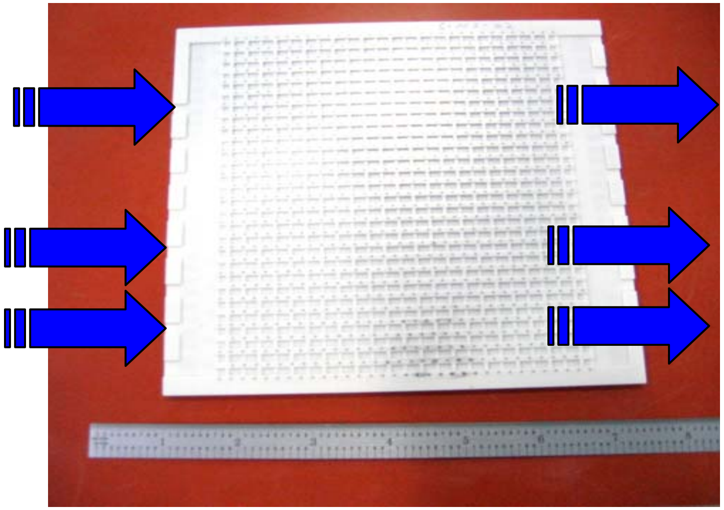
- Manufacturing processes established
  - Production moved to new facility in 2003
  - Over 450 interconnects produced YTD in 2004
- In-house prototyping demonstrated for 10 and 15-cm interconnects

Cells

- Developing commercial sources
  - 2 established
  - 1 under development
- SOFCo development work for improved performance
  - PNNL
  - NASA Glenn

Scale-up to 15 cm Interconnects

- Scale-up work began Q1 2003
  - No major problems
  - Current engineering processes applied
- 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 with AFT-FATHOM
  - Electro-chemical model being developed from 10 cm baseline (2 dimensional EZ-Thermal)
- Produced preliminary 15 cm prototype parts in December 2003
- Prototype parts available for short stack testing in October 2004



15-cm Interconnect

SOFC Stack Development - Summary

- Stack Scale-up
  - Successful scale-up to tall stack for C1
  - On track with 70-cell PCU for C2 (mid 2005)
- Performance and Cost
  - Significant reduction in non-cell contributions to stack ASR and degradation
  - Stack performance largely driven by cells
  - Dual path approach to evaluating anode-supported cells and advanced ScSZ electrolyte-supported cells
  - On track to meet Phase 1 performance targets
  - Achieving cost target = meeting performance targets + implementing low-cost materials

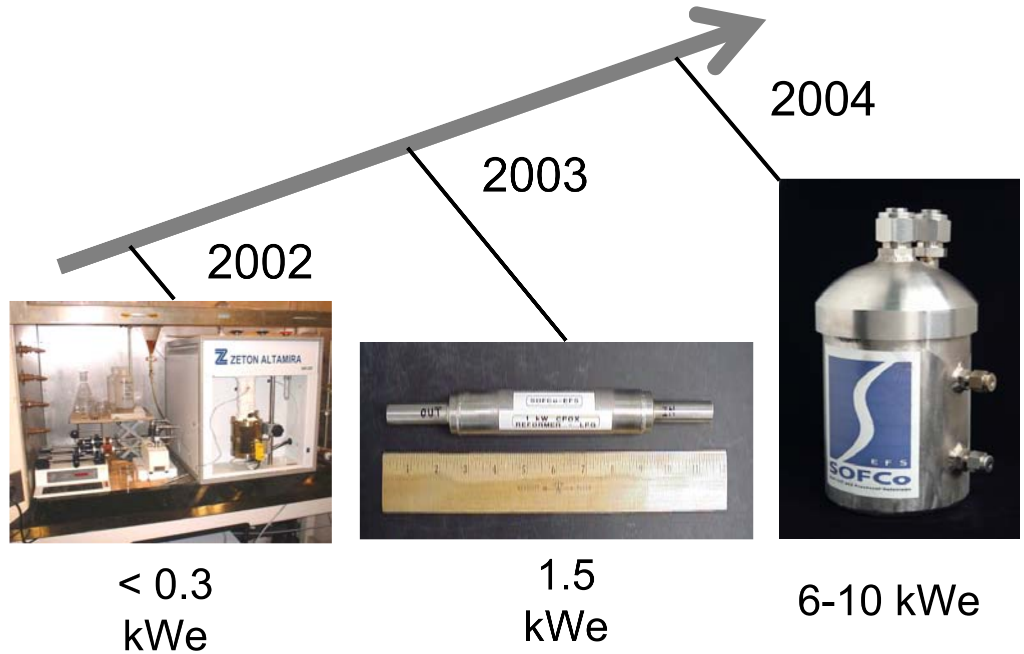
Fuel Processor Development

CPOX Propane/NG Reformer for 10 kWe SOFC System

- High capacity: 40 kW / liter
- Waterless
- Rapid start-up: < 1 minute
- Turndown ratio: > 5:1
- Lightweight, compact design
  - -Weight < 2 kg
  - -Volume ~ 0.25 liter
- Efficient reformer
  - - 70% on LP
  - - 80% on NG

Fuel Processor Success

- Scaled-up waterless CPOX meets performance goals
- Completed transition from LP to Natural Gas for SECA demonstration
- Reformer operated on natural gas for >2500 hrs at 1.5 kWe equiv
- Stack operated on NG reformate for >1800 hrs
  - Carbon free operation verified through post-test exams of stack and manifolding
  - No performance issues



Cummins Power Generation

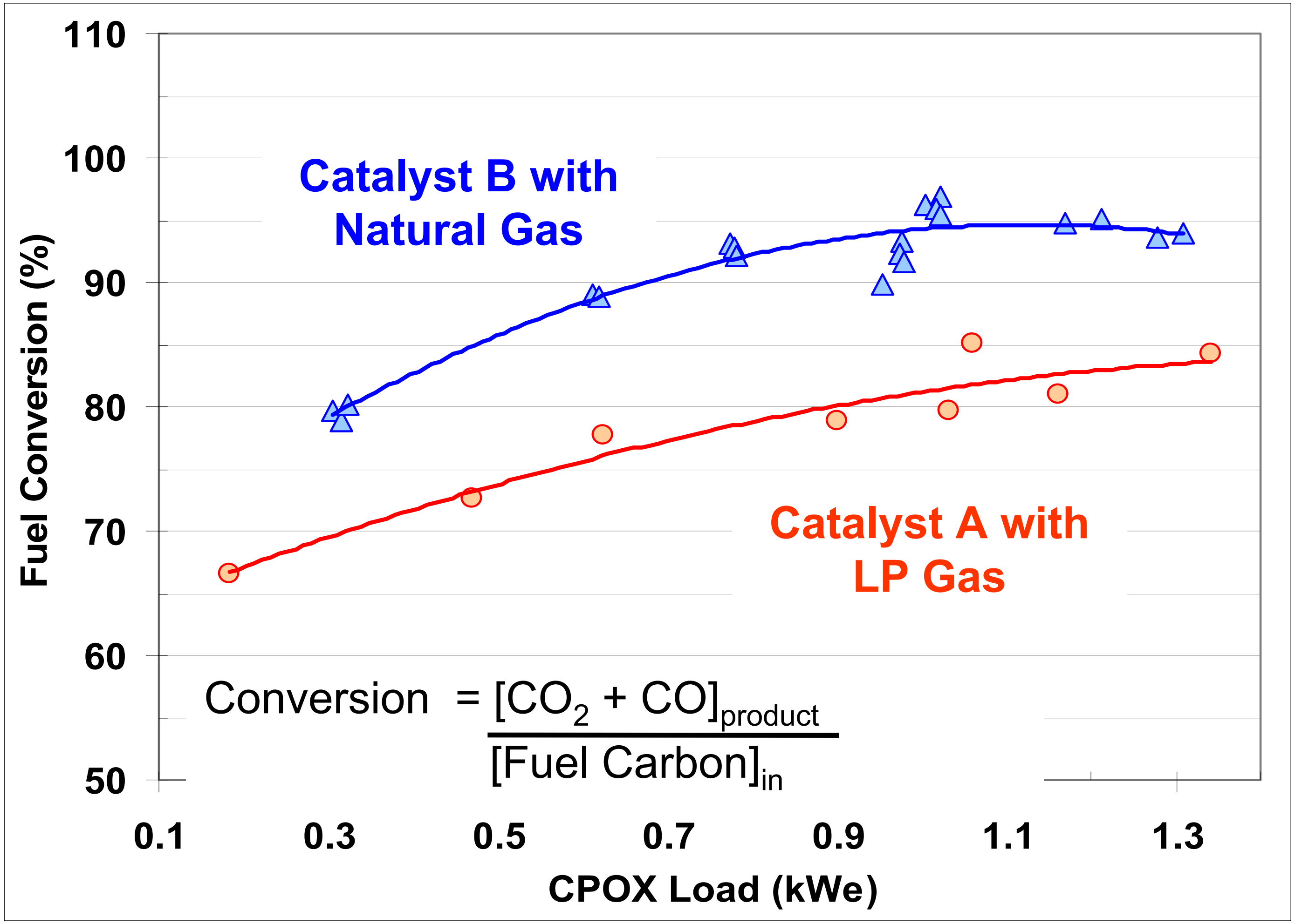
Natural Gas Reformer Status vs. Targets

	TARGET	CURRENT VALUE	COMMENTS
Scale	1 kWe 5 kWe	1.3 kWe TBD (5-10 kWe)	Complete for C1 On-going for C2
Reformer Efficiency	~88% (at equilibrium)	85 % 67 %	High load Low load
Slips (%) Methane C_2+	 0 0	 0.4 – 4.0 0 – 0.04	CH_4 converted in SOFC stack
Turndown	5 : 1	4.3 : 1	Not an issue
Carbon Deposition	No	No issues	No C deposits in stack after >1,800 hrs test
Cost	$60/kW	On target	Based on C1 experience

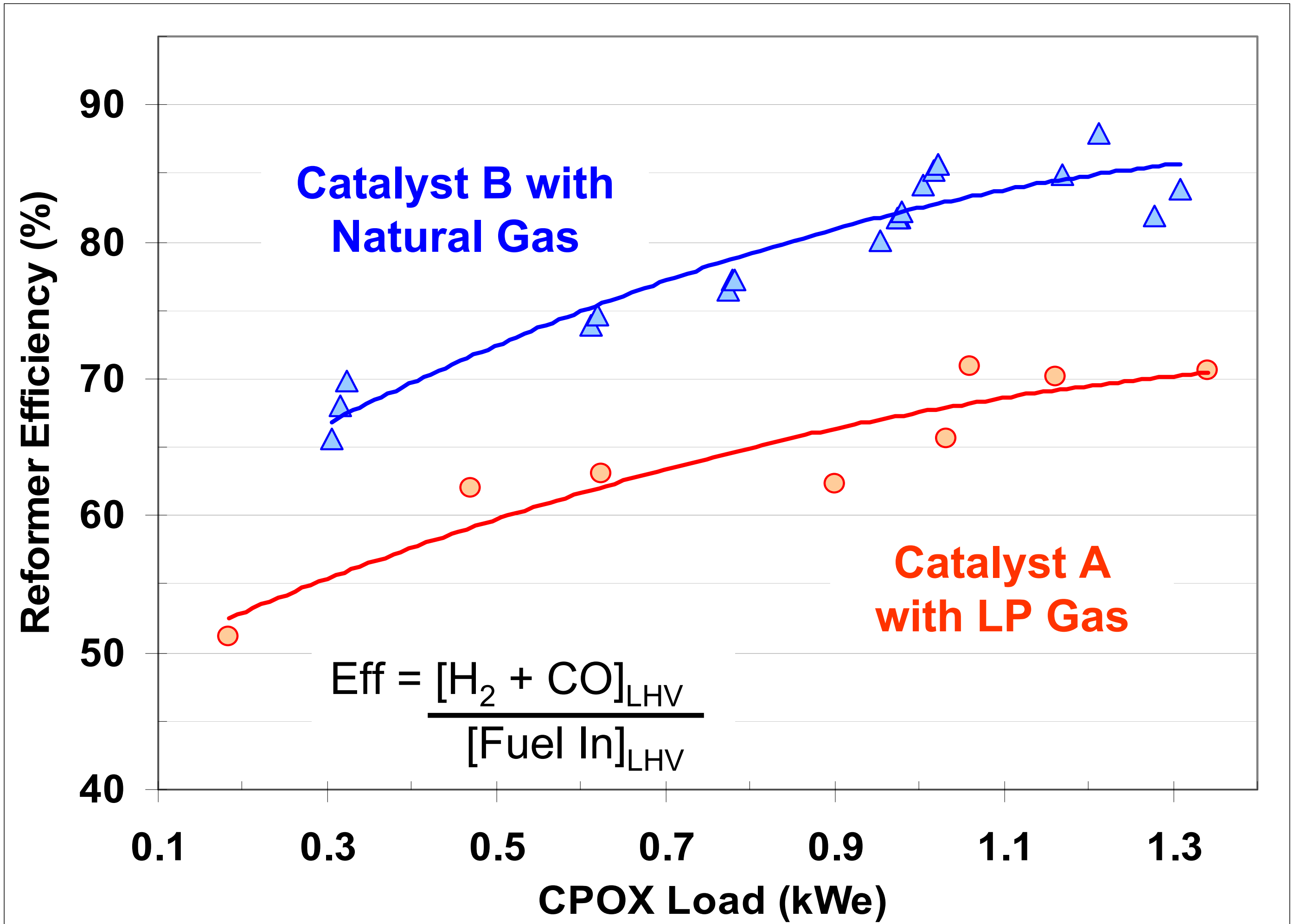
Fuel Flexible CPOX Design

Fuel	LP	Natural Gas
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

Fuel Conversion vs. Turndown

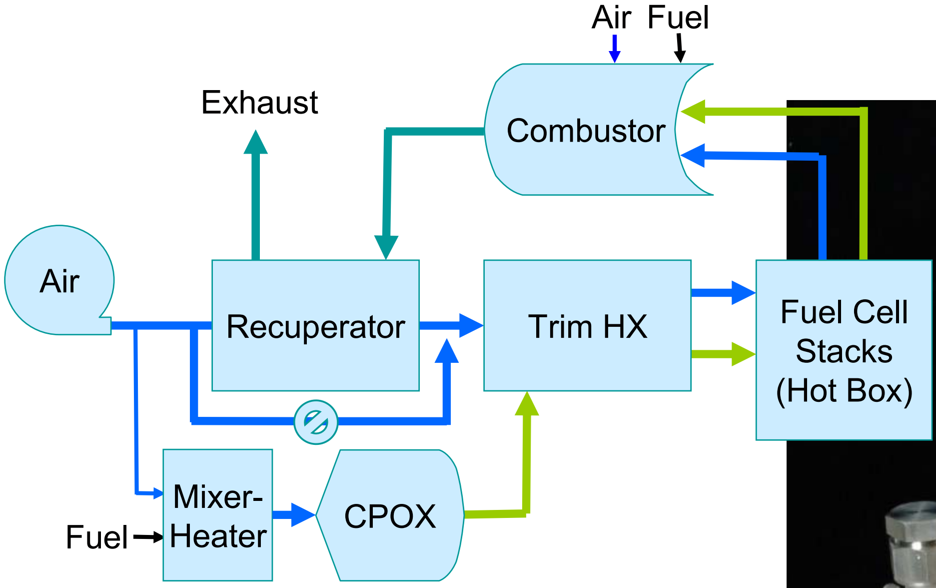


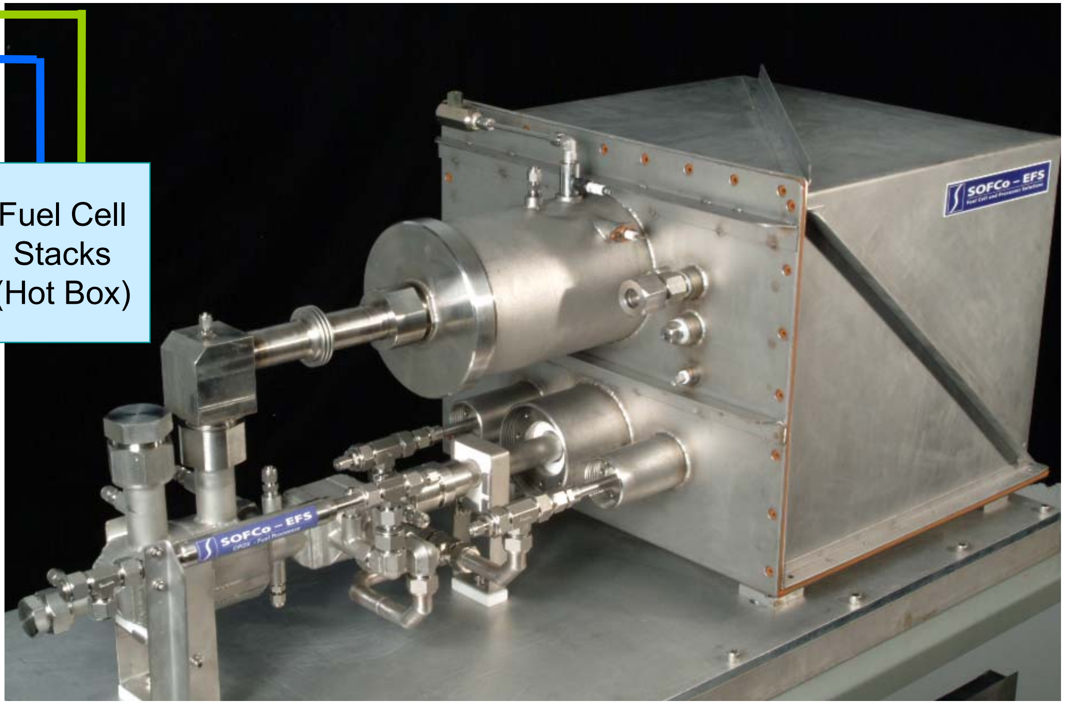
Reformer Efficiency vs. Turndown



C1 Development Unit

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





Power
Generation

C1 Prototype in Cell 21 at CPG

Ignition Control

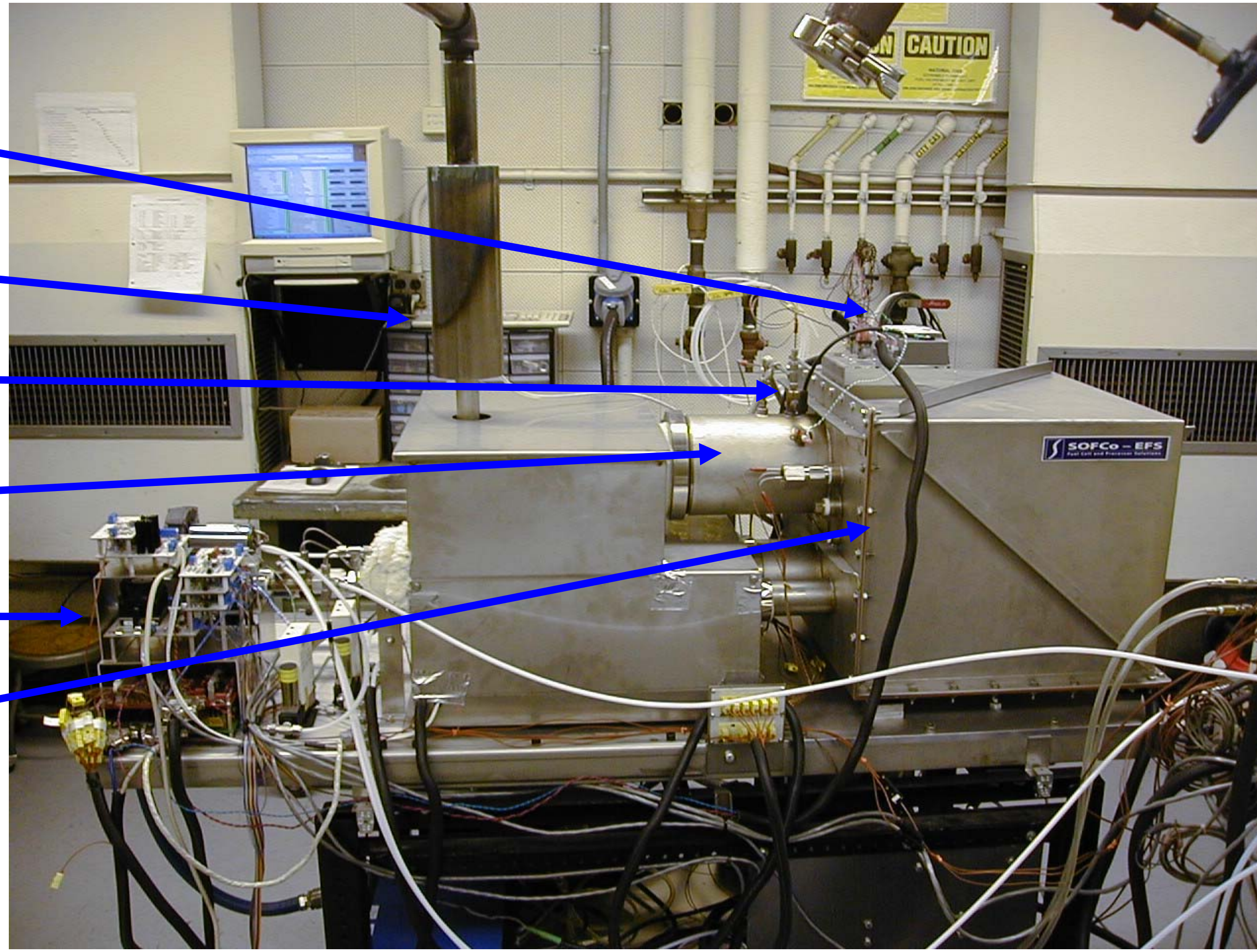
Exhaust

Startup Burner

Combustor

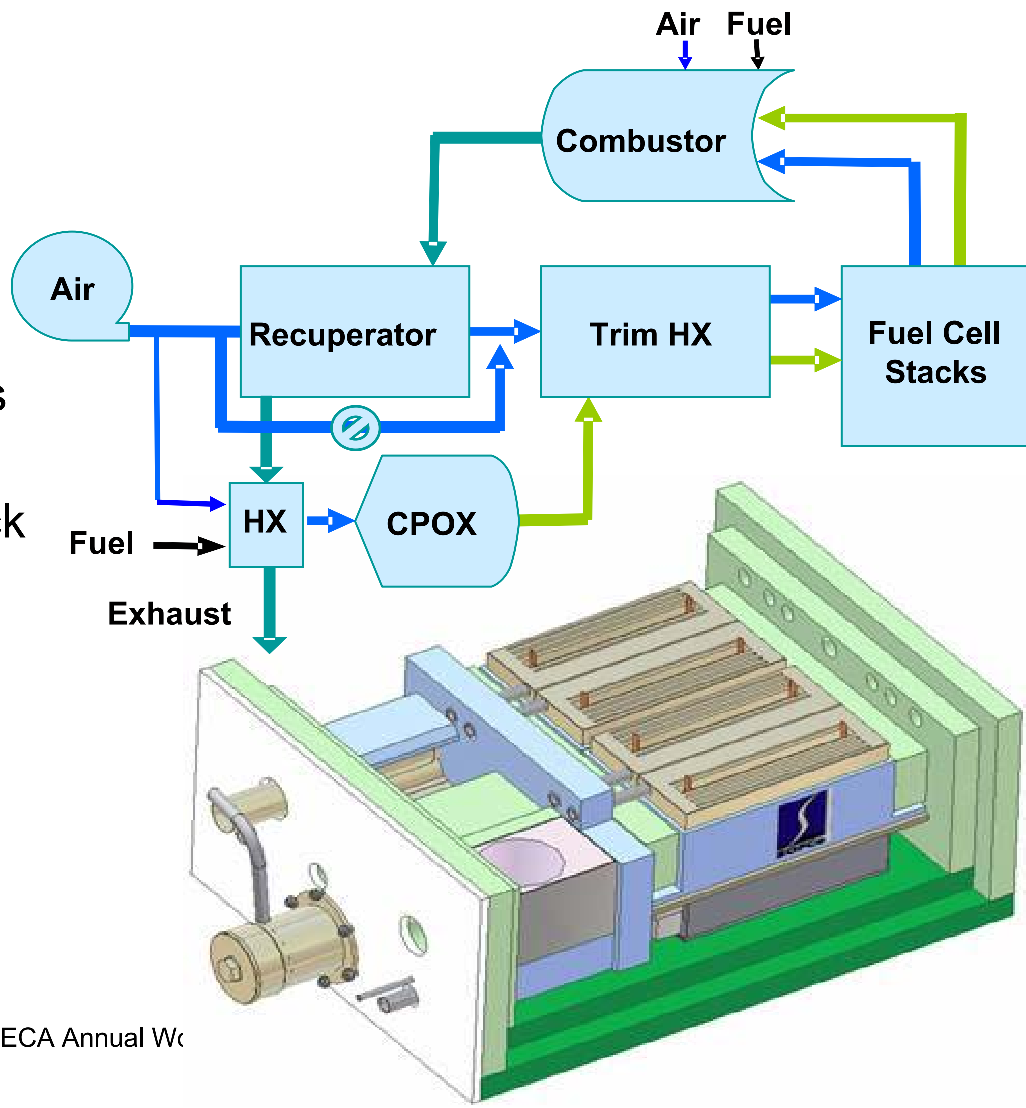
Controls

Hot Box



C2 Phase I Demonstration Unit

- Full thermal integration
- Prototype level packaging
- 4 x 70-cell (10 cm) stacks
- Hardware design nearing completion
- Long-lead hardware orders placed
- Overall size targets on track for APU product goal
  - 4-stacks
  - 85cm L x 64cm W x 41 cm H



Balance of Plant

- Balance of Plant concept translated into functional C1 systems
  - Components selected to meet the functional requirements
  - Functional checks completed on
    - Anode air and fuel supply systems
    - Cathode air supply and bypass subsystems
  - First operational testing of the C1 system with simulated stacks conducted 12/17/03
  - Test cell up-fit for fuel cell specific instrumentation, safety, and controls completed
- C1 analysis and experience will be factored into C2

SOFC Controls and Power Electronics

Purpose of controls and power electronics

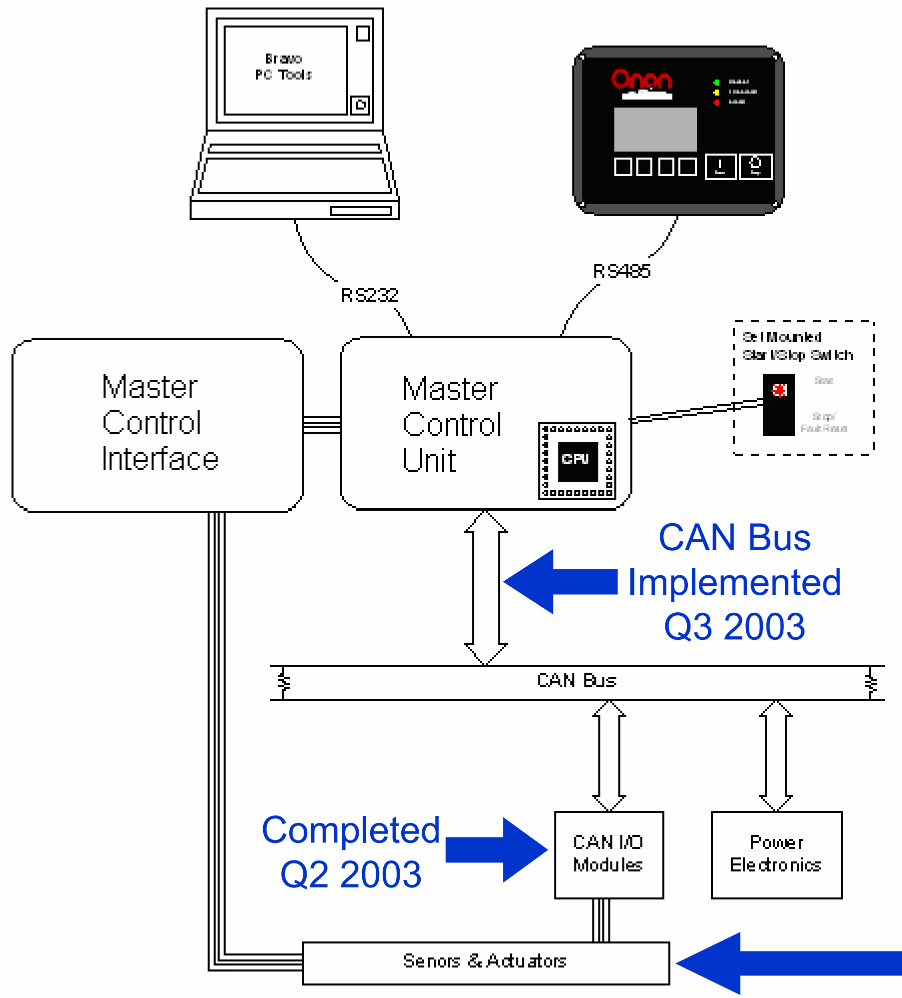
- Thermal and fluid management
  - Control stack average temperature.
  - Control temperature gradient across the stack.
  - Control flows to match current demand and fuel utilization
- Load management
  - Buffer required load power and fuel cell dynamics.
  - Ramped stack loading
  - Managed energy storage

BOP controls hardware architecture

- Controls hardware
  - Designed Q1-Q2 2003
  - Implemented Q3-Q4 2003
- Controls sited on CPG production master control unit (MCU) for development purposes
  - Adapts existing software platform and tools.
- Distributed architecture based on a CAN serial bus.
  - Provides flexibility in choice of actuators.
  - Simplified interface to power electronic controls.

SOFC Controls and Power Electronics

Completed Q3 2003

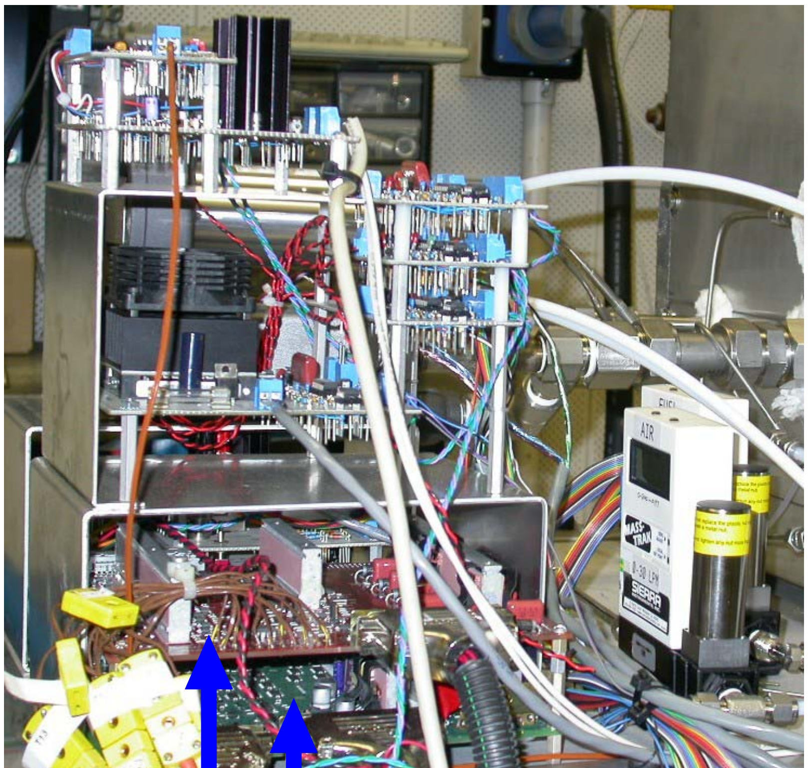


CAN Bus Implemented Q3 2003

Completed Q2 2003

Sensors/Actuators Completed Q4 2003

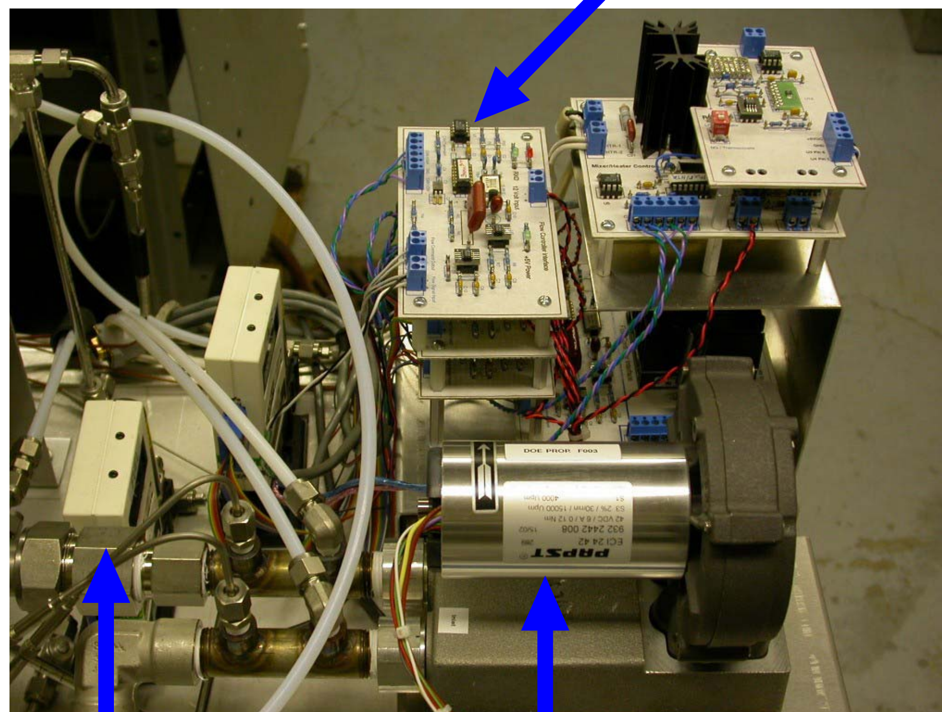
Balance of Plant Controls Hardware



MCI

MCU

CAN I/O Modules

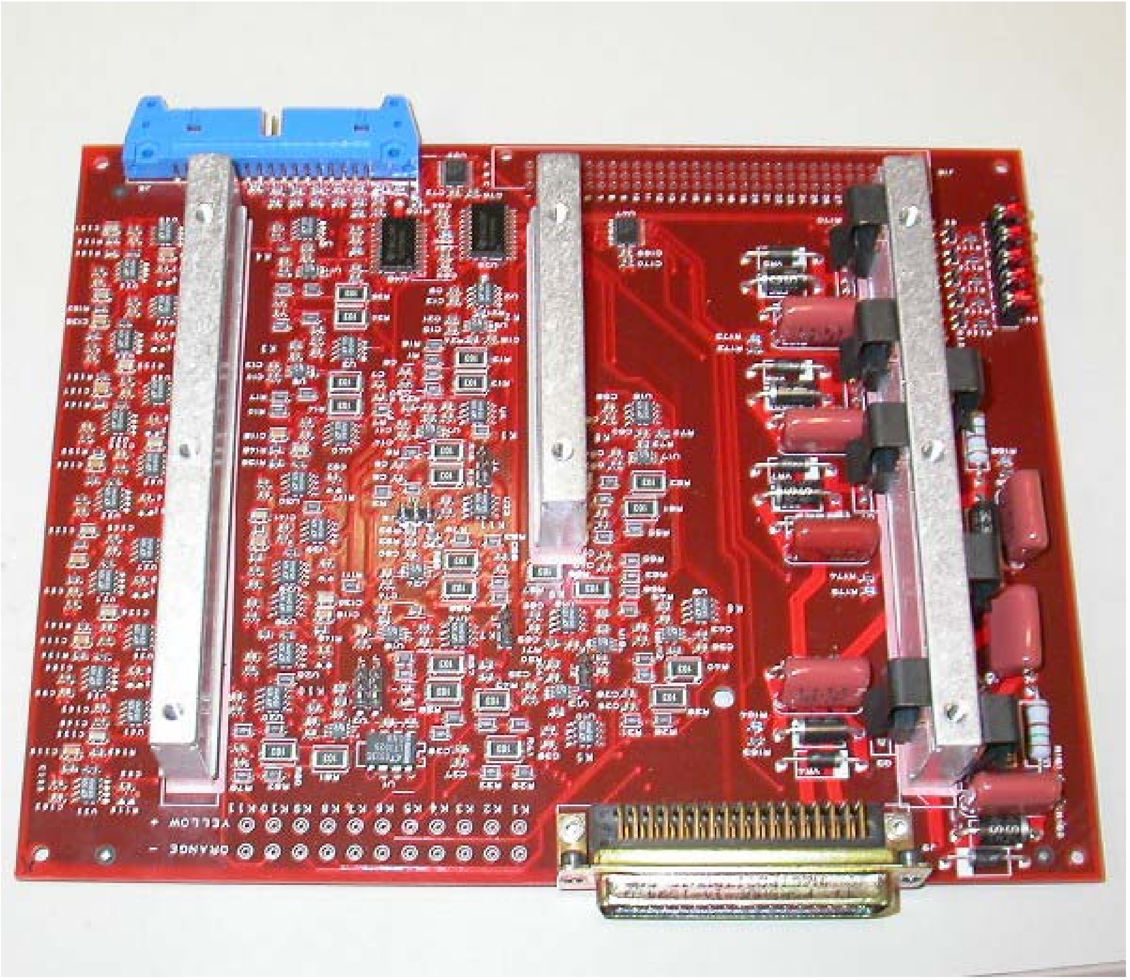


Mass Flow Controls

Cathode Blower

Power Generation

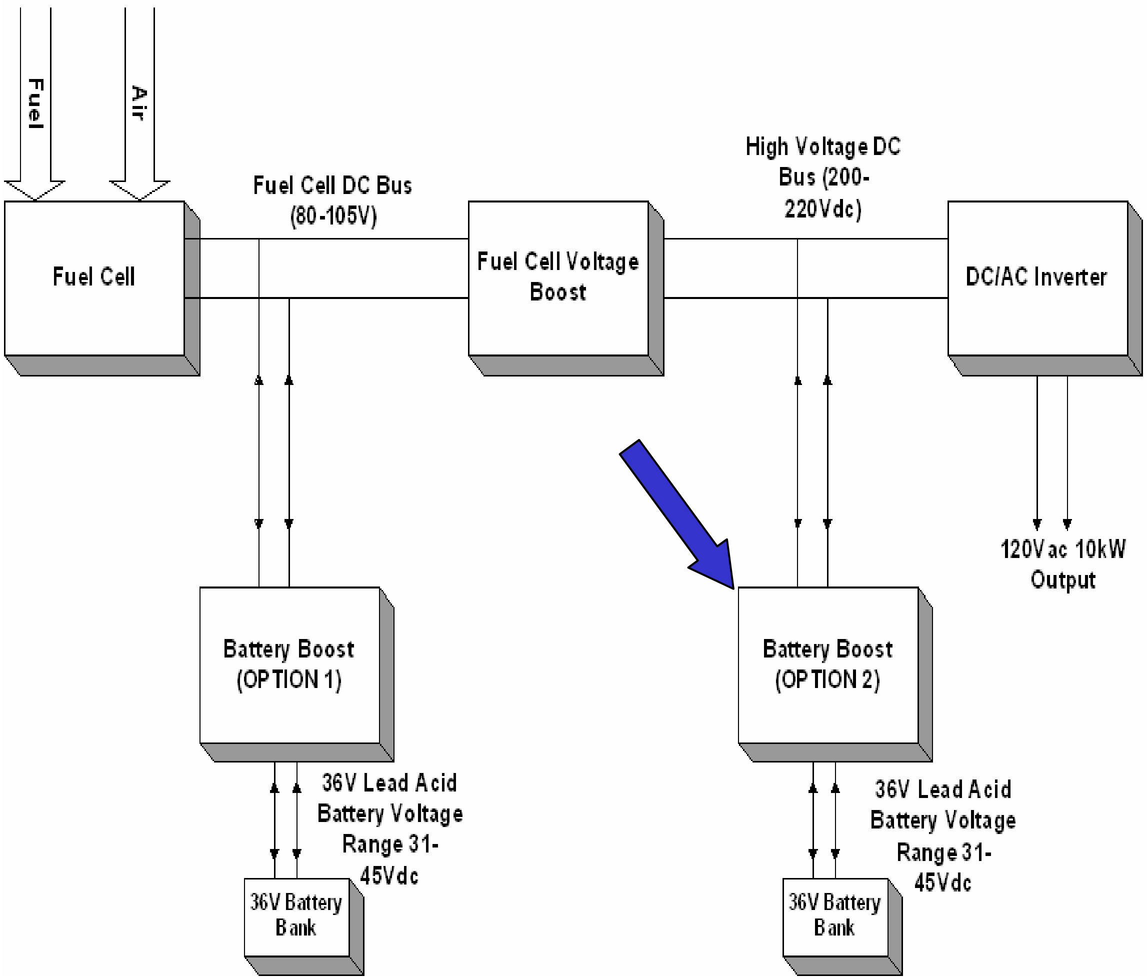
SOFC Controls and Power Electronics



Master Control Interface Board

- 11 Type K thermocouple channels.
- 11 filtered analog input channels.
- 7 discrete digital outputs, each rated to 7.5A.

Power Electronics Architecture



- Two options for Power Electronics architecture.
- **Option 1** initially selected based on lowest cost
- **Option 2** selection driven by control dynamics – cost impact reduced in parallel commercial project

Cummins Power Generation

SOFCo EFS

SECA Program Progress -- Summary

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

Cummins Power Generation

SOFCo EFS Fuel Cell and Processor Solutions

Acknowledgements

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