Power Generation

SECA Annual Workshop

Cummins Power Generation

10kWe SOFC Power System Commercialization Program

April 15, 2003
Seattle, Washington

Dan Norrick -- CPG

This presentation highlights the efforts and achievement of the CPG-SOFCo team over the course of our first year of Phase 1 of the SECA program.

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

Power Generation

SOFCo

Cummins Inc.

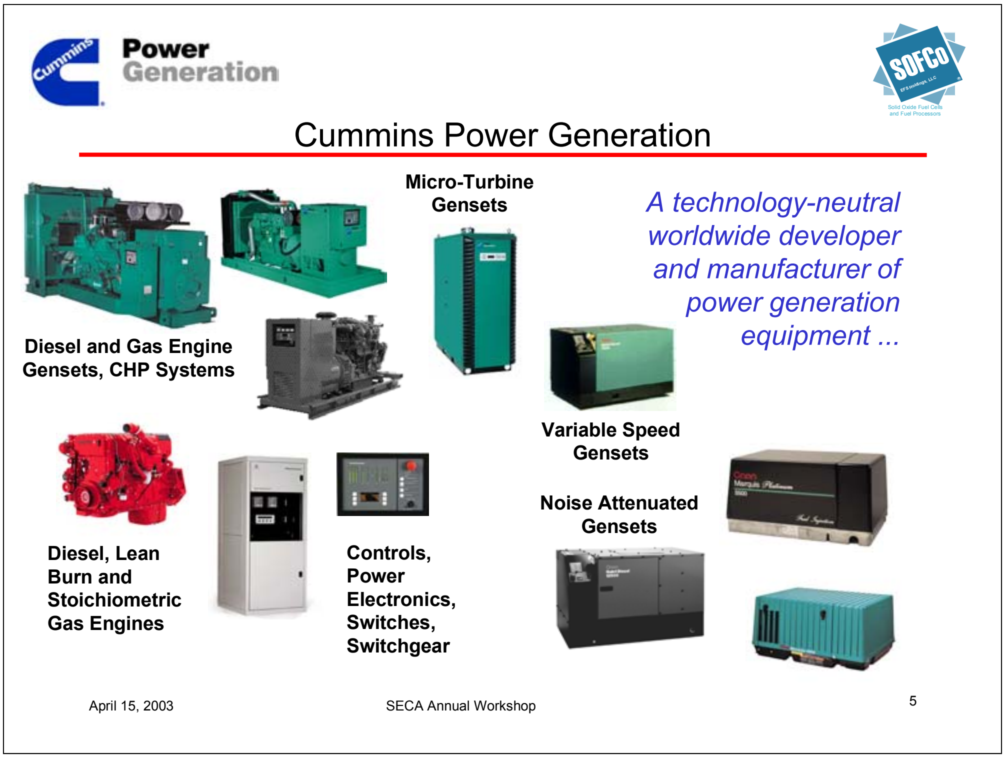
April 15, 2003 SECA Annual Workshop

Cummins manufactures and supplies diesel, stoichiometric and lean burn gas engines, power generation components, power generation systems, controls, switchgear, and filtration products on a worldwide basis.

Power Generation

Cummins Power Generation
World Headquarters and Manufacturing

Cummins Power Generation worldwide headquarters is in Minneapolis, MN. Our SECA partner, SOFCo, is headquartered in Alliance, OH.



Cummins Power Generation designs, develops, manufactures, distributes, and services a wide range of power generation solutions on a worldwide basis.

By virtue of our participation in existing power generation markets, CPG is in an advantageous position to understand the requirements of a broad range of customer needs and the relevant attributes of technologies available to meet those needs.

CPG considers the SOFC a prime candidate to meet customer needs in key markets and, as technology matures, to gradually assume a significant share of the power generation market. Key attributes will vary by market, and the success of the SOFC will be determined by competitive market forces.

Power Generation

SECA Program Entry Markets

Recreational Vehicle

Telecommunications

Commercial
Mobile

Entry markets will be driven by low noise and vibration, high reliability, low maintenance.

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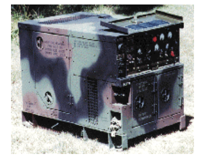
SECA Program Growth Markets

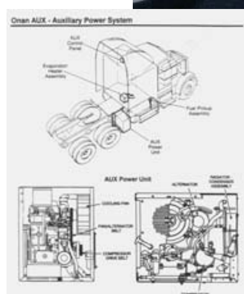
Commercial / Utility DG

Truck APU



Military

Residential DG



Marine

Growth markets will be driven by expanded fuel compatibility (diesel), durability, efficiency, reliability, low maintenance, low noise and vibration (military and marine).

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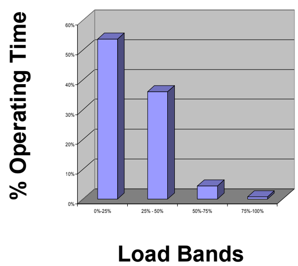
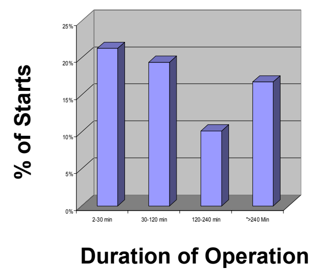
Application Data

- Historical operating data exists for target markets
- System architecture is designed to meet or exceed customer expectations





CPG has data on many applications derived from production control data logging features. Actual field applications typically indicate importance of part load efficiency.

Cummins Power Generation

- *Significant market share in target markets*
- *Existing market presence in both stationary and mobile applications from 2kW to 2.5MW*

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

The portfolio of capabilities needed to successfully commercialize the SOFC.

Organizational transition

- McDermott Technology, Inc (MTI)
  - Technology center for McDermott / Babcock & Wilcox
  - SOFCo
  - Hydrogen systems (fuel processor development)

Program Staff now dedicated entirely to fuel cells and fuel processing as…

- SOFCo-EFS Holdings LLC
  - Exclusive commitment to fuel cells and fuel processing
  - Aligned with SECA
  - Backed by McDermott (BWX Technologies)

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SECA Program
Significant Accomplishments 2002

- System profile
- System physical layout
- Process & Instrumentation Drawing (P&ID)
- System steady state model(s)
- System Transient model(s)
- Cell and Stack Thermal-Mechanical Stress model(s)
- Evolved cell design
- Waterless CPOX reformer
- Control architecture
- Power electronics architecture

A preliminary system profile has been established that defines product characteristics in customer and market terms, and translates those needs into the first level of product technical requirements.

Preliminary design work on the stack(s), manifolds, heat exchangers, reformer, balance-of-plant, and electronics have been combined in a concept layout that confirms the feasibility of meeting the target system envelope.

A steady state system model has been created to predict operational parameters such as air flow, fuel flow, temperatures, and efficiency. This model has been extensively exercised and yielded key insights used to optimize system configuration.

A system transient model has been created and used to model start-up transients. The most encouraging result of the model is the indication that market-driven target values for start time are potentially achievable without exceeding design values for temperature differentials in the stack.

Working from information developed with the system models, a detailed Process & Instrumentation Drawing has been created to document the configuration, operating values, and instrumentation for the C1 prototype.

Significant work on the Catalytic Partial Oxidation reformer indicates we should be able to operate successfully on either propane or natural gas with excellent efficiency and without carbon deposition.

A project website has been developed and incorporated into the Cummins Corporate web page.

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Staged prototyping -- C1 and C2

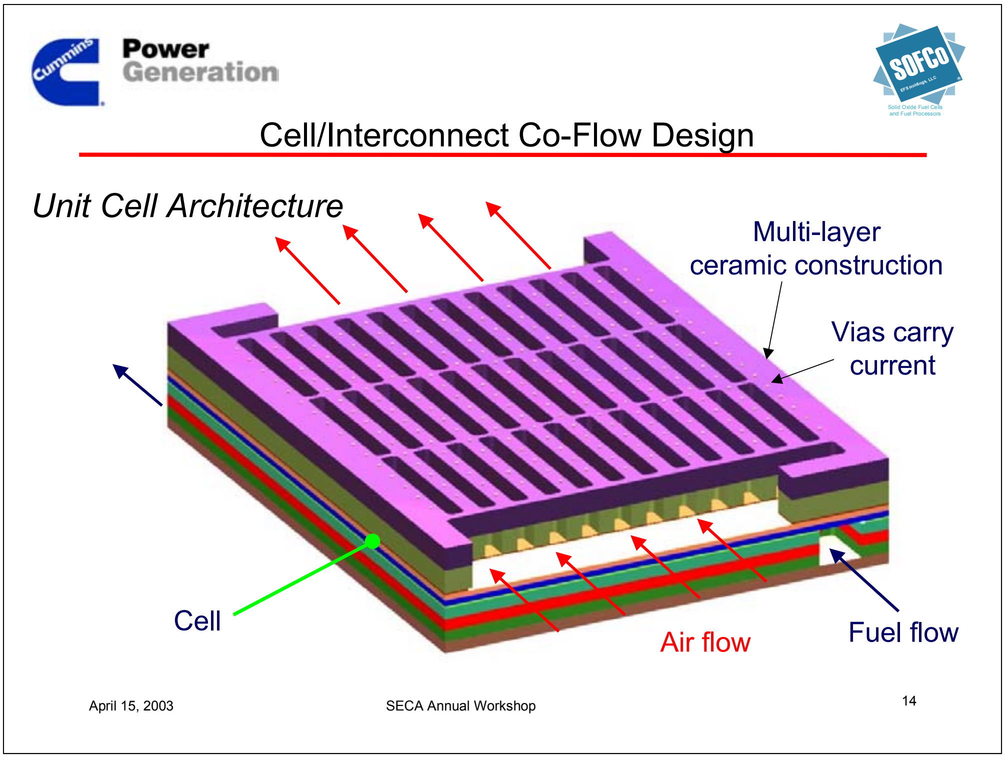
C1 Prototype

- development tool
- 10cm x 10cm cells
- 2 x 55 unit stacks
- no package limit ("brass-board configuration")
- limited operating hours

C2 Prototype

- program deliverable
- 15cm x 15cm cells
- 2 x 55 unit stacks
- integrated hot box assembly
- complete SECA test plan
- 1500+ operating hours

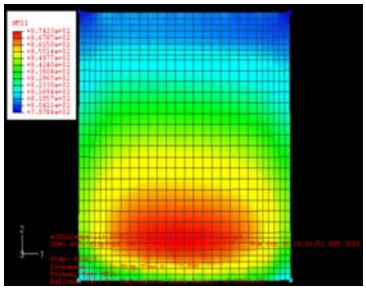
The C1 prototype will be a development mule used to confirm modeling results and allow development of control algorithms. The C2 prototype will be the SECA program deliverable.



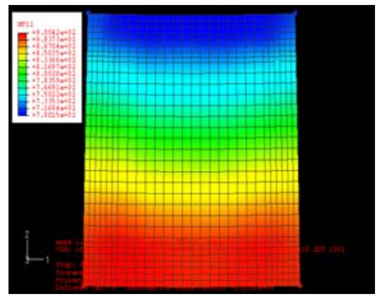
The all-ceramic interconnect allows for flexibility of manifolding design, and simplifies sealing.

Cell/Stack Design Supported by Analysis

Sample Temperature Distributions



With Edge Heat Loss



Insulated Edges

Typical thermal analytical modeling results, indicating the importance of considering thermal edge losses in evaluating cell stresses.

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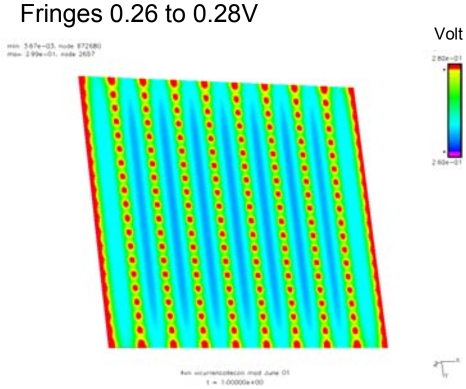
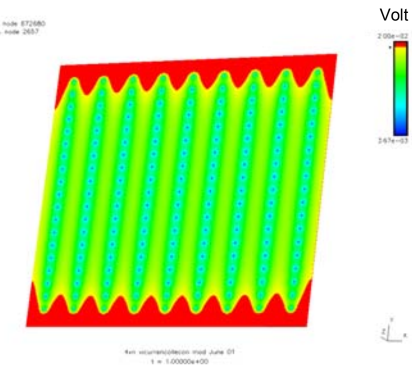
Cell/Stack Design Supported by Analysis …

In-Plane Current and Voltage Distributions

Cathode Potential Distribution
Fringes 0.26 to 0.28V





Anode Potential Distribution
Fringes 0.004 to 0.02V

Note that the Anode illustration is rotated 90 deg from the Cathode. Dots are current carrying vias. Illustrating in-plane current effects.

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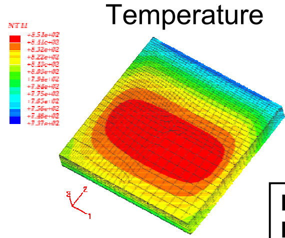
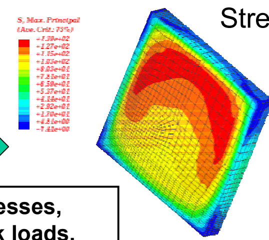
FEA Stress Analysis (ABAQUS)

Temperature



Stress



Plus residual stresses, layer CTEs, stack loads, boundary conditions, etc.

Temperature distribution from operation, transients, hot standby, etc. Calculated and confirmed with selected measurement points from operating stack.

Stress state across the range of system operation. Use stress level and duration for each condition to determine cumulative probability of failure at each element.

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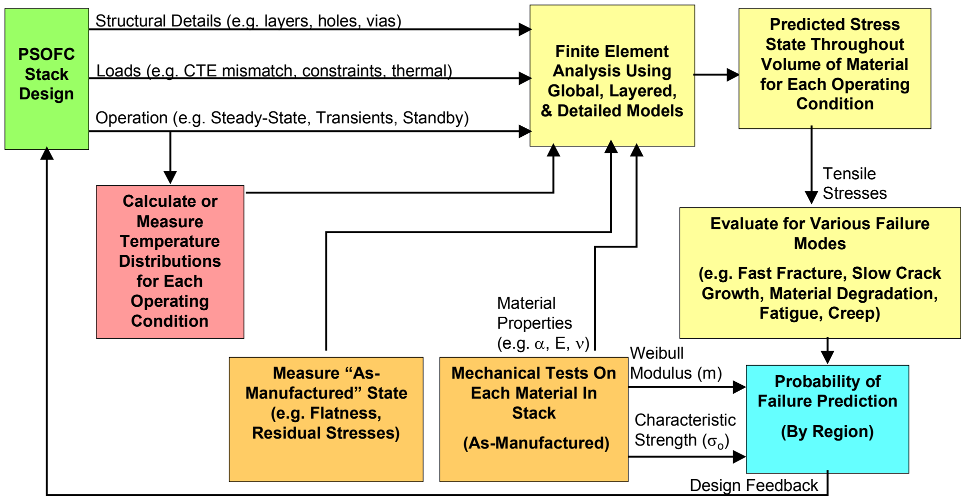
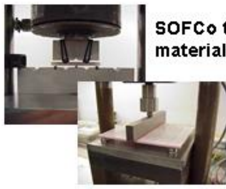
Typical Cell/Stack Mechanical Analysis Process



Team Approach to Characterization of Materials and Structures



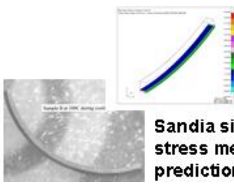
SOFCo tests on interconnect materials and structure

SOFCo tests on electrolyte and cells with various anode compositions

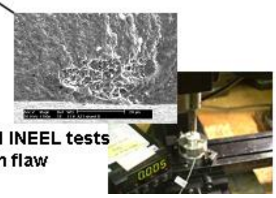
- ✓ Elastic Modulus, Poisson's Ratio
- ✓ Thermal Expansion Coefficient
- ✓ Characteristic Strength
- ✓ Weibull Modulus
- ✓ Failure Causing Flaw Types
- ✓ Residual Stress State

Penn State – E, G, ν

SOFCo - $\alpha(T)$



Sandia sintering studies, residual stress measurements and predictions



Virginia Tech and INEEL tests of electrolyte with flaw identification

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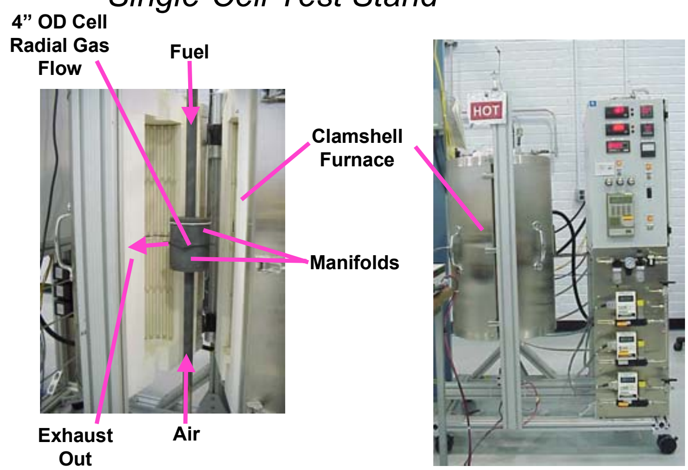
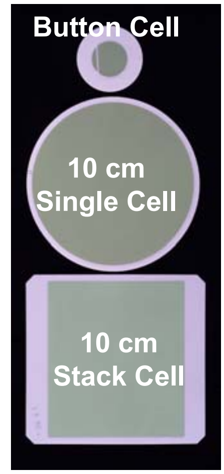
Cell Performance Testing

Single-Cell Test Stand

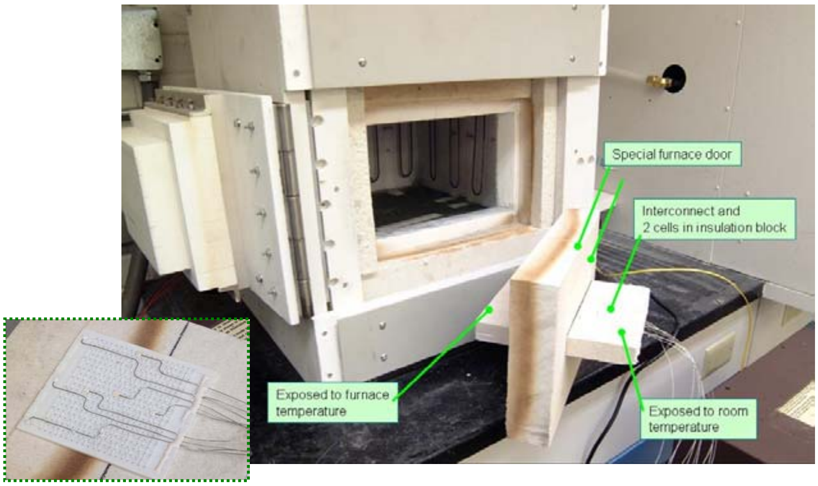




Test Cells

Active areas of 10cm round and 10cm square cells are comparable, and laboratory test results yield excellent correlation. Use ot the 10cm round cell in the new single cell test facility significantly increases the efficiency of materials and design evaluations.

Cell Structural Test: Temperature Gradient



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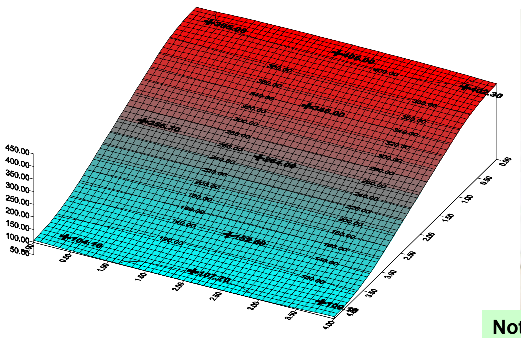
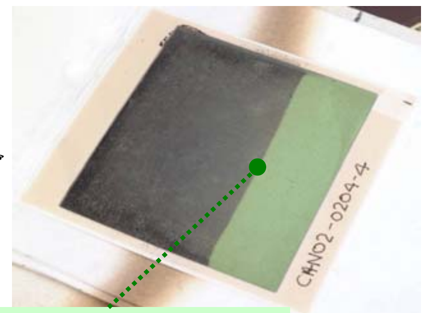
Temperature Gradient Test Results

Temperature input to ABAQUS thermal stress model for dT = 300 C

No damage to cells or interconnects





Note: Cell color change shows that temperature profile was 1-D

Preliminary thermal gradient evaluations support design assumptions on allowable operating temperature differentials.

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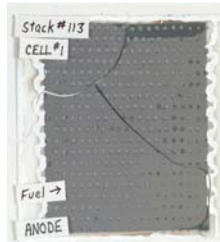
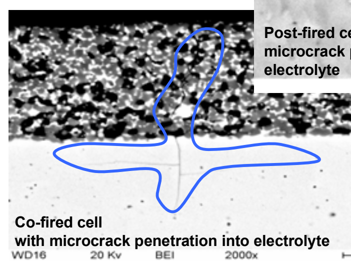
Cell and Stack Development Status

- Cell breakage slowed stack development in 2002
- Several cell designs evaluated to find a design rugged enough for stack tests
  - Baseline co-fired
  - Thin anode
  - Patterned anode
  - Graded anode
  - 3Y electrolyte
  - Various electrolyte thicknesses
- SOFCo post-fired cell and 3rd party cells are supporting 2003 stack development while SOFCo next-generation cell development progresses



Post-fired cell with no microcrack penetration into electrolyte



Co-fired cell with microcrack penetration into electrolyte

Parallel path approach provides robust post-fired cells for ongoing stack and PCU development, parallel development of co-fired cells for optimal performance.

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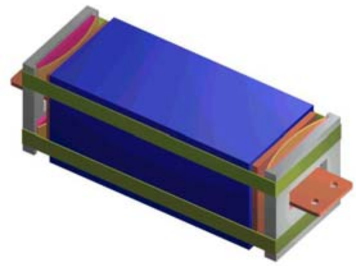
Power Cell Unit (PCU) Development

Turn this …

… Into this



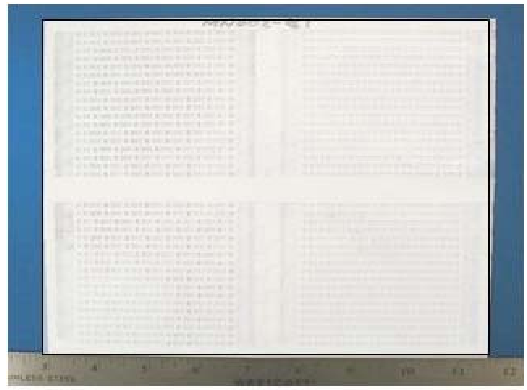
Today’s laboratory test technology

Tomorrow’s real-world product

Interconnect Scale-Up

- Scale-up to achieve SECA cost goals
- Scale-up feasibility demonstrated in 2002
- Demonstrate early prototype components by year-end

Fired 20 x 20 cm
Proof-of-Concept Part



SOFC Cell and Stack Progress

Cell/Stack Performance

- 40% reduction in ASR (cells and stacks)
  - Recent cell tests demonstrate ASR < 0.5 ohm-cm^2
- Implemented 2nd generation stack design
  - Integral gas distribution allows co-flow architecture
  - Improved performance
- High fuel utilization demonstrated
  - >85% for 10 cm single cells
  - >70% for 5-cell stacks

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SOFC Cell and Stack Progress Summary

Cell/Interconnect Fabrication

- Established capability to produce > 100 parts per month (10 cm size)
- Produced 800 cells and 500 interconnects in 2002
- First successful trial at scaling to 20cm size

Stack assembly and testing (10 cm components)

- 5 to 60 cell stacks tested
- Resolved cell-interconnect and stack-manifold sealing issues
- 30,000 hours of stack testing in 2002

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SOFCo

Fuel Processor Development

CPOX Propane/NG Reformer for 10 kWe SOFC System

- High capacity: 50 kW/liter
- Requires little or no water to suppress carbon formation
- Rapid start-up: <1 minute
- Turndown ratio: >5:1
- Lightweight, compact design
  - Weight <2 kg; volume ~0.25 liter
- Efficient reformer
  - 70% on LP and 80% on NG

Successful completion of POX catalyst screening

Demonstrated high reforming activity for LPG and NG

"Dry" CPOX data with propane (>500h) and natural gas (85h)

Operational limits for feed preheat and air level (O_2/C) identified

5:1 load turn-down demonstrated for LPG/CPOX

Experimental verification of equilibrium carbon line

CPOX design strategy for bench-scale C1/C2 scale-up

Completion of component dimensioning

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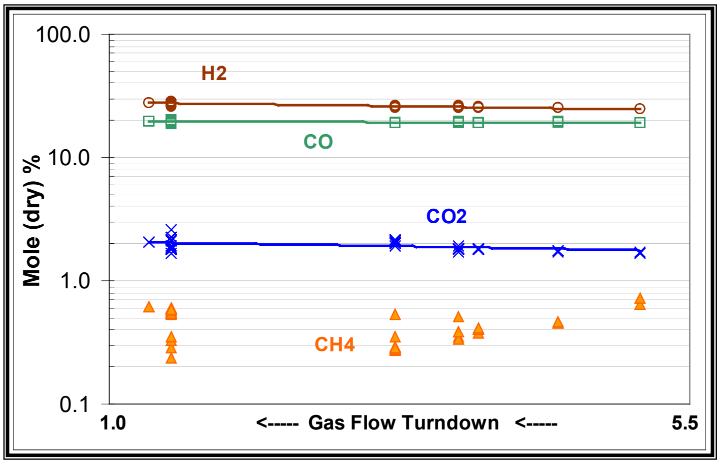
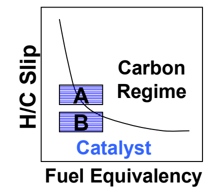
Reformer System Development

CPOX Performance with Flow Turndown (LPG, no water)



Fuel Processor Development

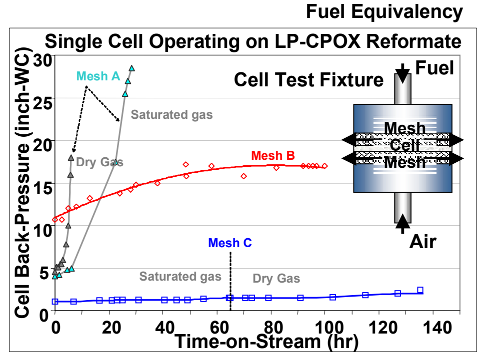
Reformate Performance / Characterization



Operating Boundaries

- Temperature threshold
- Material sensitivity
- Hydrocarbon slip
- Continuing to characterize performance

Waterless CPOX is Practical



Single cell test facility provided valuable insight into material and temperature considerations of successful soot-free operation on reformate from dry CPOX.

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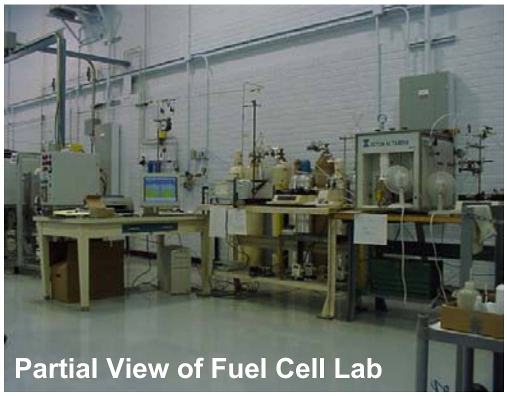
Fuel Processor Development

Testing in progress at single-cell test stand to characterize cell and reformate performance



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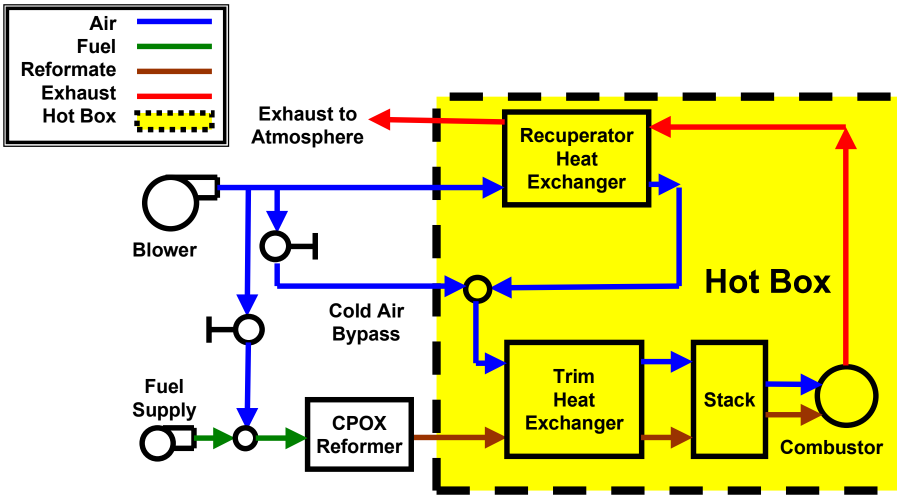
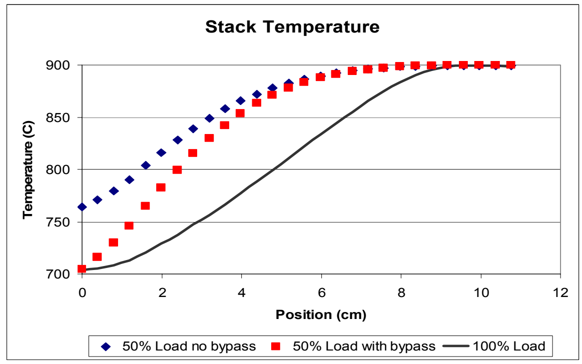
SECA C1 System Schematic



ASPEN for System and Stack Analysis

Aspen fuel cell stack model

- Steady-state and transient
- Benchmarked against SOFCo's proprietary cell / stack model
- Also correlated to DOE simplified stack model



ASPEN system model

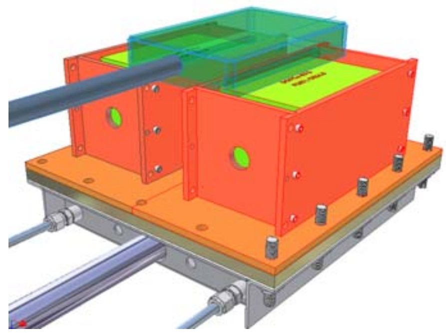
- System design and operation

Aspen modeling provides valuable insight into system configuration for high efficiency part load operations within operating temperature limits.

System Development

- C1 final design progressing
  - 1 kWe development fuel cell with two, 10 cm 55-cell stacks
  - Test by year-end with stack simulators; 10 cm stacks installed early 2004
- C2 conceptual design started
  - Define fuel cell and battery power split for 10 kWe system
  - 5 kWe demonstration fuel cell with two, 15 cm 55-cell stacks

Hot Box Internals



Cells, Stacks, Reformer, Hot Box Sub-System

- *Analysis and modeling tools in place*
- *First generation prototype design on schedule*
- *Parallel paths in place to evolve systems and components*
- *Encouraging progress with CPOX reformer*

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Phase III target: same size envelope as Diesel Genset

0.5 m3 (17.4 ft3)

Existing RV diesel genset product parameters.

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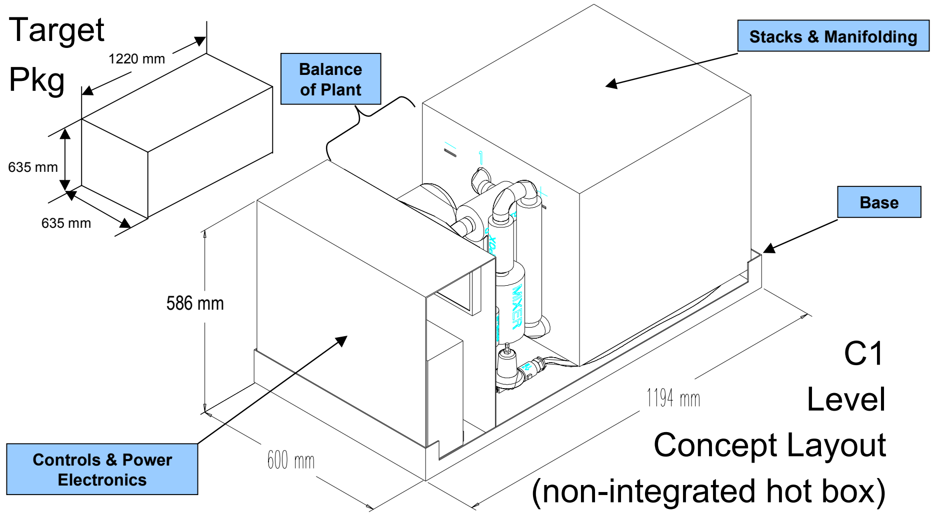
System Physical Configuration



Concept layout indicating feasibility of packaging SOFC within current product envelope.

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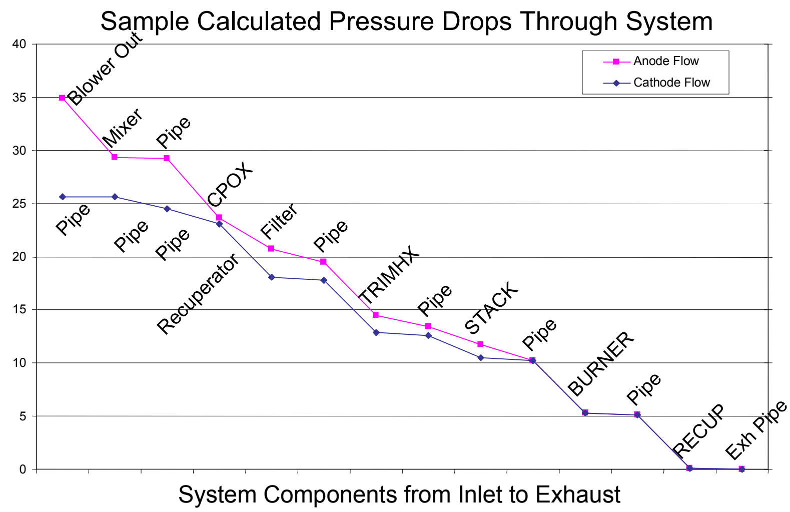
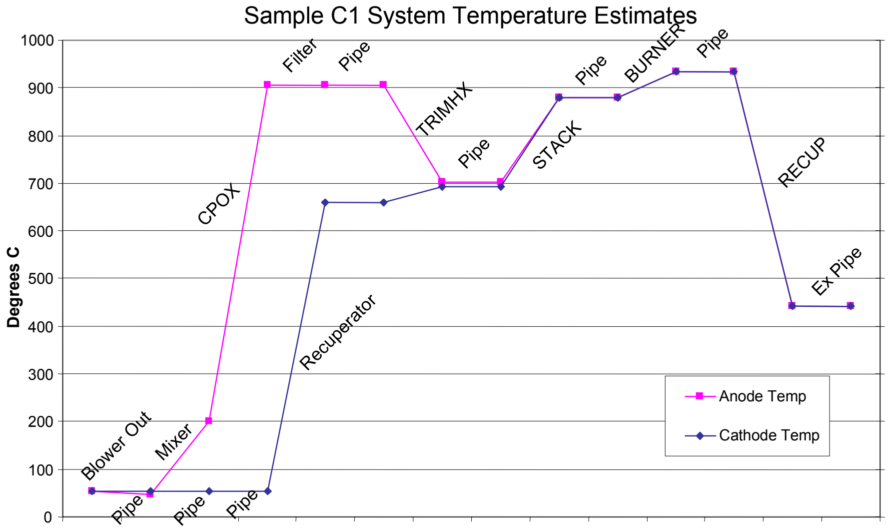
Preliminary Design Flow Losses



Boost or throttle main blower output to account for differential losses leading up to stack outlet…design trade-off for performance and cost

Sample System Temperature Modeling



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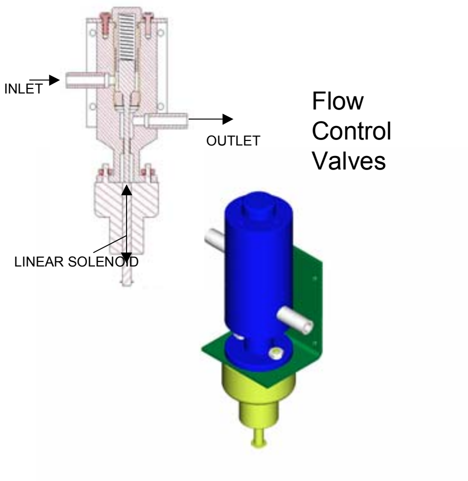
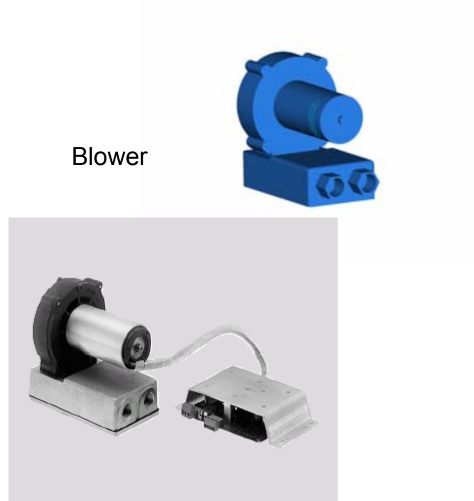
C1 Components Under Development

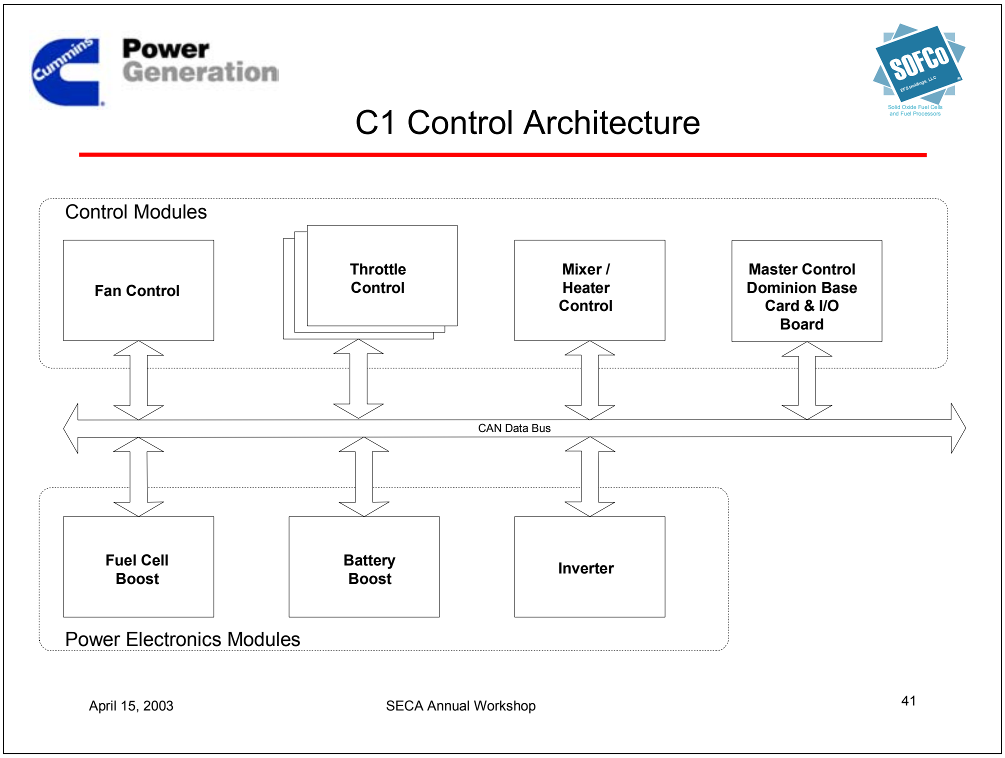


Flow Control Valves

Blower



CPG will source Balance of Plant components where possible, design and develop as required.



<u>C1/C2 Approach</u>

- *Distributed (multi-board)*
- *Master control interfacing to several changeable i/o modules via a CAN Bus*
- *Optimized for development flexibility & agility*
- *Off the shelf components where possible*

<u>Production Approach</u>

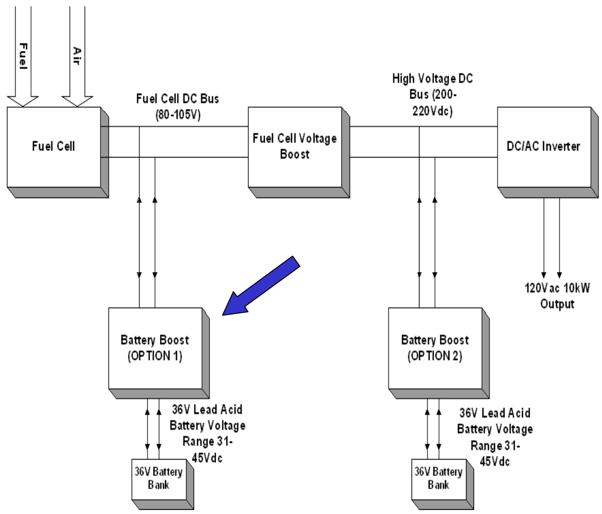
- *Centralized (single board control)*
- *Customized for fuel cell application*
- *Optimized for cost*
- *Design for costing based on current RV genset controls*

Sample Control Functionality: System Start

1) Initial Heat Up
   - preheat fuel and bring CPOX to start temperature
   - ignite combustor to initiate stack warm-up
   - maintain stack delta temperature
   - bring stack to target temperature
   - establish air/fuel flow to ignite CPOX and produce reformate
2) Stack Temperature Gradient Control
   - maintain target stack delta temperature
   - heat stack to full start temperature
3) Initial Power Generation
   - stack gradient flips
   - maintain stack delta temperature control condition
   - let stack average temperature reach full operational condition
4) Steady State Power Generation & Load Control

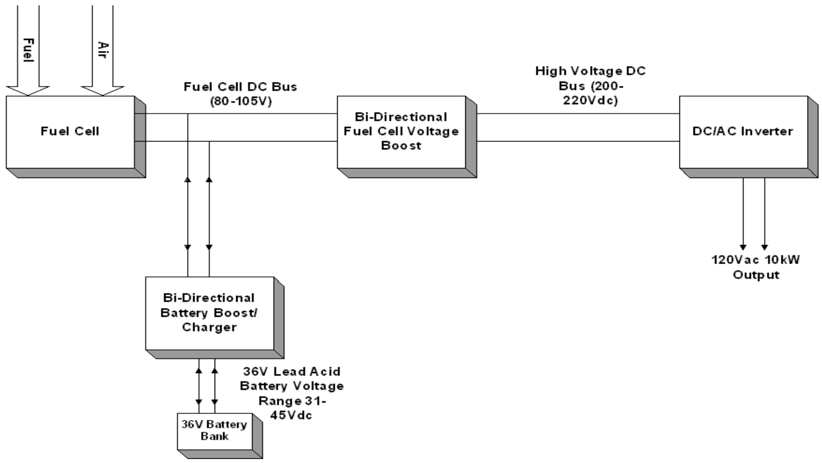
Power Generation

Power Electronics Architecture



- Two options for Power Electronics architecture.
- **Option 2** requires transformer based boost -- 50% more expensive than Option 1.
- **Option 1** only requires inductor based boost.

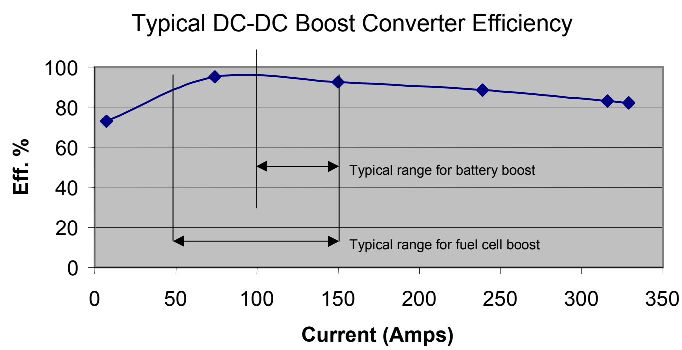
Selected Architecture



Primary Power Electronics Components

- Bi-directional Voltage Fed Inverter
  - converts boosted DC buss to 120 VAC 60Hz
- Fuel Cell Boost
  - steps fuel cell output voltage to boosted DC buss
- Battery Boost
  - steps battery voltage to fuel cell buss voltage
- Microprocessor Control
  - coordinates BOP and Power electronics

Sample Boost Efficiency



Battery boost and fuel cell boost are designed to place operating ranges in region of optimum efficiency.

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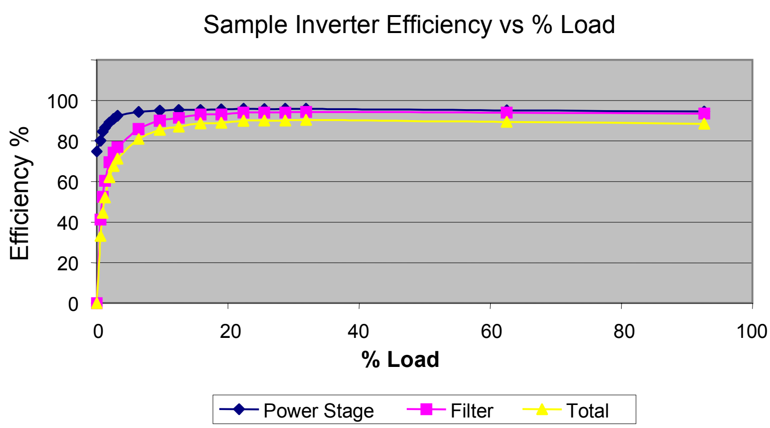
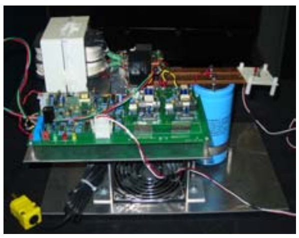
Sample Inverter Performance



Requirements for power quality and EMI/RFI must be taken into account in inverter design.

Power Electronics Architecture

- Status of Fuel Cell Boost
  - First prototype assembled
  - Received 15 kW Power Supply for simulation
  - Testing scheduled for April 2003



BOP, controls, and power electronics well underway and predictable.

Power
Generation

Summary

- Cummins Power Generation *-- a technology-neutral worldwide developer and manufacturer of power generation equipment with significant market share in target markets*
- Cummins Power Generation Markets *-- existing market presence in both stationary and mobile applications from 2kW to 2.5MW*
- Cummins - SOFCoTeam *-- with the portfolio of capabilities needed to successfully commercialize the SOFC*
- SECA Program Progress
  - *analysis and modeling tools in place*
  - *first generation prototype design on schedule*
  - *parallel paths in place to evolve systems and components*
  - *encouraging progress with CPOX reformer*
  - *BOP, controls, and power electronics well underway and predictable*

Power Generation

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SECA Core Technology Teams

SECA Program

Cummins Power Generation
10kWe SOFC Power System Commercialization Program
Seattle, Washington
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