Overview of the Rolls-Royce SOFC Technology and SECA Program

14th July 2009

Richard Goettler

Manager, Fuel Cell Development

SECA Coal-Based Systems – Rolls Royce

- Team
  - RRFCS(US) Inc.
  - RRFCS Ltd (UK)
  - ORNL
  - PNNL
  - Case Western Reserve University
  - University of Connecticut
  - Matrix Innovations
- Schedules:
  - Complete 1500 hrs of 5000 hour stack test by end-Sept. 2010

Highlights

- Improvement in cell ASR
- Greater rig availability for system relevant pressurized testing
- Lower cost material sets
- Cycle chosen for the coal-based system
- System technology demonstrated at large scale
- SECA plays critical role within RRFCS Program
  - Supports next generation cell and stack development
  - Validation of technology through system level block testing

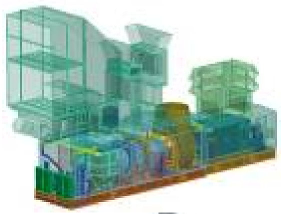
RRFCS Technology and SECA Program

- Mission and organisation
- Technology and approach
- Status – Fuel Cell & Stack
- Large-scale system demonstration
- SECA Program
- Next steps & Conclusions

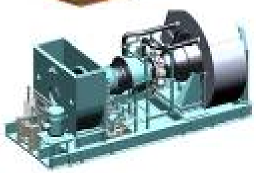
Progress at Rolls-Royce Fuel Cell Systems Limited

- **Mission and organisation**
- Technology and approach
- Status – Fuel Cell & Stack
- Large-scale system demonstration
- SECA Program
- Next steps & Conclusions

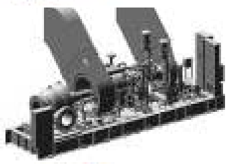
Rolls-Royce Energy Business



Trent 60 – 58MW



RB211 – 32MW



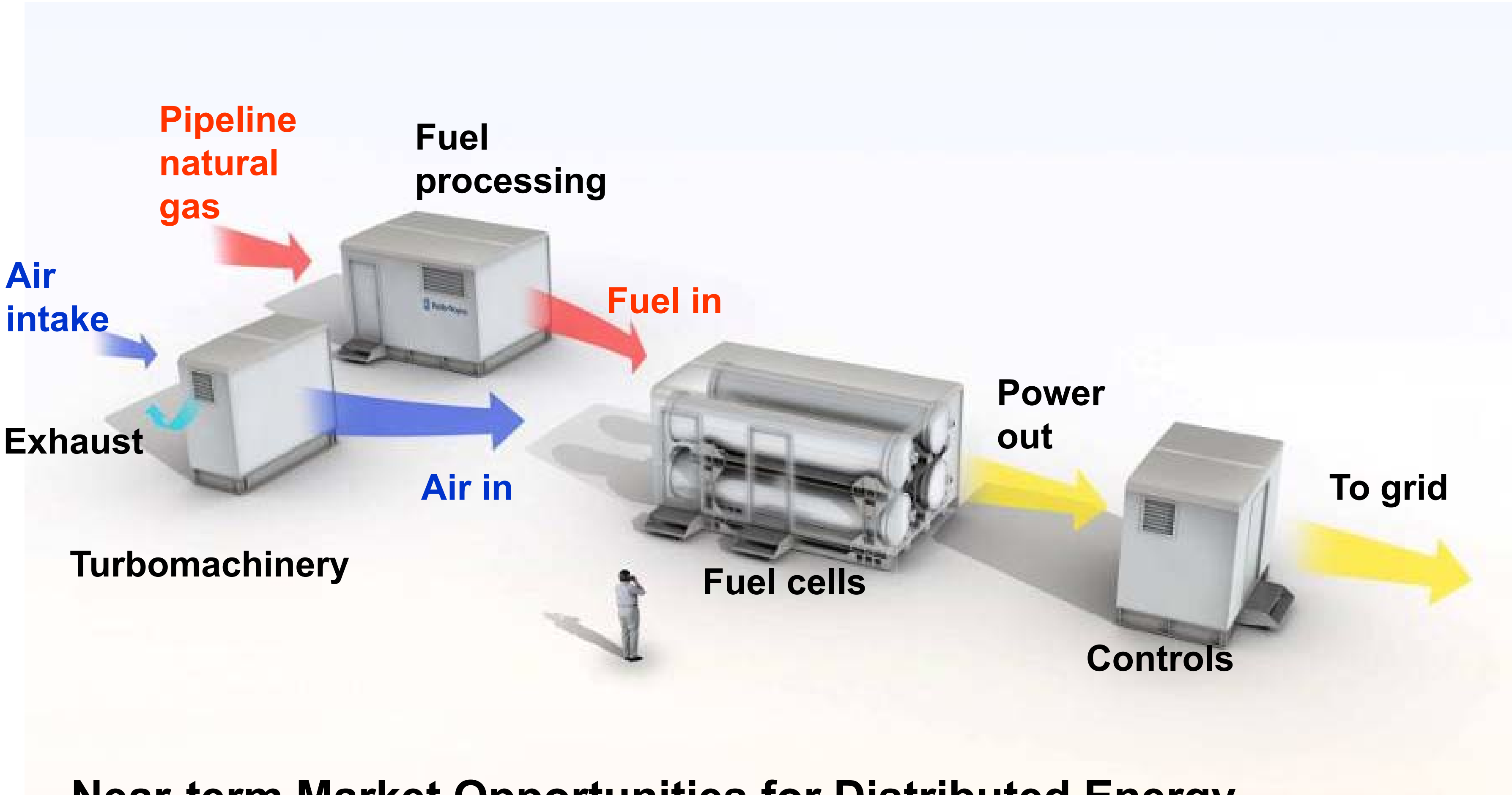
501 / Avon **5 – 14MW**

Recips **1.2 – 8.5MW**

Fuel Cells **1MW Market Entry – follow on can be larger**

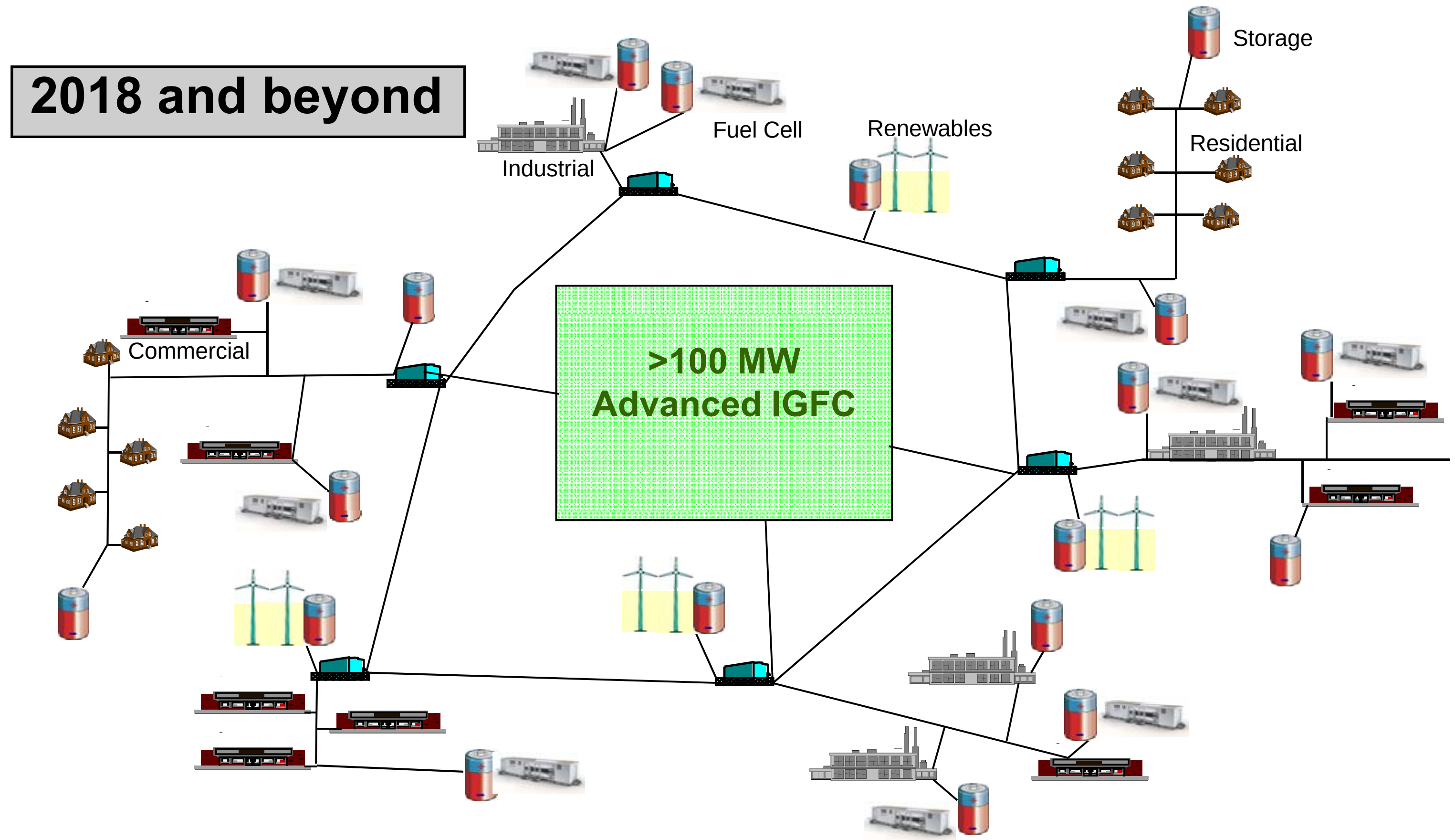
Compressors – 37.3MW

RRFCS is Developing MW-scale SOFC

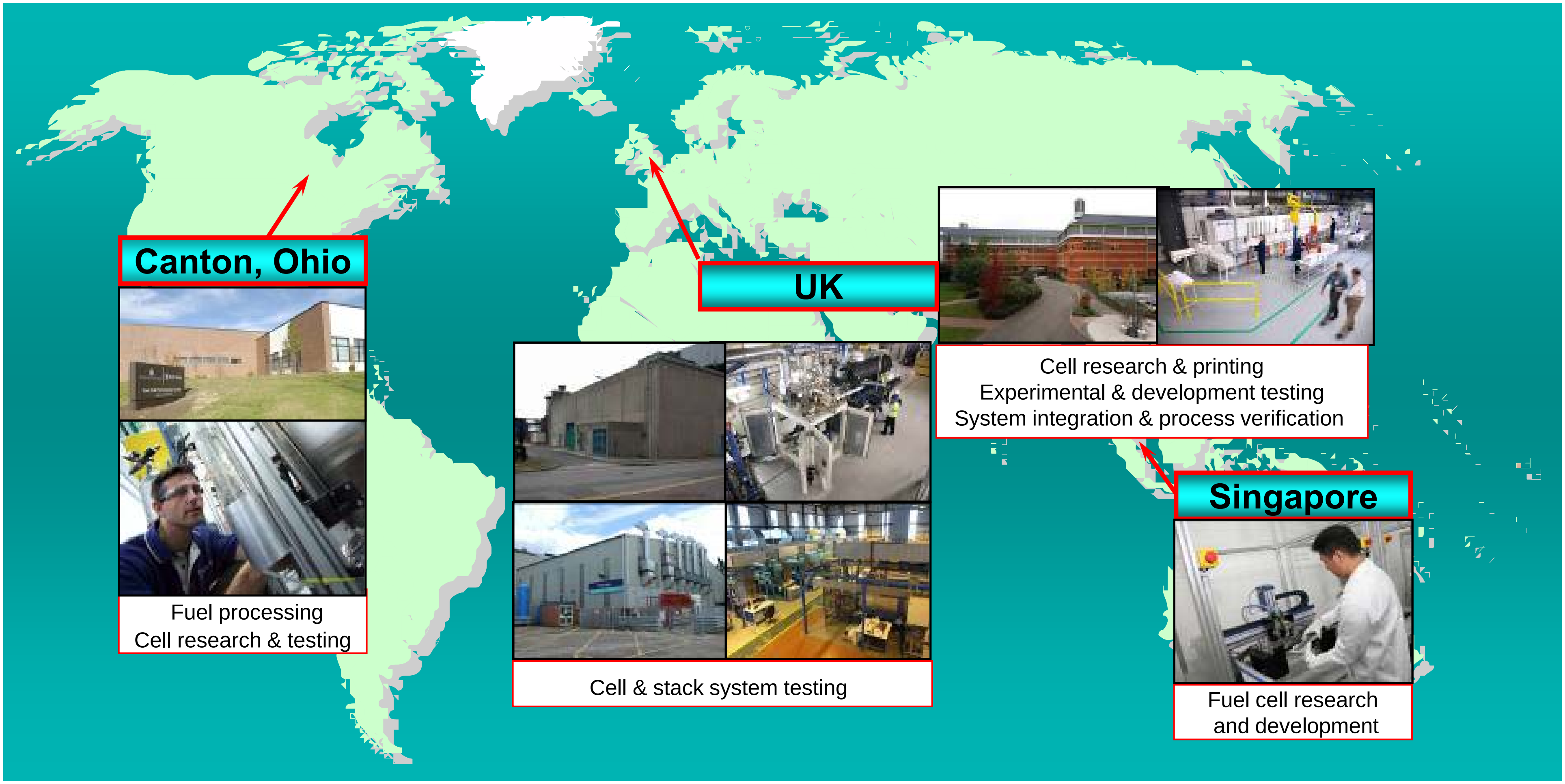


Near-term Market Opportunities for Distributed Energy

RRFCS SOFC systems combined for centralized power generation



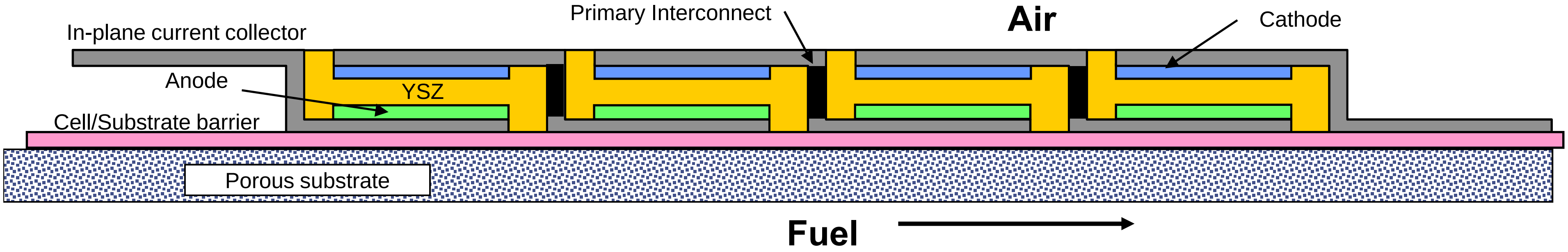
Rolls-Royce Fuel Cell Systems Limited
Locations



Progress at Rolls-Royce Fuel Cell Systems Limited

- Mission and organisation
- **Technology and approach**
- Status of Fuel Cell & Stack
- Large-scale system demonstration
- SECA Program
- Next steps & Conclusions

Rolls-Royce integrated planar solid oxide fuel cell

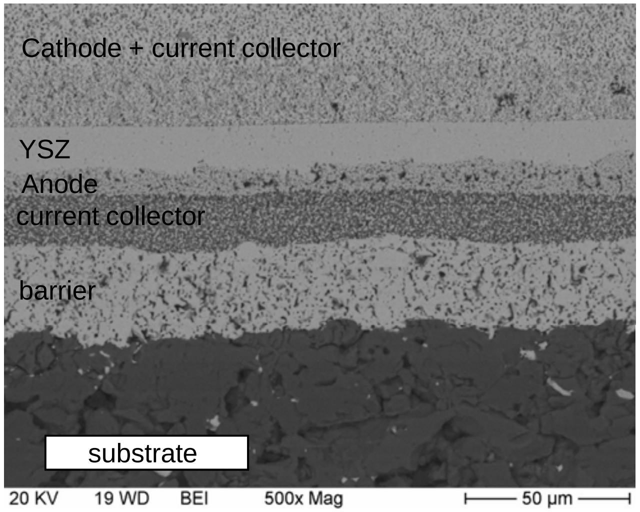


Integrated planar series arrangement

Series connected cell design for high voltage low current

Thin layers of active materials minimize cost

Ceramic support material uses low cost $MgO+Al_2O_3$ powder + low cost extrusion



High voltage low current benefits

Easier hence cheaper for power electronics to convert low current DC to AC

High voltage facilitate direct conversion to 480 V AC grid requirement

Low currents give low Ohmic I^2R losses offering greater materials options

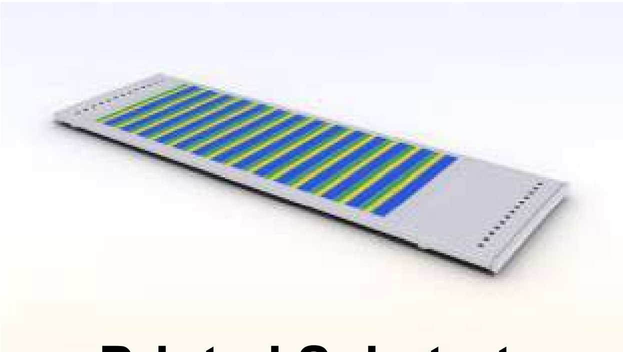
Low Cost Manufacturing Processes

Print/Dry Line

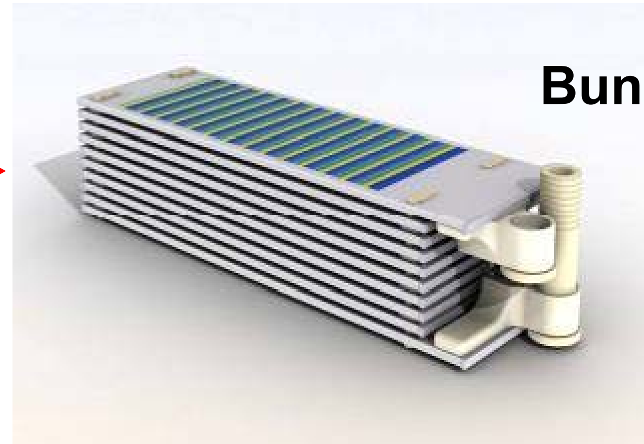
Tunnel Furnace

Glassing Area from the Process Verification Line

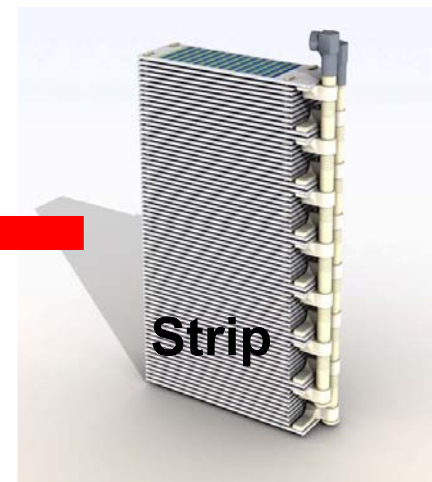
Building fuel cell stacks



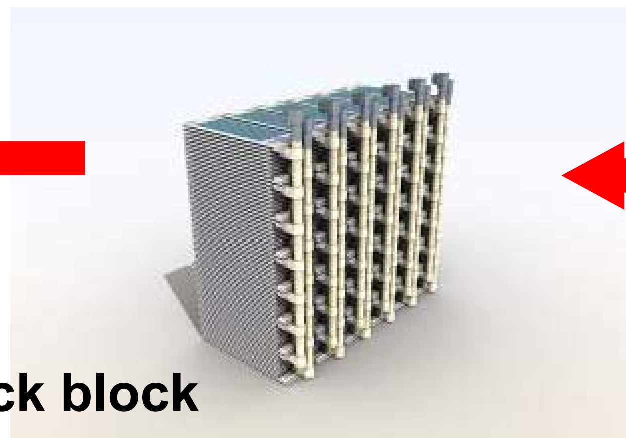
Printed Substrate



Bundle

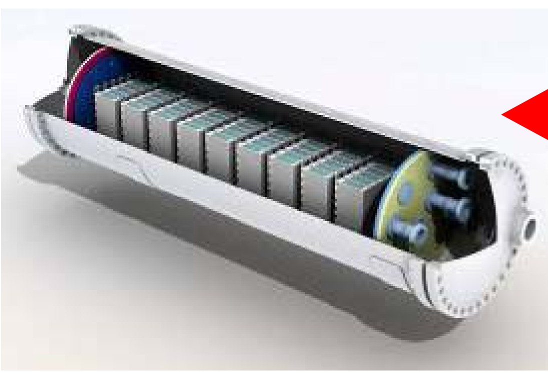


Strip



Stack block

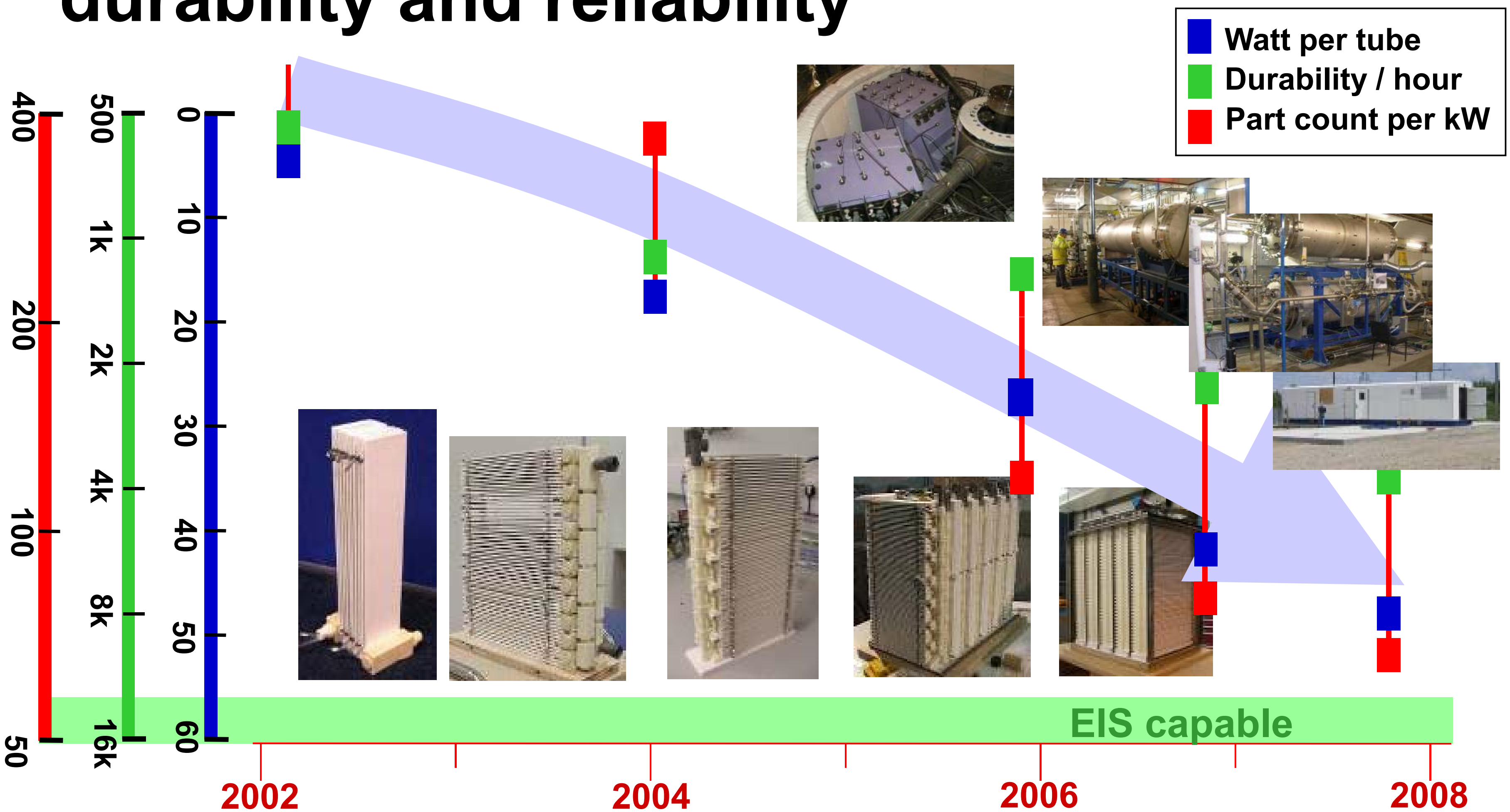
125kW-250kW tier



Progress at Rolls-Royce Fuel Cell Systems Limited

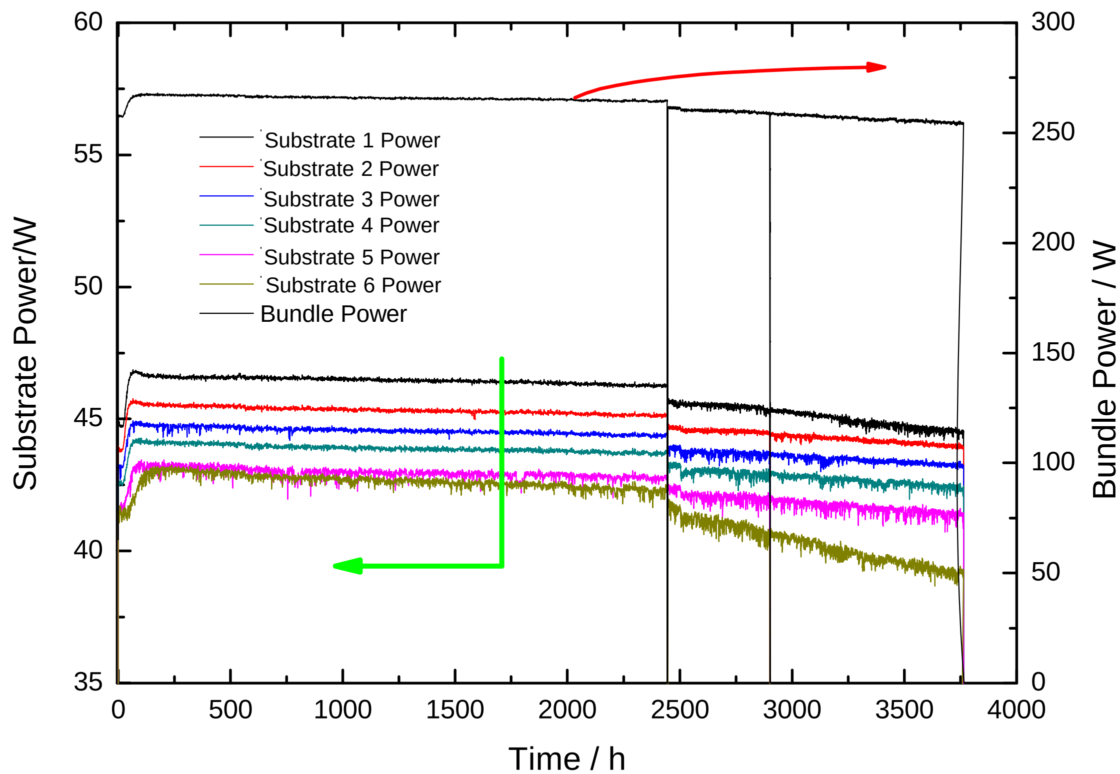
- Mission and organisation
- Technology and approach
- **Status – Fuel Cell & Stack**
- Large-scale system demonstration
- SECA Program
- Next steps & Conclusions

Progress to date on de-risking cost durability and reliability



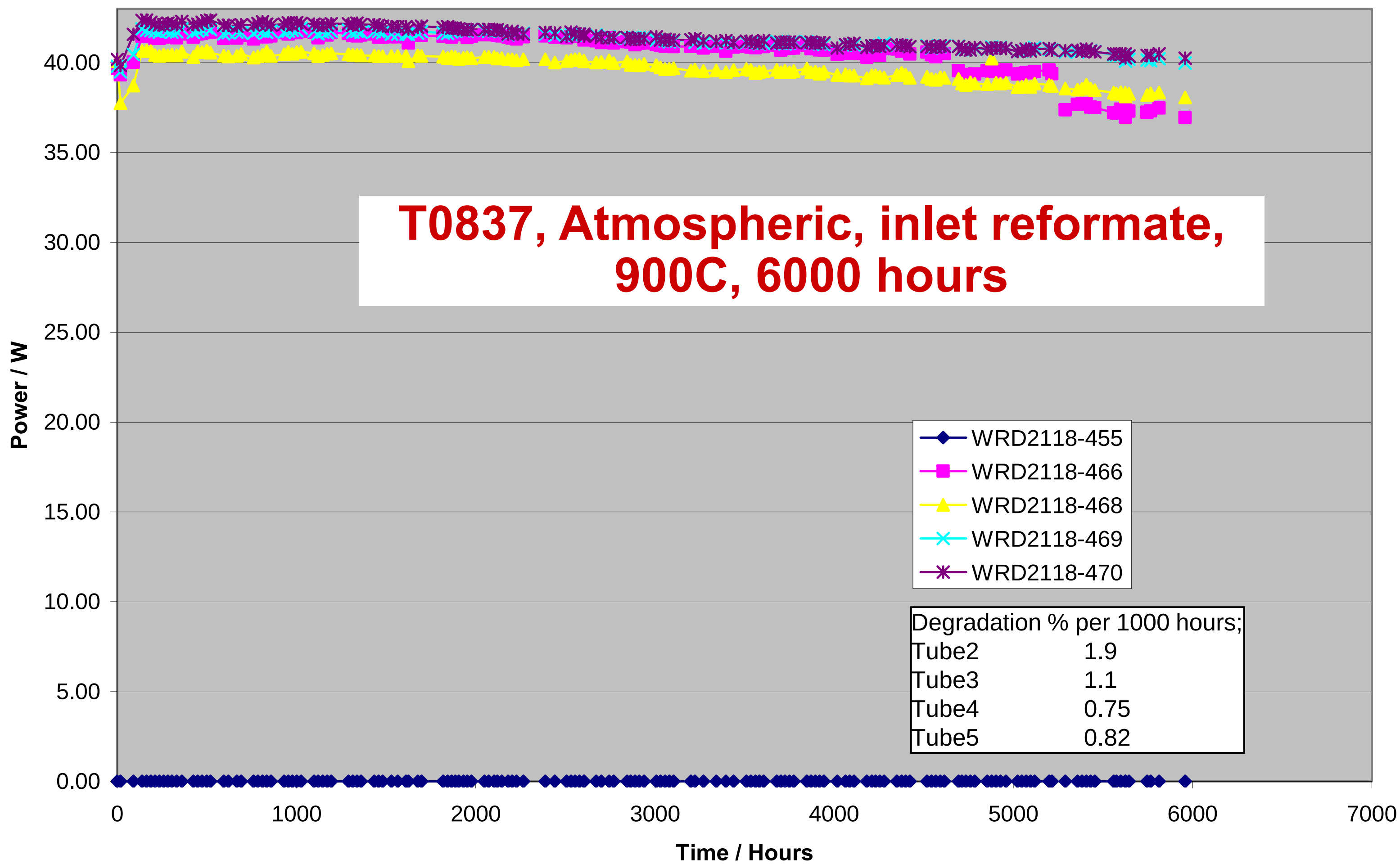
Rolls-Royce data

Pressurised bundle performance



- Six substrate bundle operated at 2.5 bar
- Substrate 1 is fuel inlet and Substrate 6 fuel exit
- Power measured at constant current (1.8 A) for the bundle data
- Unplanned shutdown (site related) at 2444 hours resulted in redox of anodes and significant change in degradation rate

Single-Substrate durability demonstrated to 6000 hr



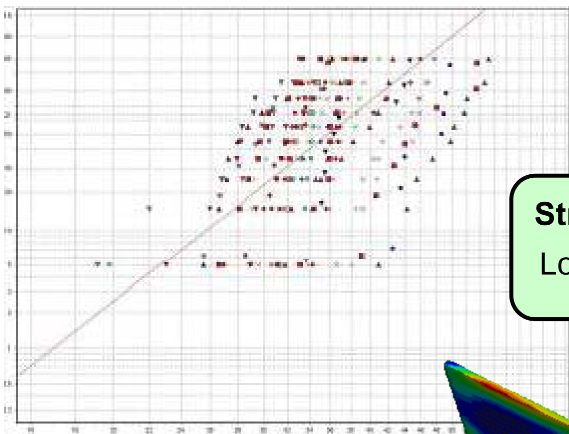
Stack reliability modelling

$$P(f) = 1 - \exp\left(-\int_V \left(\frac{\sigma}{\sigma_0} \right)^m dV \right)$$

Material Property Database
Strength, Weibull

Reliability
Weibull u/standing of ceramics

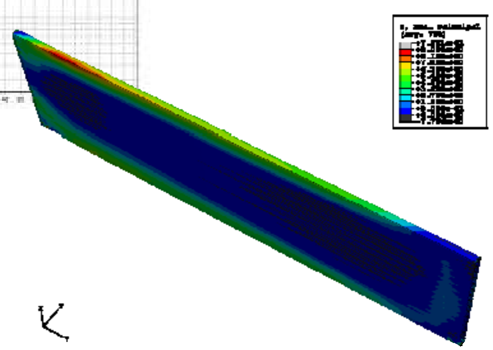
Design
Design for reliability, function & manufacture

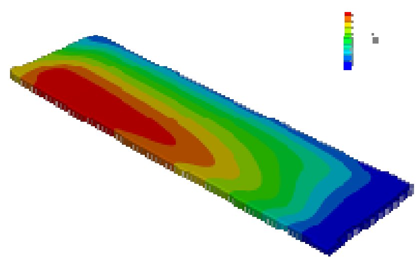


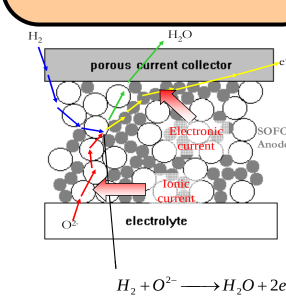
Stress
Loads, Interactions

"CFD"
Thermals
Flow
Pressure

Fundamentals
Diffusion in porous materials
Electrochemistry







Progress at Rolls-Royce Fuel Cell Systems Limited

- Mission and organisation
- Technology and approach
- Status – Fuel Cell & Stack
- **Large-scale system demonstration**
- SECA Program
- Next steps & Conclusions

Progress from 2005

- **Q1 2005**
  - **60kW/tier design (flat tier)**
  - **Single 10kW stack block run in tier**

- **Q2 2006**
  - **New design 80kW/tier**
  - **80kW tier test**
- **Q2 2007**
  - **New tier design capable of 125kW/tier from 9 blocks**
  - **Single block 15kW stack run in tier with external fuel processor**

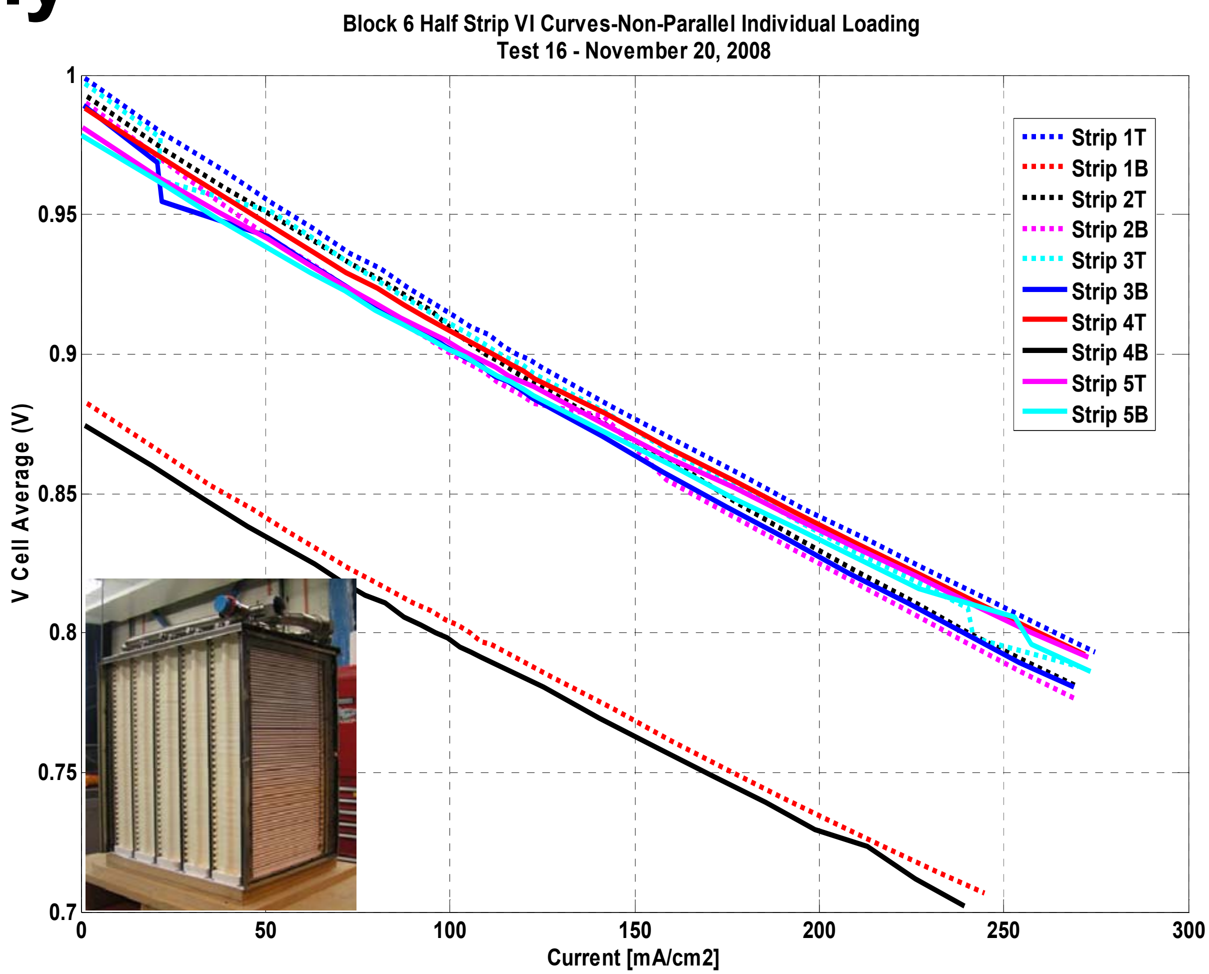
- **Since Q4 2007**
  - **Testing of single and two tier configurations with 125kW/tier design**
  - **Integrated tier and turbogenerator testing**
  - **125 kW scale test much more challenging than anticipated**

Tier level testing summary

Tests 1-4	Learning how to run the system - no active stack	Sep 07 to Nov 07
Tests 5-7	First stack test and resolution of warm-up related issues	Dec 07 to Feb 08
Tests 8-9	Attempting to load the stack but experiencing TG problems	March 08
Tests 10-11	First power runs - 42.5kW with 'damaged' stack, 90kW with new stack but at reduced voltage	Apr 08 to May 08
Tests 12-14	Diagnostic tests – Avoiding low temperature spots, leakage assessment and intra-block temperatures	Jun 08 to Aug 08
Test 15	Improved air side sealing and assessment of intra-block performance – voltages and currents	October 08
Test 16	6 block test with further intra-block performance assessment and improved electrical loading	November 08
Test 17	Re-run of test 16 evaluating effects of fuel composition	Dec 08 to Jan 09
Test 18-19	Investigation of temperature effects on performance and comparative performance testing of bundles and block	Feb 09 to Jun 09

Half strips on Block 6 all performed very uniformly

- Half strips loaded individually.
- Good individual performance although below target for block
- Uniform performance
- 2 poorly performing strips can each be explained by 1 failed bundle



Tier Level Testing Summary

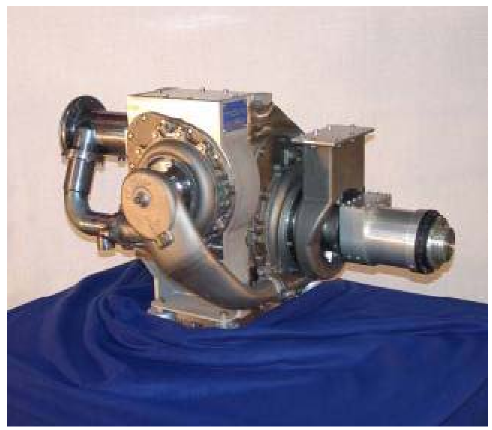
Tests 1-4	Learning how to run the system - no active stack	Sep 07 to Nov 07
Tests 5-7	First stack test and resolution of warm-up related issues	Dec 07 to Feb 08
Tests 8-9	Attempting to load the stack but experiencing TG problems	March 08
Tests 10-11	First power runs - 42.5kW with 'damaged' stack, 90kW with new stack but at reduced voltage	Apr 08 to May 08
Tests 12-14	...ots, ...es	Jun 08 to Aug 08
Test 15	...ra-block	October 08
Test 16	...e assessment and improved electrical loading	November 08
Test 17	Re-run of test 16 evaluating effects of fuel composition	Dec 08 to Jan 09
Test 18-19	Investigation of temperature effects on performance and comparative performance testing of bundles and block	Feb 09 to Jun 09

Performance short-falls and corrective paths identified. Will be re-entering durability testing program

RRFCS Sub-System Status

Start Gas system
- Factory pass-off testing completed

1MW Desulfurizer
- Factory pass-off test complete
- DOE durability program (8000 hrs)



Turbogenerator
- Full system integration tests

Power Electronics
- Completed 3-yr DOE funded demo program at Next Energy

System Packaging
- Established for 1MW field demonstrations with On-Power

Progress at Rolls-Royce Fuel Cell Systems Limited

- Mission and organisation
- Technology and approach
- Progress to date – Fuel Cell & Stack
- Large-scale system demonstration
- **SECA Program**
- Next steps & Conclusions

SECA Program Structure

- Task 1: Program Management
- Task 2: System Cost Modeling
- Task 3: Next Generation Stack Technology
- Task 4: Cell Development
- Task 5: Program Metric Testing
- To meet SECA Objectives:
  - SOFC-based electrical power generation system cost of <$400/kWe for a >100MW power plant,
  - Achieve an overall power plant efficiency of ≥50% (HHV)
  - CO_2 capture of >90%,
  - Meet DOE targets for fuel cell reliability: current Phase at 2%/1000 hr degradation

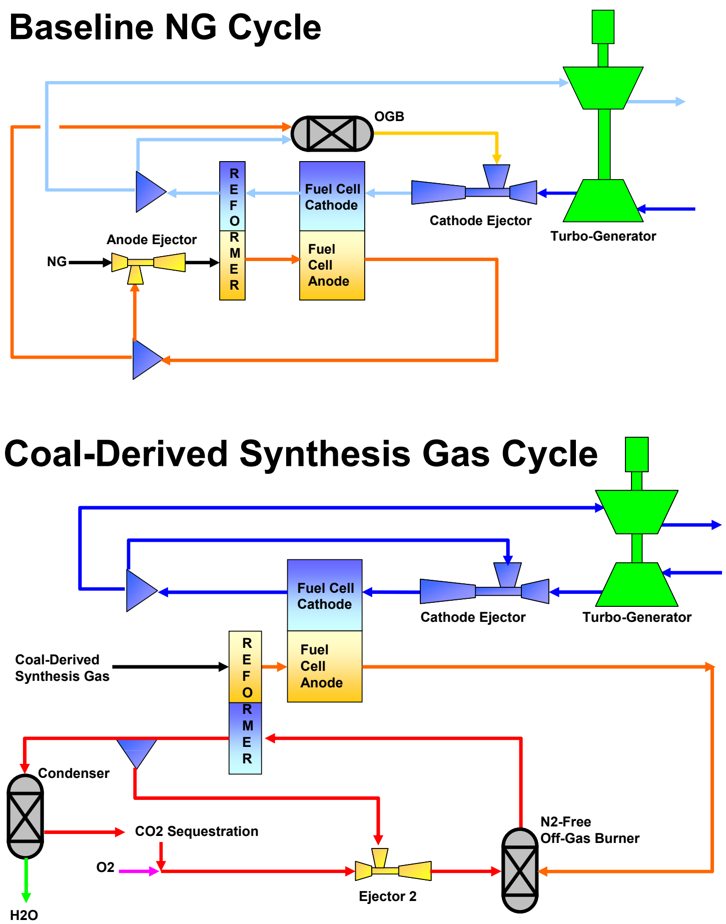
Task 2: Modeling of High Efficiency Catalytic Coal Gasification

- **Plant Operations Sequence**
  - Coal Gasifier (700C exit)
  - Primary Cyclone / Secondary (barrier) Pt. Filters
  - Steam super-heat
  - Warm-gas desulfurization (425C to 525C)
  - Barrier Pt. Filter 2
  - Re-heat Heat Exchanger, hot-side
  - Trace Metals Sorbents and Sulfur Guard Bed
  - Re-heat Heat Exchanger, cold-side
  - Turbine expanders
  - F.C Power Plant
- **Coal-syngas provides similar stack inlet fuel composition as natural gas cycle**

	Syngas Composition	
Property	DOE SECA Input	Aspen Simulation, 5% carbon loss
Mole Frac		
C_2H_6	0	0
CH_4	0.18	0.180
CO	0.05	0.048
CO_2	0.22	0.200
H_2	0.16	0.155
H_2O	0.38	0.414
N_2	0.01	0.003
O_2	0	0
Sum	1.00	1.000
Flow, g/s	52.07	51.26
MW	21.42	20.90
Flow, gmole/s	2.43	2.45
$kW_{thermal}$(HHV), Coal	unknown	566
$kW_{thermal}$(HHV)	535	536
Cold Gas Eff.	unknown	94.6
$kW_{thermal}$(LHV)	480	480

Stack Inlet Fuel Composition	
Property	Reformed Coal-Syngas
Mole Frac	
C_2H_6	
CH_4	0.030
CO	0.179
CO_2	0.124
H_2	0.419
H_2O	0.244
N_2	0.003
O_2	0.000
Sum	1.00

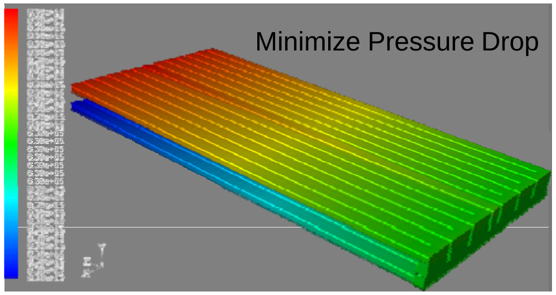
Selected SOFC cycle for IGFC Plant

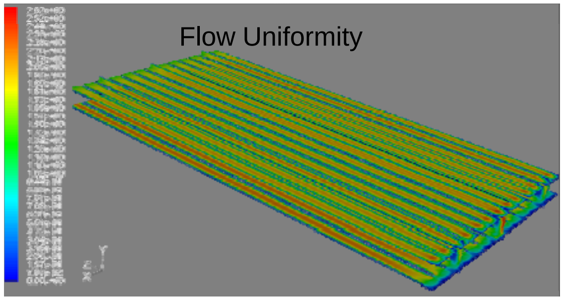


- Requires separate air and fuel streams for CO_2 capture
  - Without OGB to balance reforming endotherm, reformer removed from cathode loop
- Anode recycle eliminated given dilute coal-syngas fuel
- Operation at peak SOFC T=900C, 6 bar_a, U_f=79% yields 50% IGFC efficiency
- For SECA block test, coal-syngas supplied via CPOX reforming

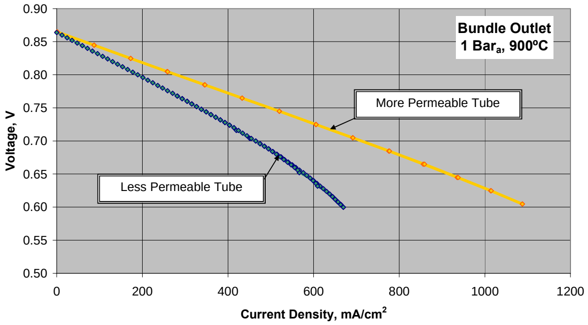
Task 3: Next Generation Stack Technology

- **Redesigned dense ceramic manifold components, lower cost processing**





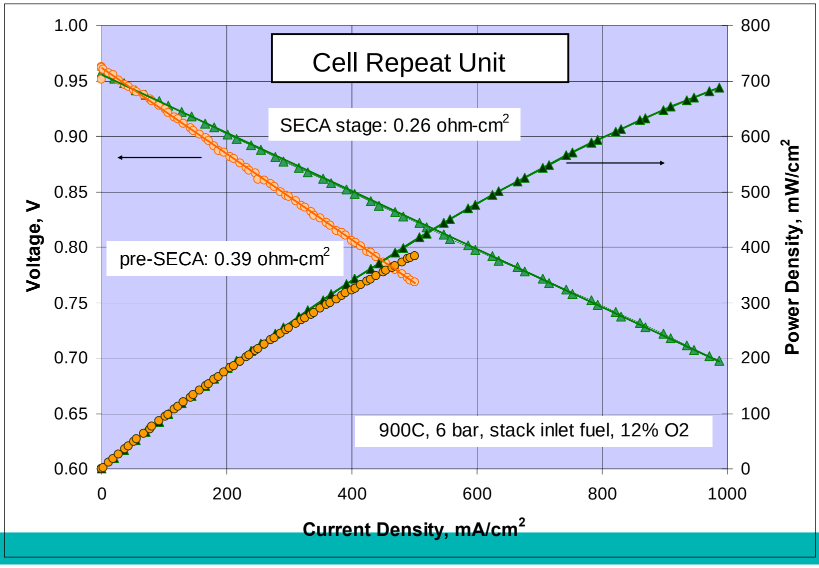
- **Understanding relationship between substrate properties, performance and strength (ORNL)**



- **Investigation of sealant glass stability and applicability to higher CTE substrates (PNNL)**

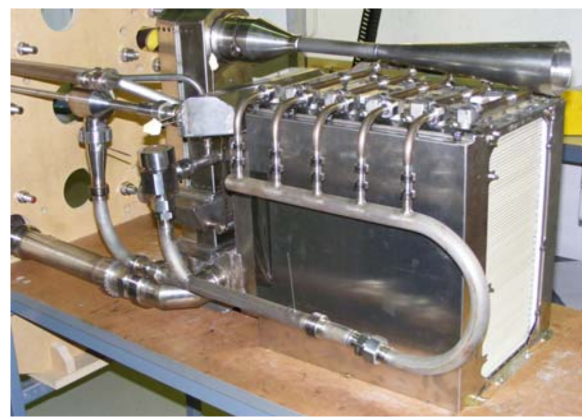
Task 4: Cell Development

- **Reduction in ASR**
  - **Lower stack temperature, lower degradation**
  - **Improved efficiency**
- **Optimization for durability improvement, emphasizing changes to:**
  - **Current collectors**
  - **Primary interconnect**



Task 5: Test Rig for SECA Stack Test

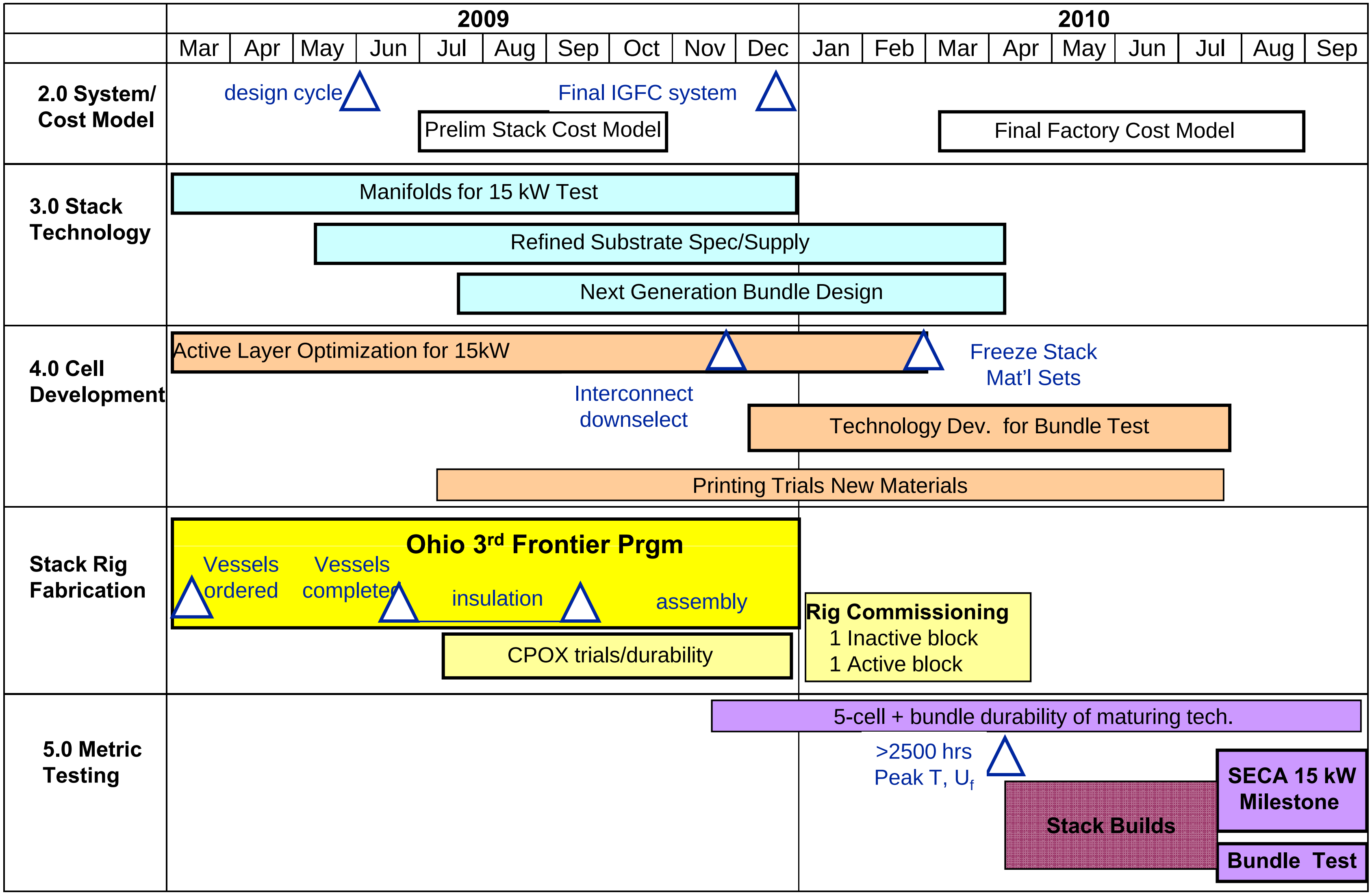
- UK commissioning in progress of two block-level rigs for durability at fully representative system conditions
- A similar rig being prepared in US with support from Ohio's Third Frontier
- SECA test will be 4 strips yielding ~15kW at normal operating condition



Task 5: Subscale Durability Confirmed Prior to Milestone Test

- 5 Pressurized Test Stands (US)
  - 2 sub-scale substrates (5 cells), or
  - 1 full-scale substrate
- 2 Bundle Test Rigs (UK)

RRFCS SECA Schedule



Summary

- Significant progress (pre-SECA) has been made in many areas
  - Maturing of the Stack Technology
  - System integration at large scale
  - Sub-system design and testing
  - System testing, understanding and modelling
- Top remaining technology challenges:
  - Confirming durability of the fuel cell
  - System demonstration testing
- SECA plays critical role within RRFCS Program
  - Supports next generation cell and stack development
  - Validation of technology through system level block testing

Acknowledgements

- This material is based on work supported by the Dept. of Energy National Energy Technology Laboratory under Award Number DE-FC26-08NT0003893
- RRFCS project manager Travis Shultz and the entire SECA program management team
- UK and US based RRFCS team
- RRFCS SECA partners

Thank you
Overview of the Rolls-Royce SOFC Technology and SECA Program

July 14th, 2009

Richard Goettler