Advanced Materials for Reversible Solid Oxide Fuel Cell (RSOFC), Dual Mode Operation with Low Degradation

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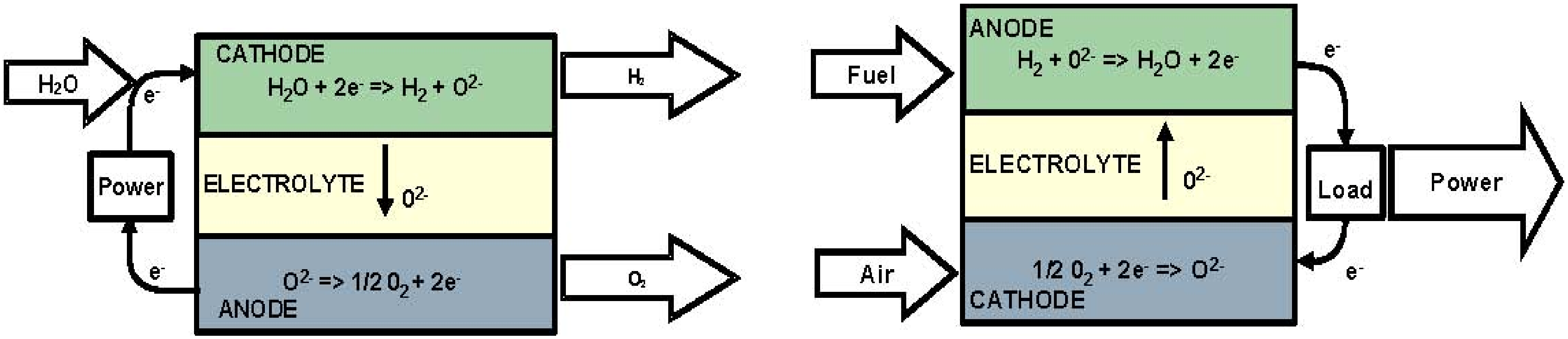
Project Background

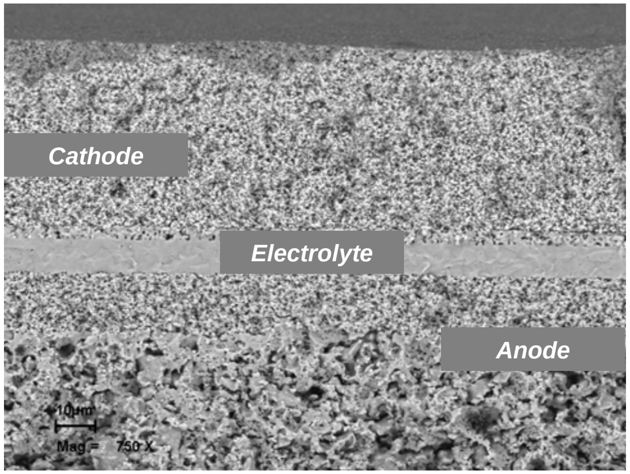
- Reversible Solid Oxide Fuel Cells (RSOFCs) are energy conversion devices. They are capable of operating in both power generation mode (SOFC) and electrolysis mode (SOEC)



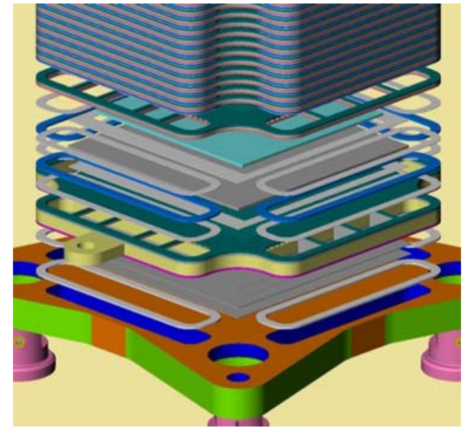
- RSOFCs can be integrated with renewable production of electricity and hydrogen when power generation and storage/steam electrolysis are coupled in a system.

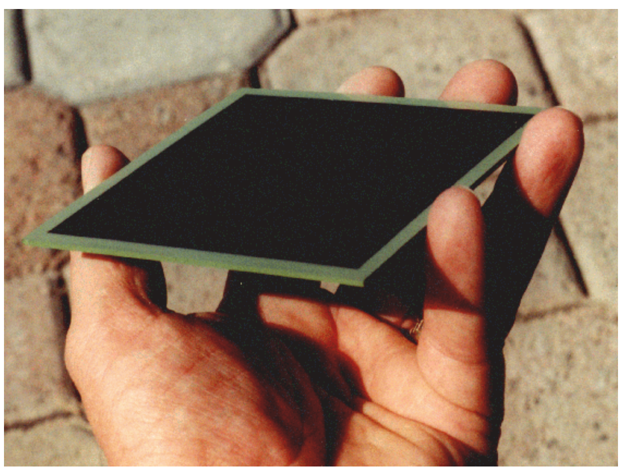
- **RSOFCs have the potential to become an energy conversion and storage technology that can enable the transformation of intermittent power sources, e.g., solar and wind energy, into "firm power".**

VPS Planar RSOFC Stack



- Anode supported cells (up to 33 x 33 cm2)
- Ferritic stainless steel sheet metal interconnect
- Cross-flow gas delivery with manifolds integrated into the interconnect but not through the cell
- Compressible ceramic gasket seals
- Standardized stack modules ready to integrate into stack towers for various applications



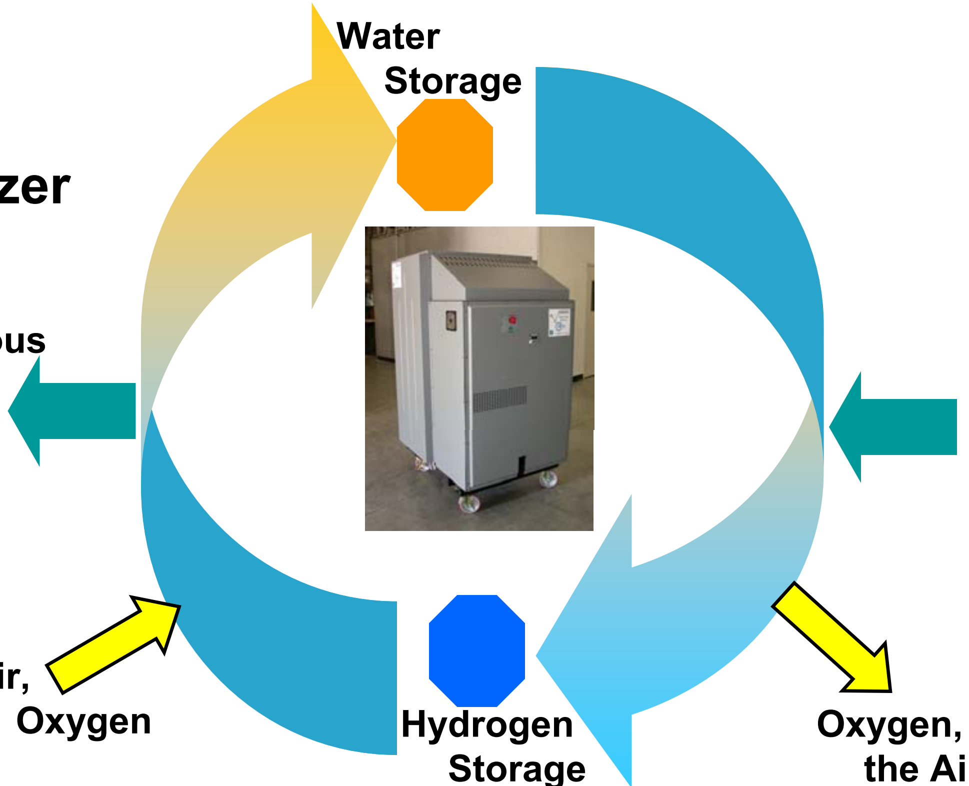


Path: 24 / 7 Reliability for Renewables:

The VPS Fuel Cell / Electrolyzer

Source:

- Wind
- Solar



- Unitized Cell
- High energy density
- High round trip efficiency

Applications

- Continuous Power for Renewables
- Grid Support: load level, peak-shave
- Hydrogen commodity production

Objectives

- To advance RSOFC cell stack technology in the areas of durability and performance, via-
  - materials development, and
  - stack design & development.

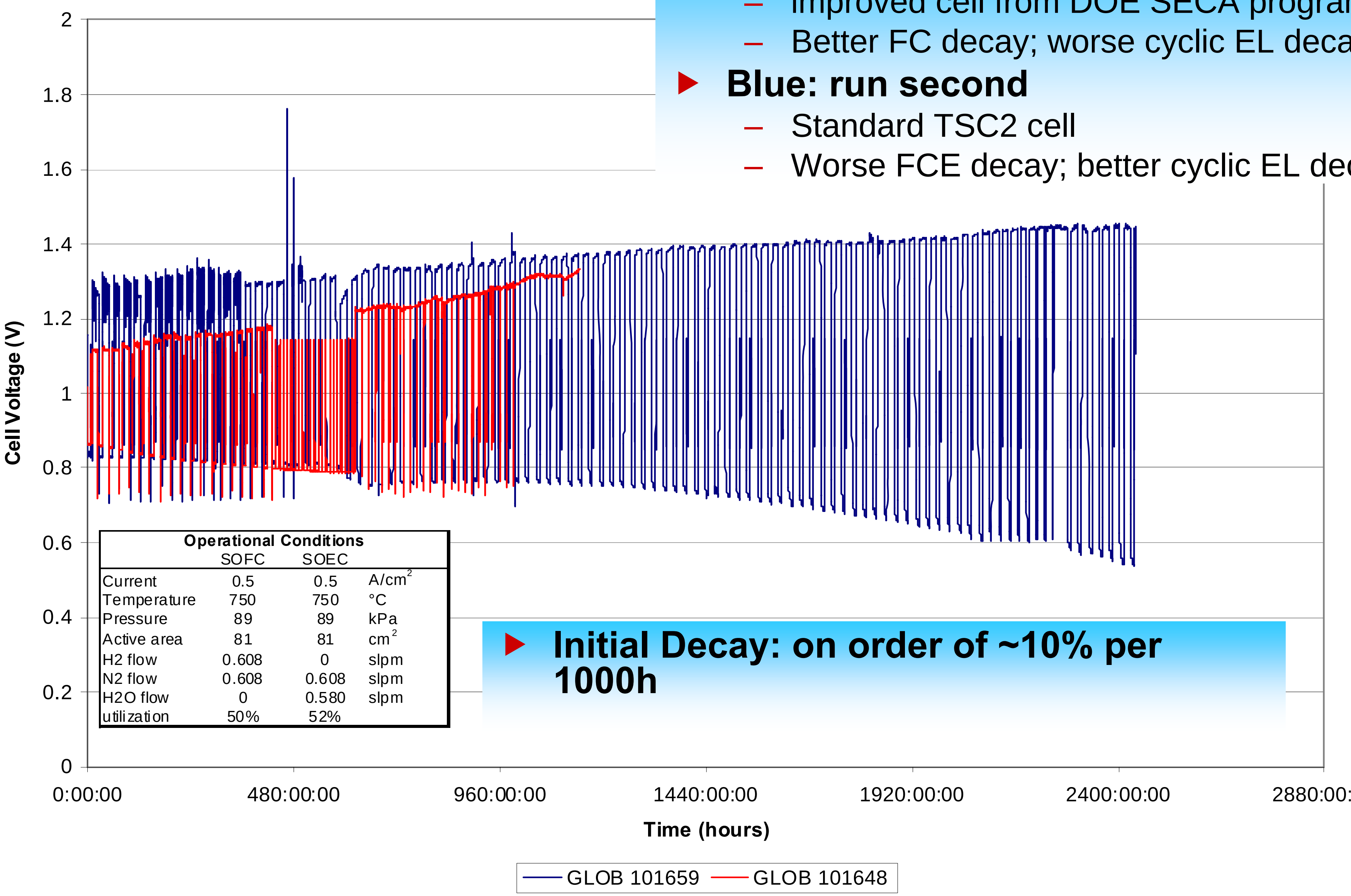
- To meet the following performance targets in a kW-class RSOFC stack demonstration:
  - Duration: RSOFC dual mode;
    - 1500 hours;
    - with more than ten SOFC/solid oxide electrolysis (SOEC) transitions
  - Current Density:
    - more than 300 mA/cm^2 in both SOFC and SOEC modes
  - Degradation:
    - Overall decay rate of less than 4% per 1000 hours of operation

Relevant SOEC Work

- **GE: ~2006, completed a 2-year, $1.8MM project, similar goals**
  - cathode performance in electrolysis, best to worst, LSCF>LSF>LSM.
  - predict higher electrode polarizations for anode and cathode in SOEC than SOFC
  - demonstrated 1000 hours SOEC operation, performance degradation not presented
  - tested a 3-cell stack for 1000 hours, performance degradation not presented
  - VPS initial performance appears better than this literature data
- **PhD thesis- Hauch at Riso National Labs**
  - tested anode-supported cells in temperature range 650-950°C.
  - Conclusion: anode electrode is responsible for most of the degradation in SOEC mode.
  - Impurity phases at the triple phase boundary (including silicates, alumino-silicates and sodium alumino-silicates) are thought to be cause of degradation (presumably from the glass-ceramic seal used).

VPS: RSOFC In-house development

- **Red: run first**
  - improved cell from DOE SECA program
  - Better FC decay; worse cyclic EL decay
- **Blue: run second**
  - Standard TSC2 cell
  - Worse FCE decay; better cyclic EL decay



Operational Conditions

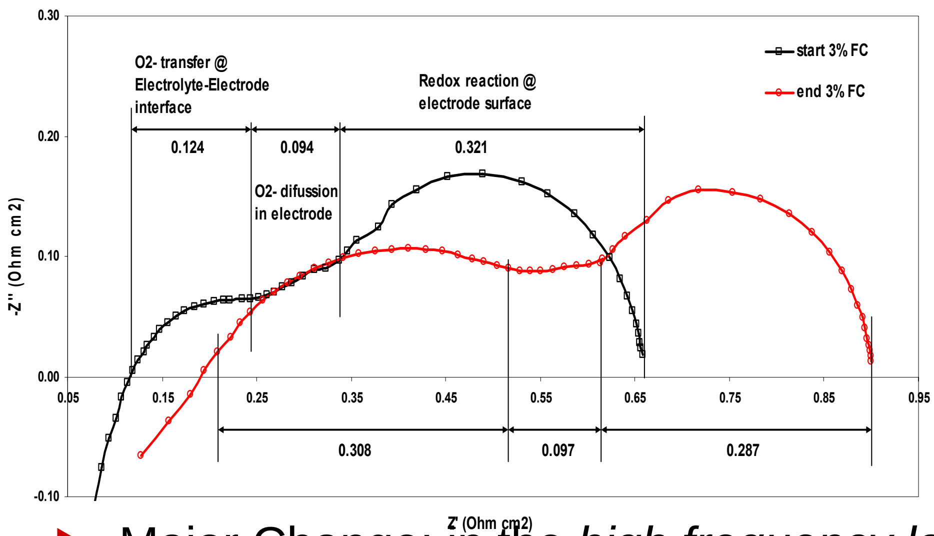
	SOFC	SOEC	
Current	0.5	0.5	A/cm^2
Temperature	750	750	°C
Pressure	89	89	kPa
Active area	81	81	cm^2
H2 flow	0.608	0	slpm
N2 flow	0.608	0.608	slpm
H2O flow	0	0.580	slpm
utilization	50%	52%	

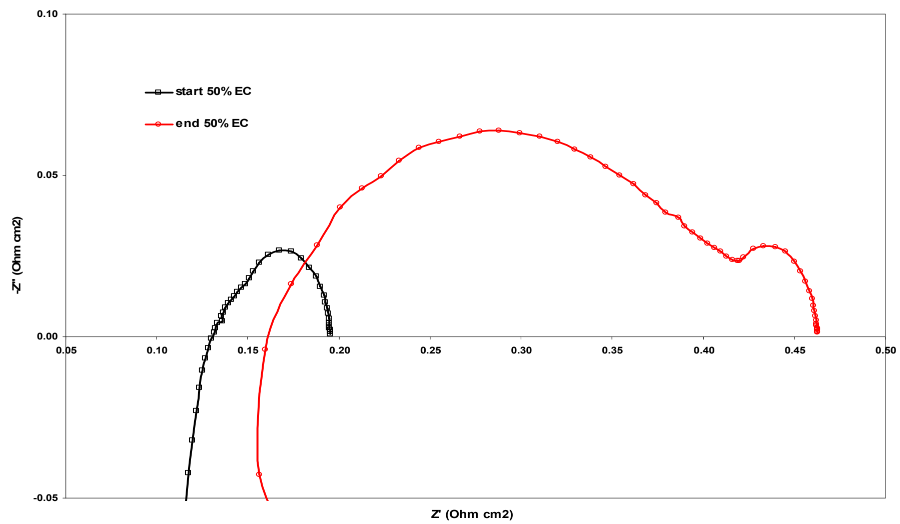
- **Initial Decay: on order of ~10% per 1000h**

EIS: e.g., High Performance Cathode ~3000h; SOR vs EOR; 750°C

3% humidity

50% humidity



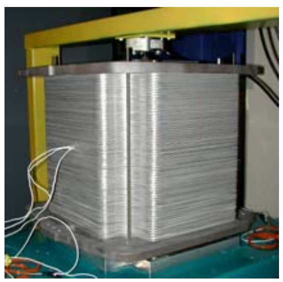


- Major Change: in the *high frequency loop* (first loop on left), *increasing in size*-
  - Associated with charge transfer.
  - Affected by changes in triple phase boundary length or activity.
  - Possible roots: microstructural changes, reaction at the triple phase boundary between electrodes and electrolyte, impurity phases collecting at triple phase boundaries, or similar.
- Little change: in the *low frequency diffusion loop*-

Suggests no significant electrode densification via sintering, (at least not sufficiently to cause a change in the measured diffusional impedance.)

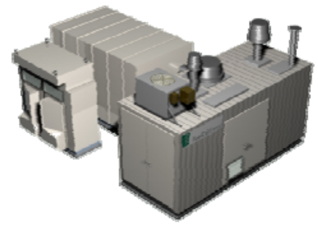
Relevant Power Plant Technology Development Work: DOE SECA- Coal Based, multi MW

10 kW Stack

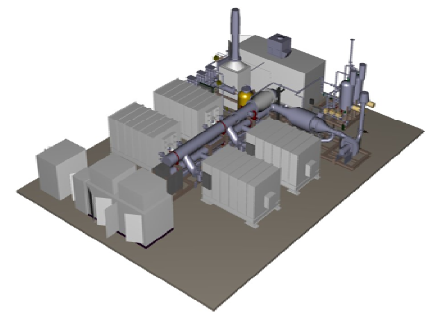


Multi-Stack Tower

≥ 250 kW Module Demonstration Unit



5 MW Proof of Concept



2008 | 2010 | 2012 | 2015

Phase I | **Phase II** | **Phase III**

Stack Scaleup Progression

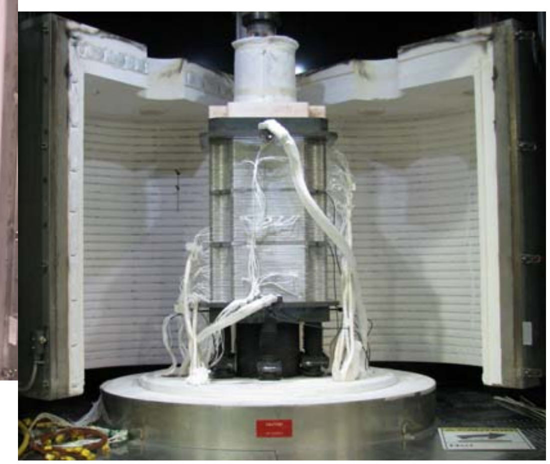
0.16 kW
1-cell

1 kW
6-cell

2.5 kW
16-cell

10 kW
64-cell

18 kW
92-cell



Phase II

Stack Design	Power (kW/stack)	Quantity	Total Power (kW)
16 cells	2.5	20	50
92 cells	18	3	54
Total		45	104

Phase I

Stack Design	Power (kW/stack)	Quantity	Total Power (kW)
6 cells	1	21	21
16 cells	2.5	18	45
64 cells	10	6	60
Total		45	126

Technical Barriers and Targets

	Barriers	Targets
Endurance	Performance decay at SOEC mode is too high for RSOFC system development – Materials system is not stable at SOEC operating mode with a decay rate more than 12 to 20% per 1000 hours – Performance decay during transient between SOEC and SOFC is high	Reducing decay rate to less than 4% per 1000 hours at both SOFC and SOEC mode – Meet endurance technical target in a 1000 hours single cell test (month 15) – Meet endurance technical target in a 1500 hours kW class stack (month 24) – Demonstrate transient capability with more than 10 transients
Performance	Performance in SOEC mode is not sufficient for viable RSOFC system development – ASR is more than 0.45 ohm.cm^2 at 800°C in SOEC mode – ASR is more than 1.0 ohm.cm^2 at 750°C and below in SOEC mode	Improve performance at 750°C in SOEC mode with reducing ASR to less than 0.3 ohm.cm^2 – Meet performance technical target in a single cell test (month 15) – Operate kW class RSOEC stack at more than 300 mA/cm^2

Approach

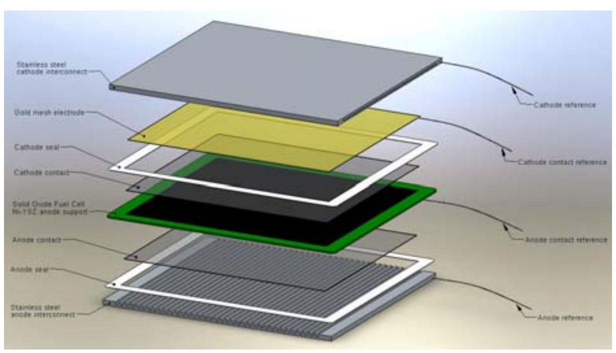
- **Build on VPS' SOFC cell and stack baseline**
  - 26,000h single stack repeat unit cell
- **Leverage cell and stack advancements from the parallel, DOE-SECA SOFC project**
  - Less than 0.5% per 1000h single stack repeat unit
  - >10 times stack scale up; >4000h; targeting multi-MW applications; 92 cells, 20kW stack block
  - Less than 1% per 1000h, stack
  - 15% performance improvement at 700ºC
- **Address RSOFC degradation mechanisms in SOEC mode with innovative cell and stack repeat unit configurations**
  - Tap VPS data base of electrode and IC formulations developed to combat similar mechanisms related to redox, direct oxidation of hydrocarbons, thermal cycling, steady-state degradation, and low temperature operation.
  - Test at least ten electrode formulations and ICs in the project
- **Conduct parallel materials development activities and integrate them with cell production technology development**
  - Attack 90% of RSOFC decay: in the cell electrodes charge transfer;
  - TEM: microstructural changes at TPB
  - Parametric; temperature, current density; steam utilization
  - Specify the cell materials and microstructure required for year 2.
- **Complete RSOFC stack and process designs to address durability, performance, and cost in both SOFC and SOEC operating modes**
  - System modeling defines SOFC and SOEC requirements: HySys, Fluent/custom code
  - Develop high level RSOFC stack design to meet requirements
  - Execute stack demonstration

WBS & Budget

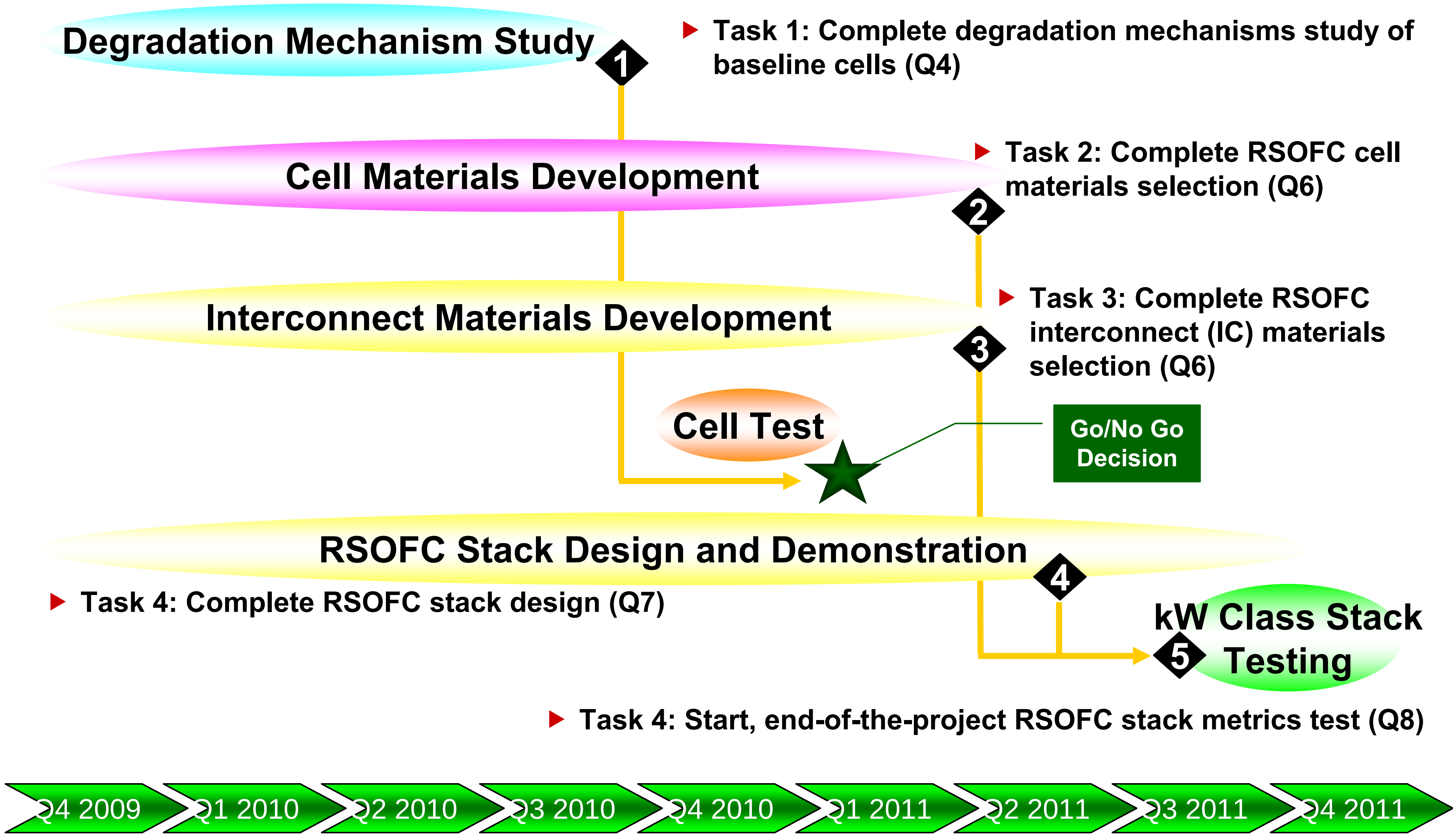
- Task 1 RSOFC Degradation Mechanism Study
- Task 2 Cell Materials Development
- Task 3 Interconnect Materials Development
- Task 4 RSOFC Stack Design and Demonstration
- Task 5 Project Management

<u>Budget:</u>

- **Budget Period One (month 1 to 15): $1,346,072**
  - **To Go/No-Go Decision**
- **Budget Period Two (month 16 to 24): $648,546**
  - **To stack metrics test**
- **Total: $1,994,618**



Timeline & Milestones



Go / No-Go Decision Point

Go / No-Go

- **Schedule: At Month 15**
- **Test: 1000 hour single repeat stack unit cell test**
- **Criteria: demonstrate-**
  - RSOFC area specific resistance of less than 0.3 Ω-cm^2 in both SOFC and SOEC operating modes
  - Operating current density of more than 300 mA/cm^2 in both SOFC and SOEC modes
  - Overall decay rate of less than 4% per 1000 hours of operation

Organization

- VPS Inc: Project Management
- VPS Ltd.: RSOFC Technology R&D

**Low Cost, Proprietary Process,
SOFC Manufacturing at Versa Power Systems**

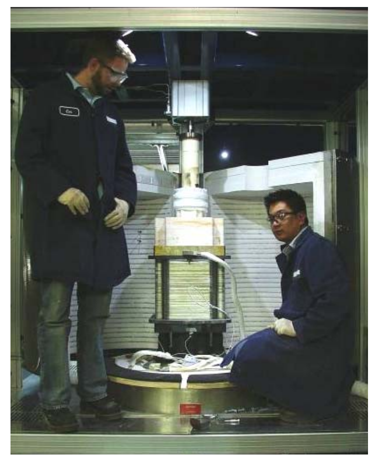
Tape Castin
"T"

Screen Printin
"S"

Co-Sintering
"C"

The VPS *"TSC"* process for SOFC manufacture is proven:

- One firing step
- Cost effective
- High yields: a result of process control



- ✓ **About 35 product development stations for cell, stack and systems,**
- ✓ **Spanning 1 to 25 kW**

Backup

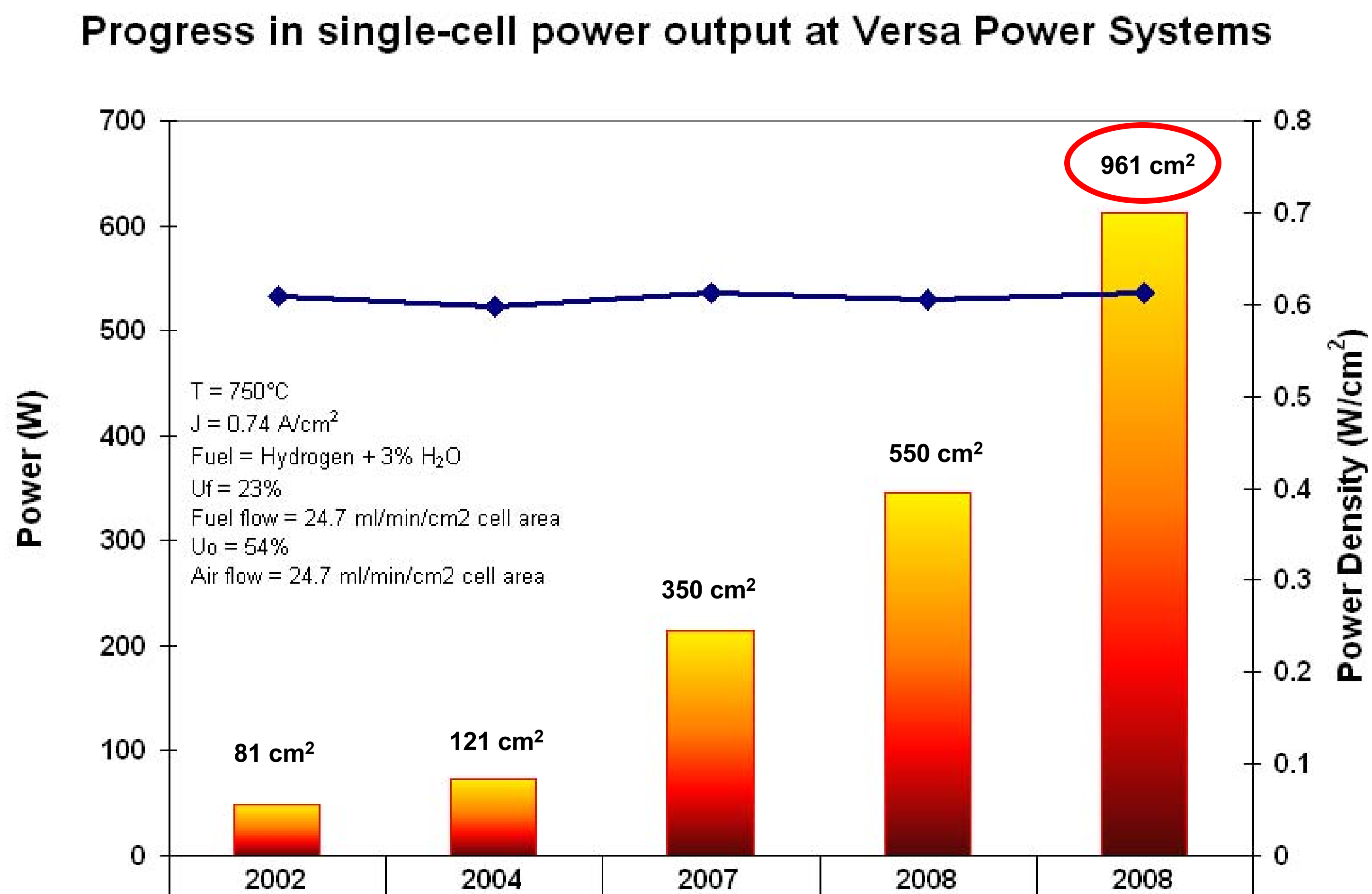
6th Generation Power System

3-1 System: 3 kWe

- Integrated power system
  - **Pipeline natural gas**
  - On-board desulfurization
  - On-board fuel processing
- Autonomous control
  - Remote monitoring and control
  - CAN bus control architecture
- Designed to comply with applicable codes, standards
- Less than $800 per kW, audited cost

✓ ***Over 10,000 hours at nearly 99% availability.***
✓ ***Verified at VPS, NETL, & Cummins***

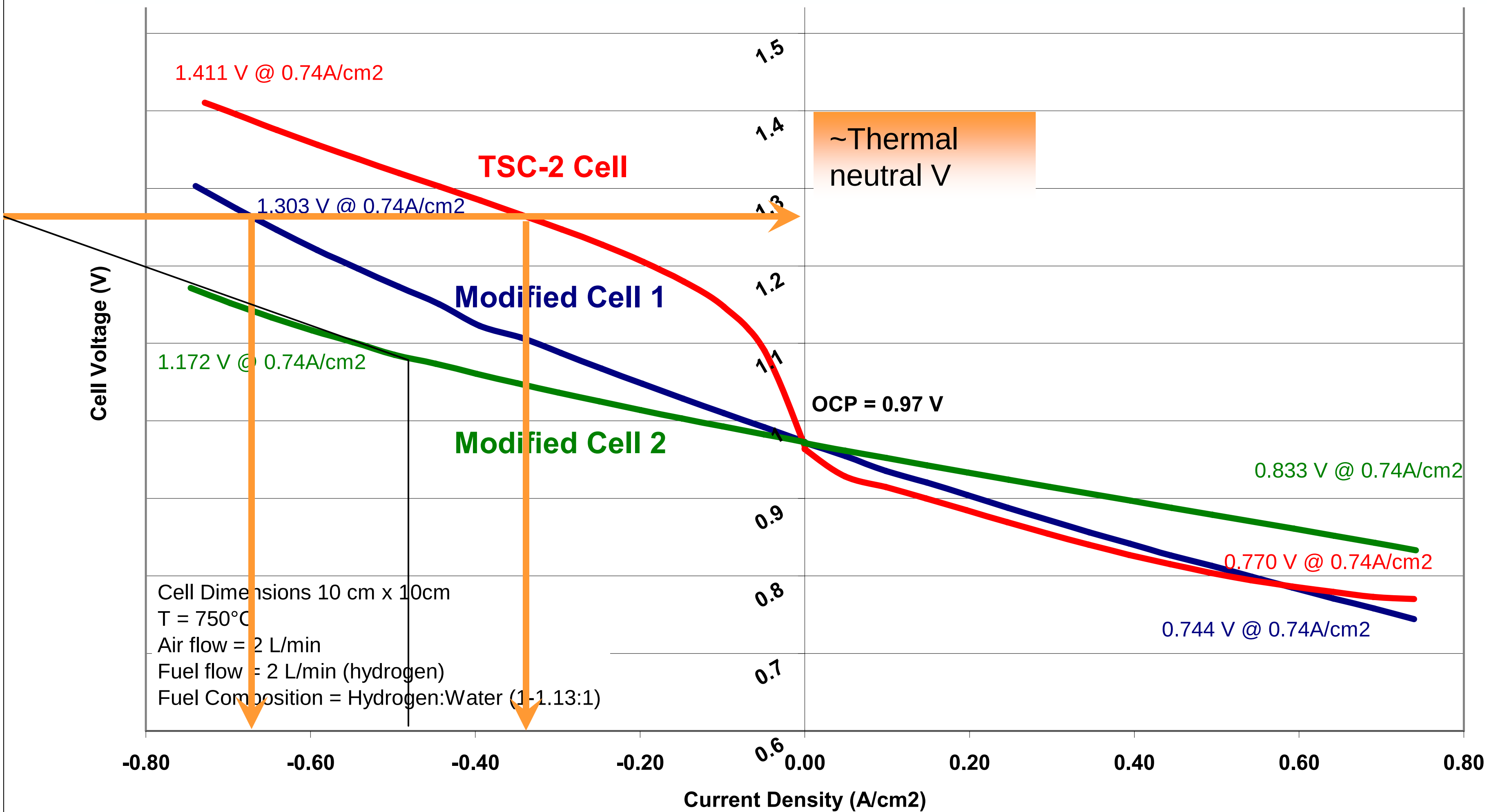
Single Cell – Large Cell Testing



	2002	2004	2007	2008	2008
Power	49	72	214	346	612
Power Density	0.608	0.598	0.612	0.606	0.612

SOFC / SOEC Cell Development

- About one year of mostly IR&D effort
- Among best in literature in SOFC and SOEL performance, from 650º to 800ºC



ROUGH- Comparison

Table 1. SOFC/SOEC Performance Comparison Between VPS and GE

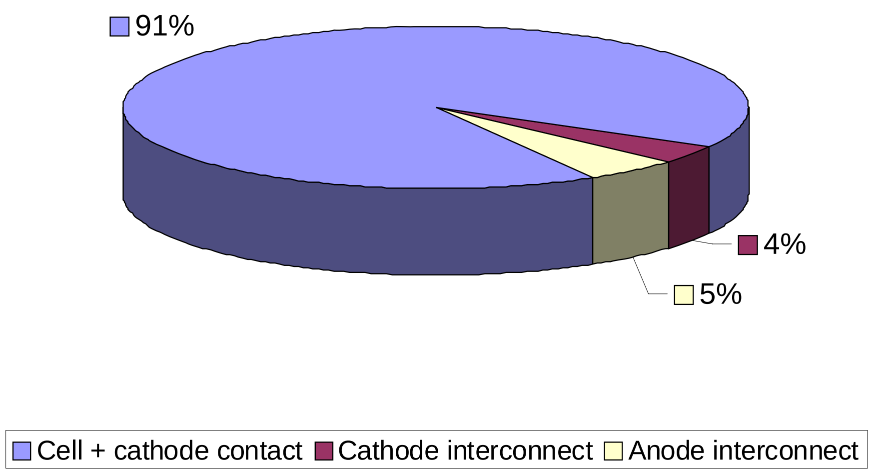
Cell Type	Operation Mode	ASR (ohm.cm^2) at 800°C	750°C	700°C	650°C
VPS Baseline TSC-2 cell	SOFC	0.161	0.180	0.293	0.657
	SOEC	0.302	0.375	0.504	0.687
VPS Improved cell	SOFC	0.152	0.184	0.250	0.381
	SOEC	0.254	0.330	0.505	0.763
GE Baseline cell	SOFC	0.846			
	SOEC	1.287			
GE Gen-I cell	SOFC	0.283			
	SOEC	0.470			

Table 2. Cell Operation Stability Comparison Between VPS and GE in SOEC Mode

		Test time (hours)	Change in ASR (mohm.cm^2 per 1000 hrs)
VPS	TSC-2 cell	1500	164
	Modified cell	3000	78
GE	Baseline cell	100	14800
	Gen-I Cell	100	400

Standard TSC2 Cell SOFC / SOEC Degradation Breakdown of Losses

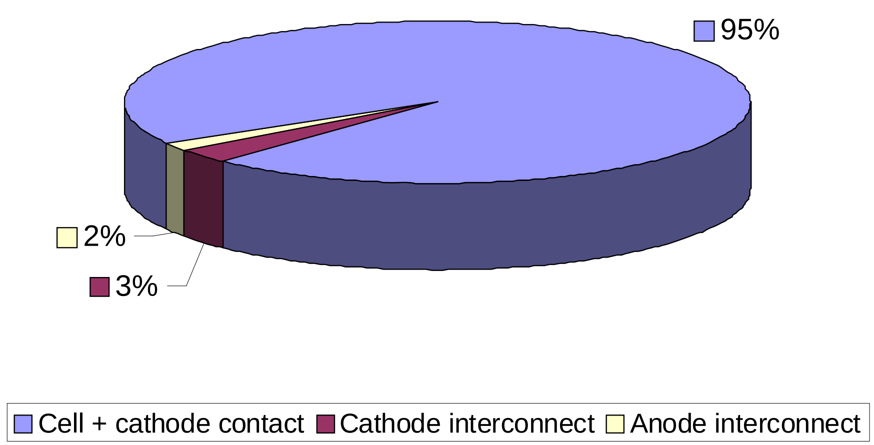
FUEL CELL DEGRADATION BREAKDOWN



- > 90 % of degradation is from cell
- < 5 % from cathode interconnect
- < 4% from anode interconnect and anode contact

- **After 1600 hours and 19 cycles**

ELECTROLYSIS DEGRADATION BREAKDOWN



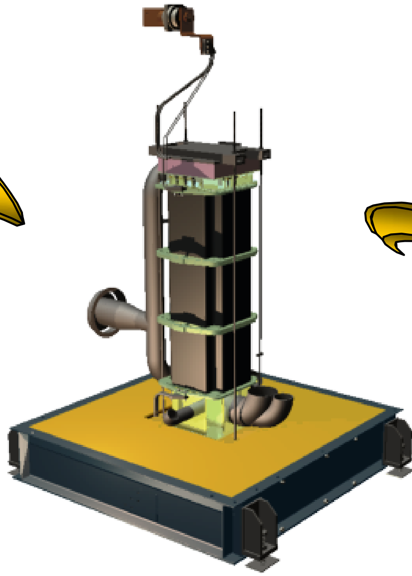
Building Block Approach

10-20 kW Stack

Building block for stack towers

Up to 80 kW

Stack Tower



Building block for stack modules of ≥ 250 kW

Stack Module

Building Block for a ≥100MWe Integrated Gasification Fuel Cell (IGFC) system