Electrodeposition of SOFC Interconnect Coatings

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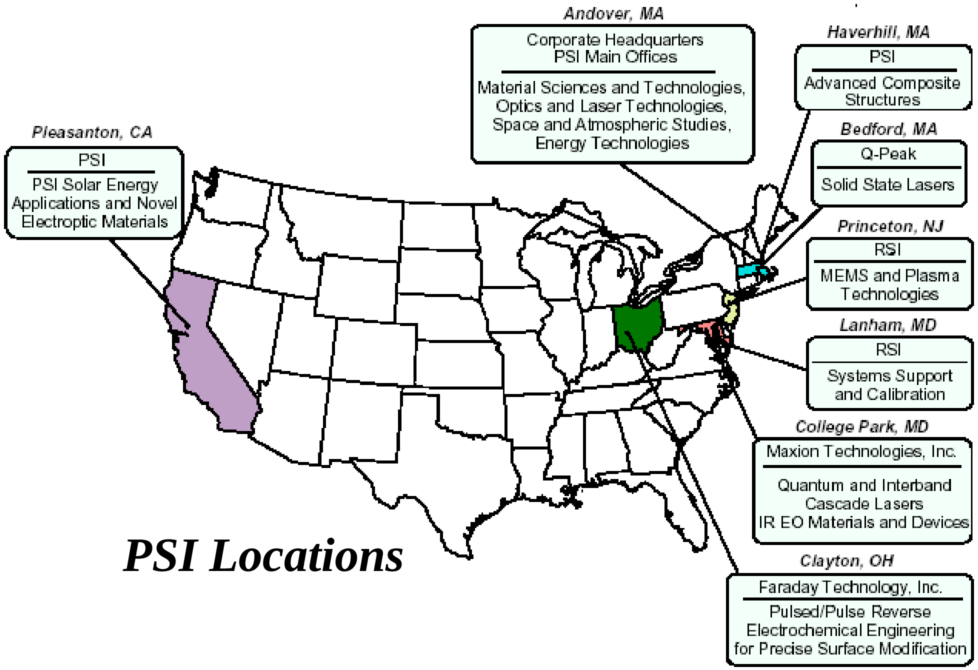
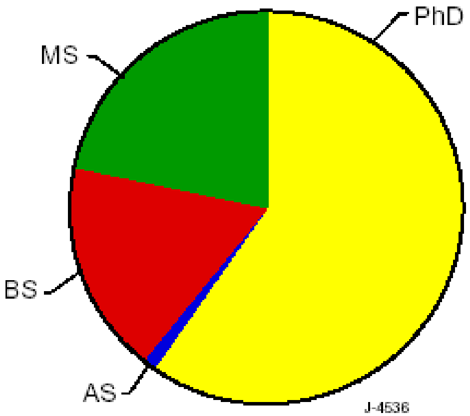
12th Annual SECA Workshop
July 26 – 28, 2011

Faraday Technology, Inc.

- Faraday Technology specializes in electrochemical engineering
  - www.faradaytechnology.com
- Faraday is a wholly-owned subsidiary of Physical Sciences, Inc. (Boston, MA)
  - www.psicorp.com
  - Collectively, the company staffs ~185 employees - ~100 with PhDs
  - Annual revenue of ~ $50M



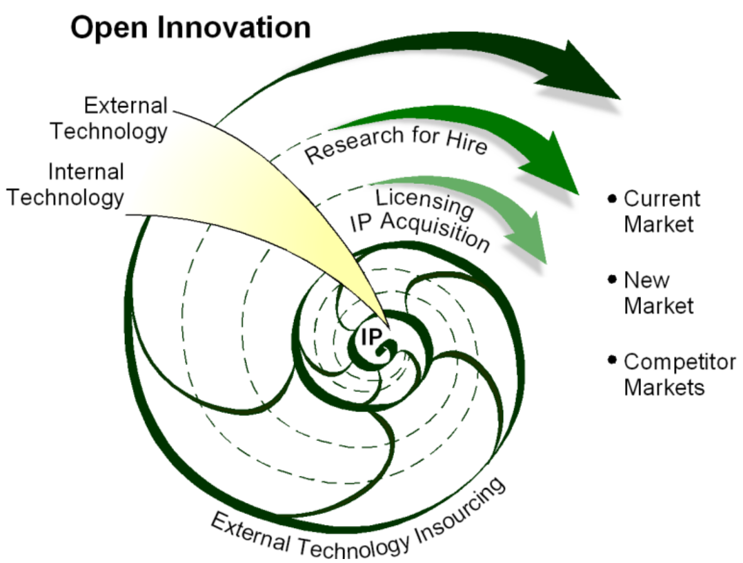
PSI Locations



PSI Employees by Education

Faraday Embraces Open Innovation

- Faraday's R&D efforts augment client company R&D needs
- Open innovation leverages government R&D dollars to solve current industrial issues.
- Faraday's strong IP portfolio reinforces our open innovation position and provides a competitive advantage for strategic partners.



26 Issued Electrochemical Patents
25 Pending Electrochemical Patents

Investment Dollars —*Discovery* / *Research*→ **Knowledge** —*Innovation*→ **Market Dollars**

Faraday Technology, Inc.

Platform Technology: Pulse/Pulse Reverse Processing

Total Manufacturing Solution

Core Competency: Design and Engineer of Novel Electrochemical Hardware

Either may be applied independently to improve current industrial practices or may be combined for a total manufacturing solution

- Electronics
- Edge and Surface Finishing
- Engineered Coatings
- Battery and Fuel Cell Power
- Environmental Systems
- Corrosion and Monitoring Services

- Enables uniform processing
- Applicable for additive or subtractive electrochemical processes
- Uniform processing is achieved over entire substrate, improving end product reliability

Objective of Program

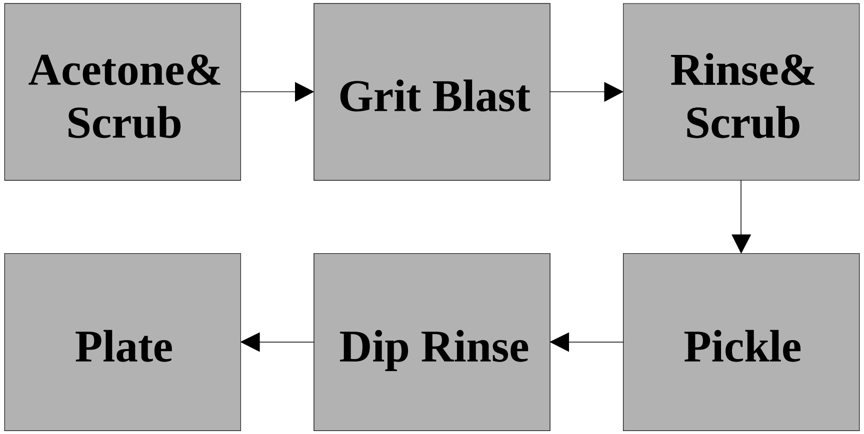
- Develop, optimize & validate an inexpensive manufacturing process for coating metallic SOFC interconnects with Co and Mn
  - Demonstrate the process's flexibility to 4"x4" and 10" x 10" single and dual-sided patterned interconnect substrates
  - Control coatings nanostructure and composition to prevent T441 exposure to O_2 and Cr diffusion to coating surface
  - Mitigate Cr diffusion by identifying diffusion mechanism via in-situ high temperature XRD and ex-situ XPS depth profiling
  - Develop a comprehensive economic assessment
  - Work closely with our the SOFC industry to enhance the commercialization plan for the program.

Program Summary

- FARADAYIC Process allows for non-line-of-sight deposition of a wide range of compositions and surface structures using a single plating bath
- Coatings prepared using the FARADAYIC Process have uniform surface composition and thickness on 2" x 2" flat panels
- Coatings exhibit adequate adhesion
- Initial ASR and crystallinity analysis showed that the as-deposited thickness/composition had little effect on performance after a 500 hr heat cycle
- 3µm thickness is capable of minimizing Cr diffusion for 500 hr testing
- Capability to coat dual-sided 1" buttons, 4" x 4", and up to 11" x 14" panels
- Based on batch manufacturing, the DOE's high volume target of 1,600,000 plates per annum at a cost of ~$1.23 per 25 x 25 cm interconnect

Coating Process

- Surface pretreatment to remove oxide and enhance coating adhesion
- Electrodeposition to coat interconnects with Mn-Co alloy
  - Pulse and pulse reverse electric fields to control deposit properties
- Elevated thermal treatment to convert alloy to spinel



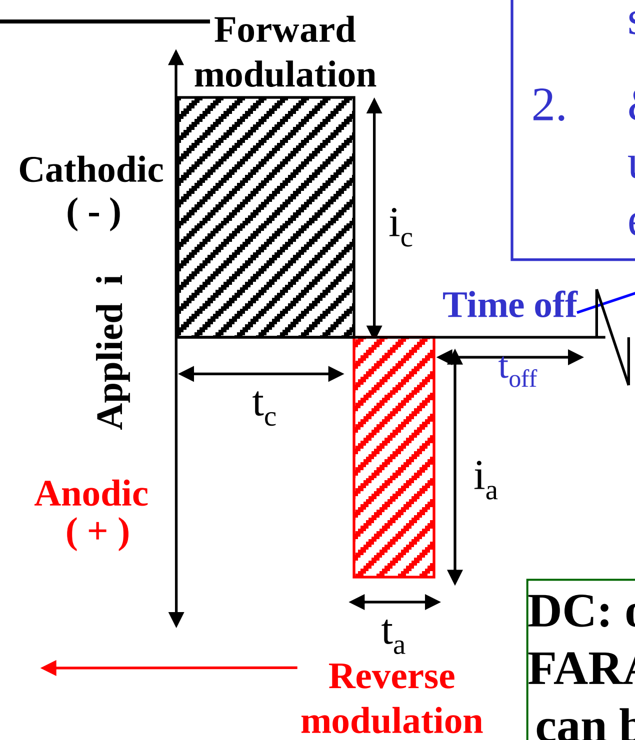
FARADAYIC Processing

"Tuned" to:

1. enhance mass transfer
2. control current distribution

⇩

Controls deposit composition & properties



"Tuned" to:

1. allow replenishment of reacting species on electrode surface
2. & allow transport of undesirable byproducts from electrode surface

⇩

Maintain uniform concentration & hydrodynamic conditions

"Tuned" to remove adverse effects of H_2

$H_2 = 2H^+ + 2e^-$

⇩

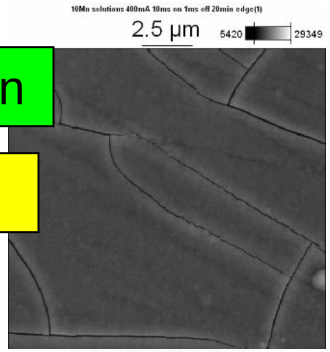
Eliminates H_2 embrittlement

DC: only i_{avg} can be chosen
FARADAYIC: i_a, t_a, i_c, t_c, t_{off} can be varied independently to achieve a desired rate

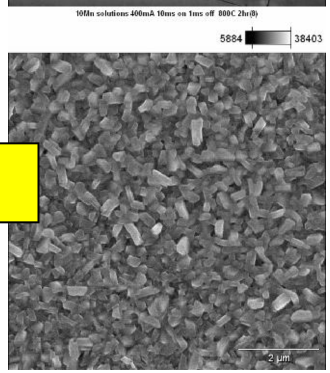
Initial Coating Development

14%Mn

As-deposited

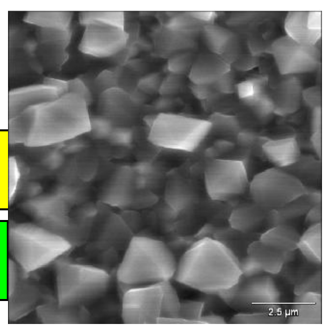


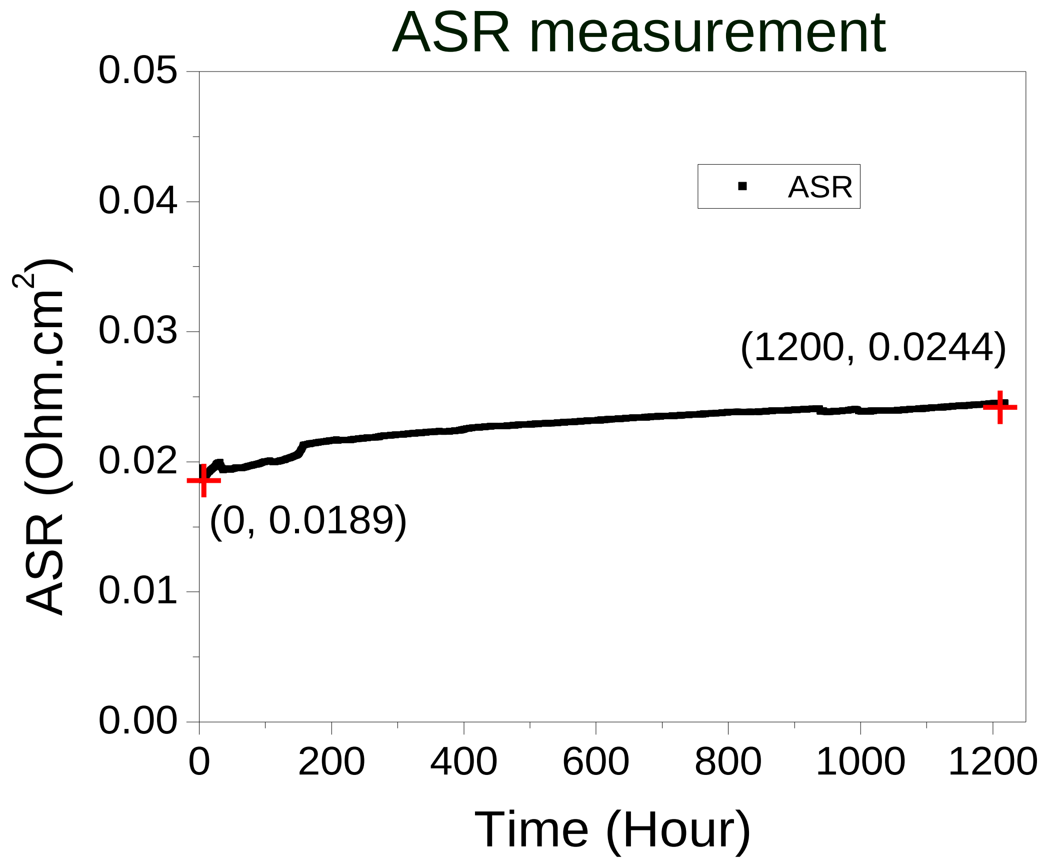
800°C 2hr



800°C 1200hr

~50%Mn





ASR prediction (40,000h, 0.0460 Ohm cm^2)

J. Wu, et al., Electrochimica Acta 54 (2008) 793–800

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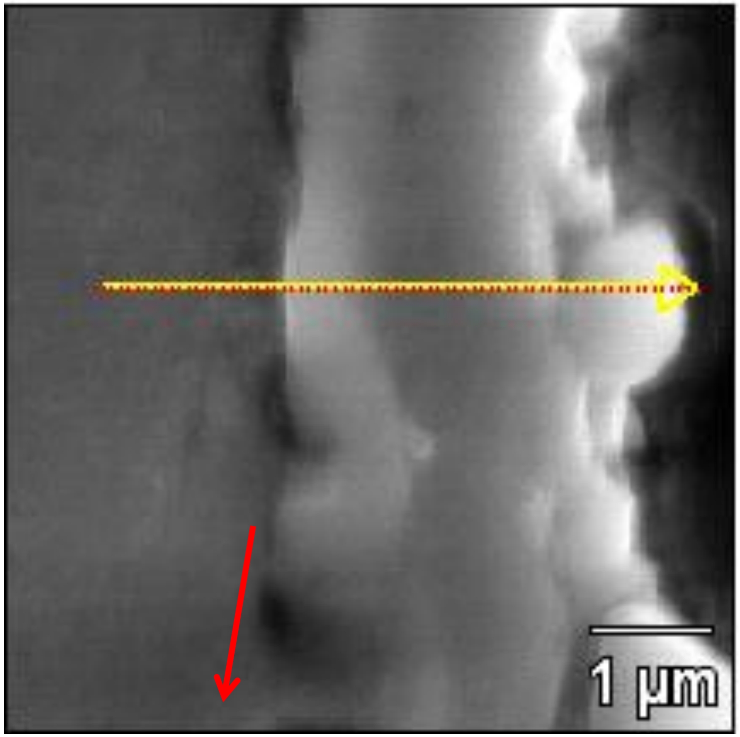
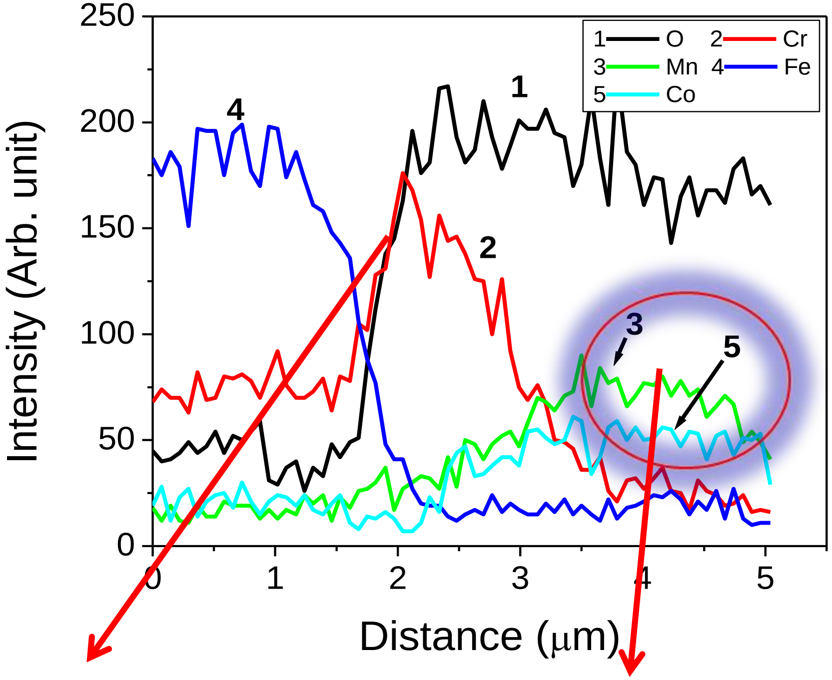
Initial Coating Development

Cross section after ASR





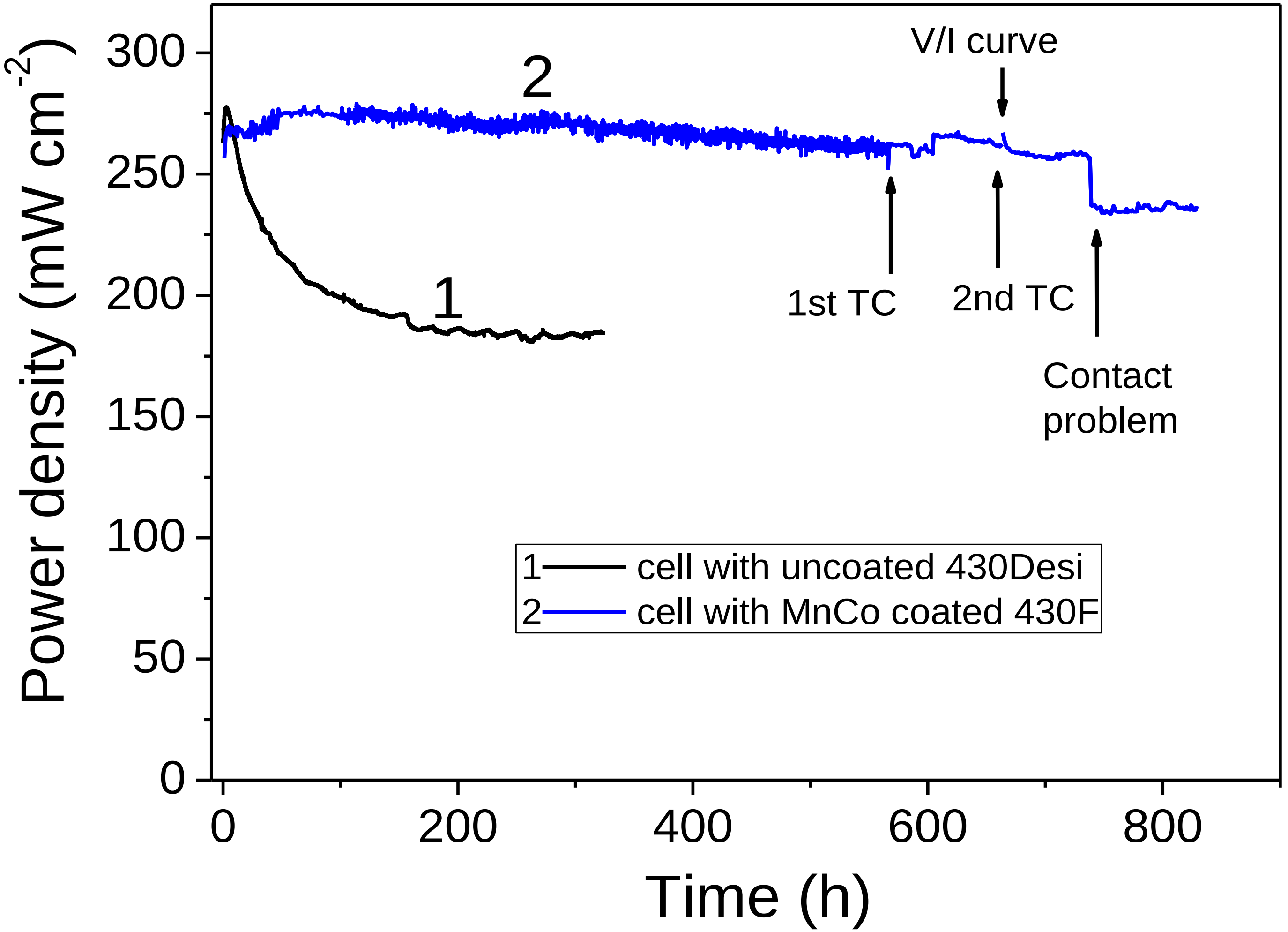
Good adhesion with substrate

No Cr penetrate through the coatings

Significant Mn diffusion from substrate

Initial Coating Development

Interconnect on button cell test



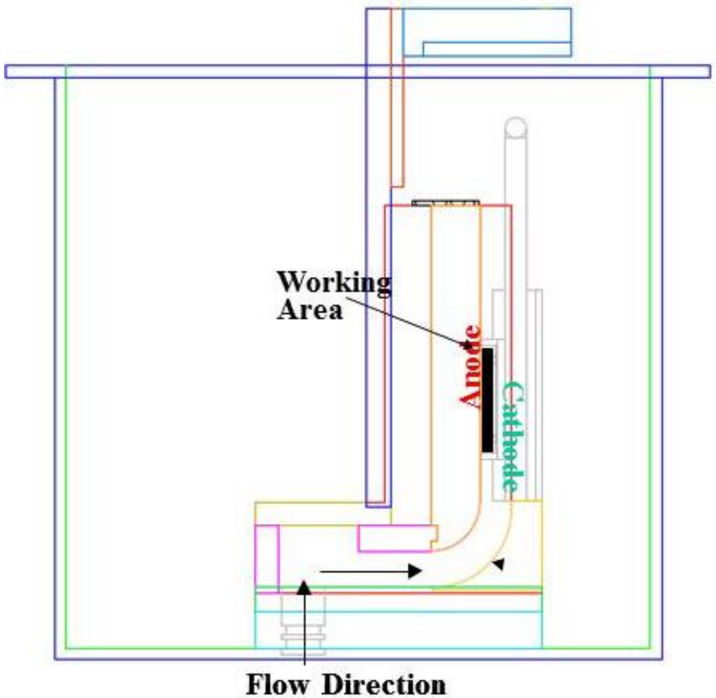
With electrodeposited MnCo coating, cell performance degradation reduced

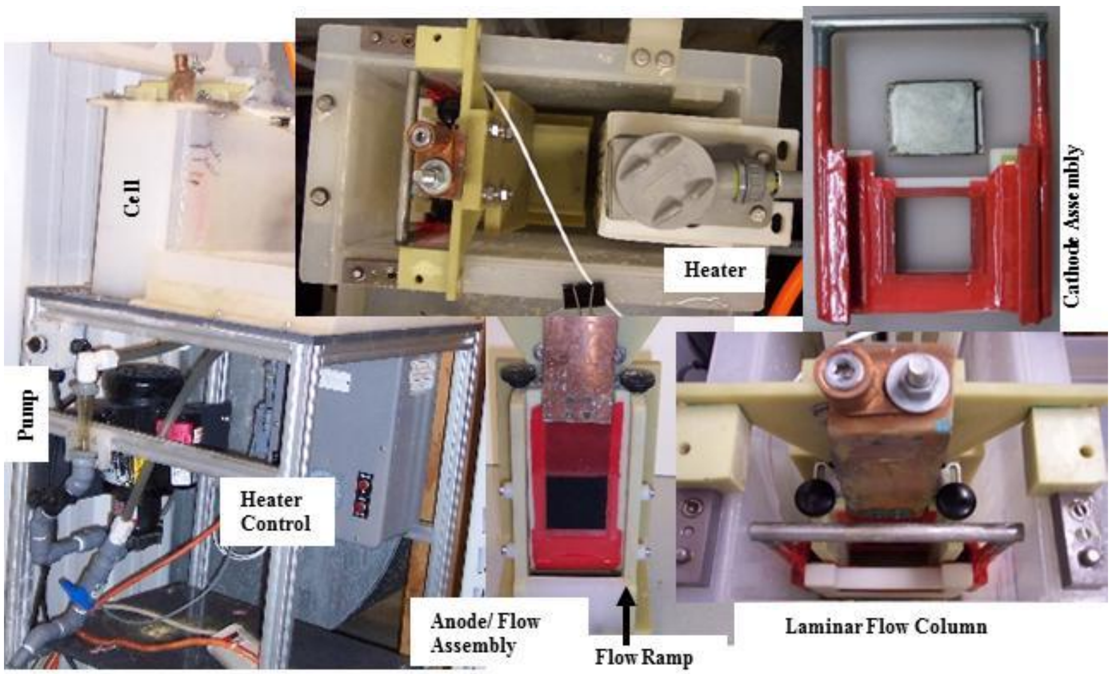
Objective of Phase I

- Demonstrate the technical and economic feasibility of MnCo electrodeposited on SOFC interconnect materials by answering the following questions:
    1. What range of coating percent compositions can the electrodeposition process deposit?
    2. Can the electrodeposition process deposit Mn-Co alloy coatings with a thickness range of 3 – 10 um?
    3. How well does the coating perform at varying alloy compositions and coating thickness?
    4. Is the electrodeposition process economically viable?

Laboratory Scale Electrodeposition Equipment

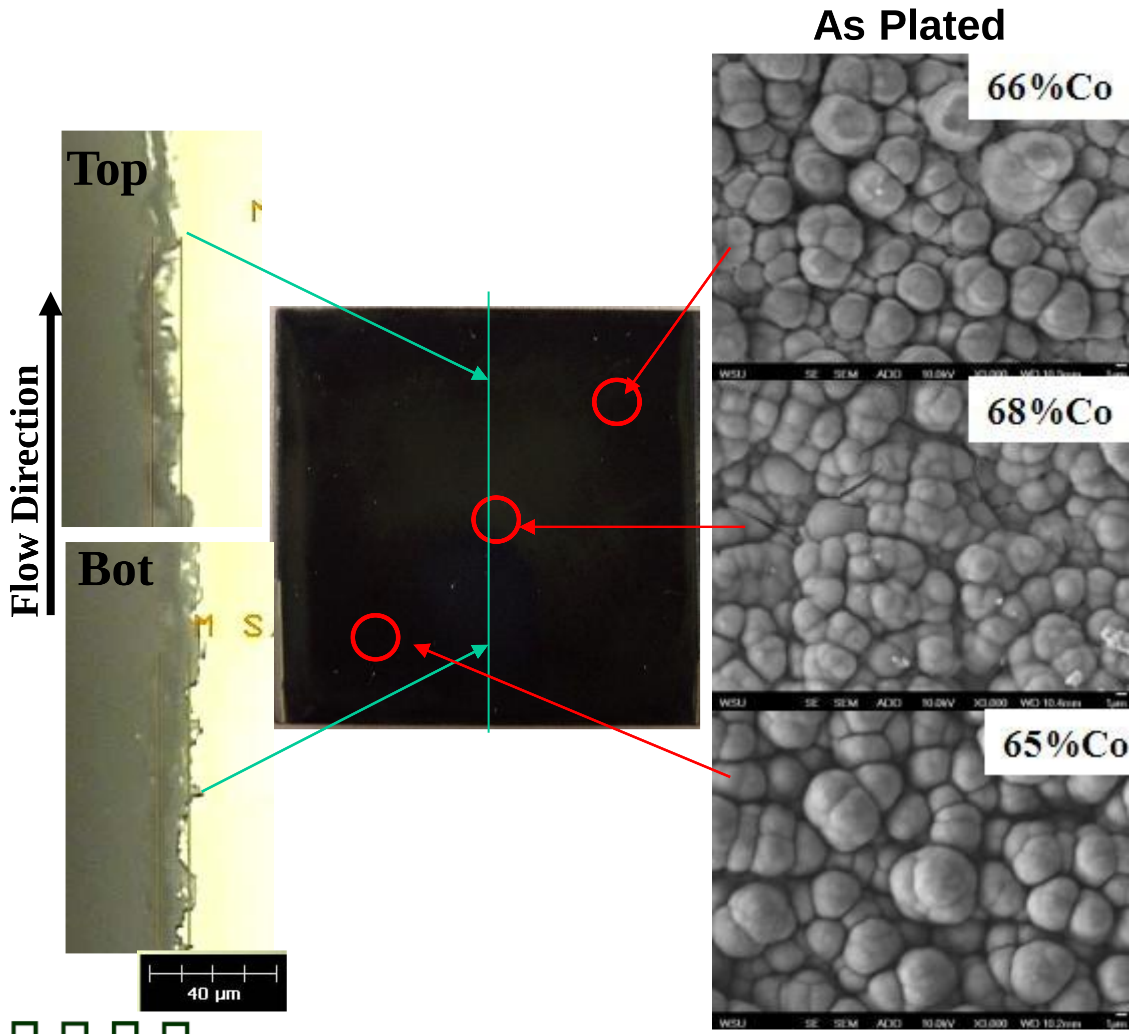
Flow cell for plating onto 2”x2” planar T441 substrates





Coating Uniformity

The electrodeposited coating exhibits a virtually uniform coating composition and thickness across the 2”x2” surface



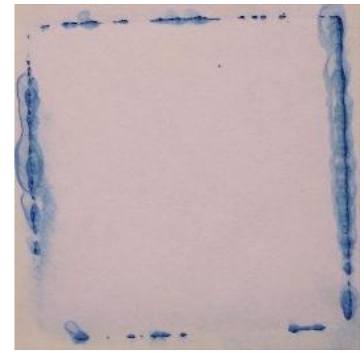
Coating Porosity and Adhesion

Feroxyl Porosity Test Results (AMS 2460 3.4.4.2)

SS Without Coating

Mn-Co Coating As Deposited

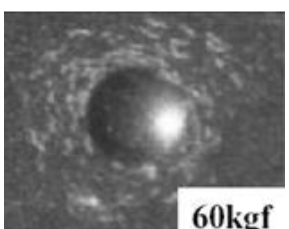
Mn-Co Coating After 72 hour Thermal Treatment at 800°C



**Rockwell test with 1/16" steel ball used to quantify adhesion after spinel growth after 72 hr. at 800°C*

*Sun, X., et. al. JPS, **176** (2008) 167

Without Grit Blast



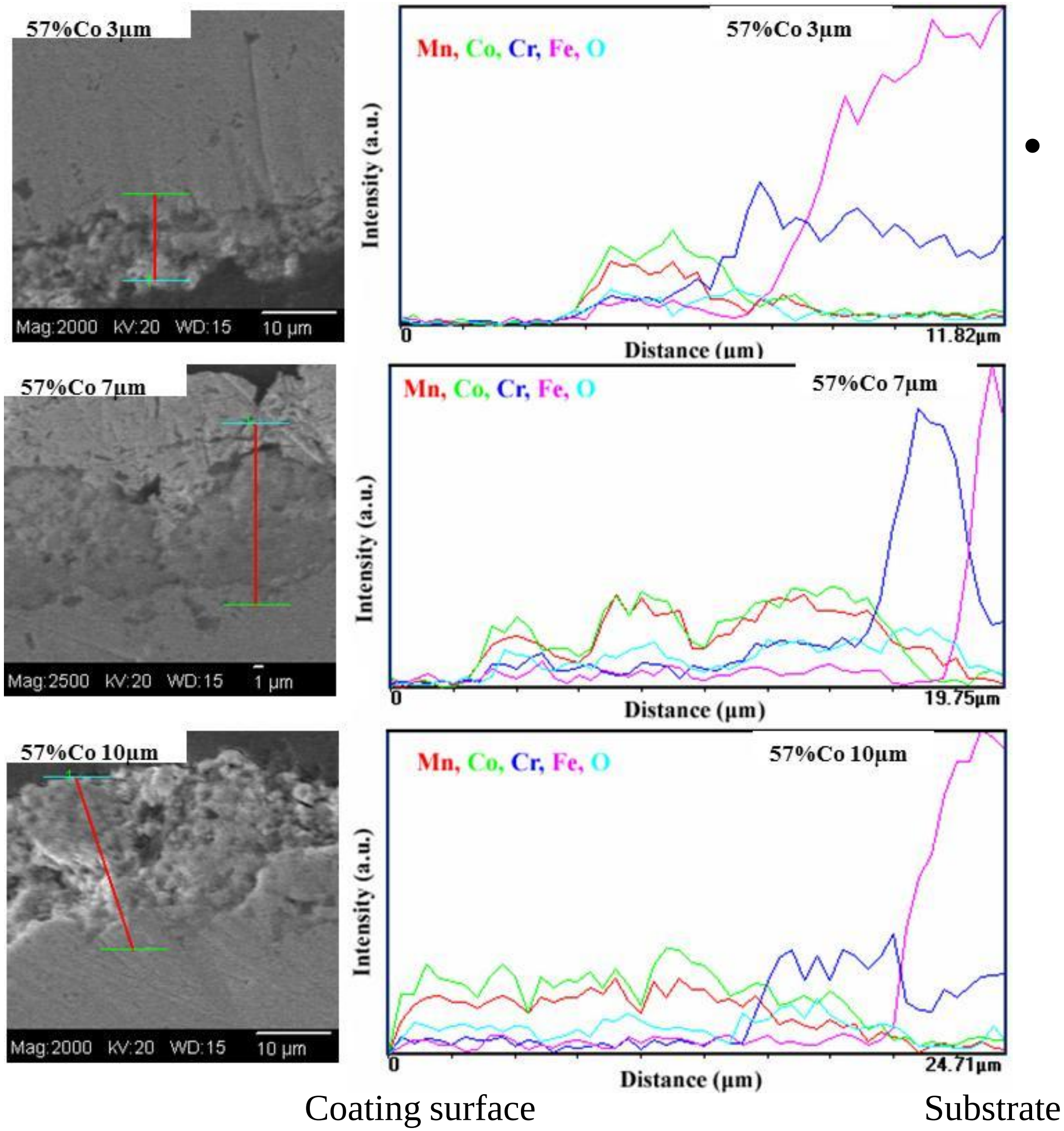
With Grit Blast

60kgf

100kgf

150kgf

Cr Ion Diffusion and Coating Porosity



- Cross-sections of samples that underwent a soak treatment at 800 C for 500 hrs
  - Coating thickness was as deposited
  - Indicates that a 3 micron layer is adequate to produce Cr complexing and minimize Cr diffusion due to minimal porosity

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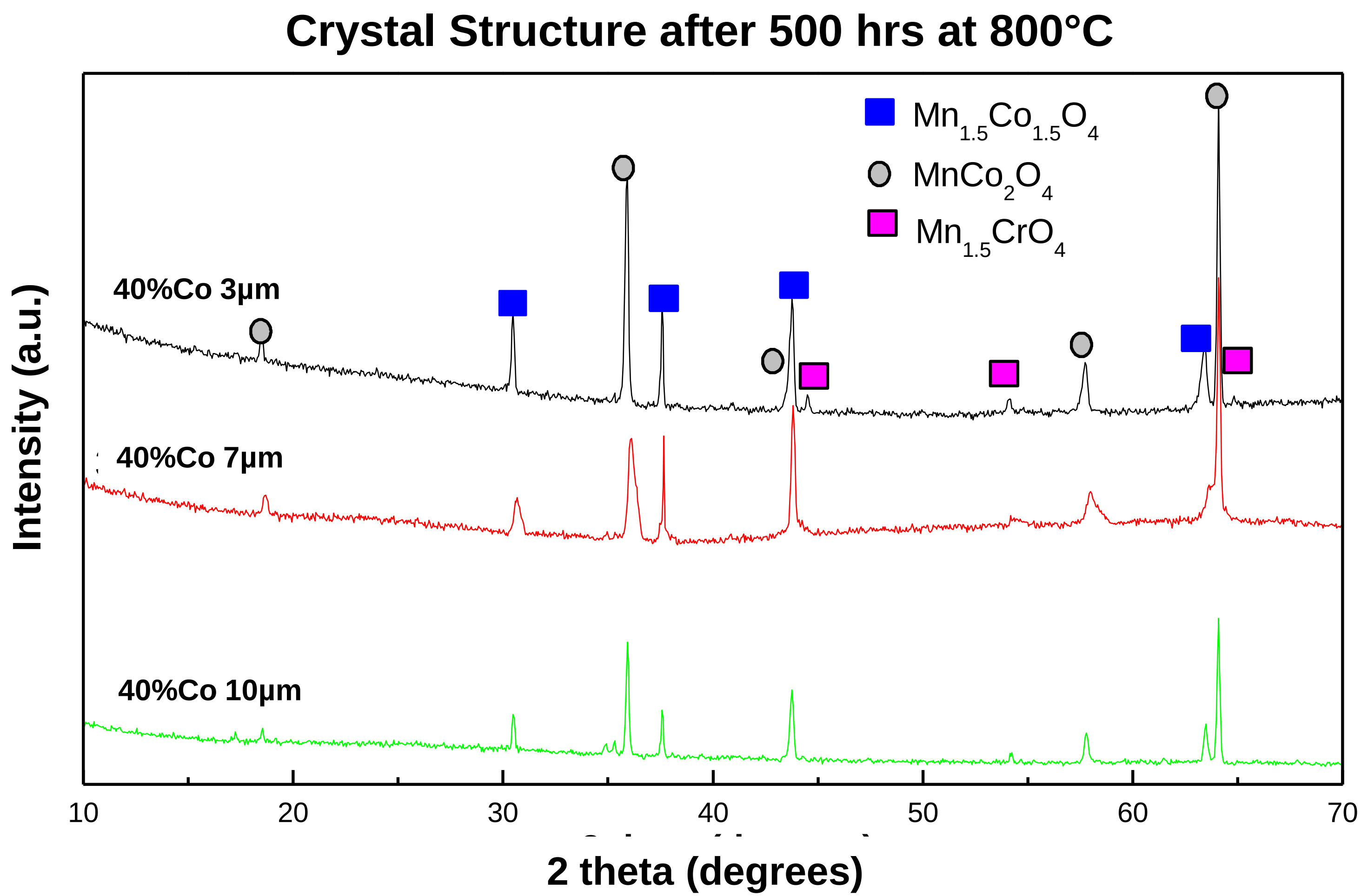
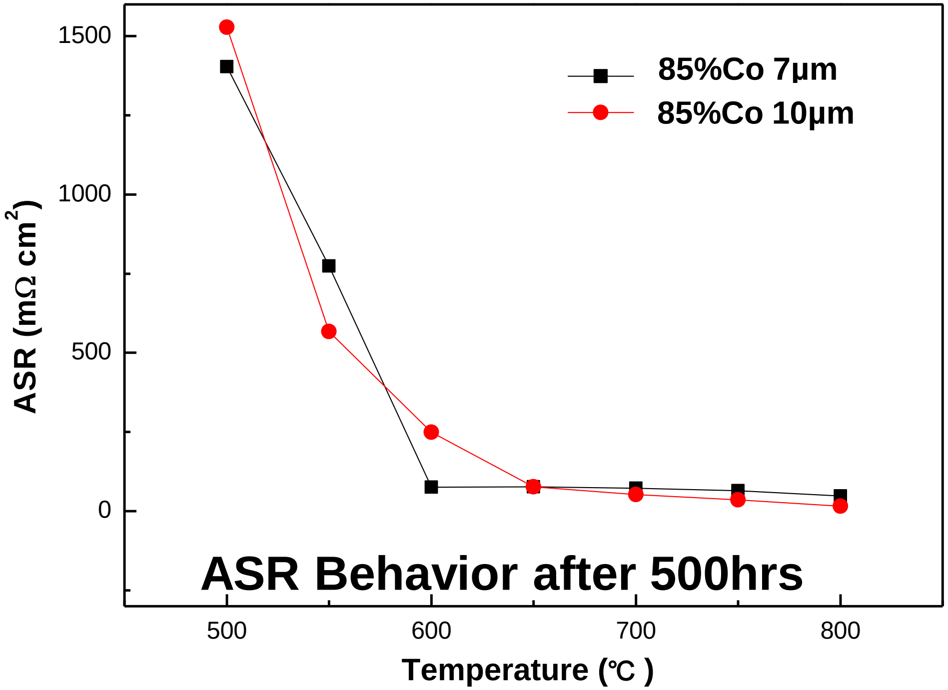
Coating Crystal Structure



Effect of Thickness and Composition on Performance

The ASR is ≤ 75 mΩ cm^2 regardless of compositions and thickness after 500 hrs at 800 C



ASR at 800 C

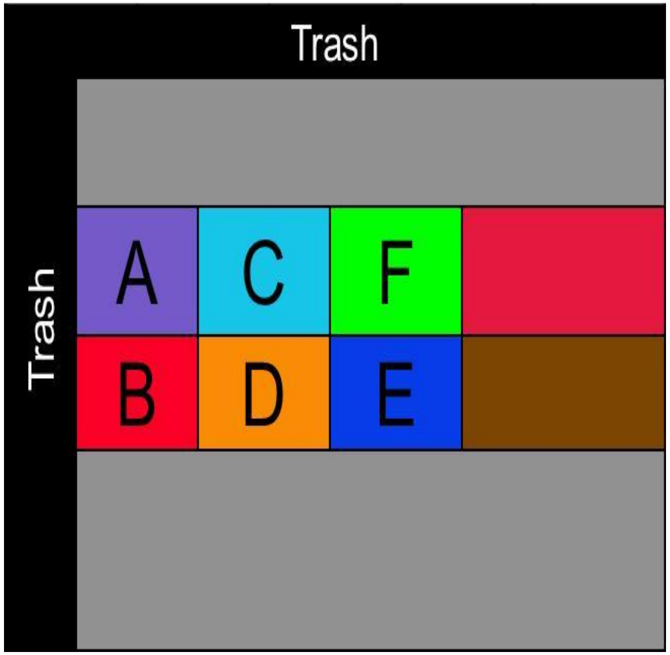
mΩ cm^2	100 hr	200 hr	500 hr
3 μm 40% Co	35	57	49
7 μm 40% Co	62	7	32
10 μm 40% Co	22	-	36
3 μm 85% Co	31	75	20
7 μm 85% Co	59	40	54
10 μm 85% Co	37	23	22
3 μm 57% Co	-	34	26
7 μm 57% Co	-	-	12
10 μm 57% Co	-	-	12

Phase II Program Milestones

Milestones			
Fiscal Year	***Title***	***Planned Completion***	***Percent Complete***
2011	1. Design/modification of 10” x 10” electrodeposition cell	May 2011	100%
2011	2. Long-term high temperature, thermal evaluation	September 2011	33%
2011	3. Process development for 4”x4” planar interconnects	September 2011	15%
2012	4. Process development for 4”x4” pattern interconnects	June 2012	0%
2012	5. Long-term on-cell performance evaluation	August 2012	0%
2012	6. Qualification/demonstration of IC in single cell test rig	September 2012	0%

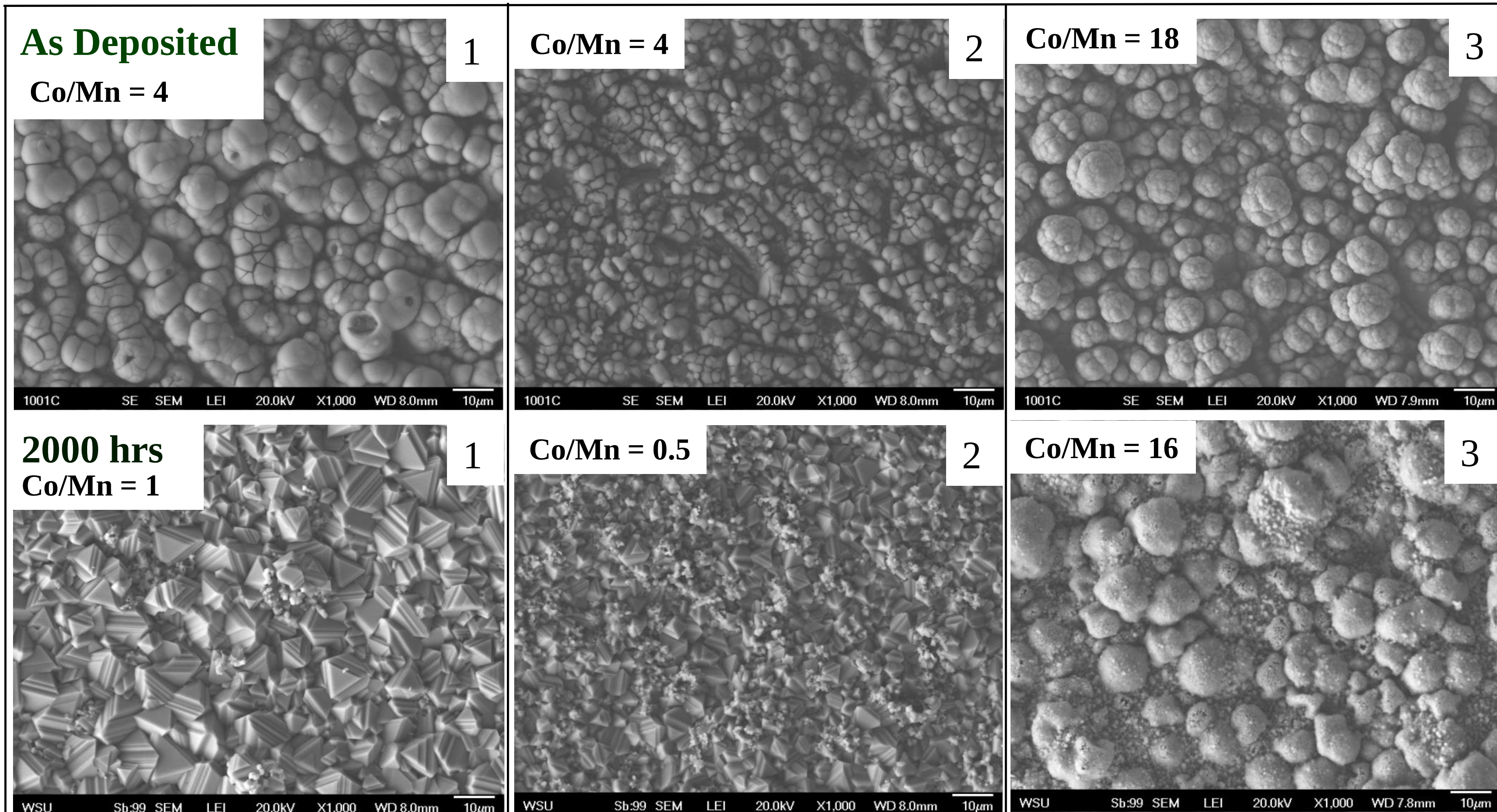
Extended Thermal Treatment Time Study

- Six samples were prepared using varying deposition parameters and placed into a tube furnace at 850 C.
  - 2 samples with higher Mn content and 4 with high Co content
  - Target alloy thickness of 5 um
- An air flow of at least 500 sccm flows through the furnace tube (to simulate air in SOFC systems)
- Samples examined after 750, 1500, and 2000 hr

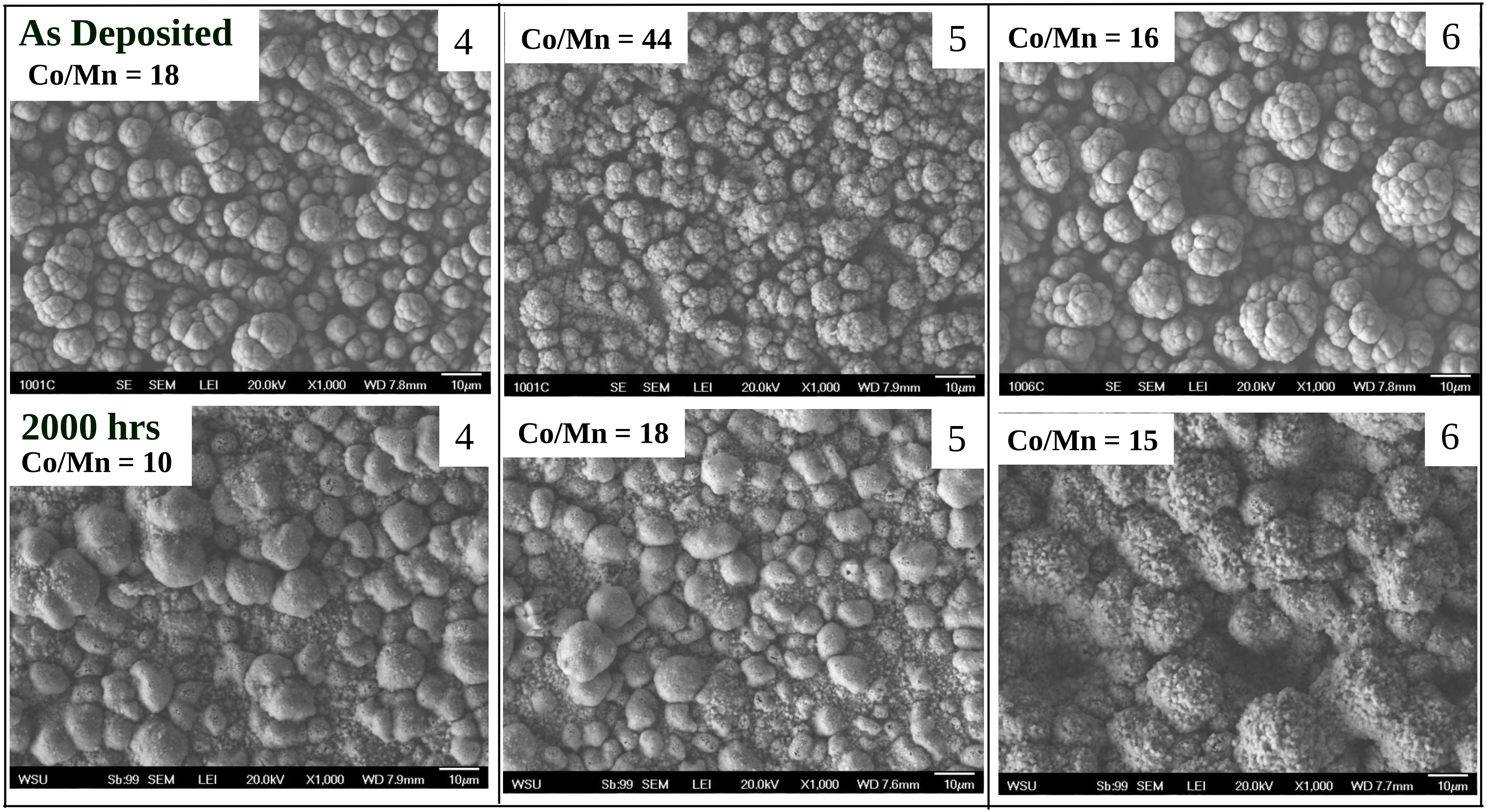


ASR Test order:C(t=0); D(t=750 hrs); E(t=1500 hrs); F(t=2000 hrs); and A(t=2000 hrs) (for Rockwell Test)

Extended Thermal Treatment Time Study

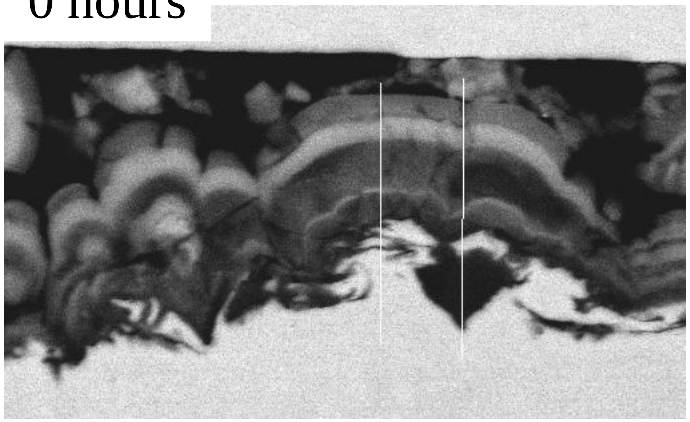


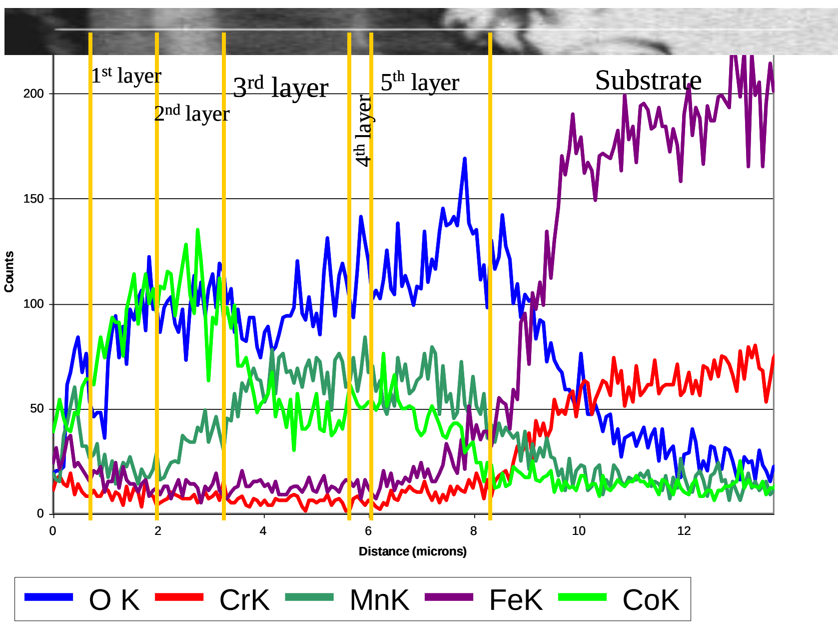
Extended Thermal Treatment Time Study



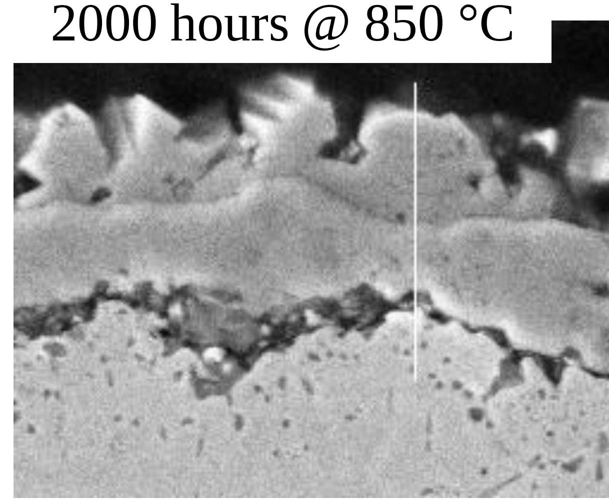
Cross Section Results - 1001

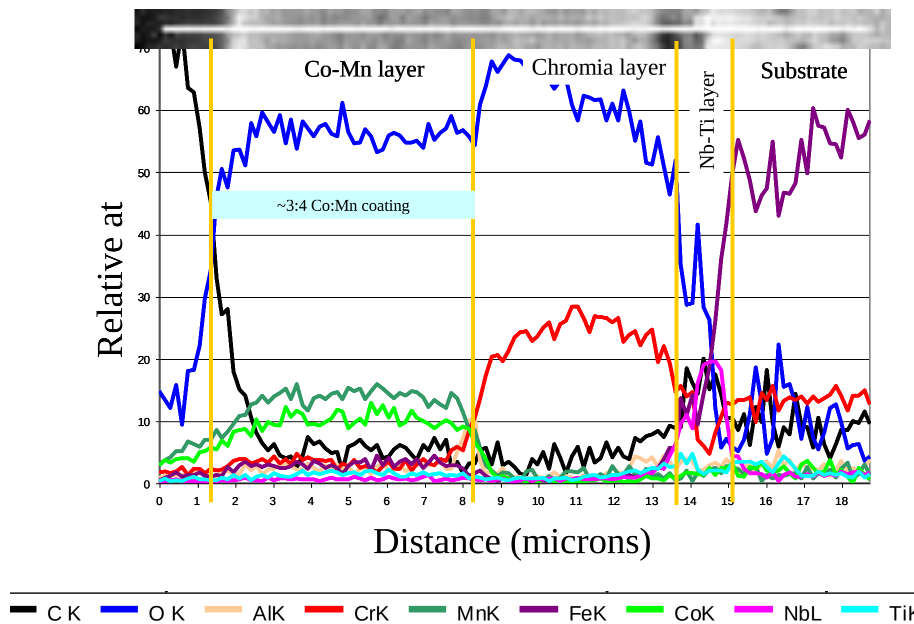
0 hours



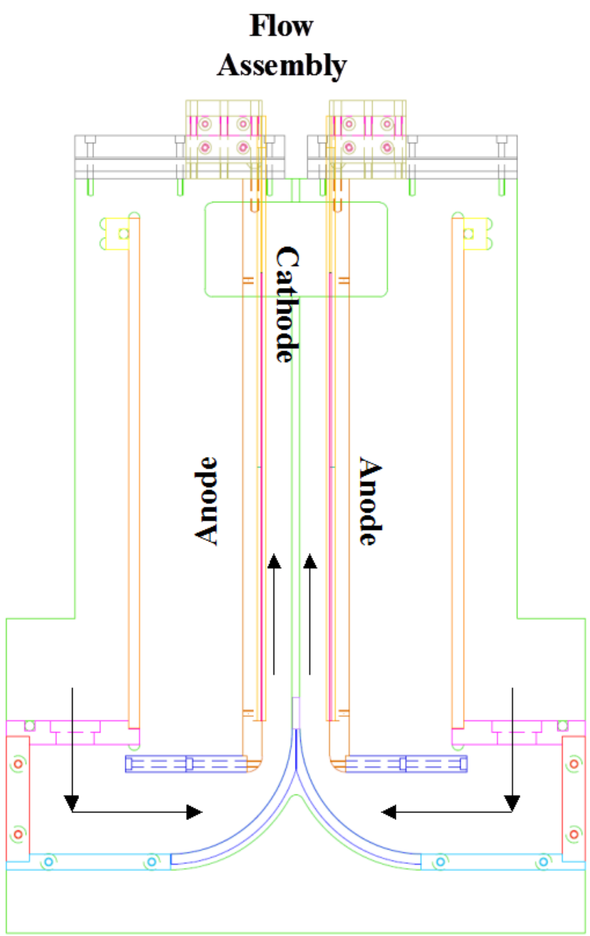


2000 hours @ 850 °C





Pilot Scale Electrodeposition Equipment

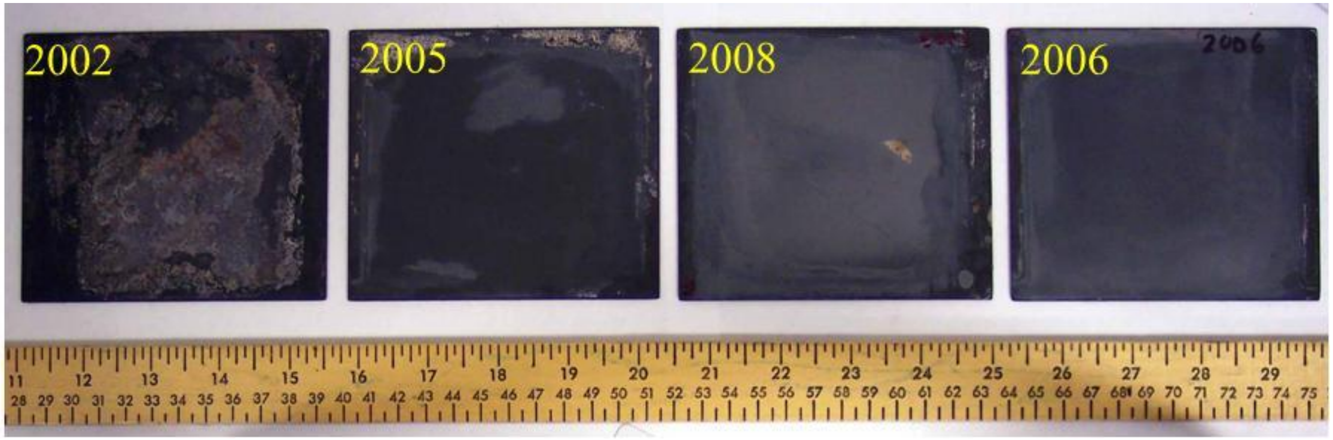


Based upon Faraday's electrochemical cell design that facilitates uniform flow across the surface of a flat substrate (US patent #7,553,401)

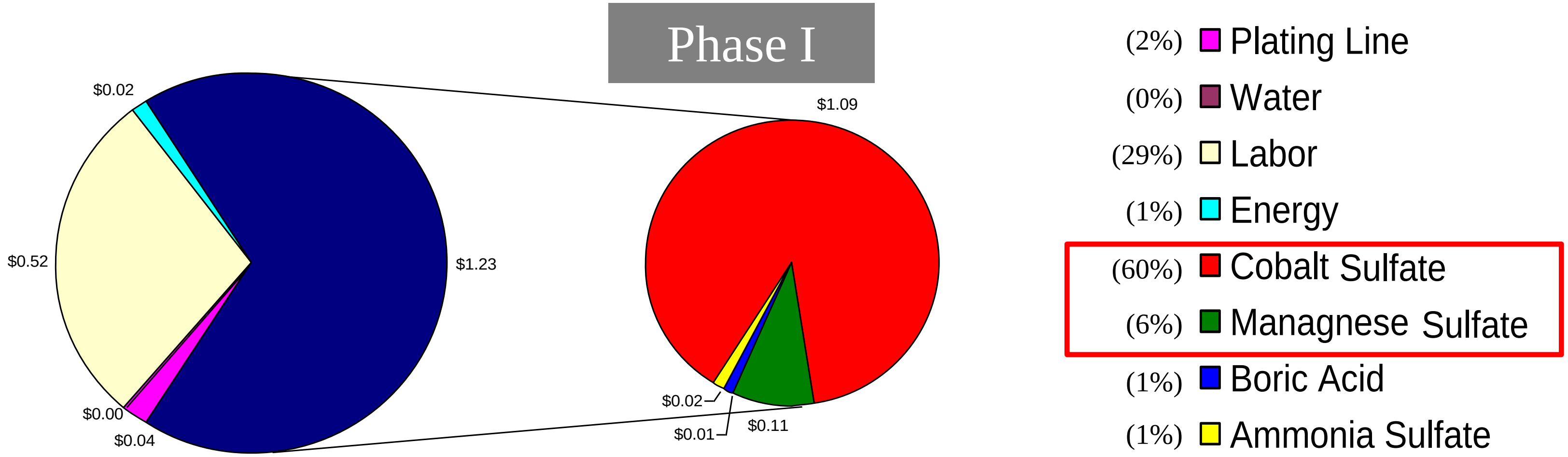
Initial Pilot Scale Experiments

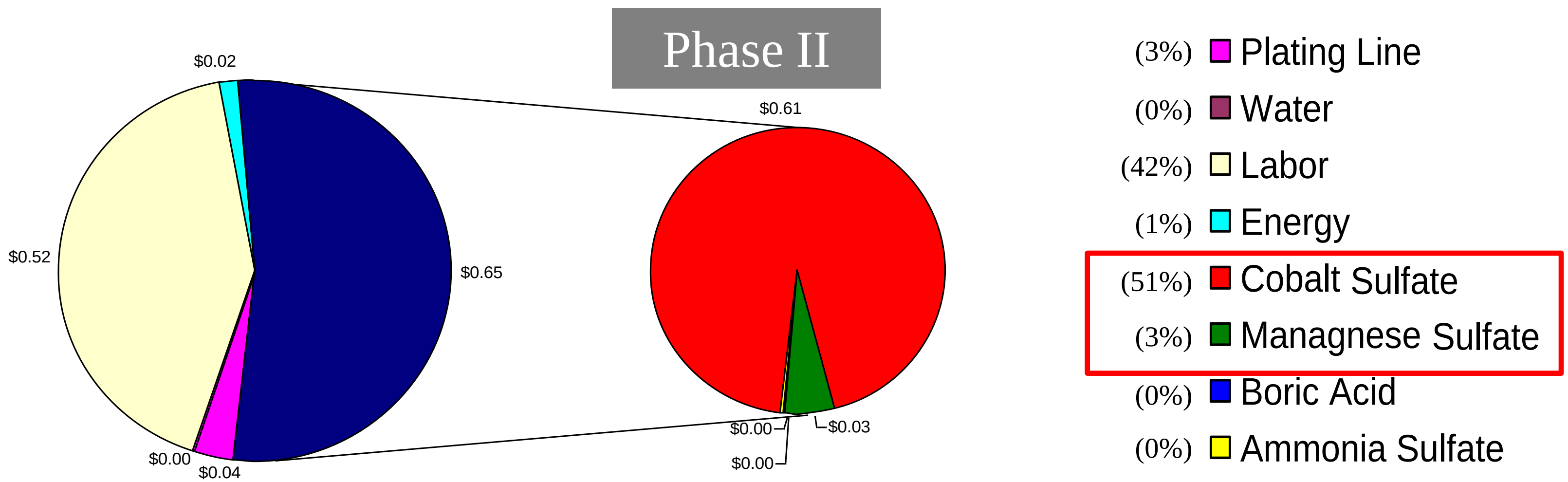
FARADAYIC Electrodeposition parameters varied for experiments conducted in the newly modified FARADAYIC Electrodeposition Cell

Trial No	Electrode Spacing (inches)	Electrolyte Flow (PSI)	Vibration	Oscillation
2001	3	16	-	-
2002	1.5	16	-	-
2003	4.5	16	-	-
2004	4.5	10	50	50
2005	4.5	16	50	50
2006	3	16	50	50
2008	3	5	50	50
2009	3	10	50	50



Electrodeposition Cost Analysis





High volume manufacturing of 1,600,000 plates per annum at a cost of ~$1.23 per 25 x 25 cm interconnect

Future Direction

- Determine plating parameters effect on chromium and oxygen diffusion
- Continue scale-up development for large area planar T441 substrates
- Begin scale-up development for large area pattern interconnects
  - Demonstrate coating uniformity and composition
- Testing in single cell and short stack SOFC systems

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Acknowledgments

- Briggs White and the entire SECA program management team

- This material is based upon work supported by the Department of Energy under Award Nos. DE-SC0001023 and DE-FE0006165. Any opinions, findings, conclusions and recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the DOE.

Thank You!

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