Electrodeposited Mn-Co Alloy Coating for SOFC Interconnects

H.A. McCrabb[1], B. Kagajwala[1] T.D. Hall[1], H. Zhang[2], X. Liu[2], S. Snyder[1] E.J. Taylor[1]

[1]Faraday Technology, Inc. 315 Huls Dr., Clayton, OH 45315
[2]West Virginia University, Dept. of Mechanical Aerospace Eng. ESB, Morgantown, WV 26506

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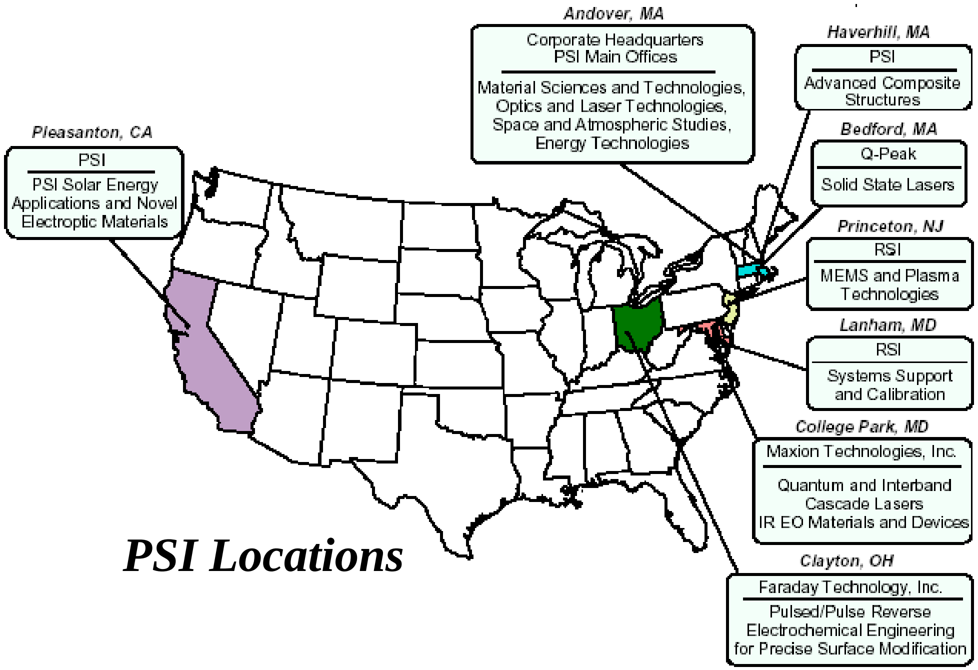
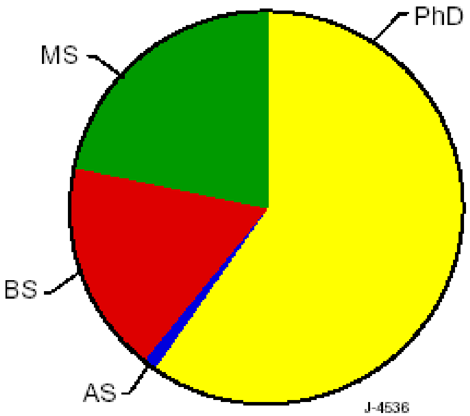
Faraday Technology, Inc.

- 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 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

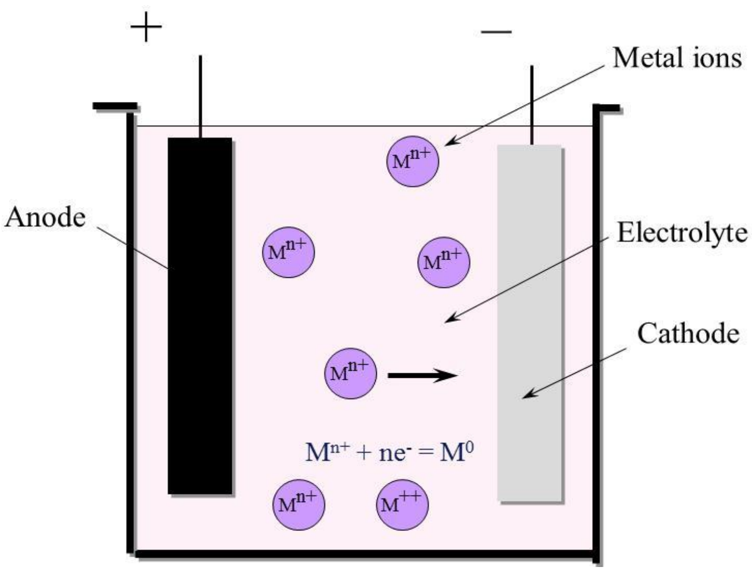
- Enables uniform processing
- Applicable for additive or subtractive electrochemical processes
- Uniform processing is achieved over entire substrate, improving end product reliability

Achievements

- Continued optimization of FARADAYIC^{SM} Electrodeposition Process parameters in order to optimize coating thickness, coating composition and coating adhesion
- Improved coating uniformity across T441 planar interconnects at the 100 cm^2 scale
- Demonstrated coating process for 25 cm^2 430 stainless steel interconnect containing gas flow fields
- Continued refinement of economic analysis to assess economic viability of FARADAYIC^{SM} Electrodeposition Process for high volume batch manufacturing

FARADAYIC℠ Processing

Conventional (DC) Electrodeposition



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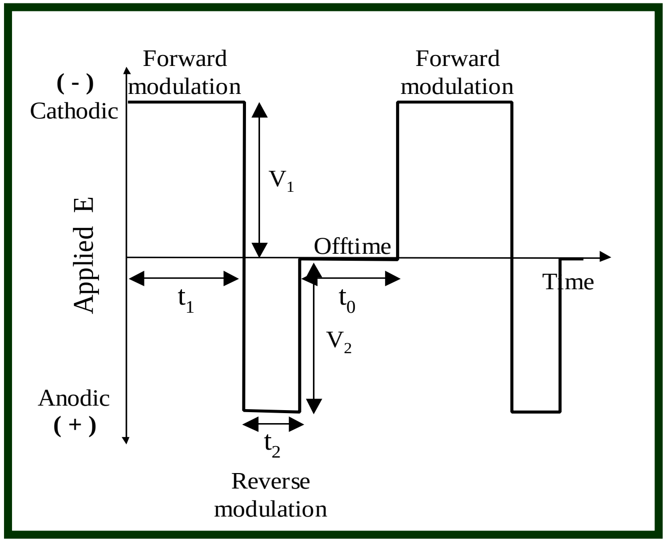
FARADAYIC℠ Process

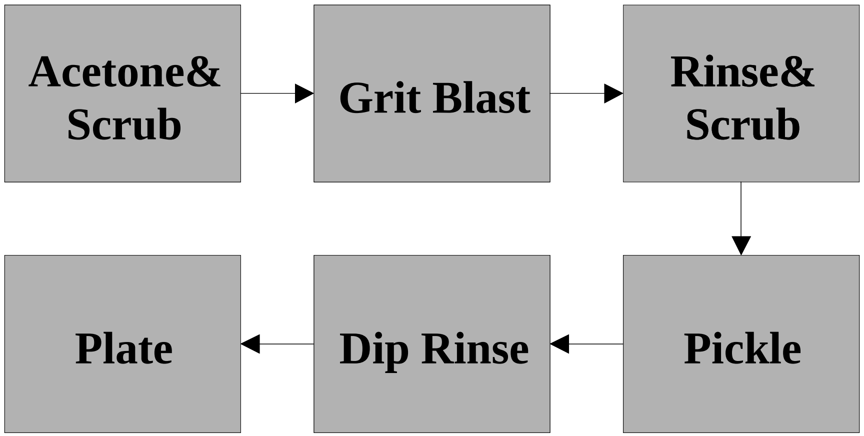


- Fast deposition rates
- Simple deposition equipment
- Non-line-of-sight deposition
- Industrially scalable

- Improved electric field control
  - Enhanced control of coating thickness uniformity
  - Enhanced control of alloy composition
- Improved coating of "hidden surfaces"

Coating Process

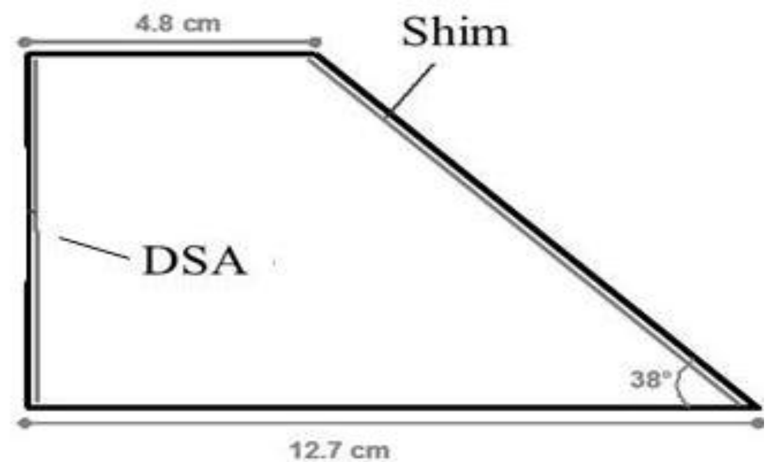
- Surface pretreatment to remove oxide and enhance coating adhesion
- Electrodeposition to coat interconnects with Mn-Co alloy
  - Pulse and pulse reverse electric fields to control deposit properties
- Elevated thermal treatment to convert alloy to spinel



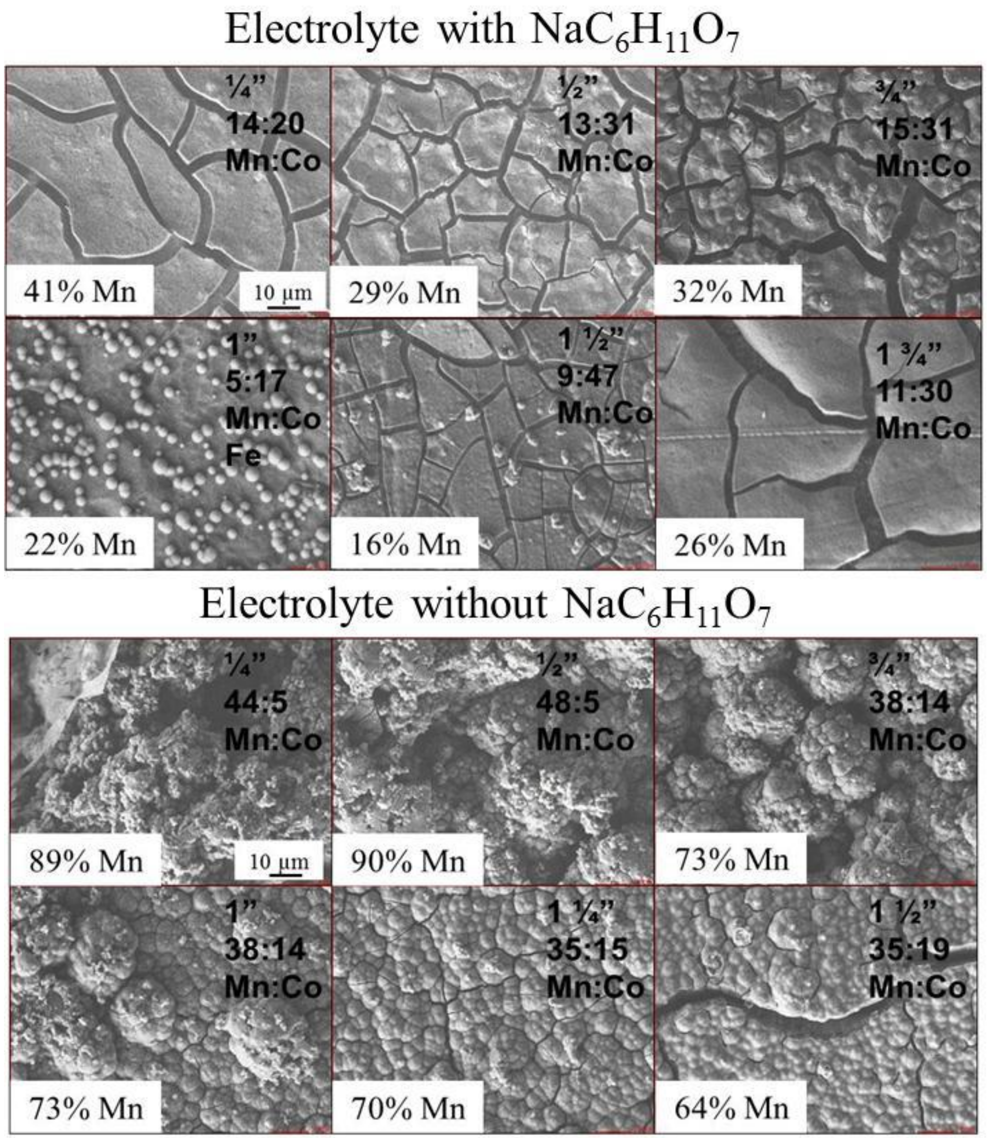
Phase I Hull Cell Experiments

Enables investigation into the effect of various parameters on deposit properties during a single experiment

- Current density
- Temperature
- Electrolyte composition
- Additives

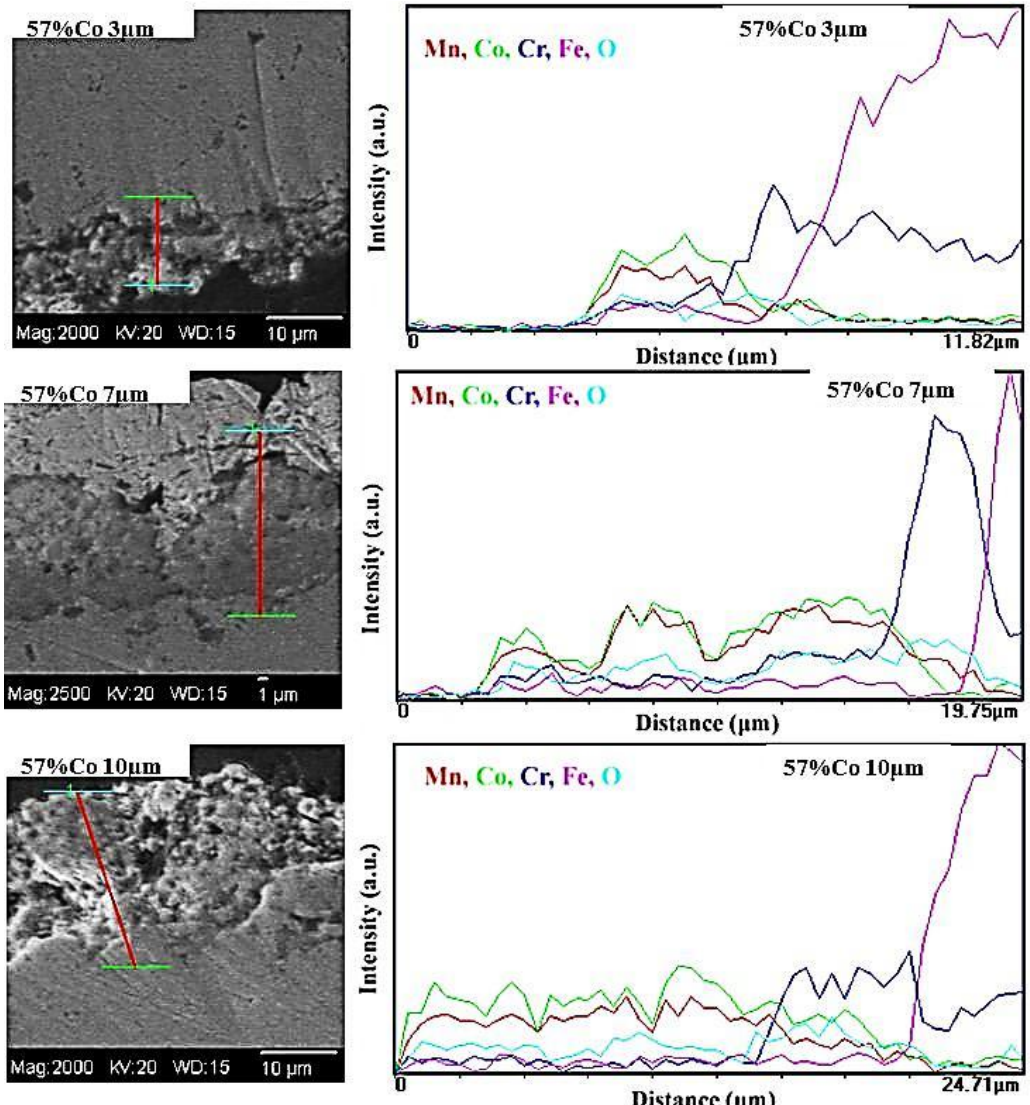


Phase I Hull Cell Experiments



- Electrolyte without $NaC_6H_{11}O_7$ was selected for Phase I work on 5 cm x 5 cm T441 planar substrates because at reasonable current densities and metal ion concentrations results suggested
  - Potential for higher Mn content in coating
  - Less microcracking
  - Higher current efficiency
    - Faster coating deposition rates

Phase I Cr Diffusion and Coating Porosity



Coating surface Substrate

- Cross-sections of samples that underwent a soak treatment at 800 C for 500 hrs.
  - Coating thickness was as deposited
  - Indicates that the 3 micron layer has low Cr diffusion and the 10 micron coating has negligible Cr diffusion into coating
  - 3 micron coating appears more porous than 7 and 10 micron film

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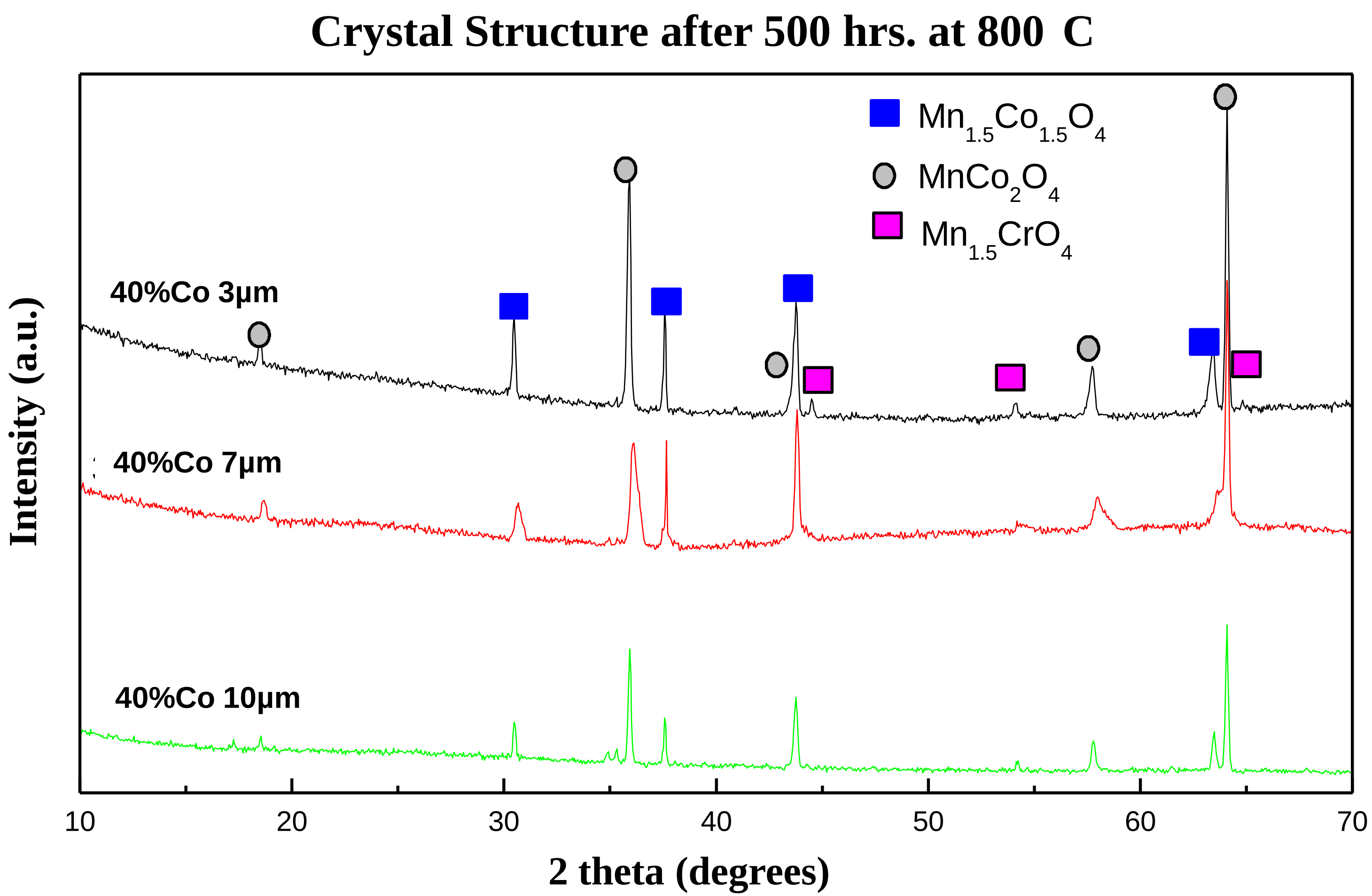
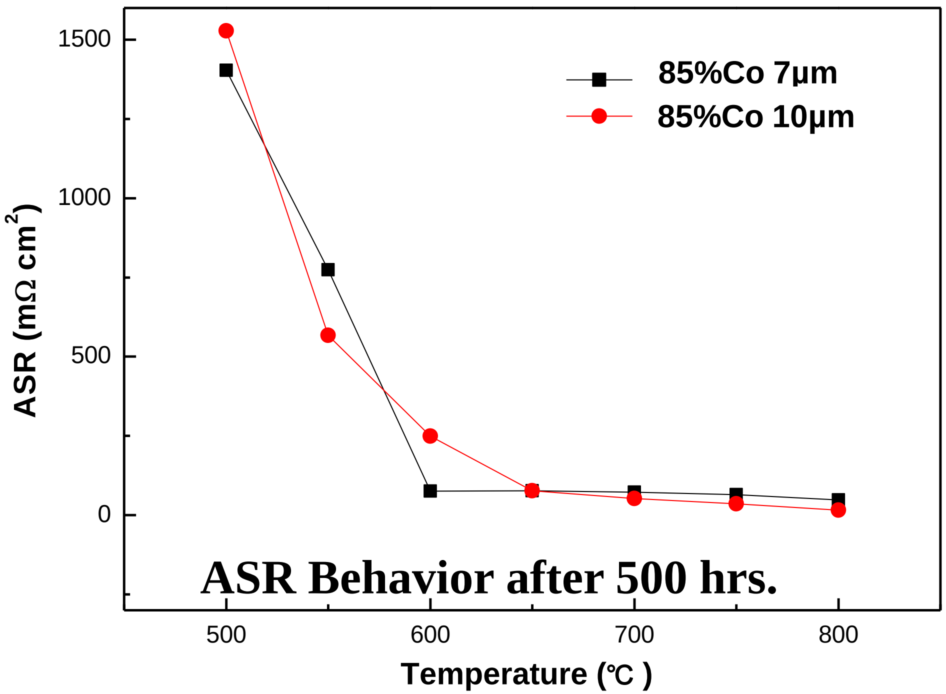
Phase I Coating Crystal Structure



Phase I Effect of Thickness and Composition on Performance

The ASR is ≤ 60 mΩ cm^2 in most cases regardless of compositions and thickness after 500 hrs. at 800 C



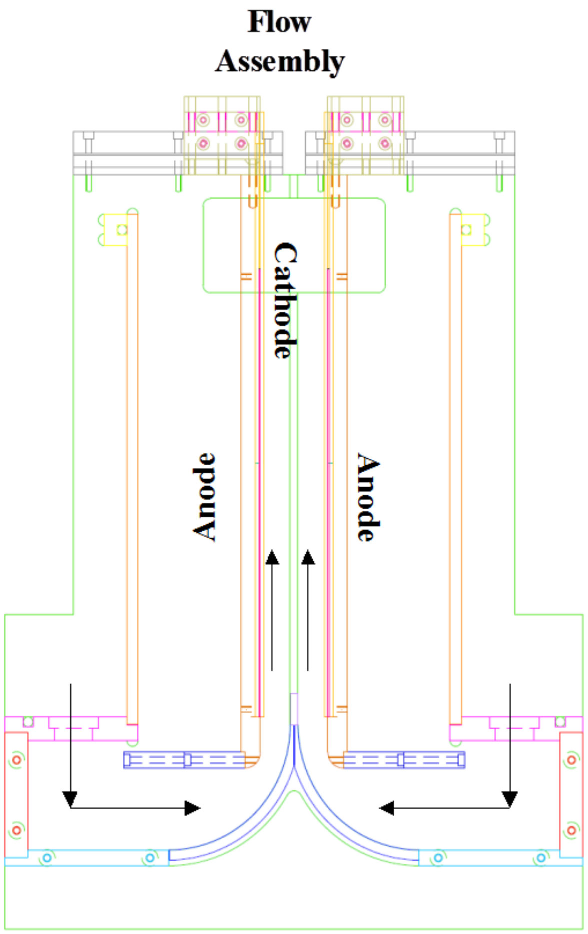
ASR at 800 C

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

Phase III Program Management Plan

Milestones			
Fiscal Year	***Title***	***Planned Completion***	***Percent Complete***
2011	1. Design/modification of 10” x 10” electrodeposition cell	May 2011	100%
2012	2. Long-term high temperature, thermal evaluation	August 2012	70%
2012	3. Process development for 4”x4” planar interconnects	May 2012	100%
2012	4. Process development for 4”x4” pattern interconnects	June 2012	10%
2012	5. Long-term on-cell performance evaluation	August 2012	10%
2012	6. Qualification/demonstration of IC in single cell test rig	September 2012	0%

Pilot Scale Electrodeposition Equipment



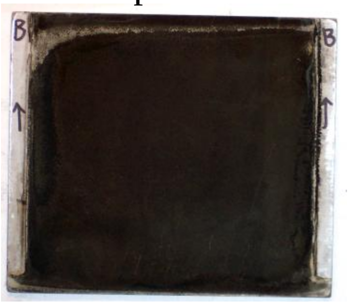
Based upon Faraday's electrochemical cell design that facilitates uniform flow across the surface of a flat substrate (US patent #7,553,401)

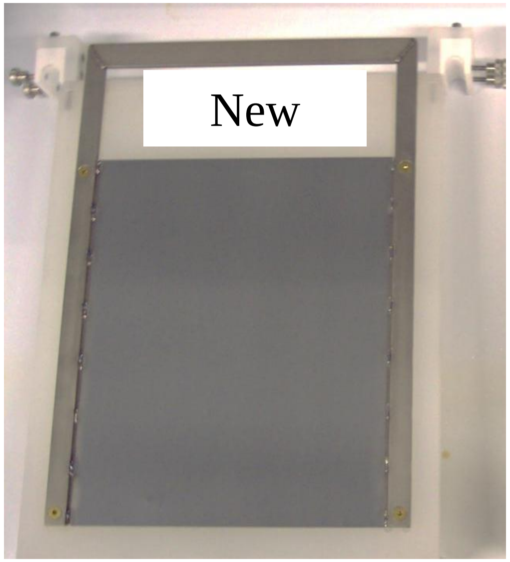
Pilot Scale Experiments

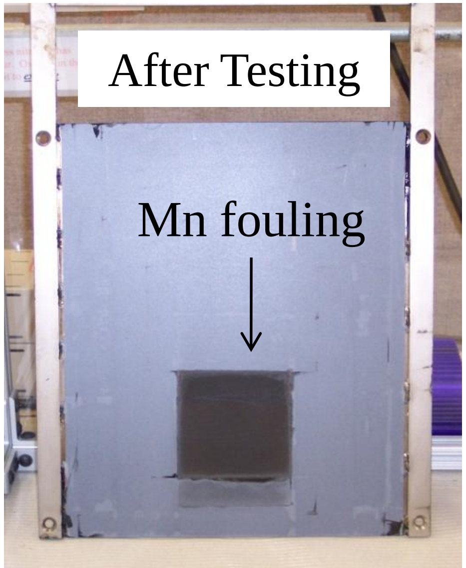
- After several tests, issues were noticed with coatings
  - Non-uniform current density on front and back of sample during plating
    - Poor chemical composition control
    - Coating thickness non-uniformity
  - Poor coating adhesion
- Anodes removed from system
  - Mn fouling
    - High surface resistivity
      - In the megaohm range after only a few tests
    - Can be removed with 30% (v/v) sulfuric acid

Sample Front

Sample Back

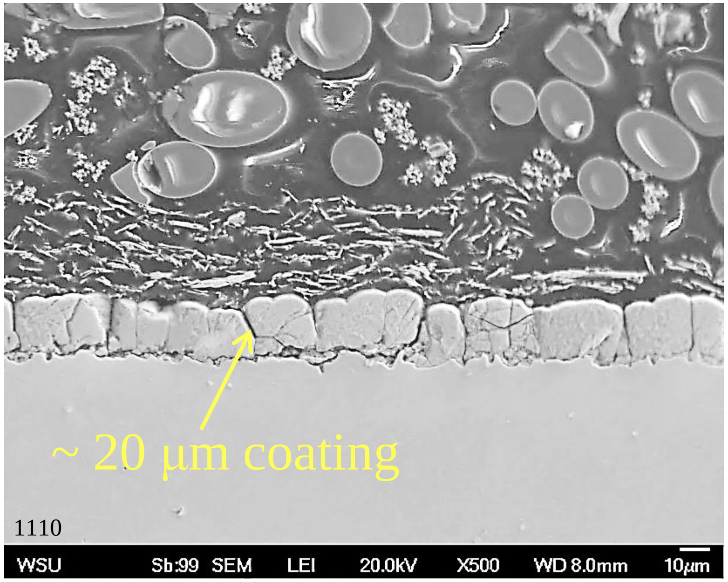


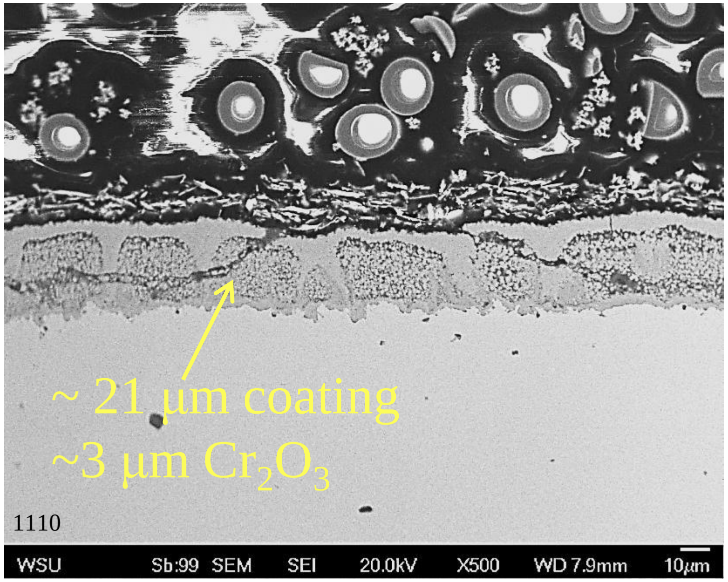




$NaC_6H_{11}O_7$ Electrolyte Revisited

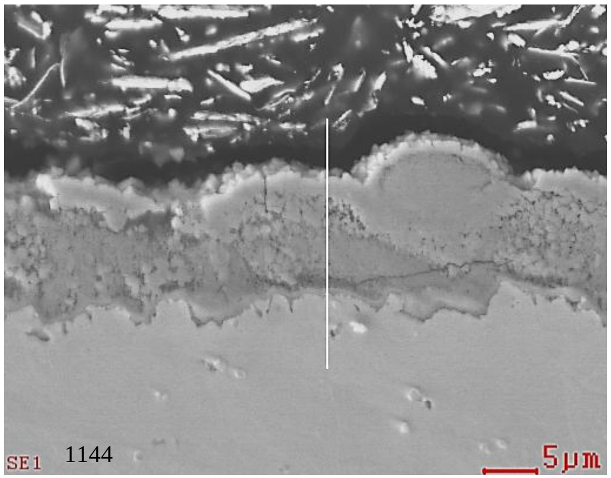
- Addition of $NaC_6H_{11}O_7$ to electrolyte
  - Observed benefits
    - Boric acid dissolves completely
    - Complexing metal ions prevents hydroxide formation
    - Improved buffer capacity
    - Anode fouling eliminated
    - Improved coating adhesion in as-deposited state
    - Coating deposition rate appears linear
    - Maintain coating thickness upon spinel conversion

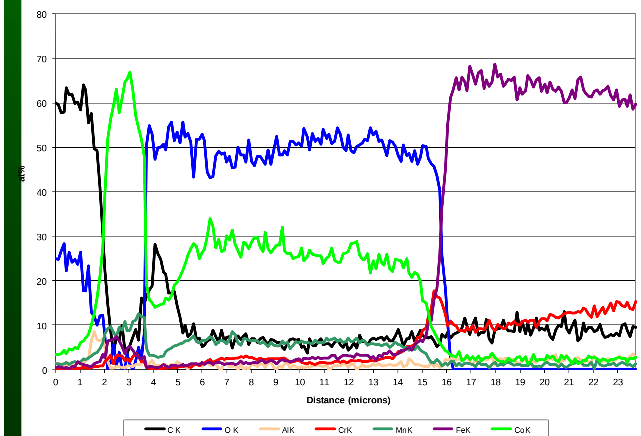




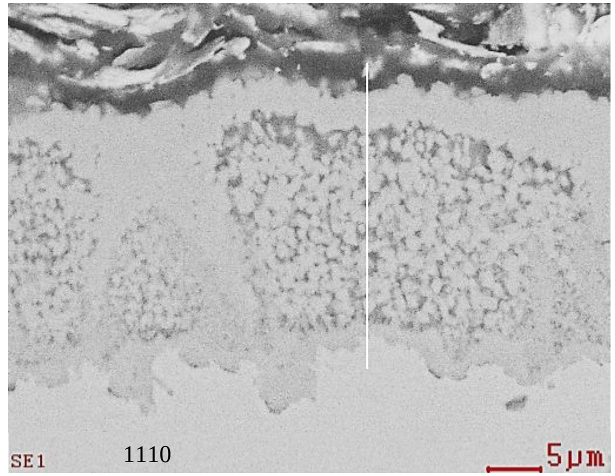
Varying Coating Thickness

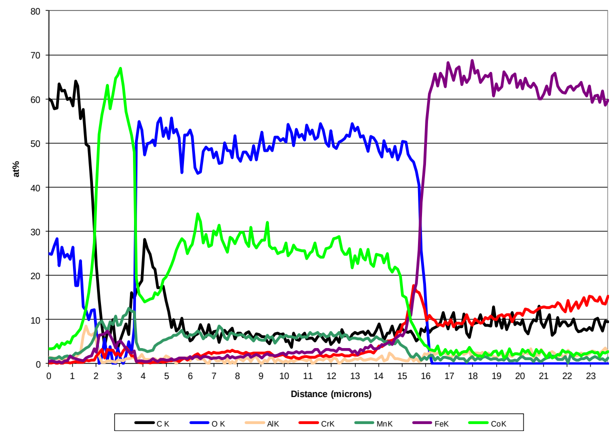
~ 10 μm coating
~ 2 μm Cr_2O_3



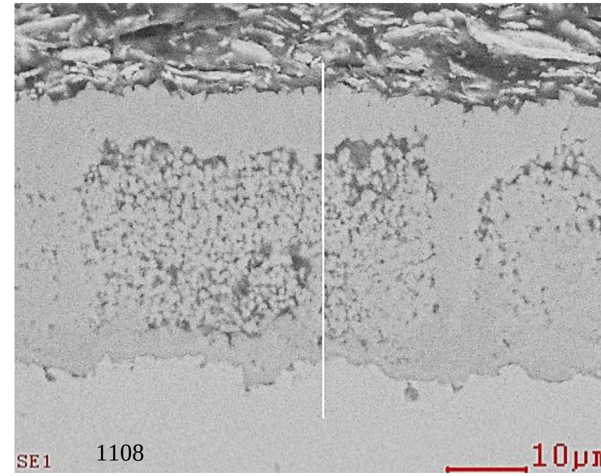


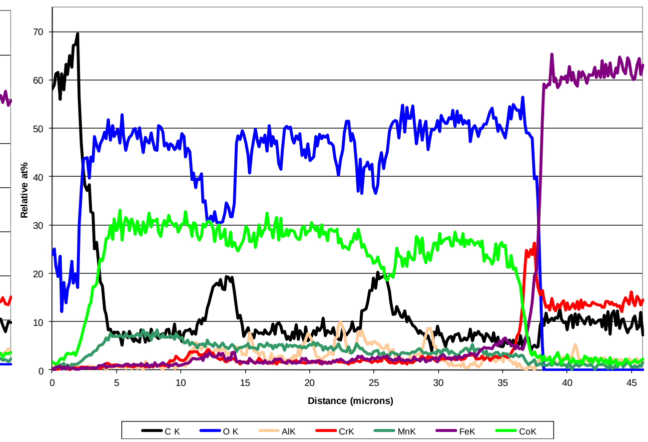
~ 21μm coating
~ 3 μm Cr_2O_3





~ 33 μm coating
~ 3 μm Cr_2O_3





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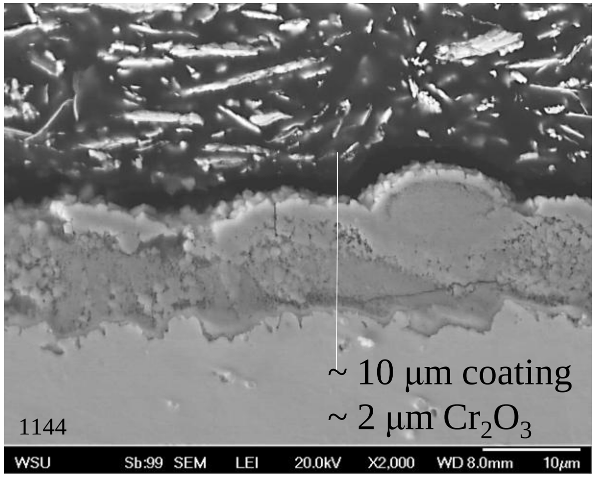
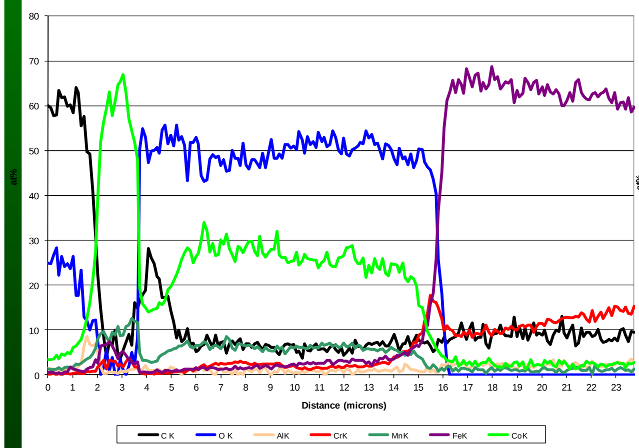
Varying Cobalt Concentration

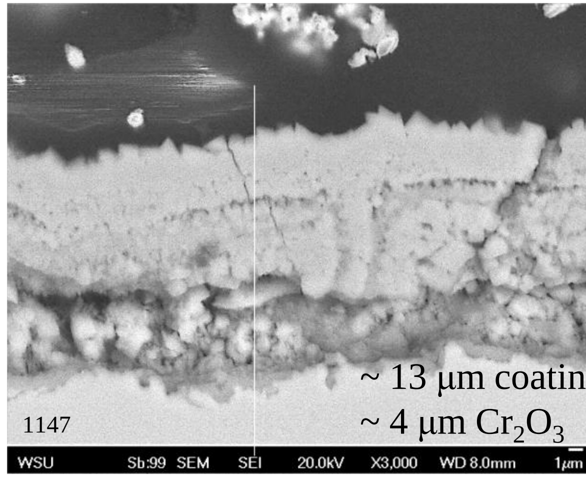
4:1 Co:Mn

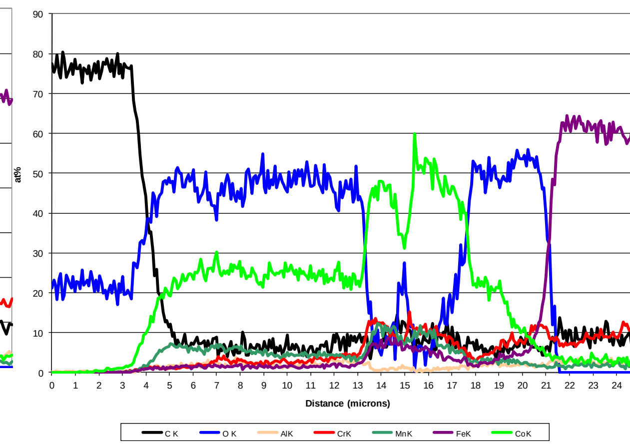




- Minor Cr diffusion
- Minor Fe diffusion

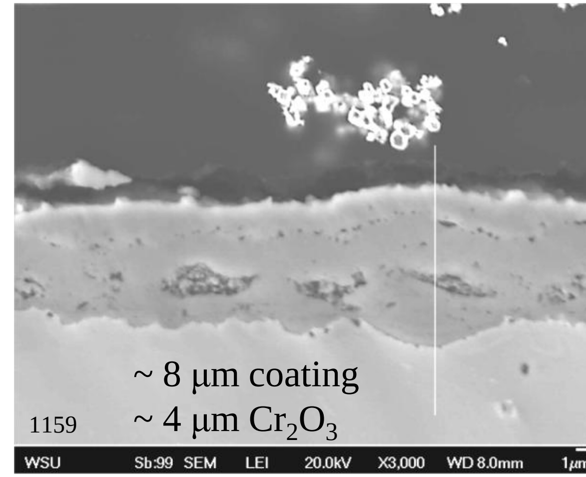
6:1 Co:Mn

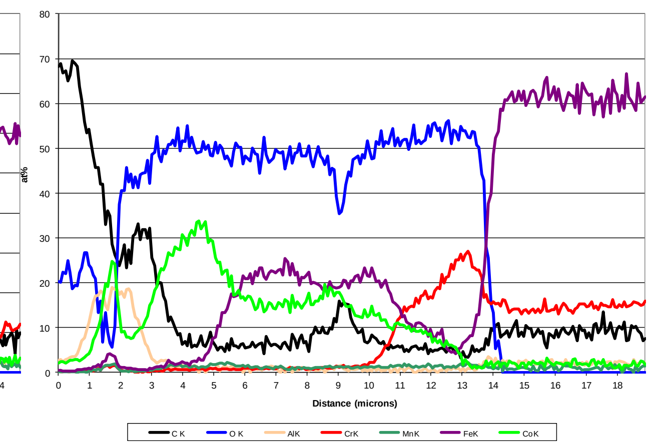




- Minor Cr diffusion
- Some Fe diffusion

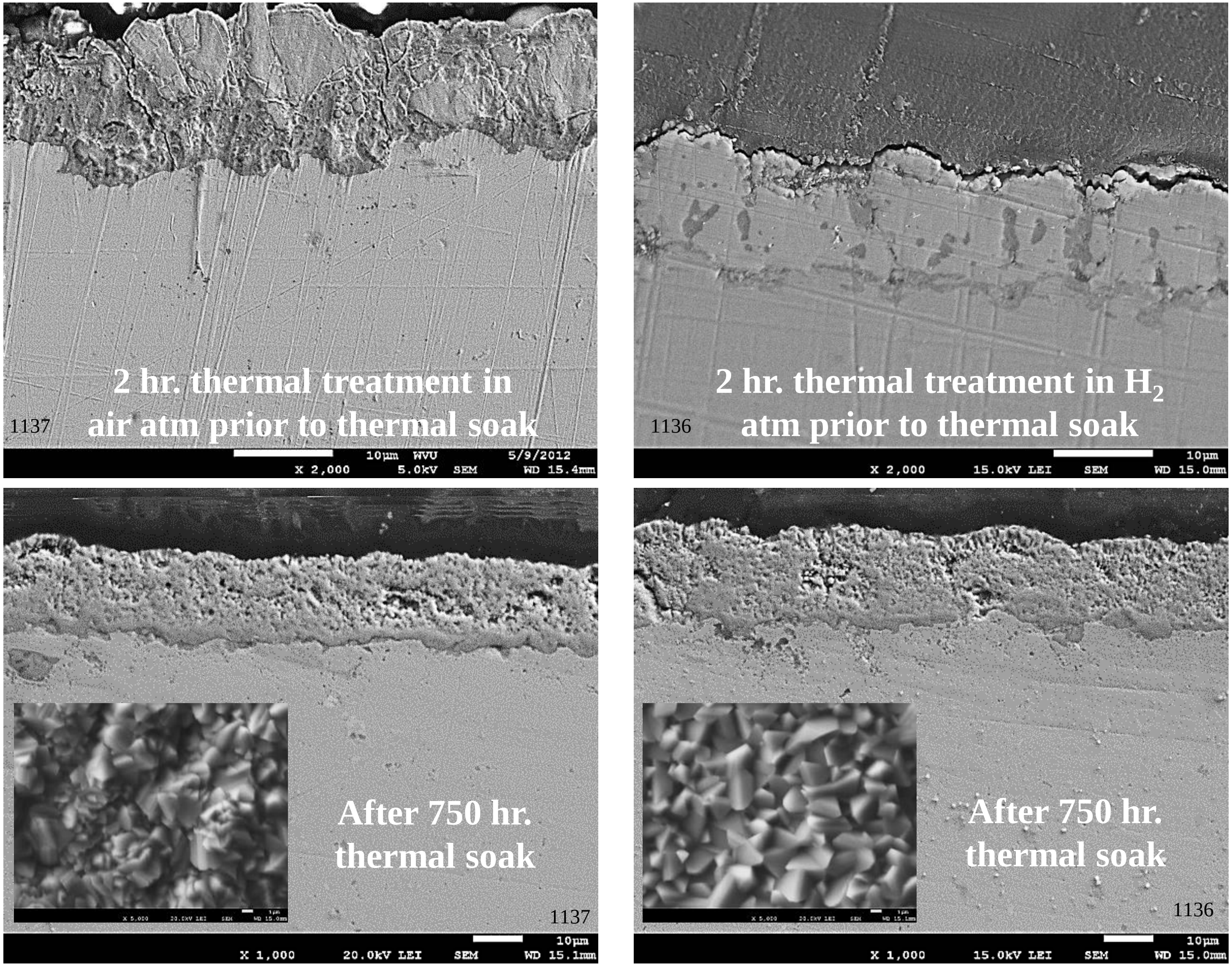
20:1 Co:Mn





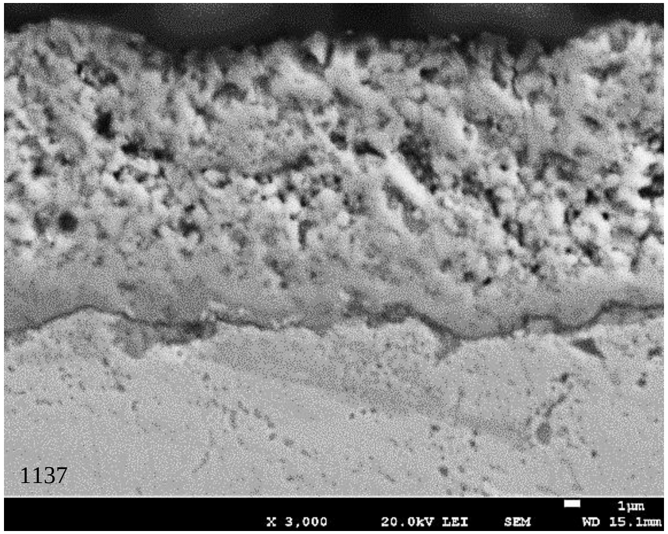
- Negligible Cr diffusion
- Fairly significant Fe diffusion

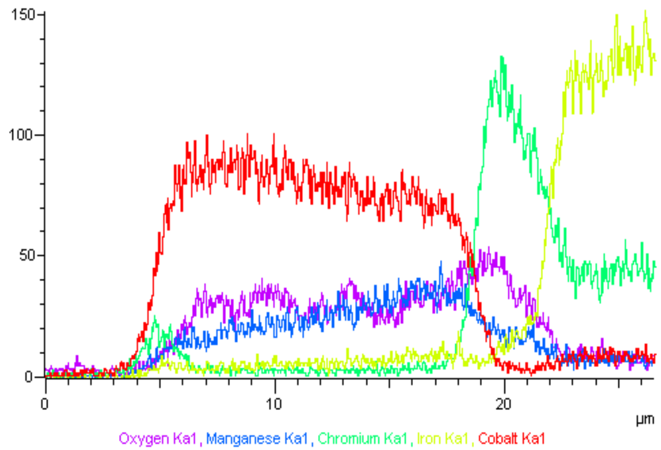
750 Hour Thermal Soak at 800 ℃



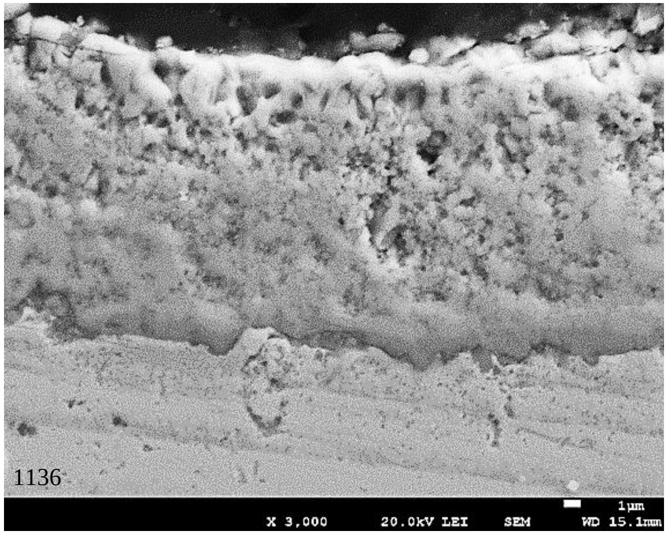
750 Hour Thermal Soak at 800 ℃

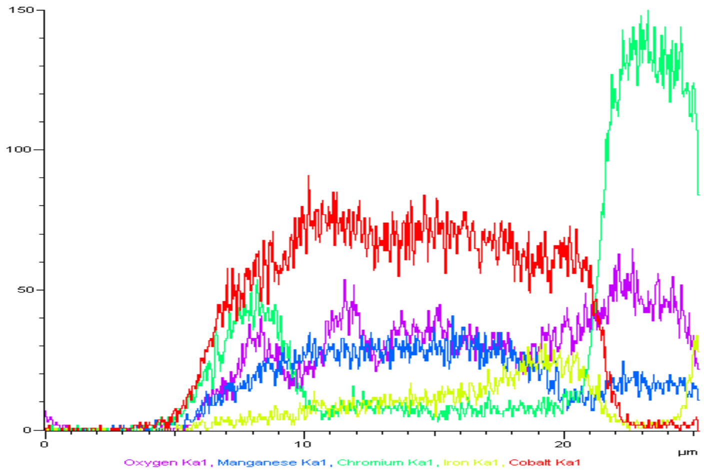
2 hr. thermal treatment in air atm prior to thermal soak





2 hr. thermal treatment in H_2 atm prior to thermal soak





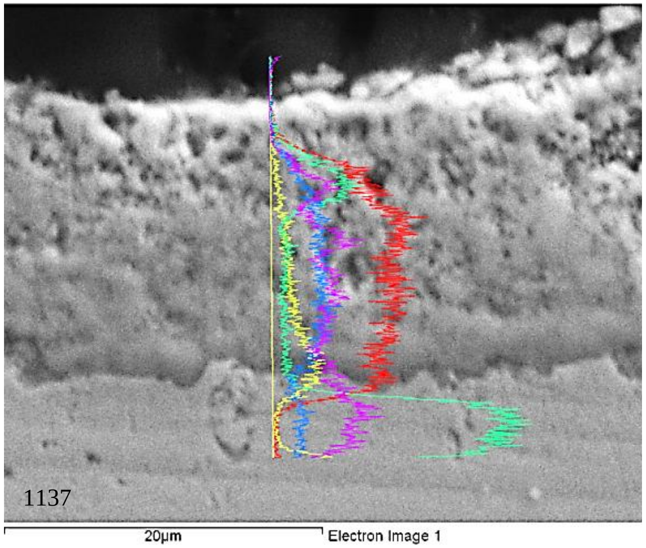
750 Hour Thermal Soak Testing

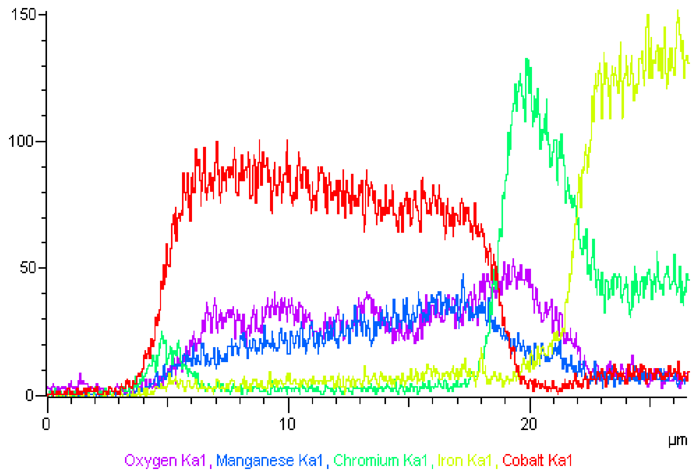
The ASR is ≤ 20 mΩ cm^2 after 750 hrs. at 800 C

	Sample No.	Thickness (µm)	Atomic%		ASR (mΩ·cm^2)
			Co	Mn	
H_2 atm exposure for 2 hours followed by thermal soak for 750 h	1132	7.5	89	11	13.3
	1134	10	91	9	16.7
	1136	13	92	8	9.6
Air atm exposure for 2 hours followed by thermal soak for 750 h	1133	12	85	15	13.0
	1135	11	85	15	19.5
	1137	14	85	15	13.8

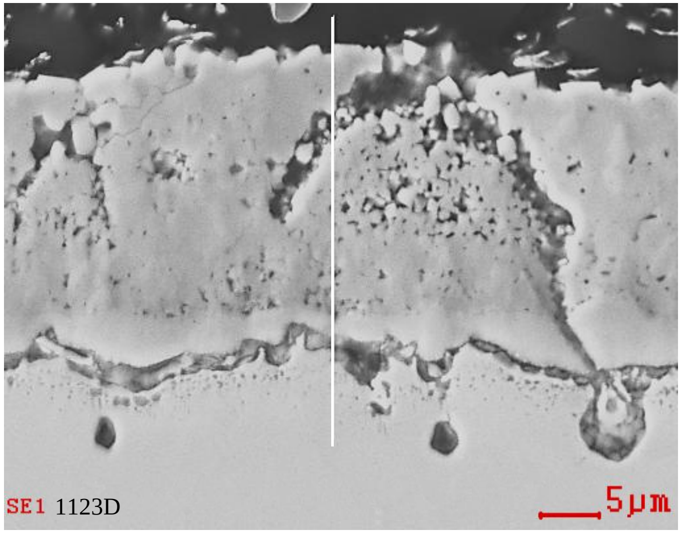
750 Hour Thermal Soak

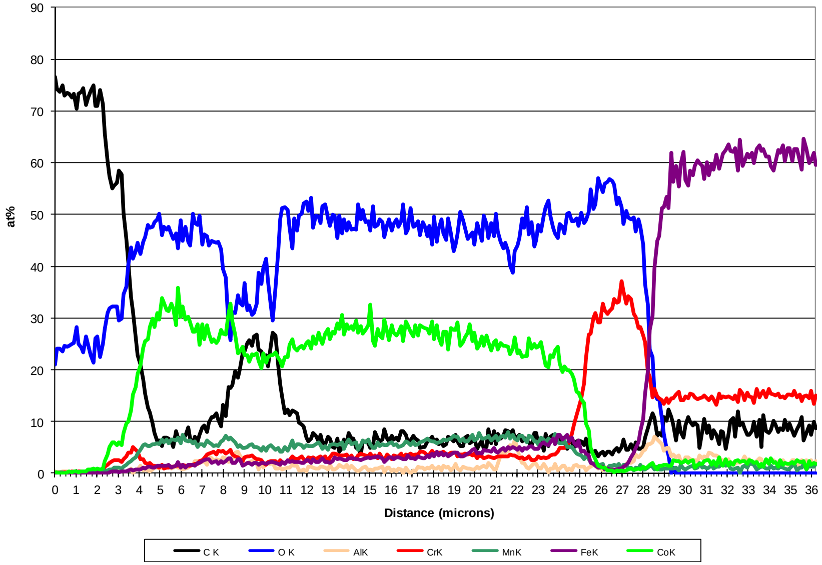
800 °C





850 °C



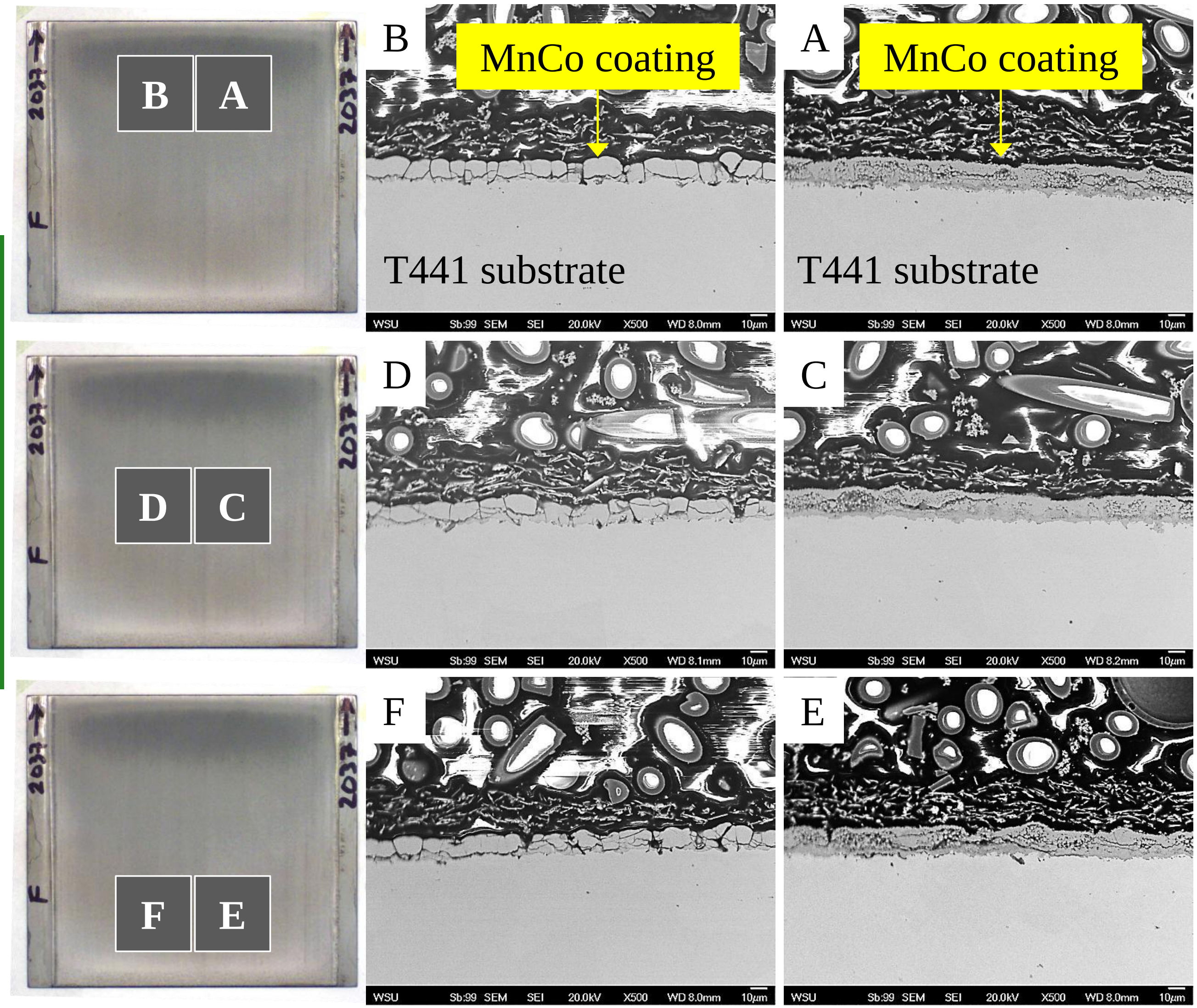


Process Scale-up from 25 cm^2 to 100 cm^2

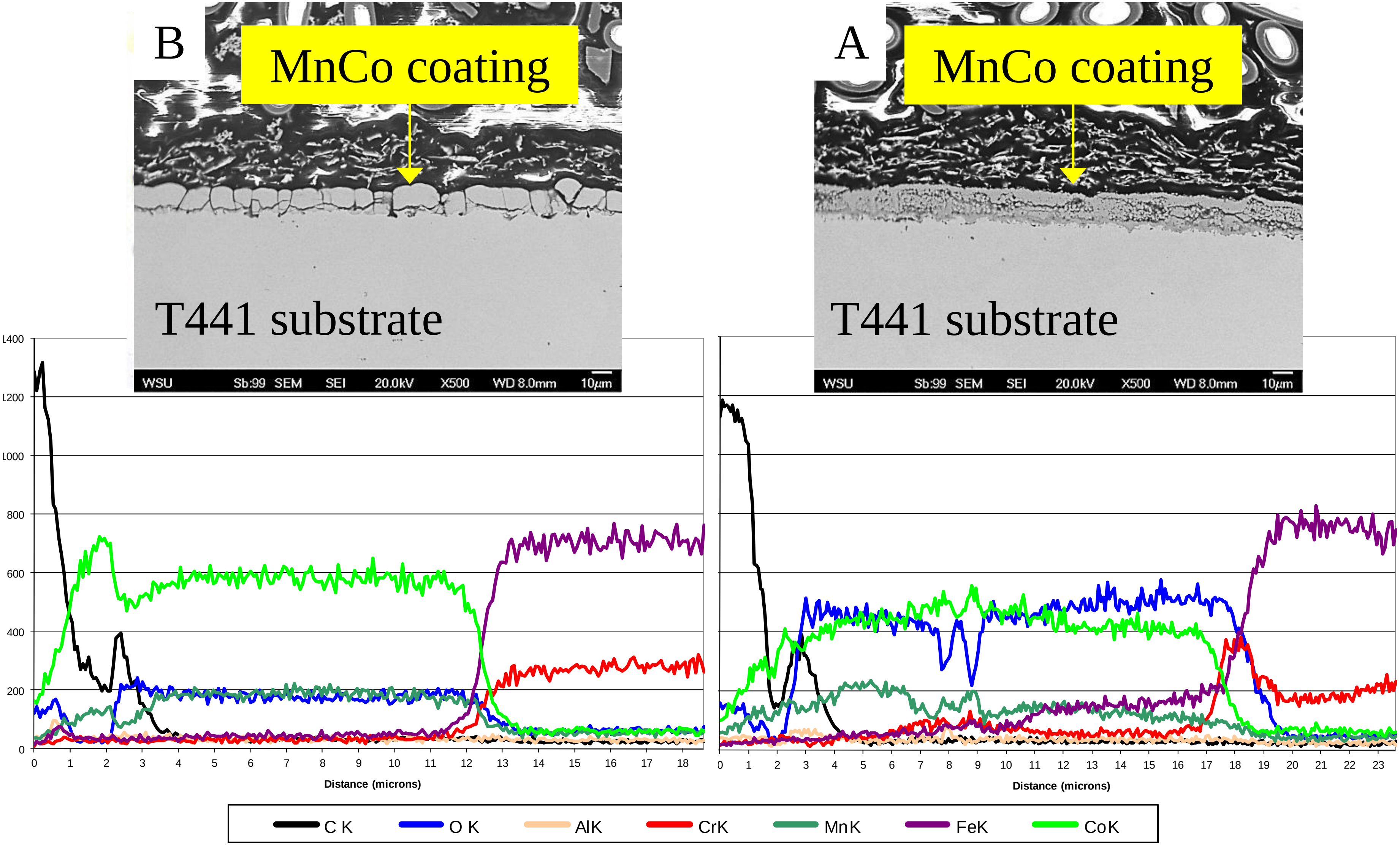
Coating thickness and compositional uniformity at the 100 cm^2 scale

- 6:1 Co:Mn
- ~ 12 μm coating
- ~4 μm Cr_2O_3 scale

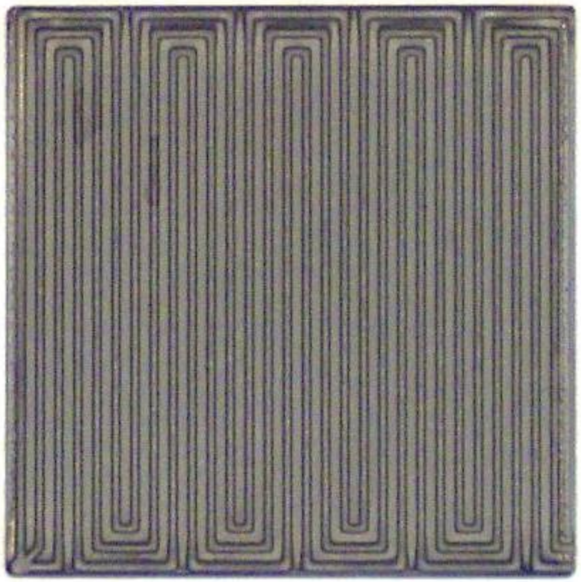
As-deposited | Post-thermal treatment

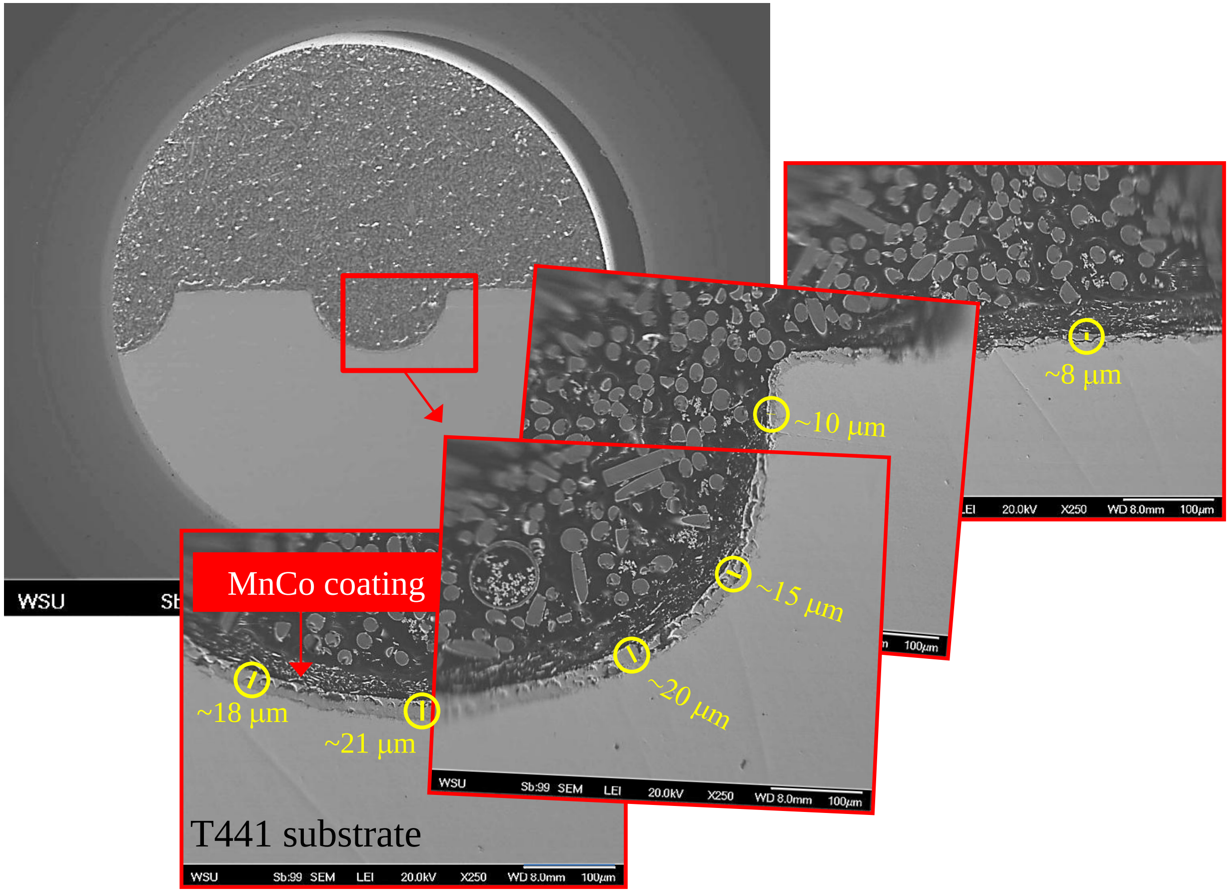


Process Scale-up from 25 cm^2 to 100 cm^2



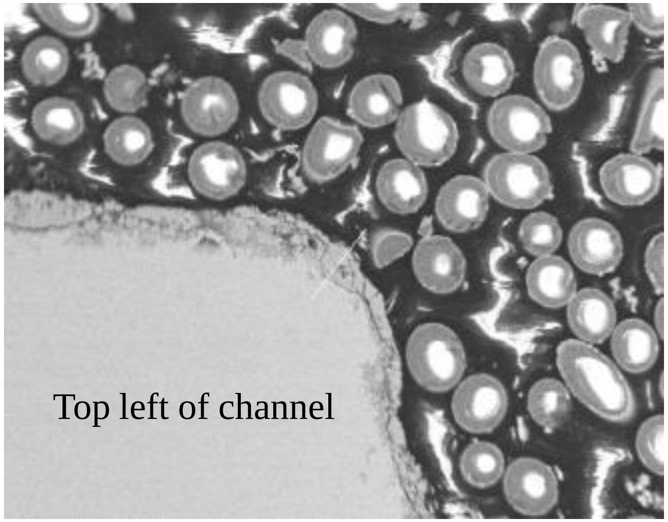
25 cm² 430 Stainless Steel Interconnect With Gas Flow Fields

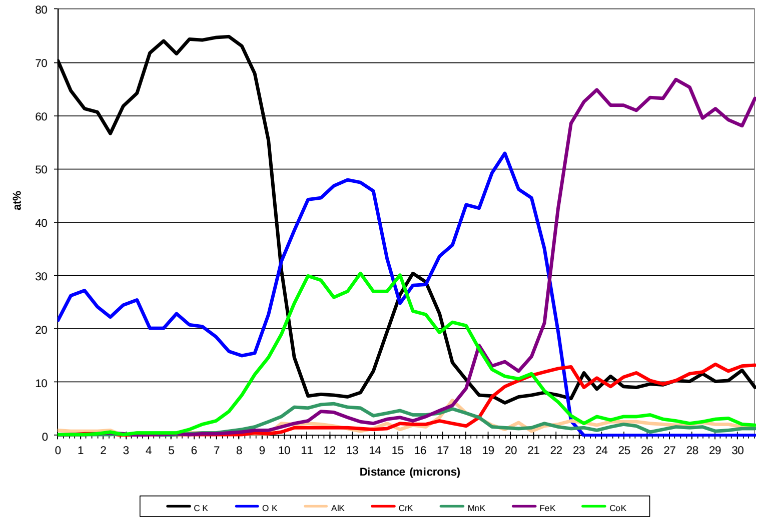


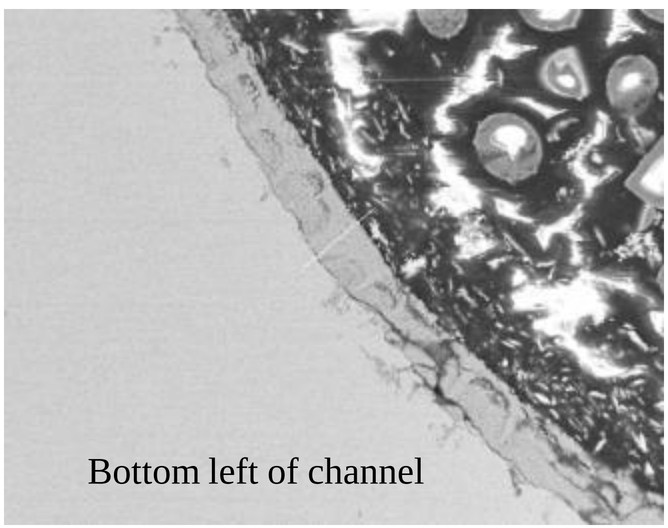


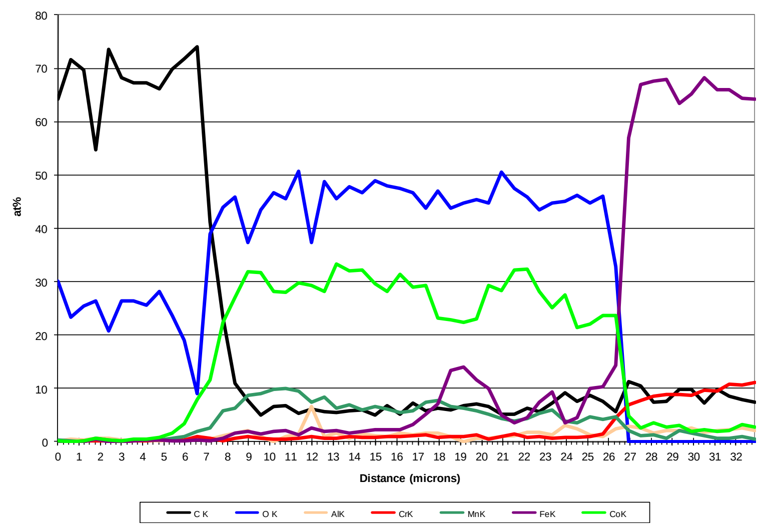
- 3 channel serpentine pattern
- Channel width ~ 0.9 mm
- Rib width ~ 0.8 mm
- Channel depth ~ 0.45 mm

25 cm² 430 SS Interconnect With Gas Flow Fields

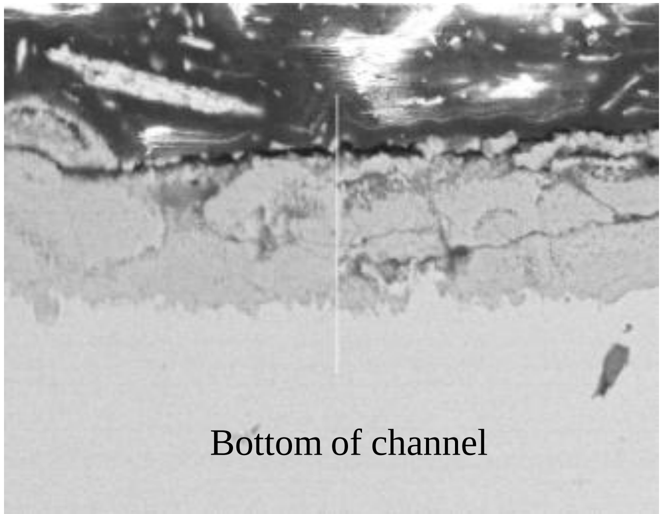


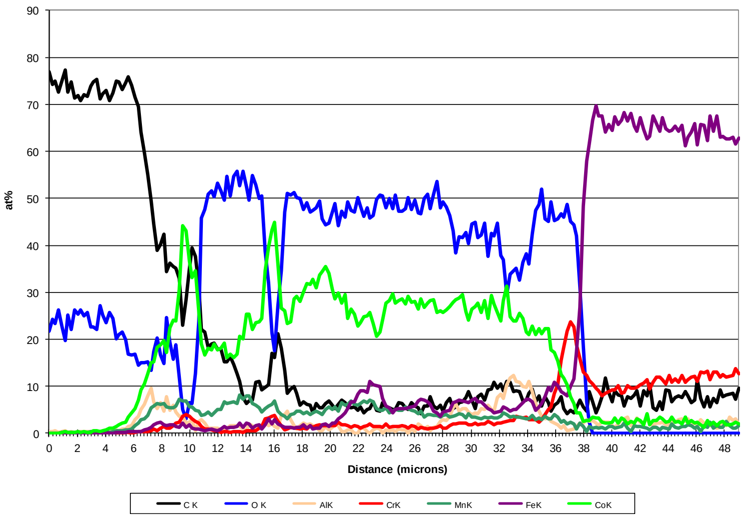


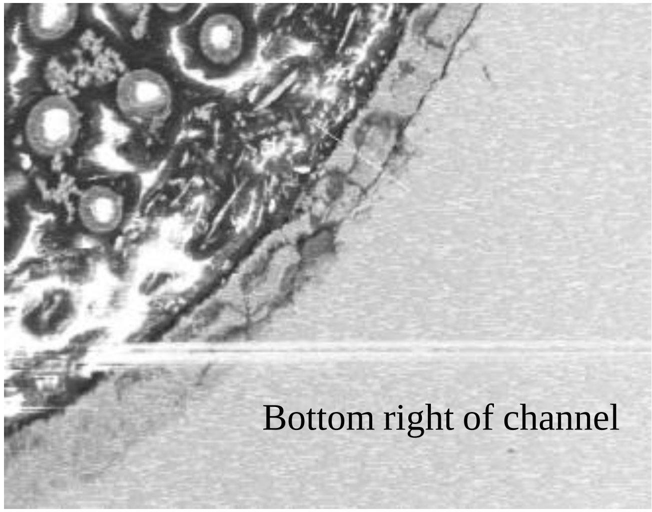


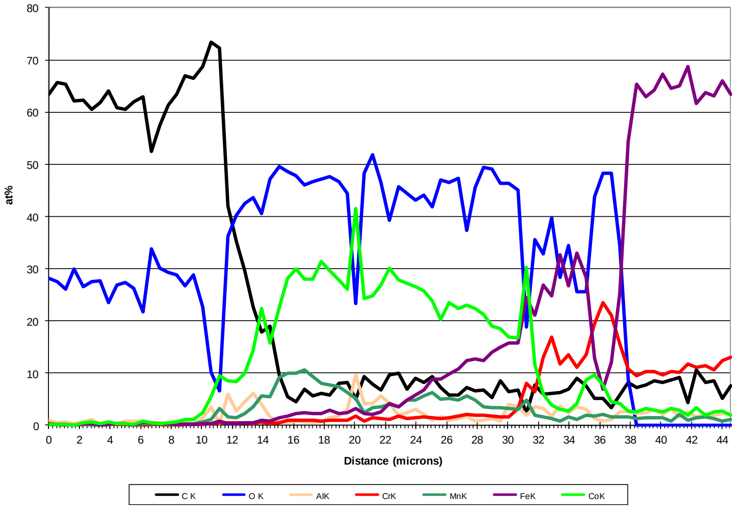


25 cm² 430 SS Interconnect With Gas Flow Fields









Future Work

- Complete thermal soak to 2000 hours for existing samples
- Development, optimization and validation of the FARADAYIC[SM] Electrodeposition Process for 100 cm^2 interconnects with gas flow field features
- Long-term on-cell performance evaluation of button cells
- Qualification/Demonstration of Interconnect Coating in Single Cell Test Rig under ideal SOFC operating conditions by potential commercial partners
- Continued development of a more comprehensive economic assessment of the electrodeposition coating process as it relates to interconnect manufacturing.

Acknowledgments

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- Contact Information:

  Heather McCrabb

  Ph: 937-836-7749

  Email: heathermccrabb@faradaytechnology.com

Thank You!