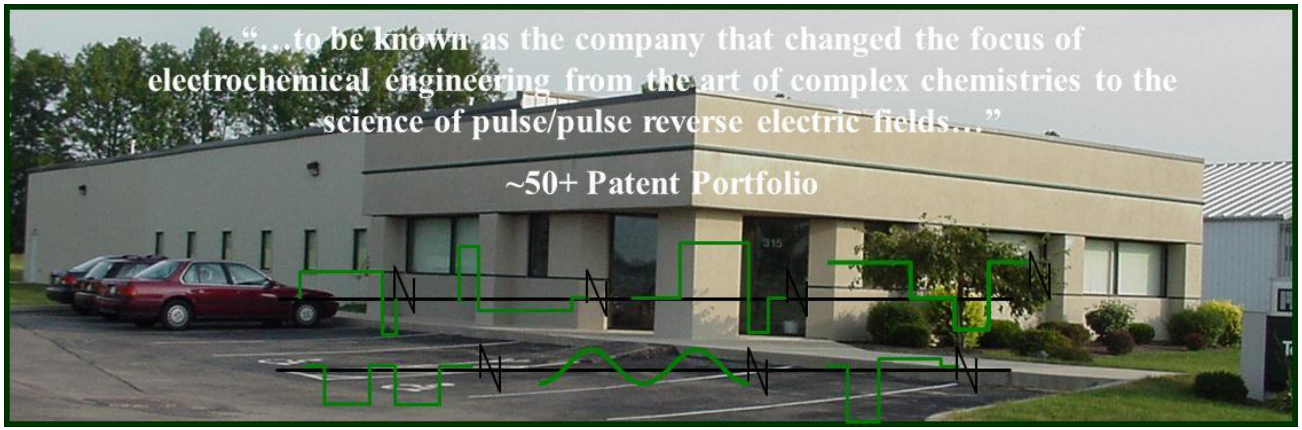
FARADAY TECHNOLOGY, INC.

Electrolyte Maintenance Technology Platform: Applying Learning Across Electrochemical Machining and Stripping Processes



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Perspective

- ***Starting from scratch for every development activity is time- and resource-consuming***
- Effective R&D applies lessons learned from one project to another
- Expands commercialization potential
- Technology platform of pulse-reverse waveforms combined with unique cell designs

Industrial Electrolyte Management

- Electrolyte management is ***critical*** to avoid excess costs associated with replacement and waste disposal.

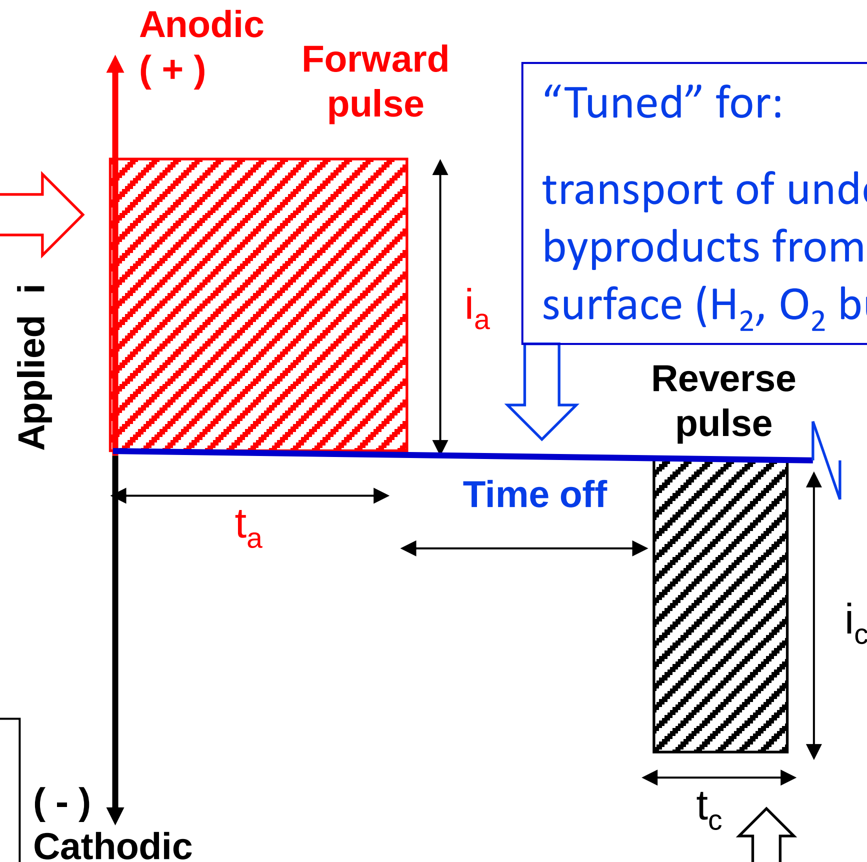
- Faraday is developing electrolyte management technologies :
  1. ***Recycling Electrochemical Machining ((R)ECM)*** to enable a zero-discharge process,
  2. ***Stripping/Recycling*** of the components of a ***High Velocity Oxy-Fuel (HVOF)*** coating, and
  3. ***Chrome Stripping*** that does not form hexavalent chromium.

- Lessons learned in each project are applied to the other projects to accelerate and enhance the chance of success.

Basis of Technologies: Pulse Reverse Waveforms

"Tuned" to:

- ✓ Machine/Strip coating
- ✓ Control speciation
- ✓ Enhance mass transfer
- ✓ Control current distribution



"Tuned" for:

transport of undesirable byproducts from electrode surface (H_2, O_2 bubbles, heat)

Provides fundamental guidance
NOT
Predictive theoretical model

Cathodic Pulse "Tuned" to:

Reduce oxide/depassivate surface

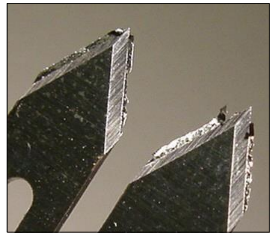
Control metal ion speciation

E.J. Taylor "Adventures in Pulse/Pulse Reverse Electrolytic Processes: Explorations and Applications in Surface Finishing" *J. Appl. Sur. Fin.* 3(4) 178-89 (2008).

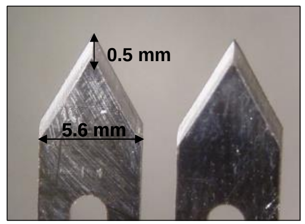
Prior Work – PRC Electrochemical Machining

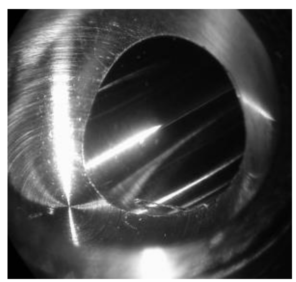
- Machining
- Electropolishing
- Deburring
- Radiusing

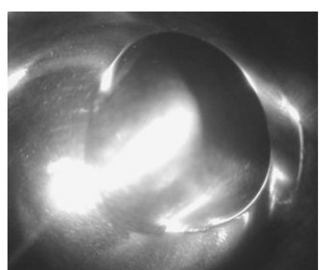
As Received



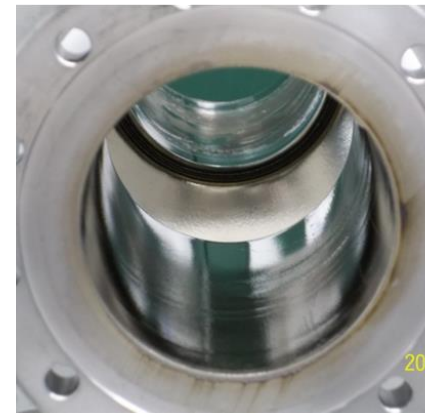
Post Edge Finishing

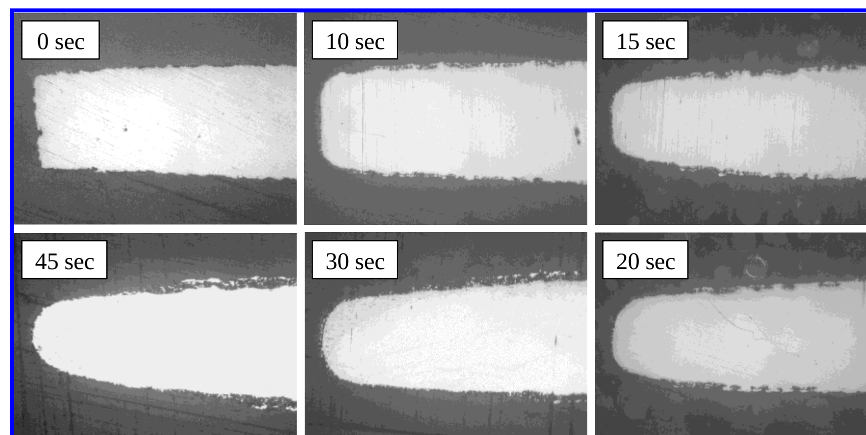






- Ni alloys, Ti alloys, Al Alloys
- Stainless Steels
- Steel
- Cu,
- Mo, Nb, Ta alloys
- Co-Cr





Prior Work – Pulsed Electrowinning

- Evaluation of pulsed fields on silver recovery for Swagelok
- Direct-current winning: Lower plating efficiency, poor plate adhesion
- Pulsed-current winning: Improve plating efficiency / adhesion

Ag: ~200 ppm → < 1 ppm

Ni: 322 ppm → 171 ppm

Fe: 14.2 ppm → 3.8 ppm

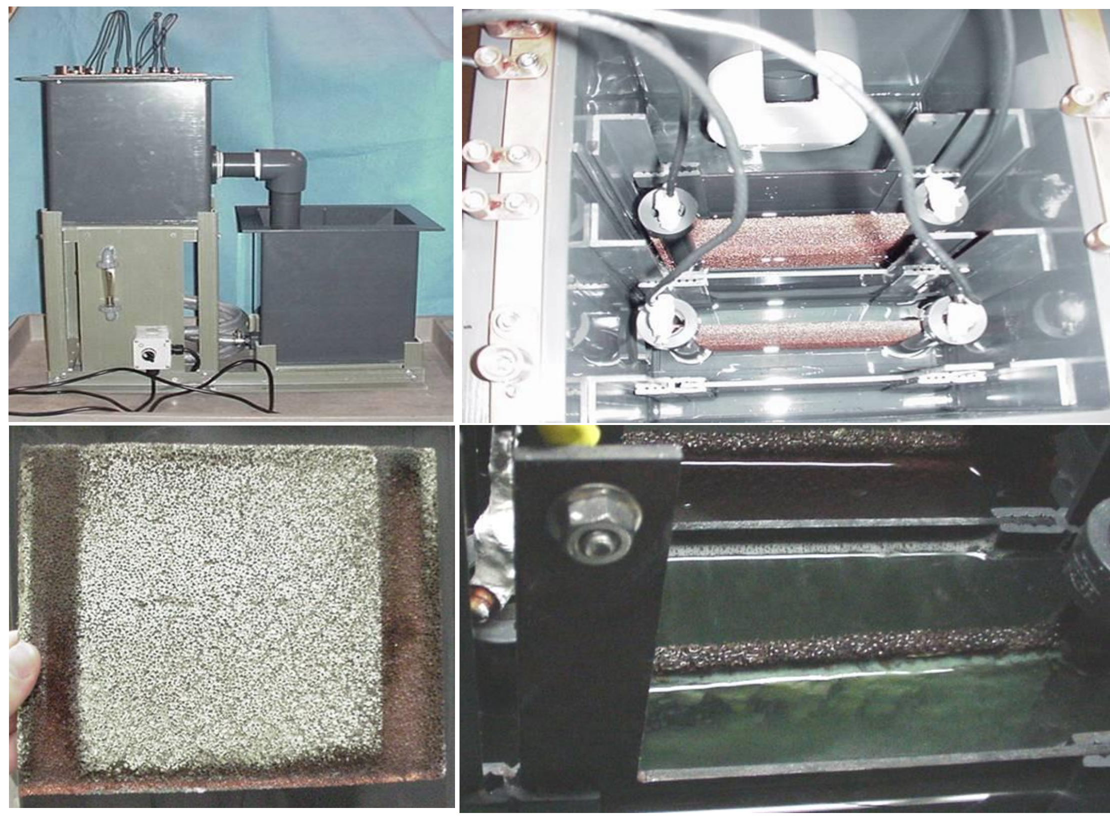
Cu: 2.2 ppm → 0.05 ppm

Cd: 2 ppm → 0.02 ppm

Cr: 4 ppm → 0.3 ppm

Pb: 29 ppm → 0.13 ppm

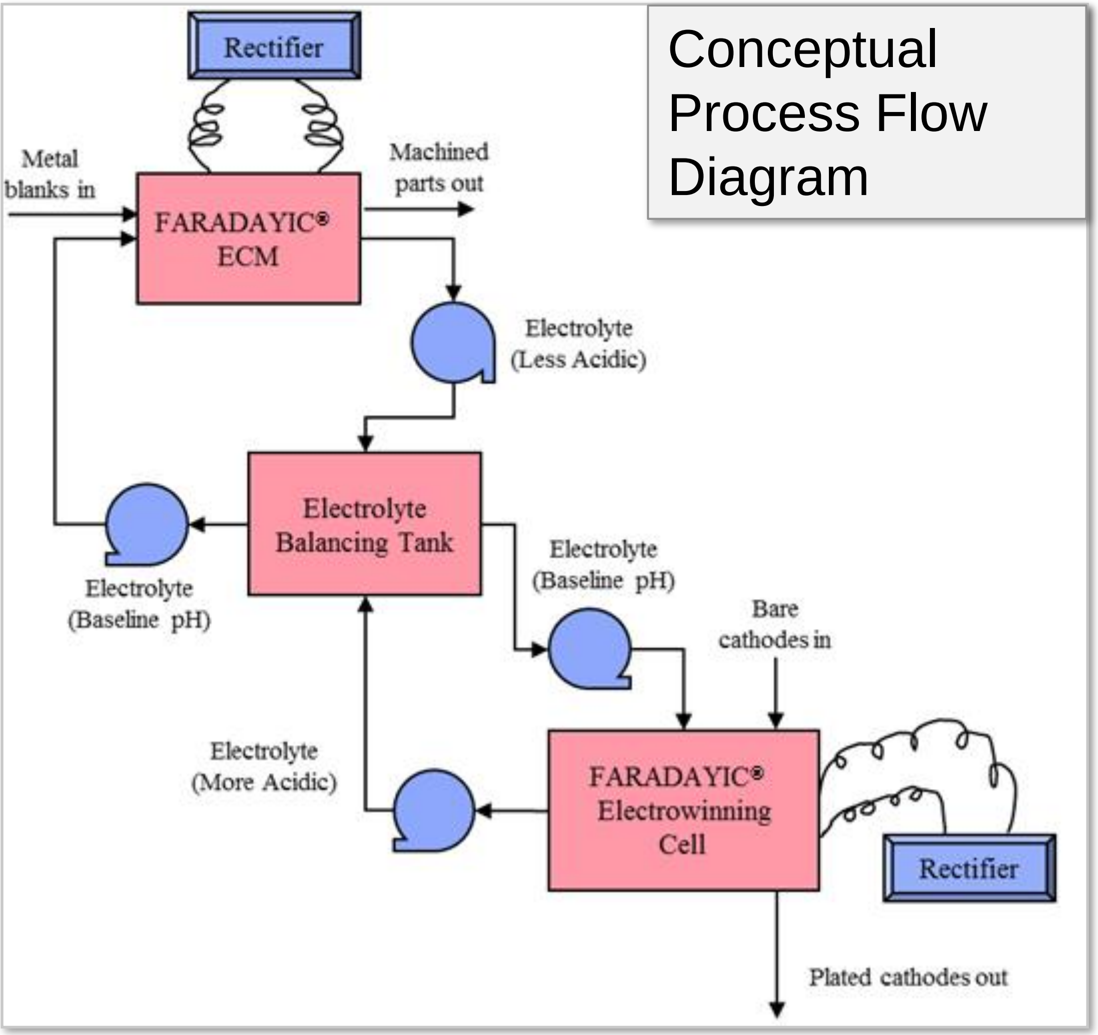
Zn: 5 ppm → 0.3 ppm



Combined Prior Work to Create (R)ECM

- DC ECM:
  - Large volume of sometimes hazardous waste (300x)
  - Metal ion buildup adversely affects performance

- Recycling ECM ((R)ECM):
  - Combined PRC ECM and PC EW
  - Metals are recovered
  - Waste is avoided
  - Water usage is minimized

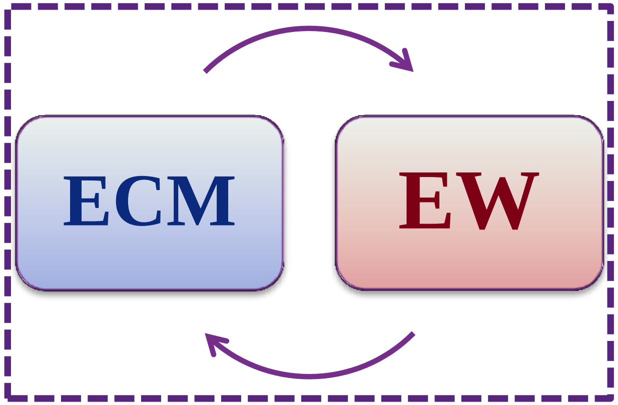


Conceptual Process Flow Diagram

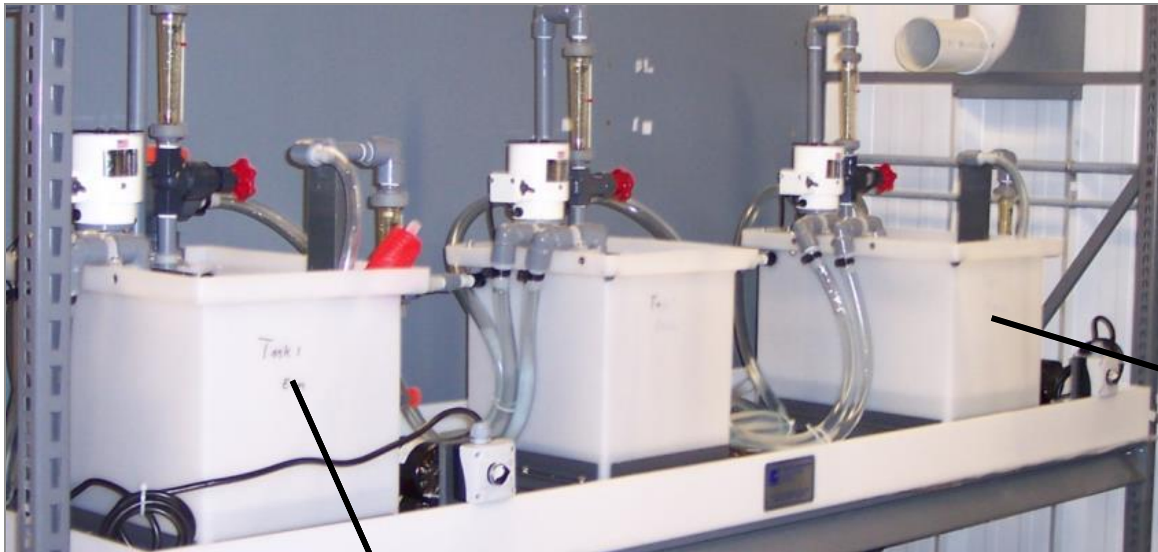
B. Skinn, S. Lucatero, S. Snyder, E.J. Taylor, T.D. Hall, H. McCrabb, H. Garich, M.E. Inman. "Sustainable Electrochemical Machining for Metal Recovery, Elimination of Waste, and Minimization of Water Usage." ECS Trans. 72 (35), 1 (2016)

(R)ECM: Lesson Learned

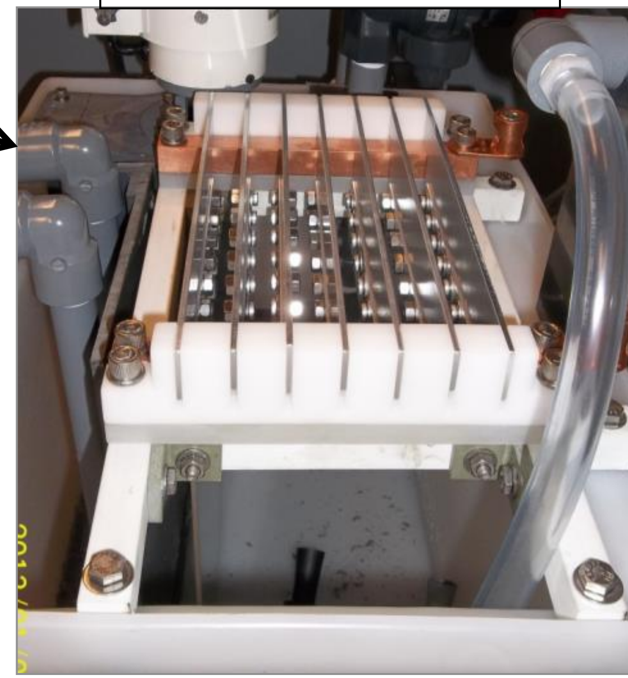
1. Screen electrolytes for electrowinning performance
2. Develop PC/PRC parameters for ECM from EW electrolyte
3. Develop PC parameters for EW
4. Integrated (R)ECM system testing



(R)ECM α-Scale System

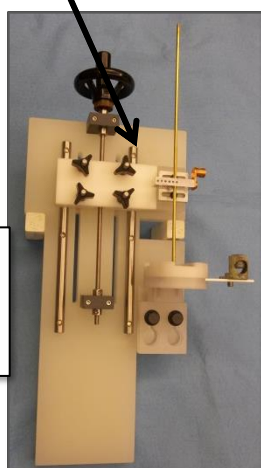


EW Unit Operation

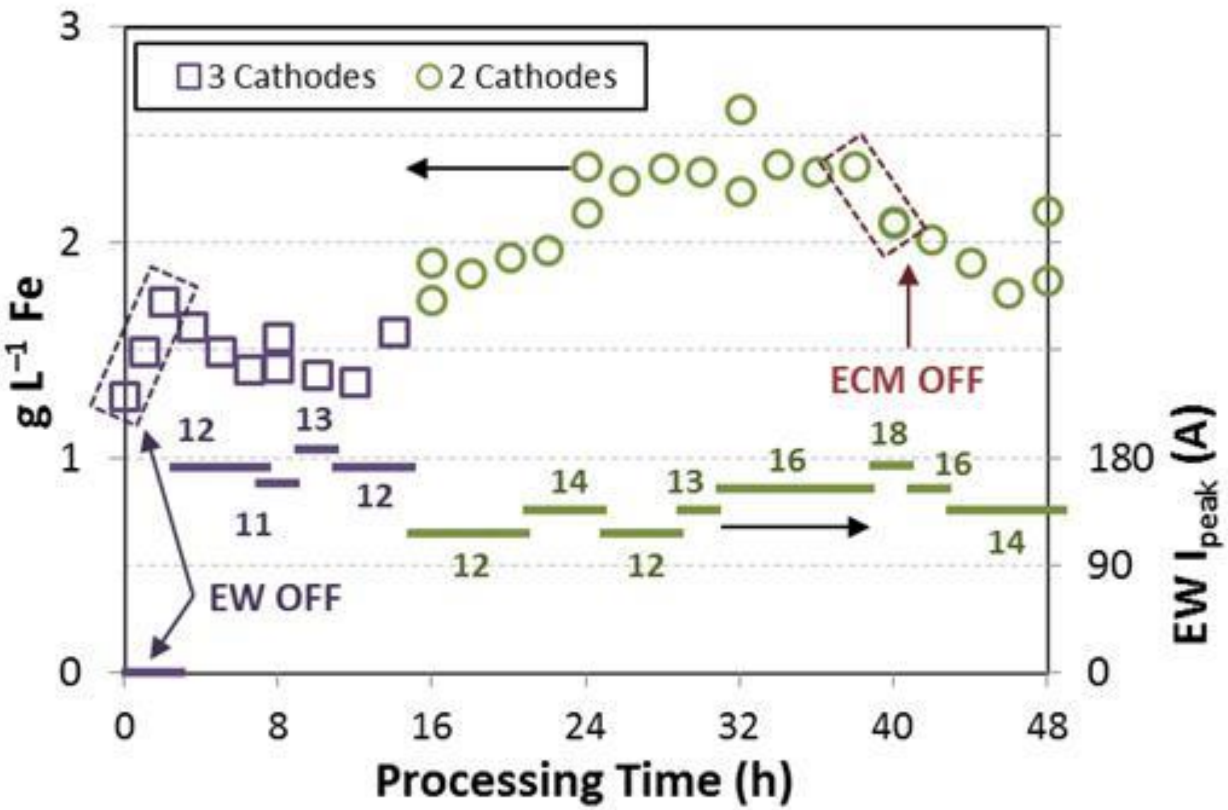


Cell design gave flexibility to investigate various anode to cathode gaps / # / material

Hole-Drilling ECM



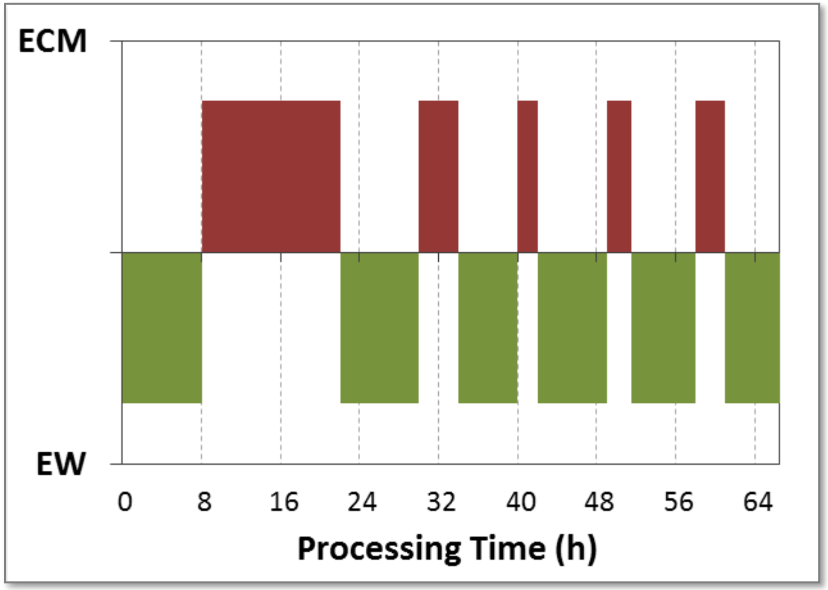
(R)ECM: Lessons Learned

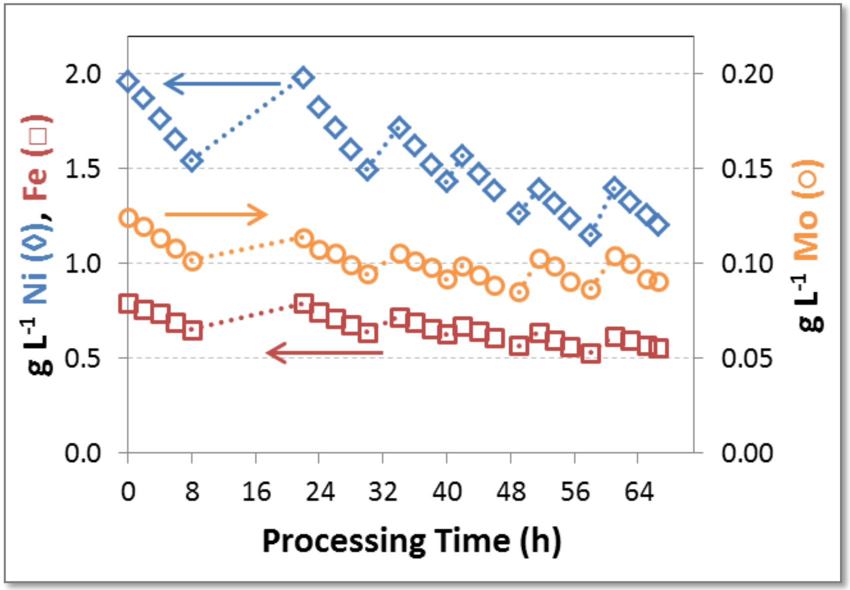


Machining SAE 4150: Maintain [Fe] "target" 2000 mg/L by adjusting EW unit operation

- # Cathodes: 3 to 2
- EW current density: 11 to 18 A/dm^2

(R)ECM Integration Testing - IN718 (Ni, Fe, Mo)





Maintain [Ni], [Fe], [Mo] by sequential operation of ECM and EW unit processes

(R)ECM: Lessons Applied/Learned

<u>LESSONS APPLIED</u>:

- Pulsed Current to:
  - Increasing machining rate and improve surface finish
- Pulsed ElectroWinning to:
  - Reclaim Fe, Ni, Mo, Cu metal
  - Extend machining electrolyte lifetime to decrease operating/disposal costs

<u>LESSON LEARNED:</u>

- Select ElectroWinning electrolyte first
  - Use EW electrolyte for machining
- Primary current distribution important for efficient removal of metal ions

Transition from Machining to Stripping/Recovery

- Why remove metallic coatings?
  1. Reclaim parts with defective or damaged coating
  2. Overhaul parts damaged during operation
  3. Remove undesired metal deposits from plating fixtures

- Based on (R)ECM results, Faraday identified an opportunity:
  - Strip High Velocity Oxy-Fuel (HVOF) WC-Co coatings
  - Recover components for recycling

- Efficient HVOF coating removal requires:
  - Increase stripping rate & decrease part tank time (72 hrs)
  - Increase stripping solution lifetime
  - Reclamation of stripped metals (currently not done)

HVOF Stripping/Recycling / Lesson Applied from (R)ECM

1. Screen electrolytes for electrowinning performance
2. Develop PC/PRC parameters for Stripping from EW electrolyte
3. Develop PC parameters for EW
4. Integrated Stripping/Recycling system testing

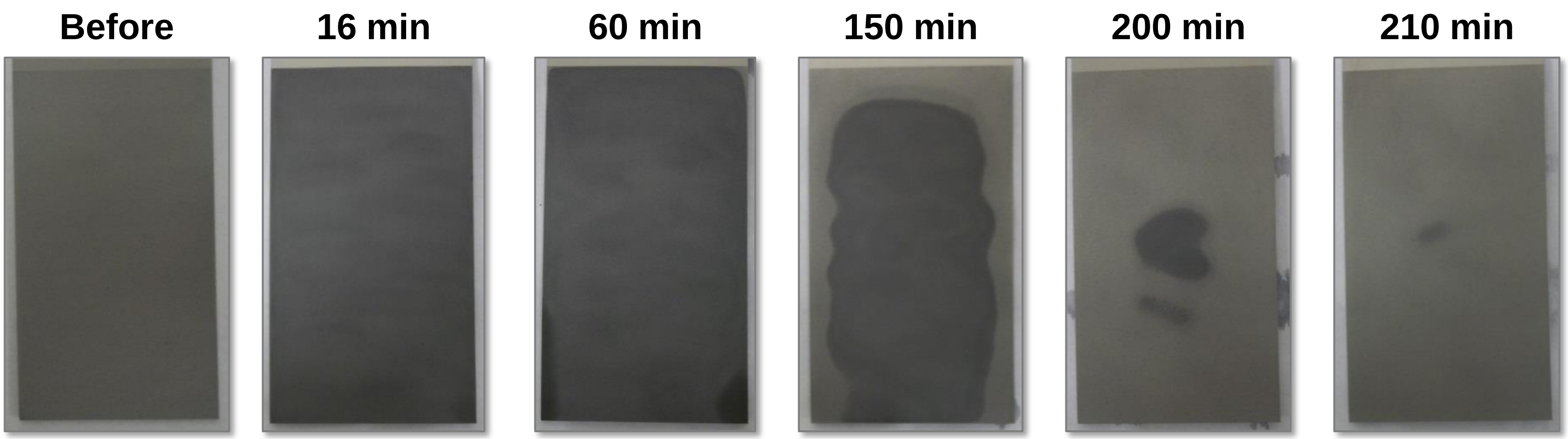
BUT: Limited by Bureaucratic Constraints
Not Allowed to Change the Mil-Spec Stripping Electrolyte

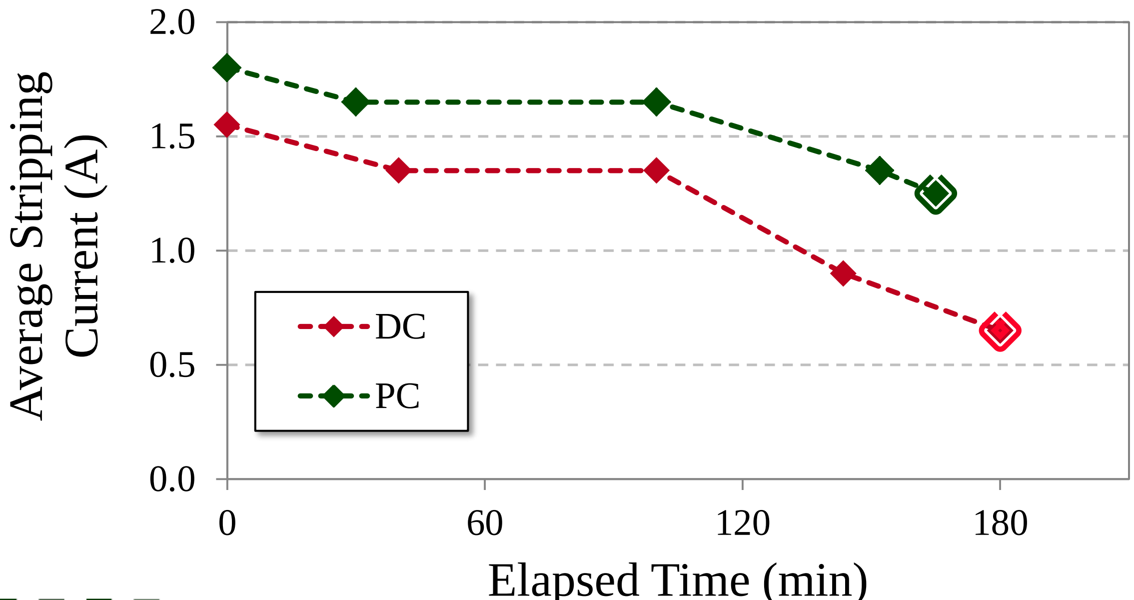
CONSTITUENTS

Component	Specification	Concentration (Optimum)
Sodium Citrate (aka trisodium citrate dihydrate)	N/A ($Na_3C_6H_5O_7 \cdot 2\ H_2O$)	(0.8 lb/gal makeup)**
Sodium Percarbonate (aka sodium carbonate peroxyhydrate)	N/A ($2Na_2CO_3 \cdot 3H_2O_2$)	(0.4 lb/gal makeup)**
	pH	9.0-11.0 (10.0-10.6)**

REFOCUS: Maintain Electrolyte by pH Adjustment and Eliminating Peroxide

Lesson Applied: Pulse Current Improved Rate





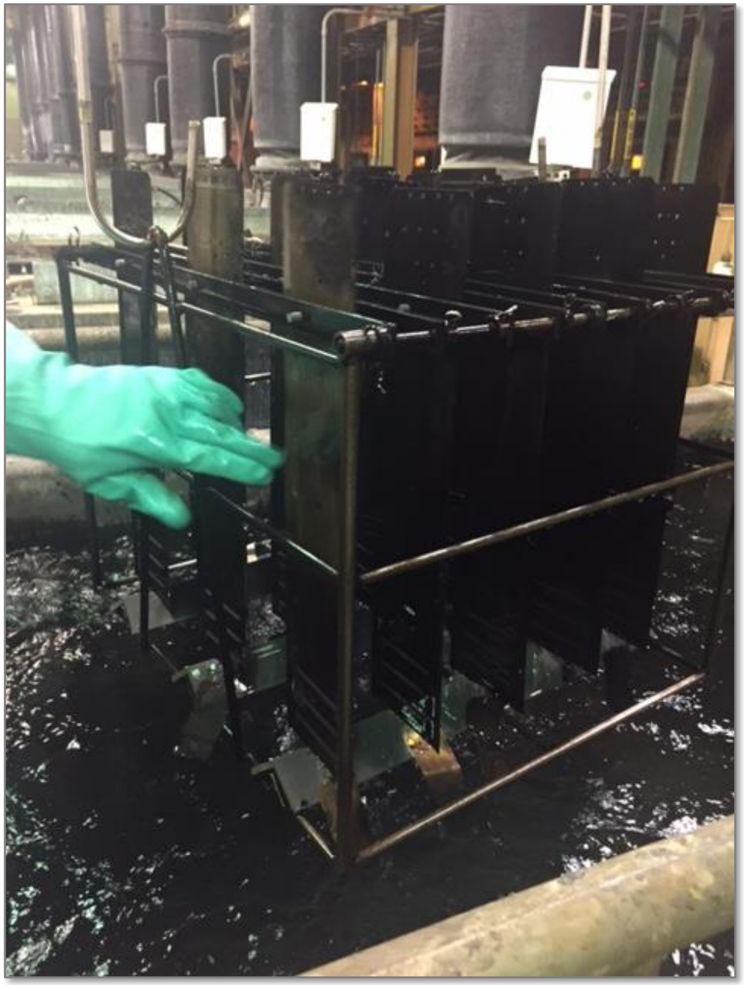
HVOF Beaker Tests – Summary

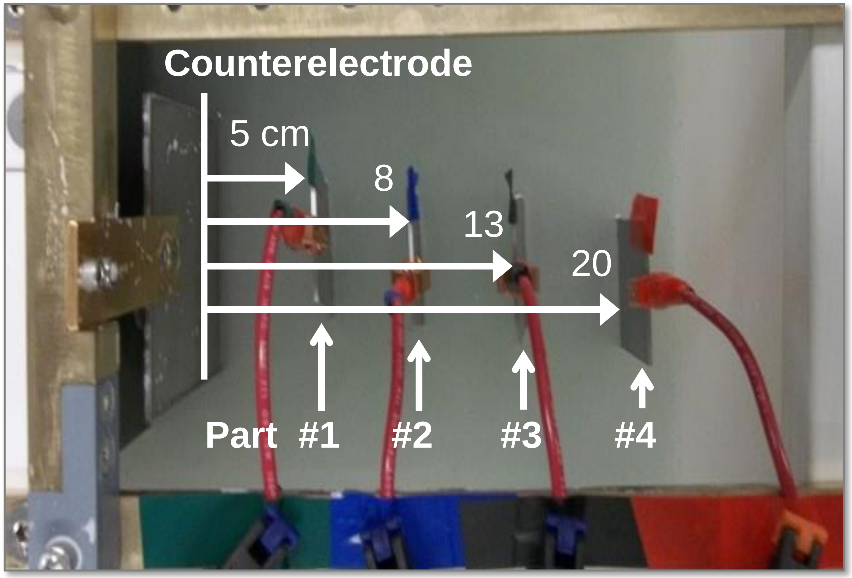
- Complete stripping in as low as 3 to 4 hours (24 h in all cases)
  - Pulsed current showed an increase in stripping rate over DC
  - Peroxide slightly increased stripping rate and only within first few hrs
  - pH could be maintained with NaOH

- Recovery of Cobalt on cathode
  - W recovery to be demonstrated

- Coatings strip edges → center
  - Primary current distribution important
  - Need to scale up to larger cells

Current Racking/Fixturing – Simulation

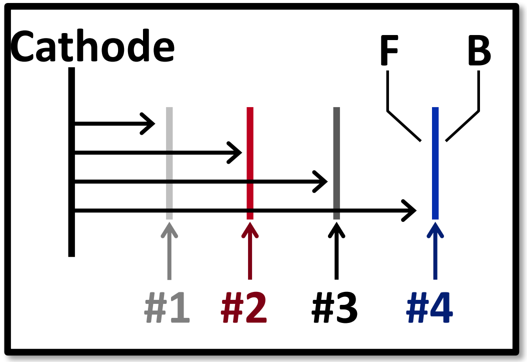


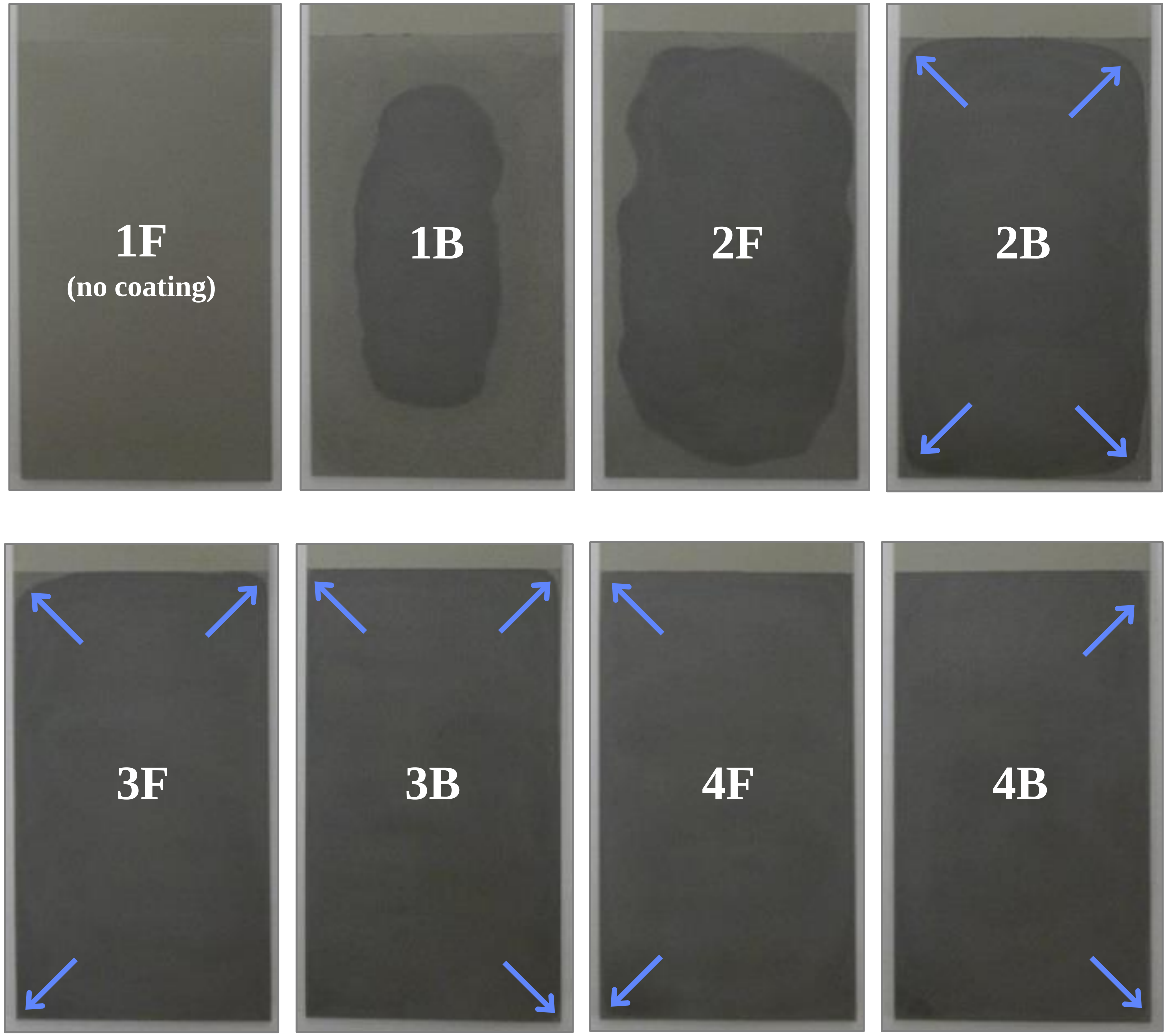


Lesson Applied: Used (R)ECM EW cell design to accelerate program

HVOF Stripping

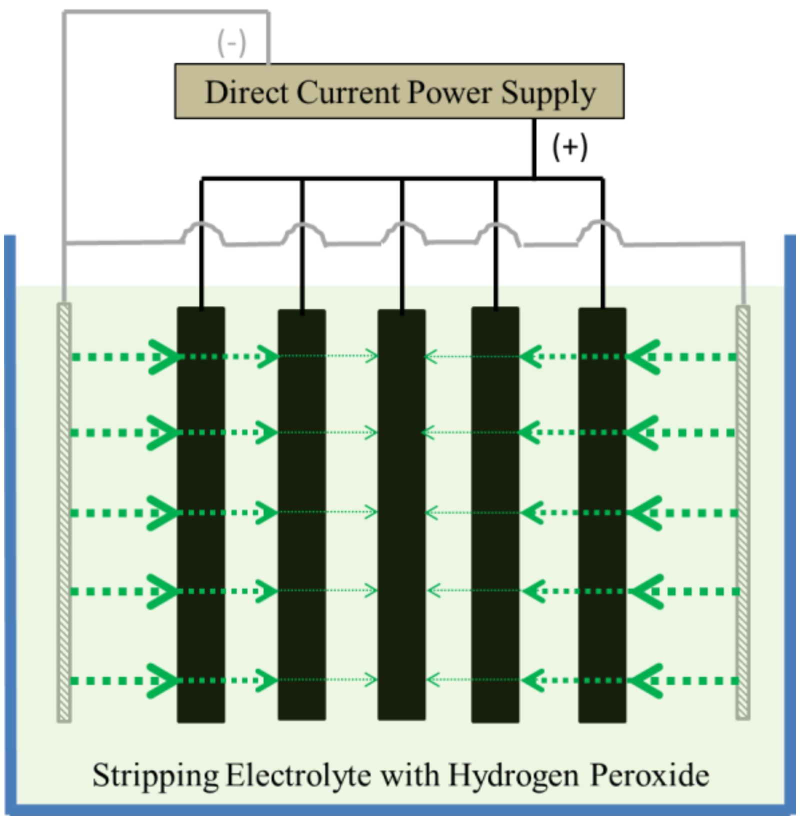
- Current distribution significant for stripping performance
  - Parts 'screened' from cathode strip much more slowly
- Parts photographed after 4 h processing
- All parts stripped completely within 24 h



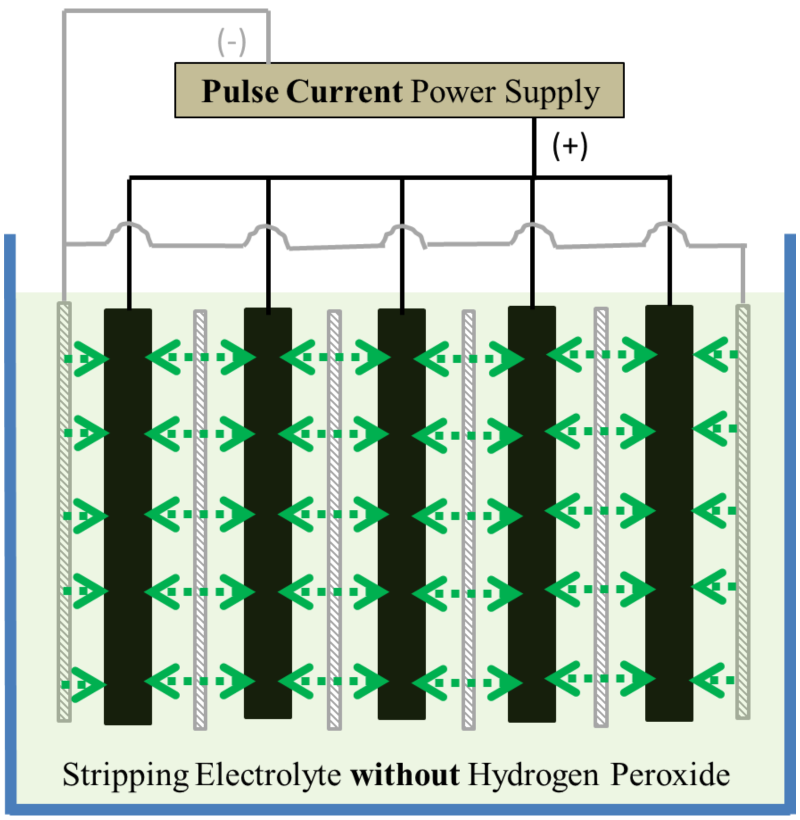


(R)ECM Design – Lesson Applied

Current Process



Enhanced Process



HVOF Stripping/Recycle – Lessons Applied/Learned

<u>LESSONS APPLIED</u>:

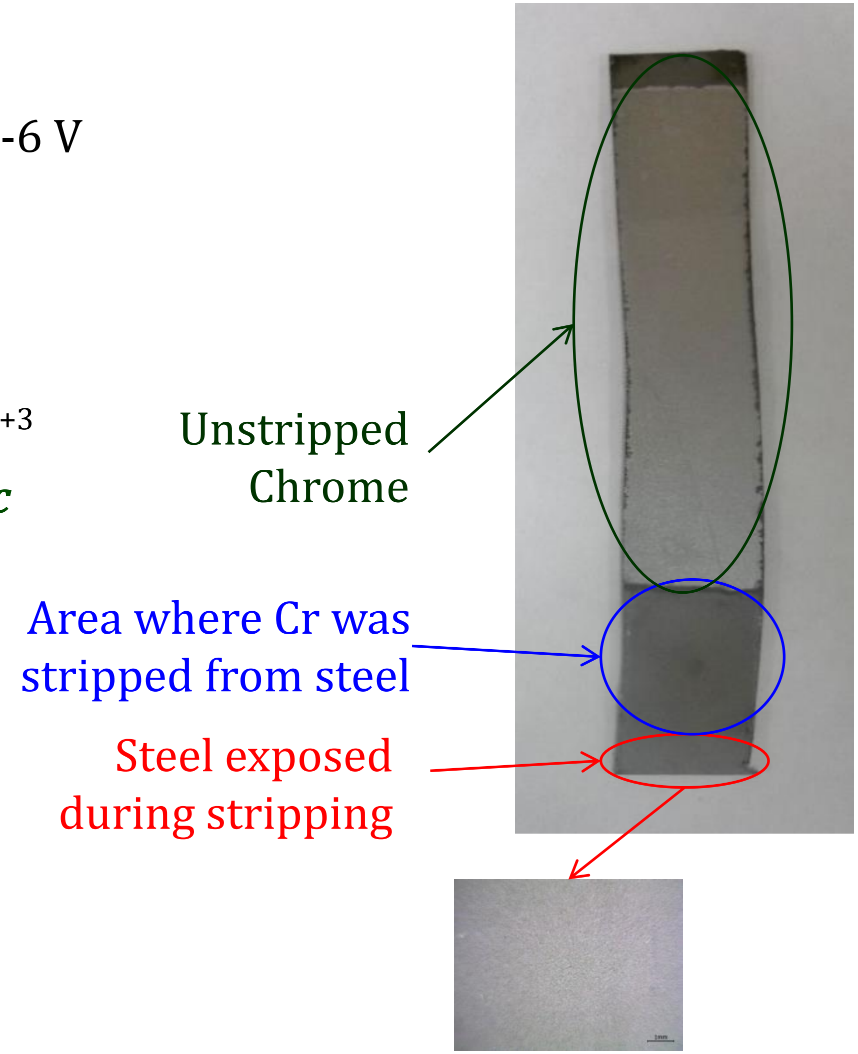
- Pulsed Current:
  - Decrease stripping time from 72 hours to as little as 3 to 4 hours
- Pulsed ElectroWinning to:
  - Reclaim Cobalt metal for recovery
  - Could return stripping bath to stripping process to decrease operating/disposal costs
- (R)ECM cell design
  - Better current distribution for more efficient stripping

<u>LESSON LEARNED:</u>

- Understand bureaucratic constraints (electrolyte) early

Chrome Stripping

- Electrolytic stripping of Cr:
  - NaOH (60 g/L) + Na_2CO_3 (75 g/L) at 4-6 V
  - Operating conditions favor Cr^{6+}
- Phase I:
  - PRC increased conversion of Cr^{+6} to Cr^{+3}
  - ***Stripping Process worked with oxalic acid – no Cr^{+6} in solution***
- Phase II:
  - ***Oxalic acid incompatible with client waste treatment system***
  - Need to find another electrolyte
  - Alternative approaches
    - Electrowinning of Cr



Cr Stripping/Recycle – Lessons Applied/Learned

LESSON LEARNED:

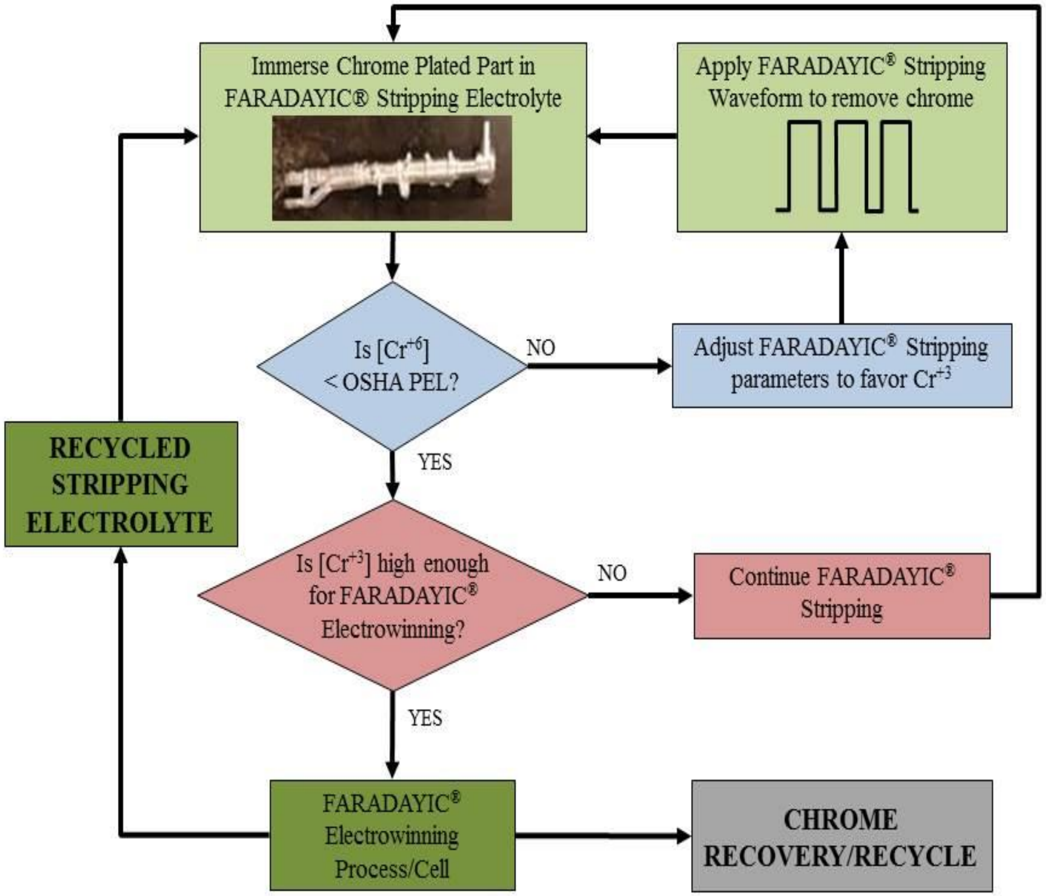
- Understand bureaucratic constraints (waste treatment) early

LESSON BEING APPLIED:

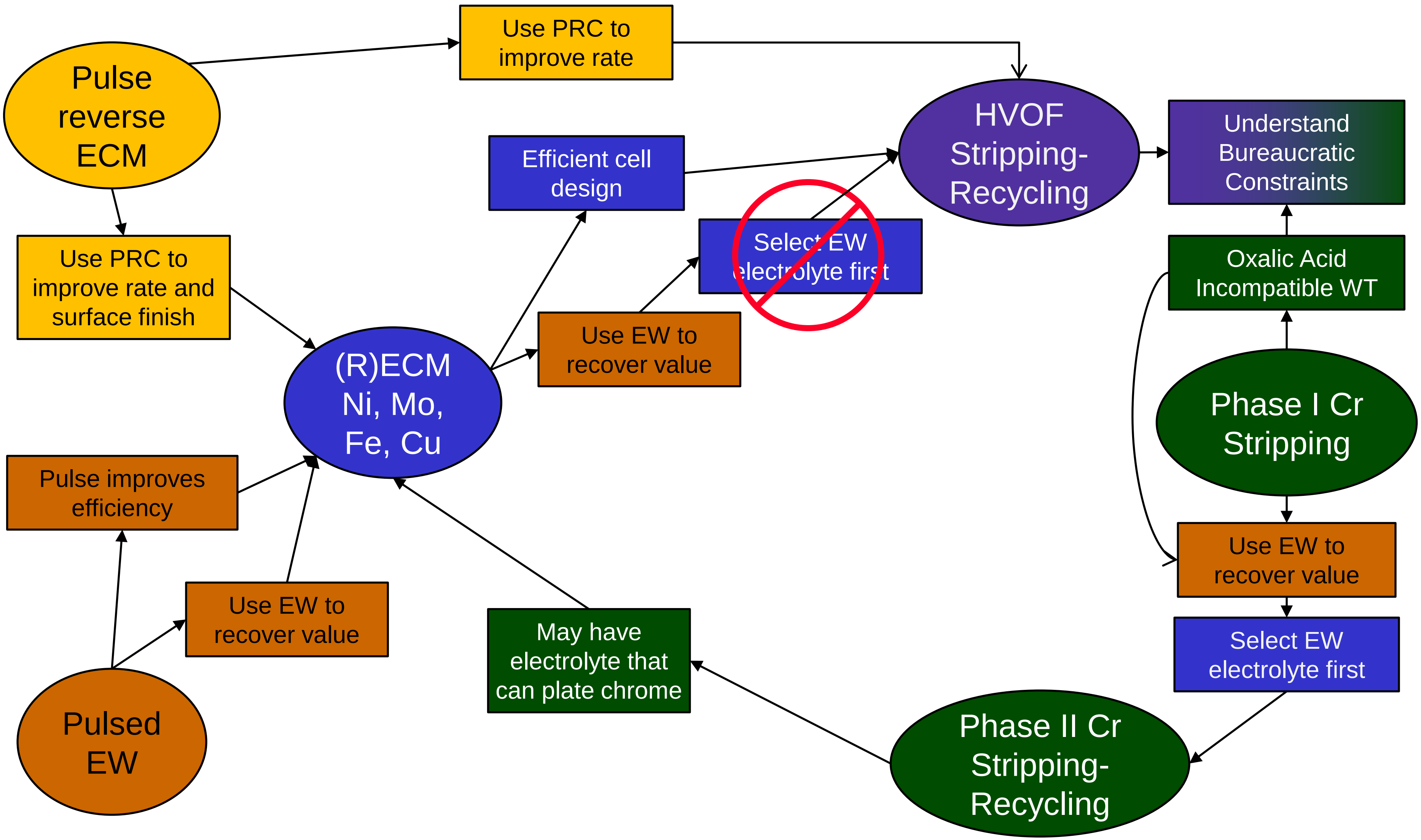
- Use Electrowinning to recover Cr to maintain stripping electrolyte

RECENT LESSON LEARNED:

- May have identified an electrolyte that can plate chrome
- Feed back to (R)ECM



Summary of Lessons Learned/Applied



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Common Themes/Lessons Learned

- Racking and fixturing design critical to effective process
  - (R)ECM tank design used for Cr and HVOF stripping/recovery
  - Don't assume industrial client is cognizant of primary current distribution constraints
- Create added value by recovery of metals
  - Cr stripping did not require this, but should add value
- Design stripping electrolyte to facilitate electrowinning
  - (R)ECM strategy
  - Being applied to Cr Stripping
- Transition process from lab to depot
  - Learn bureaucratic lessons in dealing with large organizations
  - Patience is required

Acknowledgements

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- Program partners
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  - The Boeing Company

Thank You!