Corrosion and Erosion Coatings for Biomass (Combustion) with load following

Award Number DE-FE0031911, Vito Cedro Program Manager

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Concerns, Clarification, Collaboration?
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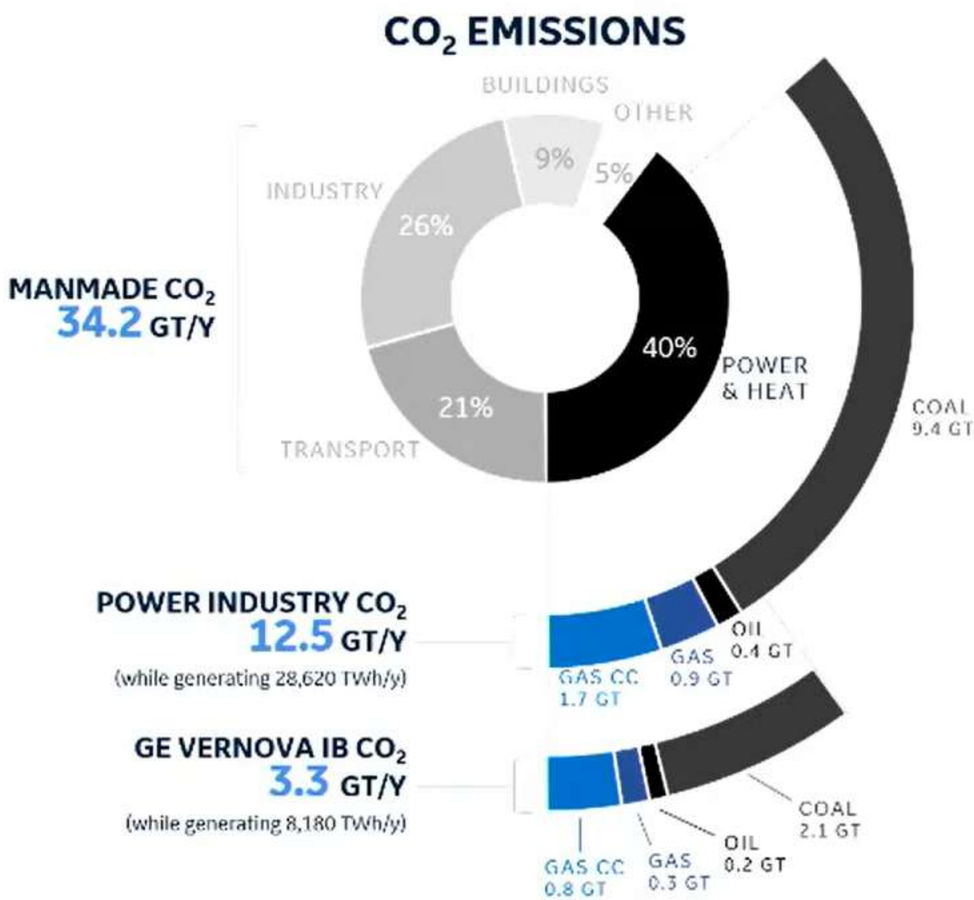
Bottom Line Up Front

- The team is developing two types of coatings:

Coatings for Boiler Tubing	Coatings for Steam Turbine Blades
– *Objective:* Corrosion Resistance	– *Objective:* Erosion Resistance
– *Lab-scale success:* 93% reduced corrosion rate at 84% reduced cost compared to Inconel 625	– *Lab-scale success:* 10 µm thick turbine coatings more durable than today's 150 µm thick coatings
– *Potential application:* ↑ Biomass Cofiring	– *Potential application:* ↑ Load Following

- Challenges have included quantifying weldability, project management, and several aspects of scale-up:
  - Timely prototype fabrication at vendors
  - Unexpected levels of variability in coating feedstock and deposition practices
  - Finding industrial- or utility-scale plants with outages convenient for prototype testing
- We are interested to hear your thoughts on future directions

Problem Statement



- Globally, ~10% of CO_2 emissions are produced using GE equipment

- This equipment can be made carbon neutral by fuel switching
  - GE Boilers can burn sustainable biomass
  - GE Gas Turbines can burn syngas and H_2
  - GE Jet Engines can burn SAF

- Done properly, this keeps fossil fuel in the ground *and* grows natural carbon stocks

Barriers to greater deployment of Sustainable Biomass

- Difficulty of long-term fuel contracts
- Storage and logistical considerations
- Public Perception
- Load following to accommodate cheaper but more variable Renewables
- Capital and Operational costs
  - More expensive fuel per unit energy basis than natural gas
  - Due to corrosive environment, more than ¼ of LCOE results from maintenance/repair
  - Expensive structural materials
  - Frequency of outages

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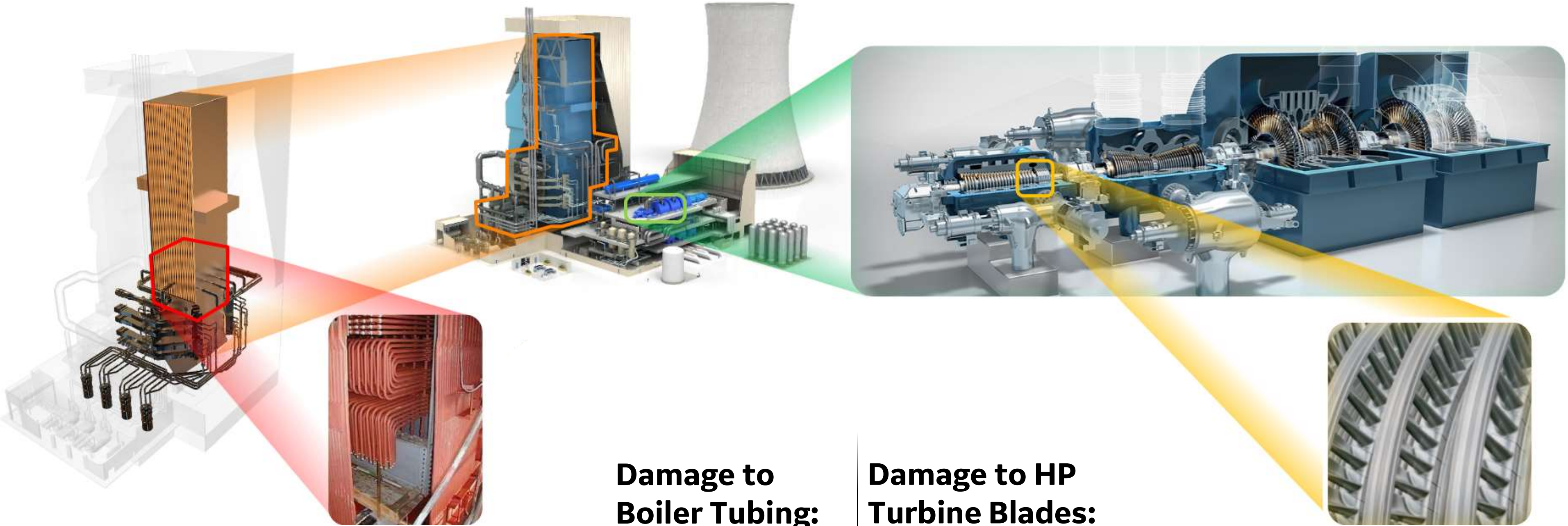


Damage to Boiler Tubing:

- Hot corrosion leads to outages
- Challenge is growing as combustion temperatures increase, fuels diversify
- Existing solutions are too costly to apply over a wide area

Damage to HP Turbine Blades:

- Blade erosion leads to outages
- Challenge is growing with load following, inlet steam conditions
- Existing solutions are too weak to be effective or cause aerodynamic debit

Reliability at lower cost is needed by the current supply chain

Project timeline

Phase 1: Proof of Concept

Develop Coating Compositions

- Test for compatibility with service environment and manufacturing process
- Minimize wastage rate for weld overlay compositions
- Minimize solid particle erosion rate for Physical Vapor Deposition (PVD) compositions

Phase 2: Scale-up

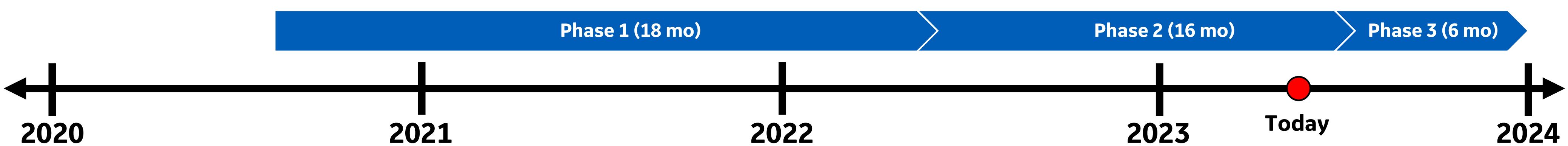
Develop Coating Methods

- Ensure that composition of interest can be reliably and uniformly deposited on parts
- Vendor produces weld overlay on ferritic and austenitic tubing
- PVD composition is deposited on HP Turbine blades

Phase 3: Evaluation

Demonstrate Performance

- Coated components are tested under field simulative conditions
- Weld overlaid tubing is mechanically tested in lab; corrosion tested in boiler
- PVD-coated HP Turbine blades are evaluated with post-steam leading edge erosion testing



Boiler Tube Coatings for Hot Corrosion Resistance

Requirements for Hot Corrosion Protection on Boilers

Attack mechanisms:

- Combination of Oxidation, Sulfate attack, and Alkali Chlorides.

Material requirements driven by cost:

Material Cost (CAPEX) — Outage Cost (OPEX)

- Corrosion rate less than or equal to Alloy 72
- "Weldable" enough to be applied with conventional overlay methods (GMAW/GTAW)

Weld overlay Materials	
Alloy	**Wire cost per 10 feet of Tube**
309	$ 0.76
312	$ 0.98
625	$ 2.64
622	$ 3.19
52	$ 3.41
72	$ 6.94

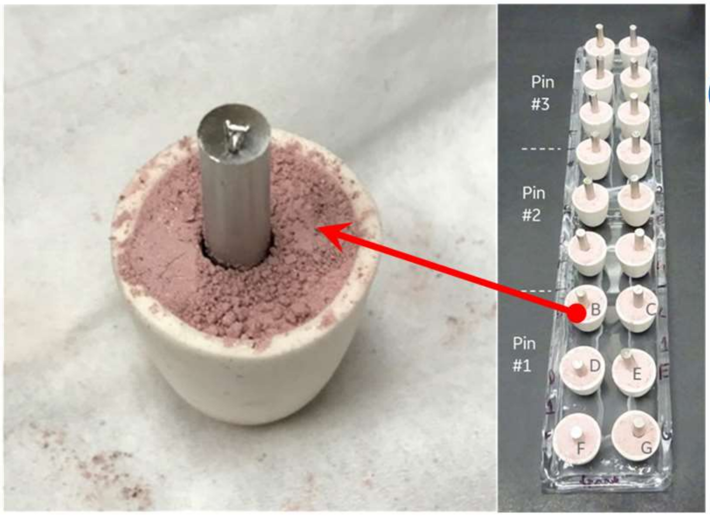
Increasing Ni content

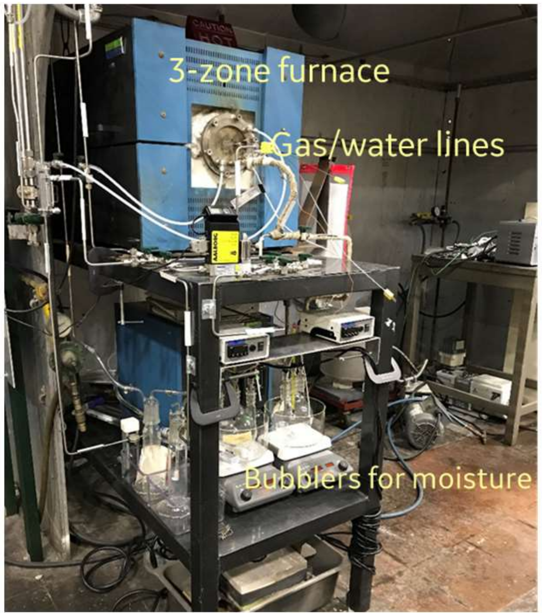
Tube Materials	
Alloy	**Cost per 10 feet of Tube**
T91	$ 1.13
304	$ 3.16
310	$ 9.03
800H	$ 28.44
625	$ 37.92

- At least 50% reduction in material cost relative to Alloy 72 (~60Ni-40Cr)

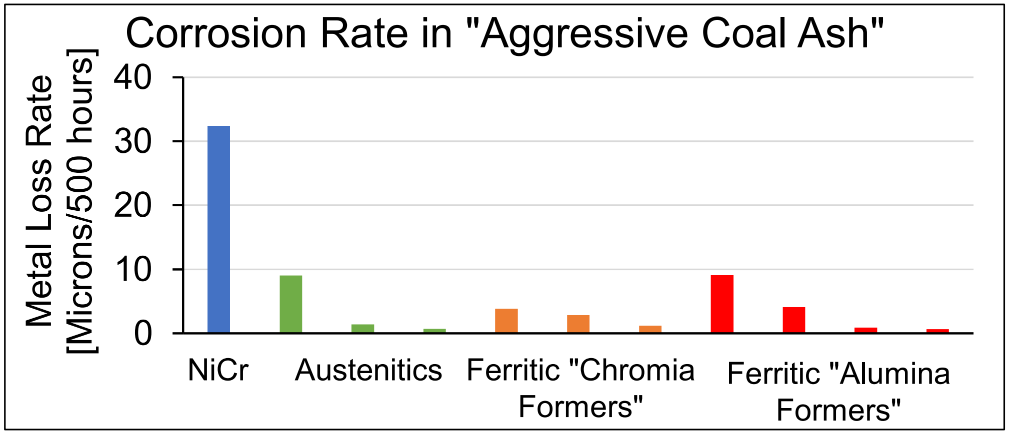
Corrosion tests

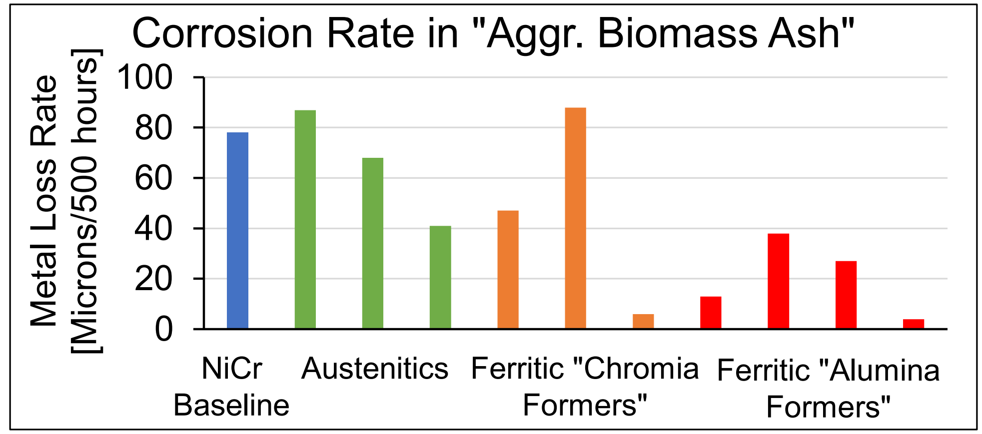
	Composition (wt%)	"Aggress. Coal"	"Aggress. Biomass"
Synthetic Ash Composition (wt%)	SiO_2	22.3	22.2
	Al_2O_3	12.5	5.6
	Fe_2O_3	4.5	4.7
	CaO	18.2	22.7
	MgO	4.0	5.3
	Na_2O	1.7	0.9
	K_2O	0.2	11.5
	TiO_2	1.0	0.8
	P_2O_5	0.7	1.3
	K_2SO_4	5	4.0
	Na_2SO_4	5	1.0
	$MgSO_3$	10	-
	$CaSO_4$	5	-
	KCl	3	16.0
	NaCl	-	4.0
Synthetic Flue Gas Vol%	N_2	72.3	60
	CO_2	15	10
	O_2	2.5	5
	CO	-	-
	H_2O	10	25
	SO_2	0.2	-
Temperature	°C	700	600
Duration	hours	500	500
Thermal Cycles	count	2	2

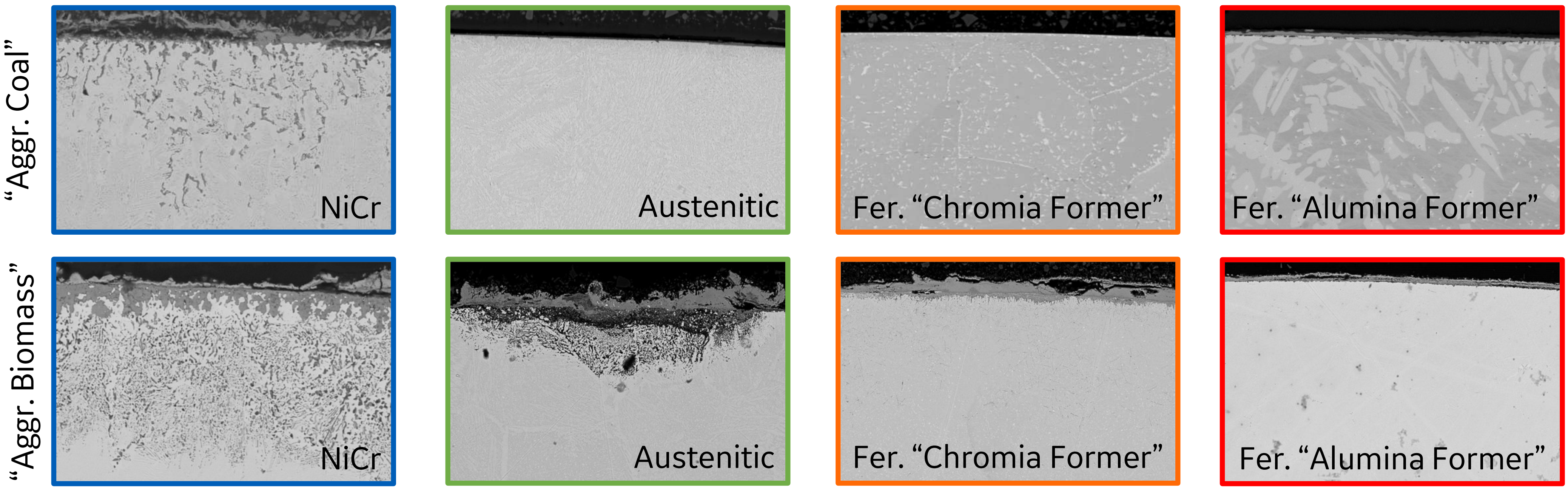




Success in developing Hot Corrosion Protection for Boilers



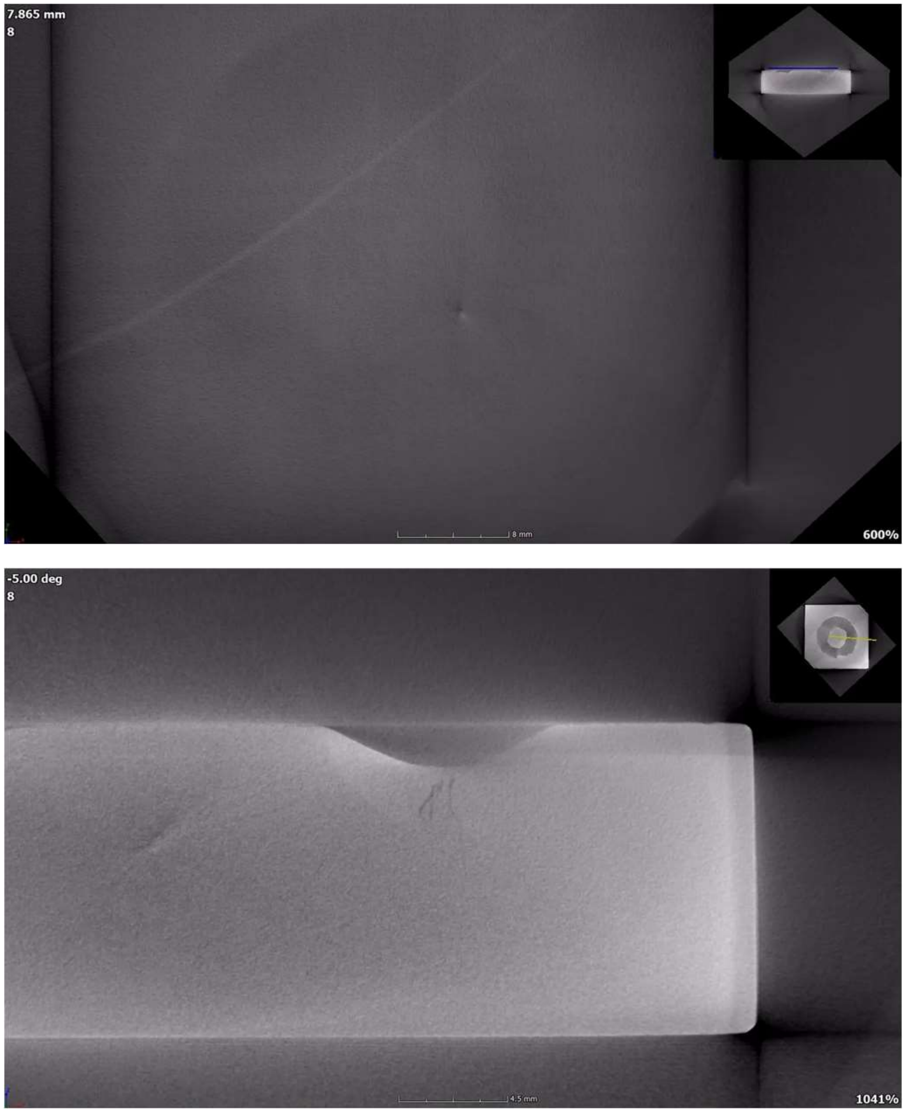




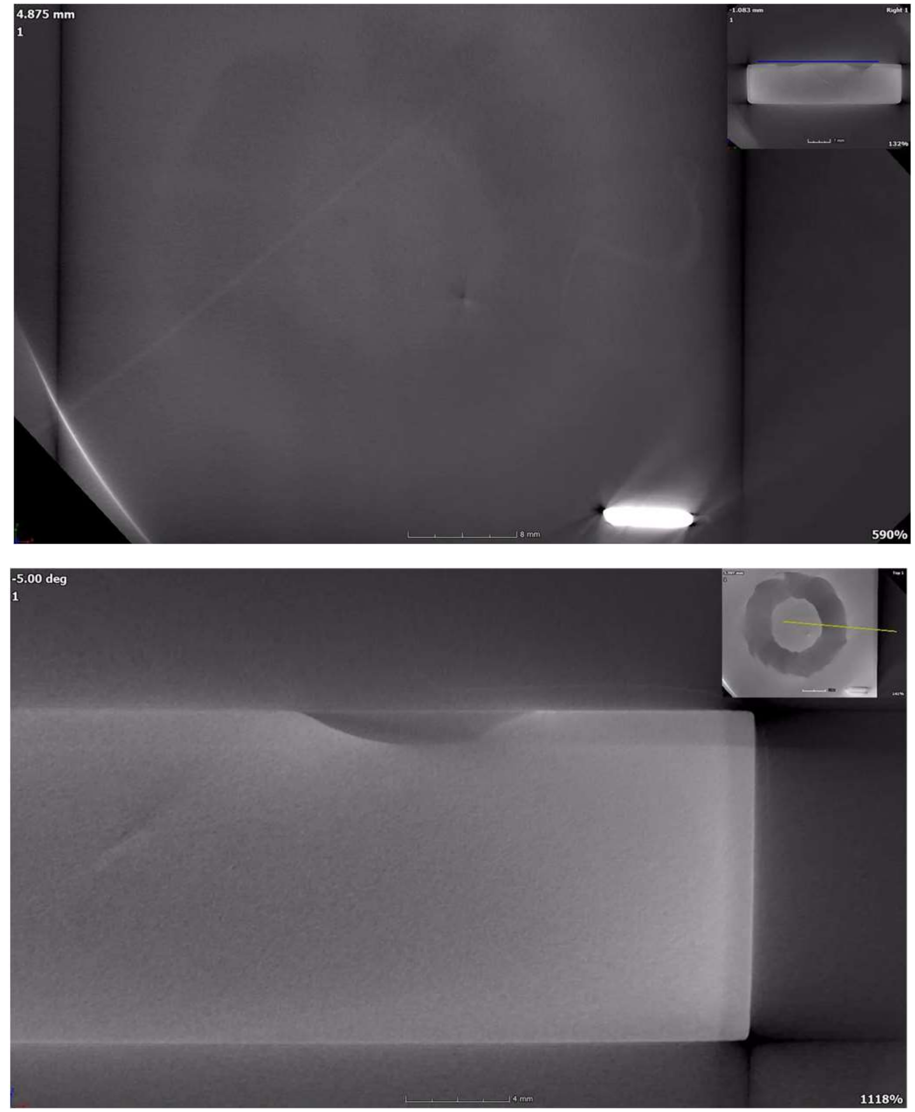
Success in developing Hot Corrosion Protection for Boilers -Constrained Patch Weld Testing

"Readily Weldable" NiCr | Austenitic | Fer. "Chromia Former" | Fer. "Alumina Former" | "Unweldable" NiCr

“Unweldable Alloy”



“Readily Weldable Alloy”



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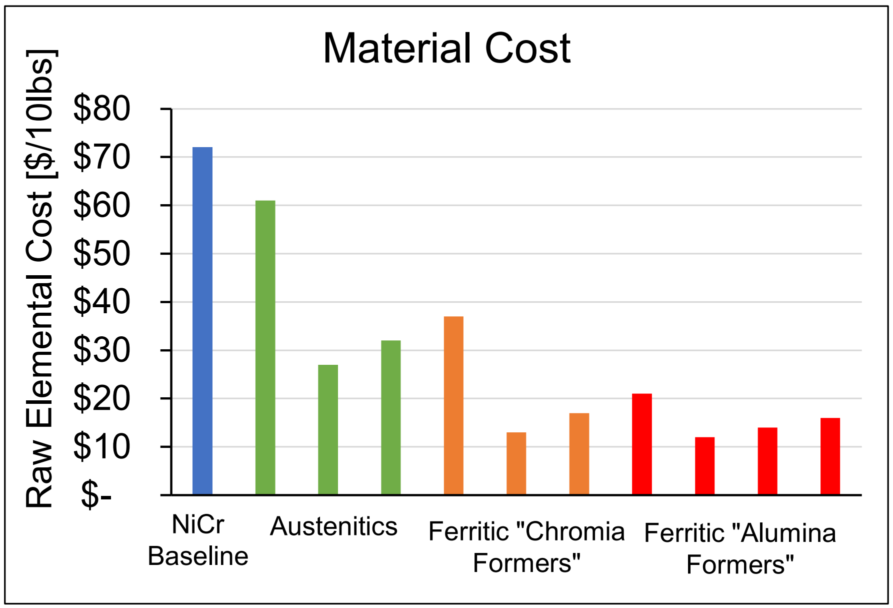
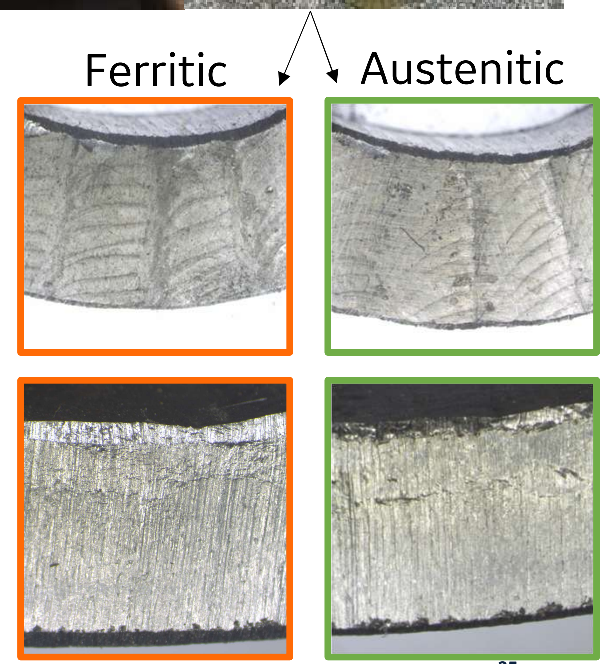
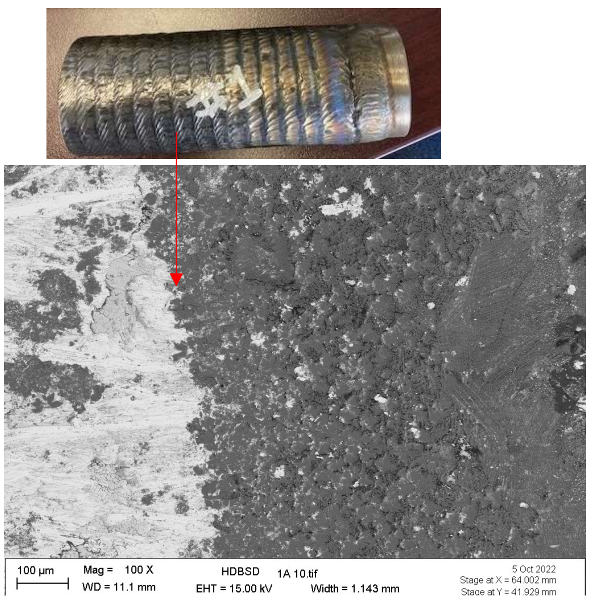


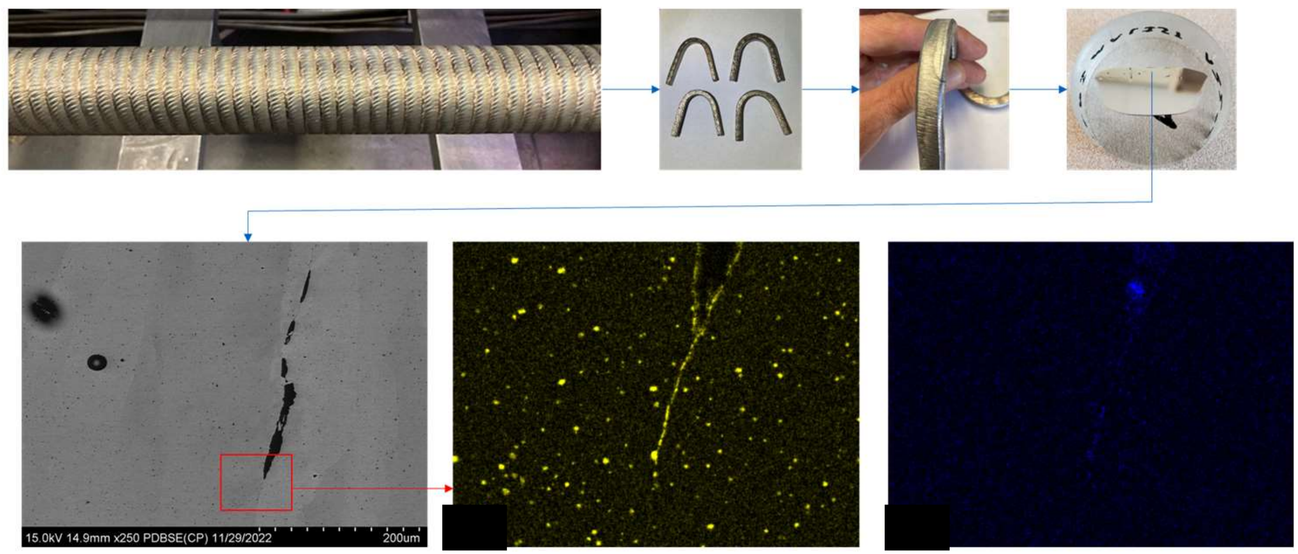
- Exceeded performance requirements in lab-scale corrosion
- Met cost targets
- Bench Scale weld tests and computational thermodynamics suggested weldability was adequate



Challenges in developing Corrosion protection for Boilers

Contributing Factor to Schedule Slide	Corrective Actions
Weldability Issues: Slag, hot cracking, solid state cracking	Reduced impurities, improved welding parameters, moving to solid wire, alloy optimization
Compositional Control: Greater variability in wire processing and impurities than anticipated	Wider supply chain study
Low Priority Job: Two weld overlay vendors withdrew after agreeing to scope	Vendor with greater availability and interest in biomass/MSW, Establish backup vendors





Steam Turbine Coatings for Erosion Resistance

Requirements for Solid Particle Erosion resistance in Steam Turbines

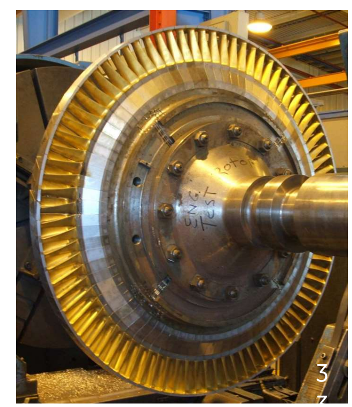
Attack mechanism:

- Spalled, oxidized material from cycling travels along steam path and enters High Pressure Steam Turbine

Mitigation options available today:

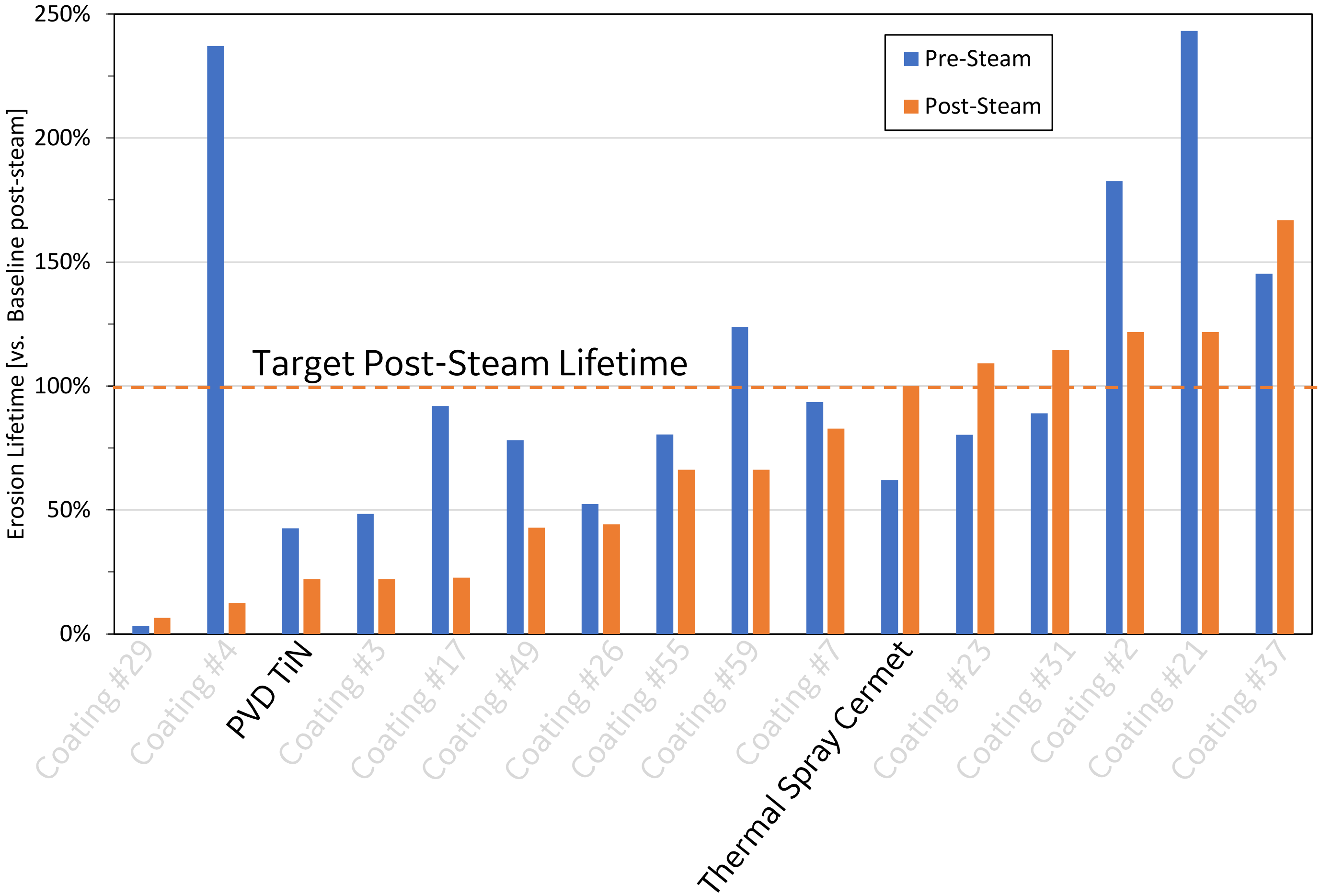
Erosion Protection Strategy	Coating Thickness	Adequate Service Life	Minimal Aerodynamic Debit	Rapid Implementation
Steam Path Redesign	N/A	✓	✓	
Thermal Spray Cermet	150 µm – 250 µm	✓		✓
PVD TiN	3 µm – 10 µm		✓	✓
Novel PVD coatings	10 µm – 30 µm	✓	✓	✓

- Decided to address reliability gap of PVD coatings to maximize impact and deployment
- If successful, will bring an improved product to an existing supply chain



Success in Solid Particle Erosion resistance for Steam Turbines

- “Erosion Lifetime” ≈ Thickness x Erosion Resistance



<u>Objectives Met</u>

- Coating thickness and surface finish of PVD TiN
- Erosion lifetime exceeding Thermal Spray Cermet

<u>Strategy</u>

- Utilize both dopants and microstructure control
- High nanohardness phases
- Internal stress modulation
- Minimal oxidation kinetics

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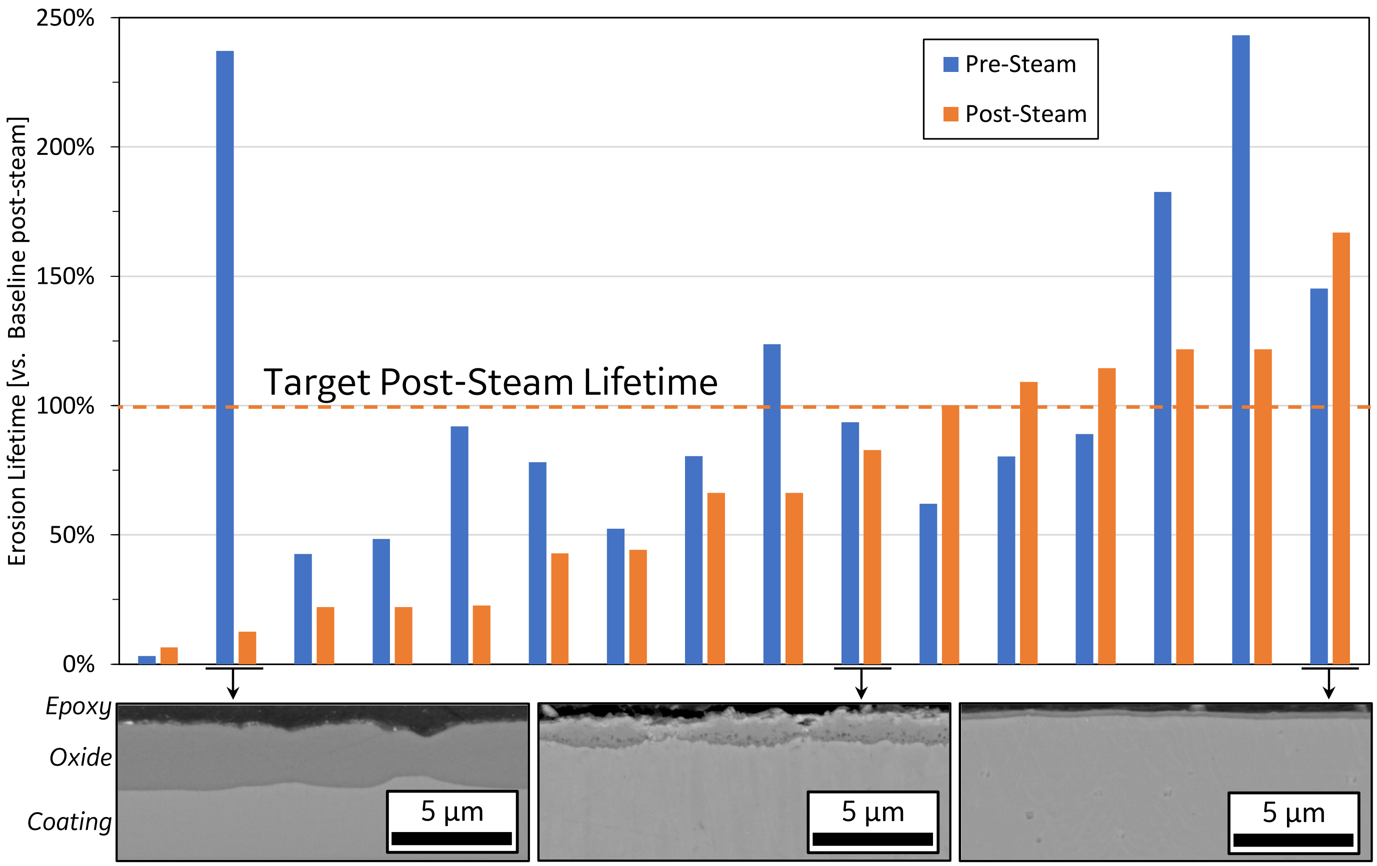

Post-steam cross sections generally show correlation between oxide growth rate and drop in erosion resistance

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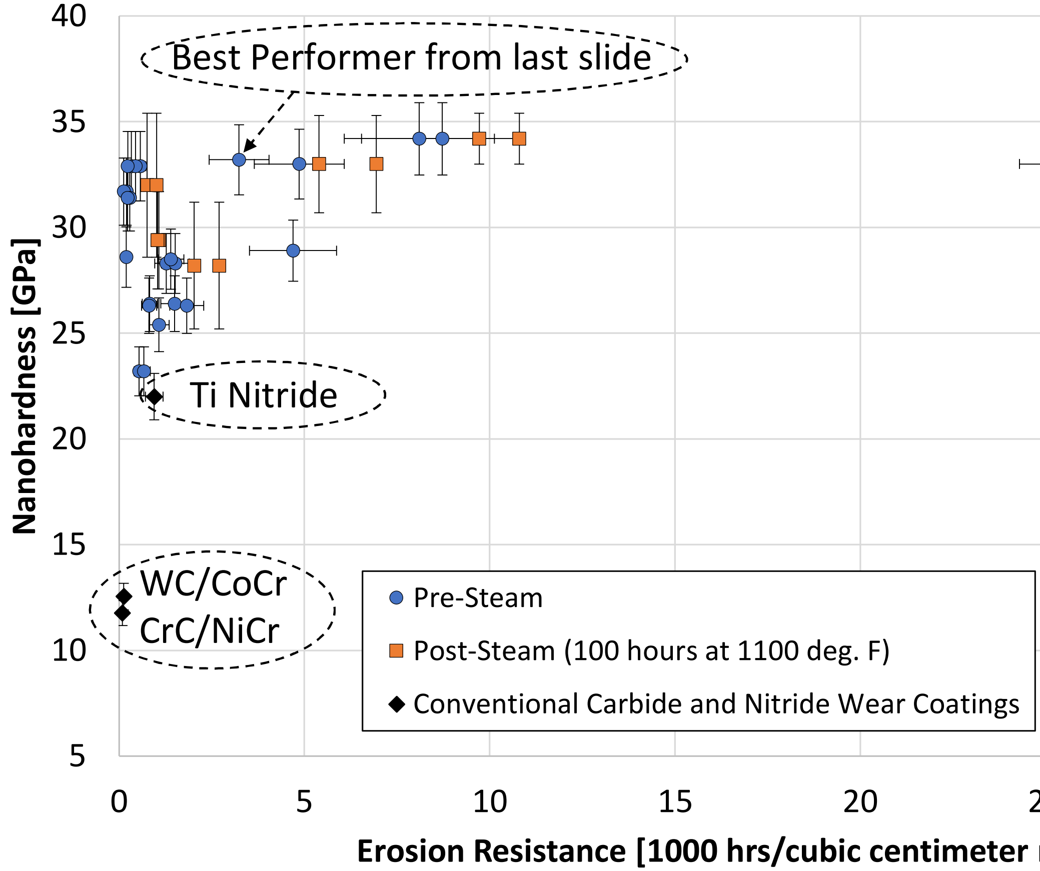


- Conventional, low cost coating hardware
- Novel process and chemistry control
- Thinner, harder, more conformal and oxidation resistant than thermal spray

Examples of Substrate Flexibility:

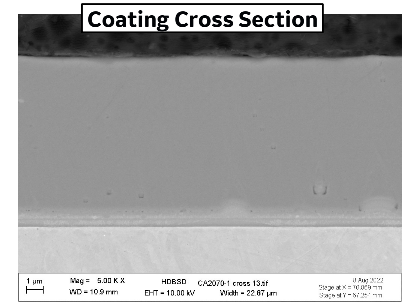
Coated SS HP Steam Turbine Blade

Coated Inc. 601

Coated TiAl Airfoil

Coated CMC

Coating Cross Section

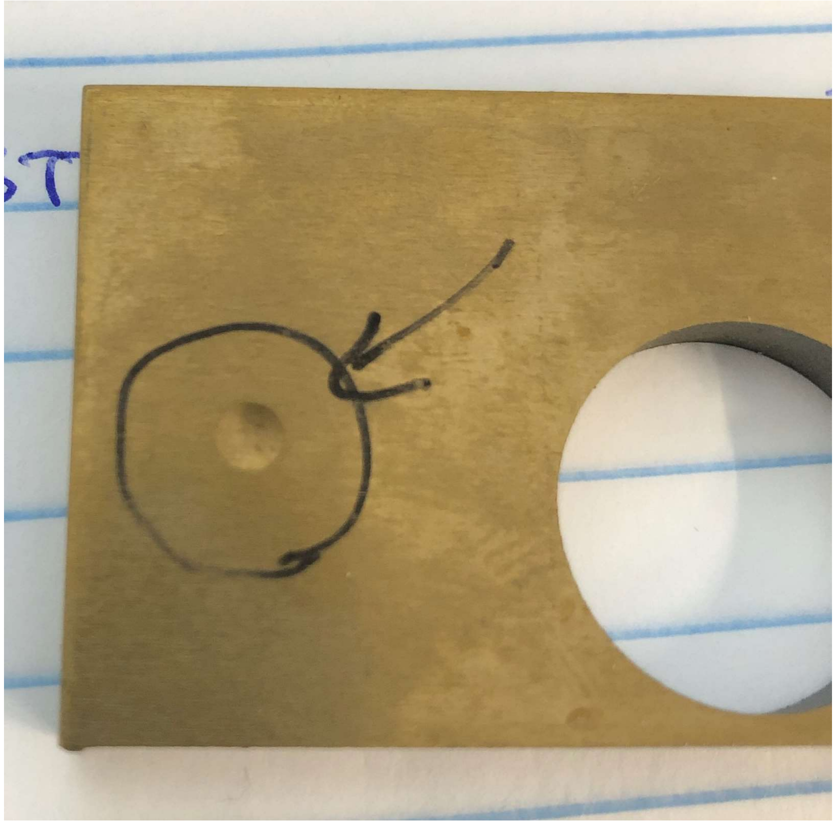


- 2 years, $2.5 MM spent already understanding how to tailor properties on 100+ comp's:

Lower COF	Increase Hardness	Decrease Residual Stress	Decrease oxidation Rate	Laminar Toughening	Decrease Modulus

Success in Solid Particle Erosion resistance for Steam Turbines

Vendor Scaleup Requirements	
Adapt novel process	✓
Meet Composition Targets	✓
Meet Erosion Targets	✓
Coating Quality on Larger Parts	✓
Advanced testing • Ballistic testing • High temperature erosion • Fatigue • Wear • Residual Stress • Process Robustness/Quality	Under-way



Challenges in developing Erosion protection for Steam Turbines

Contributing Factor to Schedule Slide	Corrective Actions
Feedstock Lead Time: 6-8 weeks to obtain custom cathode	Future cathodes are being ordered proactively
Compositional Control: Vendor required additional guidance to produce coatings with the proper amount of Si and V dopants	The difficulty has been addressed

Other GE Research Areas of Interest (incomplete list)

Established Businesses

- Utility Scale Energy Storage
- Additive Manufacturing (Metal and SiC)
- Hydrogen Combustion
- Ammonia Combustion
- Dissimilar Metal Joining
- High Temp Alloy/CMC Development
- Robotics
- Sensors
- AI

Concepts under Consideration

- Catalysis
- SOFC/Electrolysis
- SAF/H_2/RNG/Ammonia Generation
- Carbon Negative Steel and Concrete
- Point Source Capture
- Direct Air Capture

Some questions for the room:

- Are there other performance metrics you think we should be considering?
- Would you like to dummy test our coatings in your harsh environment?
  - High temperature corrosion in combustion, gasification, pyrolysis, advanced power cycle?
  - Erosion, wear, or oxidation applications requiring a thin, conformal protective surface (Cyclone Separators or Venturi Scrubbers for Syngas Cleanup)?
  - Wire-based additive manufacturing for thin-walled heat exchanger, etc?
- Do you think you can beat our coatings?
- Would you like to discuss future funding opportunities?
- Would you like to see more detailed methods, results, market analysis, or citations?
- Are you in the market for a job in metallurgy, coatings, or corrosion?

Find me after this, or email patrick.shower@ge.com

Bottom Line

- The team is developing two types of coatings:

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Our portfolio of energy businesses

CONVENTIONAL POWER *Decarbonize*	**RENEWABLES** *Accelerate*	**ELECTRIFICATION** *Secure, Flexible & Resilient*

GAS POWER NUCLEAR STEAM HYDRO	ONSHORE WIND OFFSHORE WIND LM WIND POWER	GRID SOLUTIONS POWER CONVERSION HYBRIDS

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