DE-FE0031911 Annual Review

Advanced Coating Compositions and Microstructures to Improve Uptime and Operational Flexibility in Cyclic, Low-Load Fossil Plants

May 9, 2022

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NETL, Crosscutting Technology

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GE Research

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Oak Ridge National Laboratory

The University of Tennessee Knoxville

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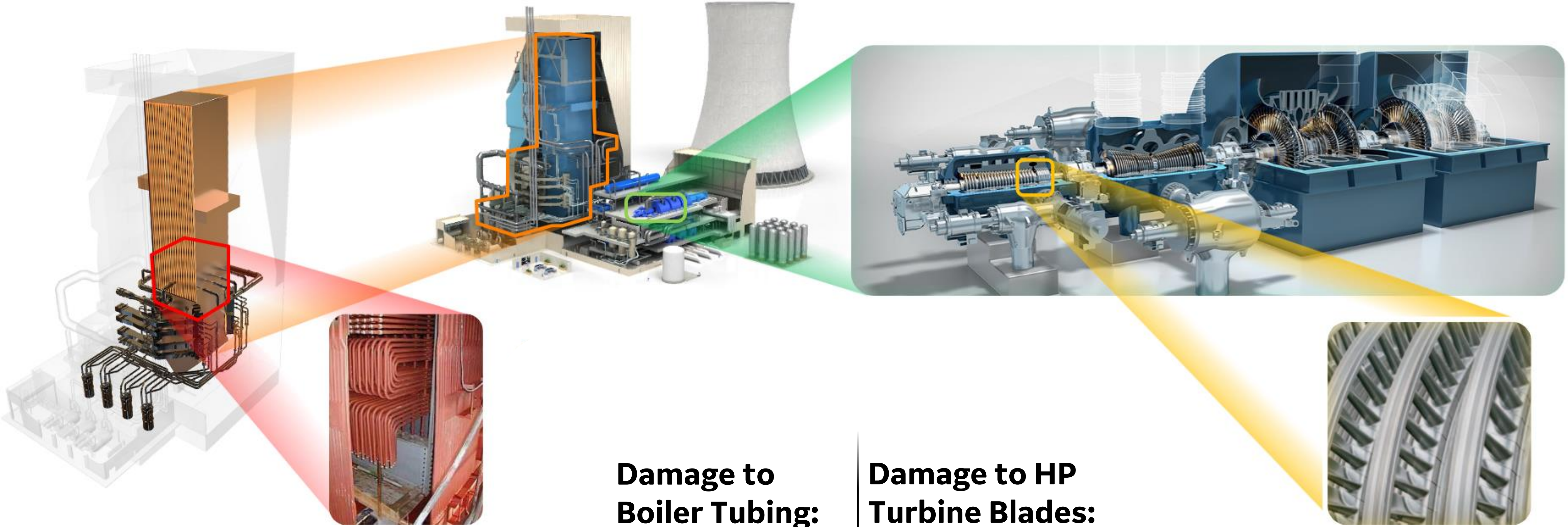
Bottom Line Up Front

- The team is developing corrosion-resistant coatings for boilers and erosion-resistant coatings for steam turbines.
- Lab-scale testing of candidate compositions indicates success:
  - Up to 97% reduction in corrosion rate while eliminating costly Ni and Co
  - 10 μm thick turbine coatings more durable than today's 150 μm thick coatings
- Pilot-scale testing will be used to optimize the coating processes and evaluate how candidate compositions perform on real parts.
  - First coated parts to be delivered in August

Challenges and Opportunities

Problem Statement



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

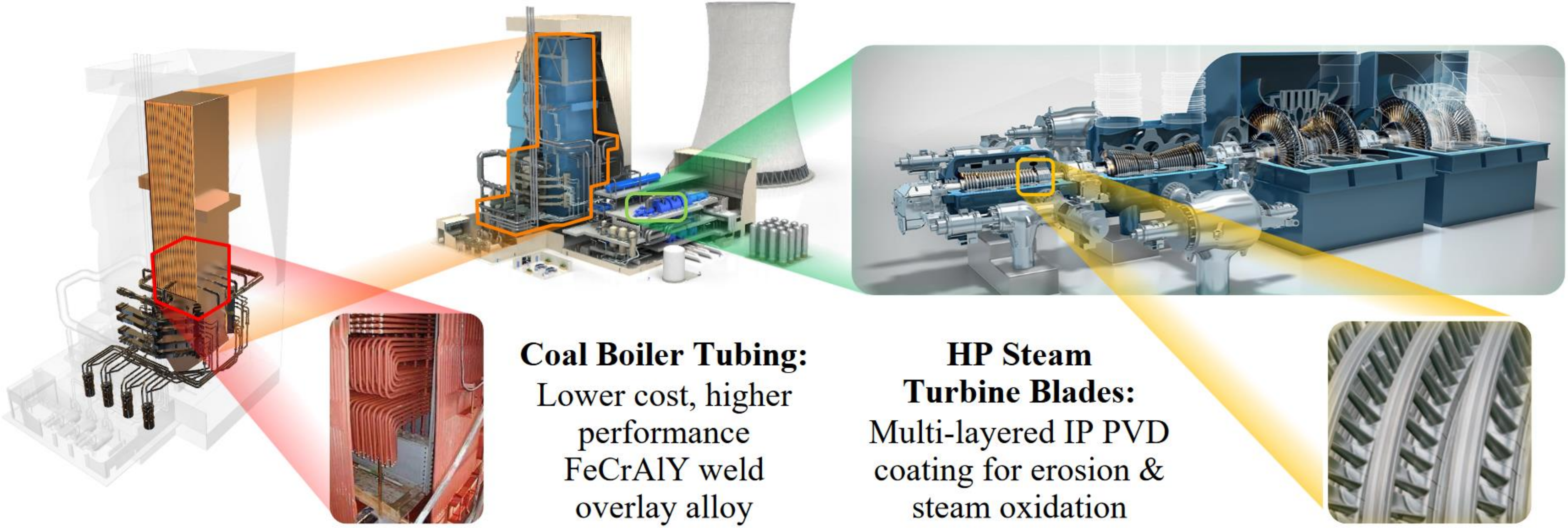
Damage to HP Turbine Blades:

- 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

Objectives

- Enable a 25%-50% increase in time between scheduled outages for both boilers and HP turbines
- Eliminate or significantly reduce the Ni content in weld overlay to reduce material cost by at least 30%
- Provide adequate oxidation and erosion resistance for HP turbine inlet steam at >620 °C and >220 bar
- Apply coatings to actual components, using today's production-scale methods



Provide cost-effective, drop in coating solutions with smarter compositions

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

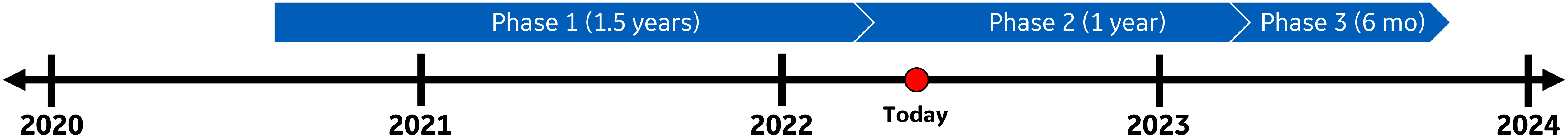
Develop Coating Methods

- 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



Steam Turbine Coatings for Erosion Resistance

How to deal with Solid Particle Erosion for HP Turbines

Attack mechanism:

- Spalled, oxidized material from cycling travels along steam path and enters HP turbine

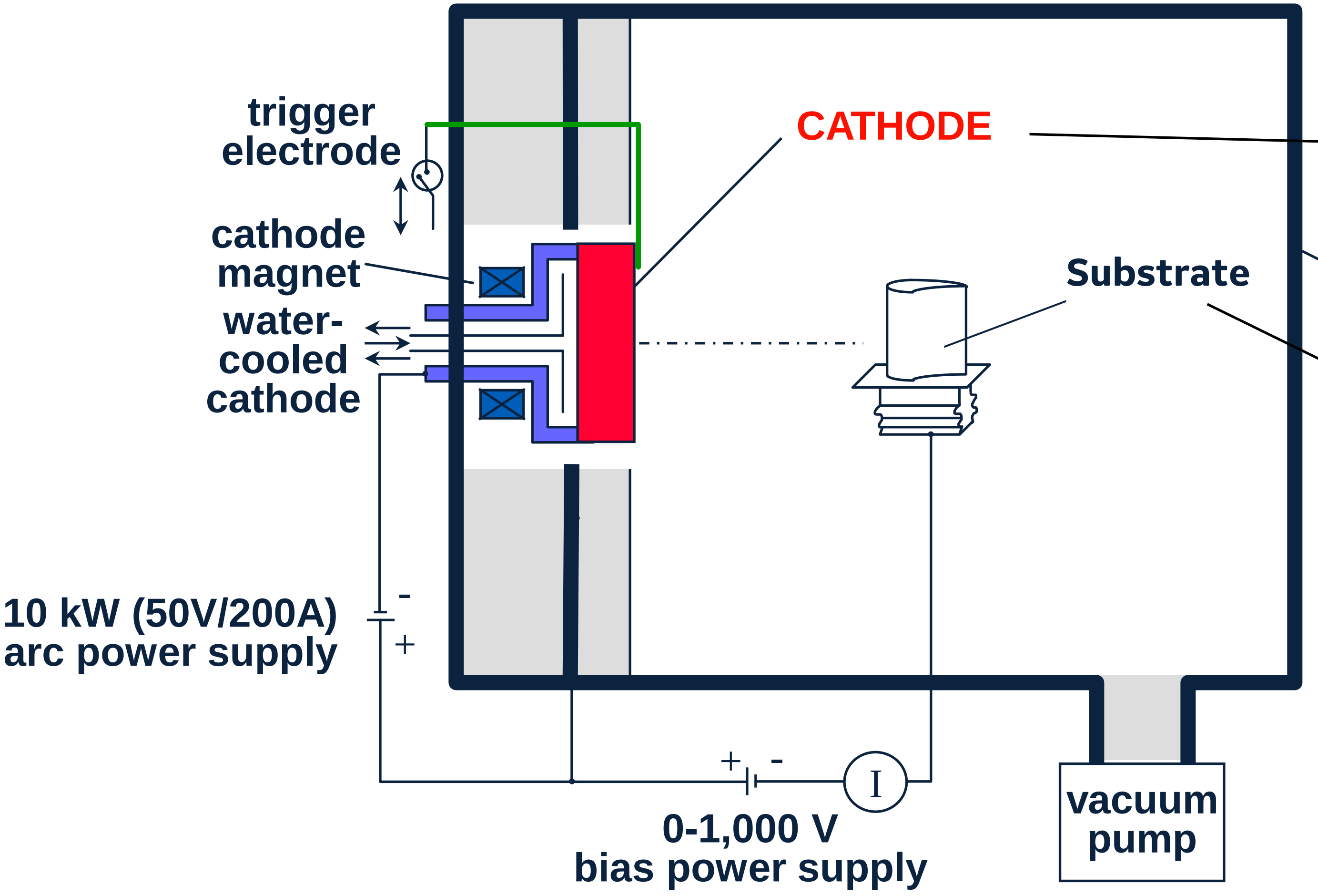
Mitigation options available today:

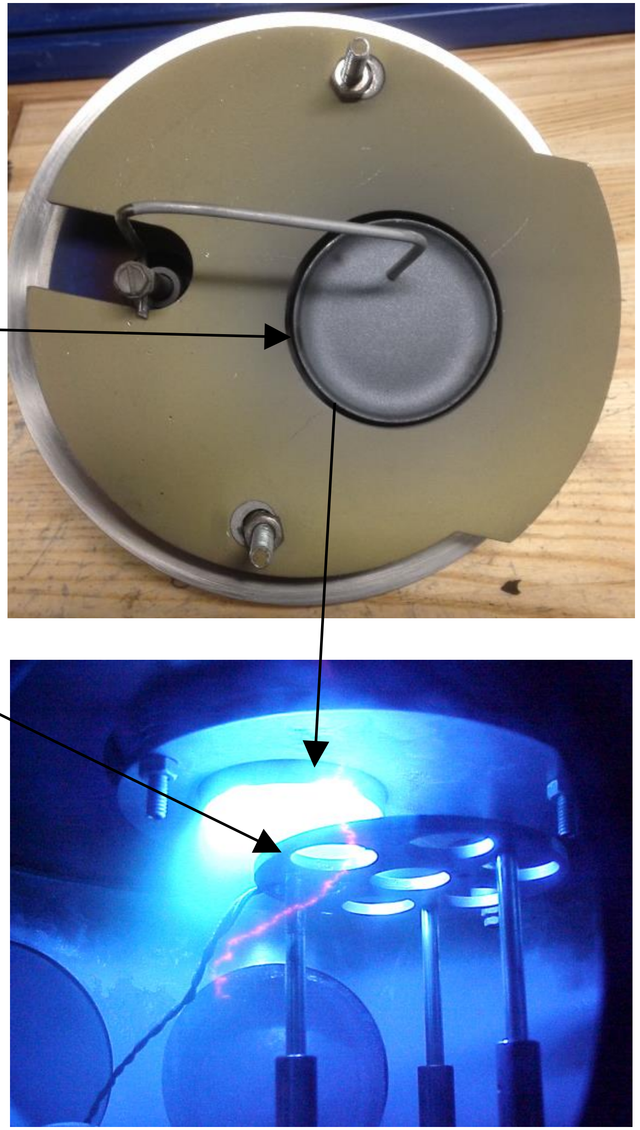
Erosion Protection Strategy	Coating Thickness	Adequate Service Life	Minimal Aerodynamic Debit	Rapid Implementation
Steam Path Redesign	N/A	✓	✓	
Thermal Spray Cermet	150 µm – 250 µm	✓		✓
PVD TiN	3 µm – 10 µm		✓	✓
Novel PVD coatings	10 µm – 30 µm	✓	✓	✓

- 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

Sample production with Ion Plasma PVD

- Gen 1: 12 Cr/Ceramic layered architectures were produced
- Gen 2: 36 additional ceramic compositions were produced
- Gen 3: 12 process and chemistry variations on best candidate





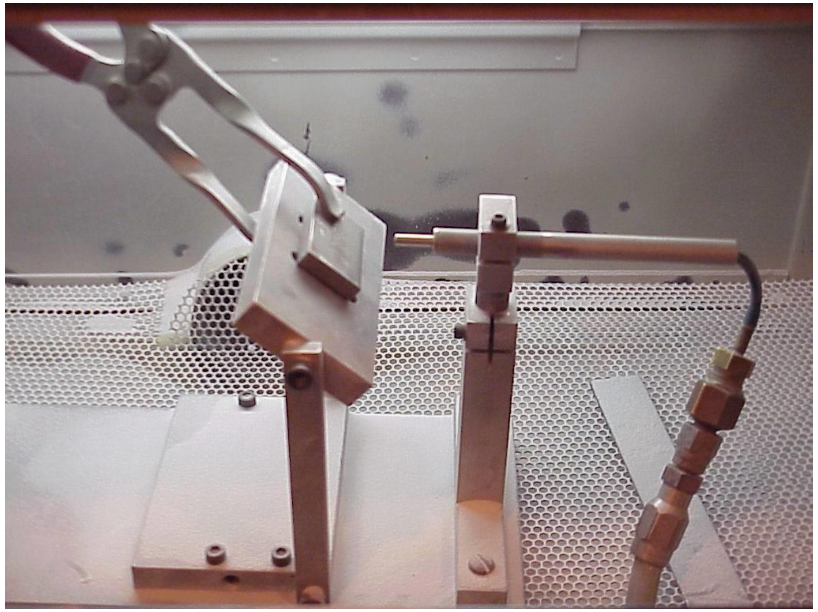
Erosion and Steam Testing

<u>Steam exposure</u>

- 600 ^{o}C, 1 Atm steam
- 100 hours

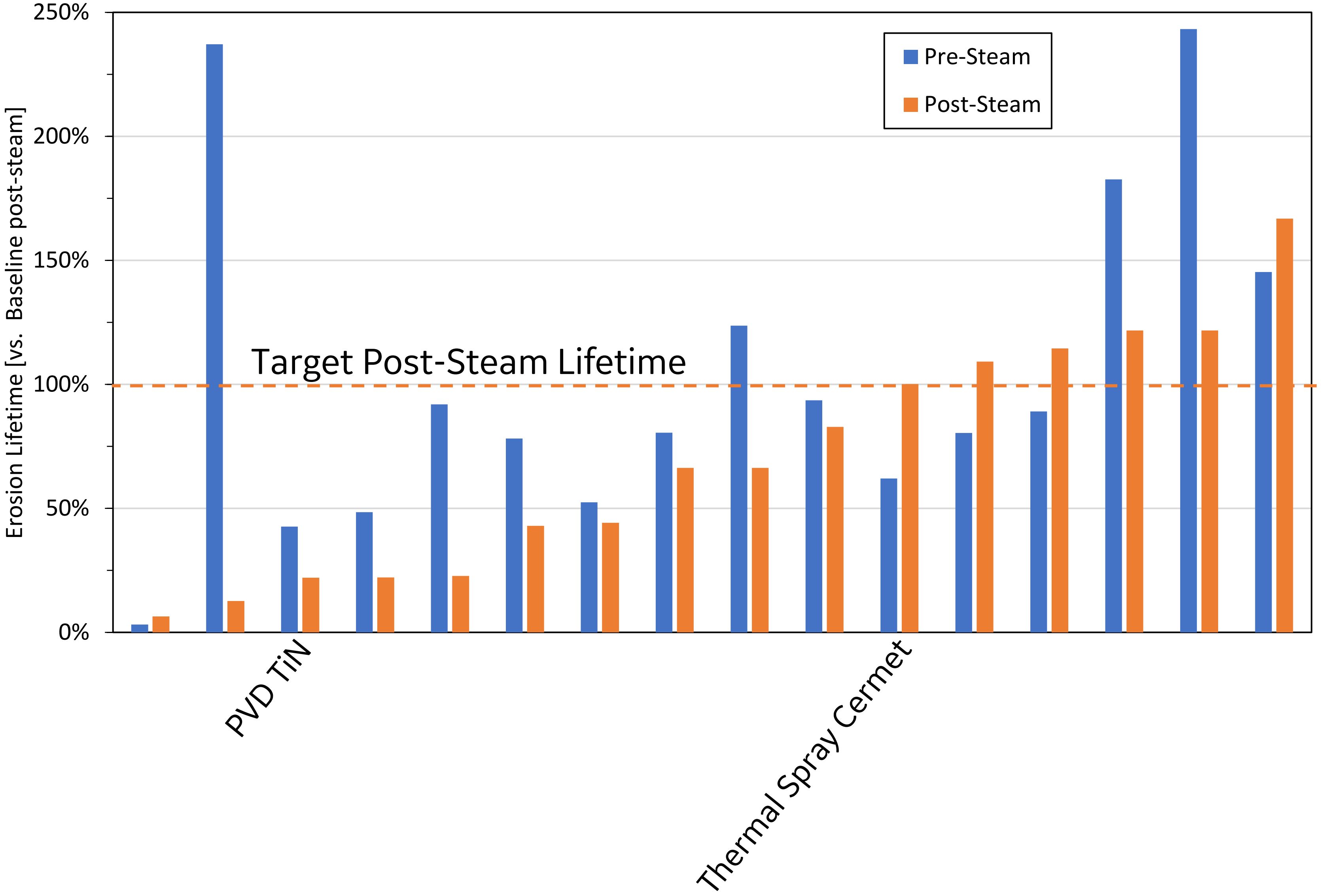
<u>Erosion</u>

- 50 micron alumina in air
- 20^{o} impingement
- 5 g/min
- 7.21 mm standoff
- 9 spots minimum
- Volume loss estimated by mass loss and theoretical coating density
- Tested before and after steam exposure



Representative Sample of Post-Steam Erosion Results

- "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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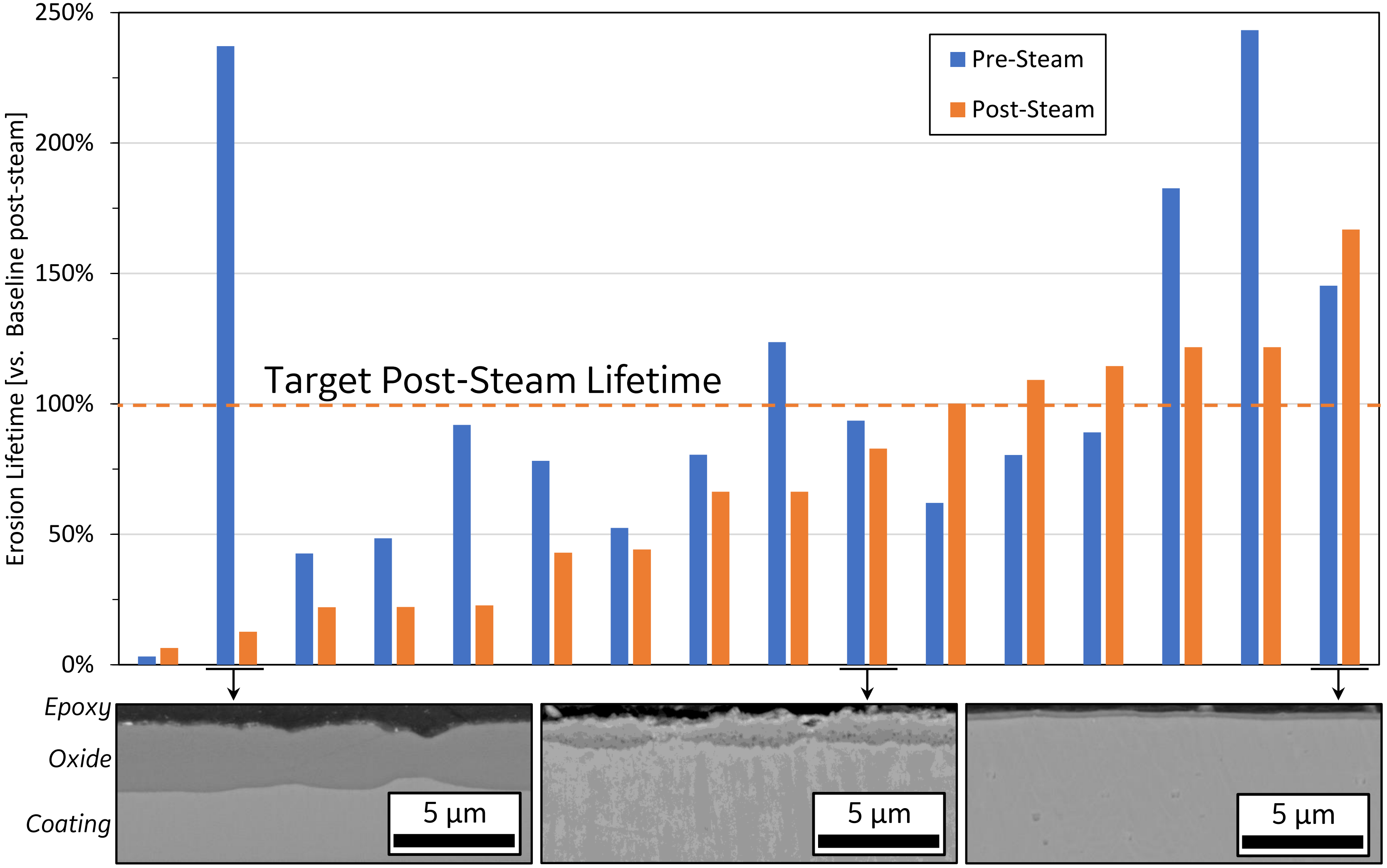

Post-steam cross sections generally show correlation between oxide growth rate and drop in erosion resistance

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Considerations for process optimization and scaleup

- Conformance
  - Uniform thickness?
  - Surface roughness below threshold that requires machining?

- Performance
  - Coating adhesion on increased curvature?
  - Longer duration steam oxidation resistance?
  - Erosion resistance at elevated temperature?
  - Erosion resistance against wide range of erodent size/velocity/composition?

Boiler Tube Coatings for Hot Corrosion Resistance

What we know about Hot Corrosion Protection for Boilers

Attack mechanisms:

- Combination of Oxidation, Sulfate attack, and Alkali Chlorides (if firing biomass).

Material (and Fuel) choice is driven by cost:

- Decreased hot corrosion rate decreases outage frequency and operational costs.
- Increasing Ni content historically decreases corrosion rate but increases material costs.
- Fossil-fired plants face a tradeoff between these two factors.

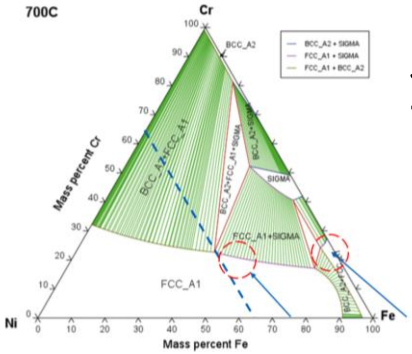
Weld overlay Materials	
Alloy	Wire cost per 10 feet of Tube
309	$ 0.76
312	$ 0.98
625	$ 2.64
622	$ 3.19
52	$ 3.41
72	$ 6.94

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

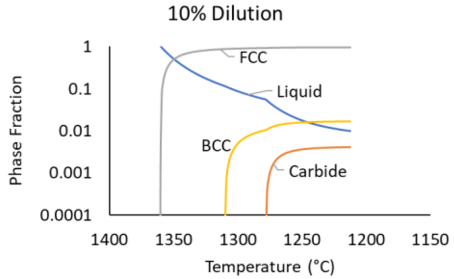
- Biomass-fired plants are typically forced to use expensive Ni-based weld overlay *and* decrease steam temperature, leading to lower efficiency and profitability.
- An ideal weld overlay would cut out Ni while providing adequate protection for T91 tubing.

Risk Retirement approach to Weld Overlay Sample Production



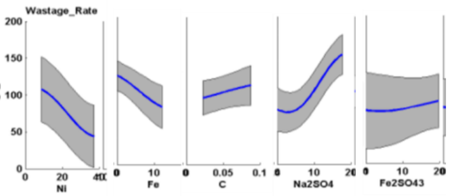
1. Must meet or exceed hot corrosion resistance of alloy 72 with Ni<35 wt. %
   - Computational thermodynamics to define possible range of Fe, Ni, Cr
   - Minor alloying elements selected based on prior work and literature review

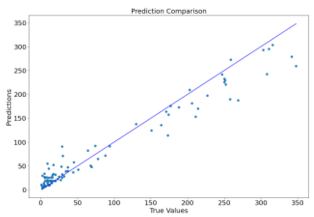
2. Must not incur additional processing costs due to inadequate weldability
   - Schiele simulation with hot cracking criterion evaluated
   - Composition adjusted until criterion is sufficiently reduced
   - Solid State Cracking and Embrittling Phases also considered

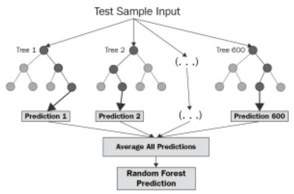


3. Candidate compositions undergo spin casting and centerless grinding
   - Cylindrical pins are used for hot corrosion
   - As-cast microstructure is similar to as-welded microstructure

4. Machine learning (Bayesian Hybrid Modeling + Random Forest) and human analysis
   - Validate or refute hypotheses from previous steps
   - Provide input for the next iteration of alloy design

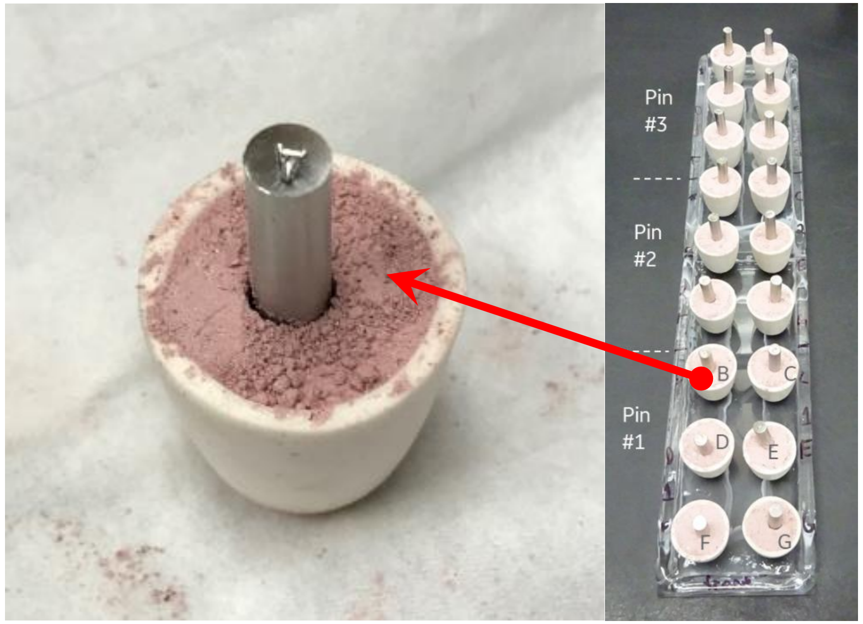






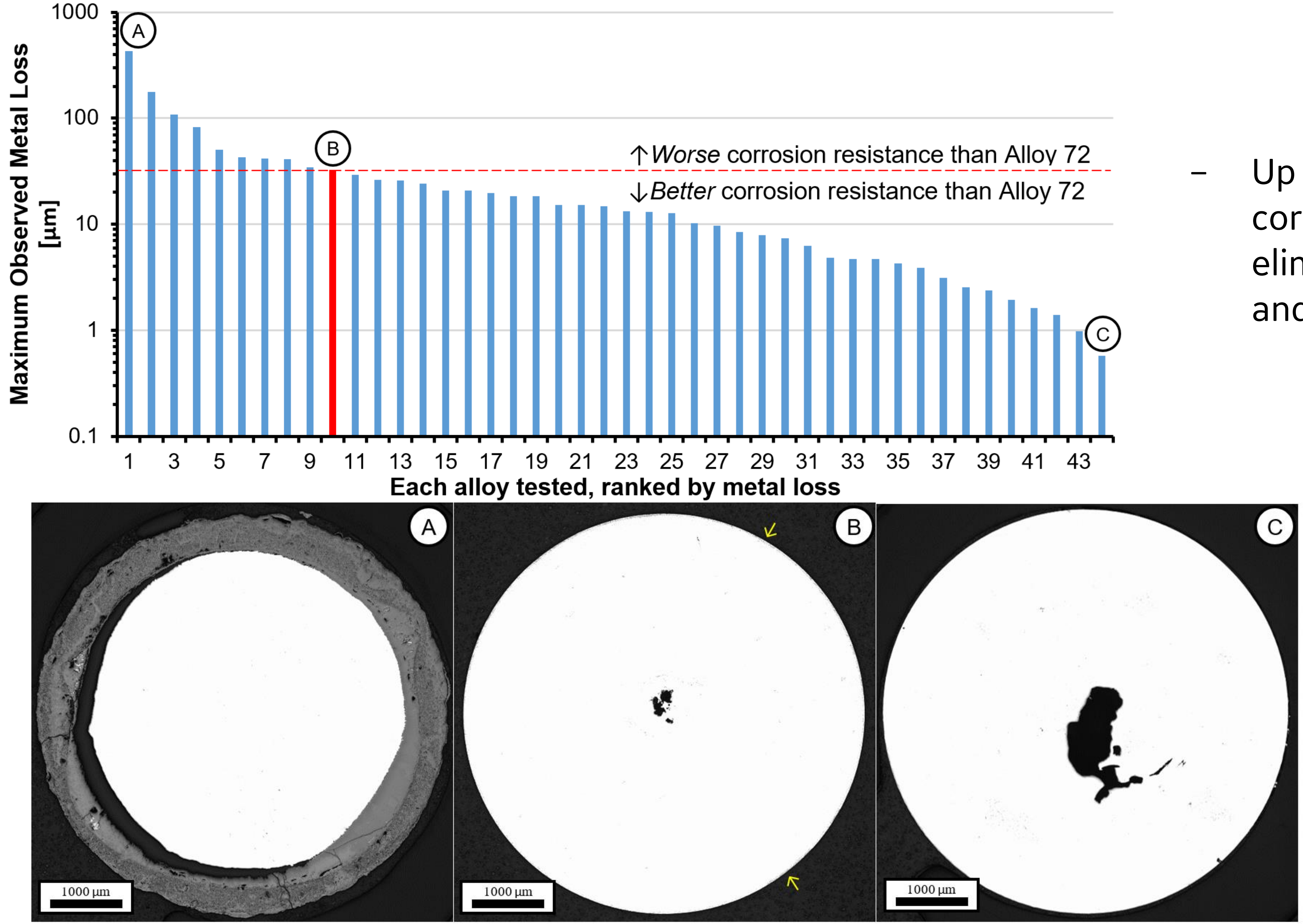
Hot corrosion test setup

- 700 °C
- 150 hrs to 500 hrs
- Oxide mix based on Powder River Basin Coal
- Sulfates, Carbonates, and Chlorides added
- Metal loss is measured after testing

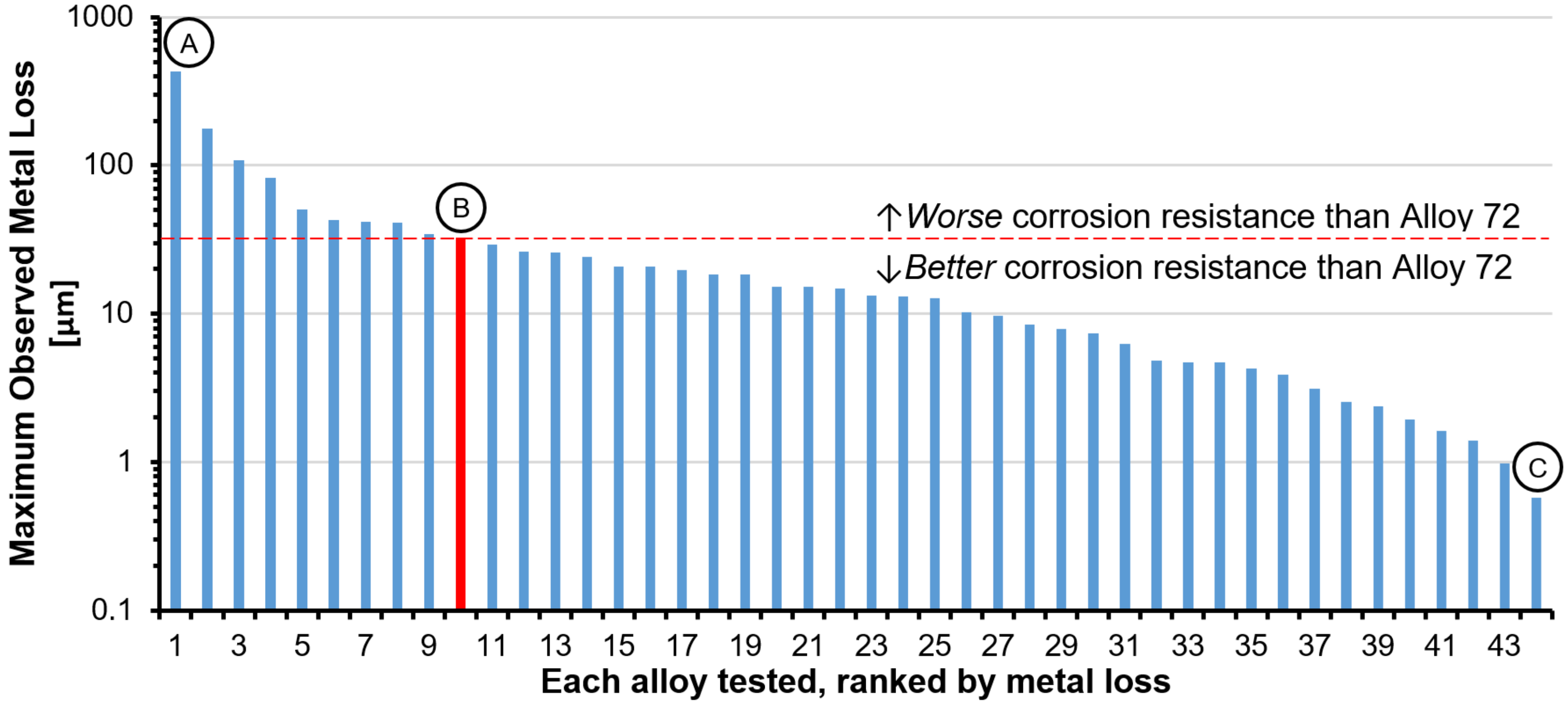


Start the test (0 hr) 3 samples → 1/3 test time (150 hr) 3 samples → End of test (500 hr) 3 samples
- 1 sample @ 350 hr
- 2 samples @ 500 hr

At 1/3 test time: Pull 1 sample @150h; Put in 1 new sample



- Up to 97% reduction in corrosion rate while eliminating costly Ni and Co



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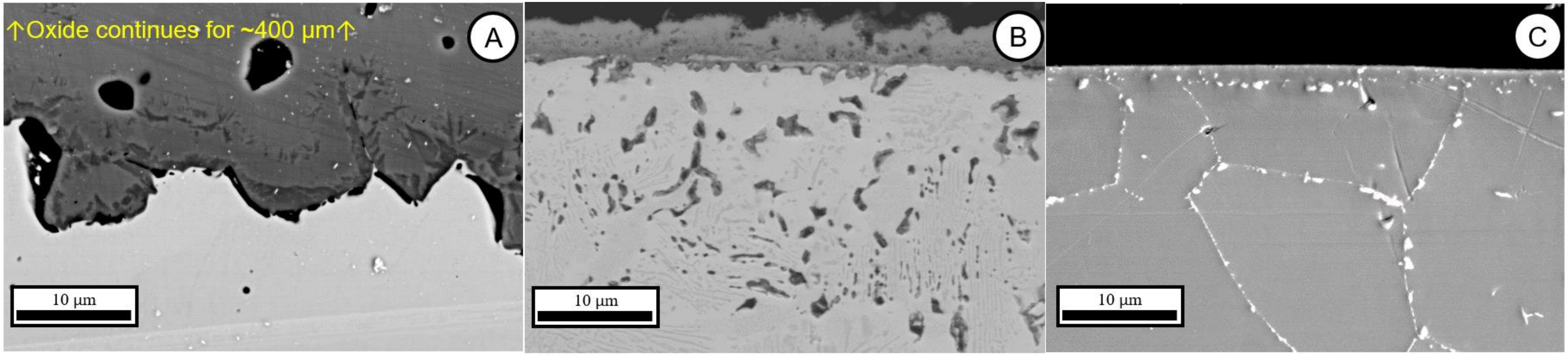
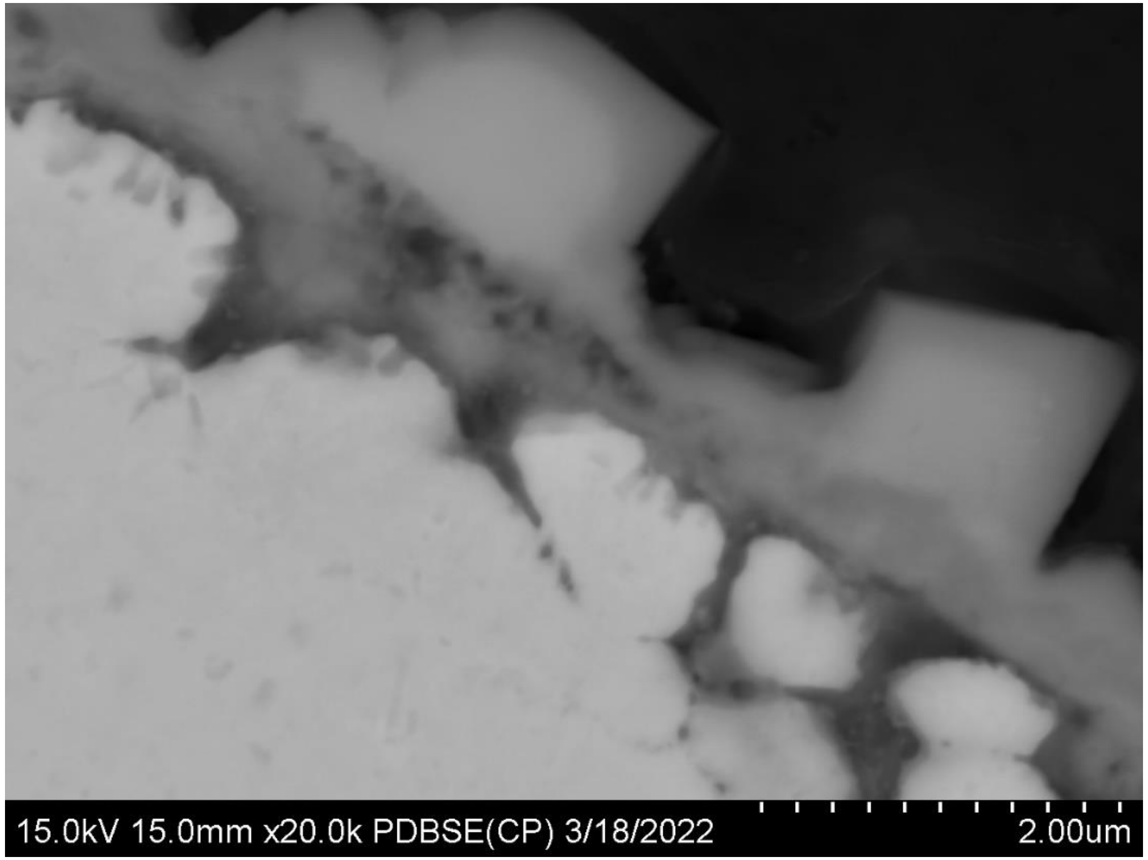
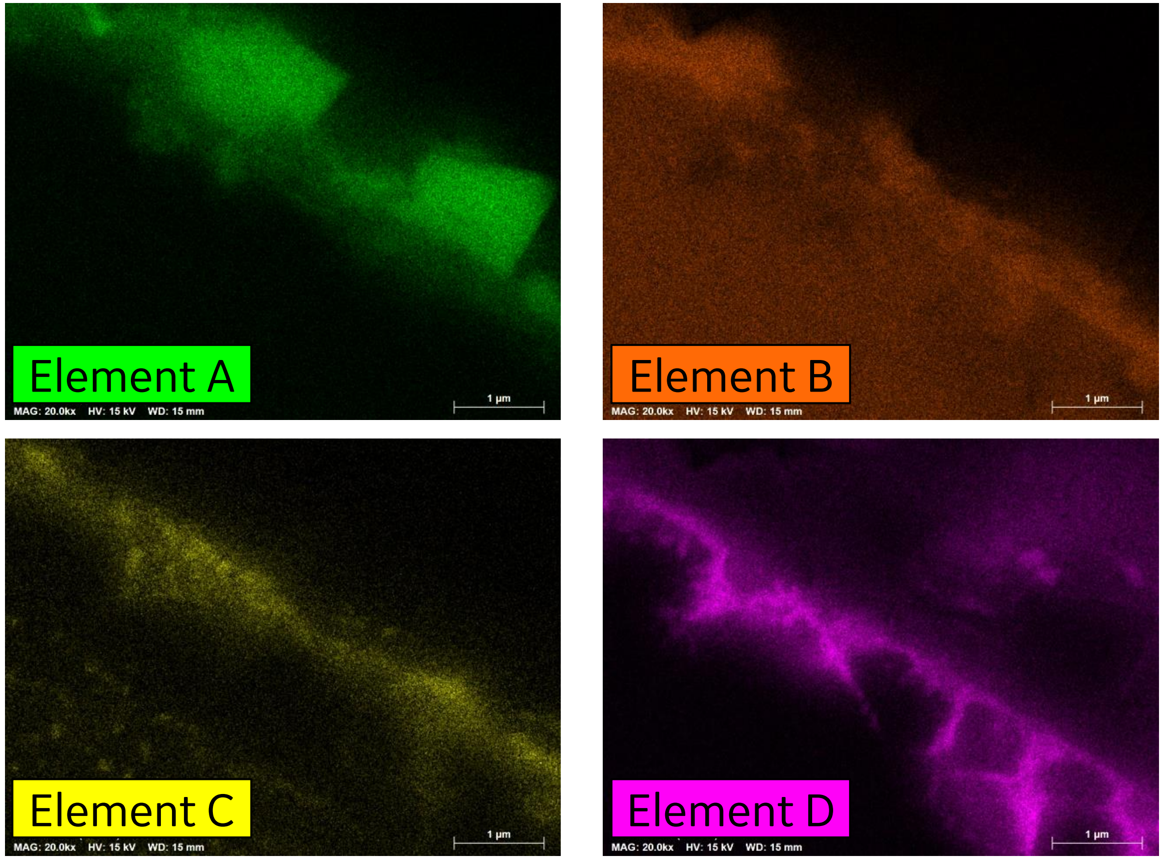


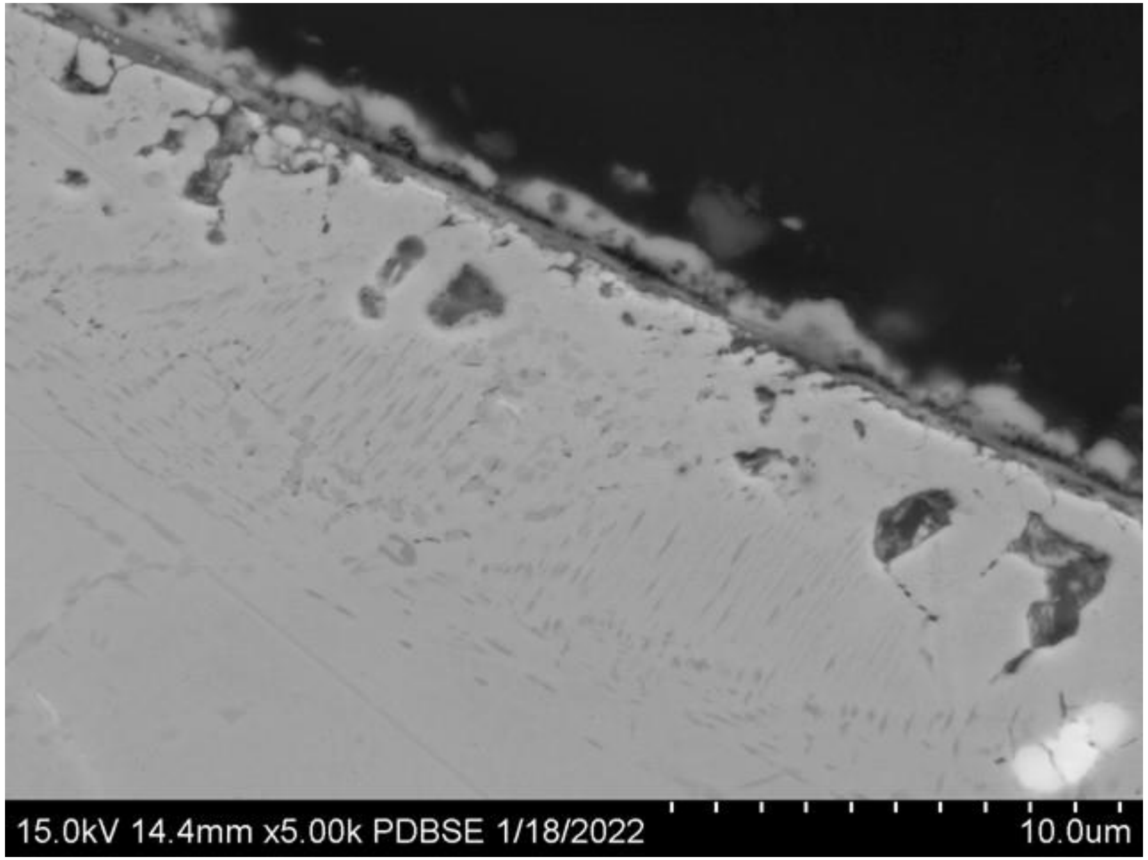
Mechanisms for Hot Corrosion Resistance

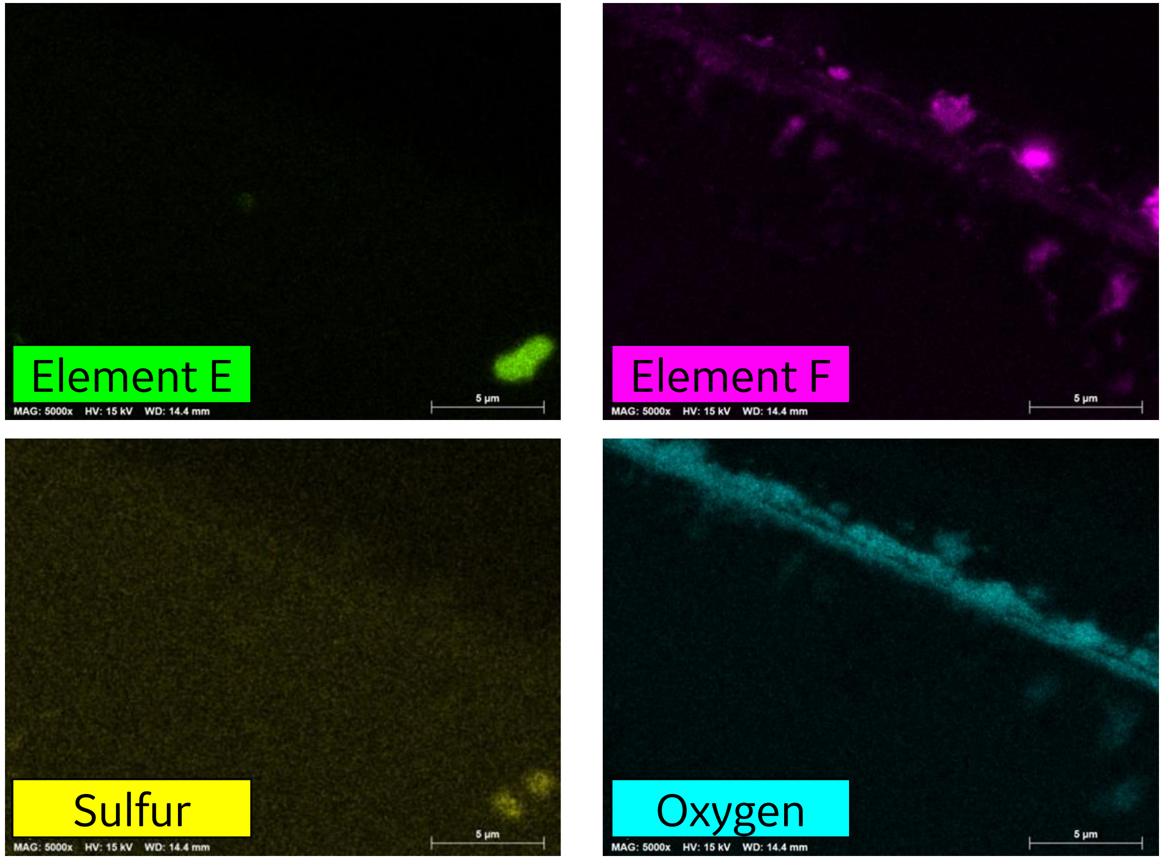




Multi-layer oxides are generally more effective than single-layer oxides

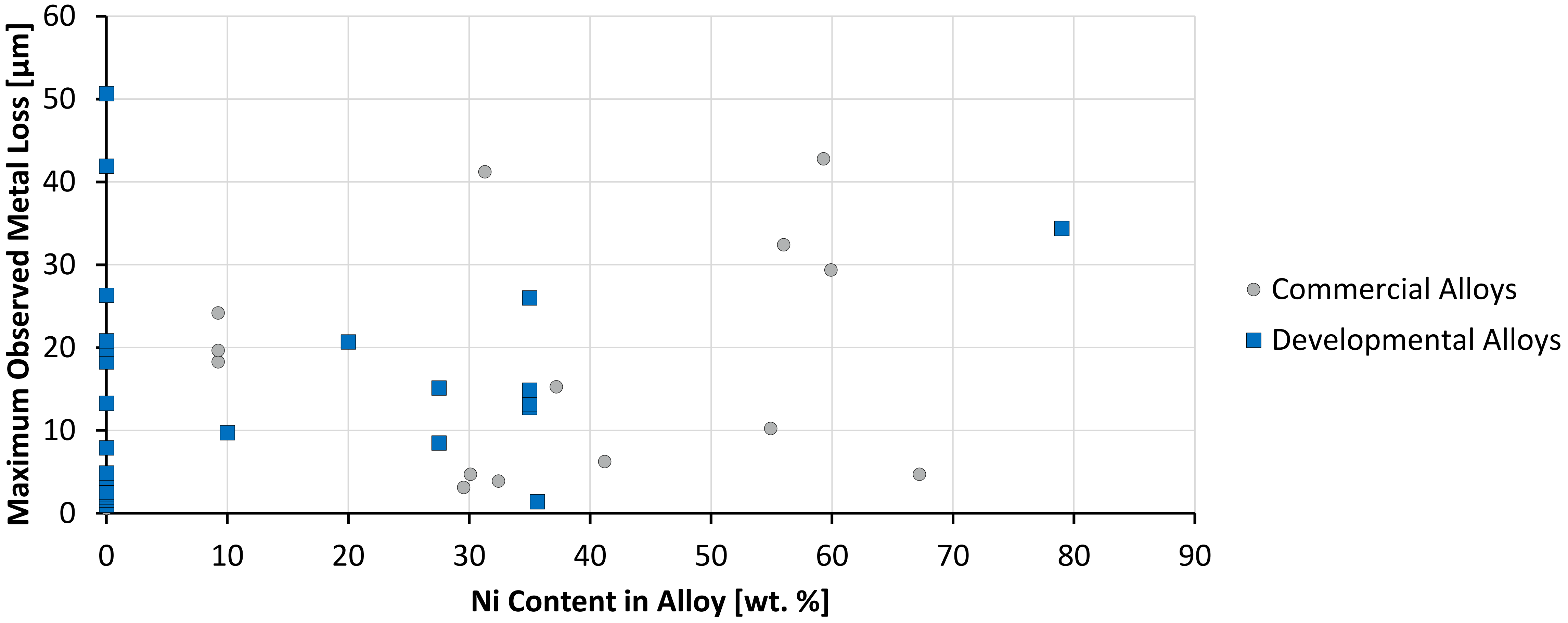
Mechanisms for Hot Corrosion Resistance





Gettering elements can help control the effects of internal oxidation and sulfidation

Successful lab-scale testing of 0 – 35 wt. % Ni alloys



Leveraging mechanistic understanding and machine learning yields lower-Ni performance

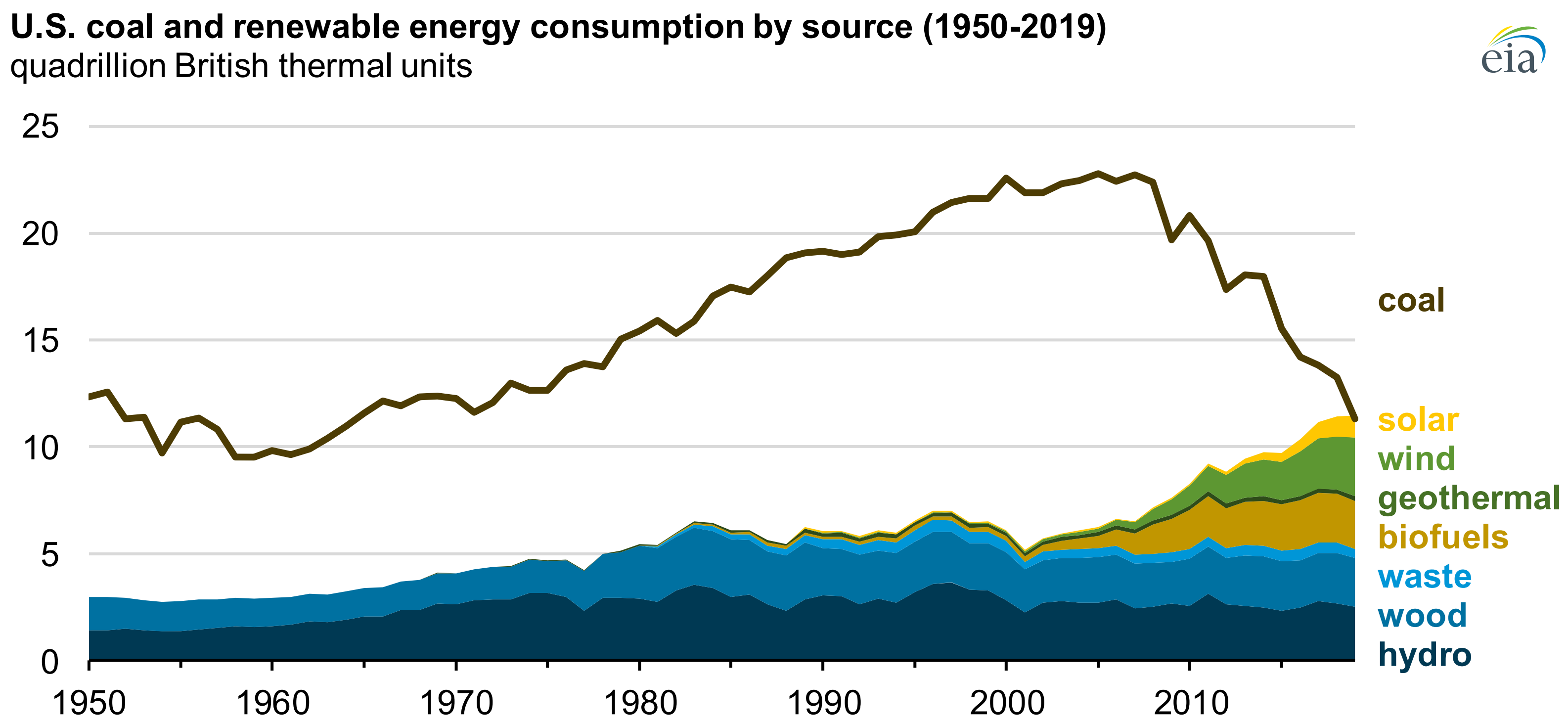
Considerations for process optimization and scaleup

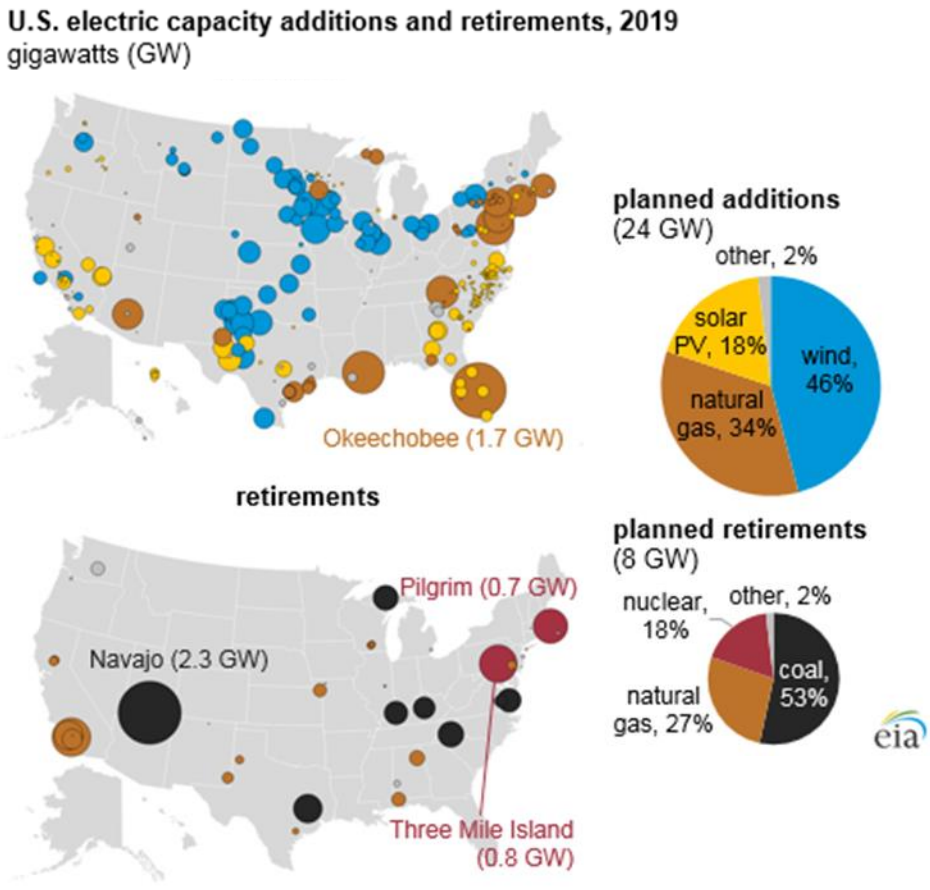
- Conformance
  - Uniform thickness?
  - Heat treating requirements to be compliant with ASME?

- Performance
  - Is candidate composition transferred effectively?
  - Does testing in a pilot scale boiler produce similar hot corrosion results?
  - Do the alloys need to be further modified to allow for “drop in” weldability?

Conclusions

Technological Context





- Renewables comprise ~20% of the nation's electricity portfolio.
- Experience in Europe suggests that this can increase to ~70% with the aid of dispatchable sources.
- Today this is primarily coal and natural gas, and even these are sometimes strained.
- Tomorrow it could be carbon neutral (biomass, green hydrogen, Gen IV nuclear) given the right technology.

Electricity Source	Nuclear	Coal	Biomass	Natural Gas (C.C.)	Wind	Solar (PV)
Levelized Cost of Electricity [$/MWh]	163	112	102	59	40	34
% of LCOE due to MRO	10.6%	12.6%	27.6%	11.4%	22.2%	13.2%

One potential outcome of this technology: coal to biomass

Challenge	Opportunity
High Boiler Tube Wastage Rate →	Deploy more protective weld overlay
High Materials Costs →	Enable low-cost ferritic tube alloys to withstand hot corrosion
Stranded Steam Utility Assets →	Make it feasible to begin cofiring an increasing percentage of Biomass
Biomass fuel is less uniform and less available than other feedstocks →	Enable fuel flexibility so that cheaper, greener, and more economically beneficial local biomass can be utilized
Economic viability depends on load following, which leads to more harsh solid particle erosion →	Provide increased protection to steam turbine components
Coal still accounts for ¼ of our energy-related CO_2 emissions →	Convert to firing carbon-neutral biomass with the option to introduce carbon capture for negative emissions
Today, Natural Gas and Petroleum account for 1.6x and 2.2x the emissions of coal, respectively →	Reduce LCOE of Biomass and use it as part of the dispatchable backbone while accelerating electrification

- Improving the economics of biomass-fired, load following steam utility plants paves the way for:

1-year transition to Reduced Carbon co-firing of biomass with coal	**5-year transition** to Carbon Neutral firing of sustainably sourced biomass	**10-year transition** to Carbon Negative production of Biomass Energy with Carbon Capture and Storage (BECCS)

"Now as you look to the future of biomass energy in the US, we see Bioenergy with Carbon Capture and Storage, or BECCS, in that future."

-Agriculture Secretary Vilsack
March 31st, 2022

"We're looking at Bio-Energy with CCS with natural systems. We're in the Southeast, and there's a lot of timber and waste wood in our system, and so using that for Bio-Energy CCS is really compelling".

-R. Esposito, Southern Co. Carbon Management Lead
February 23rd, 2022

ipcc INTERGOVERNMENTAL PANEL ON climate change

Projects that BECCS will match Nuclear deployment by 2040 for 2 °C scenario.

-RCP 2.6 projection,
February 13th, 2019

Bottom Line

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- Lab-scale testing of candidate compositions indicates success:
  - Up to 97% reduction in corrosion rate while eliminating costly Ni and Co
  - 10 µm thick turbine coatings more durable than today's 150 µm thick coatings
- Pilot-scale testing will be used to optimize the coating processes and evaluate how candidate compositions perform on real parts.
  - First coated parts to be delivered in August

Comments, clarification, or collaboration: patrick.shower@ge.com

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FE0031911.

Backup Slides

Material and Process Development | Testing | Evaluation

Boiler Coatings

Management

Technical, Financial, and Logistical Management
GE Research

Technology Manager:
Briggs White at NETL

Federal Project Manager:
Michael Fasouletos at NETL

Optimizing Chemistry

Literature Review:
GE Research

Computation:
GE Research, UTK

Prior Experience:
All, led by GE Steam Power

Sample Production

Vacuum Induction Melting:
GE Research

Machining:
GE Research

Processing/ Exposure

SO_2 Furnace Test:
GE Research

Melt Pool Test:
GE Research

Advanced Weld Test:
GE Steam Power, UTK

Quantifying Corrosion

Metal Loss Rate:
ORNL

Phase/Mechanism ID: *ORNL*

Metallography:
GE Research

HP Turbine Coatings

Optimizing Chemistry

Literature Review:
GE Research

Prior Experience:
GE Research
GE Gas Power

Sample Production

Substrate Prep and Ion Plasma Deposition:
GE Research

Thermal Spray:
GE Research

Exposure

Steam Testing:
GE Research

Quantifying Erosion

Erosion Testing:
GE Research

Metallography:
GE Research

Post-Testing

Processing/Microstructure /Performance analysis:
GE Research

Data organization:
GE Research

Annual/Quarterly/Biweekly Reports:
GE Research

Updated Technology Management Plan:
GE Steam Power

Table 1: Composition of mixed gas in volume %.

N_2	CO_2	O_2	SO_2	H_2O
Balance	15	2.5	0.2	10

Table 2: Composition of synthetic ash used in corrosion test (weight %)

Na_2O	Fe_2O_3	Al_2O_3	SiO_2	CaO	MgO	K_2O	TiO_2	P_2O_5	$CaSO_4$	$NaSO_4$	KSO_4
2.2	5.9	16.3	29.1	23.8	5.2	0.3	1.3	0.9	5	5	5

Phase 1 Roadmap for Steam Turbine Coatings

Objective: Demonstrate improved coating performance at lab scale

Requirements
- Solid Particle Erosion resistance for adequate lifetime
- Thin, smooth, conformal coating before and after steam exposure

Concepts
- Layering to improve toughness
- Cr to improve oxidation resistance
- Enhance TiN by doping

Gen 1: Layering Cr/Ceramic

Objectives
- Optimize architecture to resist oxidation and erosion
- Demonstrate feasible range of layer thicknesses

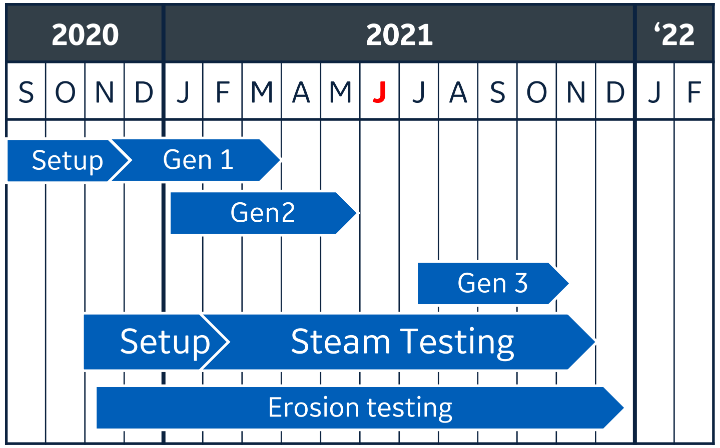
Gen 2: Optimize Ceramic

Objectives
- Prototype compositions
- Maximize erosion resistance
- Maximize coating thickness
- Determine if Cr is needed

Gen 3: Combine Learnings

Objectives
- Refine Gen 1 and Gen 2 compositions as guided by results
- Combine optimized Ceramic with Cr interlayering as needed

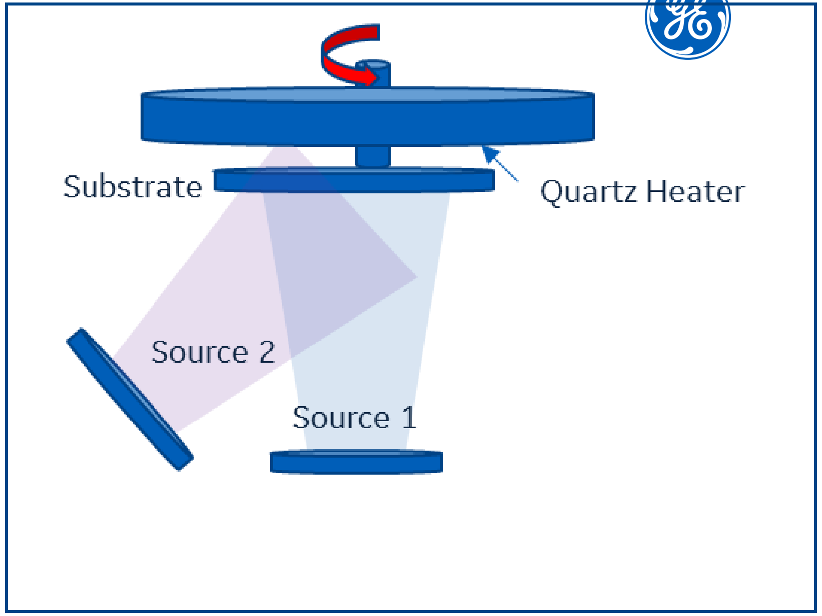
Steam + Erosion Testing

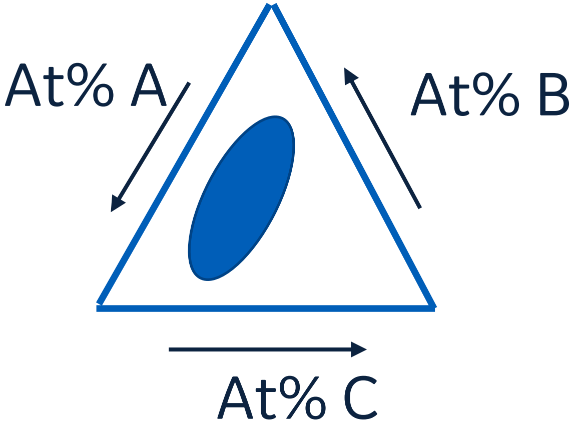


Phase 1 Milestones
- Make 40 samples (42 complete) ✓
- Erosion test 40 samples (36 so far)
- Steam test 40 samples (20 so far)
- Repeat erosion testing post-steam

Prototyping with Sputtering

- Slower but more modular form of Physical Vapor Deposition
- Used to optimize ceramic compositions
- Up to 6 elements can be combined
- Allowed us to explore the effect of various dopants

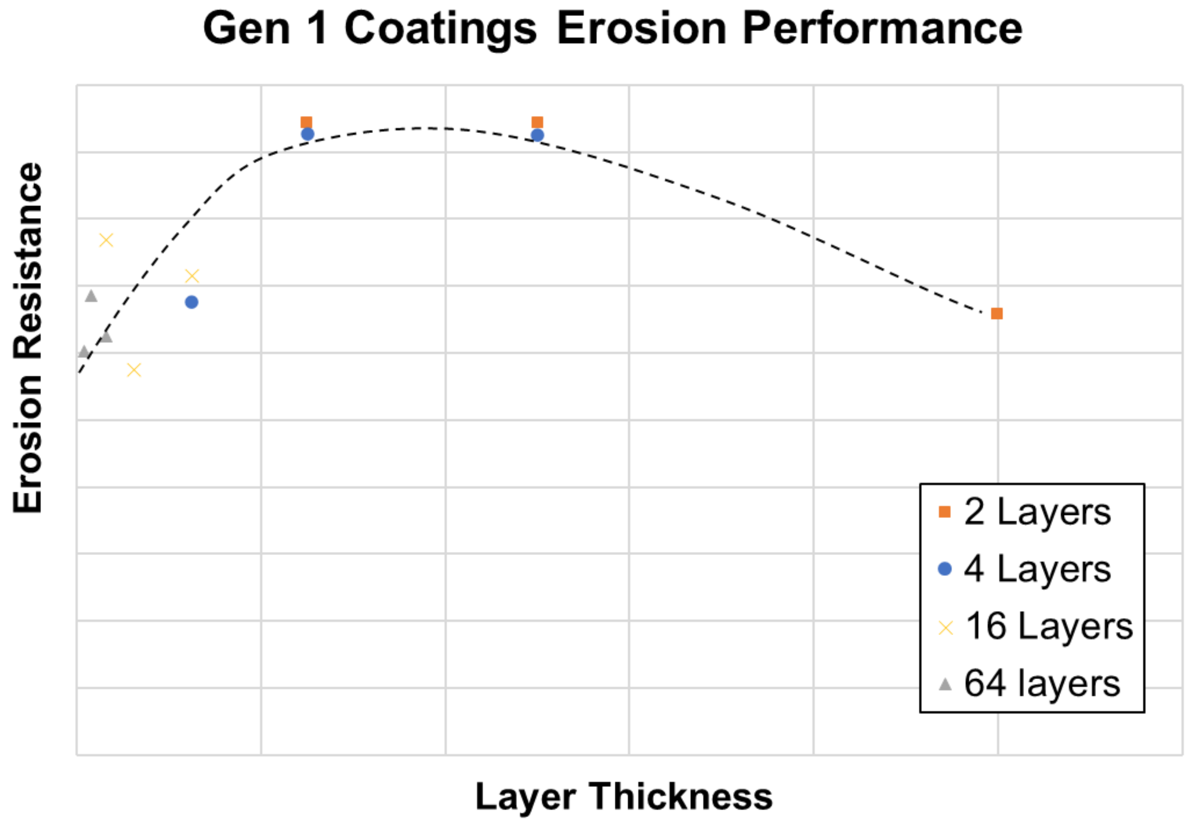




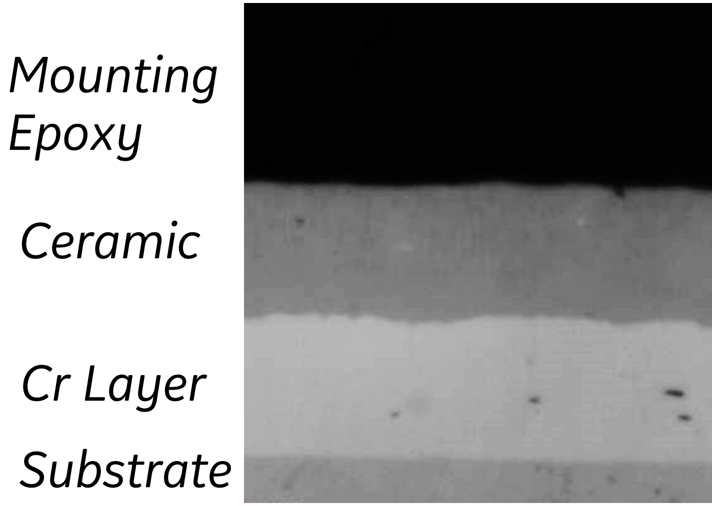
Example of ternary system with example ROI

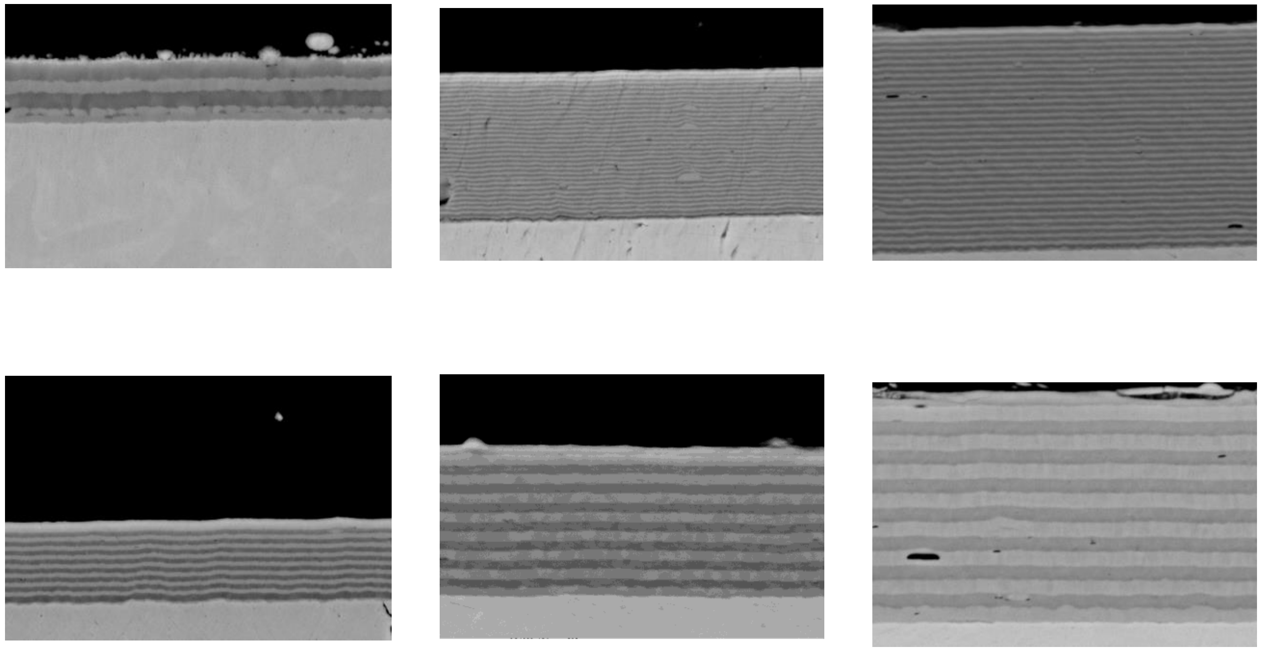
Gen 1 erosion results

- Wide range of layer thicknesses produced
- There is an optimized layer thickness for pre-steam erosion resistance
- Steam oxidation resistance effects TBD



Sample Microstructures:





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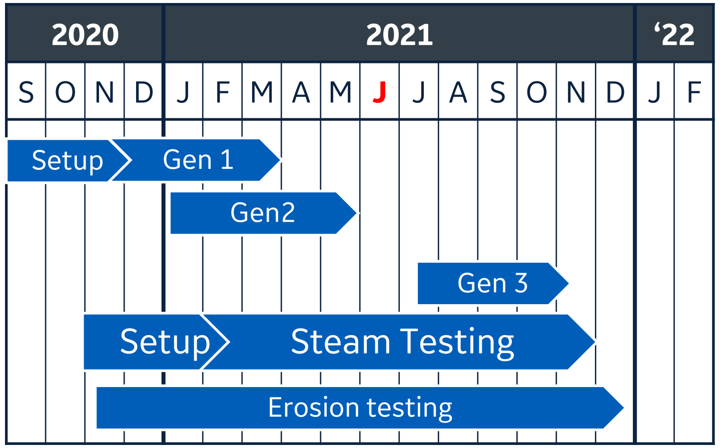

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Figure 1. Chronological steps of producing and testing bead-on-plate transverse bend samples.