# DE-FE0031911 Annual Review

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

**June 15, 2021**


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GE Research

GE Steam Power

Oak Ridge National Laboratory

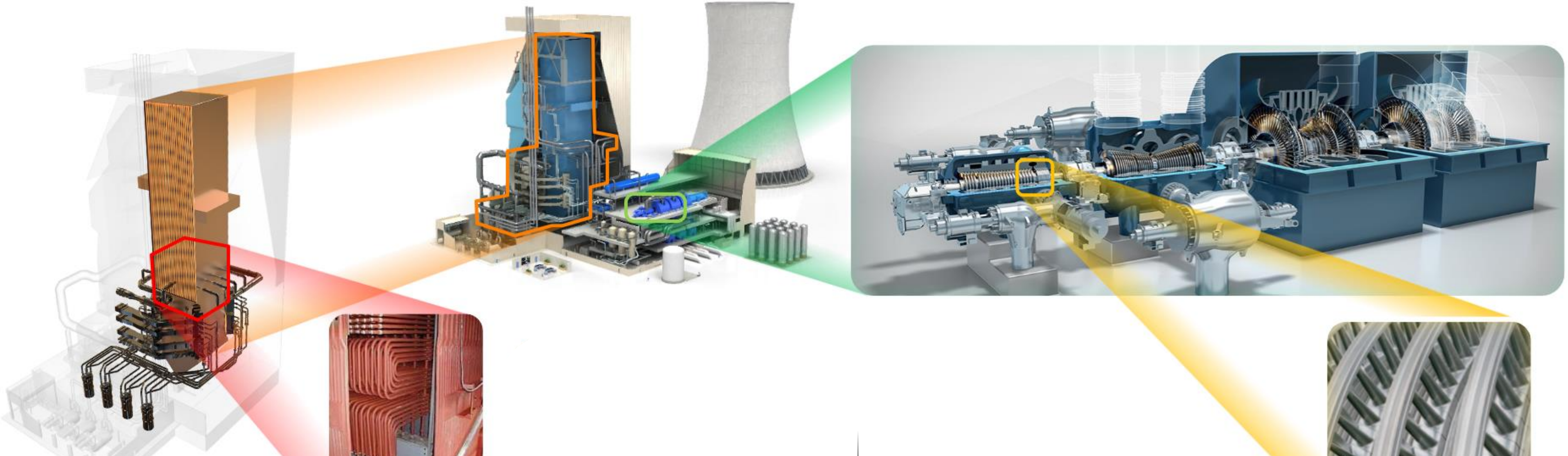
The University of Tennessee Knoxville

# Bottom Line Up Front

- The objective is to deliver coating technologies that increase reliability of the steam path
- According to GE utility customers, the most effective way to do this is to protect boiler tubing and turbine components
- Boiler tubing requires hot corrosion resistance, especially for biomass
  - We are developing weld overlay coatings that are cheap enough to be broadly applied and incorporate many layers of protection mechanisms
  - Computation guides phase compatibility and weldability
  - Within that window, alloys are designed based on prior work and tested in hot corrosion
- High Pressure Steam Turbine components suffer from solid particle erosion
  - We are developing Ion Plasma Deposited coatings with maximized lifetime by increasing erosion resistance and increasing the maximum viable coating thickness
  - Initial results suggest that lifetime can be doubled compared to conventional coatings

# Challenges and Opportunities

# Problem Statement



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 Boiler Tubing:**

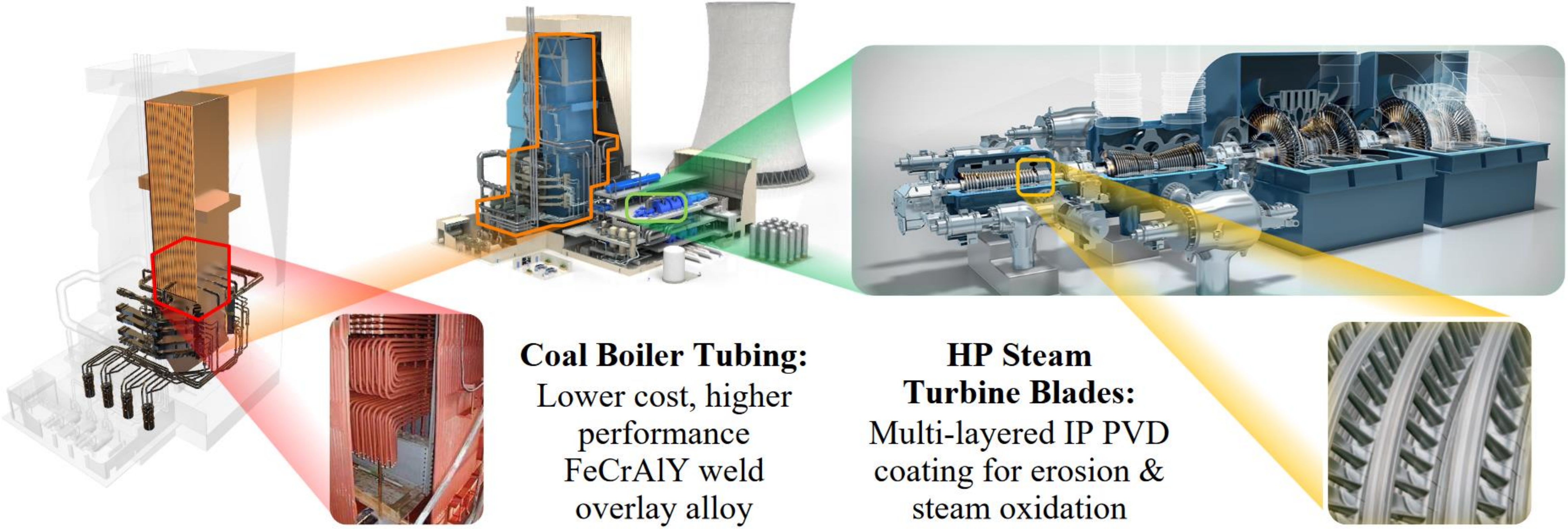
**Damage to HP Turbine Blades:**

- 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 Layered Ion Plasma Deposited (LIPD) compositions

## Phase 2:
## Scale-up

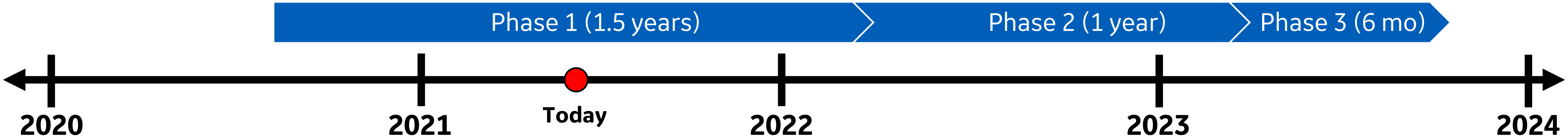
**Develop Coating Methods**

- Ensure that composition of interest can be reliably and uniformly deposited on parts
- Vendor produces weld overlay on ferritic and austenitic tubing
- LIPD 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
- LIPD-coated HP Turbine blades are evaluated with post-steam leading edge erosion testing



# Steam Turbine Coatings for Erosion Resistance

# What we know about Erosion Protection for HP Turbines

## Attack mechanism

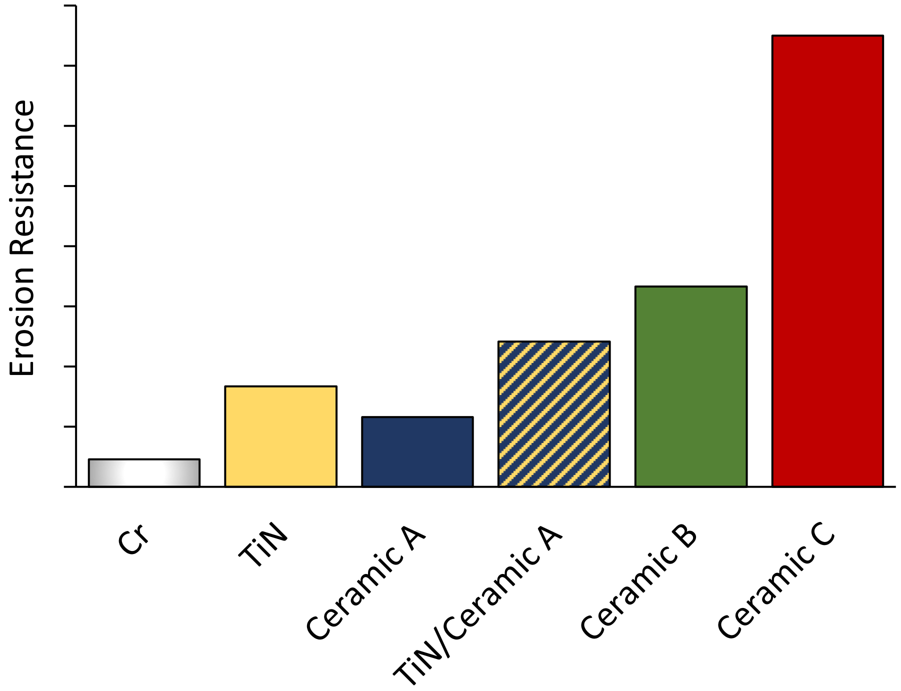
- Spalled, oxidized material from cycling travels along steam path and enters HP turbine

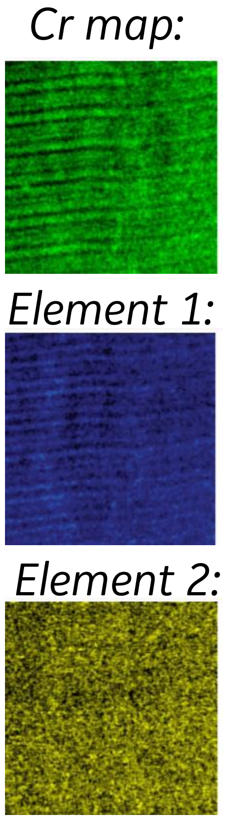
## Prior Work

- Requires redesign or protective barrier
- 250 micron thick Diamond Tuff™ is protective, but heavy and not aerodynamic
- 3 – 10 micron thick IPD TiN is conformal, but does not provide adequate protection
- GE has developed IPD coatings with 4.5x the erosion resistance of TiN
- Cr layers provide oxidation resistance

## Our Strategy

- Apply the most erosion resistant coating that is compatible with blade material
- Interlayer with Cr if additional steam oxidation resistance is needed



# 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

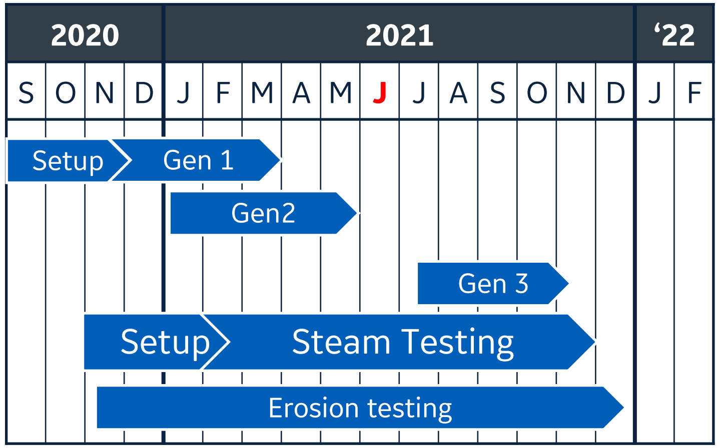
## Gen 2: Optimize Ceramic

**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

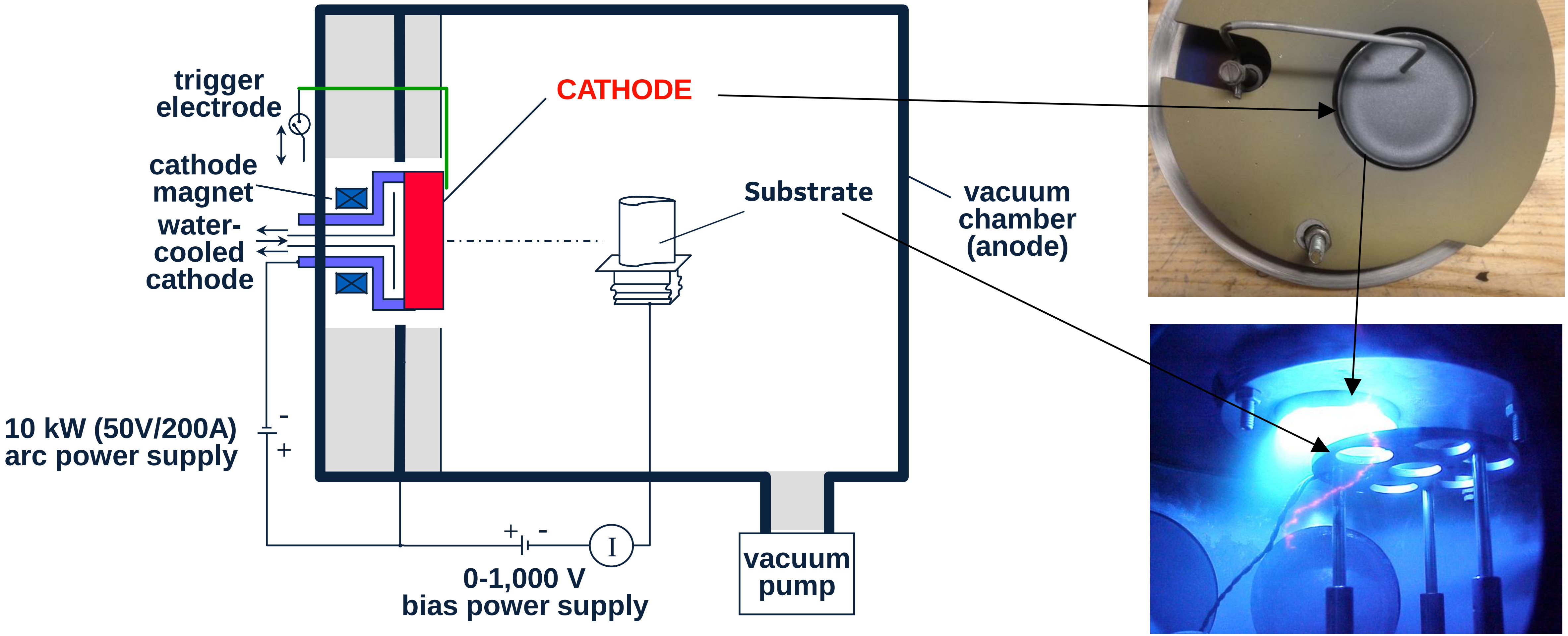
Steam + Erosion Testing




**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

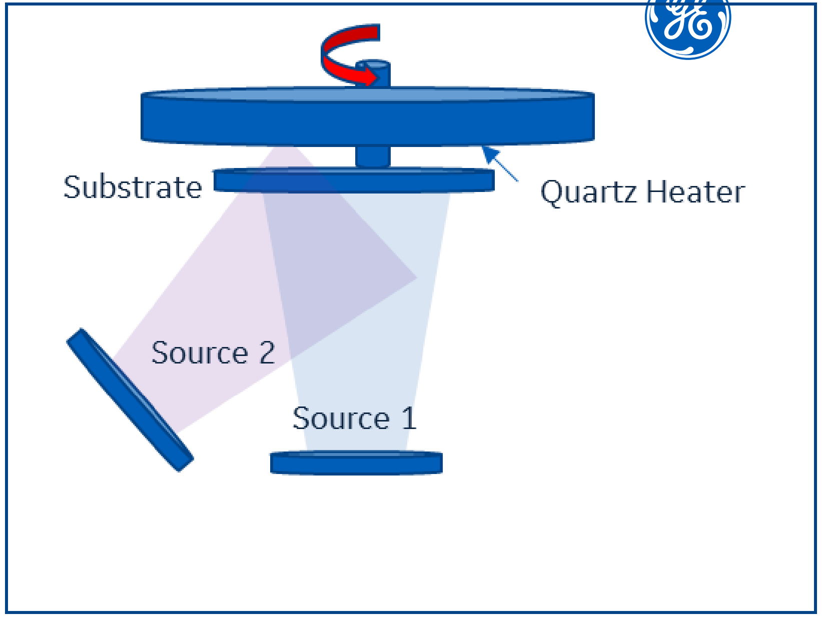
# Sample production with Ion Plasma PVD

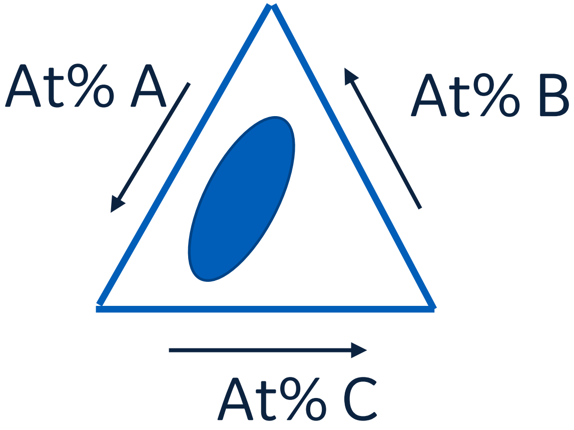
- Gen 1: 12 Cr/Ceramic layered architectures were produced
- Gen 2: 30 additional ceramic compositions were produced



# 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

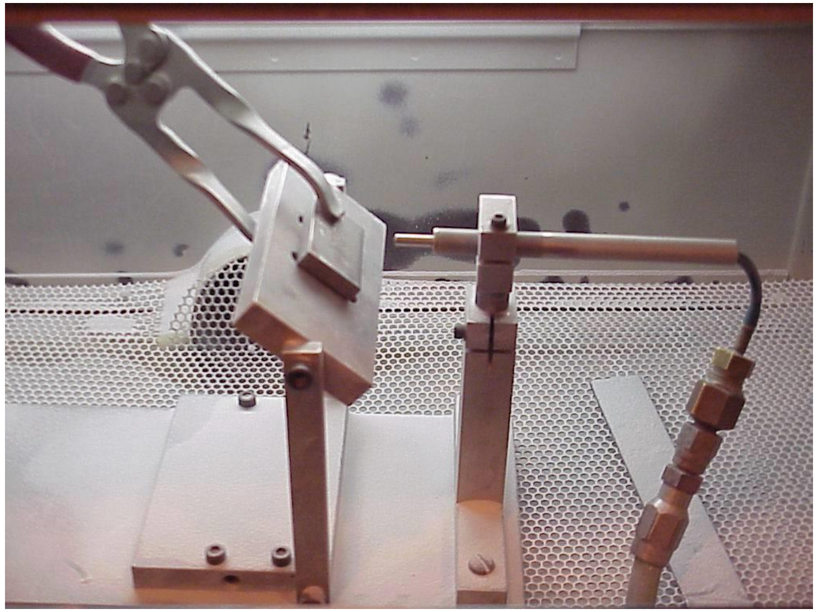



Example of ternary system with example ROI

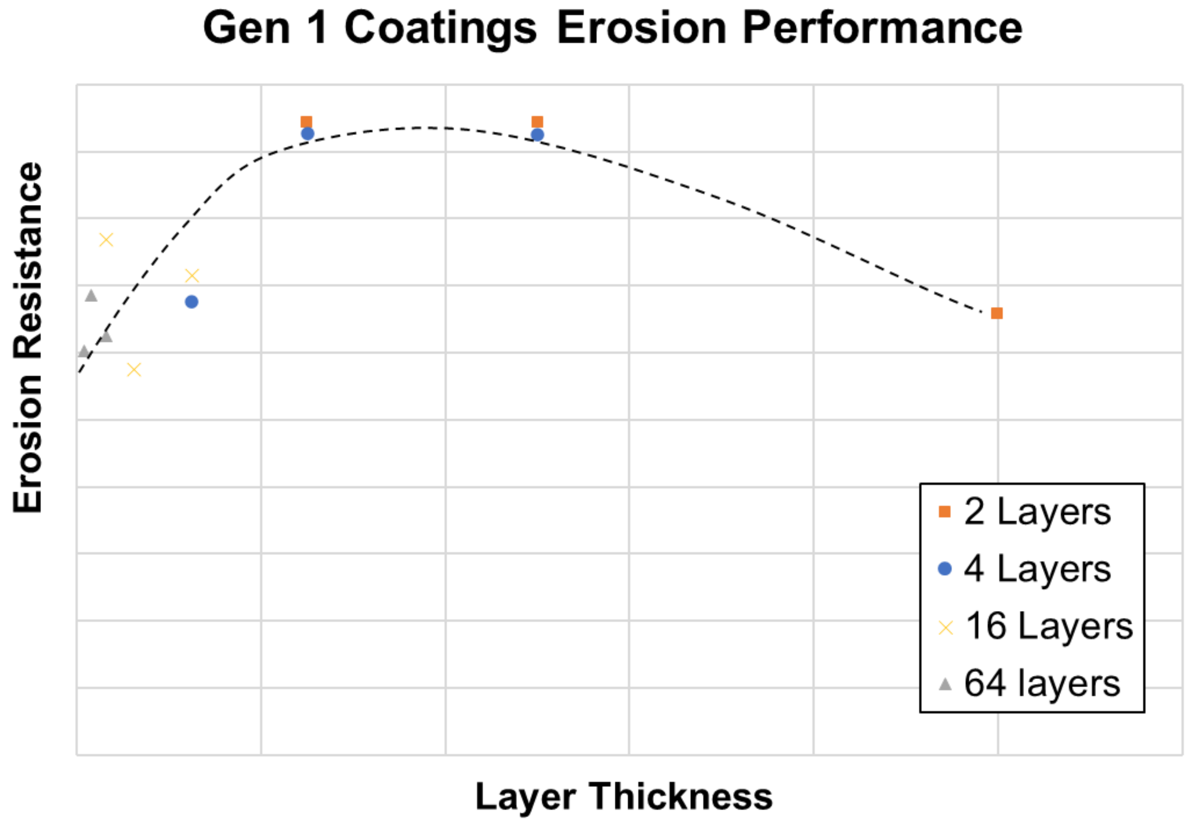
# Erosion and Steam Testing

- 100 hour, 600 $^{o}$C steam exposure
- Erosion testing before and after
- Surface Roughness measured before and after
- 36/42 IPD compositions have been erosion tested in as-deposited condition
- 20 IPD compositions have been steam tested (2 compositions per week, 2 samples per composition)

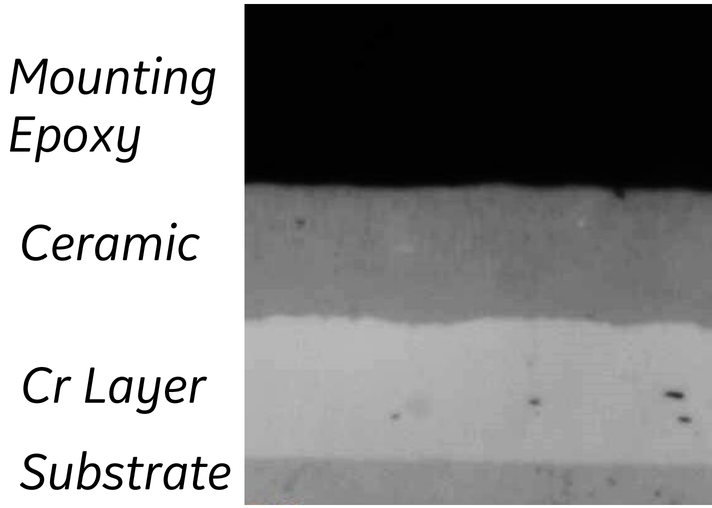


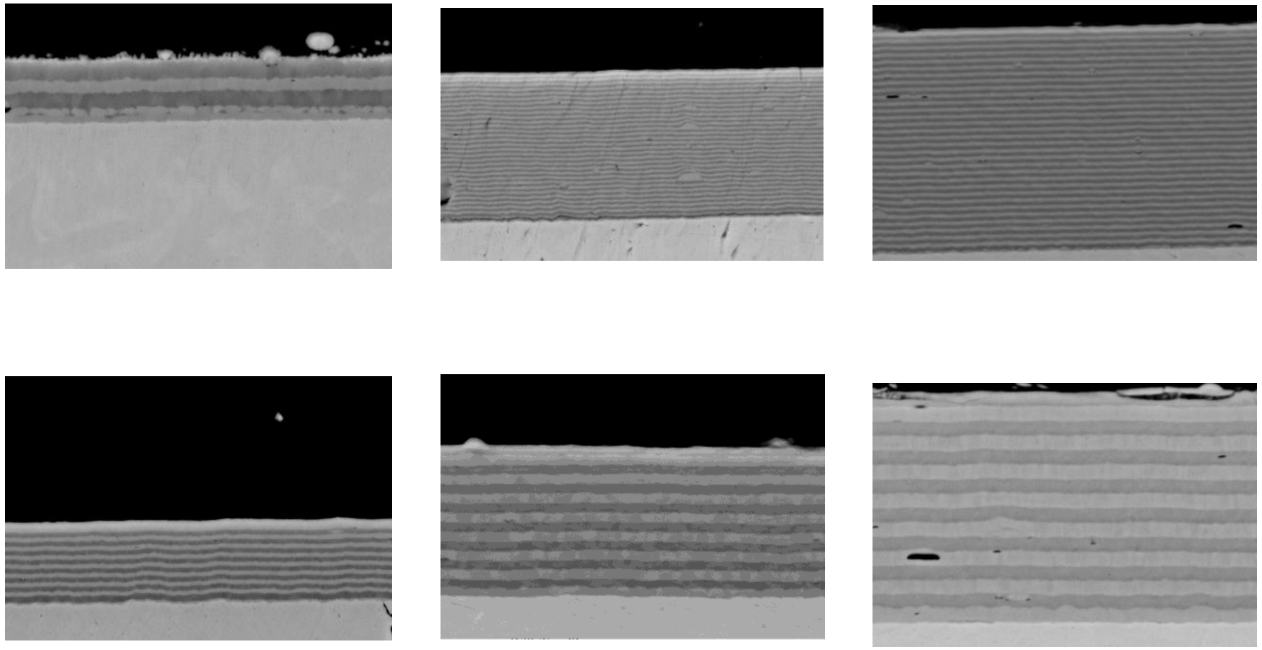
# Gen 1 erosion results

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




Sample Microstructures:



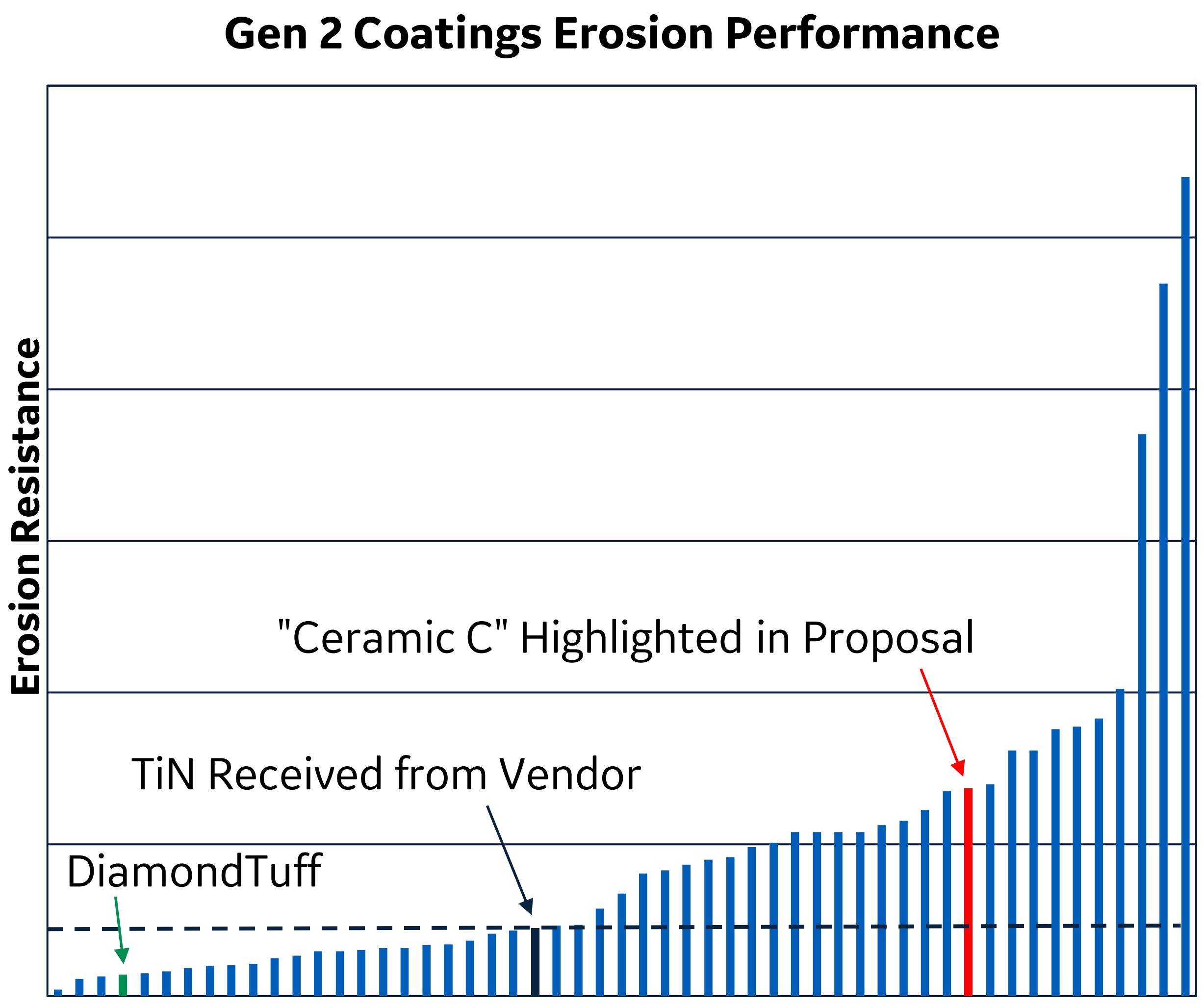



# Gen 2 erosion results

- Coating life ≈ Thickness x Erosion Resistance
  - 250 micron DiamondTuff is the baseline
  - TiN is limited to ~10 microns

- Increasing Thickness
  - With proper dopants, TiN can be deposited up to 30 microns thick.
  - Result: 1.3x coating life as DiamondTuff

- Increasing Erosion resistance
  - Novel compositions outperform TiN
  - Result: 2x coating life as DiamondTuff for only 10 microns of coating



# Ongoing work for IPD coatings

- Further optimizing TiN dopants to maximize achievable deposition thickness
- Further exploring novel ceramic compositions to maximize erosion resistance
- Evaluating the performance of Gen 1 and Gen 2 components after steam exposure
  - If needed, interlayer Cr with erosion resistant ceramic.

- Scaleup (2022 effort)
  - Option A: Work with vendor to replicate their process for coating components at GE
  - Option B: Transfer coating “recipe” to vendor for them to coat components

# Boiler Tube Coatings for Hot Corrosion Resistance

# What we know about Hot Corrosion Protection for Boilers

## Attack mechanisms

- Oxidation
- Sulfate attack
- Alkali Chlorides (cofiring waste/biomass)

## Prior Work

- Superheater tubes can be fabricated from high Cr Austenitic Steels (*e.g.* 310 HCbN) or weld overlaid with NiCr (*e.g.* alloy 72)
- Too expensive for widespread use
- Inadequate for high temperature cofiring

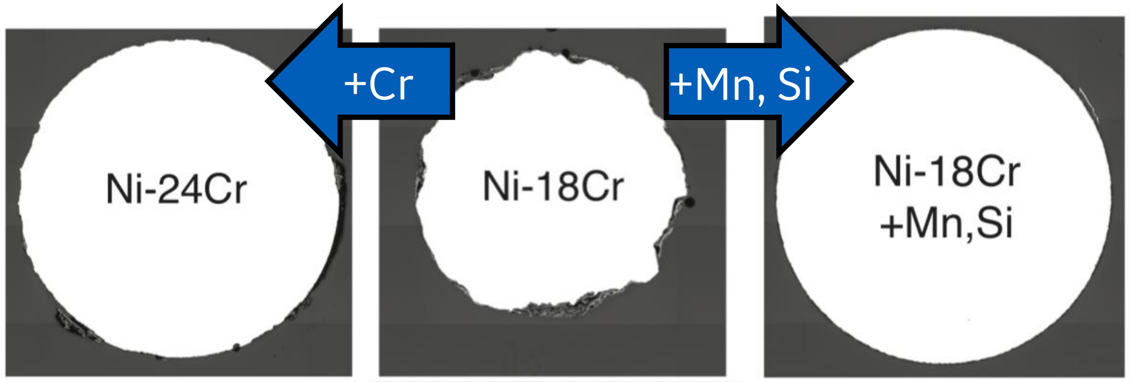
## Our Strategy

- Reduce Ni content to minimize cost
- Move beyond simple Chromia protection

**Additional Barriers**
Al and Si can form their own protective oxides

**Neutralize Attacks**
S will preferentially react with Y

**Enhance Chromia**
Mn and Ti can increase kinetics and thickness



# Phase 1 Roadmap for Boiler Tubing

## Objective: Demonstrate improved coating performance at lab scale

**Requirements**
- Reduce Ni content to 35% or below
- Maintain corrosion resistance equivalent to Alloy 72 (60Ni40Cr)
- Demonstrate weldability equivalent to Alloy 72

**Concepts**
- Use Computation for major alloying elements
- Lit review/Experience for minor

## Gen 1: Establish Baseline

**Objectives**
- Test the best performing alloys available today
- Produce model alloys to test effects of each major element

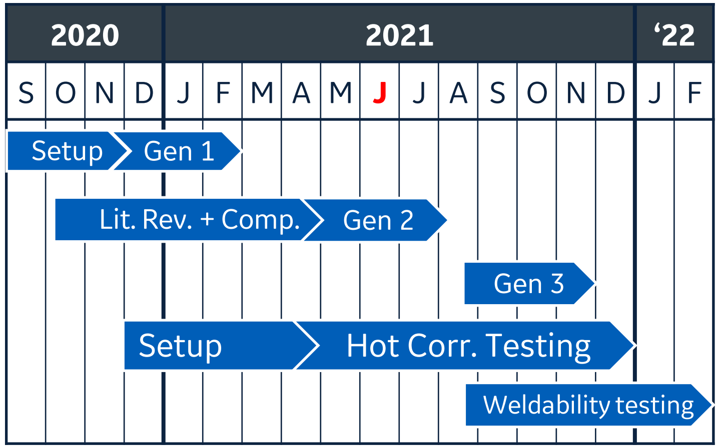
## Gen 2: Better alloys

**Objectives**
- Improve upon state-of-the-art alloys available today
- Fe, Ni, Cr levels from comput.
- Minor elements are tested

## Gen 3: Combine Learnings

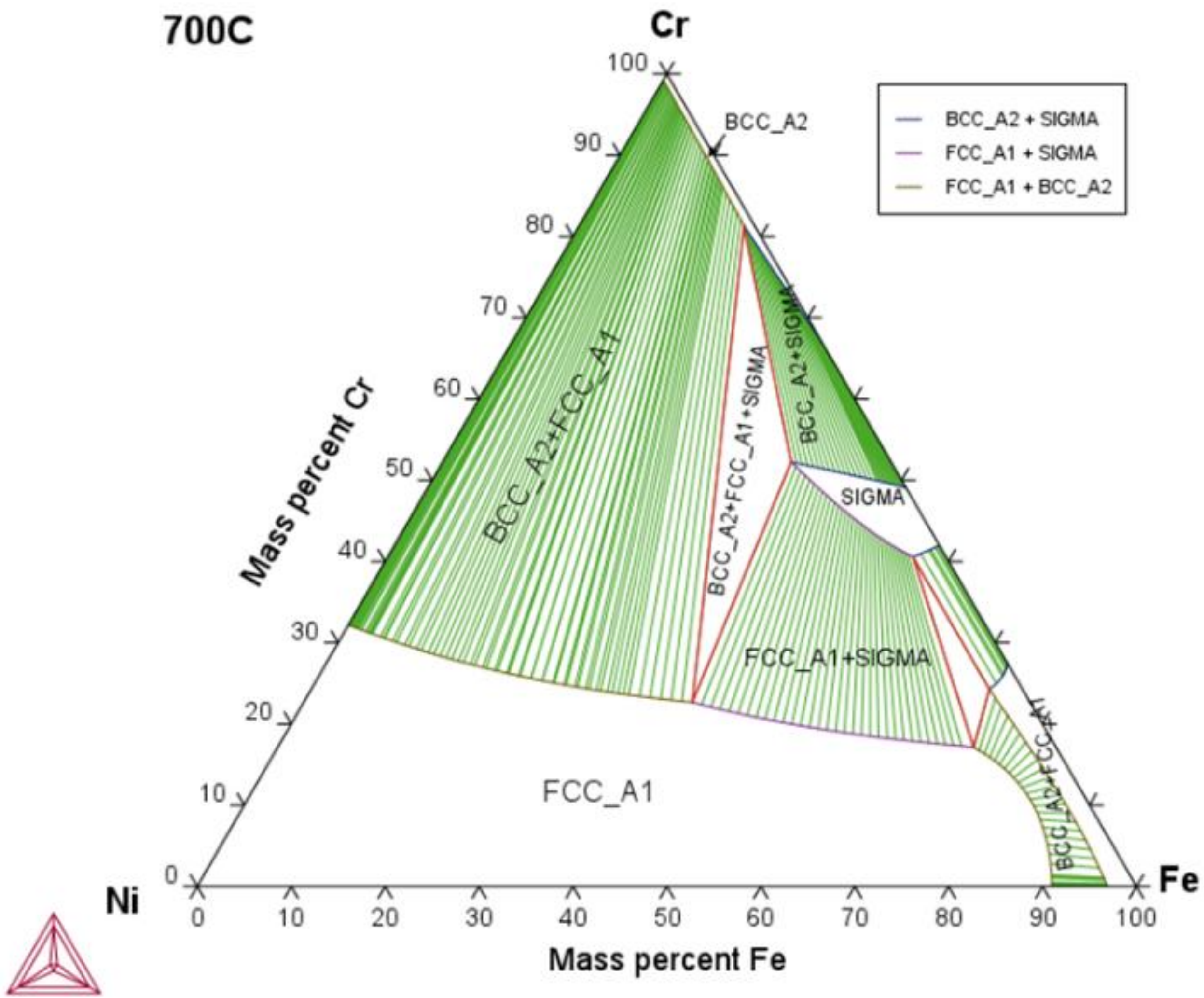
**Objectives**
- Refine Gen 1 and Gen 2 compositions as guided by results

Hot Corrosion Assessment



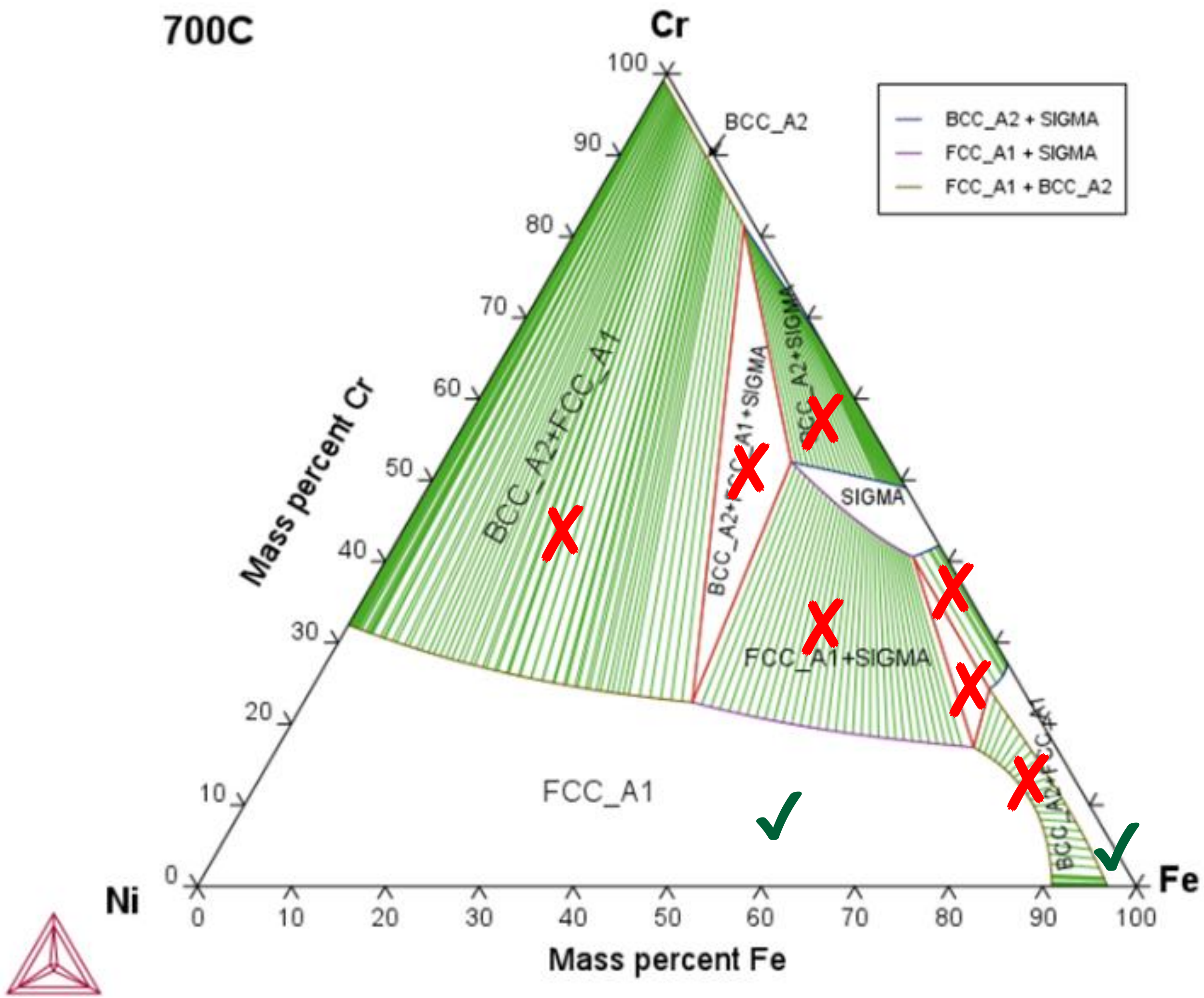

**Phase 1 Milestones**
- Cast 30 samples (46 complete) ✓
- Test 30 samples (6 underway)
- Weld trials of top candidates

# Computational Approach to Alloy Selection



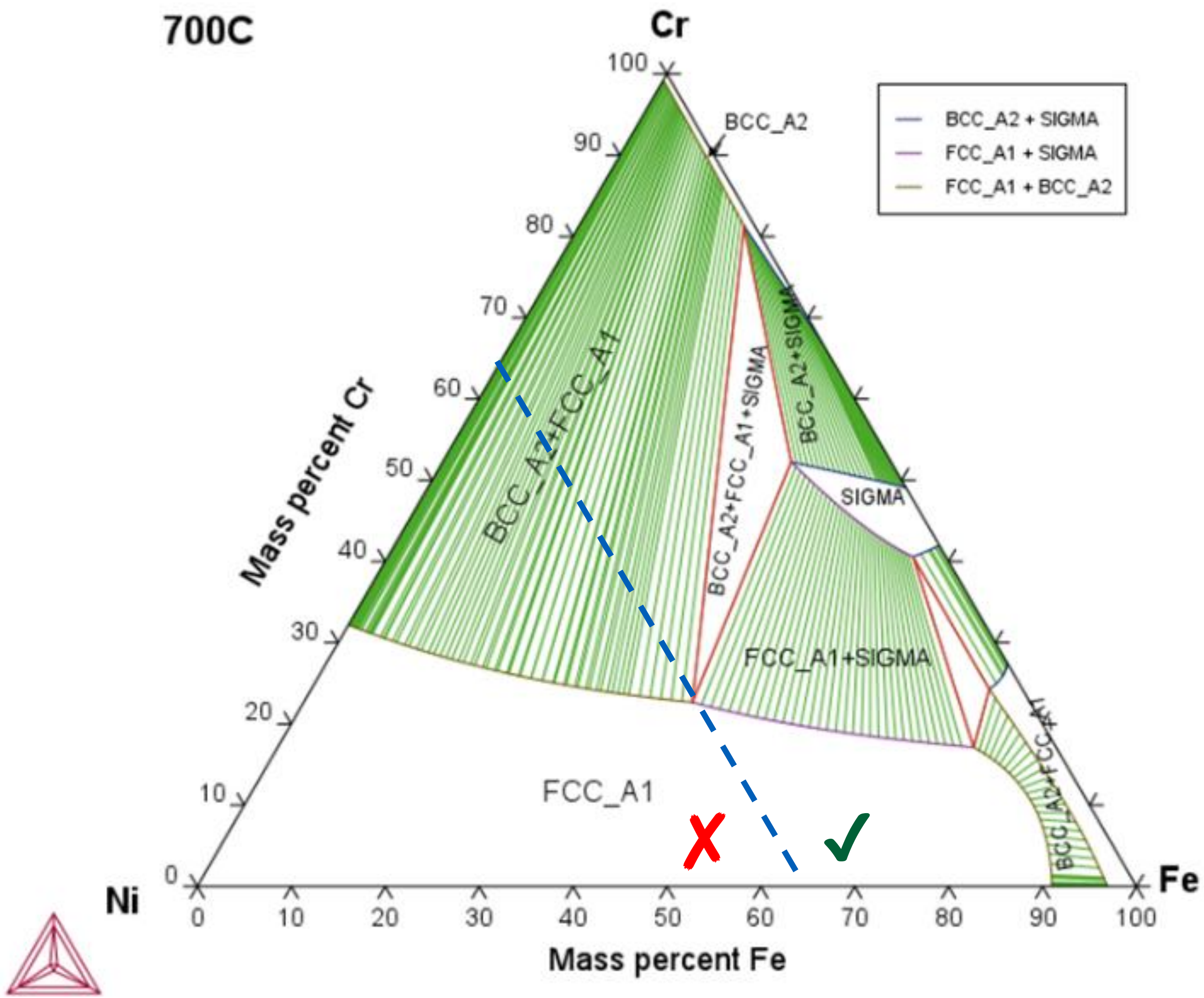
# Computational Approach to Alloy Selection

- We are targeting a single phase solid solution



# Computational Approach to Alloy Selection

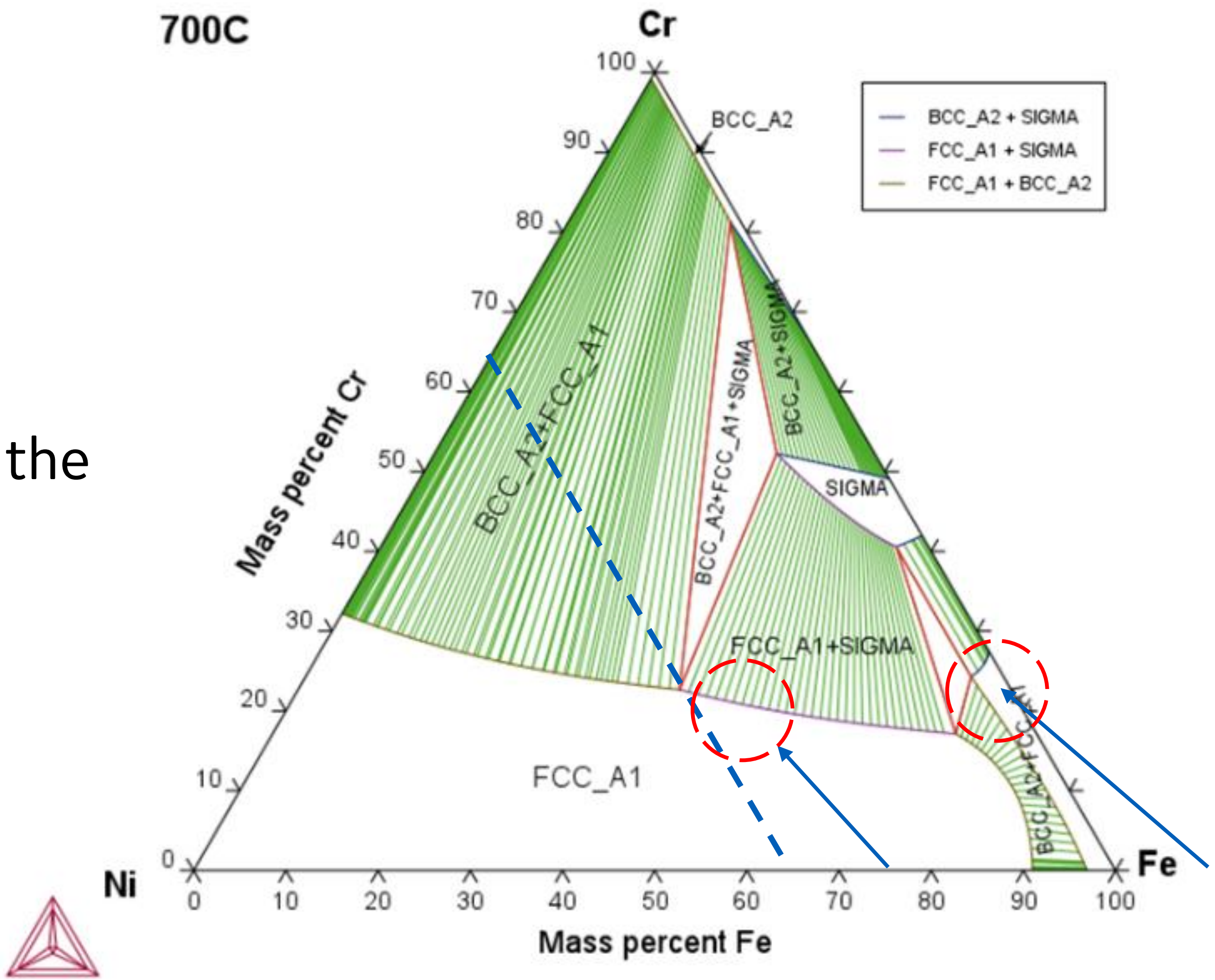
- We are targeting a single phase solid solution
- Ni content should be ≤35%



# Computational Approach to Alloy Selection

- We are targeting a single phase solid solution
- Ni content should be ≤35%
- Cr should be maximized

∴Two areas of interest are identified, guiding the Fe, Ni, and Cr content of alloys



# Computational weldability testing

- Compositions were further screened using a physics-based weldability simulation.

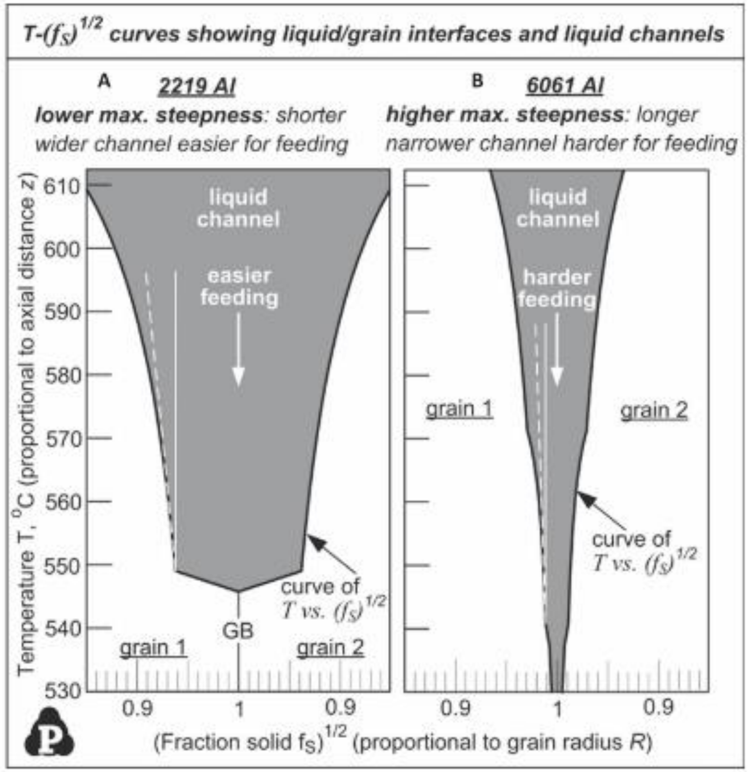
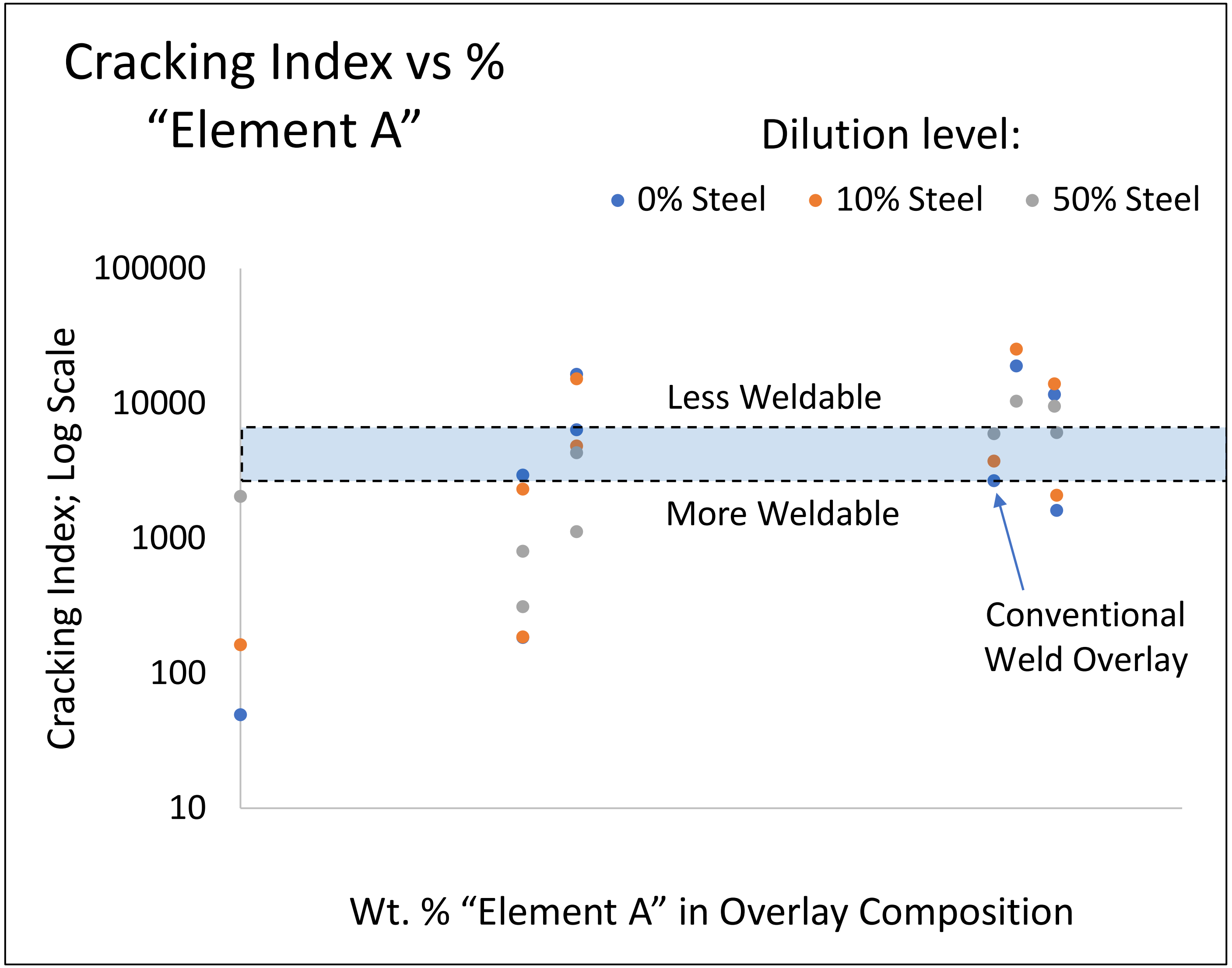


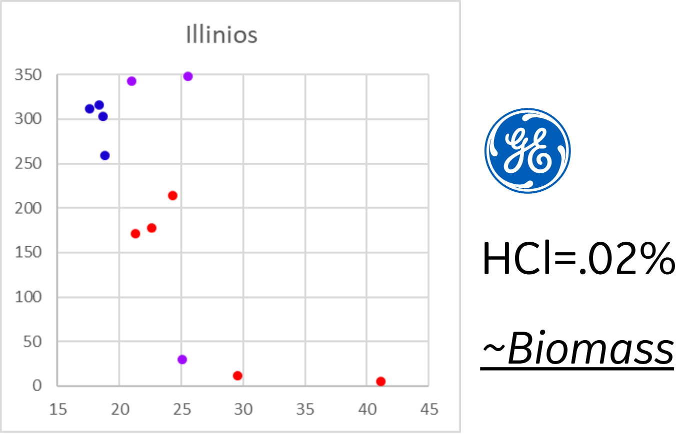

Fig. 12 — T-$(f_S)^{1/2}$ curves showing liquid/grain interfaces, liquid channels and tangents to curves at locations of maximum steepness. A — 2219 Al alloy; B — 6061 Al alloy. A longer, narrower channel hinders liquid feeding because of the resistance to flow caused by the viscosity of liquid.

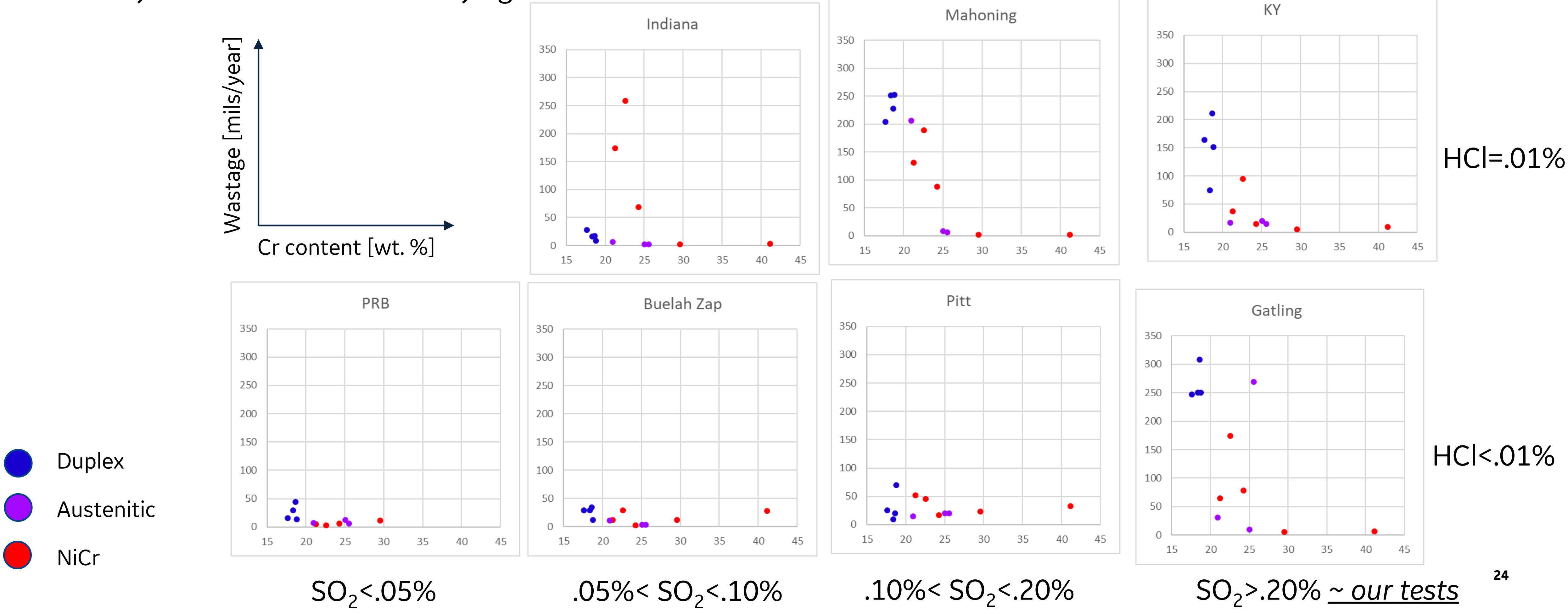
Kou, 2015



# Lessons learned from Prior Work

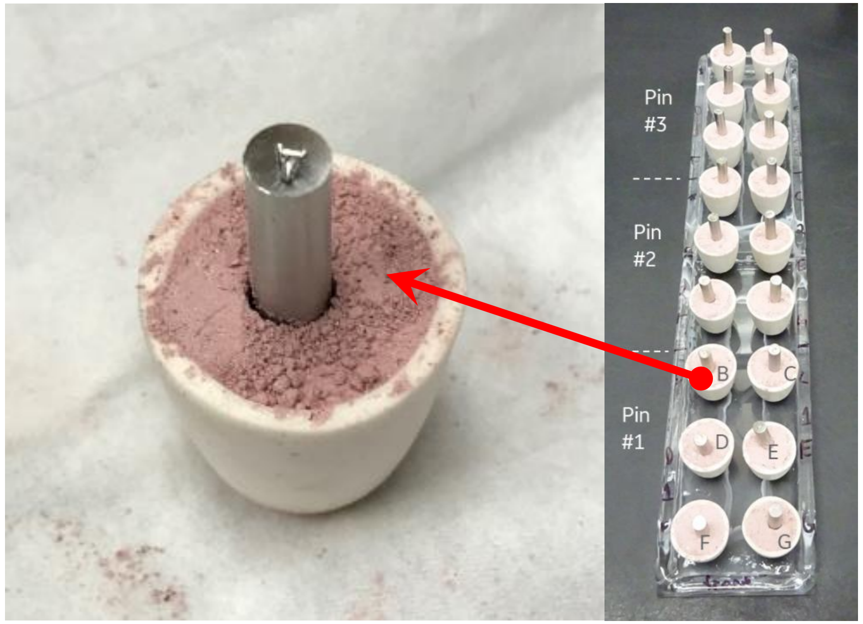
- 2007-2014 Babcock/Wilcox study: Example of DOE-funded research used as a basis for alloy design.
- Corrosion data for 12 different alloys across 8 different coal-fired environments were evaluated.
- Data analysis reveals beneficial alloying elements.



# Hot corrosion test setup

- 700 °C
- 150 hrs to 500 hrs
- Synthetic ash based on Powder River Basin Coal
- Metal loss is measured after testing





Start the test
(0 hr)
3 samples

→

1/3 test time
(150 hr)
3 samples

Pull 1 sample @150h

Put in 1 new sample

→

End of test
(500 hr)
3 samples
- 1 sample @ 350 hr
- 2 samples @ 500 hr

# Initial Results

- First round of samples have completed 150 hours and will be characterized
- Selected from a broad compositional spectrum: ferritic steel, austenitic steel, NiCr, CoCr
- Drawing knowledge from many branches of alloy development
- Probing a wide range of performance to establish sensitivity of test


| Sample | Alloy Type | Observations |
|---|---|---|
| B-1 | Ni (EI-2019) | Dull(er) surface, dark gray oxide |
| C-1 | Fe (EI-2019) | Red oxides, ash sticking more than in other samples |
| D-1 | APMT | Shinny surface, red-ish oxides |
| E-1 | 625+ | Dark gray oxide |
| F-1 | SS310 | Dark oxide, gas side has a little red tint, in ash has a bit of blue/greenish tint |
| G-1 | UMCO50 | Greenish oxides on the top (gas part), in the ash, several large dark blotches |

# Ongoing work for weld overlay coatings

- Corrosion screening of Gen 1 alloys is underway
- Gen 2 alloys are being cast
- Weldability trials of most promising candidates will begin in August
- Gen 3 alloy selection will be based on Gen 1 and Gen 2 results

# Bottom Line

- The objective is to deliver coating technologies that increase reliability of the steam path
- According to GE utility customers, the most effective way to do this is to protect boiler tubing and turbine components
- Boiler tubing requires hot corrosion resistance, especially for biomass
  - We are developing weld overlay coatings that are cheap enough to be broadly applied and incorporate many layers of protection mechanisms
  - Computation guides phase compatibility and weldability
  - Within that window, alloys are designed based on prior work and tested in hot corrosion
- High Pressure Steam Turbine components suffer from solid particle erosion
  - We are developing Ion Plasma Deposited coatings with maximized lifetime by increasing erosion resistance and increasing the maximum viable coating thickness
  - Initial results suggest that lifetime can be doubled compared to conventional coatings

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

**Optimizing Chemistry** → **Sample Production** → **Processing/ Exposure** → **Quantifying Corrosion**

**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** → **Sample Production** → **Exposure** → **Quantifying Erosion**

**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*

**Management**

Technical, Financial, and Logistical Management
*GE Research*

Technology Manager:
*Briggs White at NETL*

Federal Project Manager:
*Michael Fasouletos at NETL*

**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 |