Corrosion Issues in Advanced Coal-Fired Boilers FEAA116 (2014 – 2018?)

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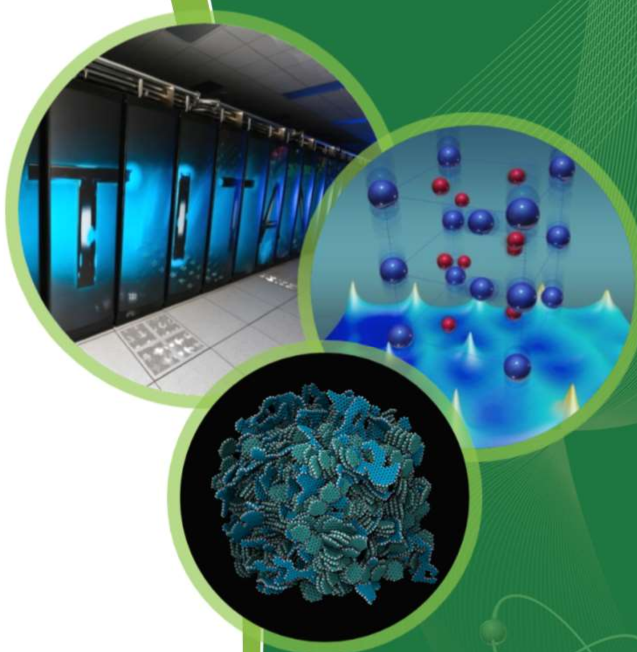
April 11, 2018



ORNL is managed by UT-Battelle
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Acknowledgments

- G. Garner, M. Stephens, M. Howell — oxidation experiments
- T. Lowe — SEM, image analysis
- T. Jordan — metallography, hardness
- D. Leonard — EPMA
- A. Willoughby, P. Doyle, R. De Las Casas Aranda — water loop
- Special thanks for shot peening and steam oxidation tasks:
  - American Electric Power (commercial 304H tubes)
  - EPRI (J. Shingledecker, I. Wright, S. Kung)
  - Barry Dooley (Structural Integrity Assoc.)
  - Steve Paterson (PIKA Solutions)

Project is studying corrosion issues relevant to current and advanced boilers

- Goals and Objectives
  - This project is addressing critical corrosion & environmental effects issues in current and future coal-fired boilers focusing on the water-steamside for waterwalls and superheaters
- Milestones
  - FY17
    - Complete final report on shot peened stainless steel oxidation (3/31/17, delayed)
    - Compare oxide microstructure formed on steam at 1 & 200 bar (6/30/17, delayed)
    - Demonstrate in-situ crack growth measurements in 200°C water (9/30/17, delayed)
  - FY18
    - Submit publication comparing crack growth behavior of 2.25 & 9%Cr in flowing water (6/18)
    - Report on the effect of pressure and water chemistry on oxide scale growth (9/30/18)
    - Complete a report assessing current importance of oxide scale exfoliation (9/30/18)

Science approach to "real world" corrosion issues

- Task 1: Steam oxidation
  – Study of baseline alloys and shot-peening "solution" at 550°-650°C
- Task 2: Stress corrosion cracking
  – 2¼ %Cr waterwall steels: Grades 22, 23, 24
  – Significant issue in new boilers
  – Need for more detailed understanding

Cracks in longitudinal direction

Cracks in transversal direction

- Task 3: Effect of pressure on corrosion
  – Steam-side difference between laboratory and field
    - EPRI: does water chemistry also play a role?
  – Fire-side effects
    - SPOC: staged pressurized oxy-combustion (with Wash. U @ St. Louis)
  – CO_2 effects from related project FEAA123

"USC" John W. Turk Plant solution (commissioned 2013)

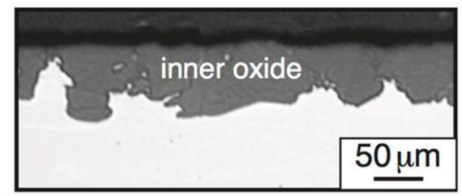
"Ultra-supercritical" coal-fired steam plant by B&W/AEP in Fulton, AR

- 600MW, ~39% LHV efficiency
- \$1.8billion (\$2.8b?)
- Steam: 599°/607°C SH/RH 25.3MPa (1110/1125°F)
  - Eddystone (1960): 613°C/34.5MPa
- Superheater: shot-peened 347H
  - 17.5Cr-10Ni-0.5Nb-1.5Mn-0.4Si-0.07C

Task 1: Why focus on shot peening?

- Scale exfoliation is the main driver for this task
  - H_2O-accelerated oxidation of steels (steam-side)
  - Simultaneous spallation of thick oxide
  - Tube failures & erosion damage
  - Costs: unplanned shutdowns, mitigation
- Shot peening of austenitic tubes
  - Industry standard to address exfoliation
  - Reduced scale growth: avoids exfoliation issue
  - Limited understanding of benefit and procedure

TP304H
22,0000 h



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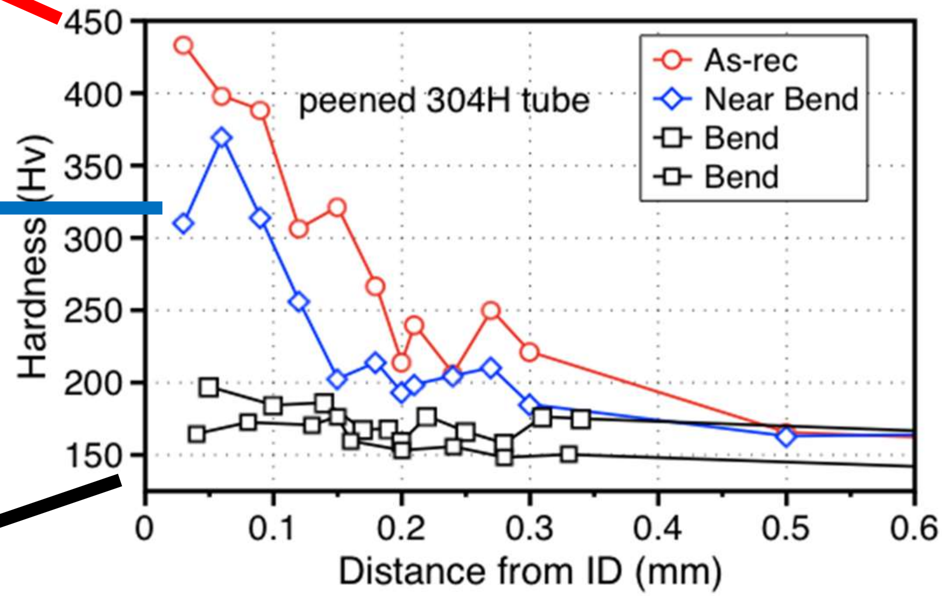
Shot peening increases the near-surface dislocation density which increases hardness and Cr diffusivity

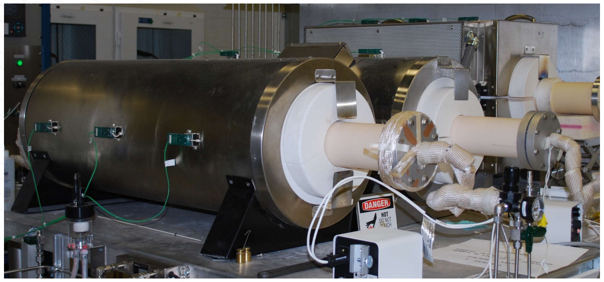
ASME-specified 1100°C annealed U-bend



2011 EPRI-funded project

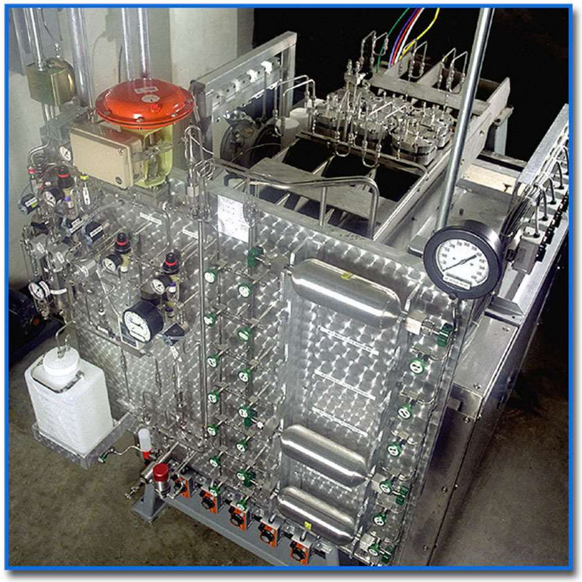
Several options for steam exposures

Tube furnace: 1 bar CO_2
500-h cycles



Standard procedure

"Keiser" rig:
500-h cycles, 1-43 bar CO_2



Pressures of 1-43 bar

Autoclave: 275 bar water
500-h cycles

1L volume restricts exposure

High purity Ar-bubbled, filtered water with conductivity <0.1µS and <10 ppb O_2

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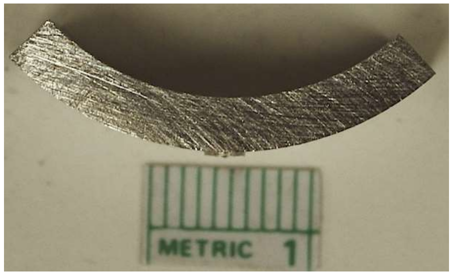
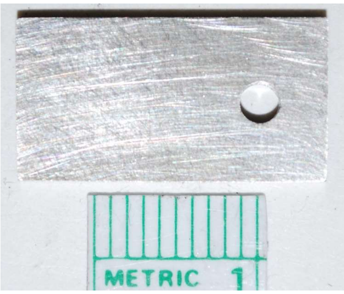
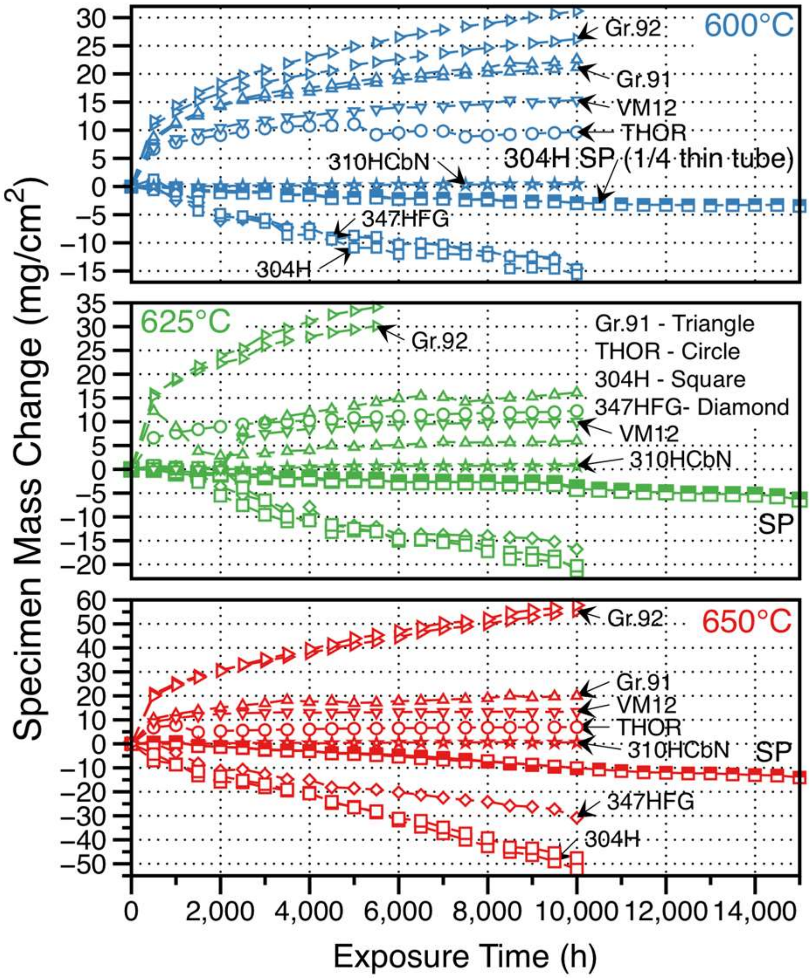
Completed 15,000 h of testing

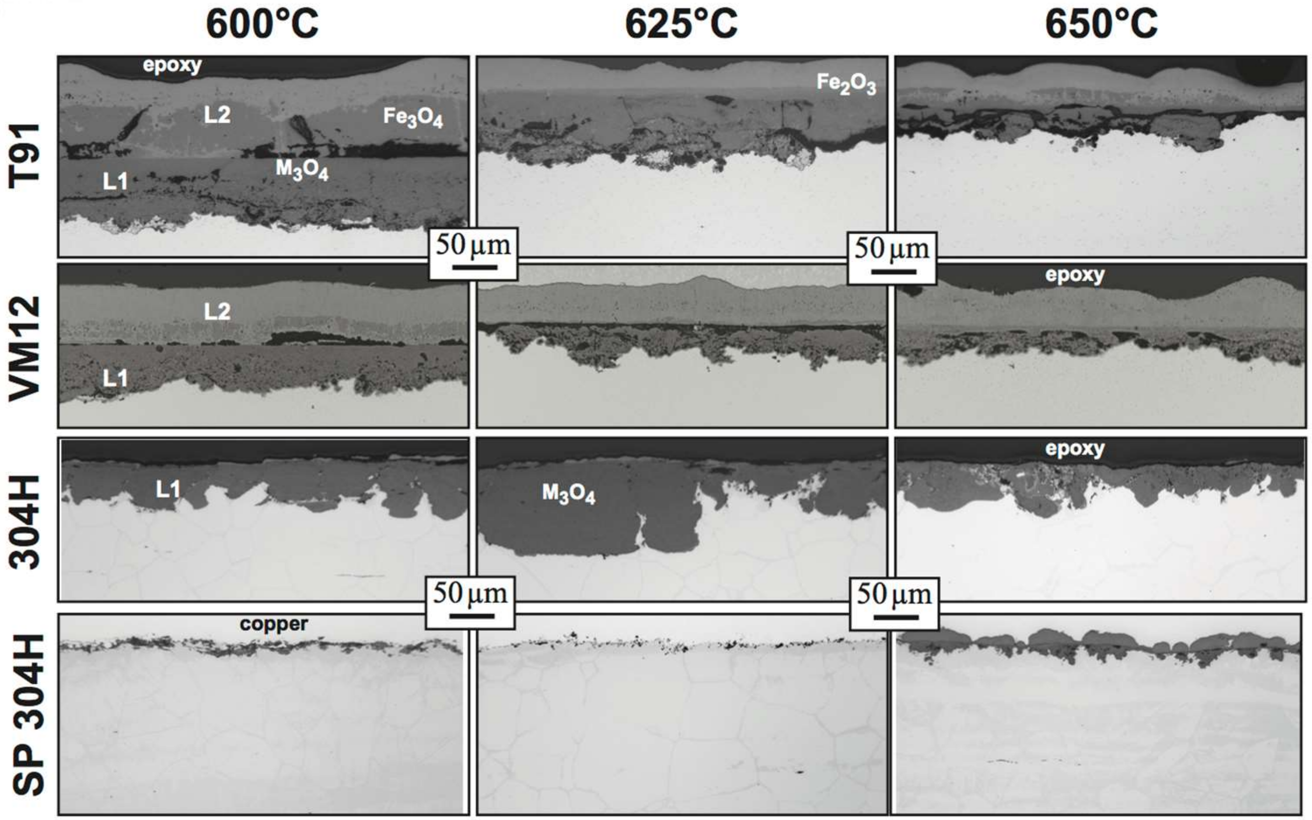
- Tube sections removed at various times
- Polished alloy coupons for comparison
  - Gr.91
  - Gr.92
  - THOR
  - VM12
  - Gr.93 (new CSEF steel)
  - CPJ7 (just started)

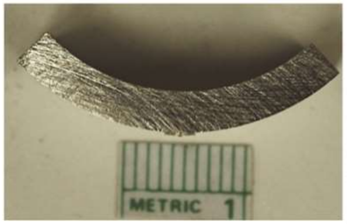






Clear shot-peening benefit at 10,000 h but oxide growing thicker at 650°C





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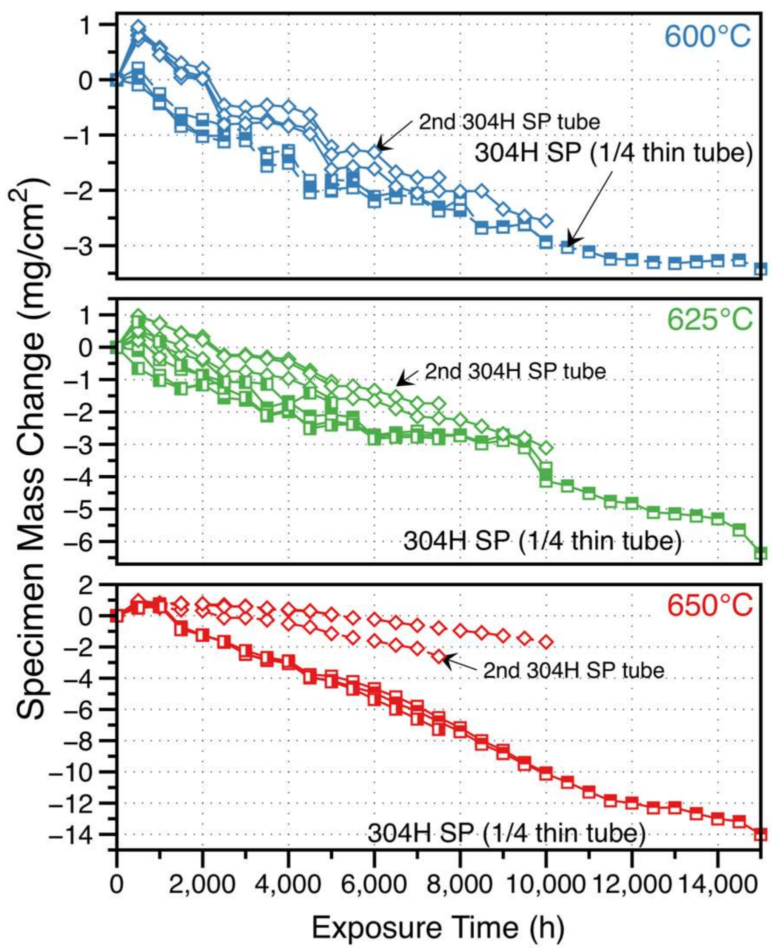
Specimens from 2nd 304H tube finished 10,000 h in 2017



Specimens removed at:
0.5, 1, 2.5, 5, 7.5, 10 kh
(15 kh only for 1st tube)

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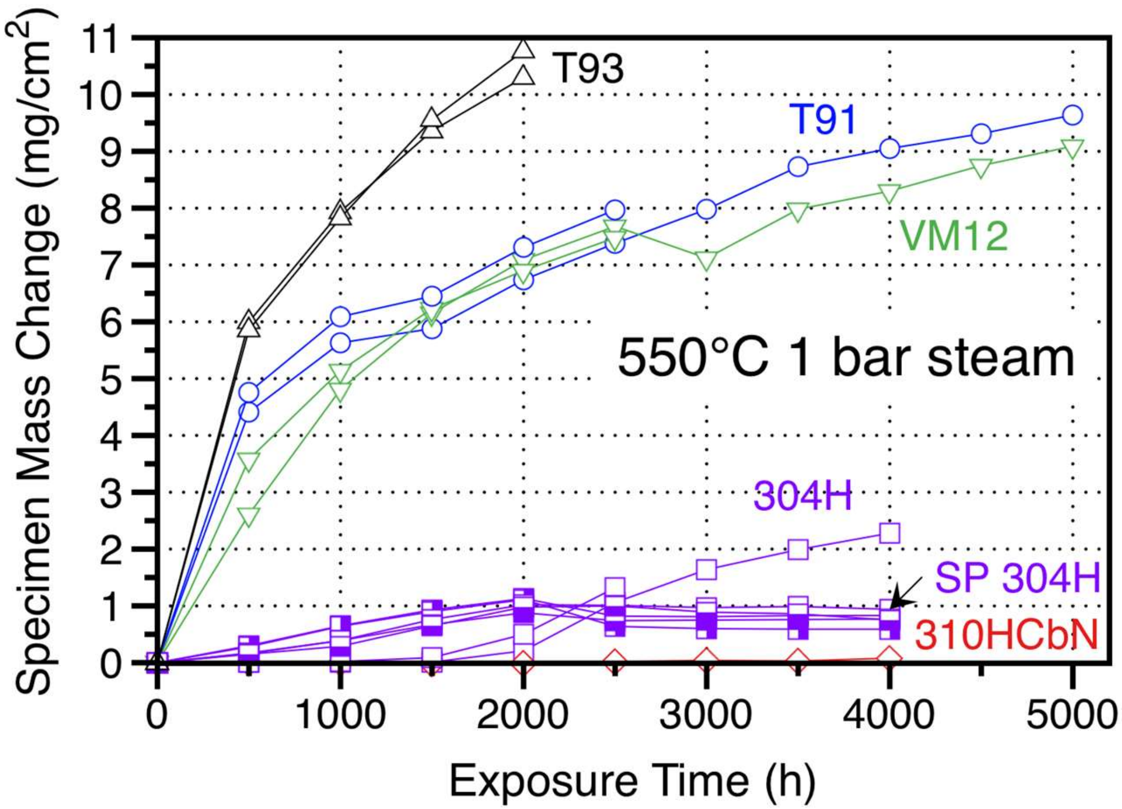
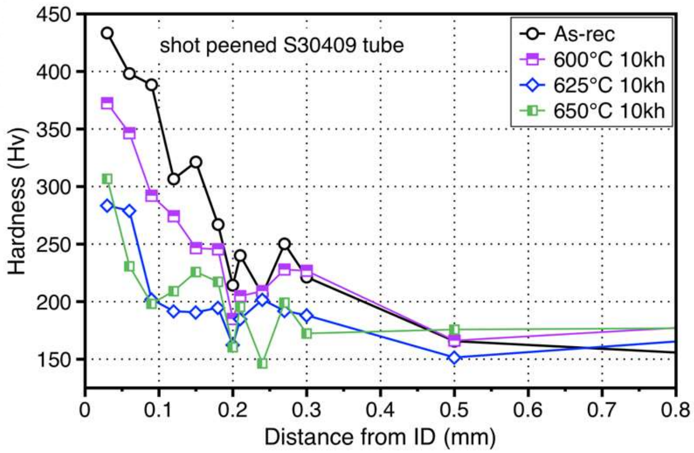
Currently running 550°C (relevant to more boilers)

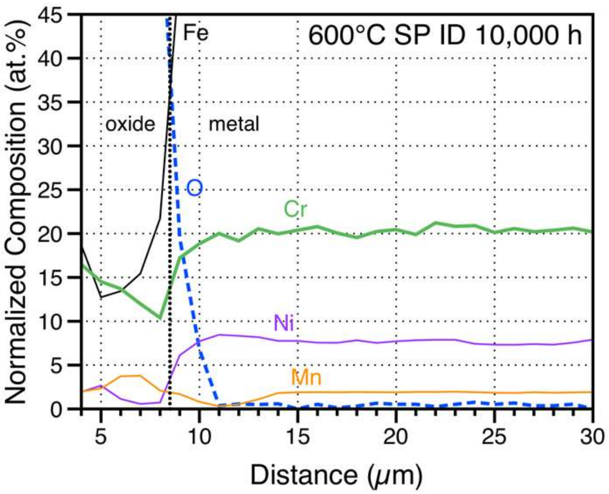


Considerable characterization work remains to complete journal article

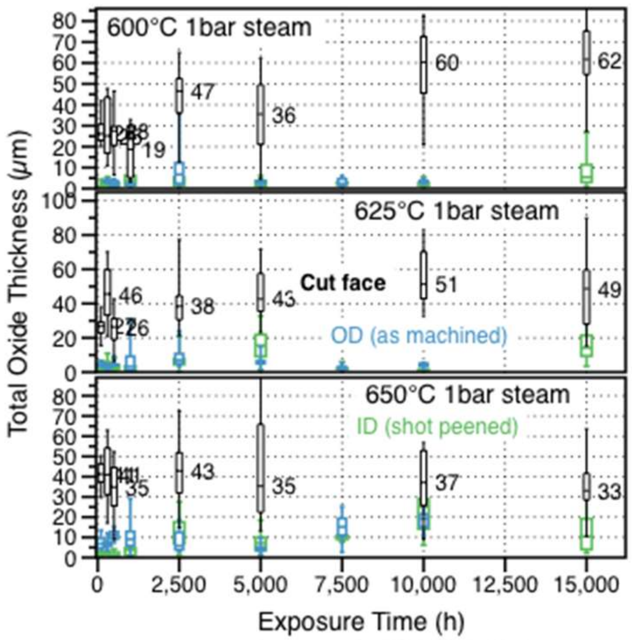
Post-exposure hardness measurements



Microprobe of scale and Cr depletion



Quantified oxide thickness on 1st tube



Finish similar work for 2nd tube and microscopy (e.g. EBSD)

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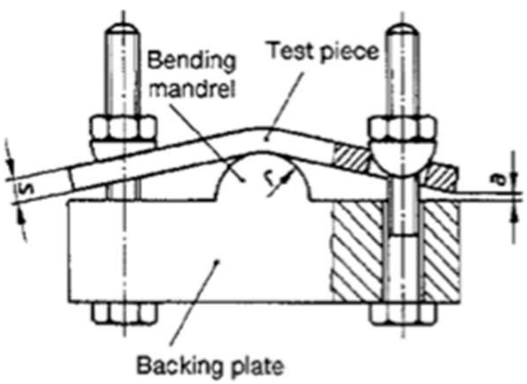
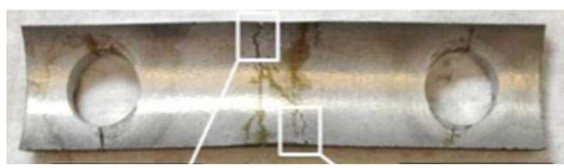
Task 2: stress corrosion cracking

- 2.25%Cr waterwall steels: Grades 22,23,24
  - High strength steels are susceptible
  - Including 9Cr steels (Grades 91,92)
- significant problem for new boilers in US (T23) and EU (T24)
- Stress-environment interaction: 25°-300°C
- Jones test to apply stress (complicated)
- prior results in aerated and deaerated water





Alloy	Test Condition			
	As Received		Normalized	
	Aerated	Deaerated	Aerated	Deaerated
T23	☐	☐	☑	☐
T24	☐	☐	☑	☐
T92	☐		☑	☐

☐ Did Not Crack
☑ Cracked

Water loop built to have better environment control

Recirculating water system
- based on GE systems

200°C autoclave

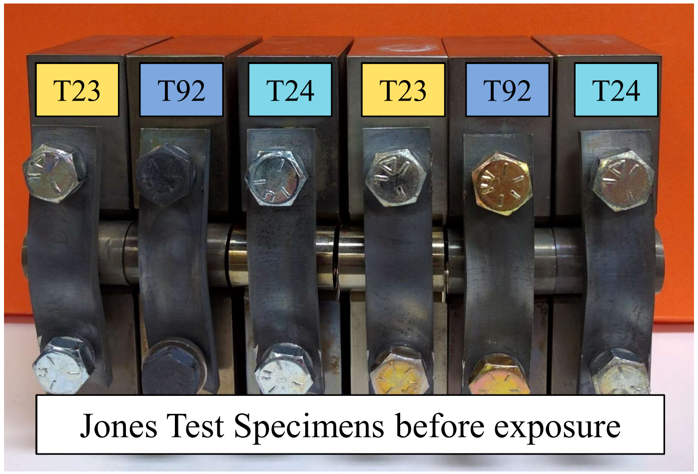
Simulate actual fossil environments with controlled pH and pO_2 levels

Next phase of testing completed in 2017

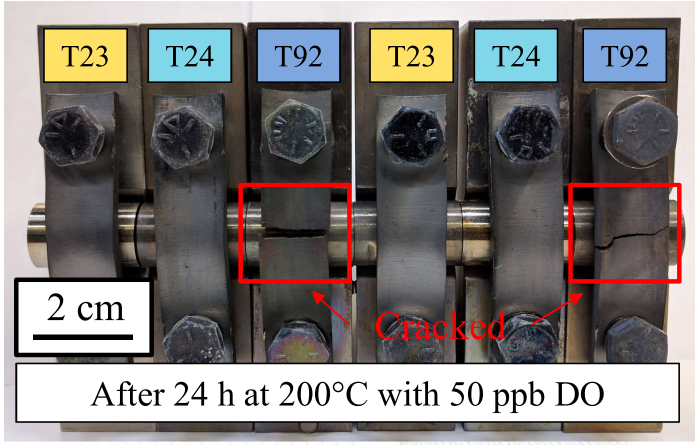
- Jones test conducted in 200°C water
  - Normalized steel (0.5h,1065°C WQ)
  - 50 ppb O_2
  - 100 ppb O_2
- Increasing attack as O_2 level increased
- Previous work concluded only 24 h needed

DO	Deaerated*	50 ppb	100 ppb	Air saturated* (~8400 ppb DO)
Time	72 h	24 h	24 h	72 h
T23	O	O	O	X
T24	O	O	X	X
T91	O	X	X	X

O: Uncracked X: Cracked *J.K. Thompson, S.J. Pawel, 2015



Jones Test Specimens before exposure



After 24 h at 200°C with 50 ppb DO

Progression of SCC testing planned
SCC = stress + environment + microstructure

- Closed autoclave
  - Aerated or deaerated water (no cracking without O_2)
- Autoclave with controlled flowing water
- In-situ probe to monitor crack growth in autoclave
  - Monitor Jones test while incrementally increasing O_2 content in water
  - Task deferred to 2018 to explore electrochemical methods
- Controlled stress in flowing water
  - Tensile test frame needed
  - Monitor crack growth rate changes with water chemistry
  - GE Global Research specialty that was downsized
- Are their critical temperatures? Hardness? Any solutions?

Task 3: effect of pressure (adding water chemistry)

- Steamside
  - steam oxidation field-lab disconnect
  - field (high pressure) ≠ lab (typically 1 bar)
  - need uniform test procedure to study
- \- Fireside
  - for Staged-Pressurized Oxy-Combustion (SPOC)
  - previous work with Washington Univ. (St. Louis)
    - R. Axelbaum and B. Kumfer

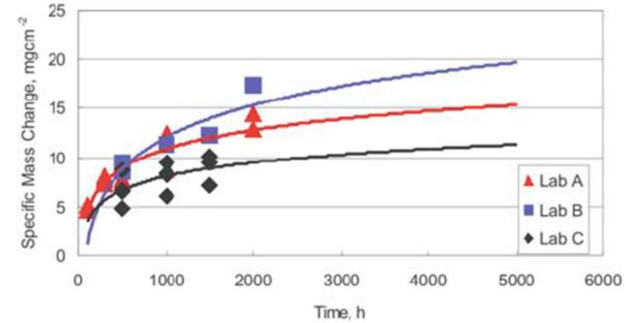
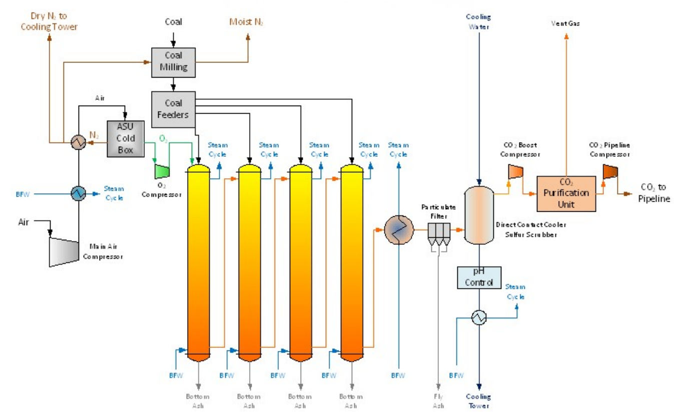
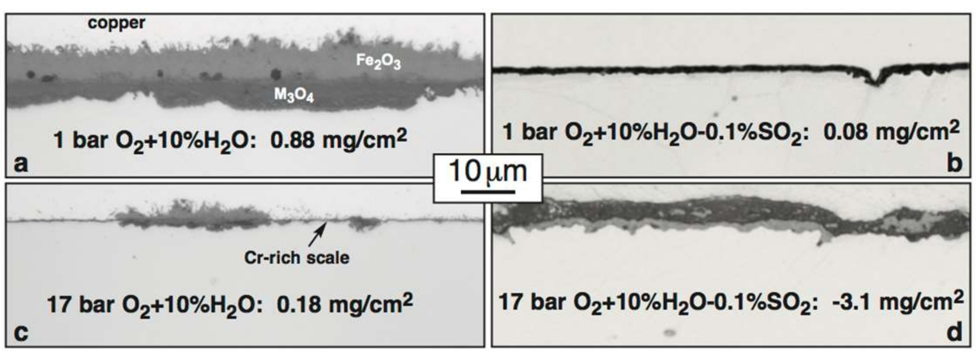


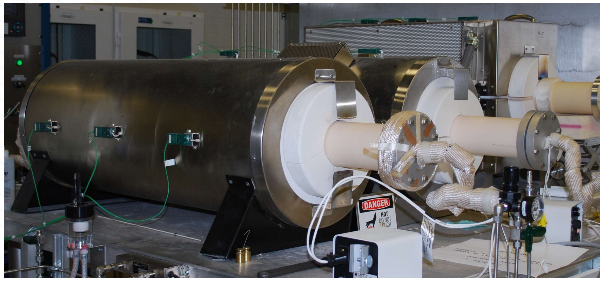
Figure 2 Intercomparison of specific mass change measurements on T92 martensitic steel after exposure to steam for up to 2000 h at 600°C (after [4]).





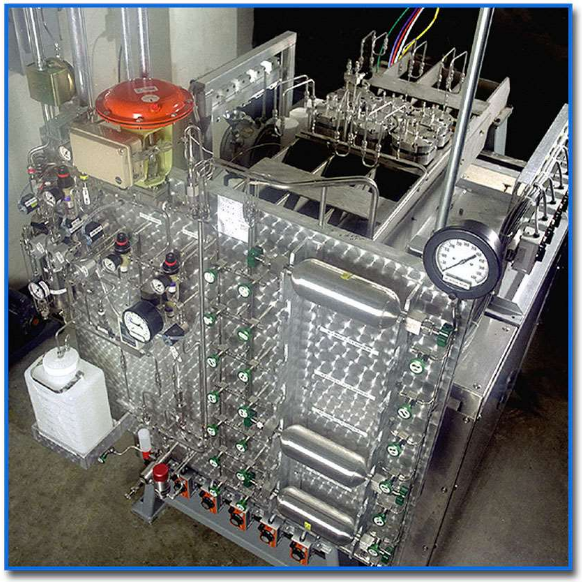
Several options for steam exposures

Tube furnace: 1 bar CO_2
500-h cycles



Standard procedure

"Keiser" rig:
500-h cycles, 1-43 bar CO_2



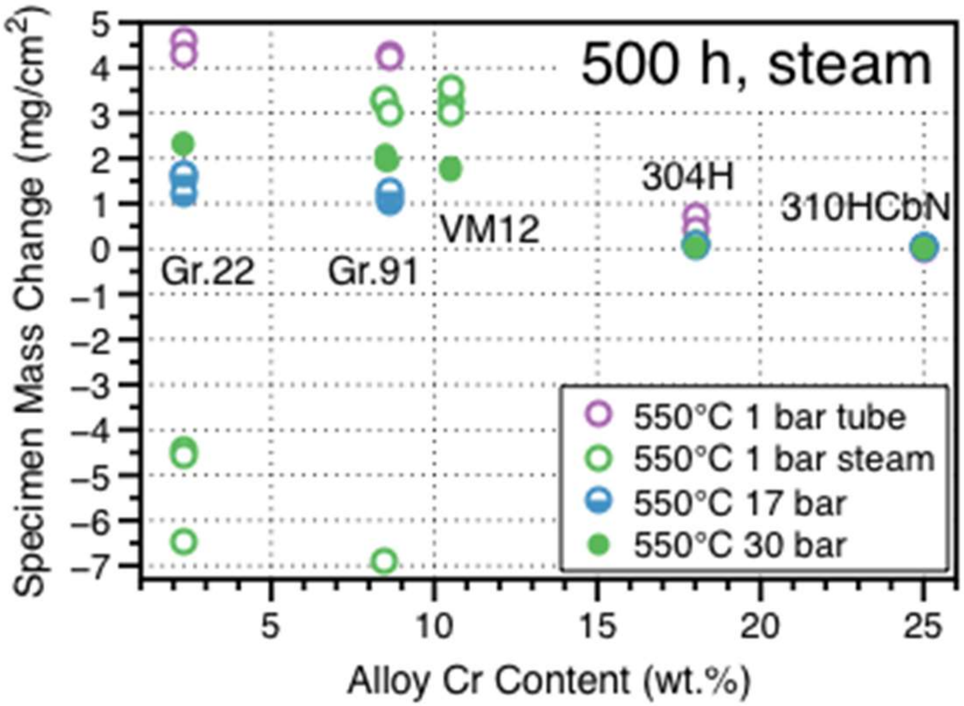
Pressures of 1-43 bar

Autoclave: 275 bar water
500-h cycles

1L volume restricts exposure

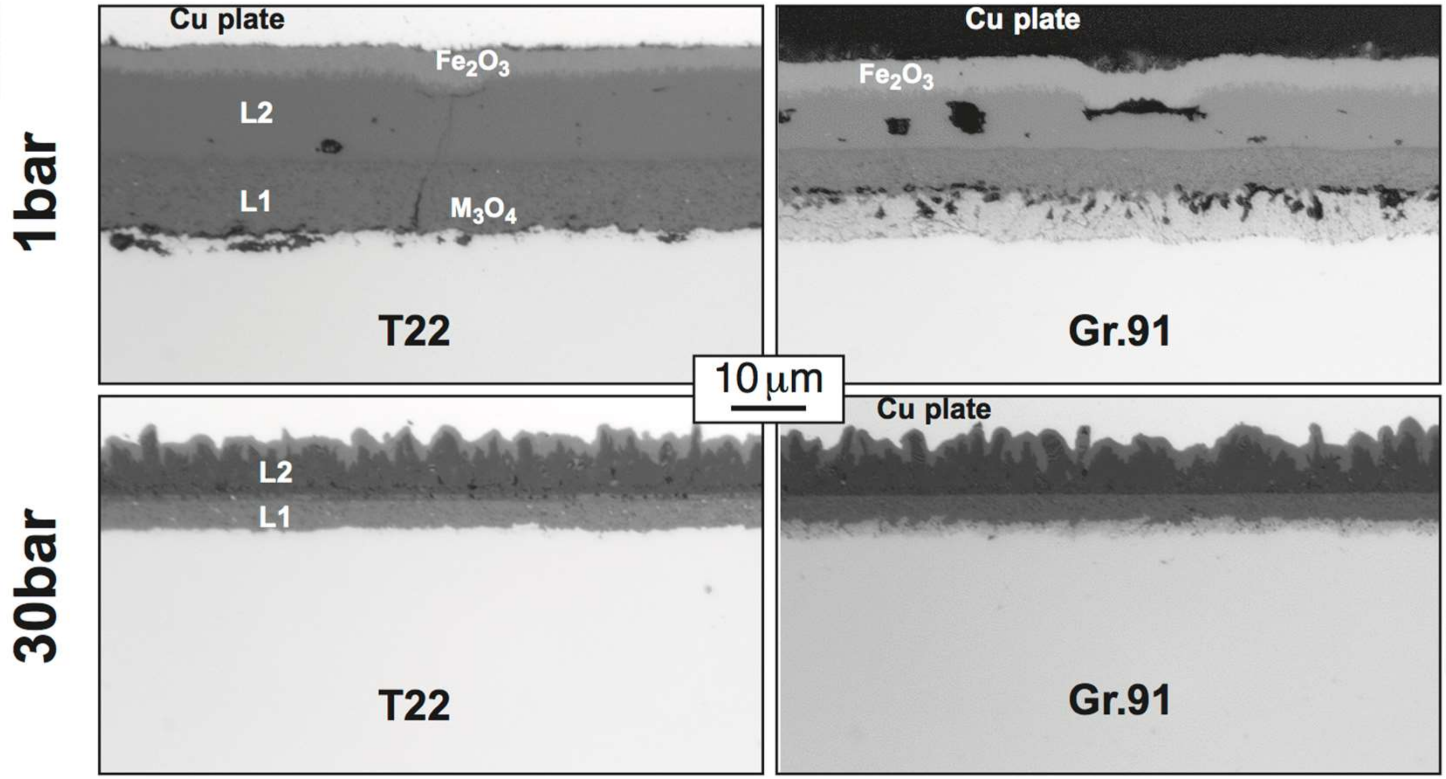
High purity Ar-bubbled, filtered water with conductivity <0.1µS and <10 ppb O_2

2017: 550°C, 500 h comparison of 1, 17 and 30 bar



- 1 bar steam in tube: higher mass than Keiser rig
- 1 bar Keiser rig - scale spallation for T22
- 17 bar less mass gain than 30 bar (run at different times)

Whoa. I wonder what scale at 275 bar looks like.



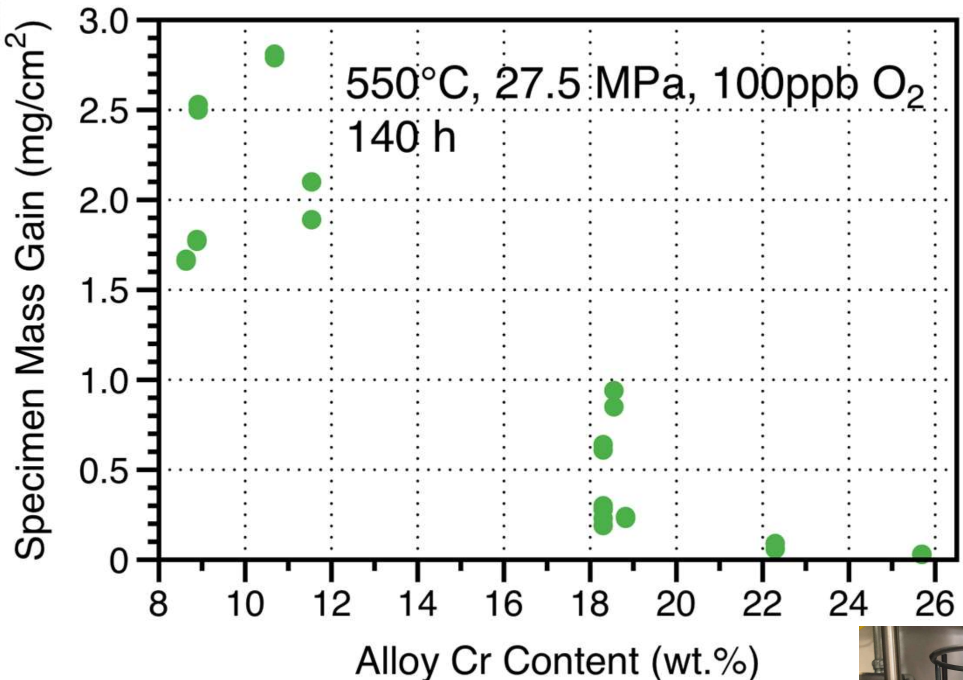
Cr content means little at this temperature: diffusion is too slow

Partnering with EPRI to go supercritical (650°C/27.5MPa)

- 1L alloy 625 autoclave
- Temperature up to 650°C
- Pressure to 27.5 MPa (4000 psi)
- Controlled & monitored water chemistry
  - Purified water loop for start
  - <0.06 μS/cm
  - UV, deionization, gas sparging
  - pH controlled by ammonia addition
  - Novel ammonia and hydrazine injection

Two conditions:
(1) All volatile treatment (hydrazine)
(2) Oxygenated treatment (100 ppb O_2)

First 500-h cycle aborted after 140 h



Issues resolved with:

- Heater
- Gasket
- Back pressure regulator

Planned test matrix:

	AVT	OT
550°C	1,000 h	1,000 h
650°C	1,000 h	1,000 h

All volatile treatment (AVT)

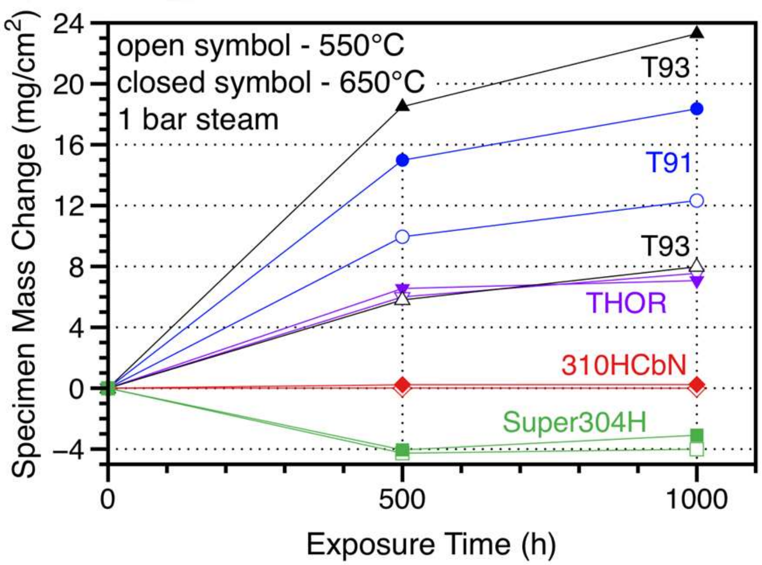
- < 10 ppb O_2
- Typical for sub-critical

Oxygenated treatment (OT)

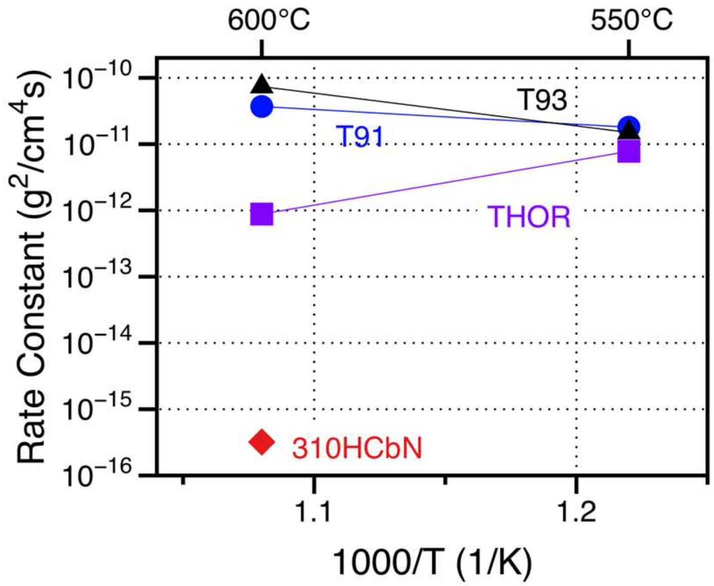
- 50-150 ppb O_2
- Typical for super-critical
- Oxide to prevent erosion

Created baseline 1,000 h exposures in 1 bar steam

Two 500-h cycles



Calculated rates



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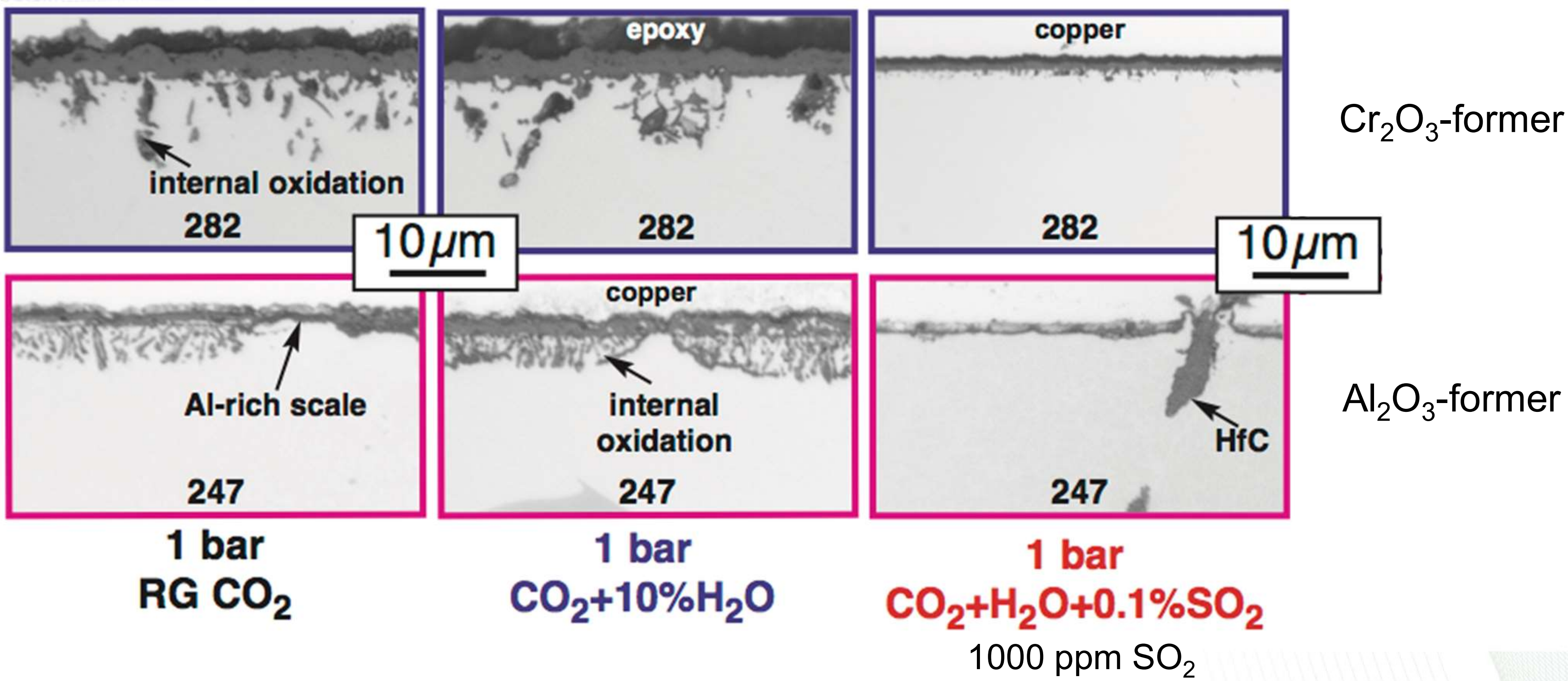
Corrosion task addressing several issues

1. Quantify shot-peening benefit on 304H
   - Completed 15 kh exposures at 600°-650°C
   - Now exposing at 550°C
   - Baseline alloy coupons also being exposed
2. SCC issue in current waterwalls
   - Testing completed in controlled water chemistry
   - Next task is in-situ monitoring
3. Effect of pressure on steam oxidation
   - Initial comparison: 500 h at 550°C, 1-30 bar
   - New matrix: 1000 h at 550° and 650°C in two water chemistries

- Expecting to complete all tasks in 2018

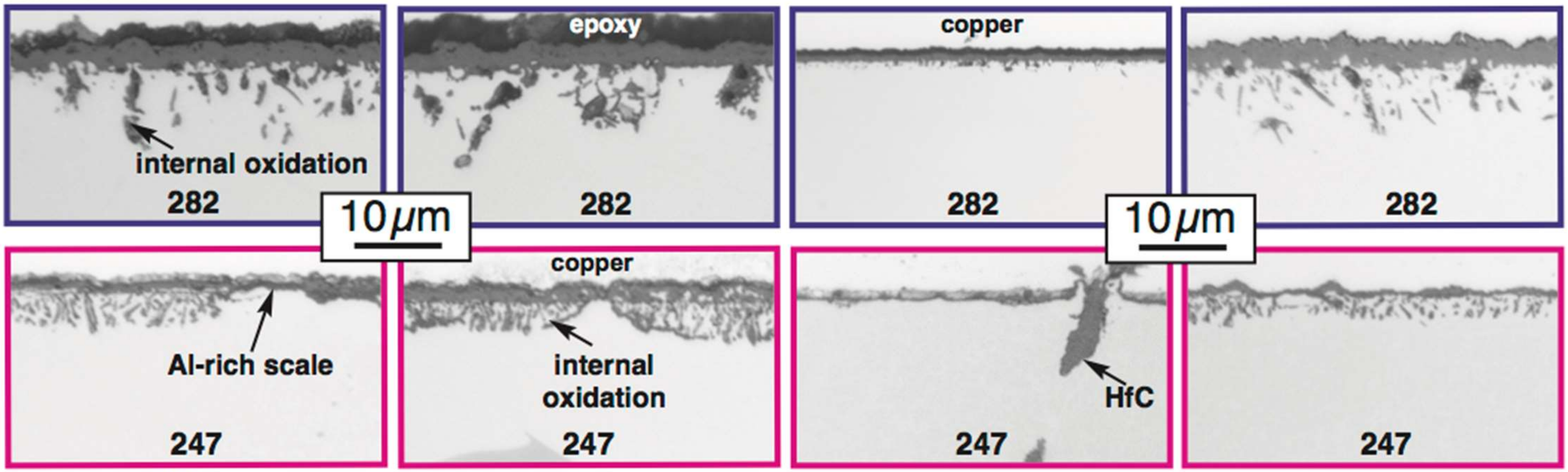
Backup slides

500h at 800°C: SO_2 suppressed internal oxidation at 1 bar



Similar results for SO_2 reported by Young (UNSW) and Quadakkers (Jülich)

500h at 800°C: at 25 bar, 0.1%SO_2 resulted in more attack



1 bar
RG CO_2

1 bar
CO_2+10%H_2O

1 bar
CO_2+H_2O+0.1%SO_2

25 bar
CO_2+H_2O+SO_2

Haynes 282: Ni-20Cr-11Co-9Mo-1.6Al-2.2Ti

MarM247 superalloy: Ni-9Cr-10Co-1Mo-6Al-1Ta-3Ta-1.4Hf

Similar observation with 600°C ORNL study for staged pressurized oxy-combustion (SPOC):

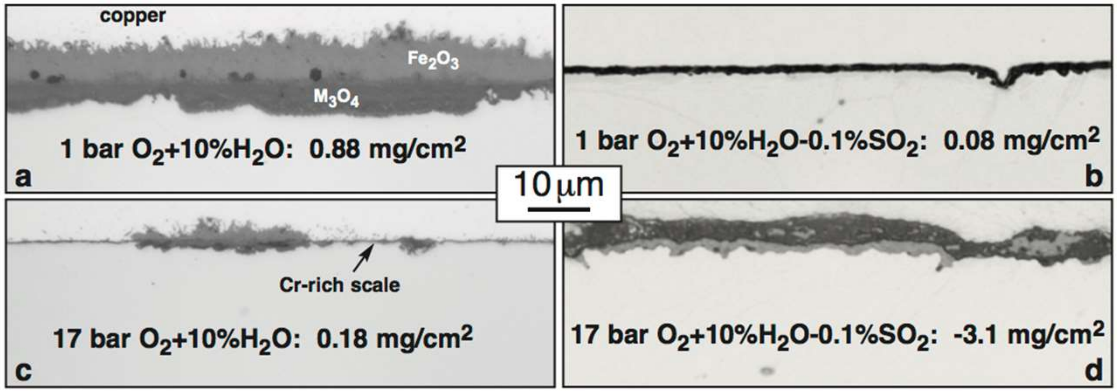


Figure 5: Light microscopy of S30409 specimens exposed at 600°C for 500 h in two environments and two pressures.

No CO_2 in this study

O_2-10%H_2O: reduced attack at 17 bar compared to 1 bar

0.1%SO_2 1 bar: inhibited negative CO_2/H_2O effect (protective scale)

Similar result for Young (CO_2+H_2O) and Quadakkers (H_2O)

0.1%SO_2 17 bar: sulfidation attack with 17X higher p_{S_2}

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