Corrosion Issues in Advanced Coal-Fired Boilers (FEAA116)

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ORNL

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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

FY16

Complete shot peened SS characterization after 10,000h (5/31/16 Met)

Complete initial SCC assessment in 2 water chemistries (12/31/16 Met)

Complete steel characterization in 3 steam pressuress (in progress)

FY17

Complete final report on shot peened stainless steel oxidation (3/31/17)

Demonstrate in-situ crack growth measurements in 200°C water (9/30/17)

Compare oxide microstructure formed on steam at 1 & 200 bar (6/30/17)

FY16-17: science approach to "real world" corrosion issues

1) Steam oxidation
   - study of shot-peening "solution"

2) H-induced stress corrosion cracking
   - 2.25%Cr waterwall steels: Grades 22,23,24
   - significant problem in new boilers
   - need for more detailed understanding

Cracks in longitudinal direction

Cracks in transversal direction

3) Effect of pressure on corrosion
   - relevant for steam oxidation (lab. vs. field)
   - SPOC: staged pressurized oxy-combustion (with Wash.U@StL) also relevant on fireside

John W. Turk Plant (2013) solution

"Ultra-supercritical" coal-fired steam plant by B&W/AEP

Fulton, Arkansas
600 MW
2013 commission
~40% LHV efficiency
$1.8 billion ($2.8b?)

Turk (2013): 599°/607°C SH/RH 25.3MPa (1110/1125°F)

Eddystone (1960): 613°C/34.5MPa (1135°F/5000psi)

Turk superheater tubes: shot-peened 347H

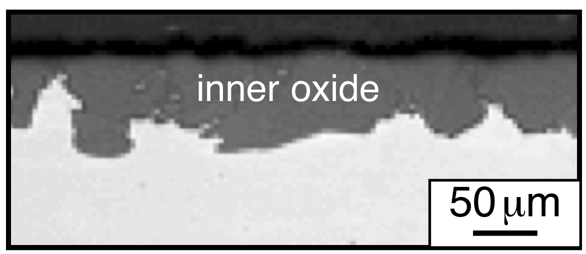
Fe-17.5Cr-10Ni-0.5Nb-1.5Mn-0.4Si-0.07C

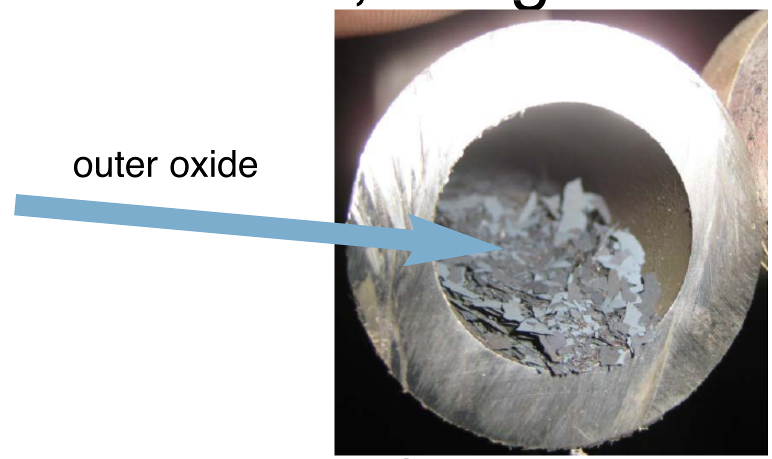
Task 1: Why shot peening?

Exfoliation problem is a main driver for research

- H_2O-accelerated oxidation of steels (steam-side)
- Simultaneous spallation of thick oxide
- Tube failures & erosion damage
- Cost: planned/unplanned shutdowns, mitigation

TP304H (22,000h)





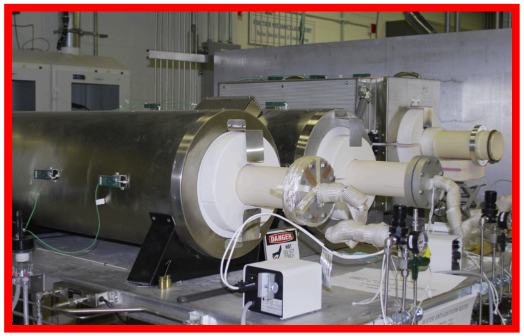
Source: EPRI

Shot peening of austenitic tubes

- Reduced scale growth: avoids exfoliation issue
- Limited understanding of benefit and procedure
- Ex: How do oxide nodules evolve at 600°-650°C?

Specimens exposed in laboratory

ORNL has several options



1 bar steam

Atomized deionized water (no carrier gas)

H_2O: ~0.065μS/cm, filtered, deaerated

Temperature: 550°-650°C

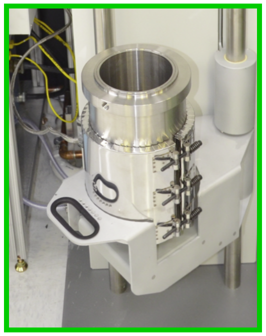
Time: 500 h cycles

1-30 bar steam testing

H_2O: ~0.065μS/cm, filtered, deaerated, deionized

Temperature: 550°-900°C

Time: 500 h cycles



≤ 275 bar steam testing (in 2017)

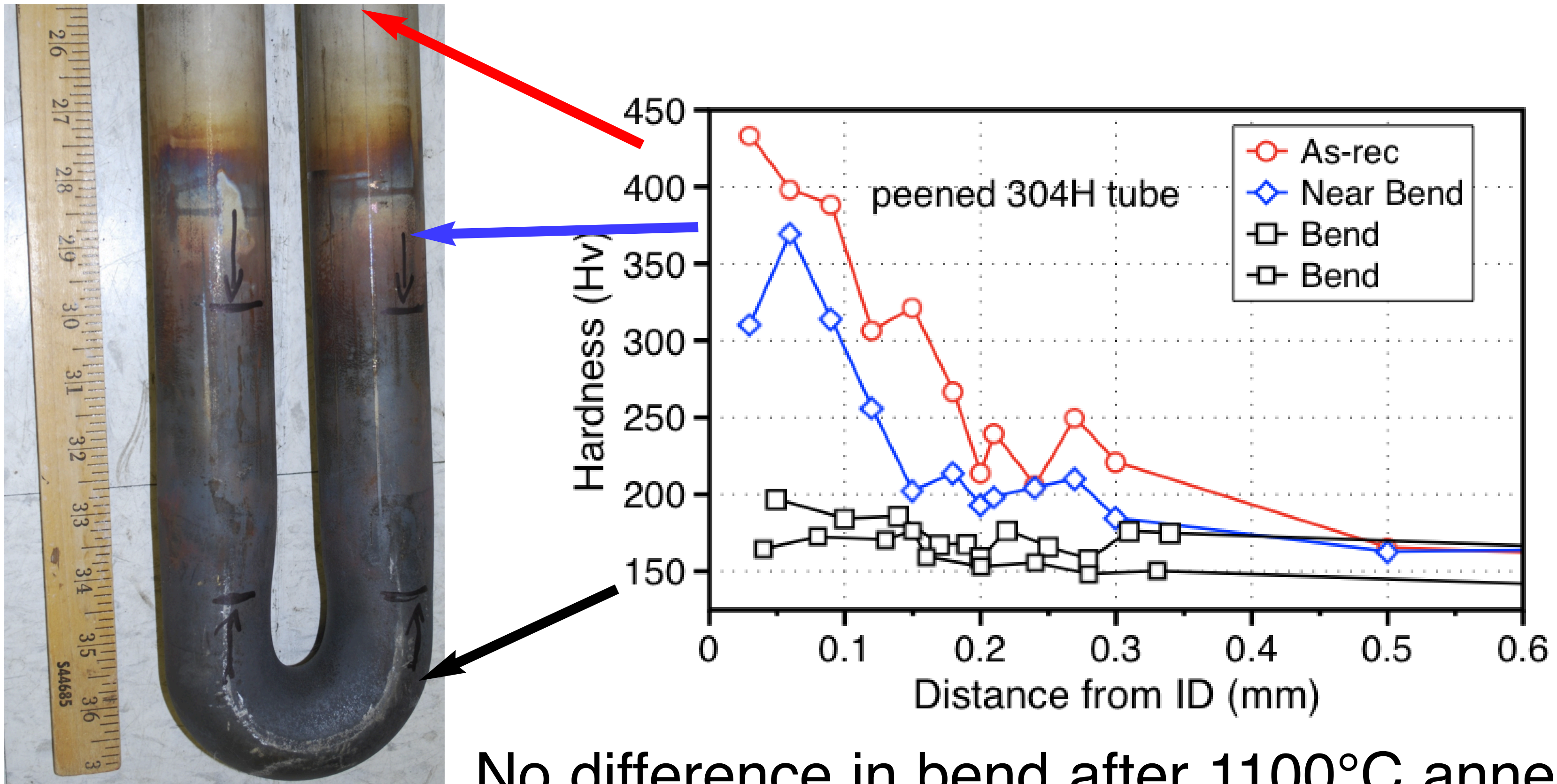
Controlled water chemistry loop

Temperature: 450°-650°C

Time: 500 h cycles

Cold work–hardness–fast D_{Cr}

Well known cold working affects transport



No difference in bend after 1100°C anneal

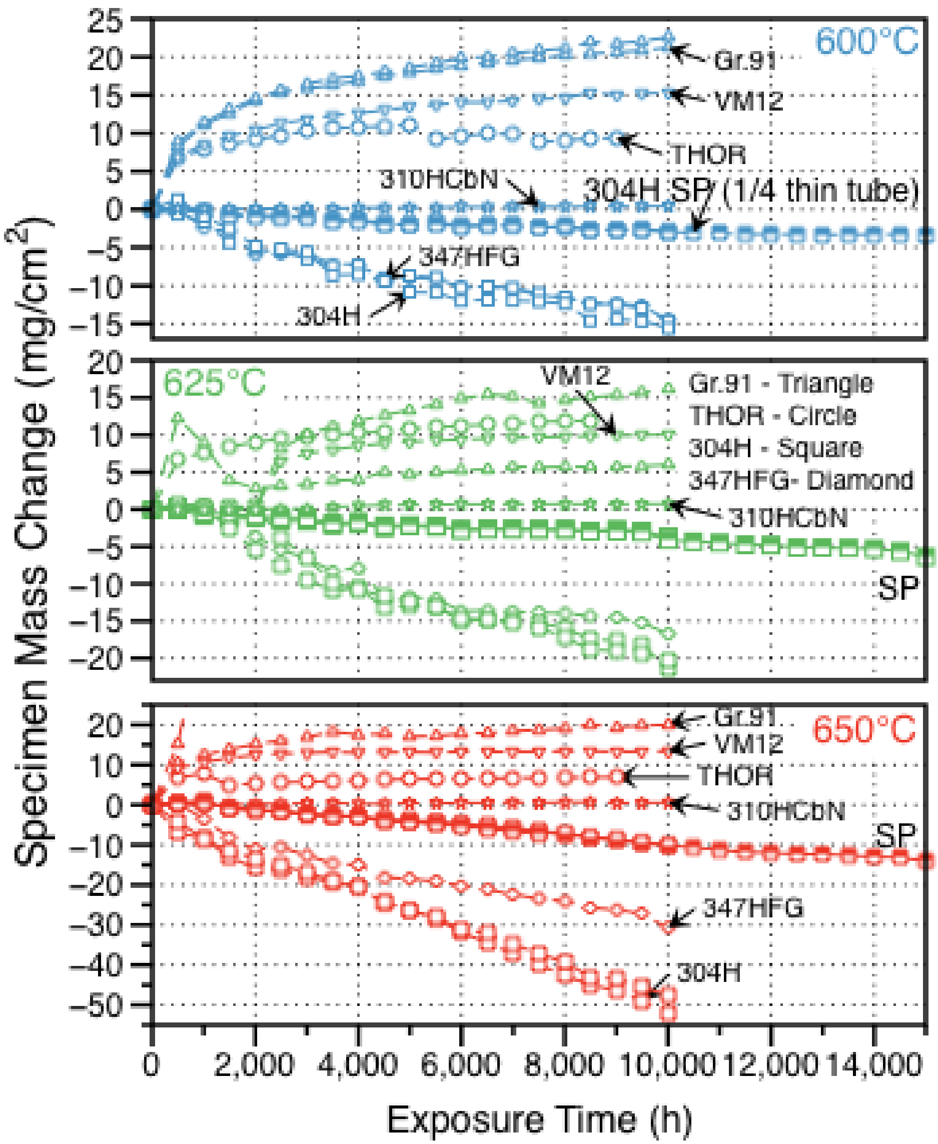
304H tube from an EPRI partner:

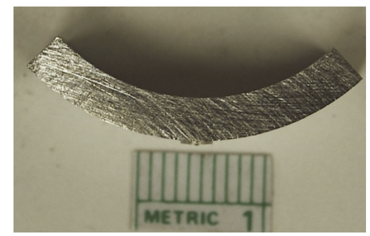
No hardness difference remained in the bend after required 1100°C annealing

Completed 15kh of exposures

600°,625°,650°C 1bar steam; 500-h cycles

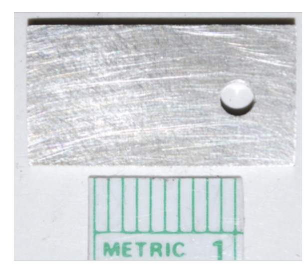
Shot peened coupons: commercial 304H from a utility





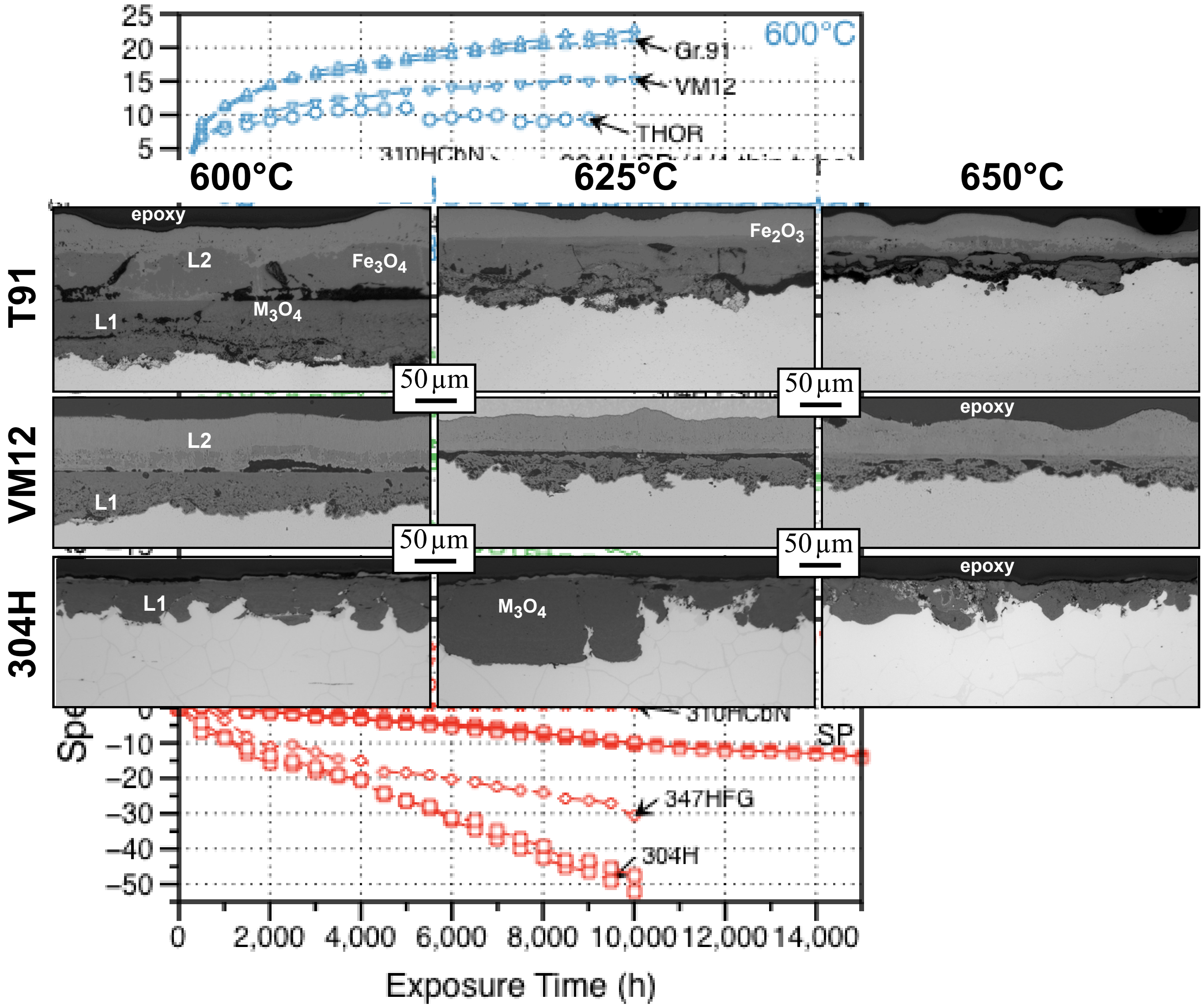
Shot peened coupons:
- tube sections
- reduced wall thickness

Polished alloy coupons:
- comparison



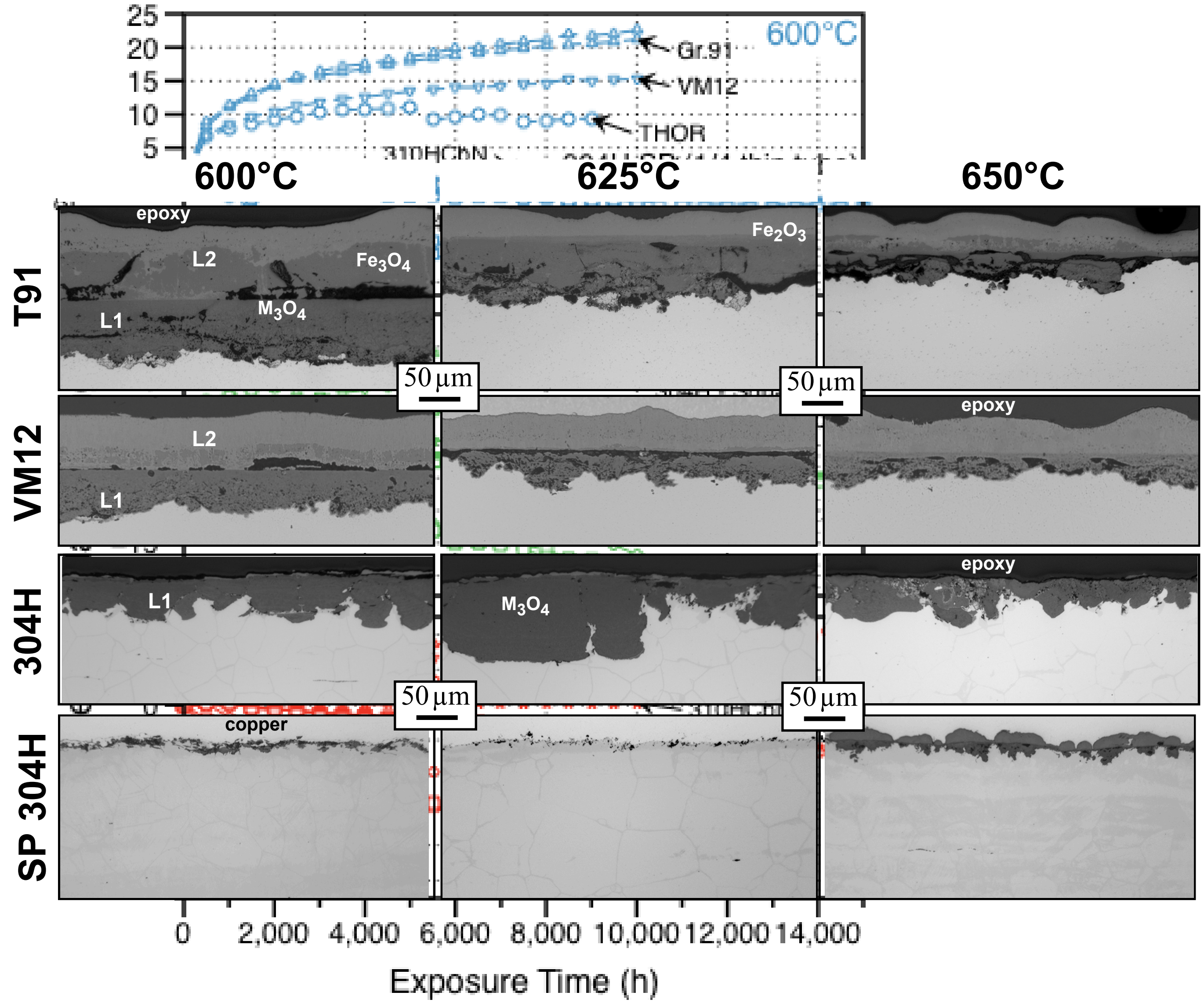
Alloy coupons stopped at 10,000h

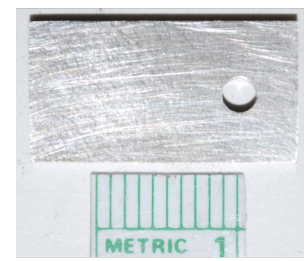
Alloy coupons: conventionally polished

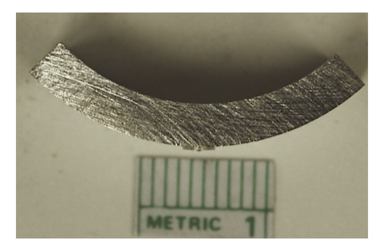


10,000h: Clear shot peening benefit

600°,625°,650°C 1bar steam; 500-h cycles

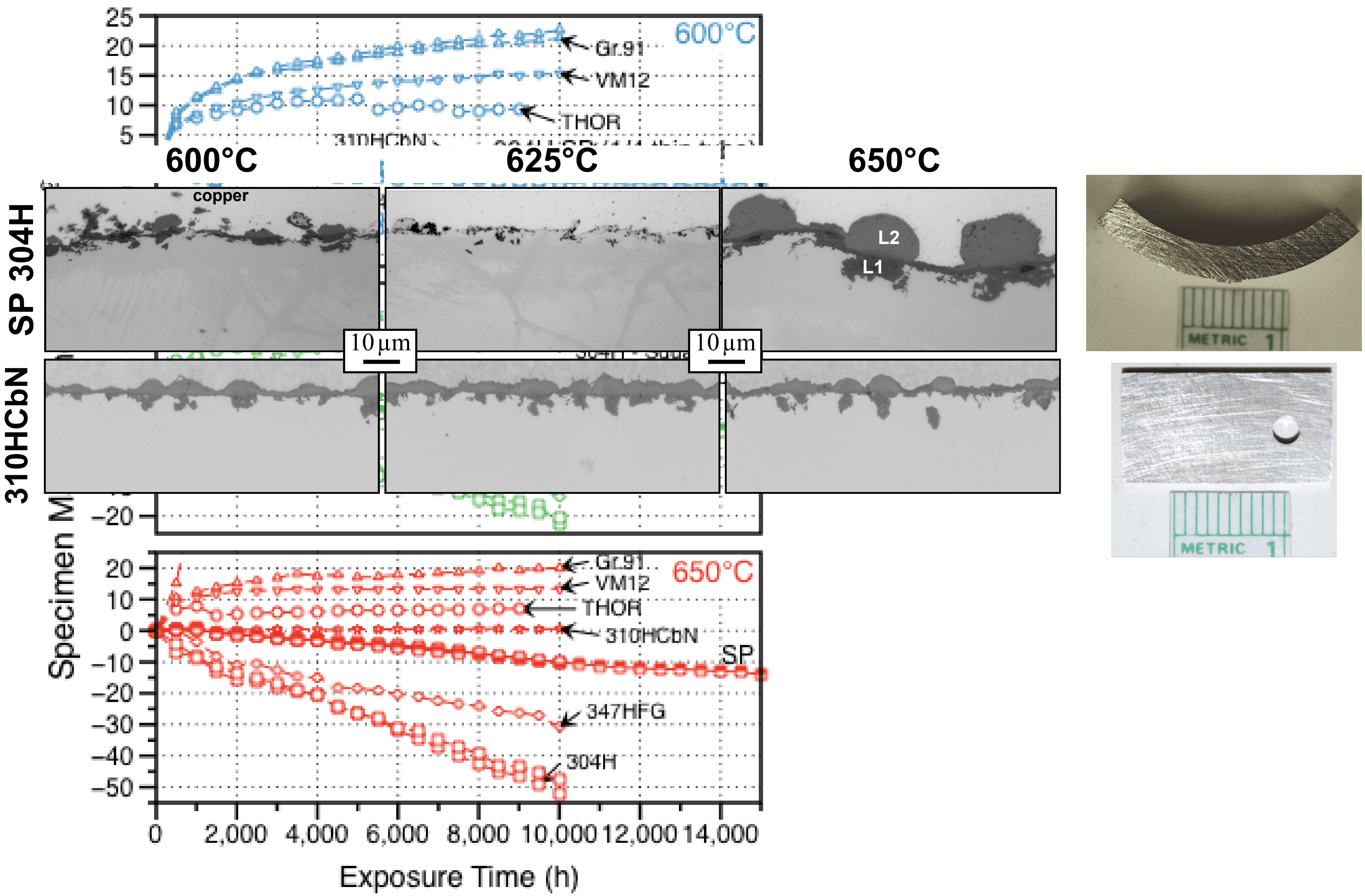






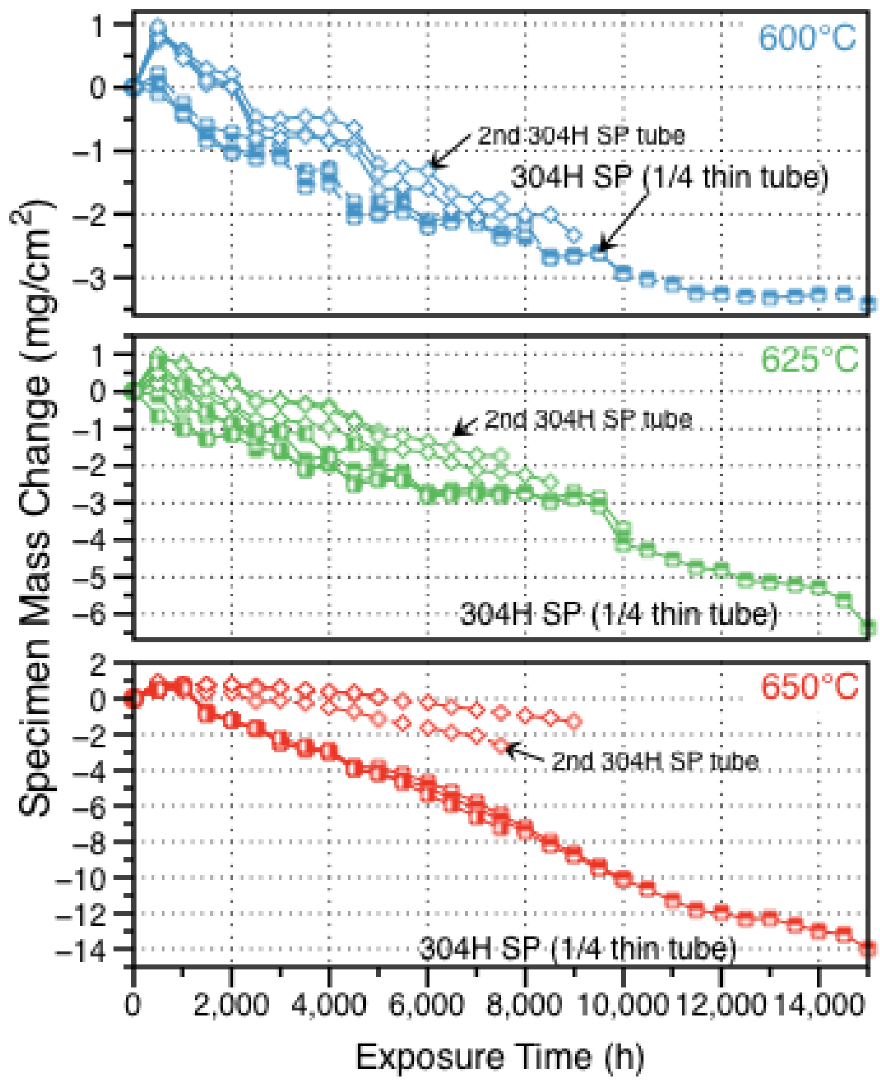
10,000h: thin scale like on 310SS

600°,625°,650°C 1bar steam; 500-h cycles



Two differented peened tubes

600°,625°,650°C 1bar steam; 500-h cycles



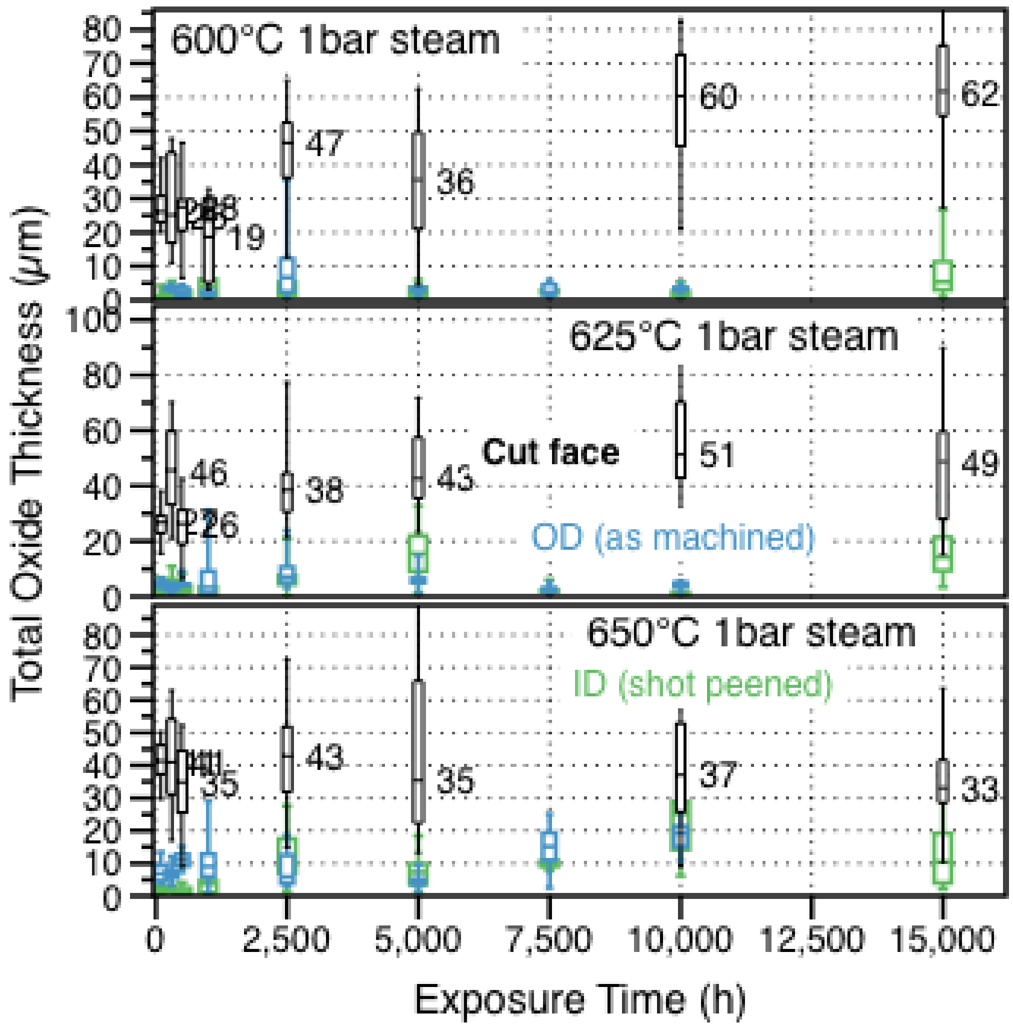
commercial shot-peened 304H

Each: 0.5, 1, 2.5, 5, 7.5, 10, 15 kh specimens

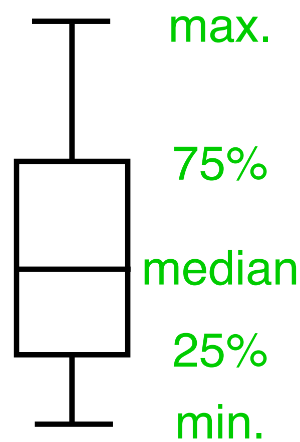
Series of SP specimens exposed

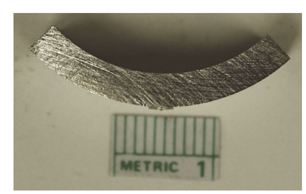
Oxide thickness measurements from polished sections

commercial shot-peened 304H



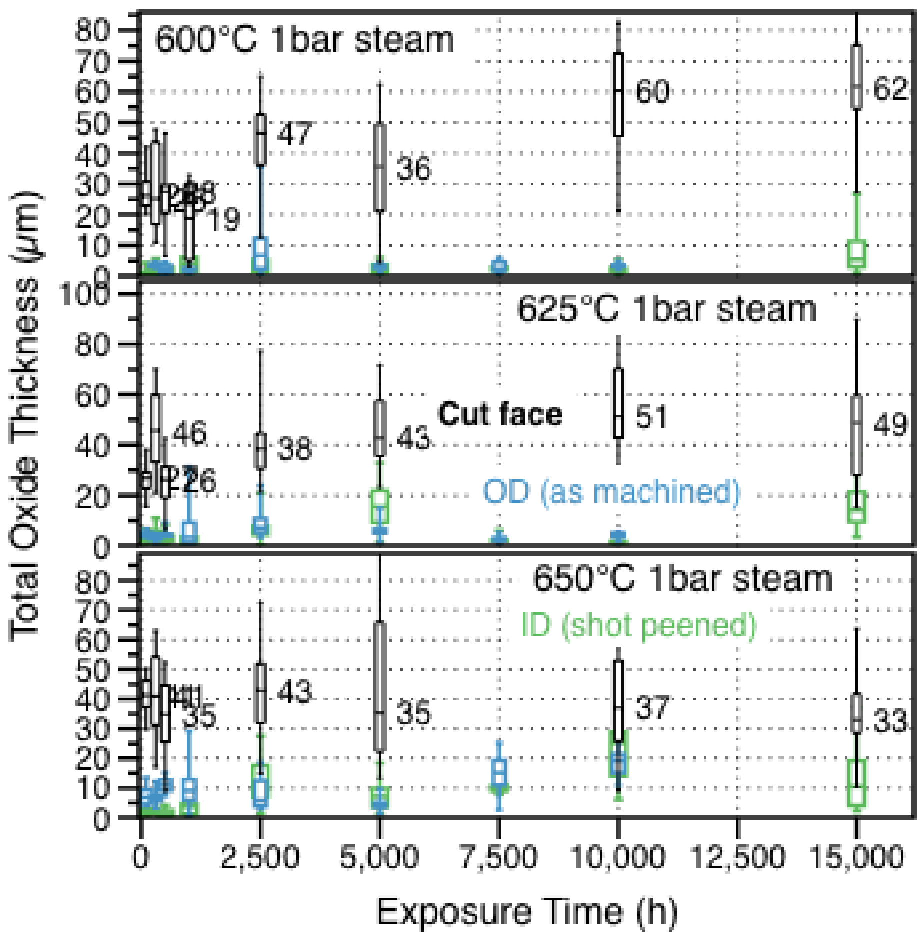
Box & whisker plot

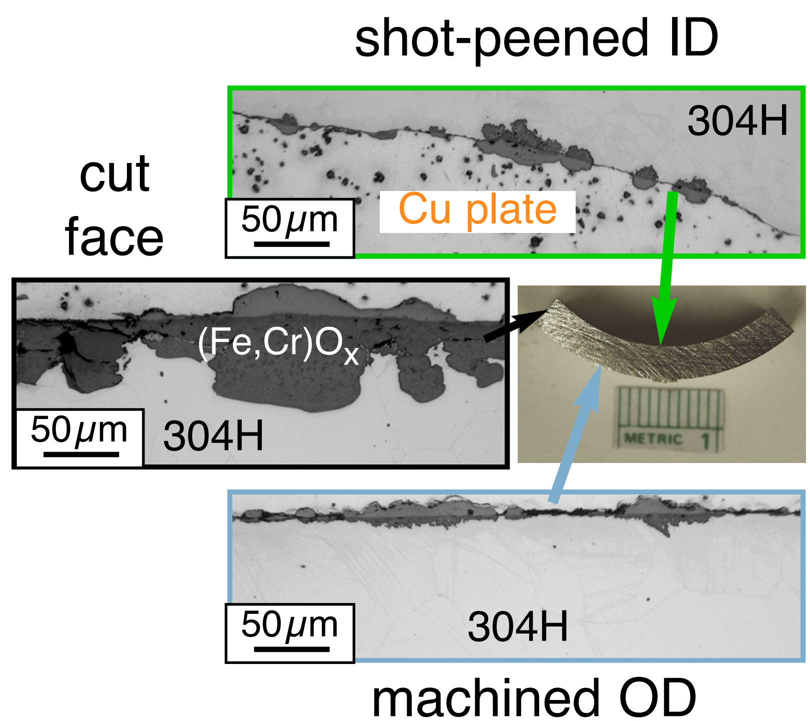




“Cut” face grows thick oxide

Oxide thickness measurements from polished sections

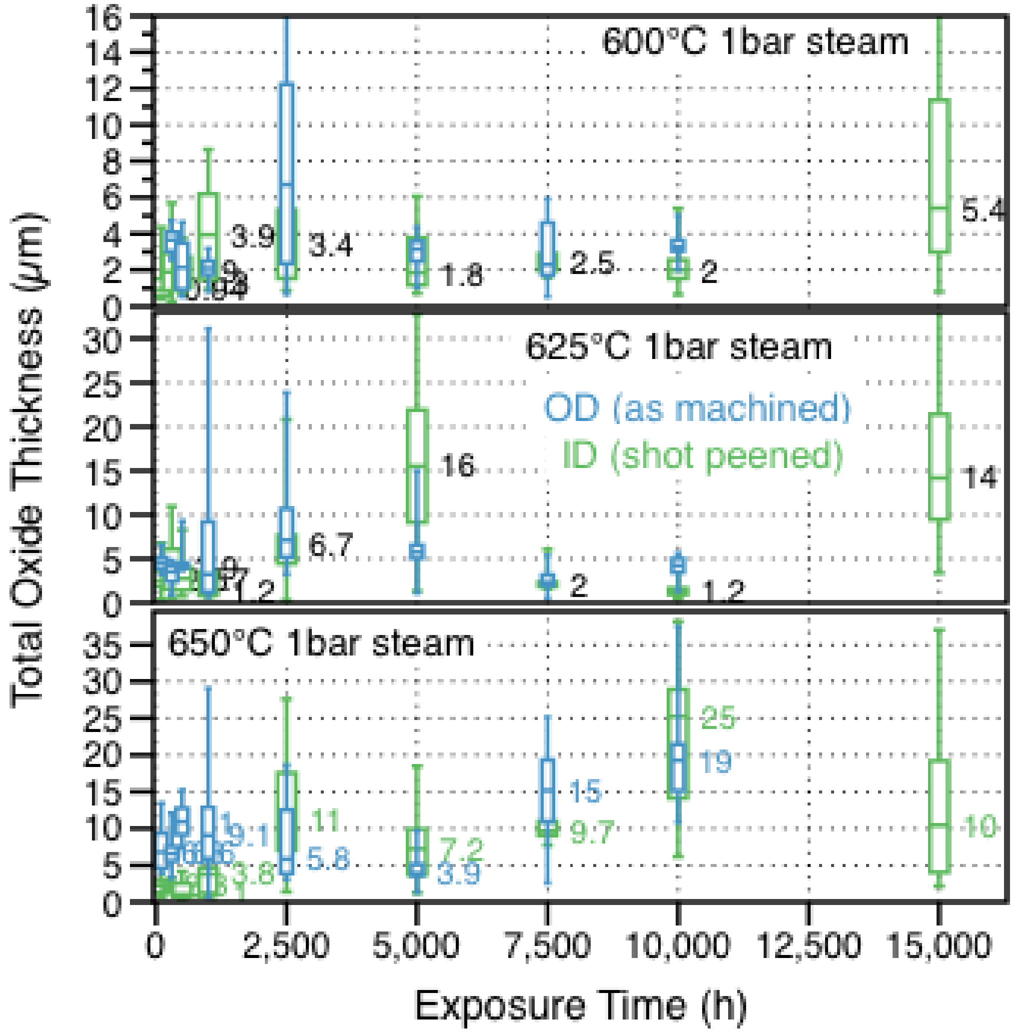


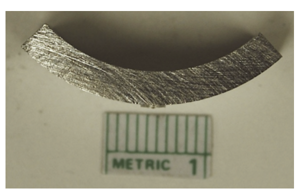


Example: 2,500h, 625°C

Similar benefit on machined OD

Oxide thickness measurements from polished sections

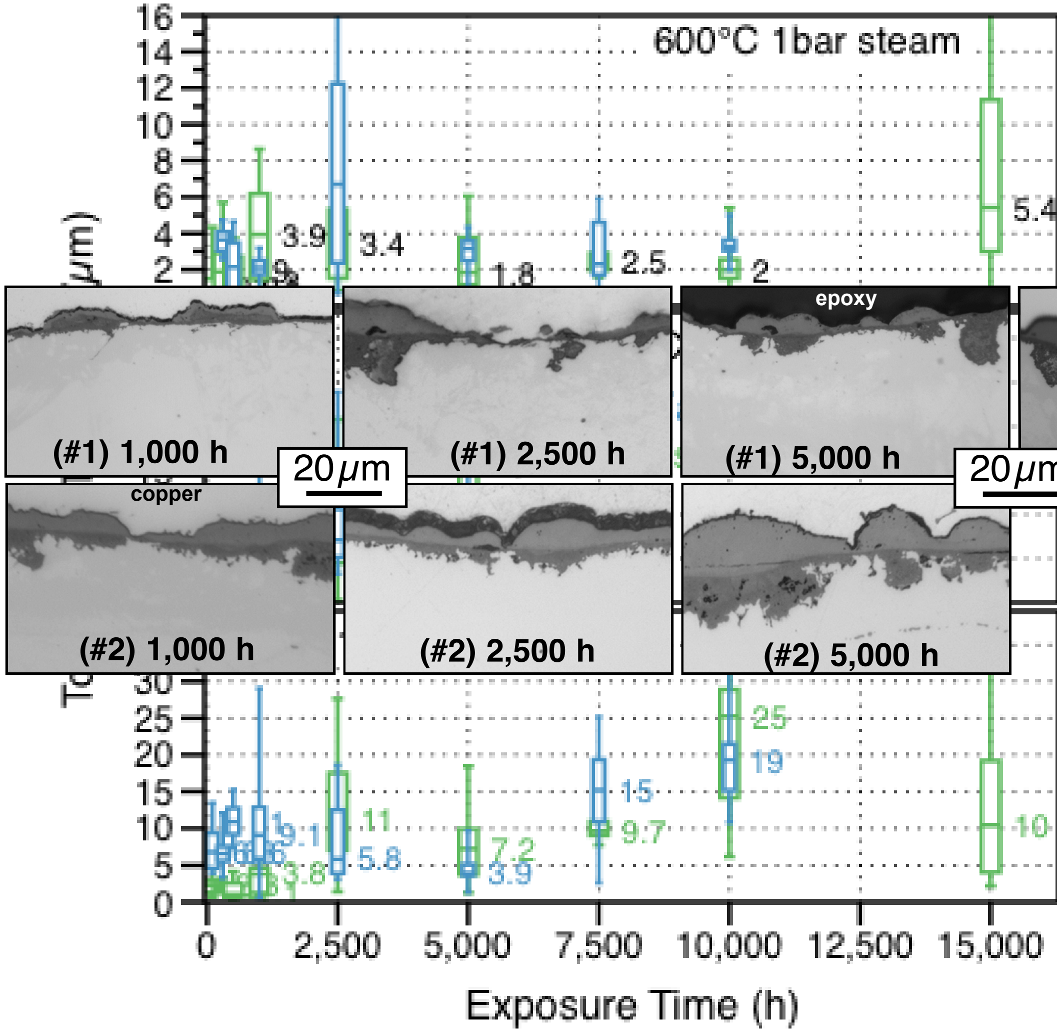


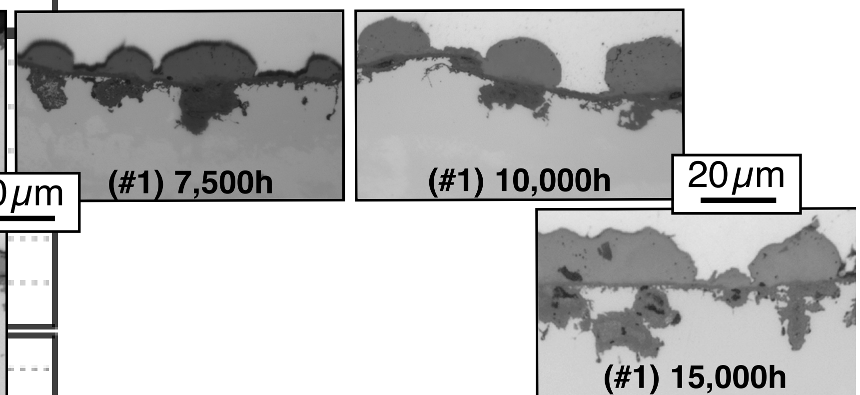


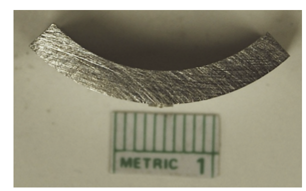
600°-625°C
- thin ID oxide
- similar thin OD oxide

Losing peening benefit at 650°C

650°C 1bar steam; 500-h cycles





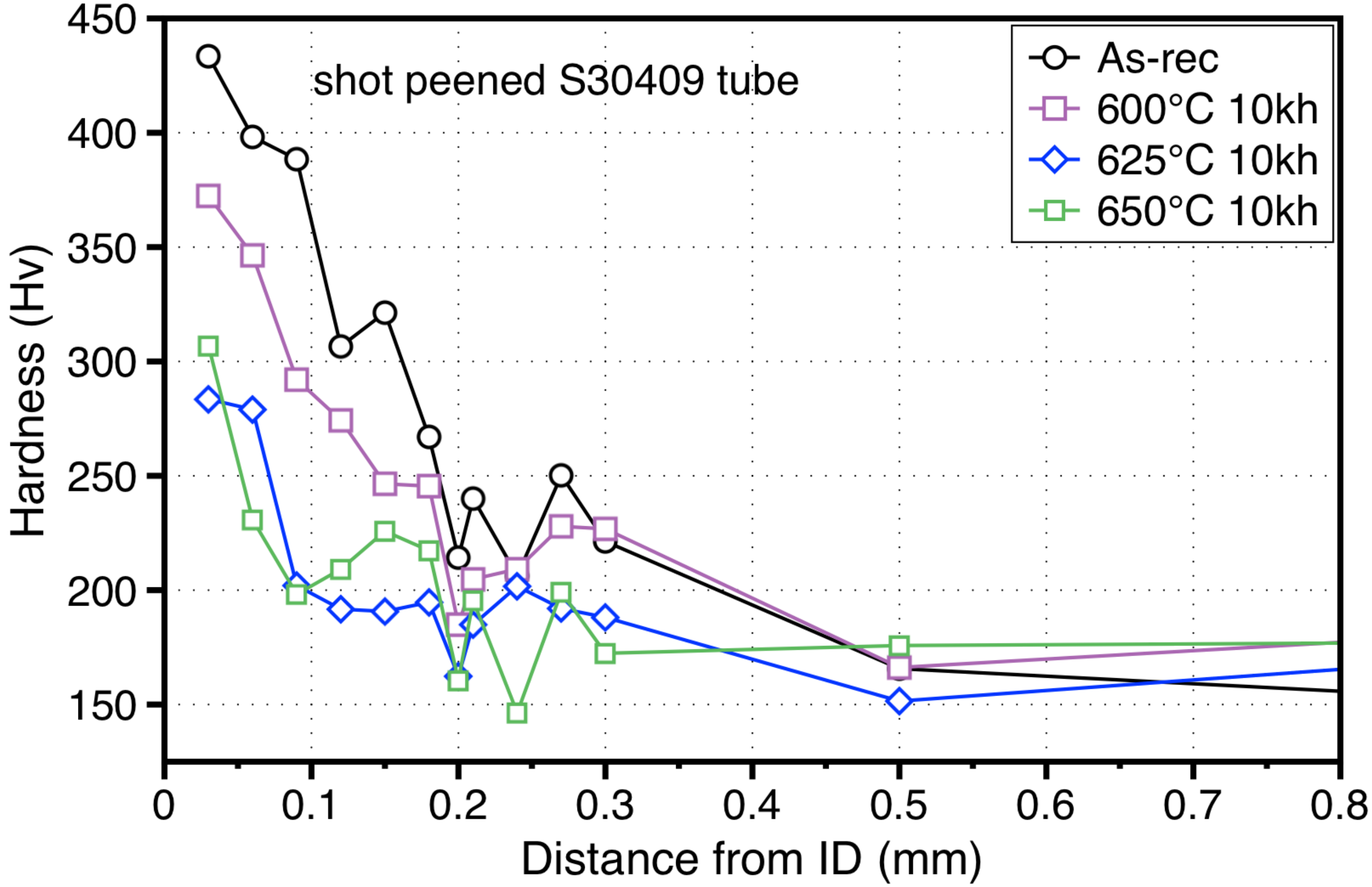


Light microscopy
Shot peened ID

Each: 0.5, 1, 2.5, 5, 7.5, 10, 15 kh specimens

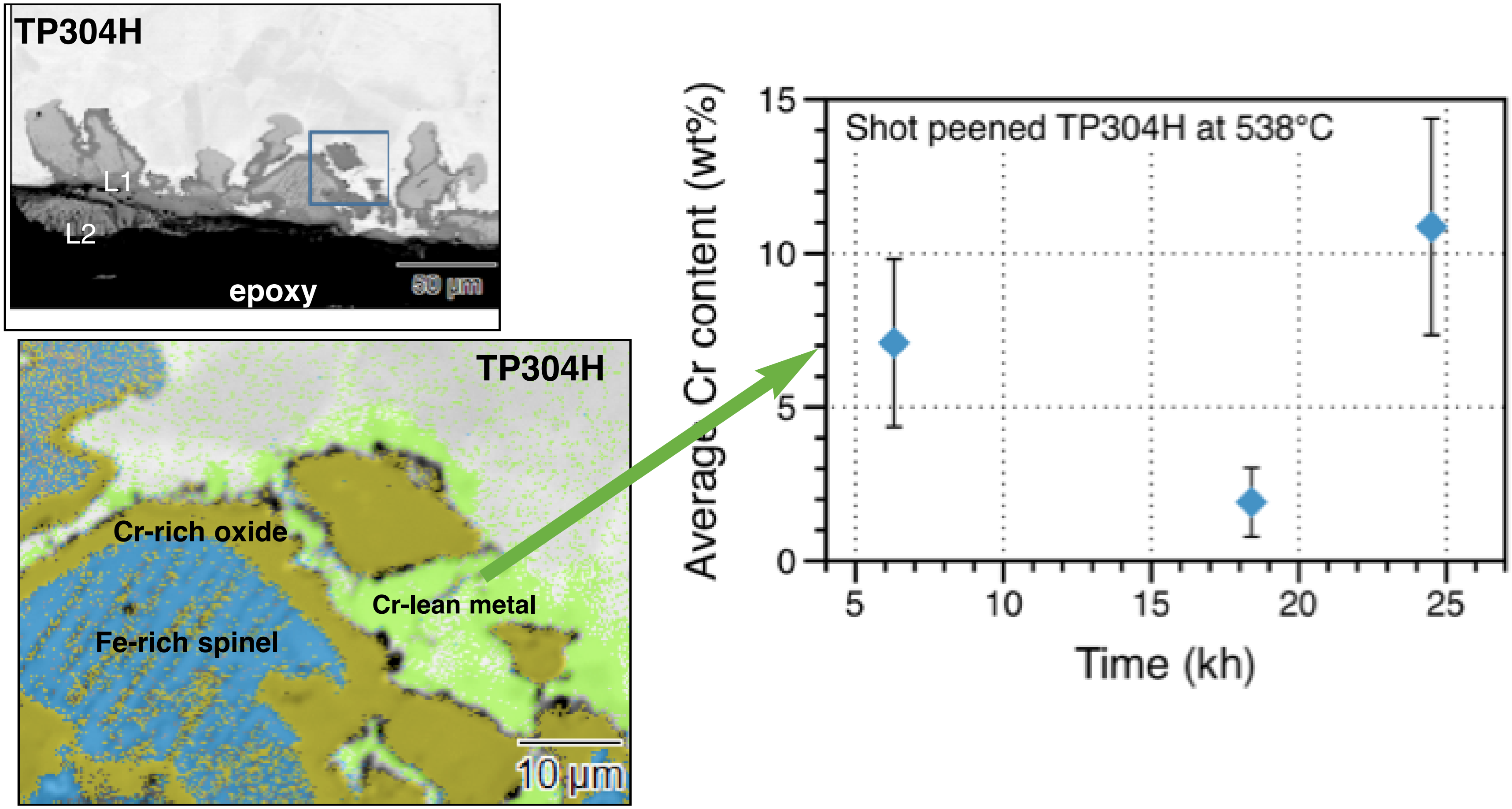
Hardness changed with exposure

Measurements on 10,000 h specimens



Field (EPRI): high Cr depletion beneath scale

Shot peened TP304H: up to 24,500 h, 538°C steam



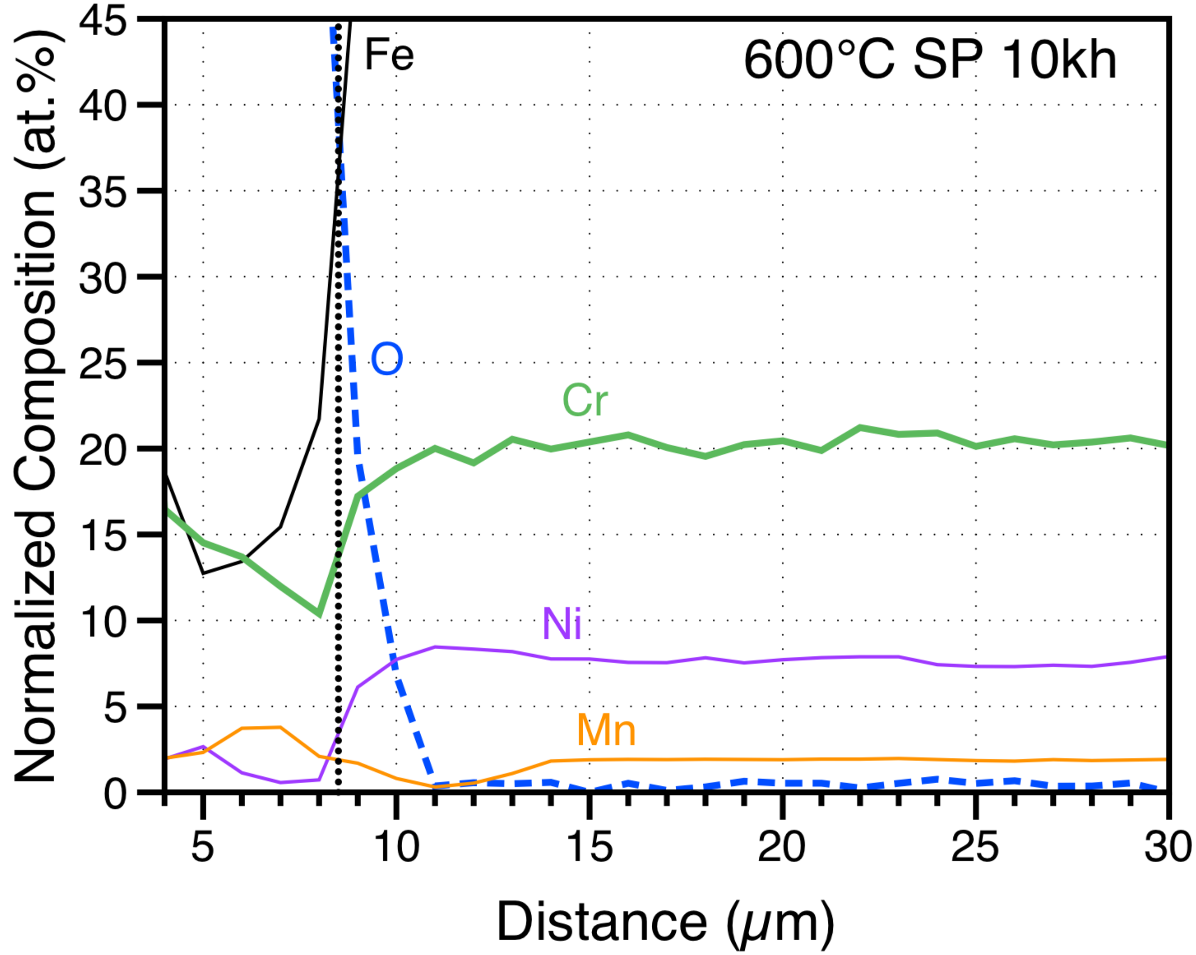
Models: 10-15%Cr is susceptible to form FeO_x

Higher Cr depletion here: unstable situation

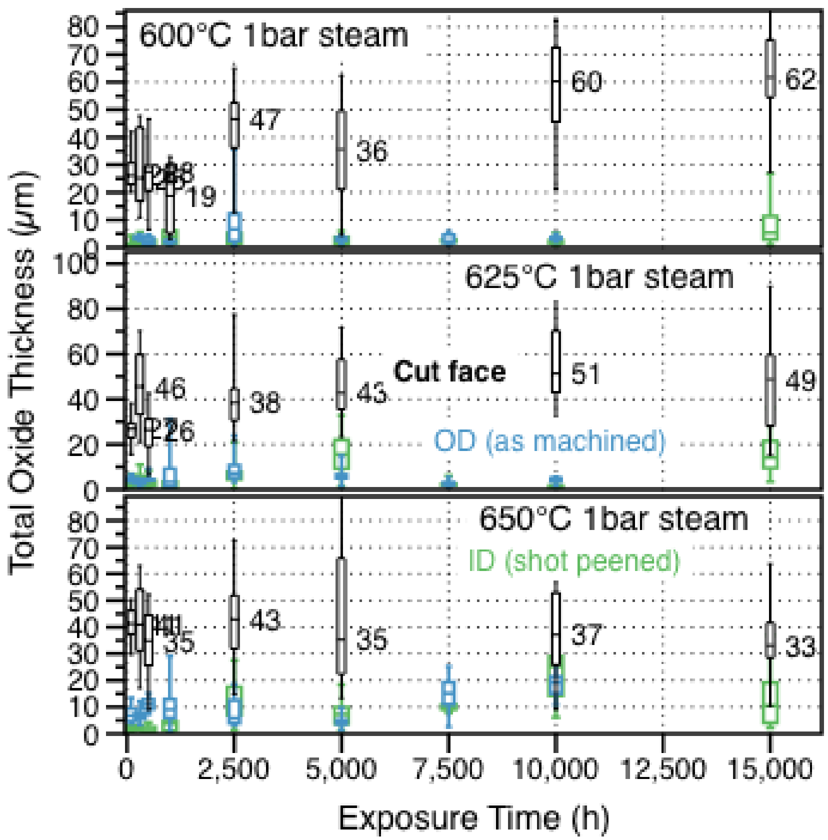
- any disruption in Cr-rich oxide likely to grow nodule

Minimal depletion in lab specimens

EPMA line profile after 10,000 h at 600°C



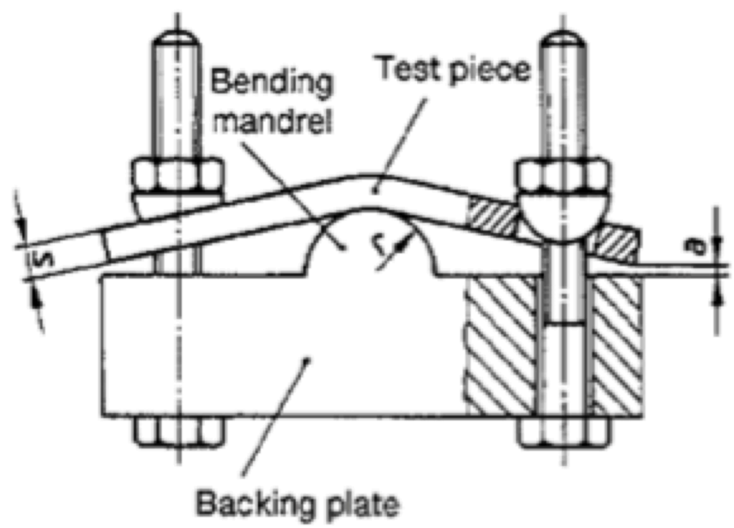
Wrapping up Task 1



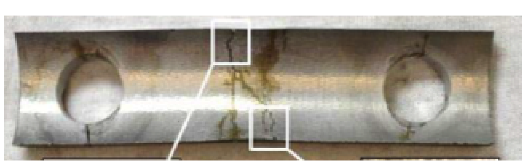
- Second SP tube specimen running to 10,000 h
- Alloy coupon specimens running to 10,000 h
- More characterization
  - complete measurements
  - improved image statistics
  - 15kh hardness check
  - 15kh Cr depletion (EPMA)
  - EBSD

Task 2: stress corrosion cracking

- 2.25%Cr waterwall steels: Grades 22,23,24
  high strength steels susceptible
- significant problem for new boilers
- Stress-environment interaction: 25°-300°C
- Jones test to apply stress (complicated)
- prior results in aerated and deaerated water



Jones Test



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

☐ Did Not Crack
☑ Cracked

Water loop: next level of testing

Simulate actual fossil environments
with controlled pH and pO_2 levels

water control system
- based on GE systems

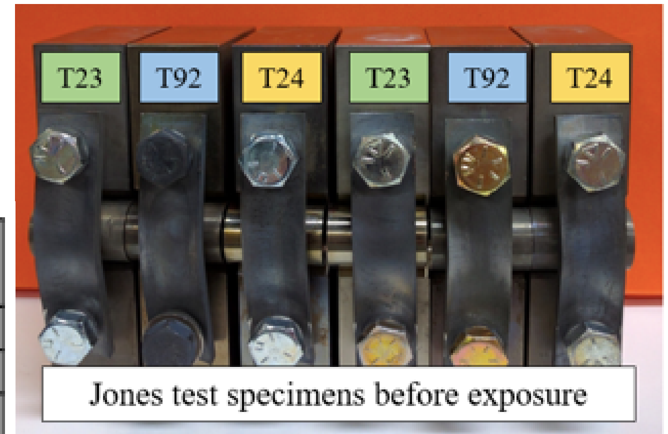
200°C autoclave

O content affected cracking

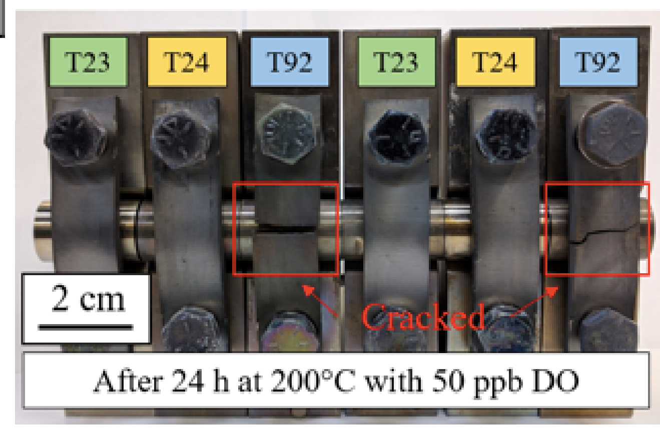
1st Jones tests with controlled water chemistry at ORNL

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
T92	O	X	X	X

O: Uncracked X: Cracked



Jones test specimens before exposure



After 24 h at 200°C with 50 ppb DO

200°C, untempered steels
Normalized (0.5h,1065°C WQ)

Earlier work concluded no need to run 72-168h
100ppb O 24h test conducted first
Reduced O to 50ppb for second experiment

Next steps

SCC = microstructure + stress + environment

In-situ crack growth monitoring (FY17)
- exploring electrochemical methods
- incrementally change water chemistry
- determine when crack begins in Jones test

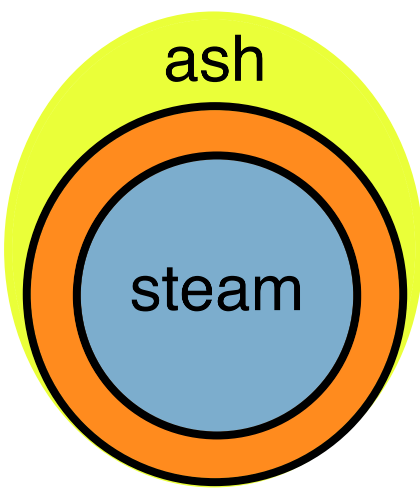
Controlled stress experiments (tensile tests)
- (GE downsizing their laboratory)
- Change crack growth rate with chemistry

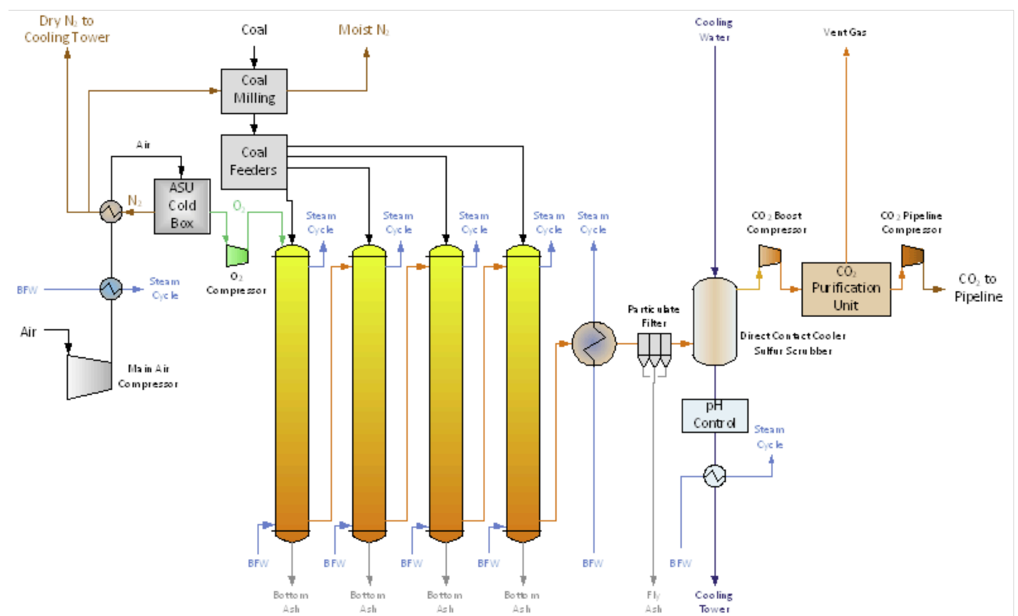
Are there critical temperature and hardness values for susceptibility?

Are there solutions for Grades 23 and 24?

Task 3: effect of pressure

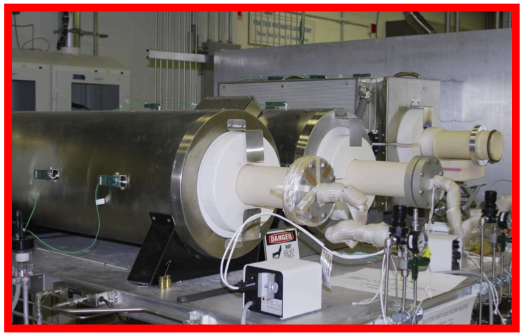
- Steamside
  - steam oxidation field-lab disconnect
  - field (high pressure) ≠ lab (typically 1 bar)
  - need uniform test procedure to study
- Fireside (future topic)
  - for Staged-Pressurized Oxy-Combustion (SPOC)
  - previous work with Washington Univ. (St. Louis)
    - R. Axelbaum and B. Kumfer





Specimens exposed in laboratory

ORNL has several options



1 bar steam (tube test)

Atomized deionized water (no carrier gas)

H_2O: ~0.065μS/cm, filtered, deaerated

Temperature: 550°-650°C

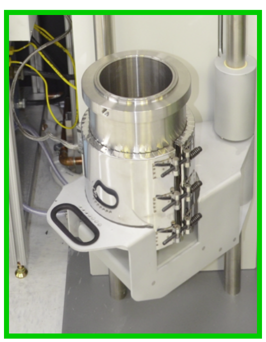
Time: 500 h cycles

1-30 bar steam testing (Keiser rig)

H_2O: ~0.065μS/cm, filtered, deaerated, deionized

Temperature: 550°-900°C

Time: 500 h cycles



≤ 275 bar steam testing (in 2017)

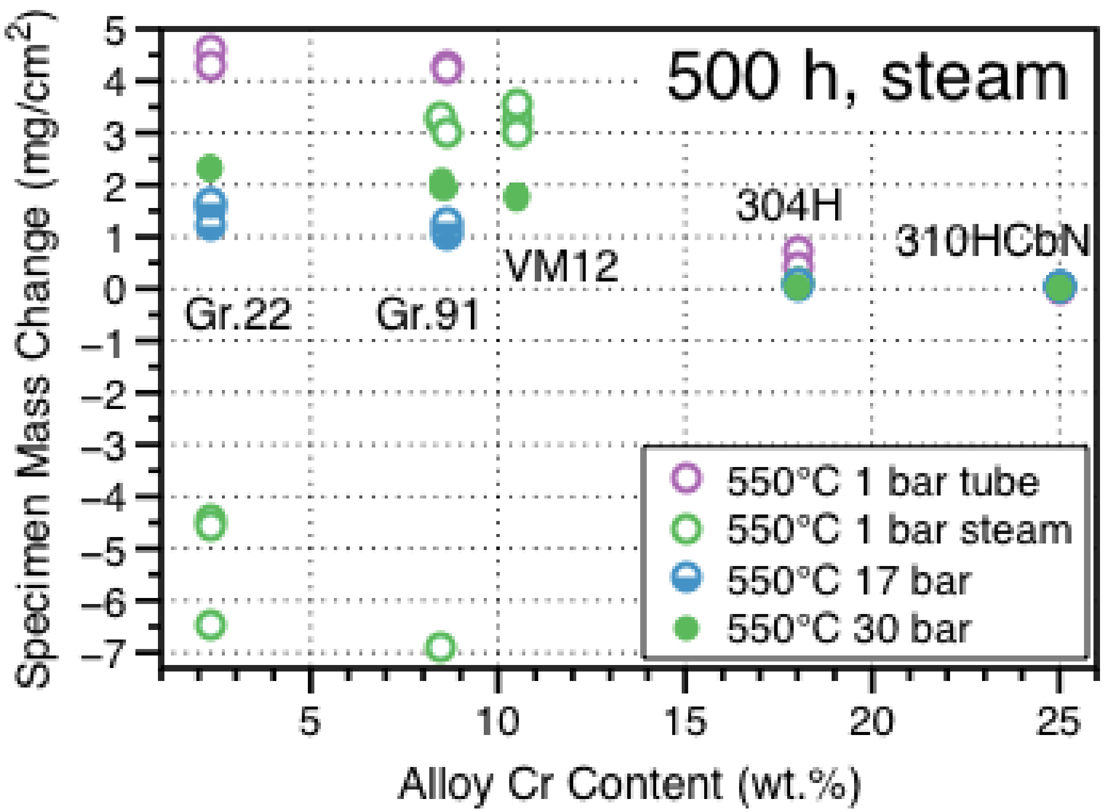
Controlled water chemistry loop

Temperature: 450°-650°C

Time: 500 h cycles

Initial results in 550°C steam

500 h exposures: Tube vs. Keiser rig



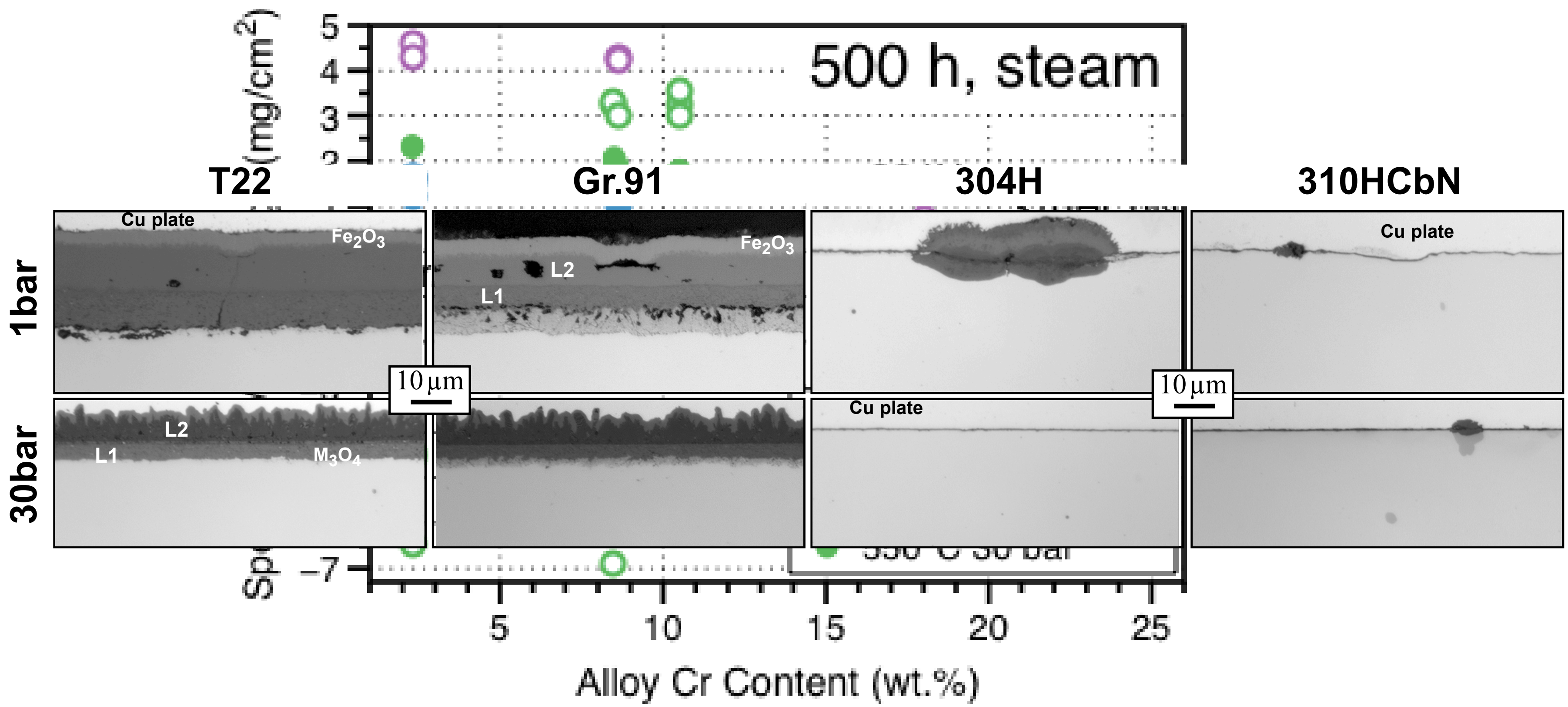
1 bar steam in tube: higher mass than Keiser rig

1 bar Keiser rig - scale spallation for T22

17 bar less mass gain than 30 bar (?)

Initial results in 550°C steam

500 h exposures: Tube vs. Keiser rig



1 bar steam in tube: higher mass than Keiser rig

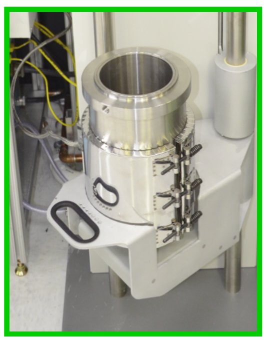
1 bar Keiser rig - scale spallation for T22

17 bar less mass gain than 30 bar (?)

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

Initial investigation of water chemistry effect

1st EPRI experiment (2017)
- compare oxygenated water to all-volatile treatment (10 vs. 150 ppb O, plus pH control)



≤ 275 bar steam testing

Controlled water chemistry loop

Temperature: 450°-650°C

Time: 500 h cycles

Summary

Corrosion task addressing several issues

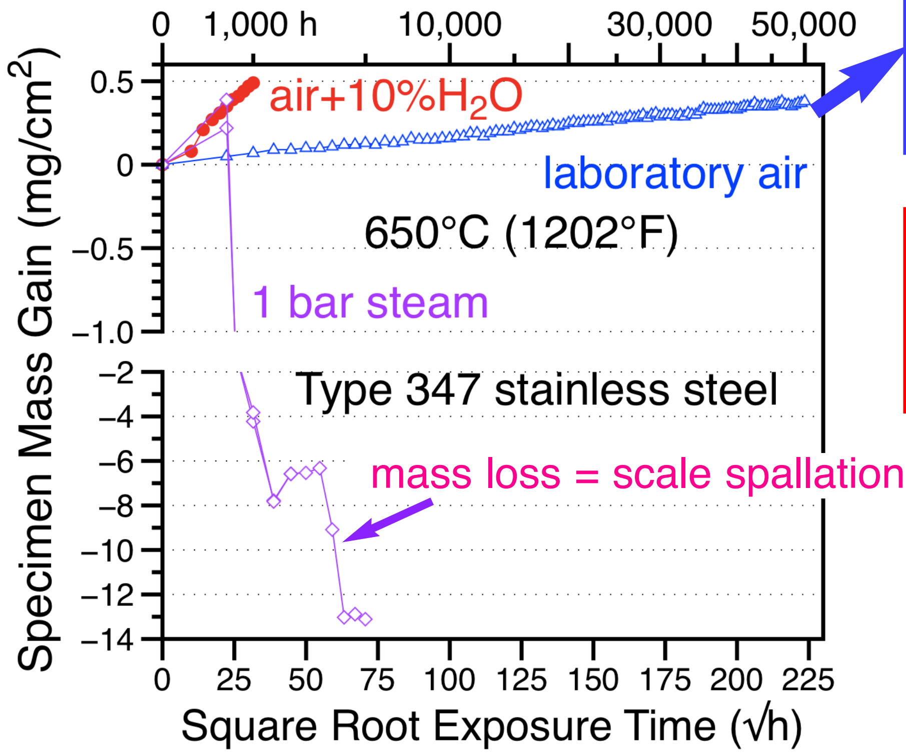
1. Quantify shot-peening benefit on 304H
   - completed 15 kh specimens
2. SCC issue in current waterwalls
   - testing in controlled water chemistry
   - next step is in-situ monitoring
3. Effect of pressure
   - initial comparison steam, 500 h at 550°C
   - next work: steam, 650°C

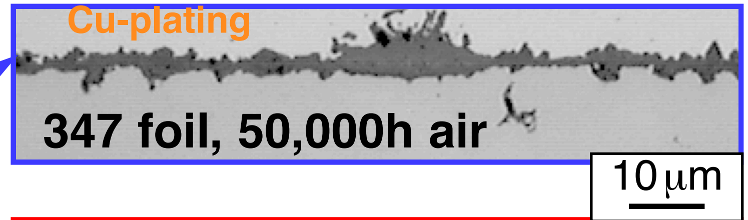
Task 1 is finishing in 2017, Task 3 expanding
Seeking industry feedback on Task 2

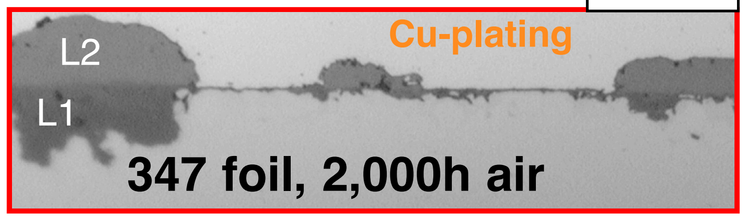

CLEAN COAL.
COOL.

H_2O drives steels crazy

Steam or exhaust gas accelerate oxidation

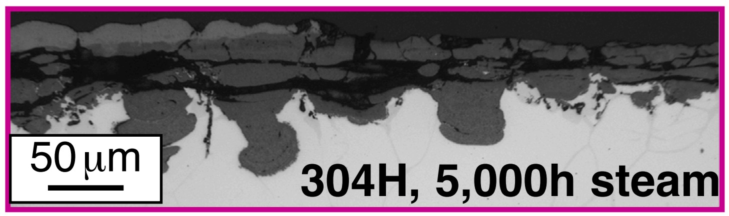




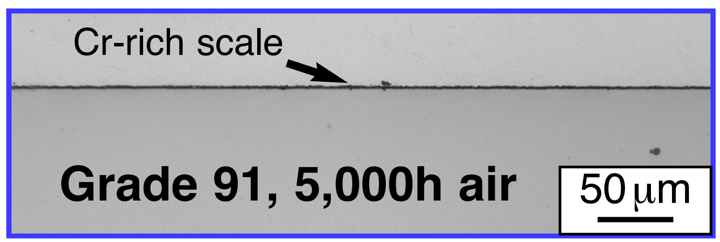


347: Fe-18Cr-10Ni+Nb

650°C, 1202°F



91: Fe-9Cr-1Mo

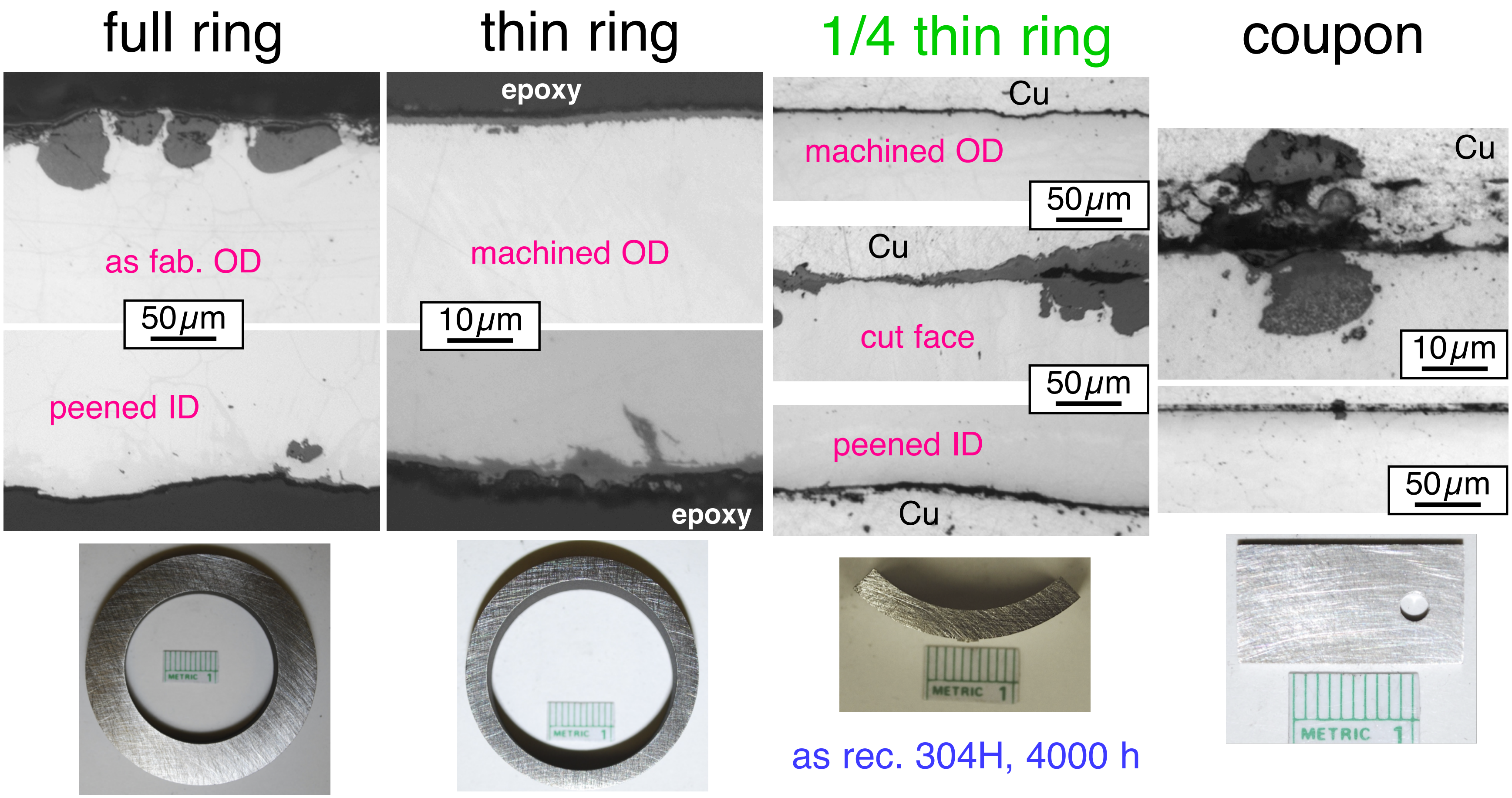


Laboratory air - thin, Cr-rich oxide

+ H_2O - thick, Fe-rich oxide

Specimen type showed minor effects

peened 304H 650°C 17bar steam 4,000h



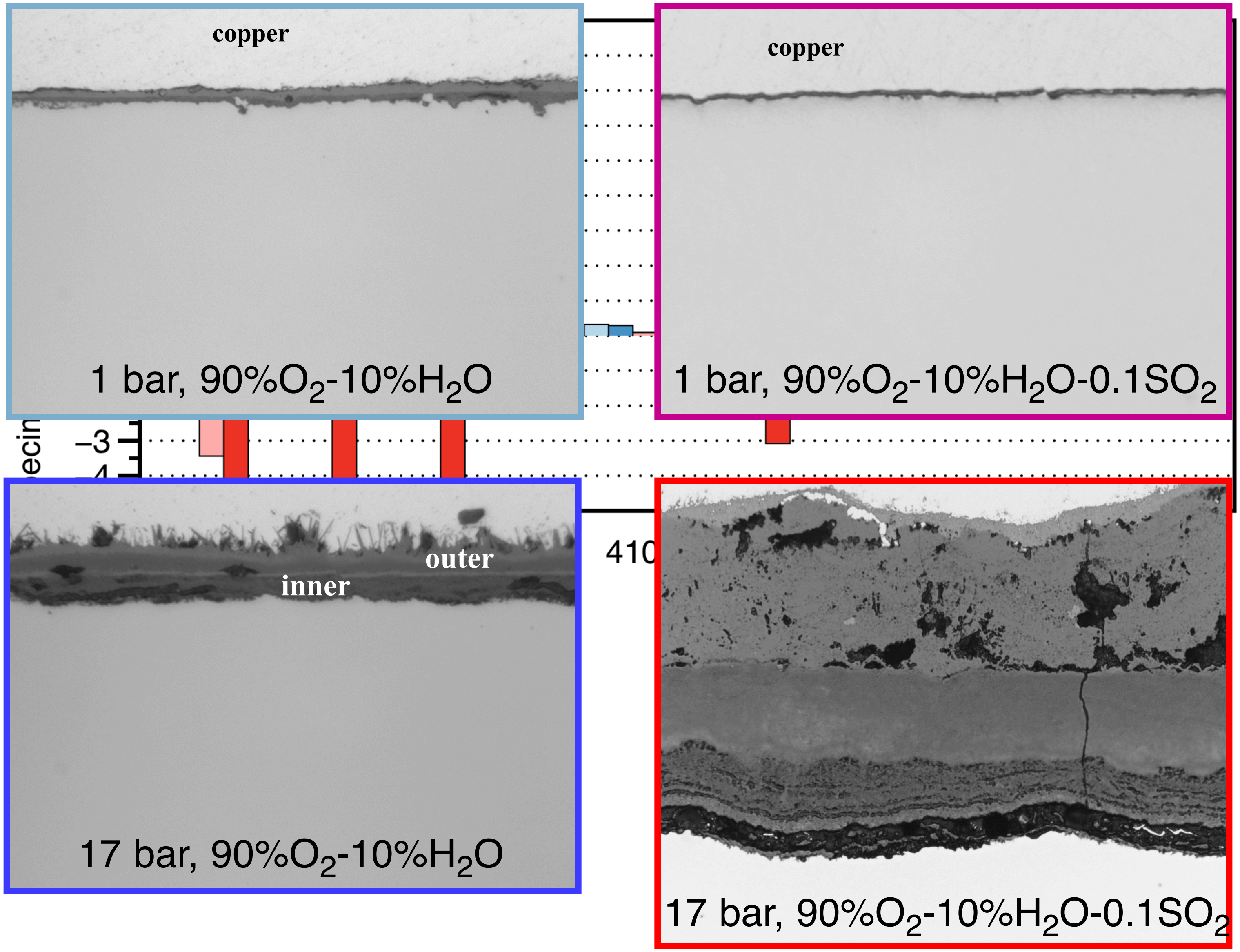
Peened ID: no effect of specimen geometry

OD difference: as-received vs. machined (thin ring)

- cold work due to machining similar to peen-

Initial ORNL study of pressure

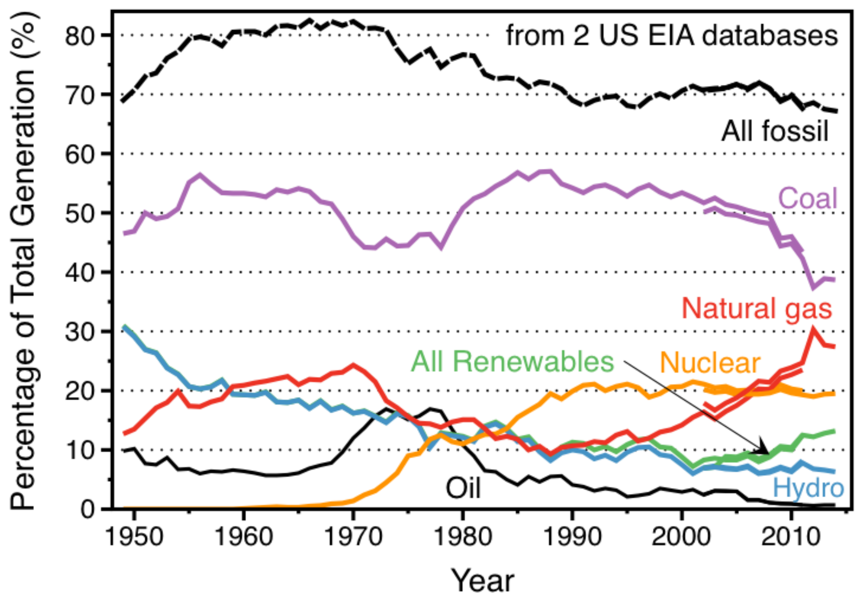
VM12: ~11Cr-1.5Co-1.5W steel



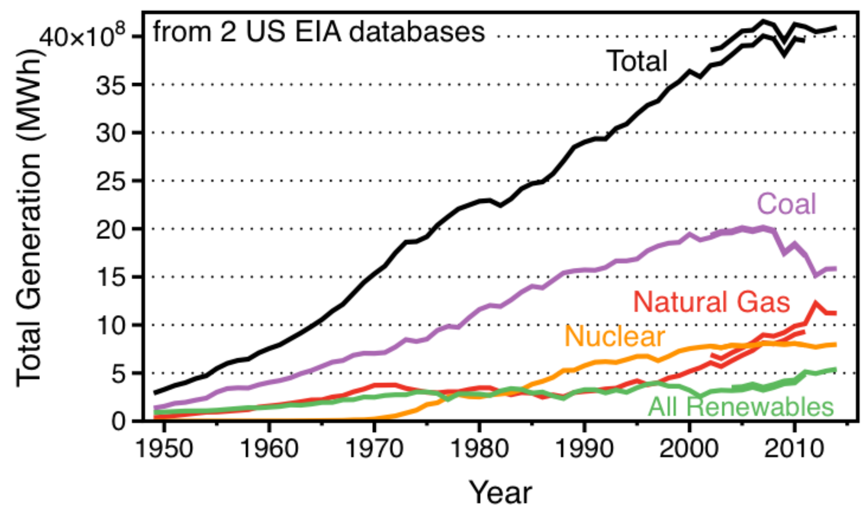
Fossil energy continues to dominate

Source mix is changing & demand is stagnant

How does US generate electricity?



How much does US use?



Prior work with EPRI

Characterizing field exposed shot-peened tubes