Steamside Oxidation Issues in Current Coal-Fired Boilers

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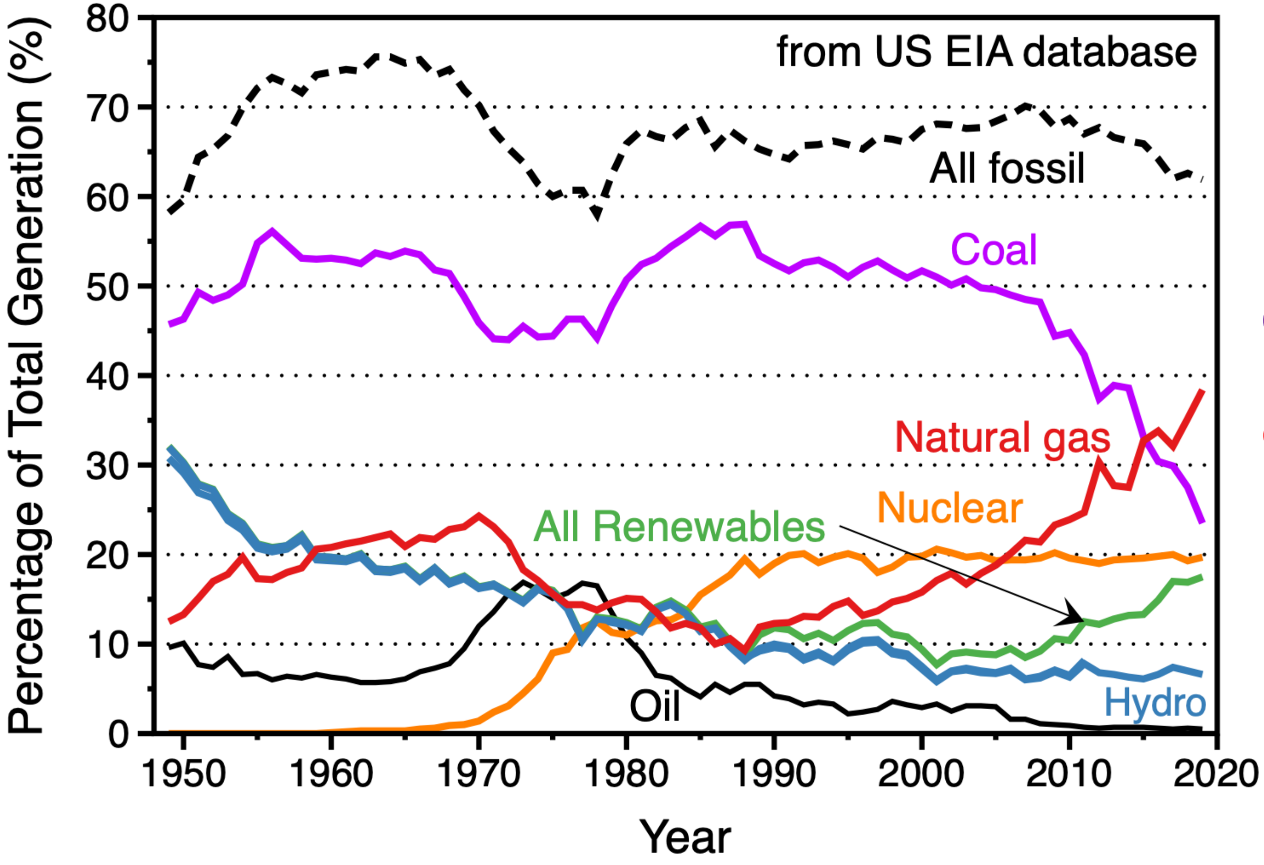
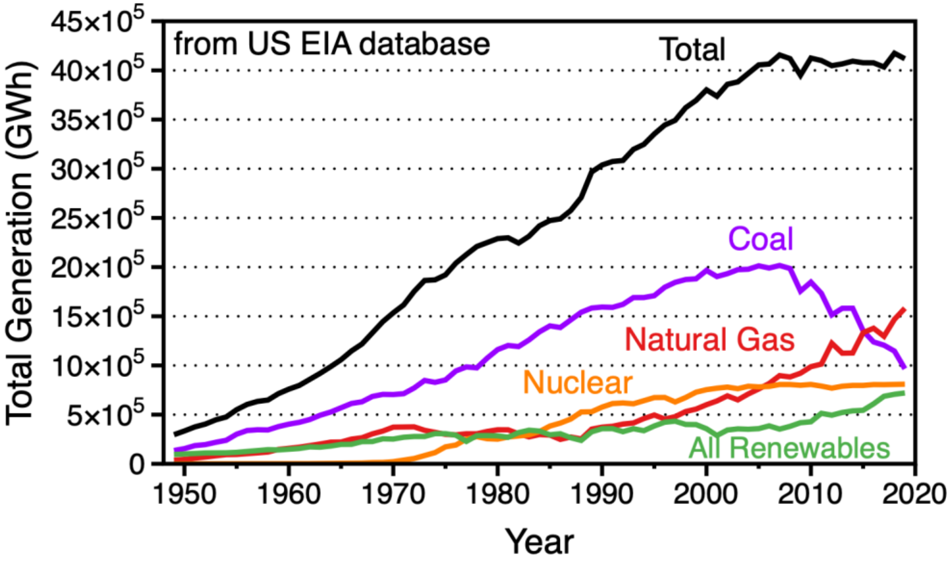
  - Barry Dooley (Structural Integrity Assoc.)
  - Steve Paterson (PIKA Solutions)

Steam oxidation still relevant in 2020



Coal: Fewer boilers operating

Gas: More HRSGs (combined cycle) Heat Recovery Steam Generators



DOE FE Strategic goals 1 and 2:

1. Develop **secure and affordable fossil energy** technologies to realize the full value of domestic energy resources.
2. Enhance U.S. economic and energy security through prudent policy, **advanced technology**, and the use of strategic reserves.

Science approach to "real world" corrosion issues

- Stress corrosion cracking at 200°C
  - 2¼ %Cr waterwall steels: Grades 22, 23, 24
  - Significant issue in many recent boilers
- Shot-peening solution for exfoliation
  - Study of baseline alloys and shot-peened tubes
  - Long term testing in 1 atm steam at 550°-650°C
- Effect of pressure on corrosion
  - Steam-side difference between laboratory and field
    - Phase 1: does water chemistry play a role? (2017-2019)
    - Phase 2: do water additives (e.g. amines) play a role? (2020-2022)
  - Fire-side effects
    - SPOC: staged pressurized oxy-combustion (with Wash. U @ St. Louis)
  - CO_2 effects from related project FEAA144

Cracks in longitudinal direction

Cracks in transversal direction

Scale exfoliation blockage

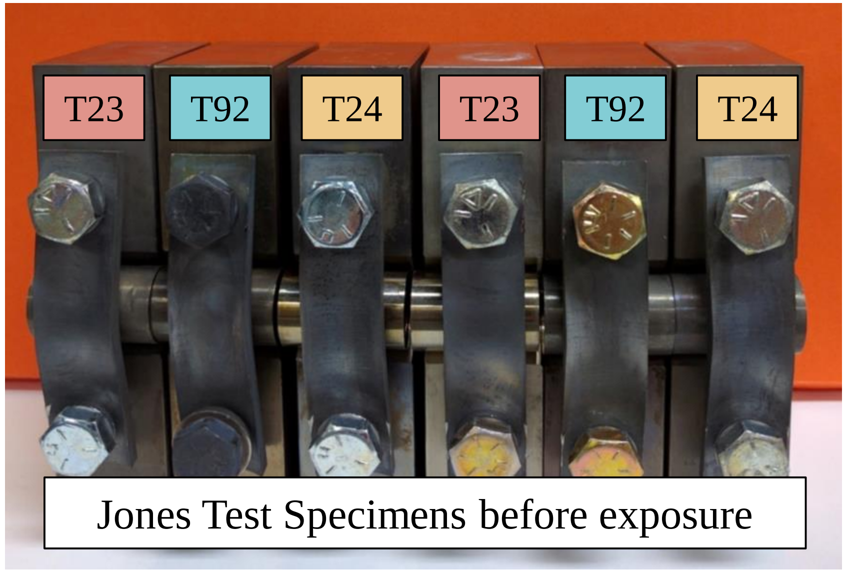
Stress corrosion cracking: demonstrated O_2 effect

- "Jones" test conducted in 200°C water
  - Normalized steel (0.5h,1065°C WQ) (no temper)
  - 50 ppb O_2 (autoclave)
  - 100 ppb O_2
- Increasing attack as O_2 level increased
- Previous work concluded only 24 h needed

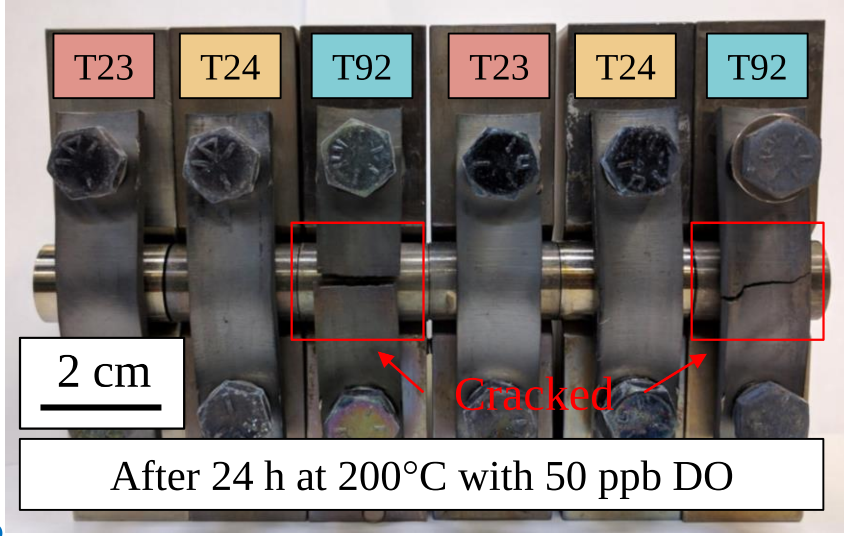
DO	Deaerated*	50 ppb	100 ppb	Air saturated* (~8400 ppb DO)
Time	72 h	24 h	24 h	72 h
T23	O	O	O	X
T24	O	O	X	X
T91	O	X	X	X

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

- Final task to measure cracking in-situ
  - As O_2 increased in water, can crack be detected in autoclave?



Jones Test Specimens before exposure



After 24 h at 200°C with 50 ppb DO

"USC" John W. Turk Plant (commissioned 2013) used shot-peened 347H tubing to prevent exfoliation issues

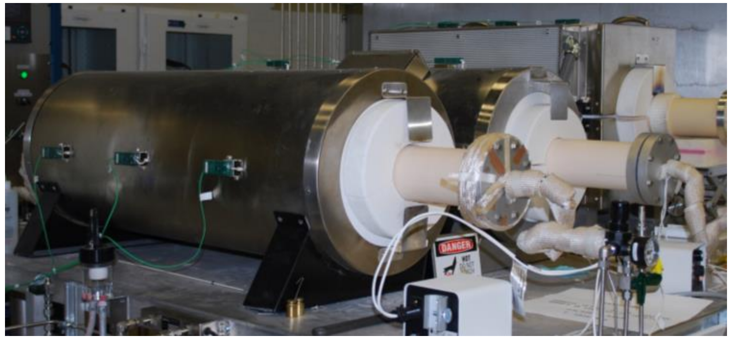
"Ultra-supercritical" coal-fired steam plant by B&W/AEP in Fulton, AR

- 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

Multi-billion dollar plant protected by shot peening with little published literature

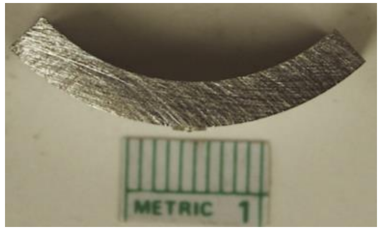
Shot peened tube ID: benefit to 625°C/15,000 h

Tube furnace: 1 bar steam
500-h cycles

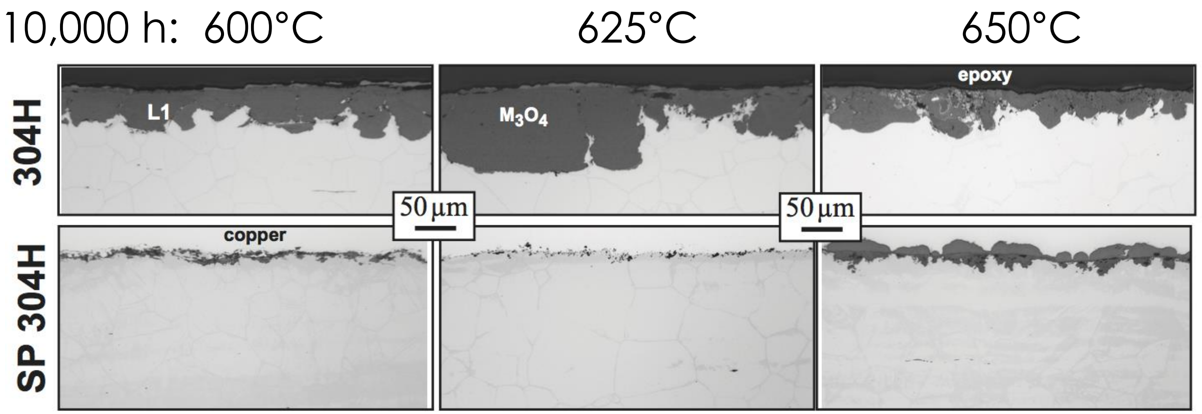


Water: <0.1µS and <10 ppb O_2

Alloy coupon

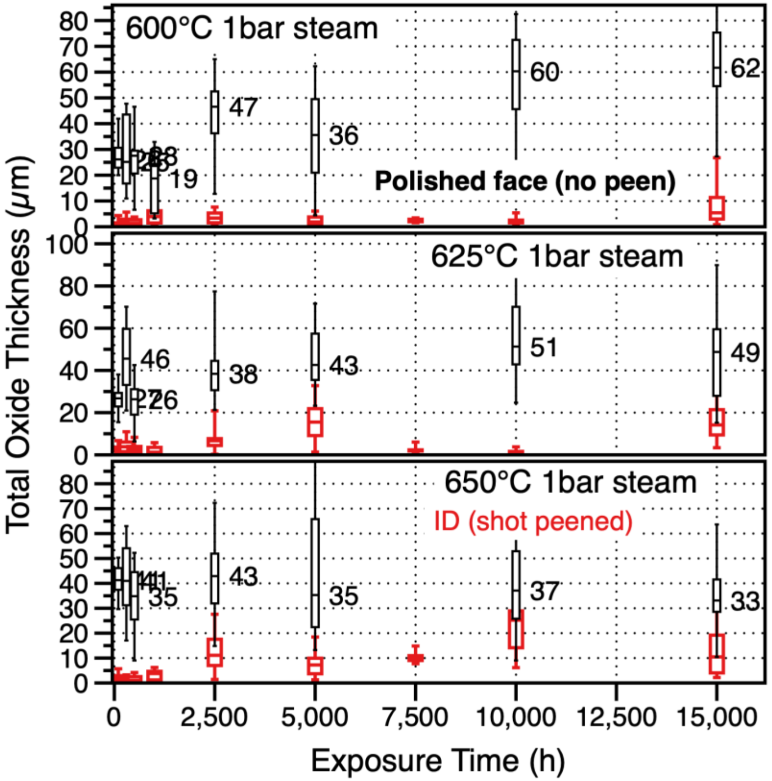


Shot peened tube specimen

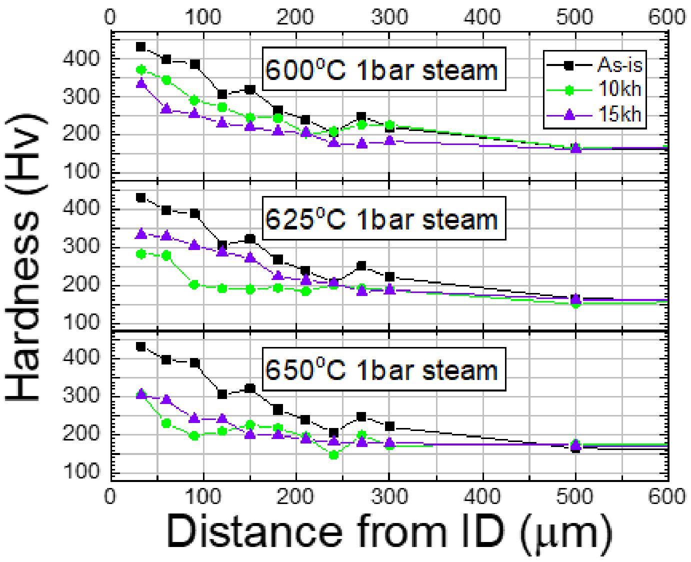


No SP: Spalled outer oxide

SP: Thinner, adherent, little spall



High hardness from peening
Hardness drop with exposure:



Task Complete: J. M. Kurley and B. A. Pint, "The Effect Of Shot Peening On Steam Oxidation Of 304H Stainless Steel," Oxidation of Metals, 93 (2020) 159-174.

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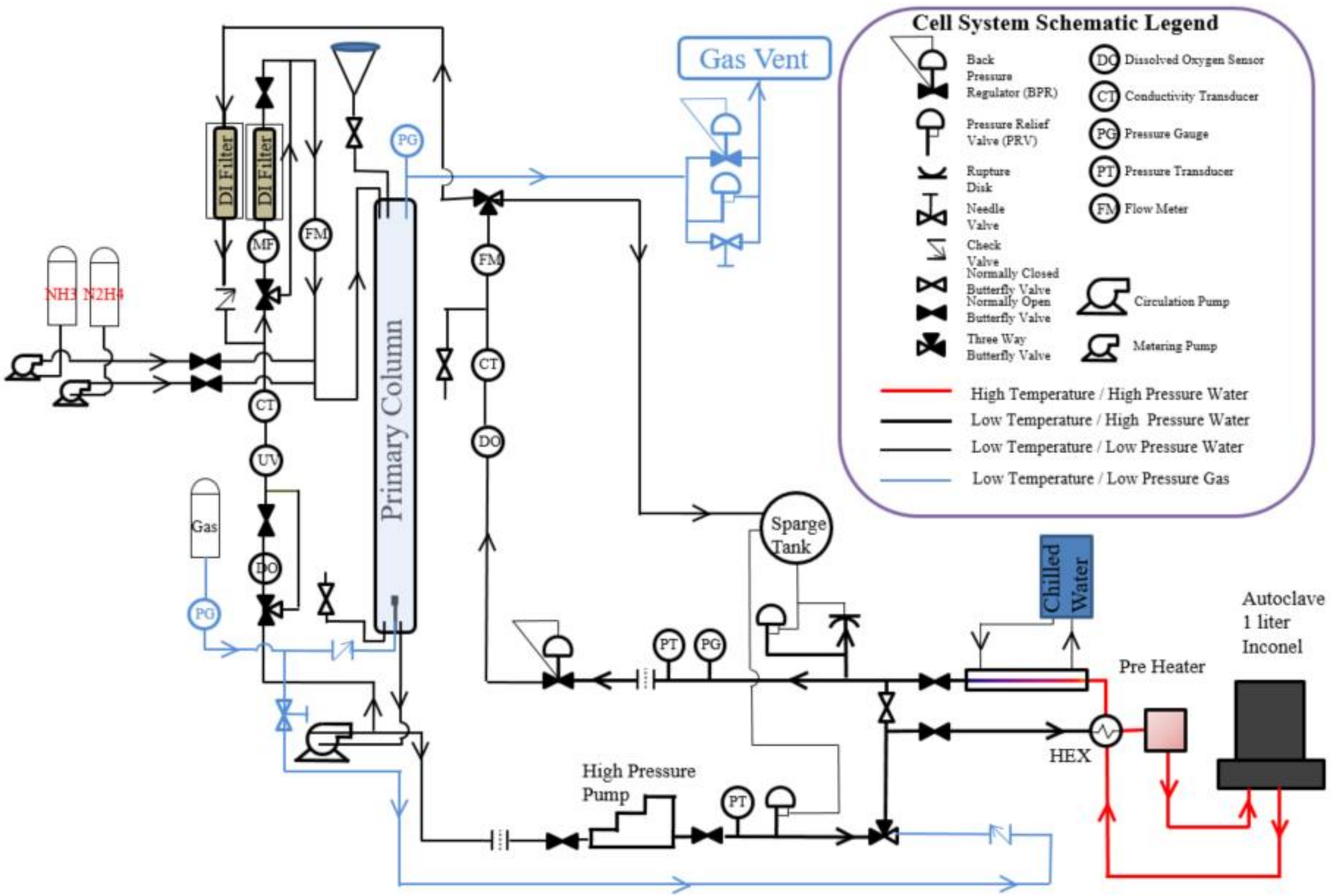
doi.org/10.1007/s11085-019-09951-9

Water loop constructed for pressure & water chemistry



Raiman: loop architect

Similar system used for SCC experiments

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Phase 1: 4 x 1000 h experiments all 276 bar (4000 psi) 1L autoclave volume restricts specimens in 500-h cycles

	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

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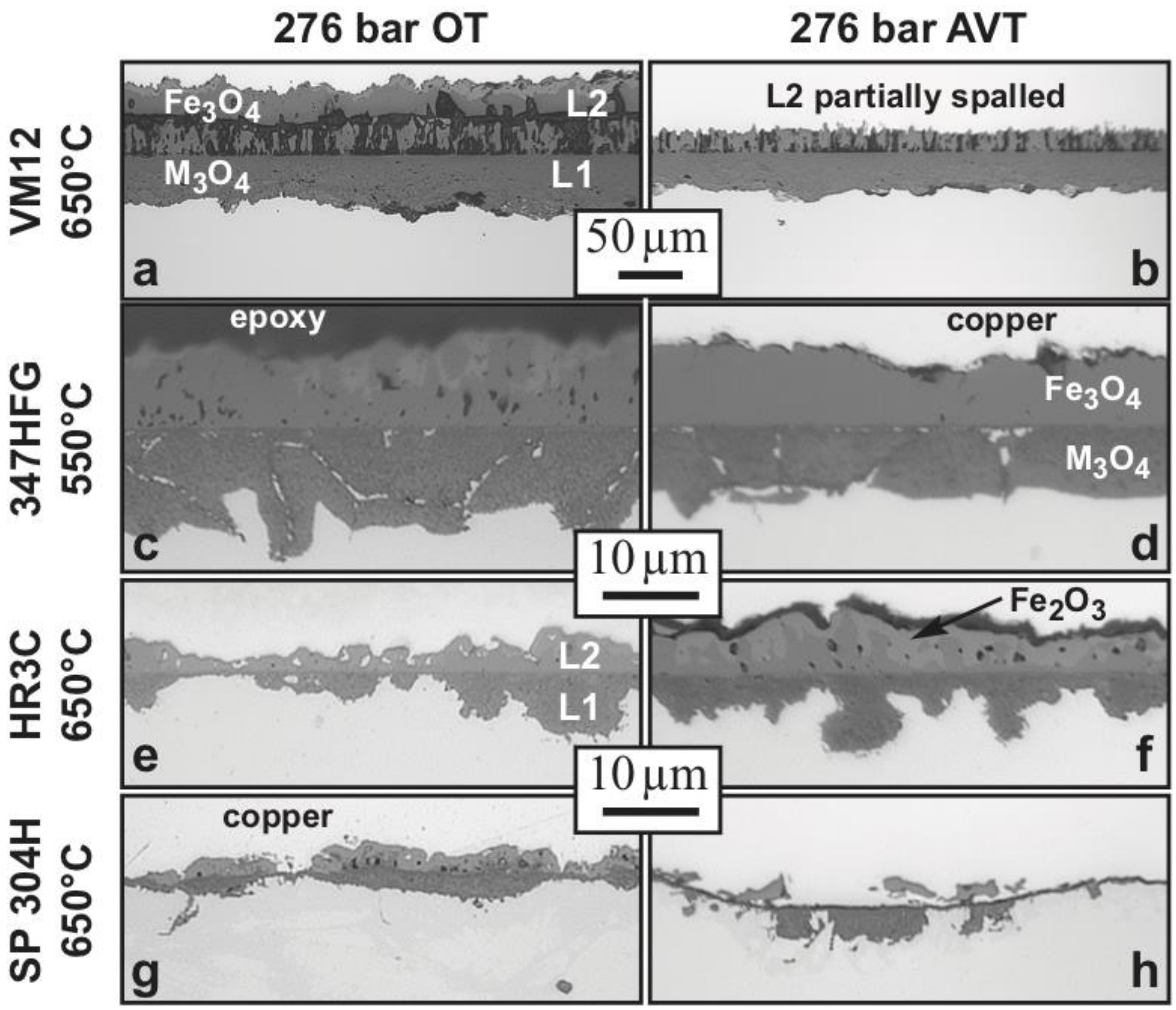
OT vs. AVT: slight differences observed, similar reaction rates

High O_2:
Some Fe_2O_3
Light oxide

High O_2:
Some Fe_2O_3
Light oxide

No Fe_3O_4

Fe_2O_3 outer layer



Light microscopy, all 1000 h

Spall?

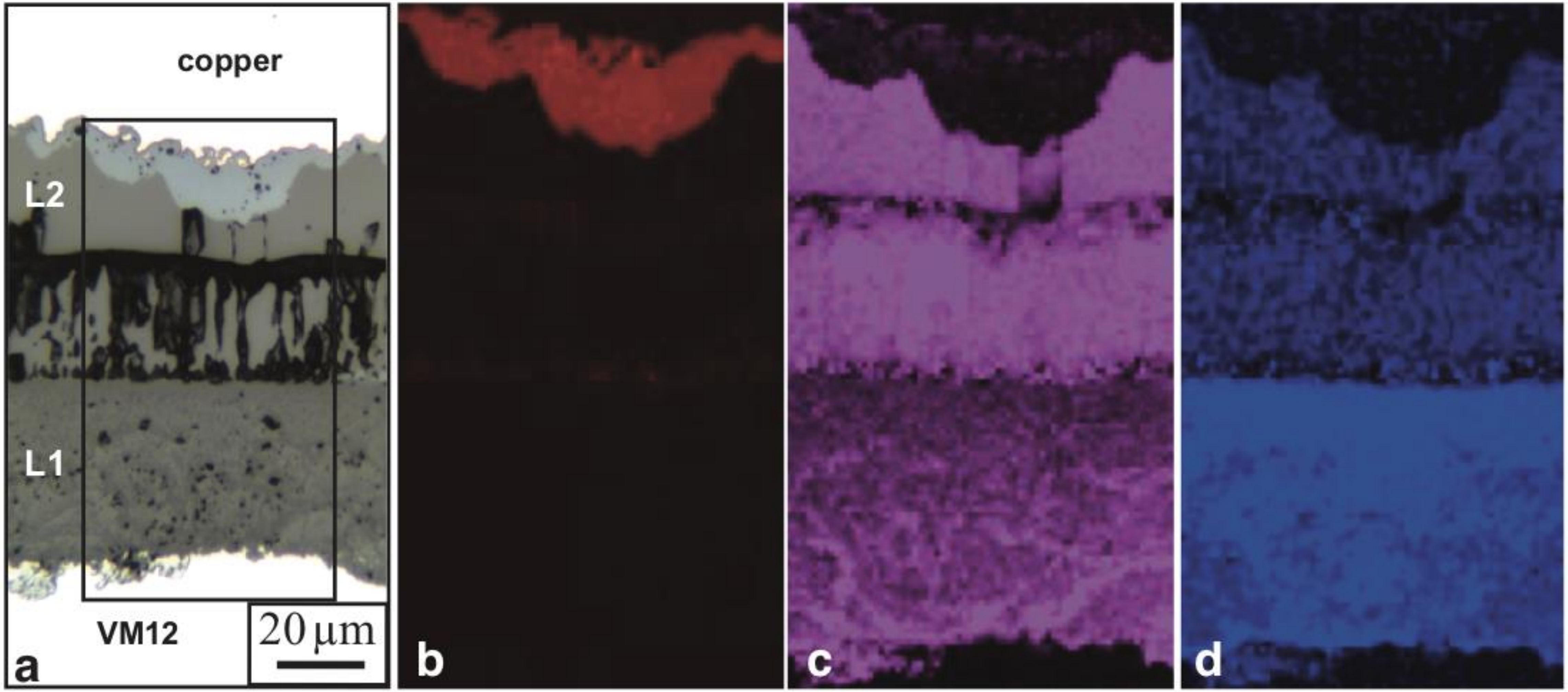
Low O_2:
Only Fe_3O_4

Some Fe_3O_4

Some Fe_2O_3
Inner layer inhibits
Cr transport?

Raman spectroscopy confirms lighter oxide is Fe_2O_3

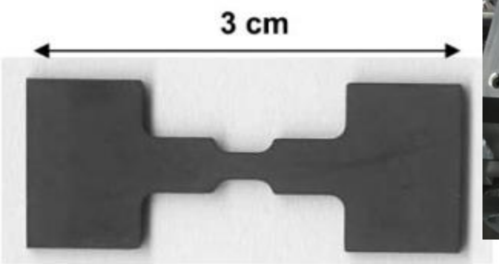
VM12: 276 bar OT 650°C 1000 h

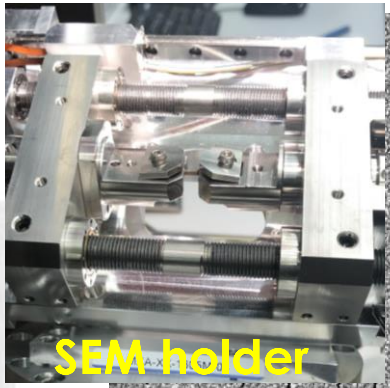


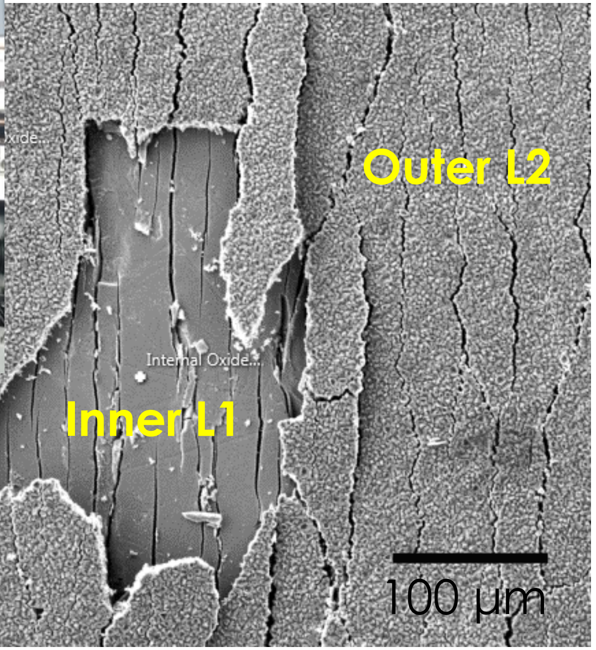
Fe_2O_3 Ordered M_3O_4 Disordered M_3O_4

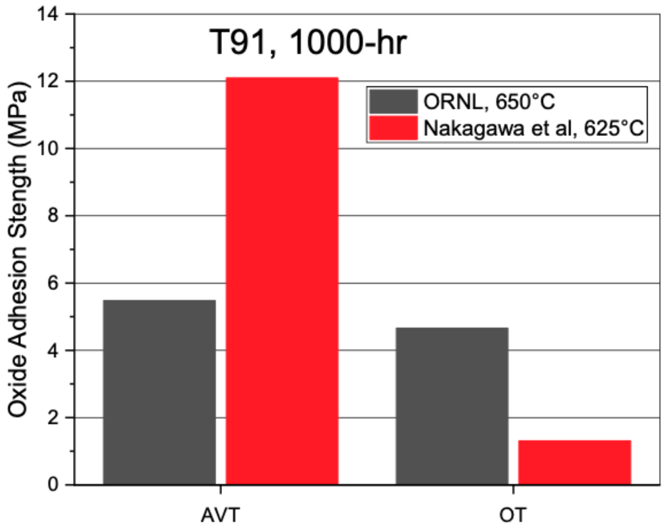
Current task to explore different methods to test adhesion

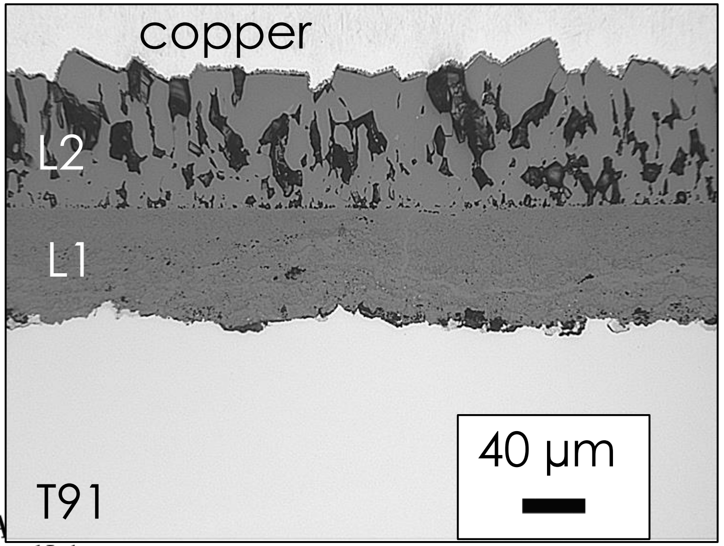
- Adhesion between L1 and L2 oxide layers
  - Key factor in exfoliation
- ASTM pull test (10 mm stub)
  - Values obtained
- In-situ SEM tensile testing
- Scratch test
  - Need larger load cell

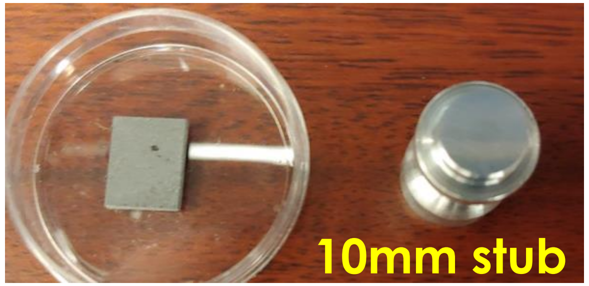


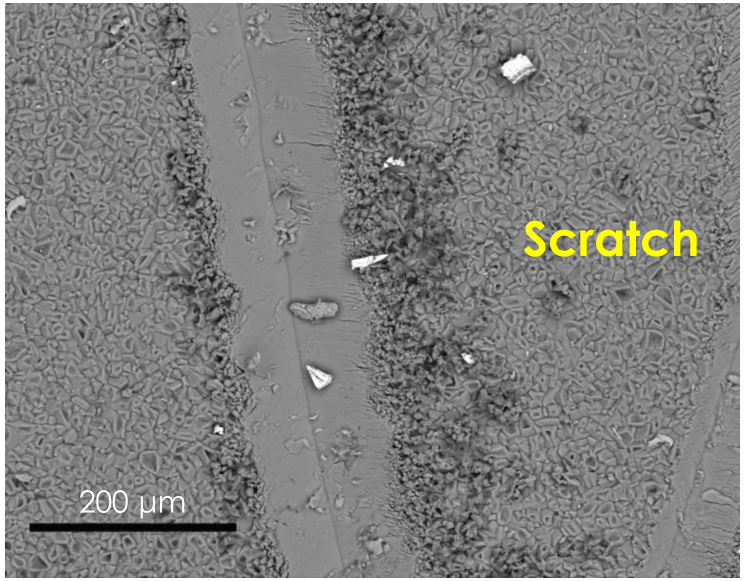












Controlled chemistry steam oxidation-exfoliation studies are continuing

- Three-year project started in FY20, delayed by COVID response
- Industrial partner EPRI (S. Kung)
  - Co-funding research: $125K Phase 1, $100K Phase 2
    - Based on utility interest in exfoliation issues
  - Phase 2: effect of water additives on steam oxidation (e.g. amines)
    - Challenge: Currently working on non-disclosure agreements with additive suppliers
    - Exploring several strategies to measure scale adhesion
    - Emphasis on modeling steam oxidation
      - Autoclave experiments expensive and require significant system maintenance
- Shot peened tubes donated by American Electric Power
- Relation to other projects
  - Effect of pressure on corrosion relevant to sCO_2 and SPOC (Wash. U.)

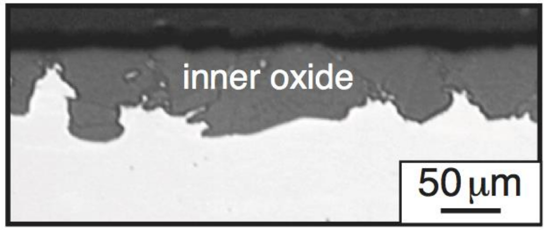
(supercritical CO_2 and stage pressurized oxy-combustion)

Backups

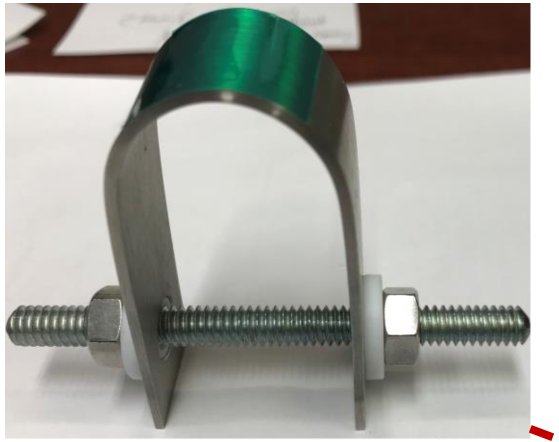
Why focus on shot peening?

- 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

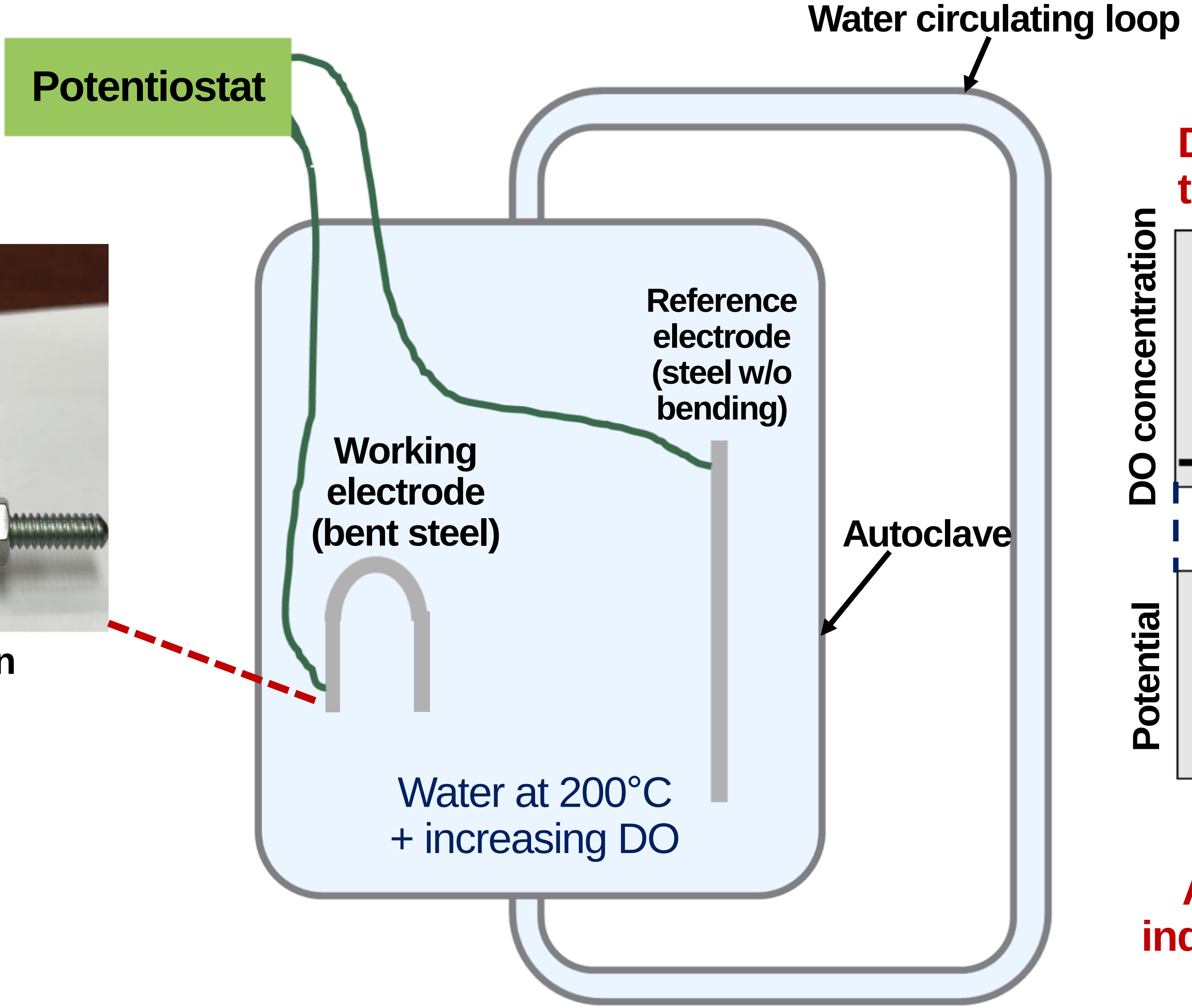
TP304H
22,0000 h



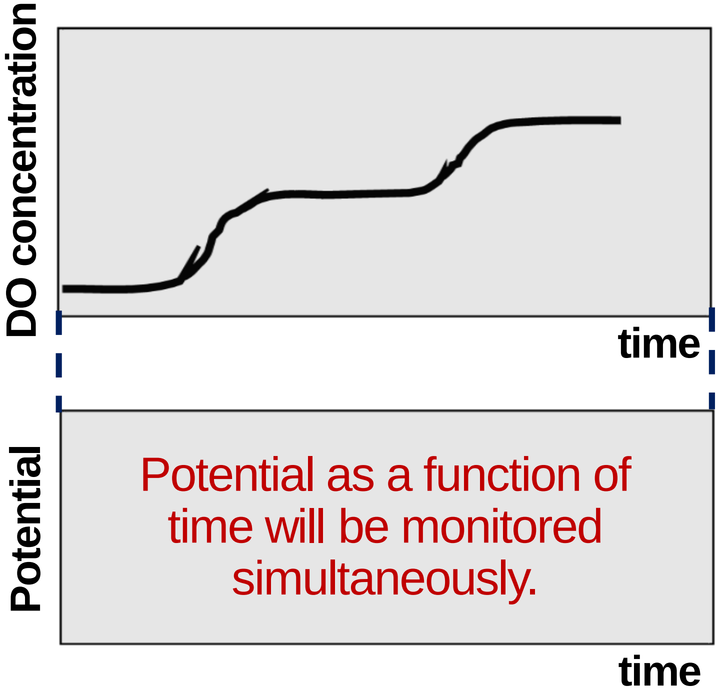
In-situ SCC experiment redesigned: Electrochemical noise measurement will detect the potential transient(s) associated with crack initiation as O_2 increased



C-ring specimen



DO in water will be controlled to increase with time.



Any potential transient could indicate the initiation of cracking.