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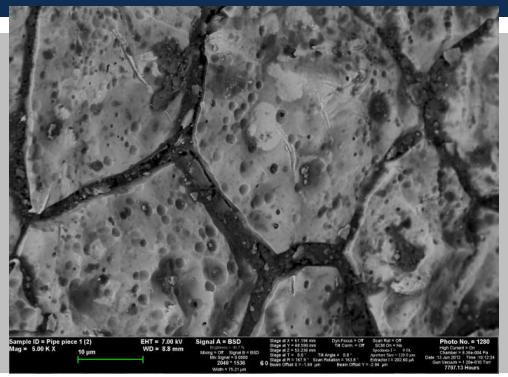

RCBC Engineered Materials

Alan Kruizenga, Darryn Fleming

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

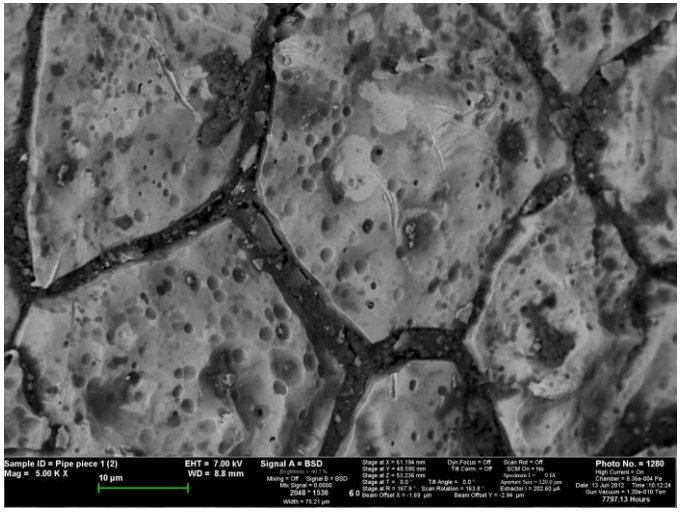
- A brief background on corrosion in CO2
  - Enhanced Oil Recovery
  - Magnox Reactors
  - Current sCO2 Brayton
- Materials analysis on system components
  - Manufacturing considerations in received pipe
  - Turbine/nozzle analysis
- Potential research for mitigating maintenance issues in Brayton systems
  - Basic parameters (temperature, pressure, etc.) result in system maintenance issues
  - Determine limits on gas purity and composition for systems
  - Utilize existing knowledge base in steam water chemistry for CO2 based systems

Preventative Maintenance: Previous Corrosion Data Sources

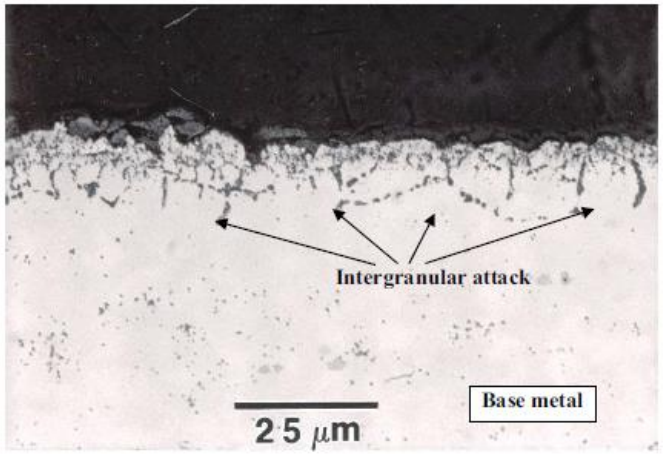
- Enhanced Oil Recovery
  - Significant number of studies focused on carbon steels (common transportation in petroleum)
  - Application space tends to involve CO_2 saturated in water
  - For water saturated CO_2:[1]
    - Low temperatures (80-120° C) corrosion mechanisms indifferent to pressure (subcritical vs. supercritical)
    - Scales are iron oxide and iron carbonate (an effect of carbonic acid formation)
    - Corrosion rates increase for supercritical pressures
    - sCO_2 has a higher equilibrium concentration of carbonic acid
  - Data is valuable for selection of cold materials (low temperature piping, etc.)
- Magnox reactors
  - Studies focused on a variety of alloys, over a range of temperatures (375-825° C) at low pressures (0.1-5.2MPa)
    - Increases in silicon content improved corrosion performance
    - Complex gas streams (2% CO, 60ppm CH_4, 100ppm H_2, 300ppm H_2O)
  - Excellent resource, though more difficult to find at times.
- Recent Studies by University of Wisconsin Madison and CEA France
  - 550° C, 25MPa[2-4]:T91, 316, 308, 800; limited kinetic information, did indicate carburization occurs
  - 650° C, 20MPa[5-7]: T91, HCM12A, 800H, Al-6XN, 316, 310, PE-16, 230, 625; thermogravimetric data, FM steels are not adequate at temperature

Preventative Maintenance: Pipe Analysis

- 316L pipe was removed from RCBC loop during periodic maintenance
  - Intergranular attack (IGA) was observed with surface pitting of the grains
  - Fe-18.5Cr-14Ni-3Mo
  - Laboratory partners expressed concern based on concurrent observations

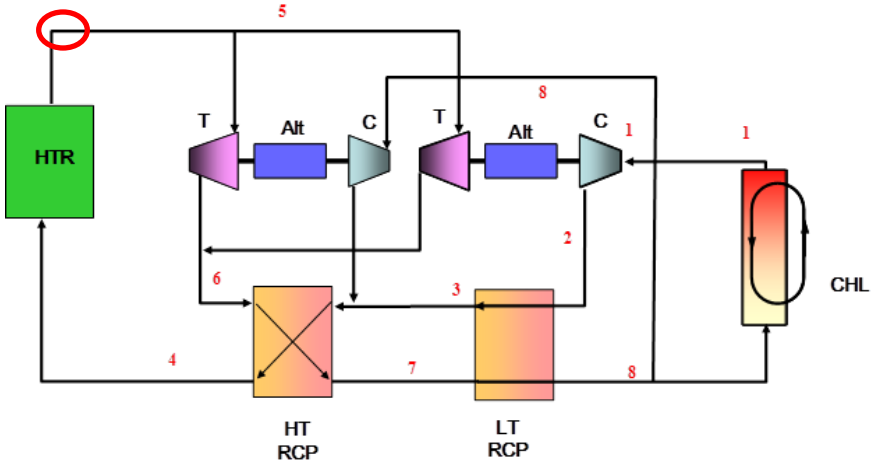


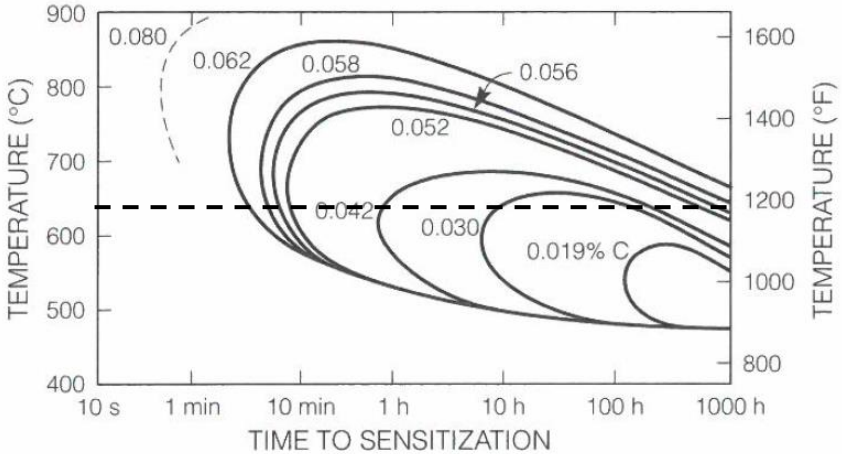
- Aroused concern as high temperature IGA was documented at INL[1]
  - S-CO2 @ 1000° C on I-617
  - Ni-24Cr-15Co-10Mo-3Fe (solid solution)
  - Quite different conditions and alloy



Pipe Location and Conditions

- Pipe location was at the connection between recuperator and turbine
  - Temperature maximum 550° C
  - Up to 150 hours at temperature (nominal)
  - Within range of sensitization (425-815° C)
- Sensitization of stainless steel
  - Chromium carbides precipitate at grain boundaries
  - Cr depletion along boundaries may result in IGA
- Low carbon content should increase time to sensitization
  - Carbon content of 316L: 0.03% max (vs. 0.08% for 316)
  - At least 10 hours at 550° C may cause this
  - Doubtful that this effect would occur so rapidly





18Cr-8Ni stainless steel[1]

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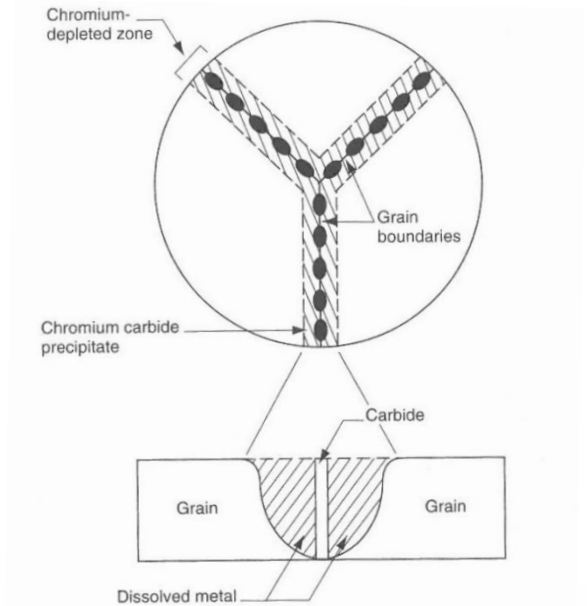
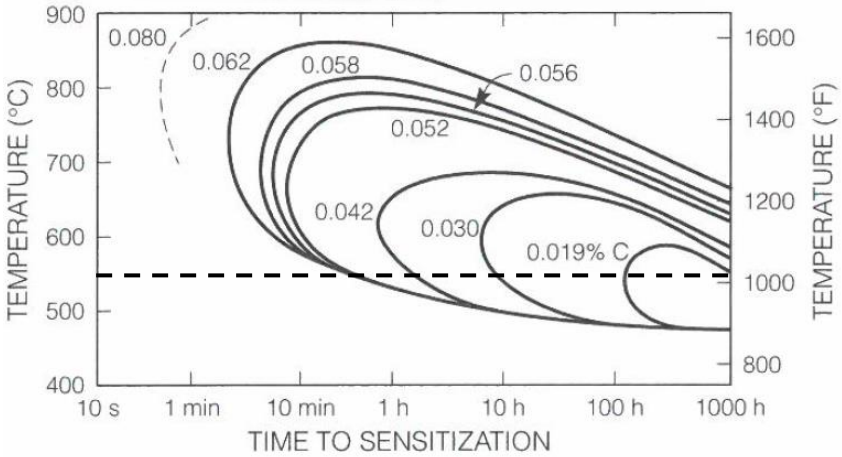


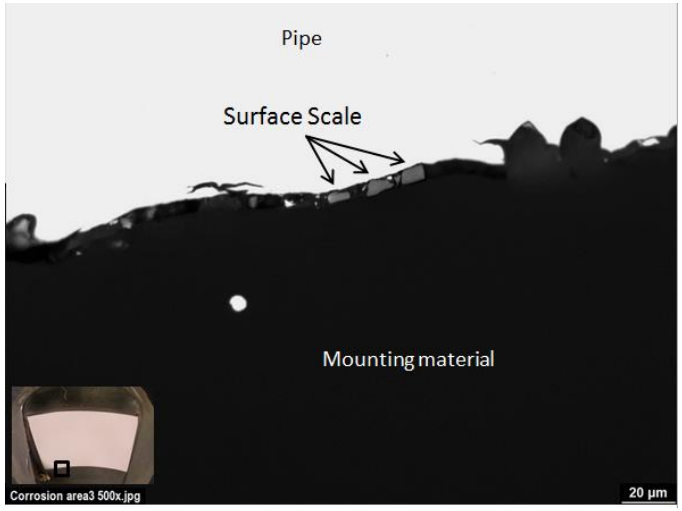


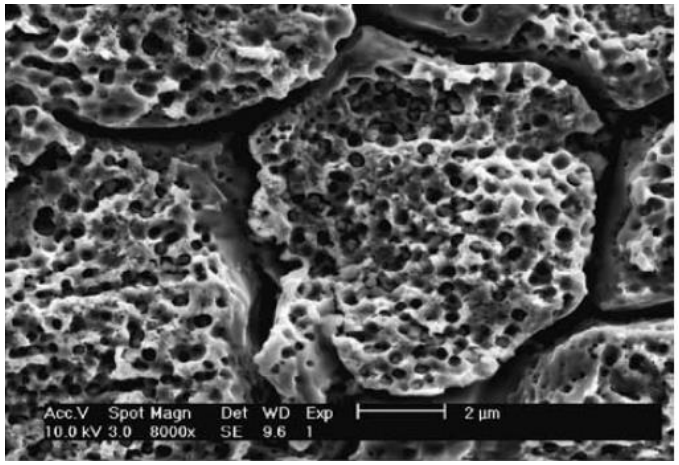
18Cr-8Ni stainless steel[1]

Effect due to manufacturing

- Relatively little oxidation products were observed.
  - Could the IGA be an artifact of pipe manufacturing?
  - Materials specs called out a generic pickled process for cleaning
  - Contacted manufacturer to obtain specs on pickling; would not provide any data
  - Possibly counterfeit materials

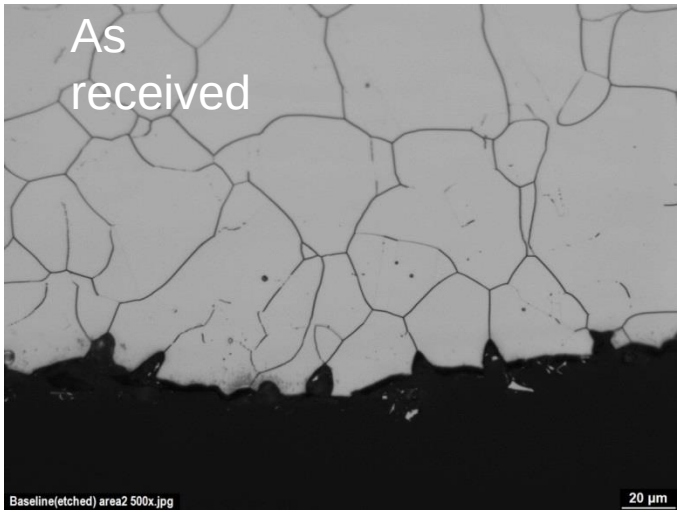
- Lack of chemistry control on pickling liquor can lead to severe pitting and grain boundary attack[1]
  - Image: 42 second exposure in an HF based solution.

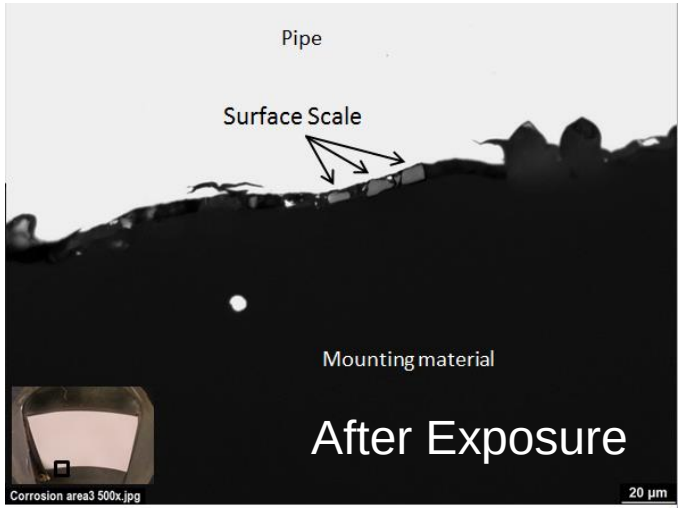




Baseline sample comparison

- Analysis of an unexposed 316L showed similar results.
- No observed chemical attack of the sCO2 in the 316L piping
- Lessons Learned:
  - Implement periodic as-received/exposed comparisons (assess performance)
  - Obtain materials from trusted vendors
  - Side issue: Certified welders are critical
  - Deleterious effects from improper welding



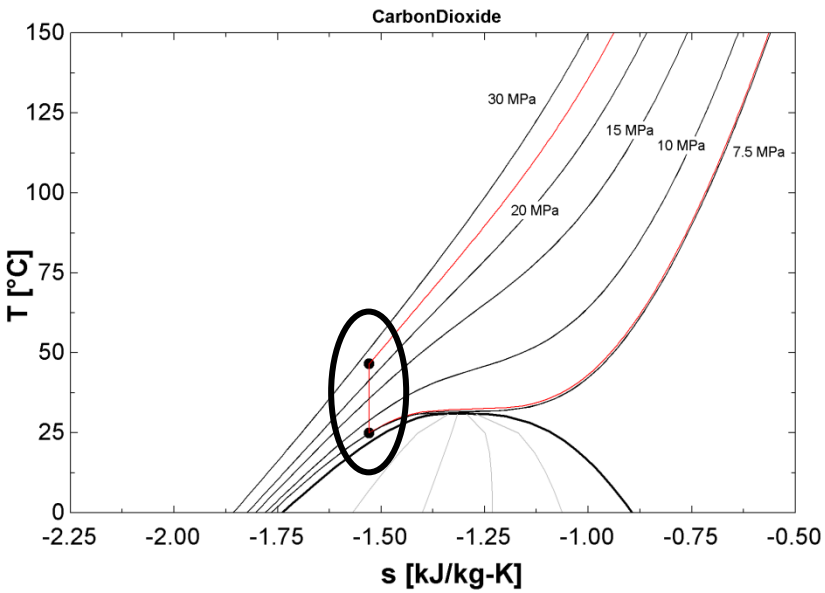


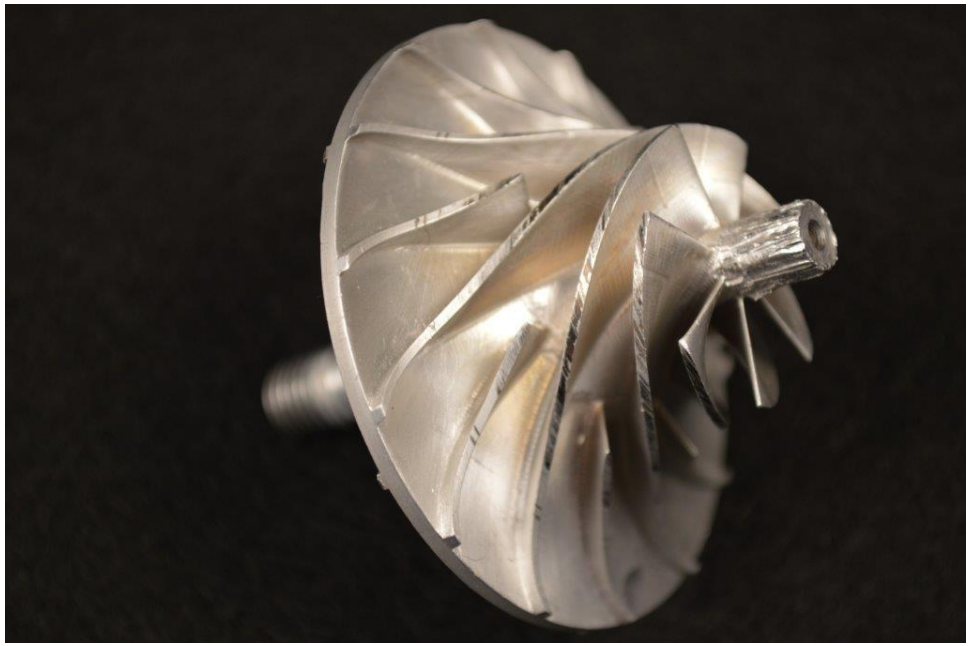
Preventative Maintenance: Turbine and Nozzle Wear

- Nozzle wear was observed after operation
  - Obvious changes in geometry was present
  - Alloy 718
    - Fe-55Ni-21Cr-5.5Nb-3.3Mo; age hardenable
    - Modulus of Elasticity: 24.8 (ksi x10^3) @ 540° C
    - Hardness: 331(Brinell Hardness HB)
- Resulted in further inspection of the turbine and compressor blade
- Turbine wear was also observed:
  - Alloy C-22
    - Ni-22Cr-13Mo-3W-3Fe-2.5Co
    - Modulus of Elasticity: 25.7 (ksi x10^3) @ 540° C
    - Hardness: 212 (Brinell Hardness HB)
- No wear observed on compressor
  - Alloy 6061
    - Al-0.8Mg-0.7Fe-0.4Si
    - Modulus of Elasticity: 10 (ksi x10^3) @ RT
    - Hardness: 95

Operational Regions: Compressor

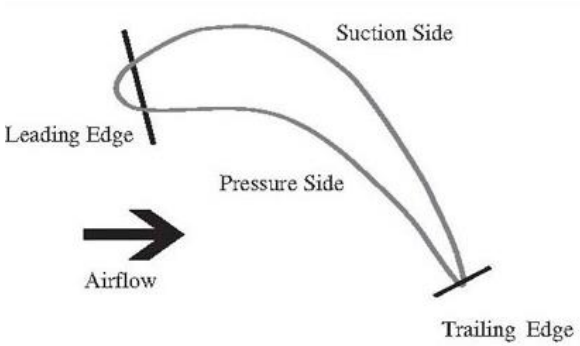
- Compressor has the possibility of operating in 2 phase flow regime
  - Liquid impingement could be

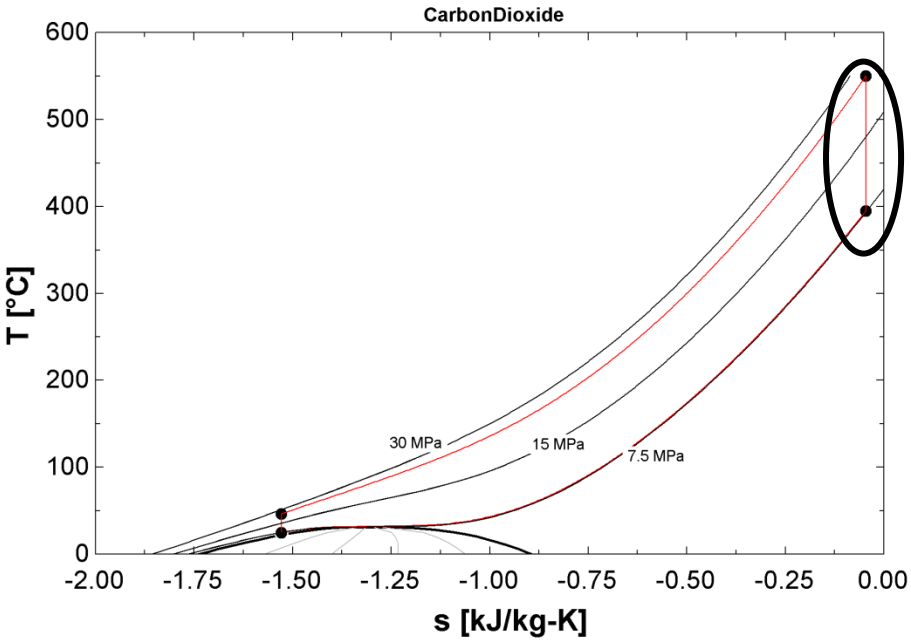




Operational Region: Turbine

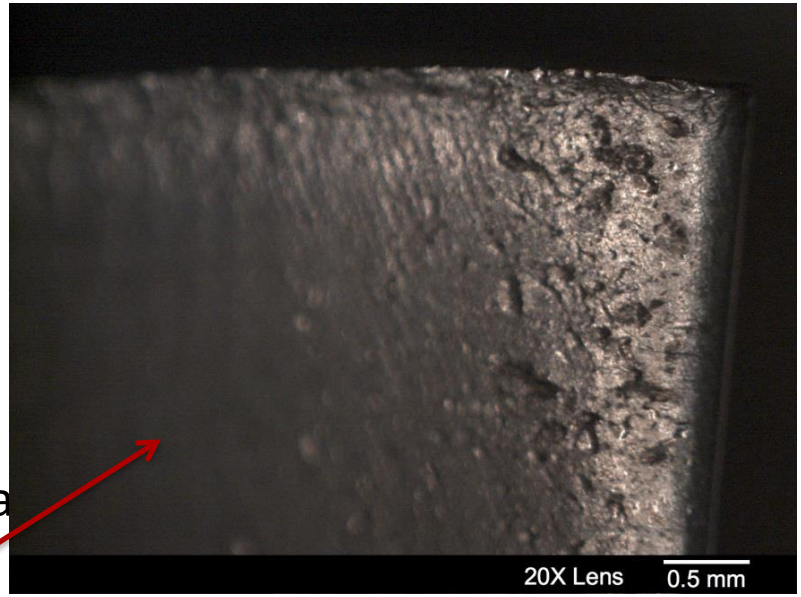
- All wear can be attributed to erosion:
  - Liquid Impingement should never be an issue with sCO_2
- Clear difference in wear on pressure vs. suction side of turbine blades





Turbine Erosion: Suction Side

- Suction side had the most destruction evidenced by large cratered areas on turbine
- Severe abrasion resulted in matte surface finish, resembling that of a grit blasted finish.



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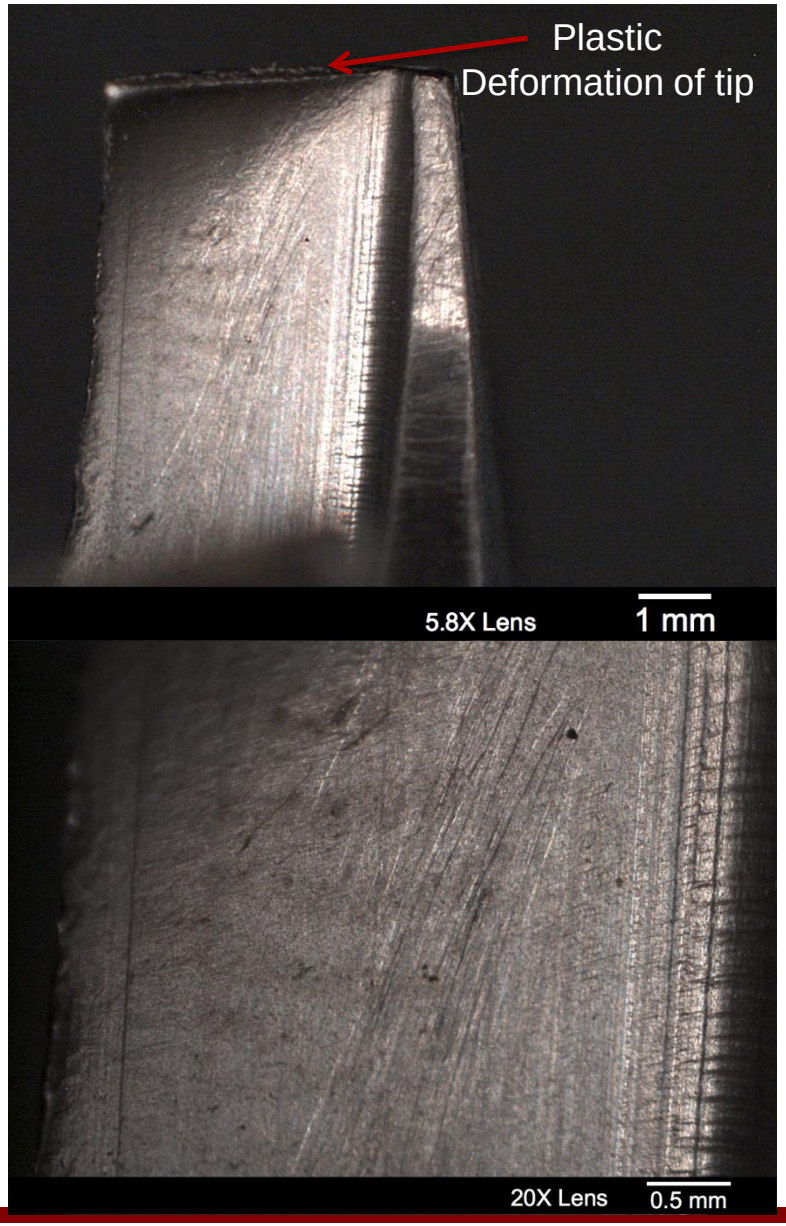
Turbine Analysis: Suction Side

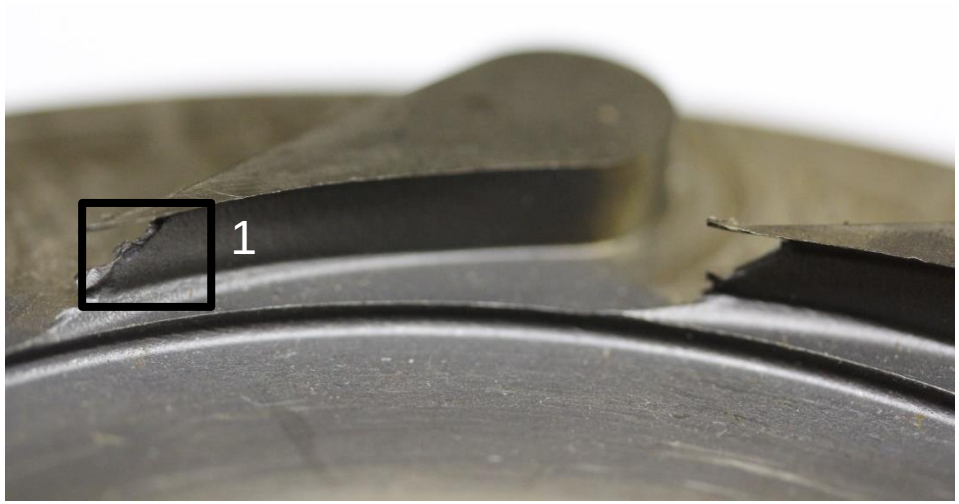
- Pressure side had features remaining as expected from fabrication due to machining operations
- Turbine blade showed clear plastic deformation

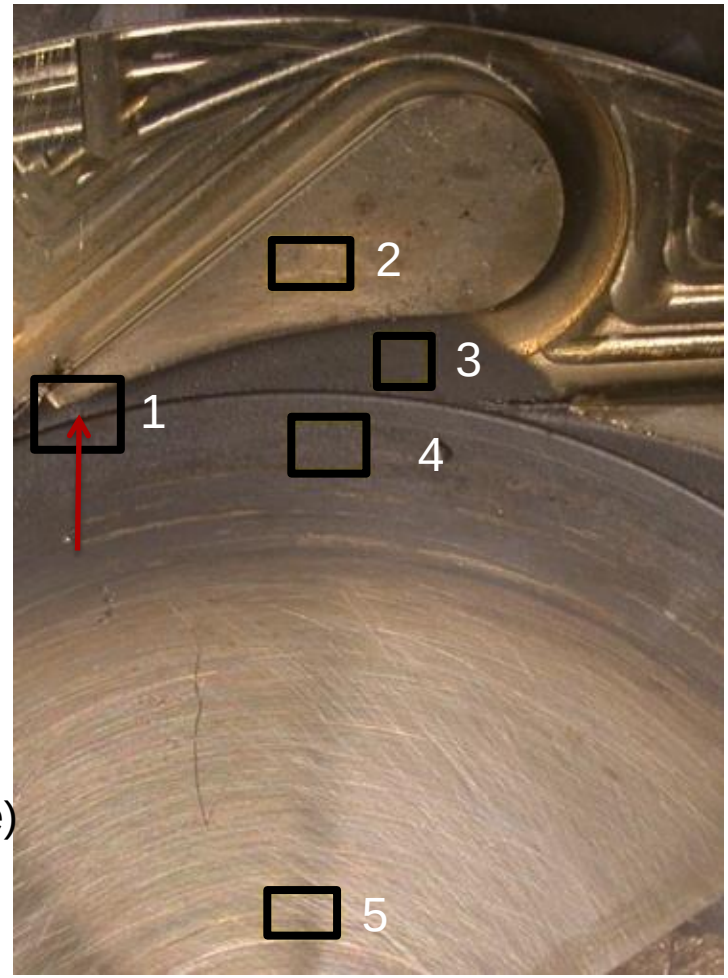


Turbine Analysis: Suction Side

- Pressure side had features remaining as expected from fabrication due to machining operations
- Surface wear was evident near blade tip given machining artifacts were not present

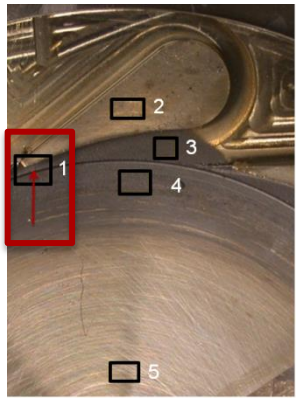
Nozzle Analysis

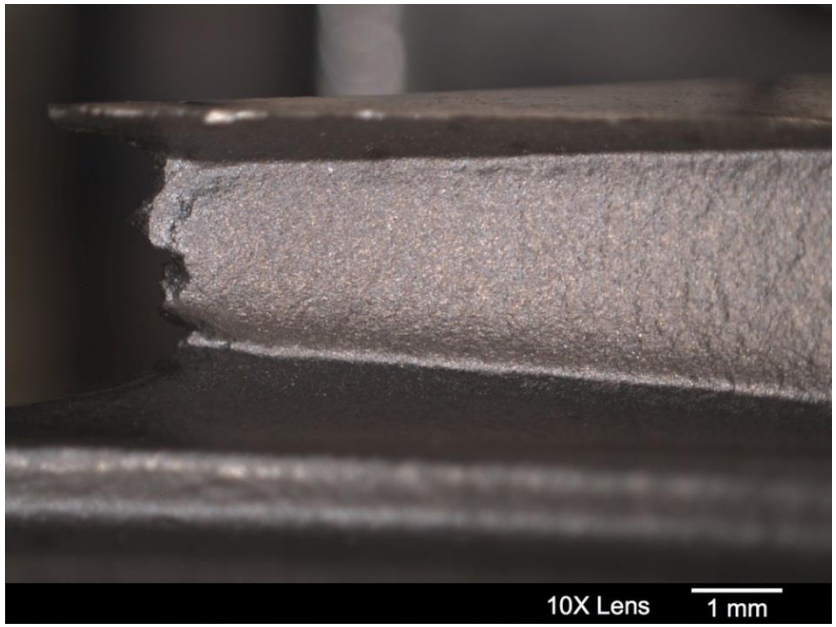


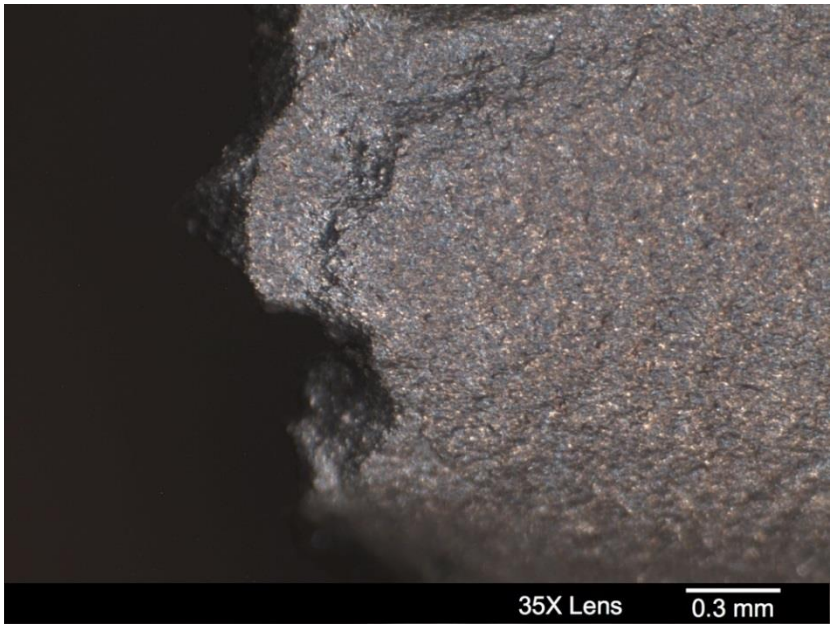


1: Inner tip of nozzle
2: Nozzle top face
3: Flow surface
4: Outer Turbine housing(Turbine spins above surface)
5: Inner Turbine housing

1: Nozzle Tip

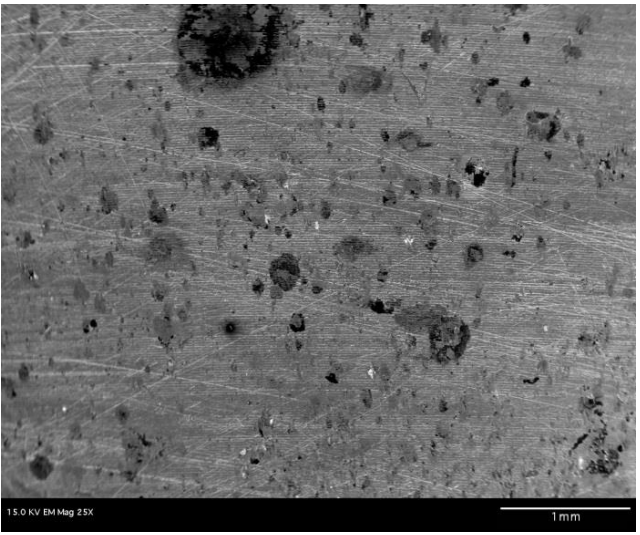


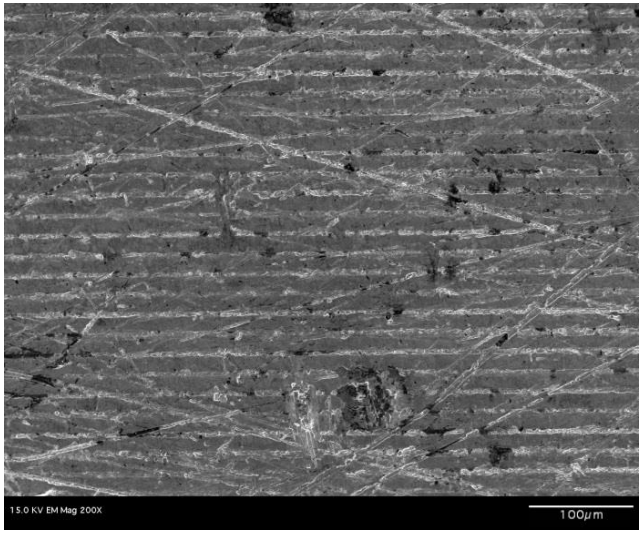


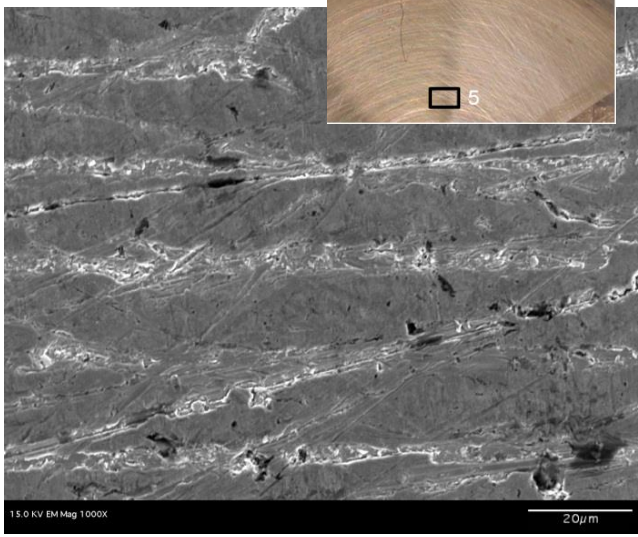


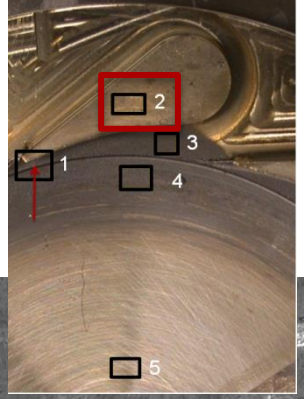
- Surface appears morphologically similar to the suction side blade tip.
- Nozzle wear at tip resulted in through wall damage, fundamentally changing nozzle geometries.

2: Nozzle seating face





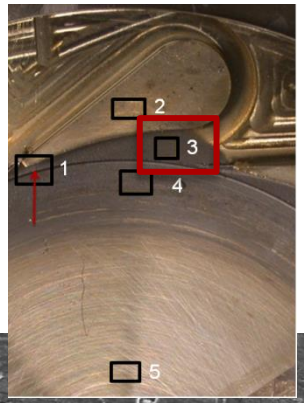


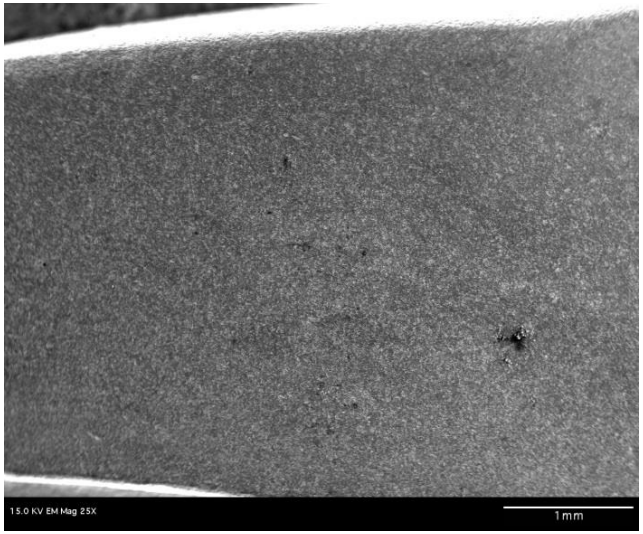


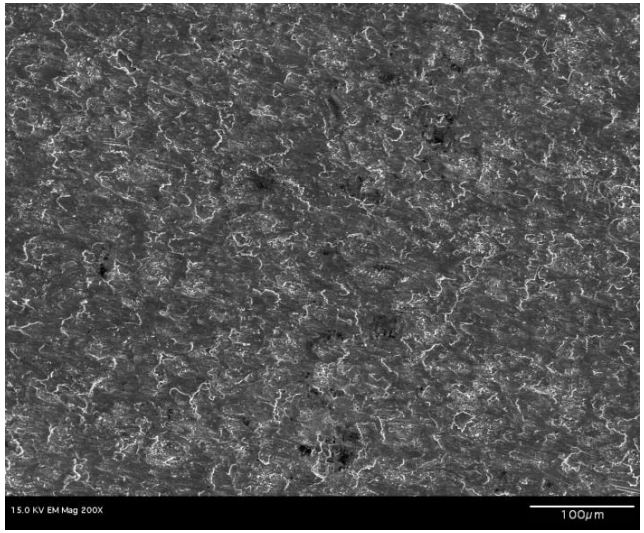
*max **bal	C	Si	Al	Mn	Cr	Fe**	Ni	Mo	Nb+Ta	Co	Ti
IN 718	0.08*	0.35*	0.35-0.80	0.35*	17-21	11.5-23.8	50-55	2.8-3.3	4.75-5.50	1.0*	0.65-1.15
EDS					18.1	18.7	56.7	5.1			

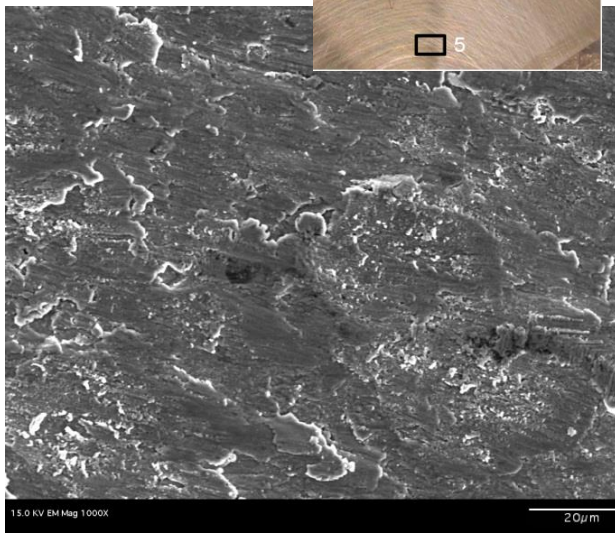
- Surface has scratches (left image), likely due to handling.
- Machining artifacts are still present (center image) and do not indicate any erosion damage.
- Result consistent with principle of operation (effectively no flow over this surface)

3: Flow surface









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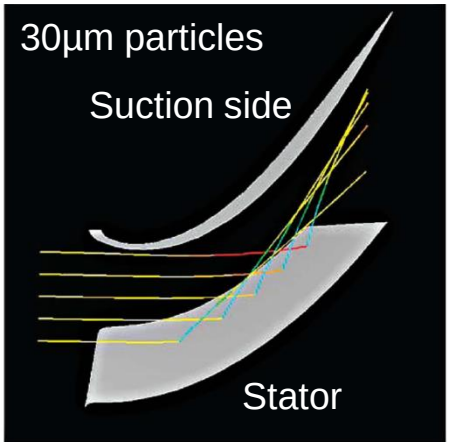
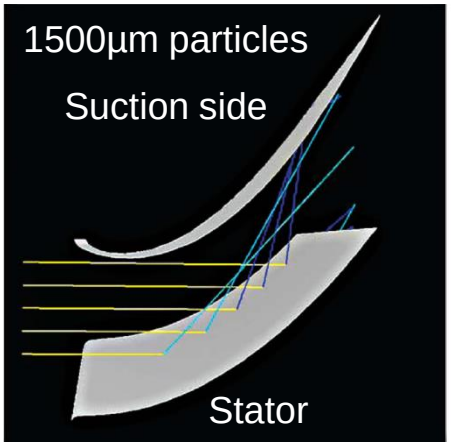
EDS					19	40.7	35.8	3.1			

- No machining artifacts were present on flow surface
- Significant iron enrichment present on surface
- Surface morphology has increased roughness resembling wear damage

Discussion of observed behavior

- Suction side and stator erosion was obvious
- Previous research indicates a strong correlation between particle size and erosion on the stator/suction side[1]

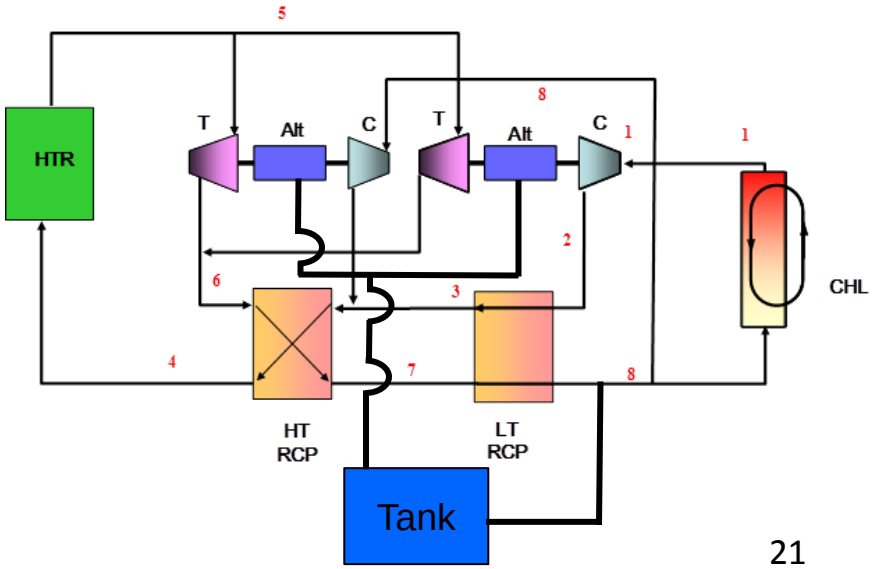




- More detailed studies, both experimental and computational, would need to be employed in order better understand this complex behavior.

Possible Particulate source

- Inventory tank is a possible source of iron oxide
- Previous tests employed vessels as both inventory and a baffling system (TAC leakage flows through tanks)
- Hydro pressure testing may have resulted in oxidation
- Keep as inventory only
  - Injection TAC leakage directly into the loop
- Periodic pigging required?



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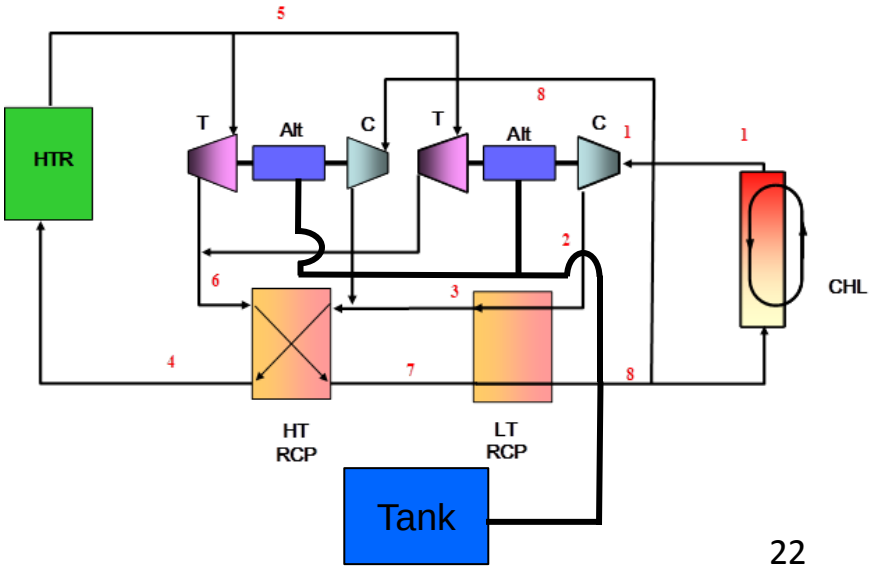
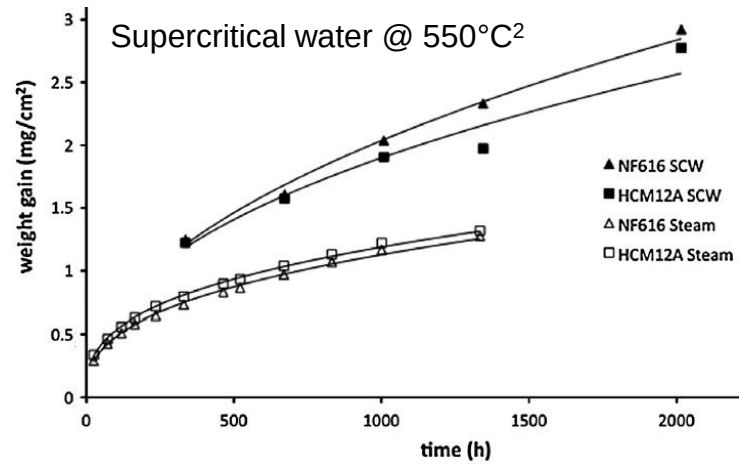
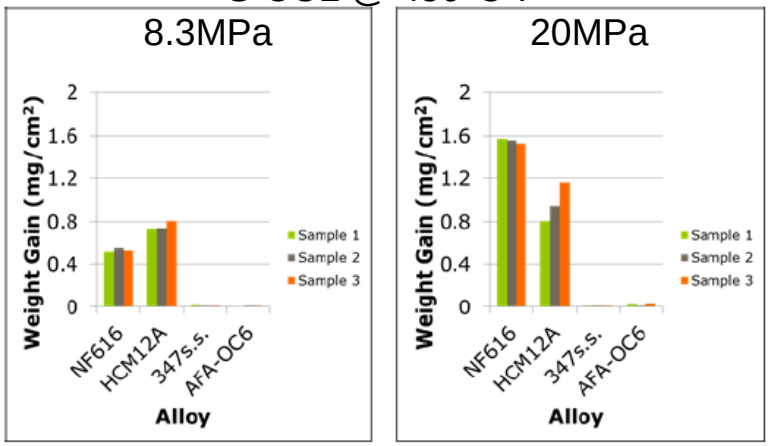


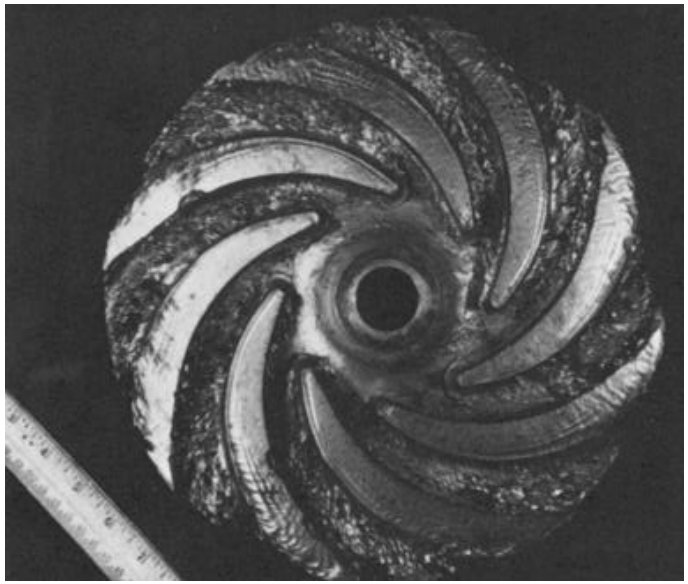
Engineered Materials: Where do we go from here?

- **Corrosion in S-CO2: wholly incomplete**
- **What is the effect of pressure on corrosion?**
  - Results are incomplete and appear contradictory
    - Low temperature corrosion had no differences in rates for dry CO2
    - Supercritical water and S-CO2 results do seem to imply increased pressure may increase corrosion rates[2,3]
- **Effects of gas purities: limits on common impurities?**
  - Specify a material (i.e. 316L) to consider
  - Investigate most obvious concerns (water, oil, etc.)
  - Vary concentrations and redox potentials
- **Develop rapid test methods to help assess and potentially down-select materials matrices**
  - Thermogravimetric are considered the standard
  - Methods that could be considered as a stepping stone toward thermogravimetric test are desirable
  - Electrochemical methods would be of interest



S-CO2 @ 450°C[3]:



Engineered Materials: Where do we go from here?

- **Erosion in sCO2: an extension of a pervasive generic problem in many power plants?**
  - Exfoliation of oxide particles in Rankine systems cause similar problems[1]
  - An issue of maintenance and materials
- **System size may not reduce erosion wear**
  - Larger turbines will spin at lower speeds but blade tip speeds should remain effectively constant
- **Utilize knowledge from current practices**
  - Pipe pigging methods may reduce oxide particles present[2]
  - Wear resistant coatings for turbines[3]