Materials for Supercritical CO$_2$ Applications

A Tutorial

Ganesan Subbaraman, Steven Kung, and Henry Saari

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Pittsburgh, Pennsylvania
Tutorial on
Materials for Supercritical CO$_2$ Applications

OUTLINE

Part I: Introduction and Objectives Subbaraman

Part II: Foundational A-USC Materials R&D Kung

Part III: Materials for sCO$_2$ Power Cycles Saari

Part IV: Summary Subbaraman
INTRODUCTION AND OBJECTIVES

Part I: What are sCO$_2$ cycles and why are materials important?
Motivation - 1

Cost of Electricity (COE)

Source: DOE-NETL
Motivation - 2

(Fuel and Water consumption & CO$_2$ Emissions)

Power Magazine May 2011
"Reference Case" – Oxycombustion (coal, petcoke, or coal + biomass)

- **Turbine inlet temp**: 1,300 F (700C)
- **Net power output (MWe)**: 544
- **Steam turbine power (MWe)**: 27
- **sCO₂ turbine power (MWe)**: 676
- **CO₂ captured (%)**: ~98
- **Net efficiency (%, HHV)**: 38.3
- **Net heat rate (Btu/kWh)**: 8,910

~9% Efficiency Improvement
Key Factors Influencing Performance

- Operating conditions of components (temperature, pressure, flow rates, static and dynamic loads)
- Influence of sCO$_2$ (oxidation, corrosion)
- Material selection (composition, impurities, form/shape)
- Material properties (tensile, yield, creep, fatigue)
  - Effects of treatments (welding, cold work, annealing)
- Materials availability and cost
  - In desired forms, shapes (e.g., pipes, plates)
- Conformance with safety codes
  - National (e.g., ASME B&PV) and local
## Reference Case Material Summary

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Departures from Reference Case

- Multiple applications of sCO$_2$ power cycle are being considered; Examples include:
  1. Waste heat utilization (lower temperature)
  2. Other indirectly-heated systems with varying temperatures (e.g., nuclear, solar)
  3. Directly-heated systems that deliver combustion products at supercritical conditions with ‘impurities’
     -- e.g., H$_2$O, O$_2$, N$_2$, Ar, NOx, SOx, HCl

Materials selection and qualifying them will depend on operating conditions for each application.
Materials Data Required for Reference Case

• A number of candidate materials are being independently evaluated for applications at temperature and pressures similar to the Reference Case (Section II of this Tutorial)
  • Creep strength and long-term stability (boiler alloys)
  • Fireside corrosion
  • Fabrication and design
  • Rotors, discs and blades (steam turbines)
  • Erosion and oxidation of blade materials (steam turbines)
  • Castings
• Materials data associated with sCO$_2$ environment and compatibility are under various stages of investigation (Section III of this Tutorial)
  • Corrosion and oxidation
• Maturing of plant designs and definitions will likely trigger
  • Determination of availability and costs
  • Applicability of existing code rules and/or need for code review

A Full Compendium of Similar Materials Data Should be the Ultimate Goal
Objectives of Tutorial

1. Provide data and information from the existing/ongoing A-USC program
2. Provide data and information from ongoing corrosion and sCO₂ compatibility tests
3. Exchange information with participants
   • Confirming and/or contradicting current data from tests or test loops
   • Need for new data, experiments and standards for inter-comparison of data
4. Obtain feedback for future tutorials
Part II: U.S. DOE/OCDO A-USC Steam Boiler & Turbine Consortium

FOUNDATIONAL MATERIALS R&D
Part II: Perspectives from a Related Program

OUTLINE

• Economics of high-strength nickel-based alloys

• Background U.S. DOE/OCDO A-USC Materials Consortium

• Major successes from the unique government-industry consortium

• A view on how A-USC Materials R&D enables sCO$_2$ and how we can leverage experience
Materials Limit the Current Technology: Today's State-of-the-Art Steam Power Plants are defined by steel technology.

- **9-12Cr Creep-Strength Enhanced Ferritic Steels (Gr. 91, 92, 122)**
- **Nickel-Based Alloys**
  - Inconel 740
  - Haynes 230
  - Haynes 282
- **Advanced Austenitic Alloys** (Super 304H, 347HFG, NF709, etc.)

**Minimum Desired Strength at Application Temperature**

**Average Temperature for Rupture in 100,000 hours (°F)**

- Steels = USC 620°C (1150°F)
- Solid Soln’ = A-USC ~700°C (1300°F)
- Age Hardenable = A-USC 760°C (1400°F)
Economics Comparison between two leading candidates: 740H & 617

ASME Section II - Allowable Stresses

Higher Allowable Stress for Inconel 740H = Thinner Pipe Walls
Higher-strength alloys provide an avenue for cost savings

Shingledecker et. al, 2012: IEA Clean Coal Centre Workshop (Vienna, Austria)

- A-USC plant design study showed using 740H compared to alloy 617 for a main steam and hot-reheat piping system:
  - Reduced piping material cost (less material) by a factor of ~2
  - Reduced welding cost (less welds)
  - Provided a buffer for nickel-based alloy price fluctuations

Federal – State – National Laboratory
Non Profit – For Profit
Cost Sharing Consortium

© 2012 Electric Power Research Institute (EPRI), Inc. All rights reserved. Other marks and logos are the property of their respective owners.
15 Year Effort to develop the materials technology to build and operate an A-USC boiler with steam temperatures up to 760°C.

Reports:

Foundational knowledge serves as basis for sCO2
Recent Results: In-Plant Testing at 760°C (1400°F)
Operating Steam Corrosion Test Loop

**Phase 1**
- Extensive laboratory testing & air-cooled probes in boiler
- Steam-cooled loop (high S coal)

**2nd Steam Loop**
- **World’s first steam loop operating at 760°C (1400°F)**
- Removed from service after 33 months with >16,000hrs in operation
- Evaluations = little to no wastage

Materials include:
740H, CCA617, HR6W, Super 304H, Coating, Overlays, and Others

Southern Company – Plant Barry

Fabrication in Alstom Chattanooga TN shop

Prior to Welding  Being Welded  After Assembly
Boiler Fabrication Successes

- No significant changes to fabrication techniques were required
- R&D was used to make changes to ASME Section I Table PG-19
- Full-size laboratory testing
- Initial tests on Inconel 740 led to additional phase 2 work on cold-work effects on creep which was needed for the code case
Major Step: Code Case 2702 (Inconel®740H) now Approved for Use in Section I and B31.1

- **Maximum Use Temperature:** 800°C (1472°F)
- **Rules for:**
  - Chemistry
  - Heat-treatment
  - Welding
  - Post-weld heat-treatment
  - Cold-forming
  - Weld strength reduction factors

A parallel effort is now underway with DOE/ORNL to develop a code case data package for Haynes 282 (single step age)
Transformational technologies will need A-USC materials and components demonstrated.
Alternative Supercritical CO$_2$ (sCO$_2$) Power Cycles Need Advanced (A-USC) Materials Technology

**NET Power Cycle 25MW Demo**
Gas-Fired 100% Carbon Capture Modified CO$_2$ Brayton Cycle is planning to use Inconel 740H for High-Temperature CO$_2$ piping

Scale-up to 250MW will require large diameter nickel-based alloy piping

**Partners:** NET Power, CB&I, Toshiba, Excelon

**DOE Sun-Shot sCO$_2$ Brayton Cycle: 1MW Closed Cycle Test Facility**

Piping, valves, castings, forgings, welding are applicable
sCO\textsubscript{2} Brayton Cycle Compact Heat Exchangers: Unique Materials Challenges

- **4-10X Heat-Duty compared to Rankine Cycle**
- **Designs:**
  - Expensive: ‘40%’ the cost of the entire plant
  - Small channels
  - Large surface area
- **Thermal fatigue resistance**
- **Creep of thin sections**
- **Brazing/diffusion bonding**
- **Corrosion/oxidation in sCO\textsubscript{2}**
  - Closed cycles: build-up of impurities
  - Open cycles: combustion by-products
  - Blockage, pluggage, reduced performance

Compact Heat Exchanger Fouling (Sandia National Lab)

New Heat Exchanger Design (Brayton Energy)
Summary: US DOE/OCDO A-USC Consortium

• Unprecedented success in developing the materials technology to enable A-USC Steam cycles up to 760°C (1400°F) based on pre-competitive R&D by a consortium of manufacturers, national laboratories, and research organizations
  • Extensive laboratory and shop R&D
  • Field applications for fireside corrosion

• sCO₂ can leverage the success of the consortium & foundational high-temperature materials R&D
  • Materials are a cross-cutting technology
  • Unique Material considerations for sCO₂ include environmental interactions, turbine materials, and compact heat exchangers
Part III: Materials in CO\textsubscript{2} Environments

MATERIALS FOR SCO\textsubscript{2} POWER CYCLES
OUTLINE

• Operating conditions and material requirements
  • Steam and gas turbines vs. sCO$_2$ power cycles

• Materials technical challenges
  • Knowledge gaps

• Materials in CO$_2$ environments
  • Previous experience, sCO$_2$ testing
  • Current and planned testing to address gaps
Comparison of Operating Conditions

[Philo 6 Steam – Electric Generating Unit, ASME International, 2003]

[GE Power Systems]
Steam Turbine Requirements and Materials

- **Relatively small range of materials**
  - Good match of thermal properties
  - High temperature strength at acceptable cost

- **Main components**
  - Turbine casing/shell
  - Bolting
  - Rotors and disks
  - Vanes and blades

- **Turbine casing/shell**
  - Large, complex shapes
  - Pressure containment
  - High creep strength, castability, weldability
  - Oxidation resistance
  - 9Cr, 12Cr steels, Ni-base alloys

- **Bolting**
  - Resistance to stress relaxation
  - Thermal compatibility
  - Low notch sensitivity
  - Ferritic steels, Ni-base alloys

- **Rotors and disks**
  - High creep strength, forgeability, weldability
  - 9Cr, 12Cr steels, Ni-base alloys

- **Vanes and blades**
  - High creep strength, machinability
  - 12Cr steel, Ni-base alloys

[Wright, et al., Materials Issues for Turbines for Operation in Ultra-Supercritical Steam]
[Babcock & Wilcox, Technical Paper BR-1884, 2011]
Gas Turbine Requirements and Materials

- Fan blades (fatigue, bird strike, erosion, corrosion, fretting fatigue)
- Fan disks (burst, LCF, HCF)
- Compressor blades (fatigue, erosion, corrosion)
- Compressor disks (burst, LCF, HCF, corrosion)
- Turbine blades (creep, stress rupture, corrosion, oxidation, HCF, thermal fatigue, fretting fatigue)
- Turbine vanes (creep, thermal fatigue, corrosion)
- Turbine disks (burst, LCF, HCF, creep, corrosion)
- Shafts (bird strike, whirling, LCF)
- Casing, bearings (bird strike, LCF, containment)

[adapted from Rolls-Royce figure]
## sCO₂ Brayton Cycle Materials

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Materials Technical Challenges

**Current Knowledge**

- **Existing materials/mechanical properties**
  - OK for main components (piping, valves, turbomachinery, etc.)

- **Environmental considerations – high temperature sCO\textsubscript{2}**
  - Corrosion testing – short-term, coupons, representative temps/pressures, mass gain (vs. depth)

**Gaps Remaining/Technical Challenges**

- **Availability**
  - Code compliant materials/qualified alloys; design codes
  - Supply chain – in required forms and sizes

- **Environmental considerations – high temperature sCO\textsubscript{2}**
  - Longer-term (short-term testing inadequate – breakaway corrosion, intergranular corrosion)
  - Testing under “real” conditions (flow, stress, impurities – H\textsubscript{2}O, O\textsubscript{2}, others; indirect vs. direct cycles)
  - Reliability of data
  - Mechanical property degradation

- **Performance of actual components/material forms**
  - Thin sections – property differences, effect of geometry
  - Diffusion bonded, brazed, welded joints – corrosion resistance
  - Erosion, fouling of microchannel heat exchangers
  - Thermal fatigue, creep-fatigue interactions, high blade bending loads/temperature + pressure combinations

- **Other challenges and considerations**
  - Coatings
  - Non-metallics – degradation of seals via swelling, rapid gas depressurization
  - Leverage previous work – comparison to steam and SCW corrosion, pressure effects

Materials are available...but gaps remain...efforts are required to complete the picture.
Materials in CO\textsubscript{2} Environments

Previous Experience

- \textbf{CO\textsubscript{2} gas-cooled Magnox reactors}
  - Many reactor years of operation
  - Structural material behaviour well-characterized
  - High temperature (650 °C) but low pressure (< P\textsubscript{c})
  - Corrosion rates higher under stress
  - Breakaway corrosion caused by exfoliation and nucleation of oxides – mainly influenced by exposure time and/or CO\textsubscript{2} gas pressure

- \textbf{Oil and gas industry CO\textsubscript{2} experience}
  - Enhanced oil recovery (EOR), CO\textsubscript{2} transport pipelines
  - Effects of contaminants
  - High pressure (<21 MPa) but low temperature (< 200 °C)
  - Pure, dry – virtually inert < 500 °C
  - Significant corrosion of steels and nickel alloys with ppm H\textsubscript{2}O, > 600 °C
  - Austenitic alloys better than ferritic-martensitic steel
  - High levels of Cr and Ni increase corrosion resistance
# High Temperature sCO$_2$ Corrosion Testing

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<tr>
<th>Organization</th>
<th>Temp. (°C)</th>
<th>Pres. (MPa)</th>
<th>PV Material</th>
<th>Materials Tested</th>
<th>CO$_2$ Purity</th>
<th>Operational Status</th>
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<tr>
<td>INL [Oh et al., 2006]</td>
<td>1000</td>
<td>7</td>
<td>IN617, 304SS</td>
<td>Ni-base: IN617</td>
<td>-</td>
<td>2 rigs, both decommissioned</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>ODS: MA 754, MA 758</td>
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<tr>
<td>TIT [Furukawa et al., 2010]</td>
<td>600</td>
<td>20</td>
<td>316SS</td>
<td>Martensitic: 12 Cr</td>
<td>99.995%</td>
<td>Not in-use?</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Austenitic: 316SS</td>
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<td></td>
<td>Austenitic: 316SS, 253MA, 800H</td>
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<tr>
<td>MIT [Dunlevy, 2009]</td>
<td>750</td>
<td>22-27</td>
<td>IN625</td>
<td>FM: F91, HCM12A</td>
<td>99.999%</td>
<td>In-use</td>
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<td>Ni-based: IN690, 693, 718, 725, 740, 740+, PE-16, Haynes 230, IN625</td>
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<td>ODS: PM2000</td>
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<tr>
<td>UWisconsin-Madison [Roman, 2013]</td>
<td>650/750</td>
<td>27/21</td>
<td>IN625</td>
<td>FM: HCM12A, NF616</td>
<td>99.95%</td>
<td>Several rigs, in-use</td>
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<td></td>
<td>Austenitic: 310SS, 316SS, 347SS, AL-6XN, 800H</td>
<td>99.999%</td>
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<td>Ni-based: Haynes 230, IN625, PE-16</td>
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<td>AFA: -OC6, -OC7, -OC10</td>
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<td>ODS: PM2000</td>
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<tr>
<td>CarletonU/NRCan [Saari, 2014]</td>
<td>700/750</td>
<td>25/15</td>
<td>IN625</td>
<td>Austenitic: 316SS</td>
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<td>Ni-based: Alloys 600, 625, 690</td>
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<tr>
<td>ORNL/GTI [Pint, 2015]</td>
<td>927</td>
<td>55</td>
<td>Haynes 282</td>
<td>Housing, disk, and blade alloys</td>
<td>-</td>
<td>In-use</td>
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<td>Haynes 230</td>
<td>Austenitic steels, Ni-base alloys</td>
<td>-</td>
<td>In-use</td>
</tr>
<tr>
<td>DNV-GL [Kung, 2016]</td>
<td>750</td>
<td>20</td>
<td>-</td>
<td>FM: Gr. 91, VM12, Crofer 22H</td>
<td>99.955%</td>
<td>In-use</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Austenitic: 304SS, 310SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ni-based: 617, 740H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNL [Walker, 2016]</td>
<td>650</td>
<td>31</td>
<td>IN625</td>
<td>Carbon steel: X65Q</td>
<td>99.5%</td>
<td>In-use</td>
</tr>
<tr>
<td>CSIRO [Stein, 2016]</td>
<td>1000</td>
<td>25</td>
<td>various</td>
<td>HR120, 160; Haynes 230, 188, 282</td>
<td>-</td>
<td>In-use</td>
</tr>
</tbody>
</table>
(High Temperature) sCO₂ Testing

- **Characterization**
  - Weight gain/corrosion layer thickness
  - Scales/mechanisms
- **Various materials tested** (steels (FM, austenitic), nickel alloys)
sCO₂ Corrosion Testing – Results

General Weight Gain Trends
FM > austenitic > nickel-base
Fe-Cr (<12% Cr) > Fe-Cr-Ni (>16% Cr) > Ni-Cr-X (>16% Cr)
Ferritic Steels

- Larson-Miller plots for comparison
- Mass gain plotted
- CO$_2$ and recent sCO$_2$
- Recent sCO$_2$ and steam

Mass gains for sCO$_2$ and steam are approx. similar...the scale morphologies in sCO$_2$ would be similar to those in steam.
Ferritic Steels

- 12Cr Martensitic steel
- Two successive layers, no breakaway corrosion
  - Outer: Fe oxide, Fe$_3$O$_4$
  - Inner: Fe+Cr oxide, Fe(Fe$_{1-x}$Cr$_x$)$_2$O$_4$
- Thin internal oxide zone (IOZ) between base metal and inner layer
- Carburizing observed near surface in base metal
  - Factor in breakaway corrosion, degradation of ductility

- T91 9Cr F-M steel
- Duplex oxide layer
  - Outer: magnetite, Fe$_3$O$_4$
  - Inner: spinel, Fe$_{3-x}$Cr$_x$O$_4$
- Internal oxidation also
- Extrapolation to 20 years
  - Corrosion layer thickness = 500 µm
- Static tests at 50 °C @ 10 MPa
  - No corrosion observed
- Flowing CO$_2$
  - Similar oxide scale at 550 °C @ 1 bar (+ outer Fe$_2$O$_3$ haematite)
Austenitic Steels

- Larson-Miller plots for comparison
- Mass gain plotted
- CO₂ and recent sCO₂

Schematic of oxidation products on austenitic steels in steam and sCO₂ [Strakey, 2014]
Nickel-base Alloys

Nickel-base alloys in CO₂ (wrought alloys left and cast alloys right) [Wright, EPRI 2015]

- Larson-Miller plots for comparison
- Mass gain plotted
- Recent sCO₂
• Alloys with high Cr and Ni, and Ti and Al more corrosion resistant
  • Build a stable, tight oxide layer that resists corrosion
• Alloys with low Cr levels less corrosion resistant
  • Build a duplex layer with that does not resist corrosion well
• In general, decreasing corrosion resistance:

<table>
<thead>
<tr>
<th>Material</th>
<th>Nickel Ni-Cr-X</th>
<th>Austenitic Fe-Cr-Ni</th>
<th>FM Fe-Cr Cr&lt;12%</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN625</td>
<td>800H</td>
<td>12Cr</td>
<td></td>
</tr>
<tr>
<td>IN617</td>
<td>AL6-XN</td>
<td>HCM12A</td>
<td></td>
</tr>
<tr>
<td>Haynes 230</td>
<td>316SS</td>
<td>NF616</td>
<td></td>
</tr>
<tr>
<td>IN718</td>
<td>310SS</td>
<td>T91</td>
<td></td>
</tr>
<tr>
<td>IN738</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Increased corrosion with temperature
• Not much (if any) pressure effect
**Summary of Main Findings**

**PRELIMINARY TECHNOLOGICAL RECOMMENDATIONS FOR STEELS**

From past studies carried out in the 60-70’s for MAGNOX reactors and AGR:

\[ \text{CO}_2 + 1\% \text{vol CO} + 300 \text{ vpm H}_2\text{O} + 300 \text{ vpm H}_2 + 350 \text{ vpm CH}_4 \text{ at 20-40 bars} \]

<table>
<thead>
<tr>
<th>Grade</th>
<th>Mild steels</th>
<th>9Cr-1Mo steel</th>
<th>Austenitic steels (316L type)</th>
<th>Austenitic steels (310 type, Nimonic 80, PE16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{max}} )</td>
<td>&lt;350°C</td>
<td>&lt;450°C</td>
<td>&lt;660°C</td>
<td>&gt;660°C</td>
</tr>
</tbody>
</table>

- «Breakaway oxidation» possible = Fast oxidation kinetics which incubation time and kinetics depend on Temperature (bad), \( \text{CO}_2 \) total pressure (bad), \% Si (good), \( [\text{H}_2\text{O}] \) in \( \text{CO}_2\text{(g)} \) (bad)
- At 520°C and 40 bars, 9Cr steel is on «breakaway oxidation» before 30 years if \%Si < 0.45 wt%
- For using «mild steel» at \( T > 350\text{°C} \), \%Si has to be > 0.4% or \( [\text{H}_2\text{O}] < 50 \text{ vpm} \) (reasons?)

Corrosion behaviour of «Mild steel» with \%Si > or < 0.4% under SC-CO\(_2\) at 250 bars at 400°C?

[Rouillard, sCO\(_2\) PCS 2011]
Where are the temperature cut-offs for different materials when corrosion is considered?
Current Knowledge

- **Existing materials/mechanical properties**
  - OK for main components (piping, valves, turbomachinery, etc.)
- **Environmental considerations – high temperature sCO₂**
  - Corrosion testing – short-term, coupons, representative temps/pressures, mass gain (vs. depth)

Gaps Remaining/Technical Challenges

- **Availability**
  - Code compliant materials/qualified alloys; design codes
  - Supply chain – in required forms and sizes
- **Environmental considerations – high temperature sCO₂**
  - Longer-term (short-term testing inadequate – breakaway corrosion, intergranular corrosion)
  - Testing under “real” conditions (flow, stress, impurities – H₂O, O₂, others; indirect vs. direct cycles)
  - Reliability of data
  - Mechanical property degradation
- **Performance of actual components/material forms**
  - Thin sections – property differences, effect of geometry
  - Diffusion bonded, brazed, welded joints – corrosion resistance
  - Erosion, fouling of microchannel heat exchangers
  - Thermal fatigue, creep-fatigue interactions, high blade bending loads/temperature + pressure combinations
- **Other challenges and considerations**
  - Coatings
  - Non-metallics – degradation of seals via swelling, rapid gas depressurization
  - Leverage previous work – comparison to steam and SCW corrosion, pressure effects

Materials are available…but gaps remain…efforts are required to complete the picture…and they are underway!
Materials Technical Challenges (Revisited)

Current Knowledge

- **Existing materials/mechanical properties**
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  - Leverage previous work – comparison to steam and SCW corrosion, pressure effects
Availability

• Code compliant materials/qualified alloys; design codes
  • IN740H code case approved
  • Haynes 282 code case in progress
  • Design codes for valves, heat exchangers?

• Supply chain – in required forms and sizes
  • Market pull to enable capability
Materials Technical Challenges (Revisited)

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  • OK for main components (piping, valves, turbomachinery, etc.)
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Environmental Considerations

- Longer-term (short-term testing inadequate – breakaway corrosion, intergranular corrosion)
  - Currently max test duration in range of 3-6 kh
  - Carburization and internal oxidation leading to breakaway corrosion, exfoliation
- Testing under “real” conditions (flow, stress, impurities – H₂O, O₂, others; indirect vs. direct cycles)
  - GTI/Oak Ridge National Laboratory
    - C-ring testing (stressed material) in sCO₂ (750 °C, 20 MPa, 1000 hours)
    - Various materials (housing, disk, blade) [Keiser, 2016]
  - Various labs examining effects of impurities, CO₂ composition
    - Testing in impurities expected in “semi-open” fired configurations [Shingledecker, 2016]
- CSIRO
  - Pressure vessel as test specimen (stressed material)
Environmental Considerations

- **Reliability of data**
  - Round Robin Testing and Fundamental Modeling (US DOE Nuclear Energy University Programs)
  - Various test facilities, but previously no formal test program to validate data consistency
  - Comparable and reproducible results desired
  - Proposed work:
    - Round robin test plan for \(\text{sCO}_2\) corrosion testing
    - Organization of \(\text{sCO}_2\) Materials Group to guide future testing
    - Elucidate mechanisms of \(\text{sCO}_2\) corrosion
  - Lead: OSU, Collaborators: UofW-Madison, ORNL, NETL, Carleton University, KAIST, EPRI

- **Mechanical property degradation**
  - Compact tension specimens exposed, study subsequent fatigue crack growth [Holcomb, 2016]
  - Evaluate effects of \(\text{sCO}_2\) exposure on tensile properties [Pint, 2016] and [Jang, 2014]
Materials Technical Challenges (Revisited)

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• Existing materials/mechanical properties
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Performance of Actual Components/Material Forms

- Thin sections – property differences, effect of geometry
  - Creep debit for thin sections [Pint, 2016]
  - Oxide thickness not extent of damage [Pint, 2016]
  - Heat flux, stress from complex geometries [Kung 2016]

- Diffusion bonded, brazed, welded joints – corrosion resistance

- Erosion, fouling of microchannel heat exchangers
  - Is erosion a real problem – fluid or debris, exfoliation? [Fleming, 2014]
  - Oxide scale itself may cause blockage [Sabau, 2016]

- Thermal fatigue, creep-fatigue interactions, high blade bending loads/temperature + pressure combinations
Materials Technical Challenges (Revisited)

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  • Coatings
  • Non-metals – degradation of seals via swelling, rapid gas depressurization
  • Leverage previous work – comparison to steam and SCW corrosion, pressure effects
Other Challenges and Considerations

- **Coatings**
  - Allow use of lower-cost alloys or push corrosion limit of material
- **Non-metallics – degradation of seals via swelling, rapid gas depressurization**
  - [Tunnison, 2009] and oil and gas studies
- **Leverage previous work – comparison to steam and SCW corrosion, pressure effects (testing in CO₂)**
  - Extend ORNL/EPRI exfoliation model for steam to sCO₂ [Sabau, 2016]
    - Exfoliation of oxide scales on boiler tubes
    - Predicts scale failure and loss based on evolution of oxide
  - Little pressure effect seen in sCO₂ – low pressure CO₂ testing OK?
Part IV: Summary

SCO$_2$ CAN BENEFIT FROM A COLLABORATIVE MATERIALS APPROACH
Compressors

Turbine blades:
- Oxidation/corrosion in sCO₂
- Erosion
- Optimal coating technologies

Rotors

Sealing surfaces at these higher pressures

Lower temperature seals
- De-gassing

Others?
High temperature corrosion rates, exfoliation, and mechanisms are not well understood

Strong desire to maximize use of less expensive alloys

Long-term performance, at high-temperature, of brazed, welded, or diffusion-bonded joints is unknown

Short-list of code approved materials for highest temperatures

Potential alloys in various states of code certification

Properties needed by designers may be different in very thin sections due to processing:
  - Creep
  - Fatigue
  - Thermal mechanical fatigue and creep-fatigue
  - Oxidation, spallation of oxide scales
• **High-mass flow requires large piping for larger applications**  
  • Fabrication/welding of nickel-based materials
• **Limitations in current supply chain**  
  • Limited materials to choose from  
  • Need production of fittings, forgings, casting, etc.  
  • Valve vendors ‘not up to speed’ on market developments
• **Codes & Standards**  
  • Valve codes are highly restrictive for materials & pressures/temperatures
• **Erosion and wear performance of hardfacing and alternatives**
• **Valves and instrumentation**
• **Others?**
Summary and Recommendation

- Selection and qualification of materials for sCO$_2$ applications is a function of operating conditions and environment
  - Corrosion and oxidation characteristics are unique to sCO$_2$
- Severity of temperature, pressure conditions for the reference case are analogous to those experienced in A-USC conditions
- This tutorial draws on data available to-date from the A-USC program and other ongoing sCO$_2$-focused tests

A coordinated effort similar to A-USC materials program is recommended

Leverage data and process to accelerate maturing selection and qualification of materials for sCO$_2$ plant components (address the Gaps)
Thank You!

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