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Comparison of Grade 91 and 347H Corrosion Resistance in the Low-Temperature Components of Direct Supercritical CO2 Power Cycles

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COLLEGE OF ENGINEERING

6th sCO_2 Power Cycles Symposium

March 27-29, 2018

Pittsburgh, Pennsylvania

Outline

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- **Introduction**
  - Heat Exchangers
  - Literature review
- **Materials and Methods**
  - Stainless Steel Grade 347H and Ferritic-Martensitic Grade P91
  - Experimental Procedure
- **Results and Discussion**
  - Weight measurement
  - Corrosion products characterization
- **Conclusion**

Heat Exchangers

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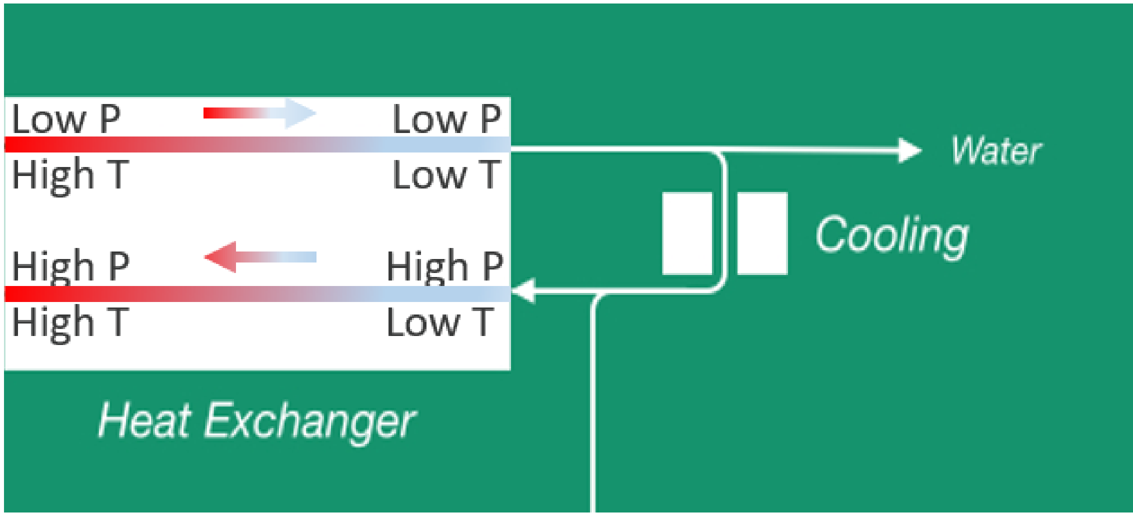
Direct sCO_2 cycle fluid (Allam et al.)



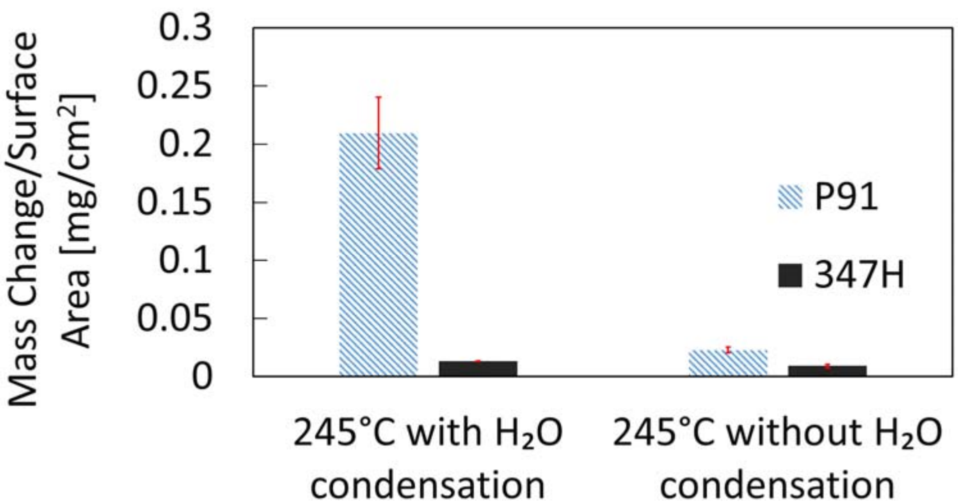
- Typical fluid composition:
  $CO_2/H_2O/O_2$ (95%/4%/1%)
- Pressure range : 3 to 35MPa
- Temperature range: Room Temperature to 750°C
- Phase change: Dissolved H_2O in sCO_2 → Aqueous fluid of CO_2

Source: R. Allam, et al. "Demonstration of the Allam cycle: an update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture." *Energy Procedia* 114 (2017): 5948-5966

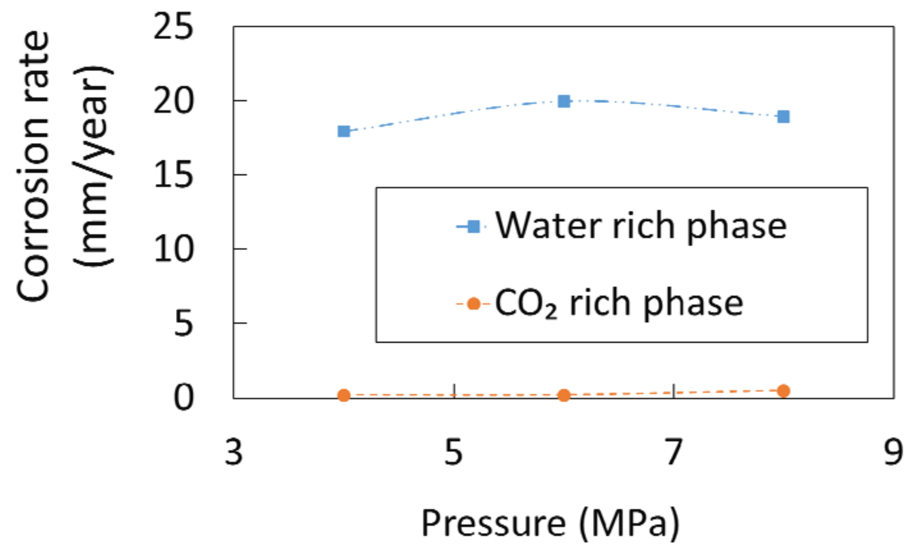
Literature Review

- **Impacts of aqueous condensation**

- **Presence of water exacerbates corrosion degradation**



Mass change of steels at 245°C with a H_2O condensation variable [*Repukaiti et al.*]



Carbon steel in water rich and CO_2 rich phases at 50°C [*Choi et al.*]

Source:

Repukaiti, R., Teeter, L., Ziomek-Moroz, M., Doğan, Ö., & Tucker, J. (2017). Corrosion Behavior of Steels in Supercritical CO2 for Power Cycle Applications. ECS Transactions, 77(11), 799-808.

Choi, Y., & Nesic, S. (2009). Corrosion Behavior of Carbon Steel in Supercritical CO2 - Water Environments. National Association of Corrosion Engineers, P.O. Box 218340 Houston TX 77084 USA. [np]. 22-26 Mar 2009., National Association of Corrosion Engineers, P.O. Box 218340 Houston TX 77084 USA. [np]. 22-26 Mar 2009.

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Materials

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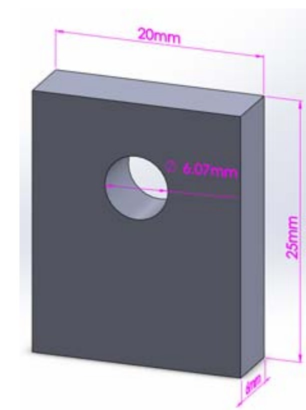
- Stainless steel 347H
- Martensitic-ferritic steel P91

Alloy	Description	Cr	Ni	C	Mn	P	Mo	Fe
347H	Austenitic stainless steel	17.3	9.09	0.05	1.5	0.03	0.41	Balance
P91	Ferritic-martensitic steel	8.37	0.09	0.09	0.45	0.01	0.9	Balance

- Sample dimension: 20 × 25 × 6 mm with a 6 mm diameter hole
- 1200 grit SiC sandpaper surface finish



Immersion Test Configuration

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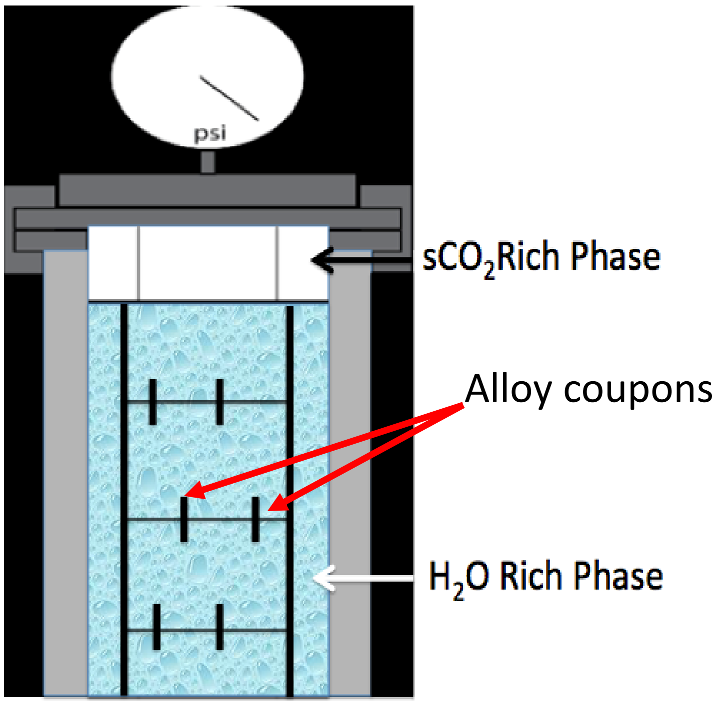

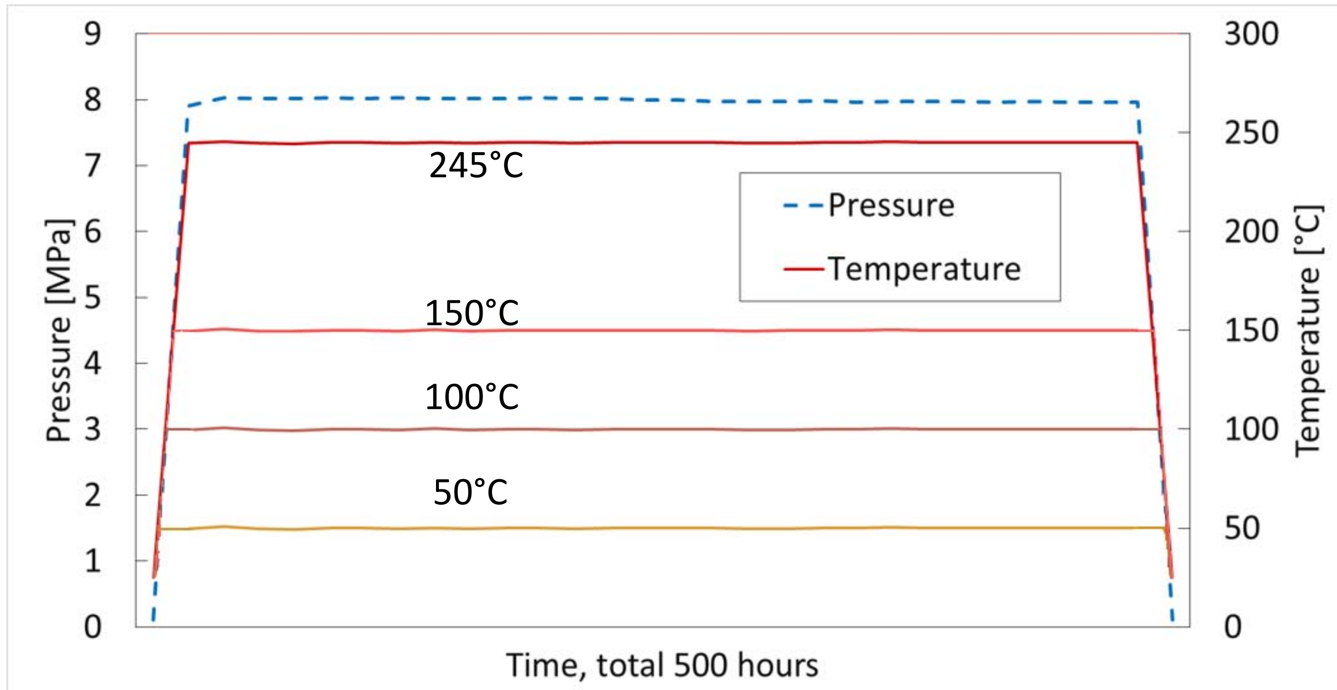

CO2 and H2O Phase Diagrams

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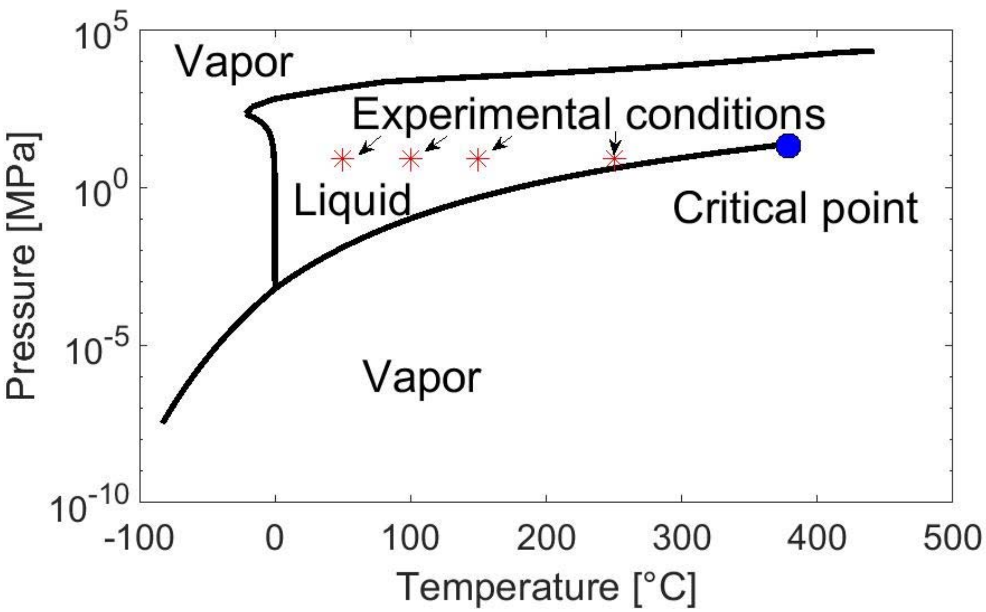
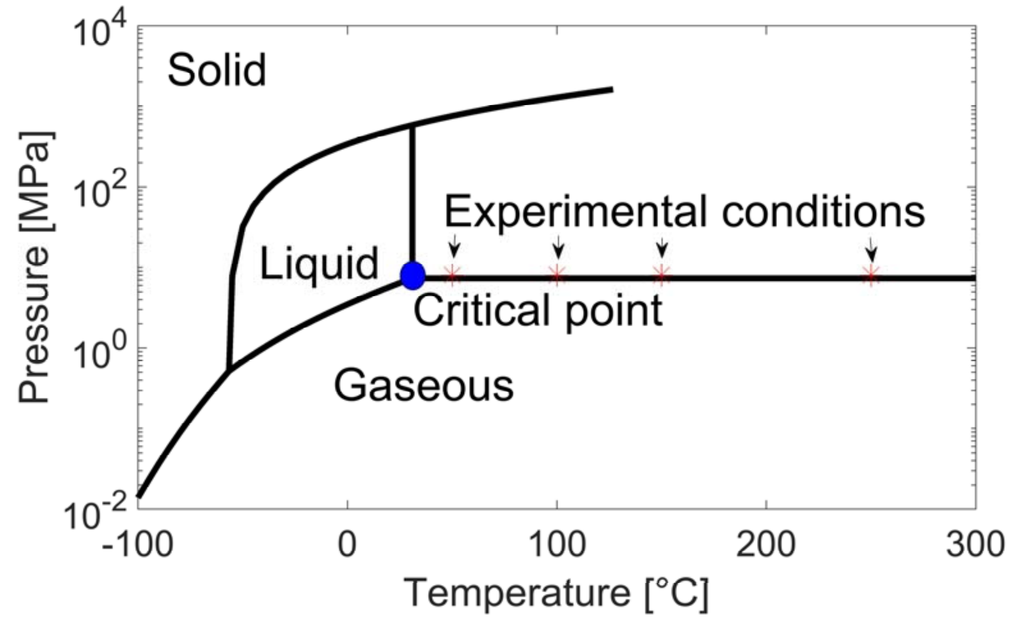
Pressure: 8 MPa, 95% CO_2 : 1%O_2 molar ratio
Temperature: 50°C, 100°C, 150°C, and 245°C



H_2O



CO_2

Source: NIST Standard Reference Database, Material measurement laboratory, Data Gateway." 1977, Chemistry WebBook. Data collected.

CO2 and O2 Solubility in H2O

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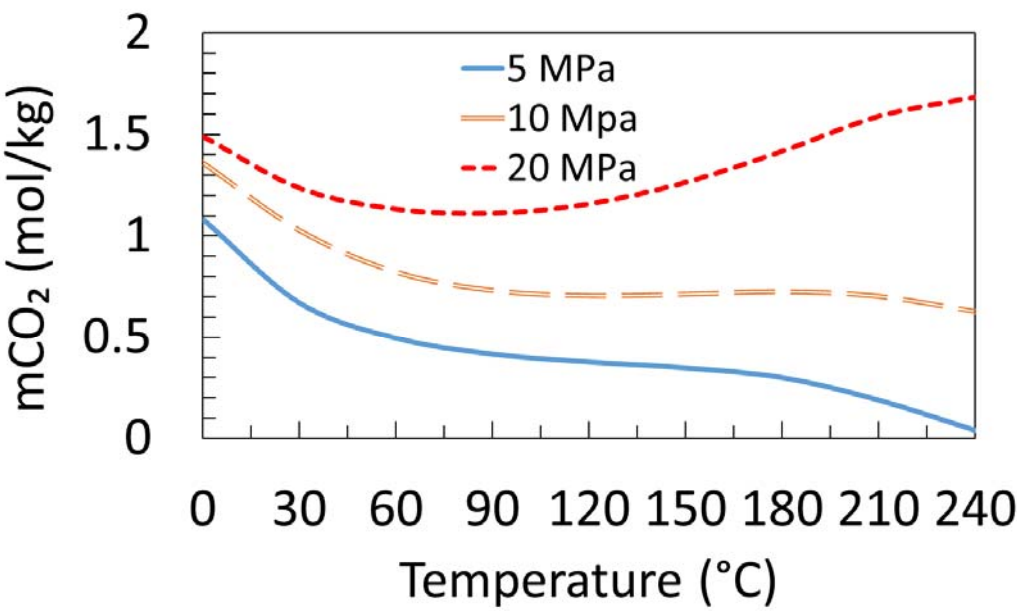
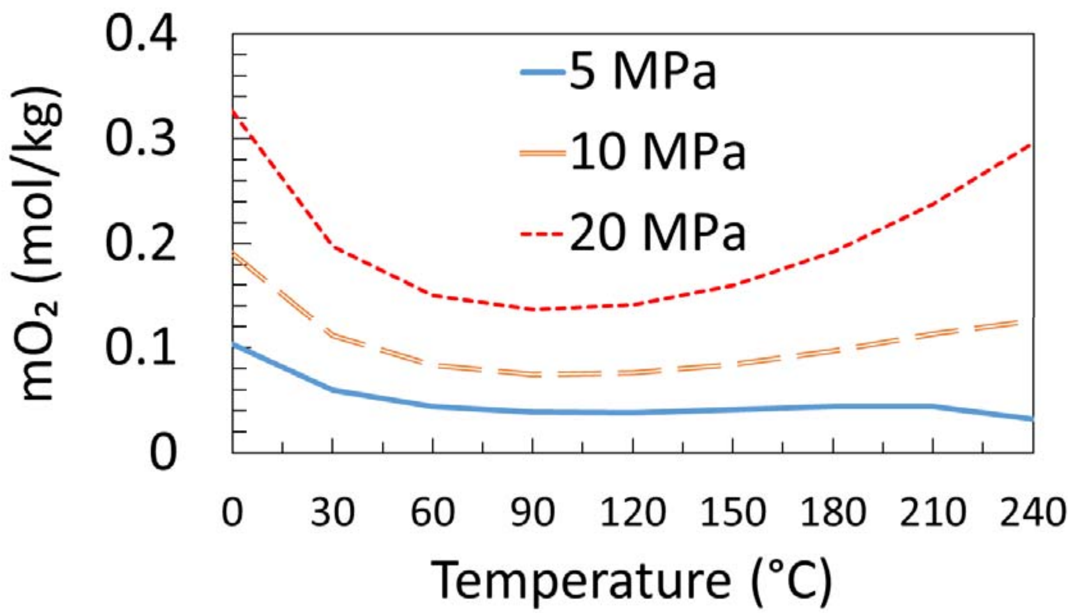
CO_2



Solubility of CO_2 in pure H_2O as functions of temperature and pressure [*Duan et al.*]

O_2



Solubility of O_2 in pure water as functions of temperature and pressure [*Geng et al.*]

Source: Duan, & Sun. (2003). An improved model calculating CO 2 solubility in pure water and aqueous NaCl solutions from 273 to 533 K and from 0 to 2000 bar. Chemical Geology, 193(3), 257-271.

Geng, & Duan. (2010). Prediction of oxygen solubility in pure water and brines up to high temperatures and pressures. Geochimica Et Cosmochimica Acta, 74(19), 5631-5640.

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P91 Secondary Electron Images

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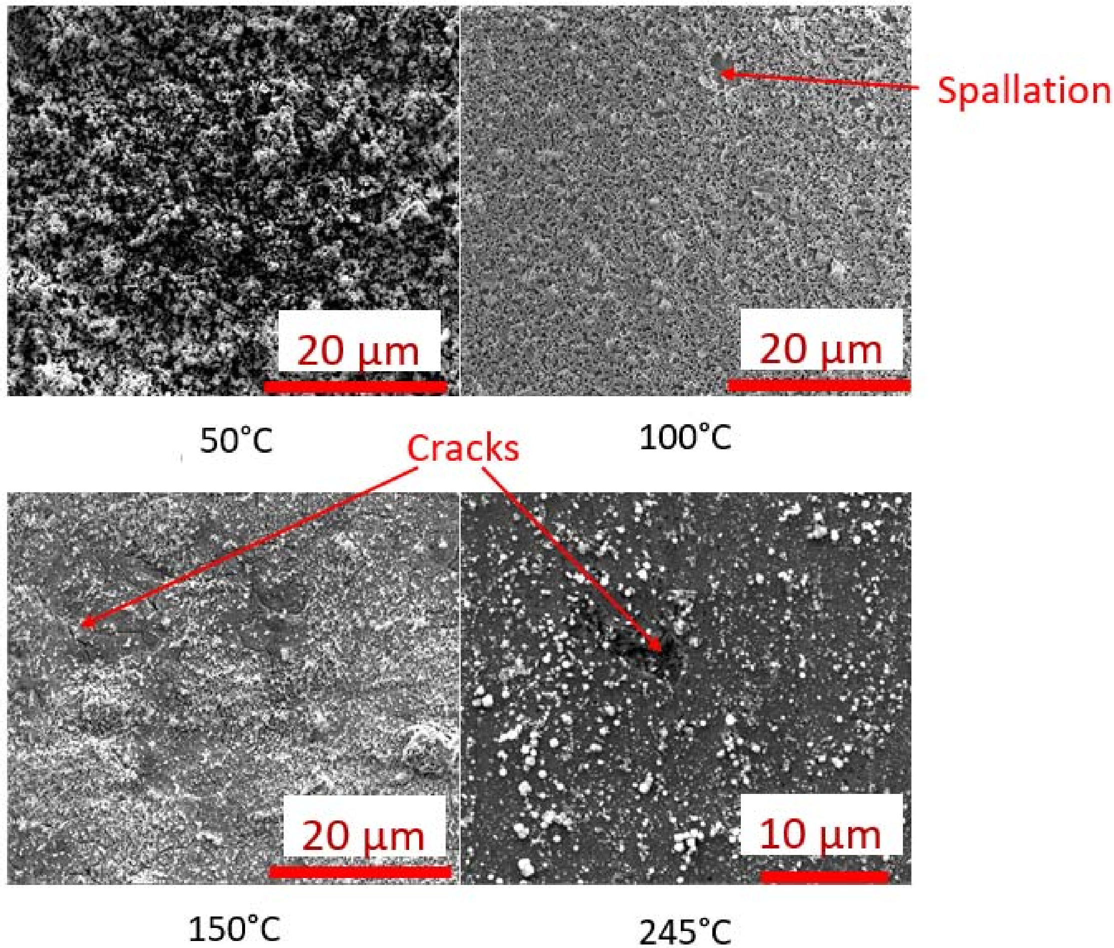

P91 Cross-Sectional Back Scattered Electron Images

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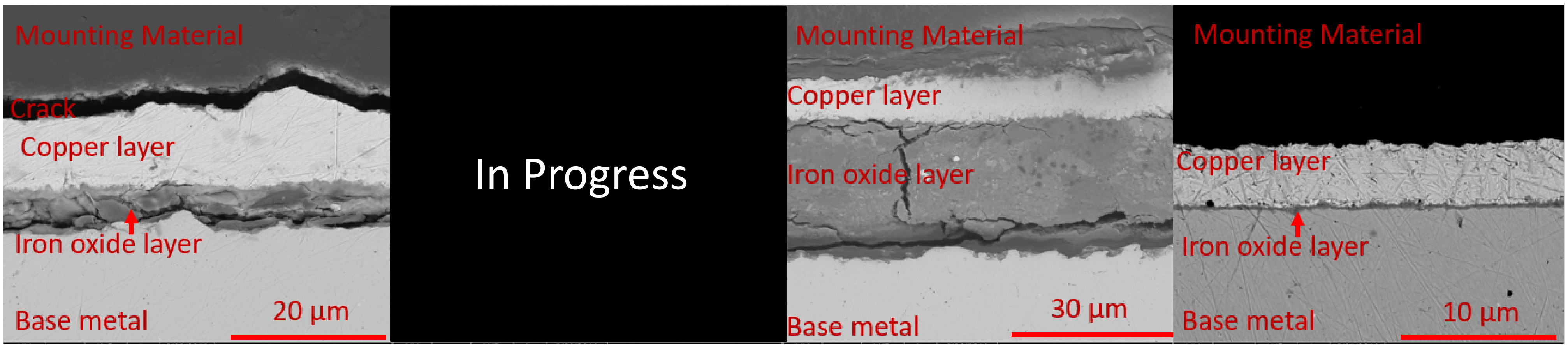

50°C 100°C 150°C 245°C

50°C	100°C	150°C	245°C
Fe_2O_3	Fe_2O_3	Fe_2O_3	Fe_2O_3
$FeO(OH)$	Fe_3O_4	Fe_3O_4	Fe_3O_4
Fe_3O_4			

XRD Analysis of P91 Corrosion Products

Pourbaix Diagram of Fe-CO2-H2O

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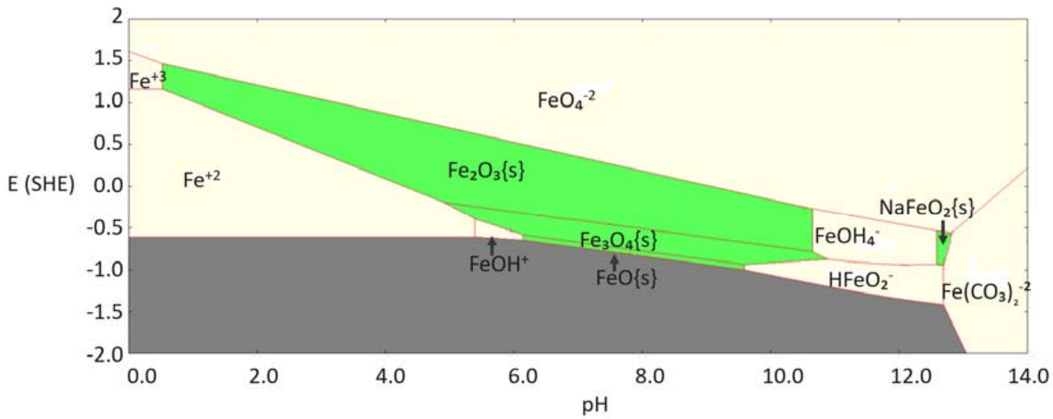
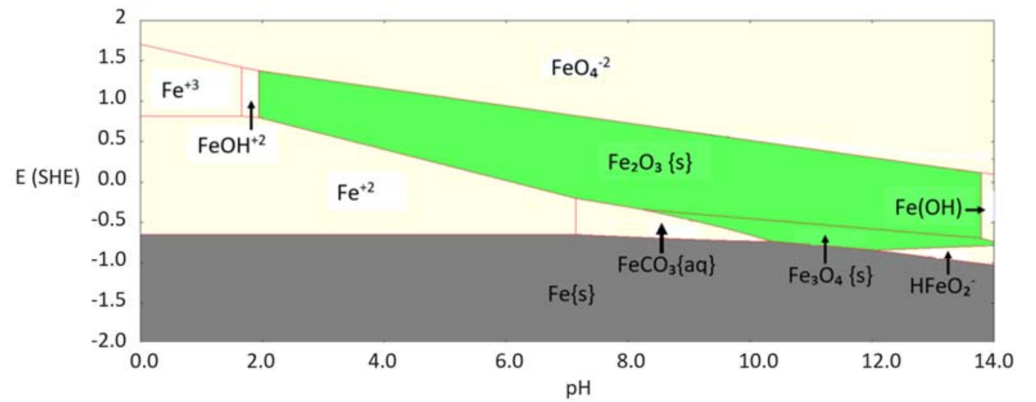
$$3Fe + 4H_2O = Fe_3O_4 + 8H^+ + 8e^-$$

$$Fe_3O_4 + H_2O = 3Fe_2O_3 + 2H^+ + 2e^-$$



Fe-CO_2-H_2O in 245 °C and 8 MPa



Fe-CO_2-H_2O in 50 °C and 8 MPa

Source: OLI Systems, Inc. *OLE Studio*, 2017

347H Secondary Electron Images

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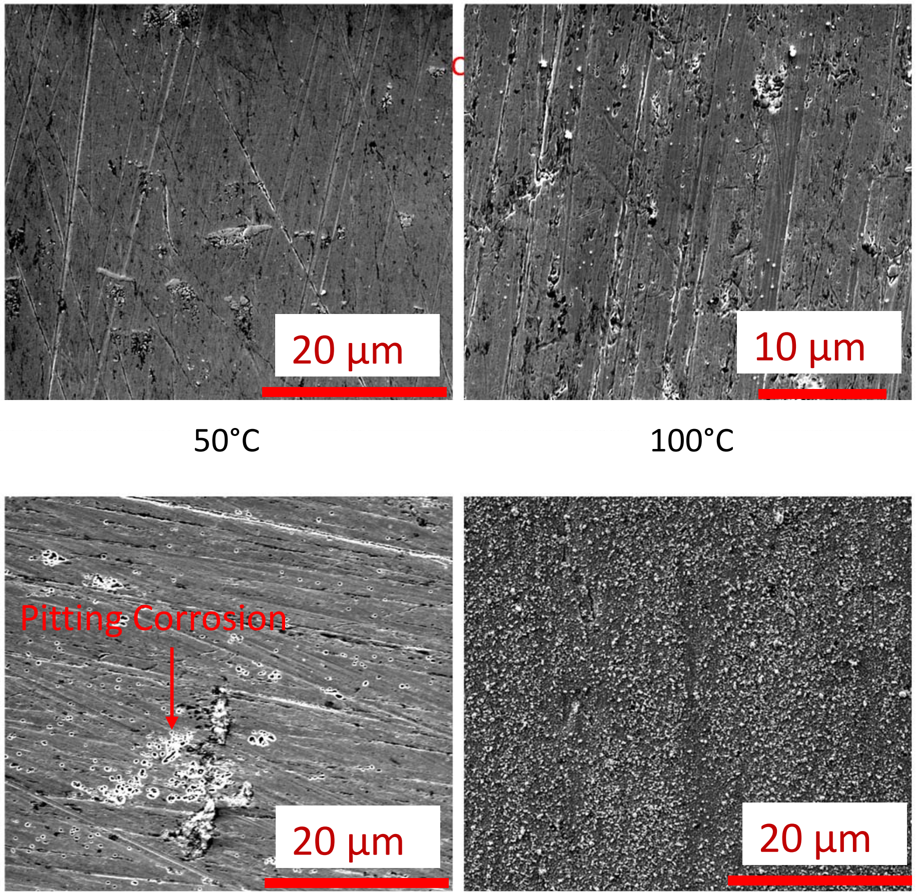

50°C

100°C

150°C

245°C

347H XPS Surface Depth Profile

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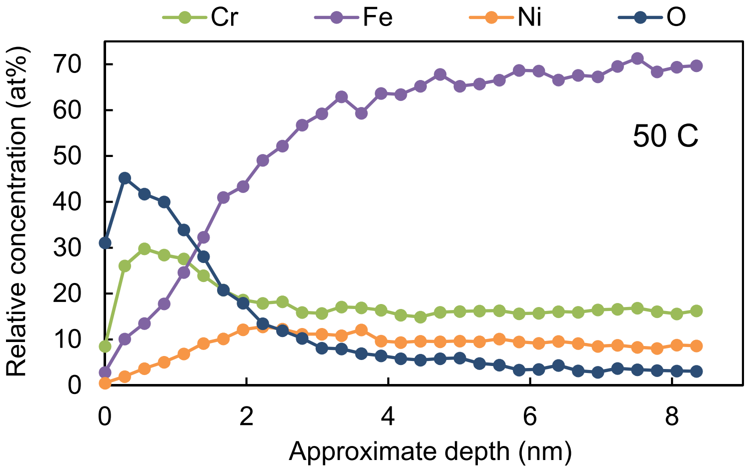

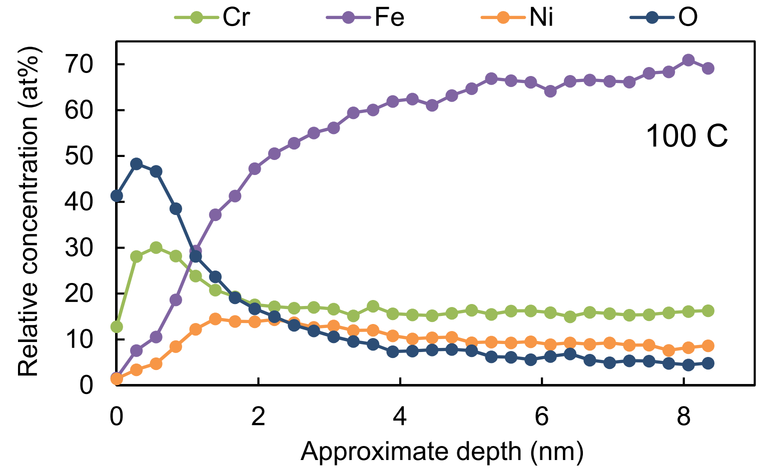

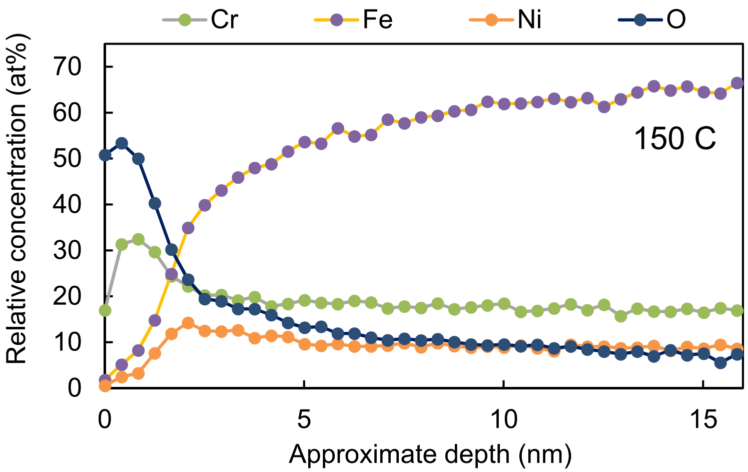

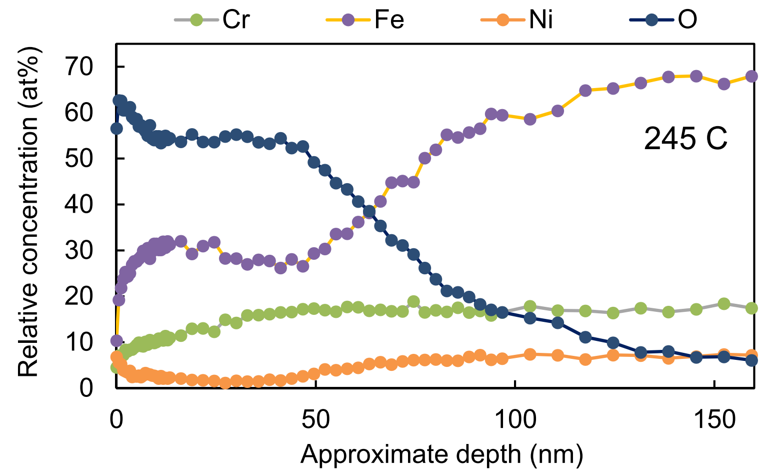

Weight Change Data

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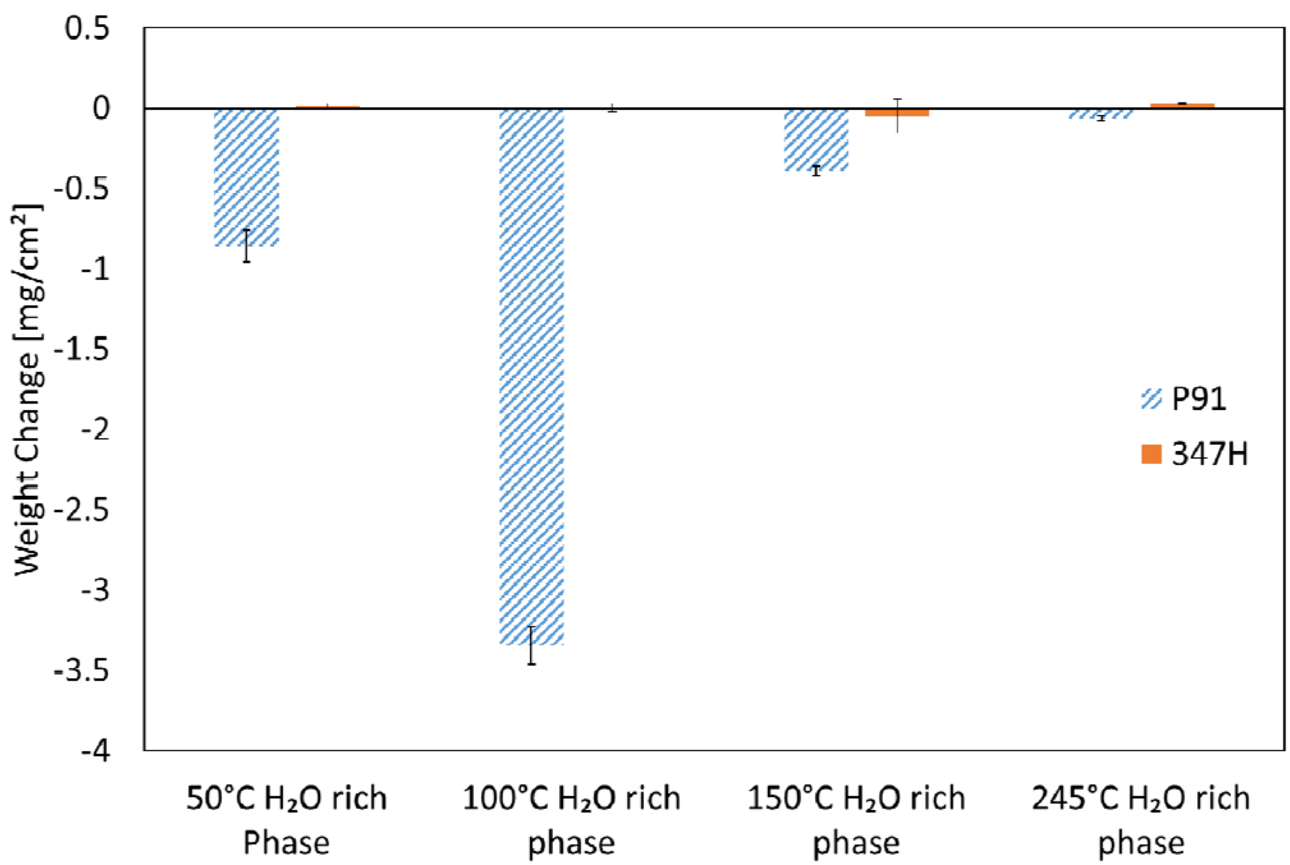

Conclusion

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- 347H is more corrosion resistance than P91 in direct-sCO_2 power cycle environment where H_2O condensation takes place
- Residual corrosion products on the P91 coupons were identified as Fe_2O_3 and Fe_3O_4, while 347H coupons showed minimal mass change and very thin passive layers.
- lower Cr steels such as Grade 91 may not be suitable for the low / intermediate temperature components in the direct sCO_2 power cycles.