Materials Evaluation and Corrosion Test Needs for a Direct-Fired sCO2 Oxy-Combustion Plant

Florent Bocher, Ph.D.
Tim Allison, Ph.D.
Southwest Research Institute

Bong Gun Shin
Hanwha Power Systems

SangMin Lee
Korea Electric Power Corporation

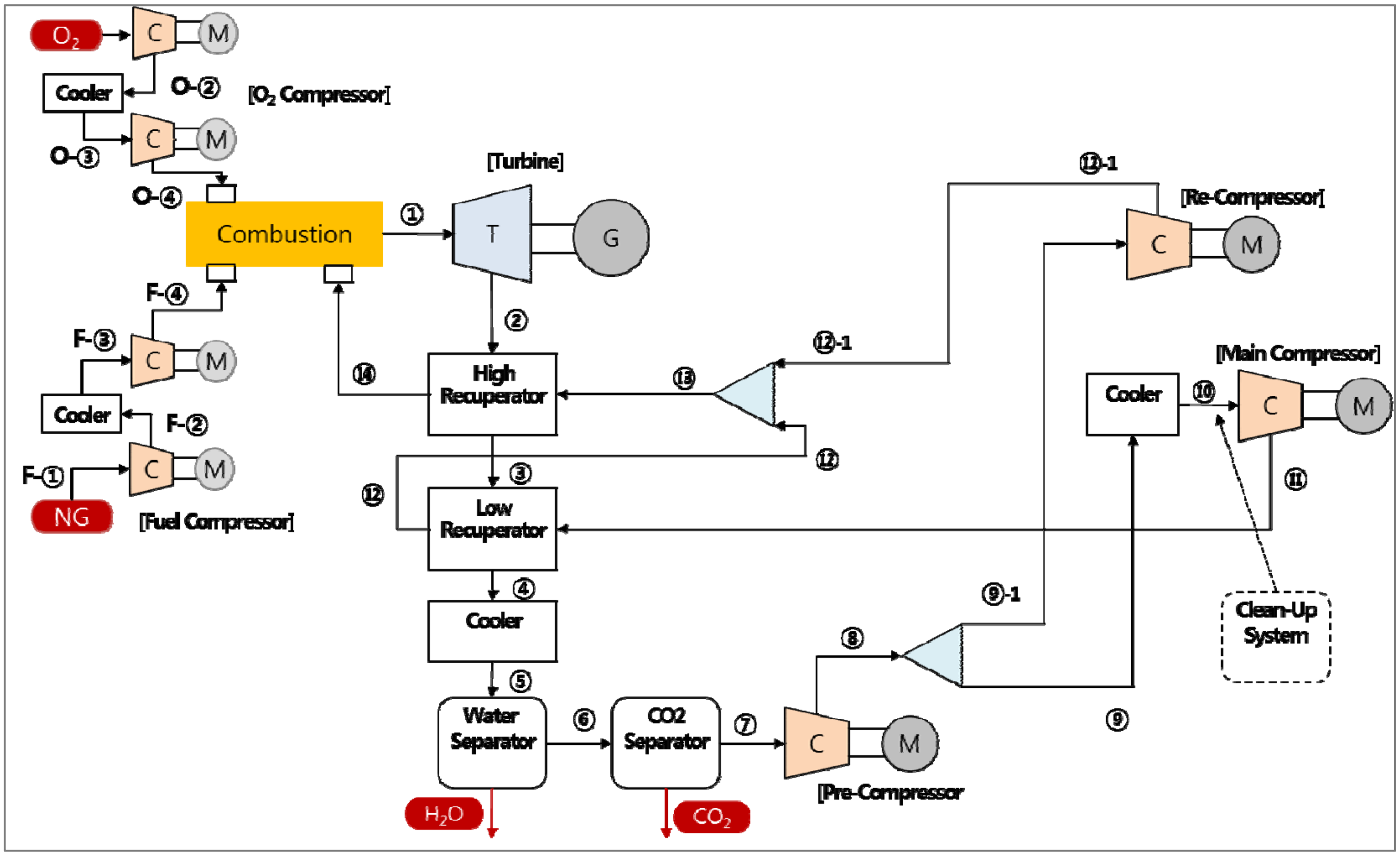
Presentation Overview

- Oxy-Combustion Application
- Overview of Materials
- Existing Test Data & Oxy-Combustion Variables of Interest
- Materials of Interest
  - 400 – 500 °C
  - 650 – 750 °C
- Future Test Needs and Recommendations

Oxy-Combustion Plant Application

- sCO2 oxy-combustion cycles have potential for
  - High thermal and plant efficiencies
  - Reduced CO2 emissions
- KEPCO Research Institute leading project to develop an oxy-combustion gas turbine power plant
  - Minimize development risk with maximum turbine inlet conditions of 750 °C and 300 bara.
  - Hanwha Power Systems (turbomachinery)
  - Southwest Research Institute (ox-combustor)
  - Other academic Institutions in Korea and U.S.

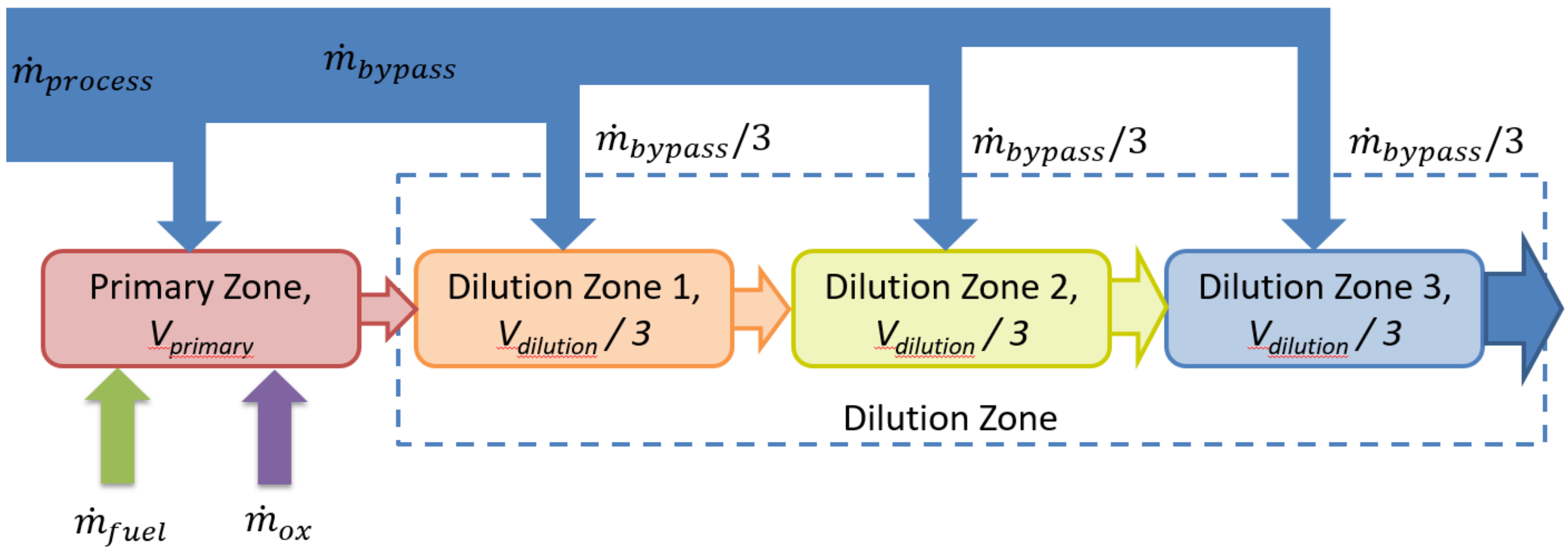
What's an Oxy-Combustion sCO_2 Cycle?



Closed Loop Composition is Affected by Air Separation, Combustion, and Cleanup

Oxy-Combustor Material Needs

- Combustor pressure vessel at process temperature
- Injector, liner cooled by process but at higher temperatures, lower stress
- Two temperature ranges identified :
  - 400 – 500 °C
  - 650 – 750 °C



Why Focus on Corrosion?

- The **majority of metal alloys** will corrode.
- Corrosion affects **every industry**: Infrastructure, Utilities, Transportation, Production & Manufacturing, Government
- Engineering design usually increase corrosion issues.
- Corrosion is **expensive**: estimated between B$575 (3.1% GDP) to T$1.1 (6% GDP).

Materials Deterioration in sCO_2

- **Corrosion:**
  - Reaction of metals with oxygen.
  - Oxygen comes from: $CO_2 = 0.5\ O_2 + CO$.
  - Growth of oxide film layer.

- **Carburization:**
  - Cr reacts with C ➔ chromium carbide.
  - Carbon penetrate through grain boundary.
  - Carburization leads to spalliation of oxide films.

Materials of Interest

- 5 families of materials:
  - **MFSS: martensitic** stainless steels (10%-30% Cr) and **ferritic** stainless steels (12%-17% Cr with 0.15 – 0.63% C)
  - **ASS: austenitic** stainless steels (16 to 30% chromium and 2 to 20% nickel).
  - **Al SS: alumina oxide** austenitic **stainless steels**.
  - **CrNi:** chromium **nickel** alloys.
  - **AlNi: alumina** oxide **nickel alloys**.

Experimental Methods Summary

Method	Measure	Pros	Cons
Weight measurement	Oxide film growth	• Easy • Cheap	• No carburization/corrosion product differentiation. • Spalliation and material loss affect measurement.
Micro hardness	Carburization	Easy	Coupled with SEM/EDS to confirm carburization
SEM/EDS	Oxide film morphology and composition		
Tensile test	mechanical properties	Environmental effect on mechanical properties	Only after exposure
GENERAL			**Lack of in-situ (HTHP problem)**

Effect of Temperature

Temperature ➚ = worsen corrosion, increase carburization

Temperature (°C) / Type of alloy	300	350	400	450	500	550	660	650	700	750	800	850	900
Martensitic & Ferritic	Green	Green	Green	Green	Red	Red	Red	Red	Red	Red	Red	Red	Red
Austenitic	Green	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red	Red	Red
Alumina SS	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green
Chromium Ni	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Red	Red	Red
Alumina Ni	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green

Based on combination of mass gain, oxide thickness, presence of crack, carburization, etc…:

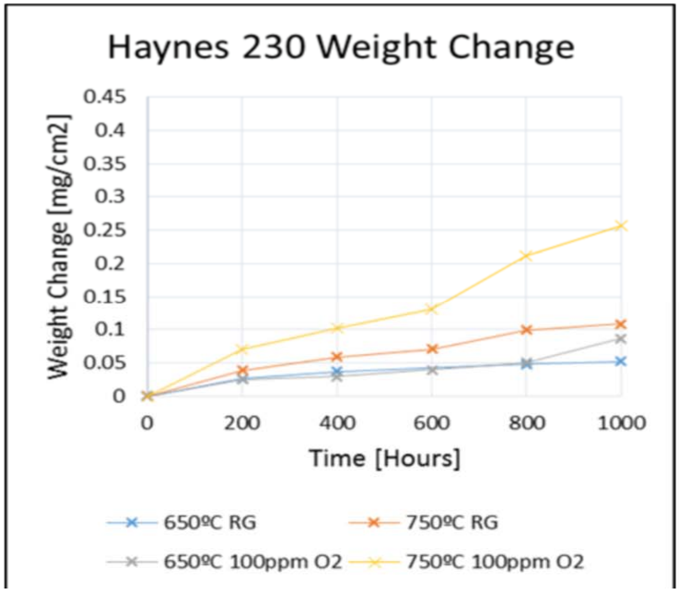
Green: acceptable

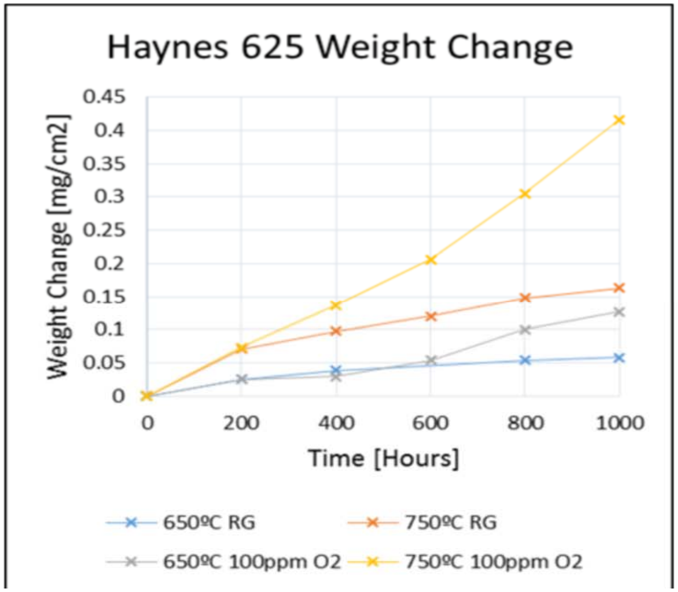
Red: avoid

Alumina alloys are not good at low temperature because the alumina oxide does not form fast enough.

Contamination of sCO_2 with O_2

- Contamination with O_2, water, and combination of both.
  - O_2: may be beneficial or detrimental.
  - Water: accelerates corrosion.
  - Combination: accelerates corrosion.

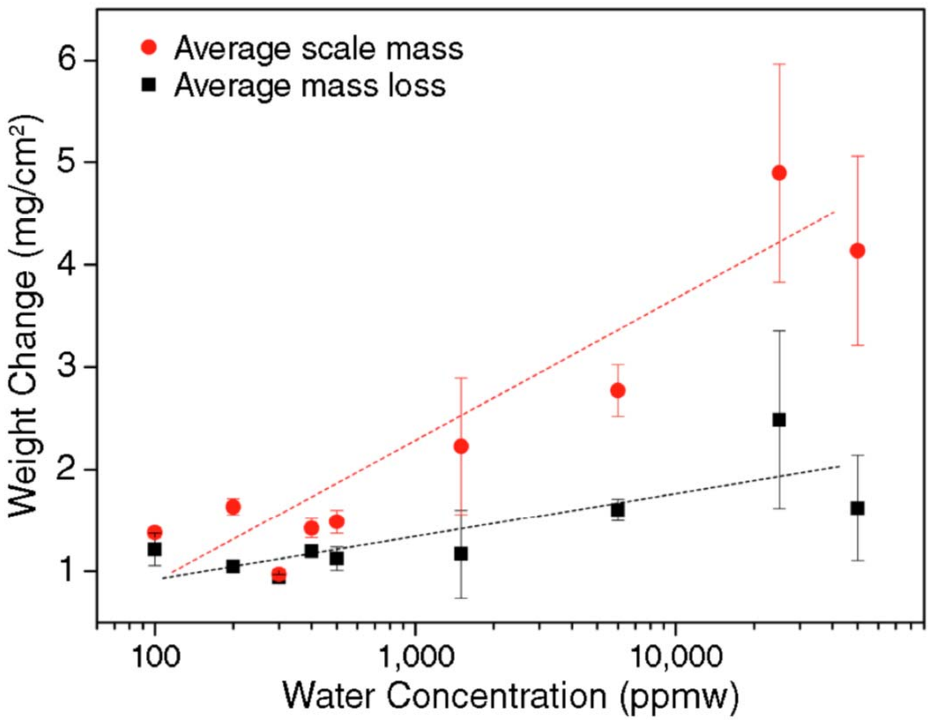




 Mahaffey, J., et al., 5th Symposium on sCO2 Power Cycles, , 2016, Paper #114.

Contamination of sCO_2 with H_2O

- Contamination with water accelerates corrosion.
- Impact of water on weight change in sCO_2 at 8 MPa, 40°C.



S. Sim, et al., Corrosion, 2, 2014

Coating

- Thermal barrier coating (TBC) for corrosion protection:
  - Diffusion bond coatings (Pt diffusion or simple or Pt-modified aluminide) with commercially vapor-deposited yttria-stabilized zirconia (YSZ) top coatings.
  - High velocity oxygen fuel (HVOF) sprayed MCrAlYHfSi bond coatings with air-plasma sprayed YSZ top coatings.
- Data only at higher temperature (1150°C): failure after 2260 1 hr cycles.
- CO_2 and/or air contamination reduces the time to failure.
- Intrinsic damages: oxide growth, internal stresses leading to cracking and failure.
- Extrinsic damages: erosion, local damages due to impact or particles melting, diffusing, and hardening the top coat leading to potential failure.

Chosen Materials – 400-500°C Combustor Inlet & Pressure Vessel

Trade Name	UNS	Standard Specification	Notes	Max Temperature Limit [°C] (BPV Code Section)	Allowable Stress at 500°C [MPa]
Gr91	K90901	ASTM A387 Grade 91 Class 2	Reference. Most commonly tested MFSS.	649 (VIII-2)	204
800H	N08800	ASTM B407		816 (VIII-2)	138
310	S31000	ASTM A965		816 (VIII-2)	116
347H/347HFG	S34709	ASTM A965		816 (VIII-2)	125

Alternative Materials – 400-500°C Combustor Inlet & Pressure Vessel

Trade Name	UNS	Standard Specification	Max Temperature Limit [°C] (BPV Code Section)	Allowable Stress at 500°C [MPa]
625	N06625	ASTM B443	593 (I) or 649 (VIII-1)	192
HK40	J94204	ASTM A351	-	-
HK50	J94224	ASTM A297	-	-
310HCbN/HR3C	S31042	ASTM A959	732 (I)	117-158
NF709	S31025	ASTM A213	-	-
HR120	N08120	ASTM B515	899 (VIII-1)	113-153

Chosen Materials – 650-750°C Combustor Exit & Liner

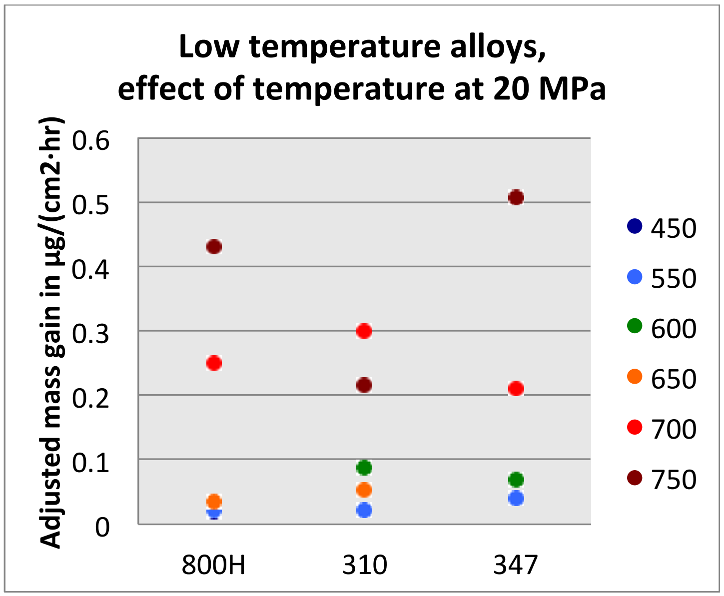
Trade Name	UNS	Standard Specs	Max Temperature Limit [°C] (BPV Code Section)	Allowable Stress at 500°C [MPa]	Yield Strength at 750-760°C [MPa]	Creep Rupture Strength at 750°C [MPa] (hr)
740H	N07740	ASTM B983	800 (I)	84.1	596	200 (10k)
282	N07208	ASTM B637-12	800 (est.)	105 (est.)	612	186 (10k)
230	N06230	ASTM B572-06	982 (VIII-1)	50.8	323	91-98 (10k)

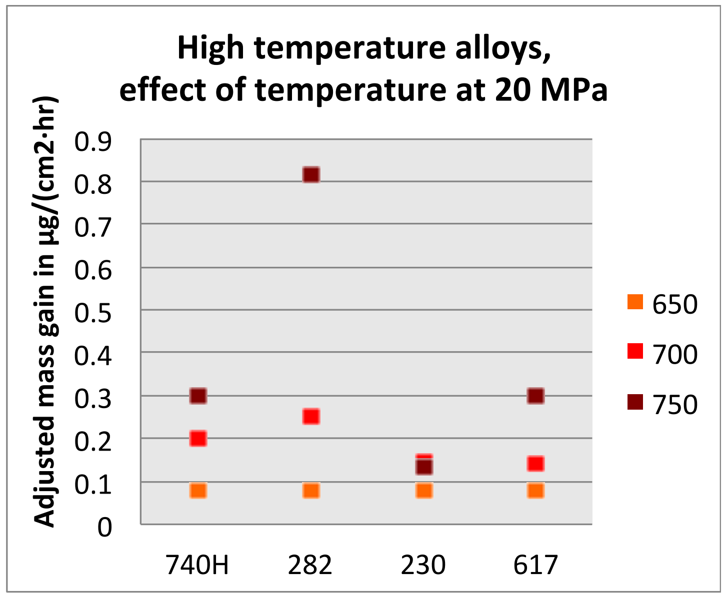
Alternative Materials – 650-750°C Combustor Exit & Liner

Trade Name	UNS	Standard Specs	Max Temperature Limit [°C] (BPV Code Section)	Allowable Stress at 500°C [MPa]	Yield Strength at 750-760°C [MPa]	Creep Rupture Strength at 750°C [MPa] (hr)
Waspaloy	N07001	ASTM B637	-	-	706	290 (1k)
Udimet 720	N07720	n/a	-	-	770	480 (1k)
Rene 41	N07041	SAE AS7469B	-	-	938	276 (1k)
617	N06617	ASTM B167	982 (VIII-1)	50.4	872	140 (1k)
MA 754	N07754	n/a	-	-	275	-
Hastelloy X	N06002	ASTM B572-06	482 (VIII-2)	-	218	107 (1k)

Proposed Materials: Existing Data in sCO_2, constant pressure.

- Data adjust to mass gain in µg/(cm^2·hr) because not all tests are the same duration.
- Increase in mass gain with increase in temperature at 20 MPa.





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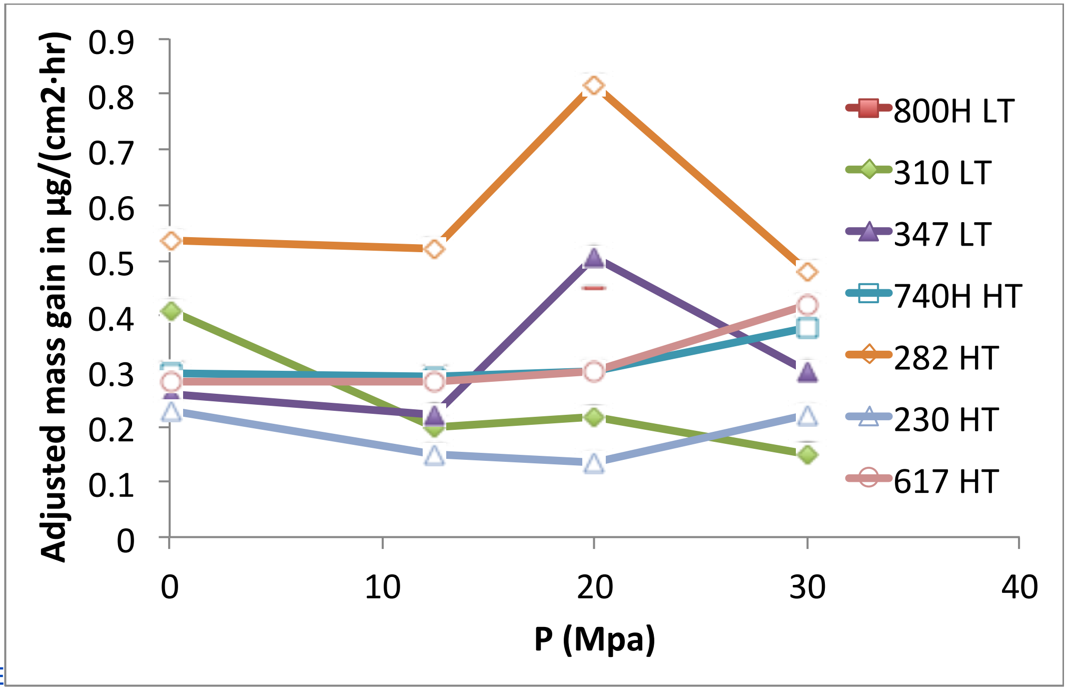
Pint, B.A., Keiser, J.R., JOM, 11, 2015

Pint, B.A., et al., NACE Paper C2016-7747

Pint, B.A., et al. 5th Symposium on sCO2 Power Cycles, , 2016, Paper #56.

Proposed Materials: Existing Data in sCO_2, constant temperature.

- No visible trend of mass gain with increase in pressure at 750C.
- High temperature materials had lower mass gain than low temperature materials.



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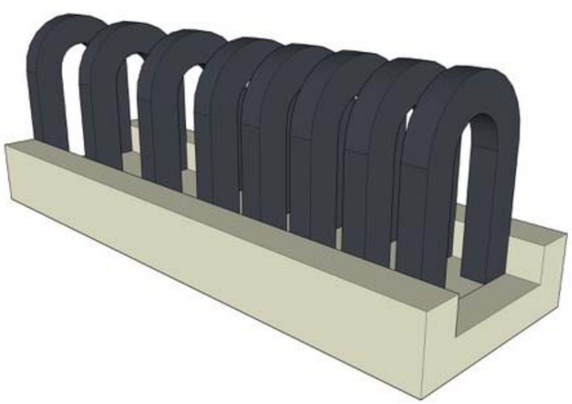
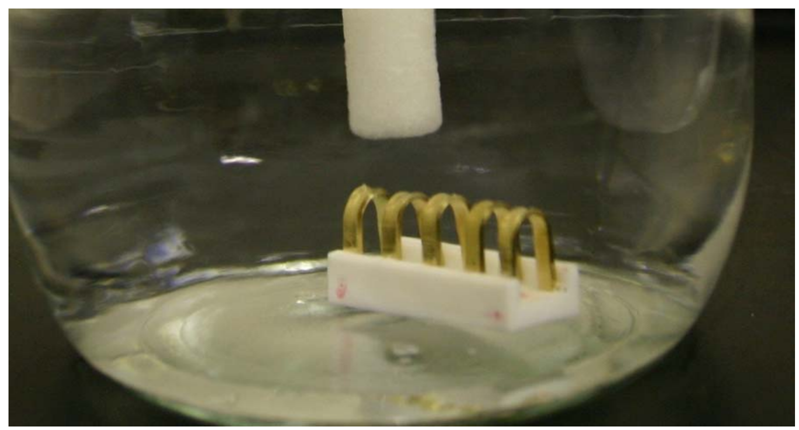
Test Plan – Variables of Interest

- Temperature: low (combustor inlet) and high (high temperature)
- Pressure: high pressure based on design
- Contamination (O_2, H_2O): CO_2, H_2O, and O_2 mixture matching predicted composition at combustor inlet (low temperature) and exit (high temperature).
- Welding: potential negative impact on the corrosion behavior of chromium-containing alloys

Test Plan – Variables of Interest

- Stress corrosion cracking: corrosion combined with stress can lead to early mechanical failure.
- Galvanic corrosion: corrosion may worsen when dissimilar materials are in contact.
- Coating: testing bare and coating materials vapor deposited YSZ, and air-plasma sprayed YSZ.





Test Plan

- The recommended tests in $O_2/H_2O/CO_2$ are:
  - **H**igh **T**emp Weight Gain with Tensile Test
  - **H**igh **T**emp C-Ring/U bend
  - **L**ow **T**emp Weight Gain with Tensile Test
  - **H**igh **T**emp Welding
  - **L**ow **T**emp C-Ring/U bend
  - Micro hardness
- Statistic: 5 specimens for each test.
- Combine all low temperature and all high temperature.