SunShot U.S. Department of Energy

CSP Program Summit 2016

Lifetime Model Development for Supercritical CO_2 CSP Systems

Bruce Pint, Group Leader, Corrosion Science
Oak Ridge National Laboratory

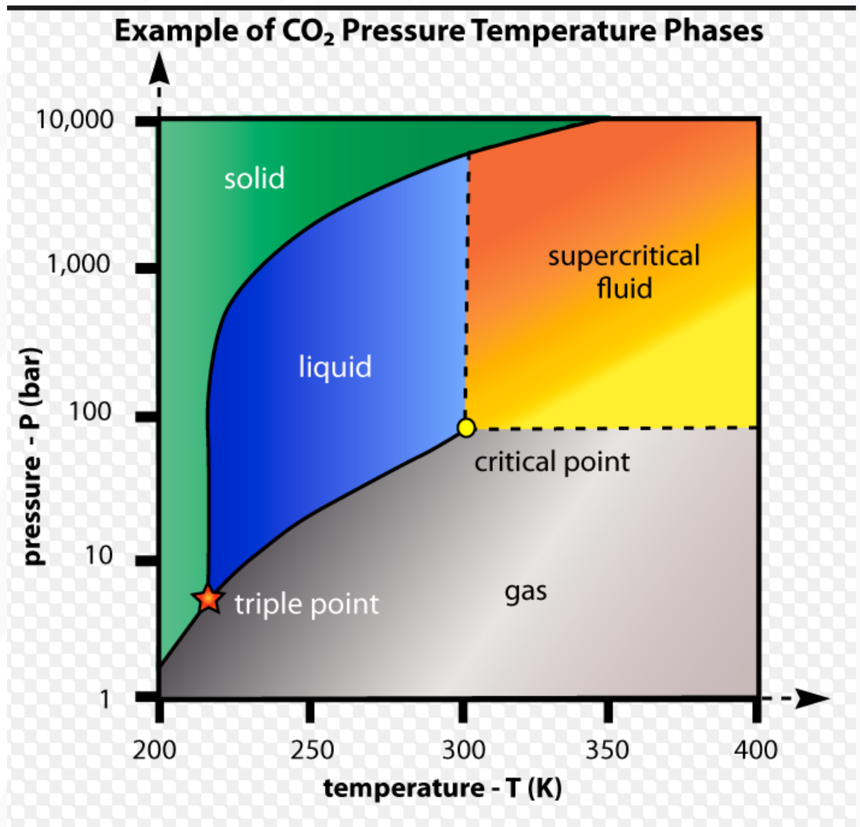
energy.gov/sunshot

Acknowledgments

- J. Keiser, R. Brese – ORNL collaborators
- J. Nash, J. Farias – Brayton Energy
- M. Howell, G. Garner, M. Stephens – CO_2 experiments
- T. Lowe, T. Jordan – characterization
- Alloy coupons
  - Haynes International
  - Special Metals
  - Sandvik
- Research sponsored by: U. S. Department of Energy, Office

Why use supercritical CO_2?

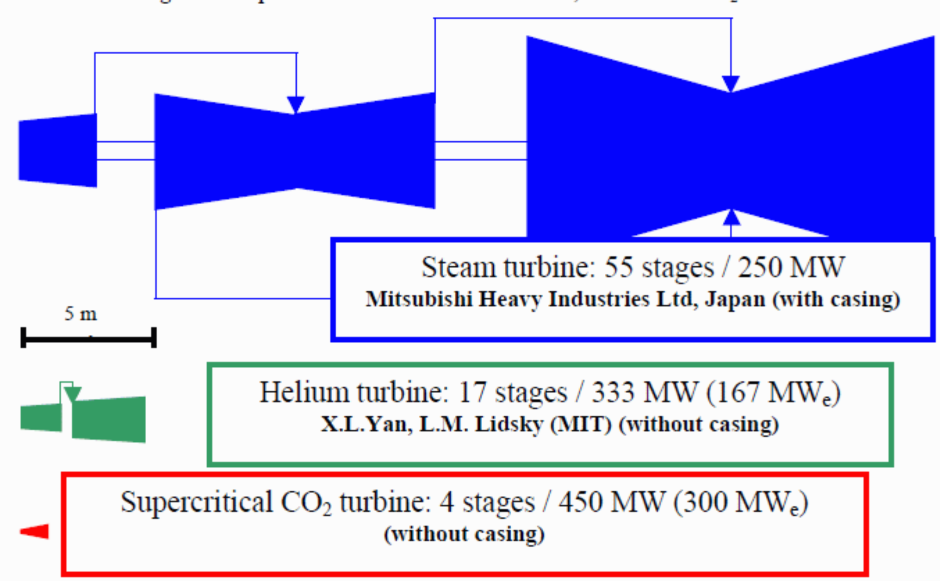
- Potential advantages:
  - no phase changes
  - high efficiency
  - more compact turbine
  - short heat up
  - less complex
  - lower cost (?)



Why use supercritical CO_2?

- Potential advantages:
  - no phase changes
  - high efficiency
  - <u>more compact turbine</u>
  - <u>short heat up</u>
  - less complex
  - lower cost (?)
- CSP-relevant
  - Turbine location
  - Deployment (load following)

Fig. 51 Comparison of turbine sizes for steam, helium and CO_2



Source: MIT report, 2004

Focus is on temperatures >720°C

High efficiency (Feher, 1968)

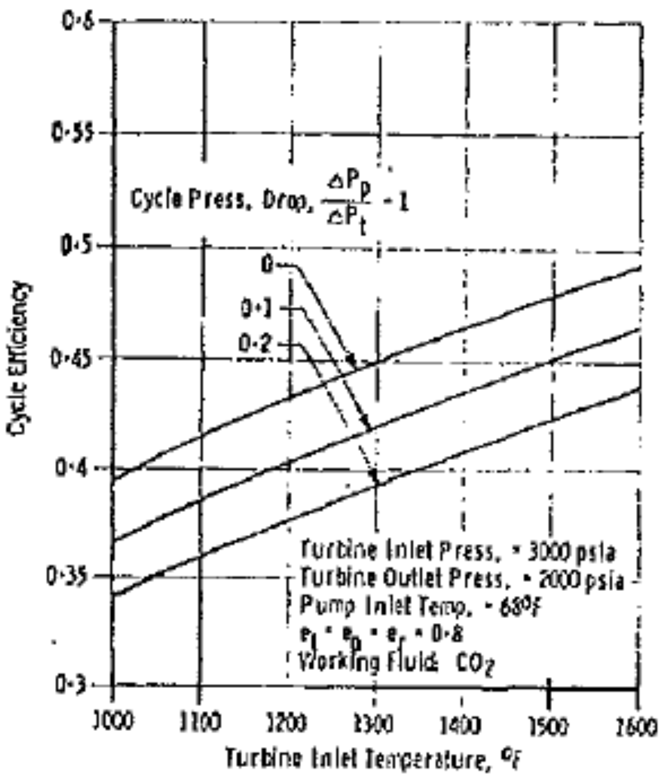
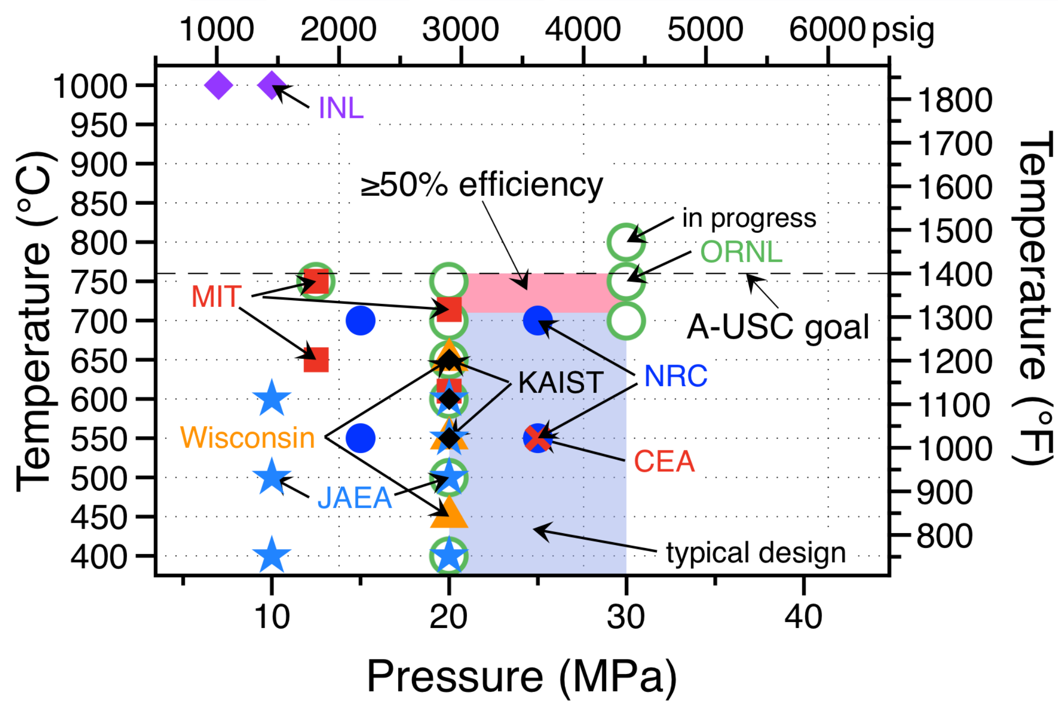


Fig. 12. Cycle efficiency vs. turbine inlet temperature.

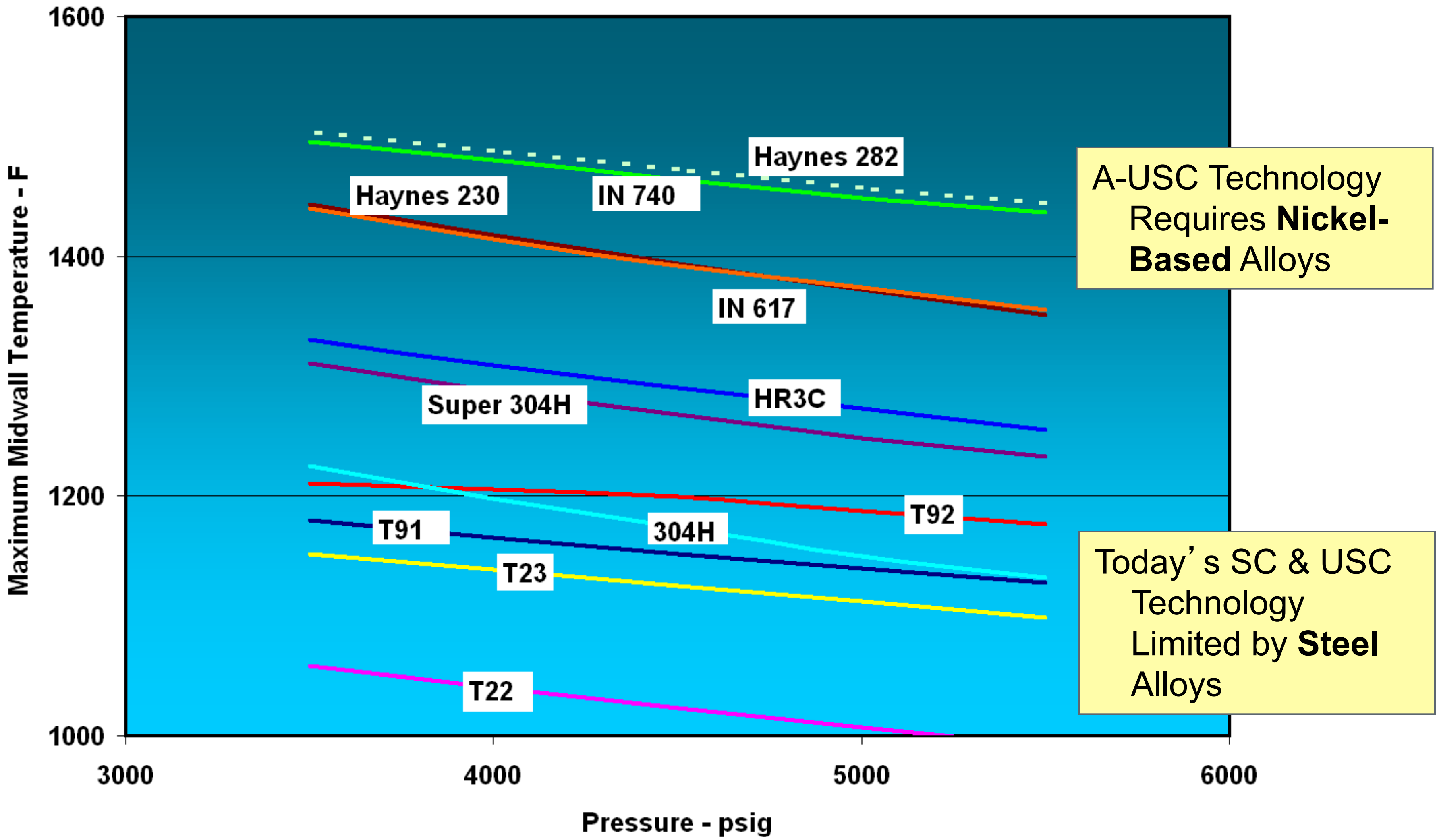


BUT, limited sCO_2 data there

ALSO, limited materials available

sCO_2 benefits from materials work of A-USC (Steam)

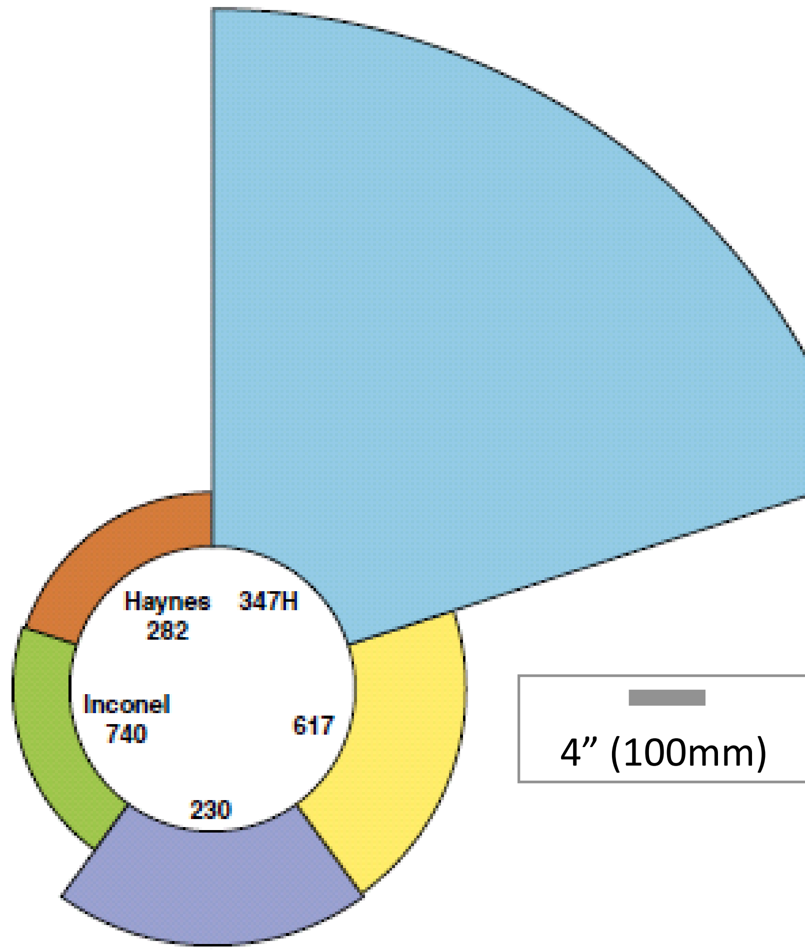
DOE A-USC (Advanced Ultra-Supercritical) Steam Boiler and Turbine Consortiums



Courtesy EPRI

Precipitation strengthened Ni-base alloys have a clear advantage for >700°C applications

- Significantly stronger than conventional Ni-base alloys such as 617 or 230
- 740H ASME Boiler & Pressure Vessel Code Qualified in 2012



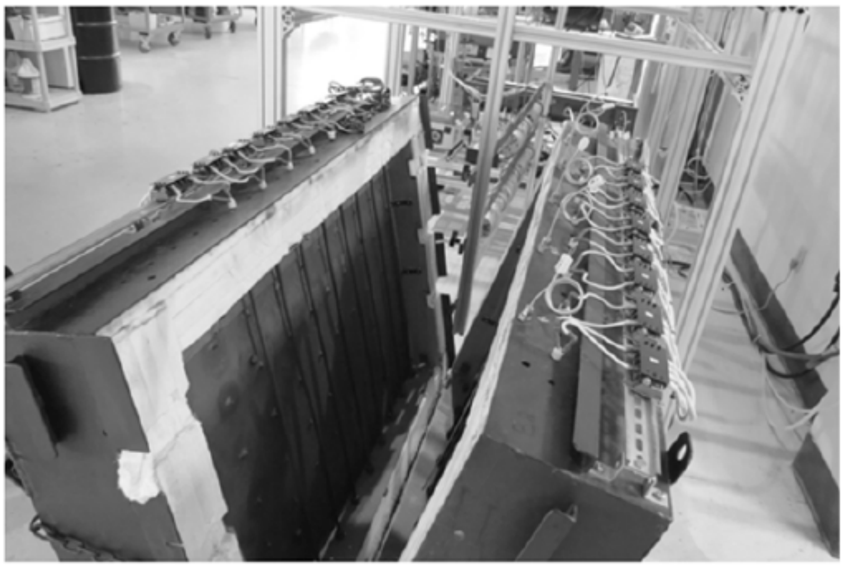
1350°F/1400°F (732°C/760°C)
5000psi (34.5MPa), 9.8” (248mm) I.D.

Project goal is to develop a sCO_2 lifetime model

- Performance metrics developed for 700°-800°C
  - mass gain rate k_p in 1 and 300 bar $CO_2 \leq 5 \times 10^{-13}$ g^2/cm^4s
  - internal oxidation rate k_c in 1 bar $CO_2 \leq 10^{-4}$ cm^2/s
  - relative creep rupture life in CO_2 vs. (argon)
  - Thermodynamics: carbon activity < 1 at all relevant conditions
- Year 1 focus on 1000h exposures
  - 10-h cycles in 1 bar CO_2 at 700°-800°C
    - 2nd set of specimens continuing to 4,000h (400 cycles)
  - 500-h cycles in 300 bar CO_2
- Creep rupture testing of tubes pressurized with sCO_2 or argon
- Several innovative features
  - First laboratory evaluations at relevant: T, P, duty cycle
  - Evaluating creep debit in sCO_2 environment
  - Partnering with 3 leading alloy manufacturers and educating the CSP industry on materials choices for ≥720°C sCO_2

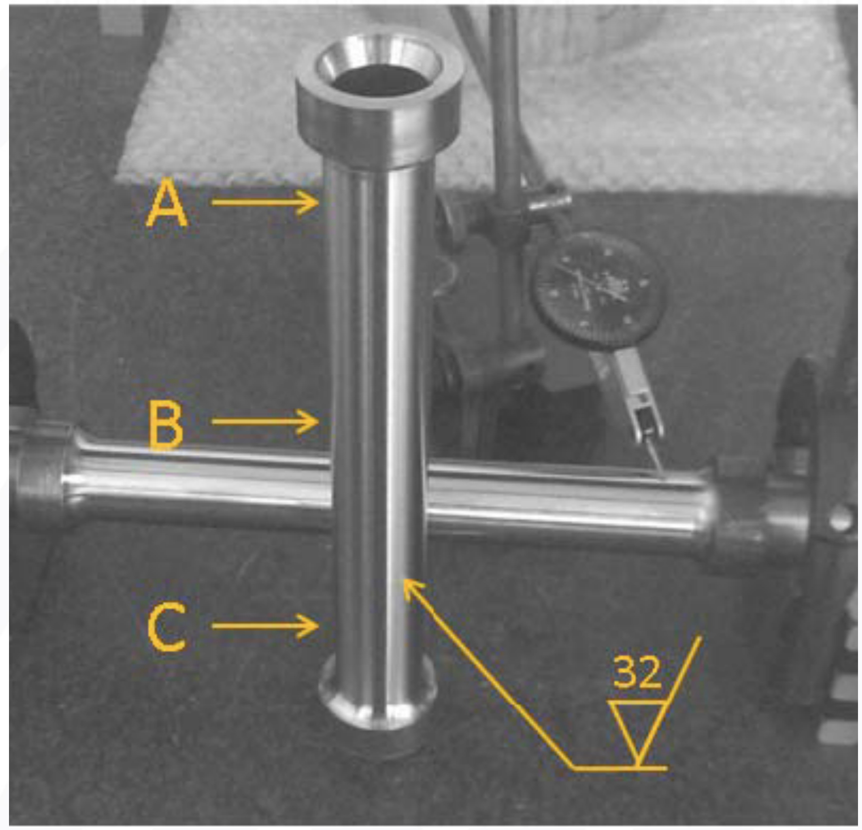
Creep testing getting underway at Brayton Energy, LLC

Creep furnace:
Parallel testing: in sCO_2
and argon



Brayton Energy LLC

740H creep specimens



Experimental facilities available at ORNL

Automated cyclic rigs: 1bar CO_2

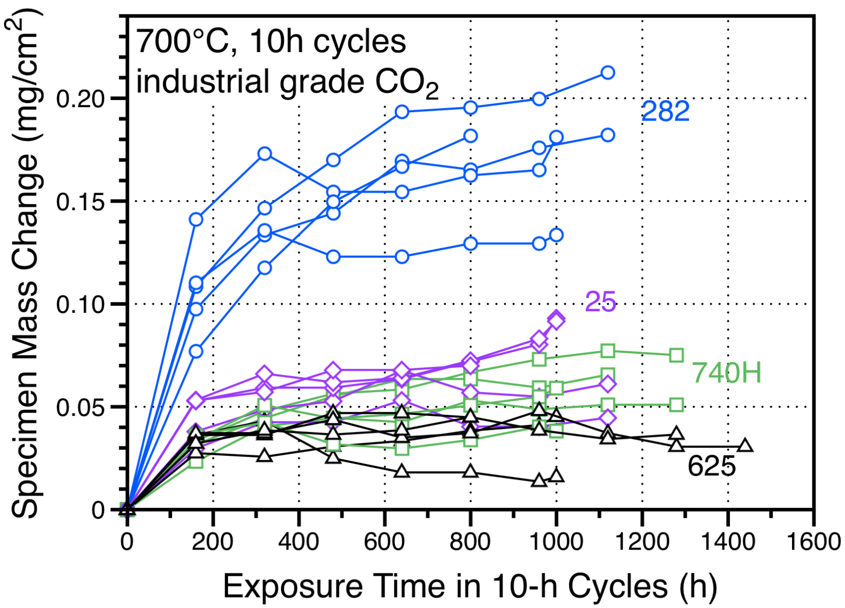
Autoclaves for 300bar sCO_2

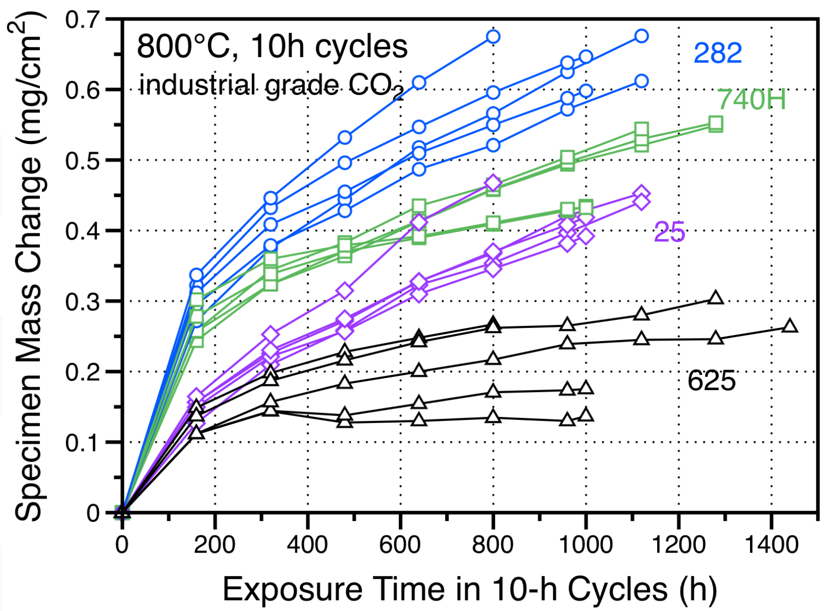
Four alloys were selected for this study

Alloy	Fe	Ni	Cr	Al	Other
Sanicro 25 (Sandvik)	42.6	25.4	22.3	0.03	3.5W, 3.0Cu, 1.5Co, 0.5Nb, 0.5Mn, 0.2Mo,0.2Si,0.2N
Haynes 282 (Haynes International)	0.2	57.1	19.6	1.6	10.6Co, 8.6Mo, 0.04Si, 2.2Ti, 0.02Mn
Inconel 740H (Special Metals)	0.1	49.7	24.5	1.4	20.6Co,1.5Nb, 1.4Ti, 0.3Mo,0.3Mn,0.2Si
625 (industry selection)	4.0	61.0	21.7	0.12	8.8Mo, 3.5Nb,0.2Ti,0.2Si,0.2Mn,0.1Co, 0.09Cu,0.06W

Composition analyzed by ICP-OES and combustion analyses by Dirats Labs.

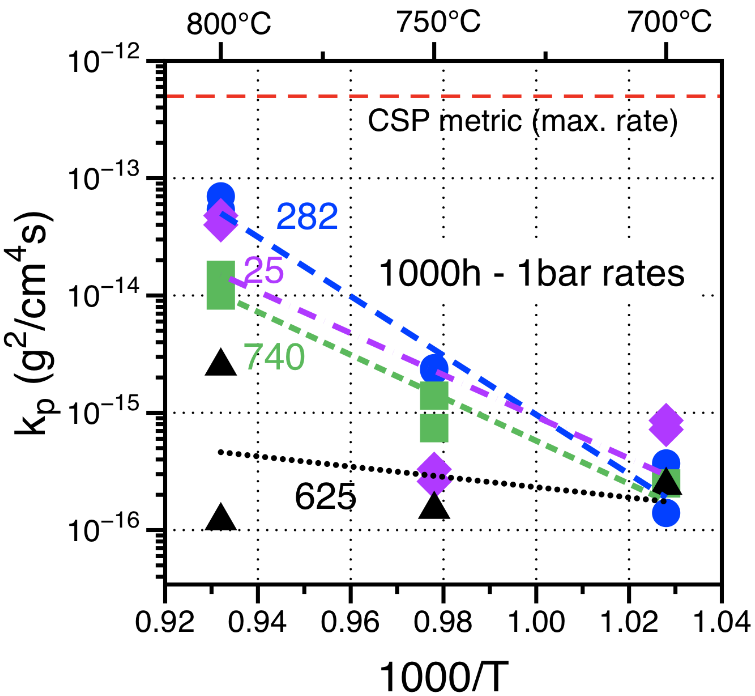
Cumulative: 50,000h completed in 10-h cycles

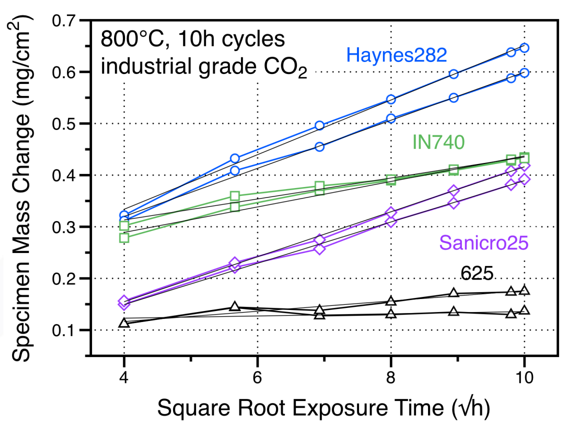




700°C: somewhat erratic behavior observed with low mass gains
800°C: more uniform behavior, still some scatter
282: higher mass gain associated with internal oxidation of Al+Ti
1st set: stopped at 1000h at 700°, 750° and 800°C
2nd set: proceeding to 4000h at 700° and 800°C

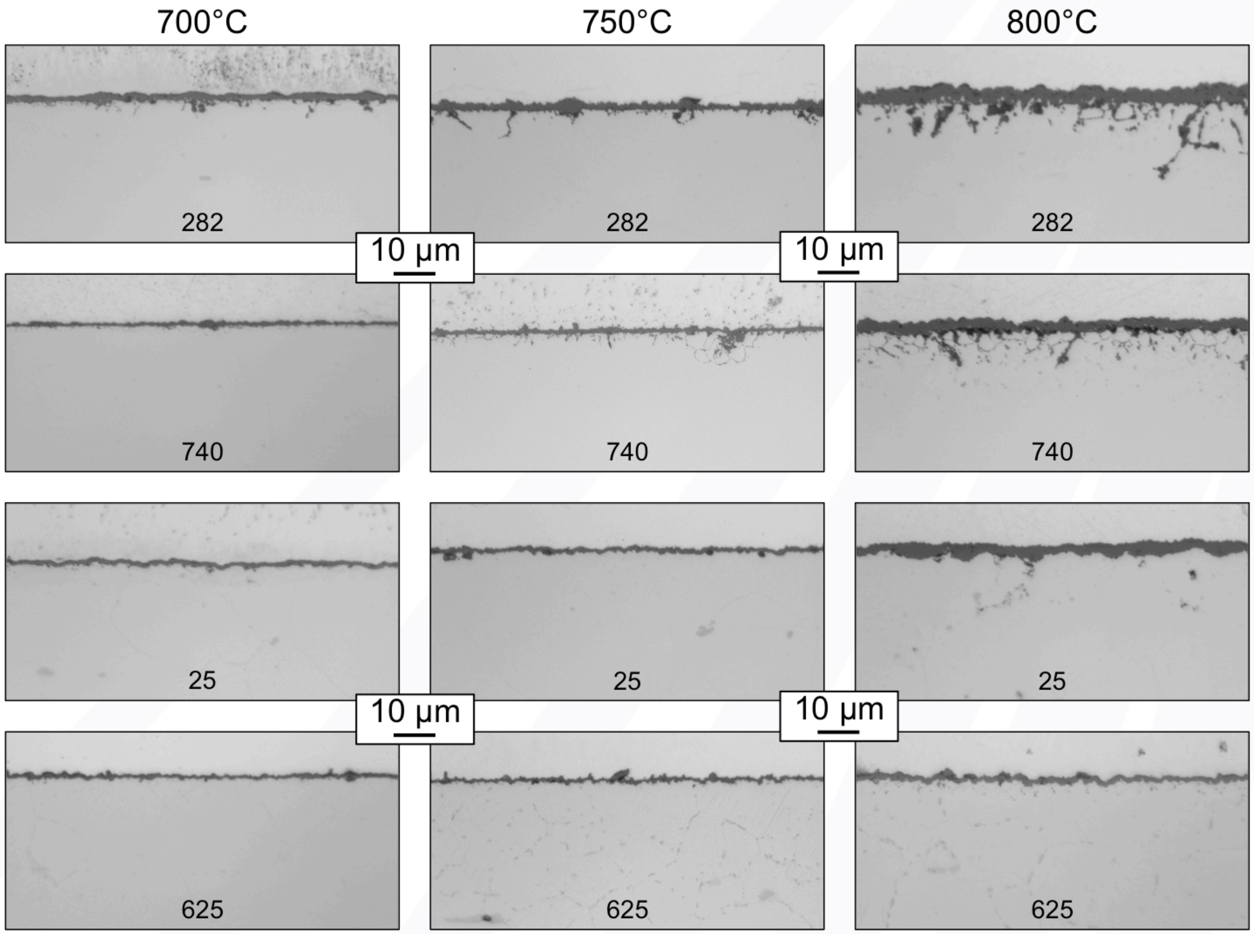
Measured rate constants below project metric



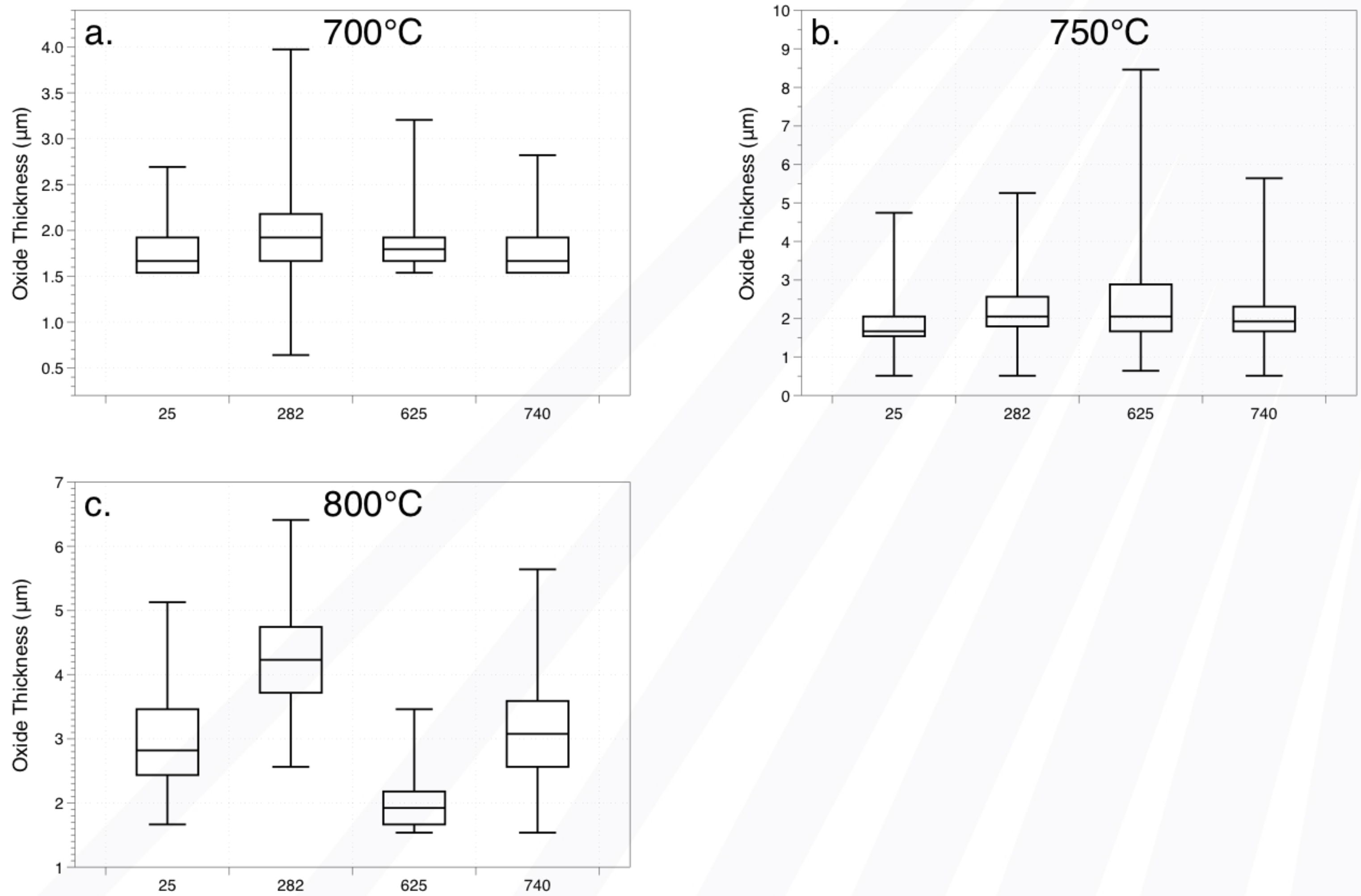


- Calculate rate constant k_p g^2/cm^4s from MG vs. √t
  - 1000h data sets
- All alloys below goal of 5×10^{-13} g^2/cm^4s
  - <100µm oxide in 100,000h

Metallography completed of 1000h specimens



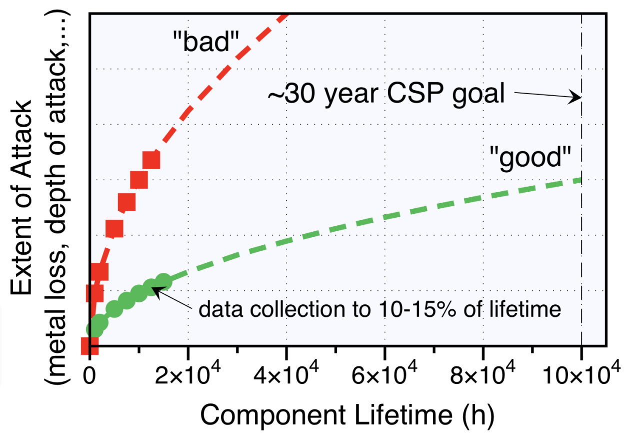
Oxide thickness from 10-h 1 bar tests will be compared to measurements from 300 bar experiments after 1000h



Summary

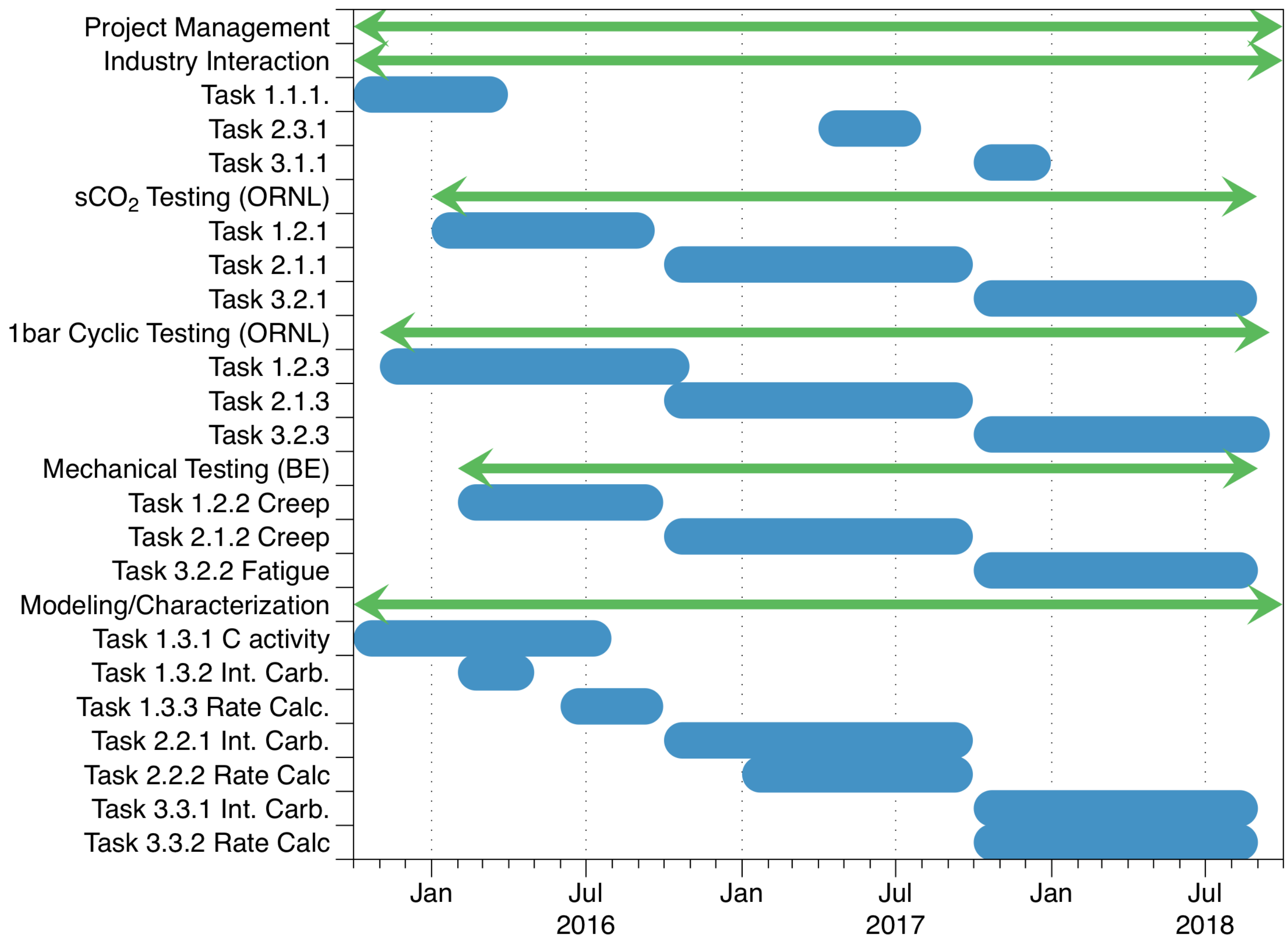
- New project started to develop a lifetime model for CSP sCO_2 applications
  - 100,000h (30 year) lifetime desired
  - Year 1 of 3 year effort
  - Data sets: mass change, reaction product depth
- Exposures in progress
  - 2nd set of 10-h cycles in progress to 4000h
  - 1st 300 bar 500-h cycle completed at 750°C
  - Creep rupture testing of 740H to begin this month
- Characterization will focus on 1000h exposures
  - 10-h cycles in 1bar vs. 500-h cycles in 300bar sCO_2

Backup slides

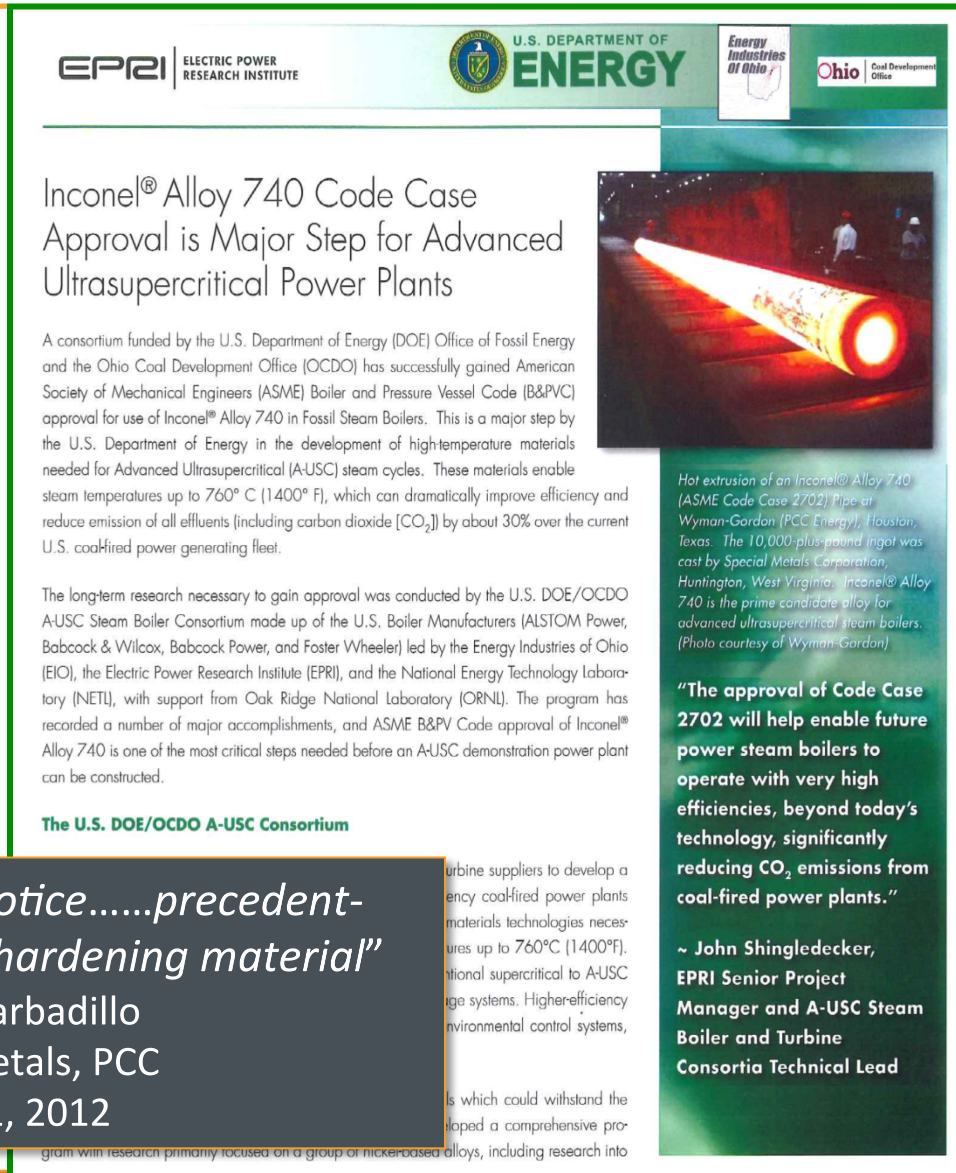


Testing proceeds for 3 years

- Project timeline:



Successful ASME Code Case for Inconel 740



EPRI | ELECTRIC POWER RESEARCH INSTITUTE
U.S. DEPARTMENT OF ENERGY
Energy Industries Of Ohio
Ohio | Coal Development Office

Inconel® Alloy 740 Code Case Approval is Major Step for Advanced Ultrasupercritical Power Plants

A consortium funded by the U.S. Department of Energy (DOE) Office of Fossil Energy and the Ohio Coal Development Office (OCDO) has successfully gained American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (B&PVC) approval for use of Inconel® Alloy 740 in Fossil Steam Boilers. This is a major step by the U.S. Department of Energy in the development of high-temperature materials needed for Advanced Ultrasupercritical (A-USC) steam cycles. These materials enable steam temperatures up to 760° C (1400° F), which can dramatically improve efficiency and reduce emission of all effluents (including carbon dioxide [CO_2]) by about 30% over the current U.S. coal-fired power generating fleet.

The long-term research necessary to gain approval was conducted by the U.S. DOE/OCDO A-USC Steam Boiler Consortium made up of the U.S. Boiler Manufacturers (ALSTOM Power, Babcock & Wilcox, Babcock Power, and Foster Wheeler) led by the Energy Industries of Ohio (EIO), the Electric Power Research Institute (EPRI), and the National Energy Technology Laboratory (NETL), with support from Oak Ridge National Laboratory (ORNL). The program has recorded a number of major accomplishments, and ASME B&PV Code approval of Inconel® Alloy 740 is one of the most critical steps needed before an A-USC demonstration power plant can be constructed.

The U.S. DOE/OCDO A-USC Consortium

...urbine suppliers to develop a ...ency coal-fired power plants ...materials technologies neces... ...ures up to 760°C (1400°F). ...tional supercritical to A-USC ...ge systems. Higher-efficiency ...nvironmental control systems,

...s which could withstand the ...loped a comprehensive pro... gram with research primarily focused on a group of nickel-based alloys, including research into

Hot extrusion of an Inconel® Alloy 740 (ASME Code Case 2702) Pipe at Wyman-Gordon (PCC Energy), Houston, Texas. The 10,000-plus-pound ingot was cast by Special Metals Corporation, Huntington, West Virginia. Inconel® Alloy 740 is the prime candidate alloy for advanced ultrasupercritical steam boilers. (Photo courtesy of Wyman-Gordon)

"The approval of Code Case 2702 will help enable future power steam boilers to operate with very high efficiencies, beyond today's technology, significantly reducing CO_2 emissions from coal-fired power plants."

~ John Shingledecker, EPRI Senior Project Manager and A-USC Steam Boiler and Turbine Consortia Technical Lead

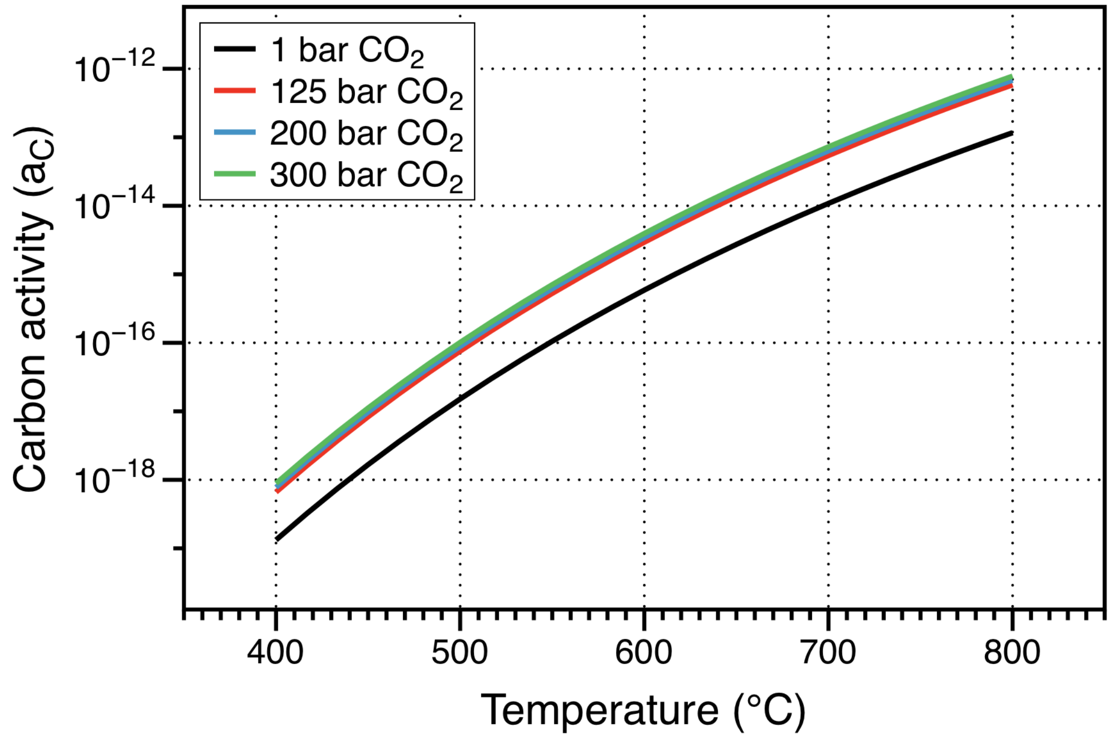
"World has taken notice......precedent-setting case for age-hardening material"

Jack deBarbadillo

Special Metals, PCC

April 11, 2012

Thermodynamics being evaluated



- Very low carbon activity (a_c) in the gas
- Next step is to calculate a_c at the Cr/Cr_2O_3 interface

Industry survey used to select 4th alloy: 625

Alloy	OEM-1	OEM-2	OEM-3	OEM-4	OEM-5	HX-1	HX-2	HX-3	HX-4	Total
625	0.5	3	3		2			1	2	11.5
617	0.5			3	3			3	1	10.5
230	0.5	2	1	1		3				7.5
120			2			1			3	6
718	3			2						5
310				0.5			1	2		3.5
800H							3			3
Other	105	224			347	X	PE16			

✓ Based of feedback, alloy 625 was selected as the 4th alloy