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Development of Advanced Materials for Advanced Ultrasupercritical (A-USC) Boiler Systems

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2014 NETL Crosscutting Research Review Meeting
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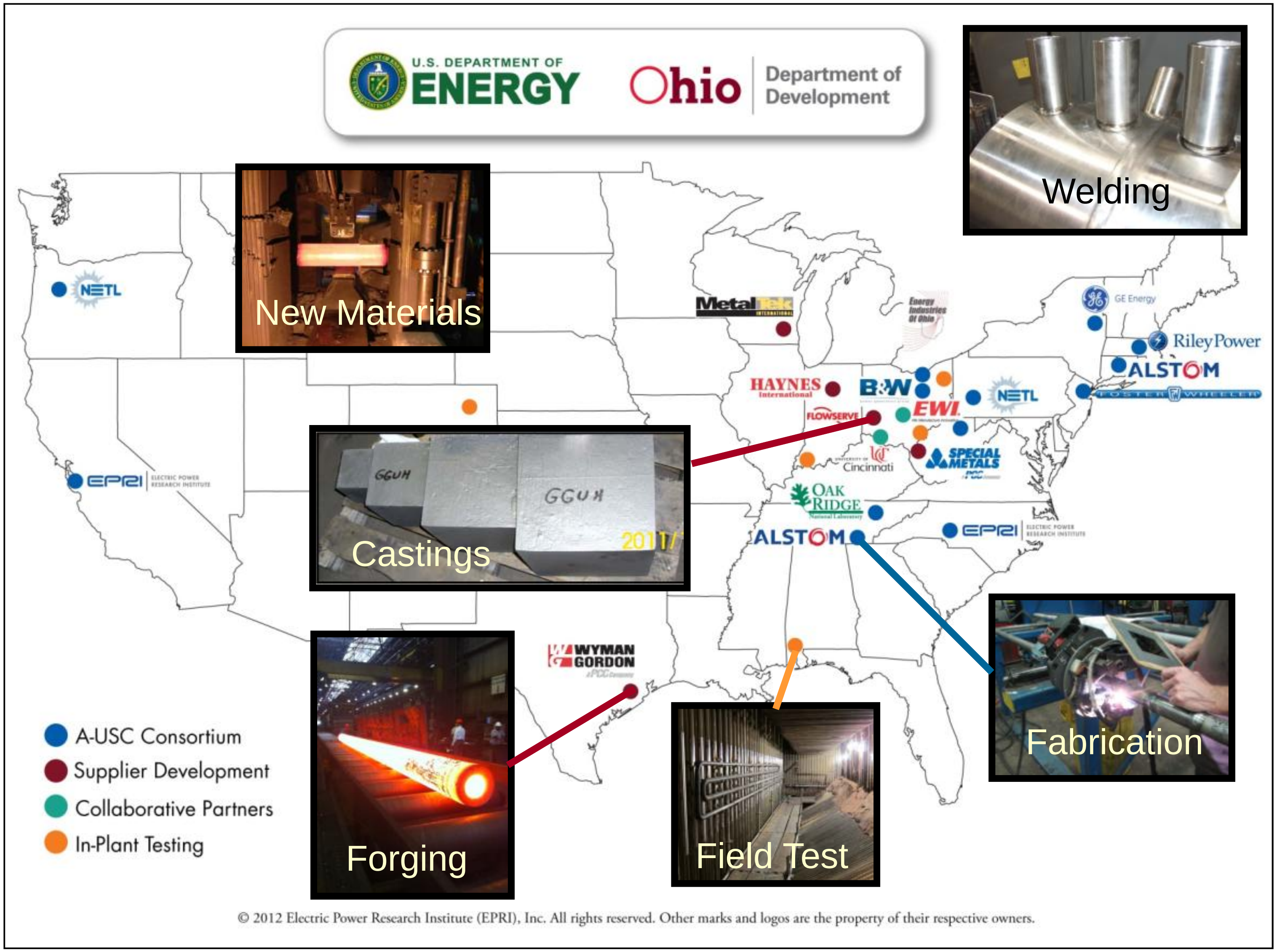
Acknowledgements: U.S. Department of Energy (US DOE) / Ohio Coal Development Office (OCDO) A-USC Steam Boiler and Turbine Consortia

Federal – State – National Laboratory

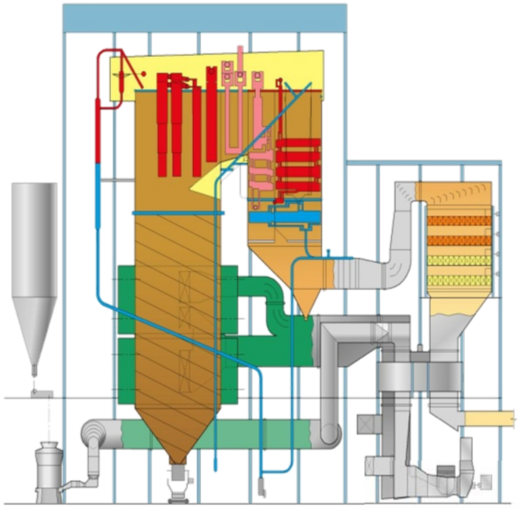
Non Profit – For Profit

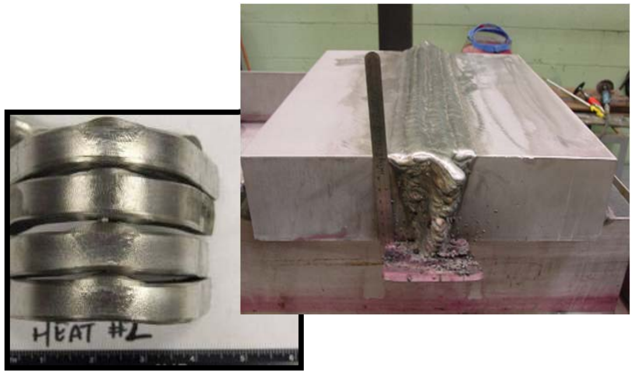
Cost Sharing Consortium



Accomplishments
A-USC Fact Book - EPRI 1022770
(download free at: www.epri.com)

General design studies show favorable economics





Welding Technology Developments

Fabrication Processes

Steam-Side Oxidation

Fireside Corrosion (High-Sulfur Coal & In-Plant Testing)

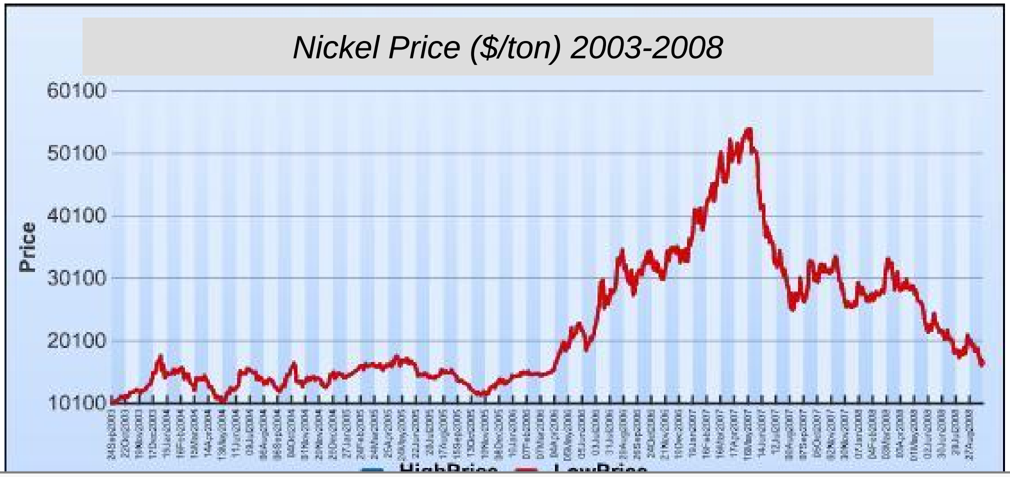
Turbine Component Scale-up

Outline

- A-USC Steam Turbine (PreviousTalk)
  - General motivation for A-USC
  - Results from Phase I study
  - Current project approach and results (Phase II)
  - Next Steps
- A-USC Boiler (ThisTalk)
  - Project Approach
  - Successes and Recent Activities
  - A-USC Economics and Future Applications

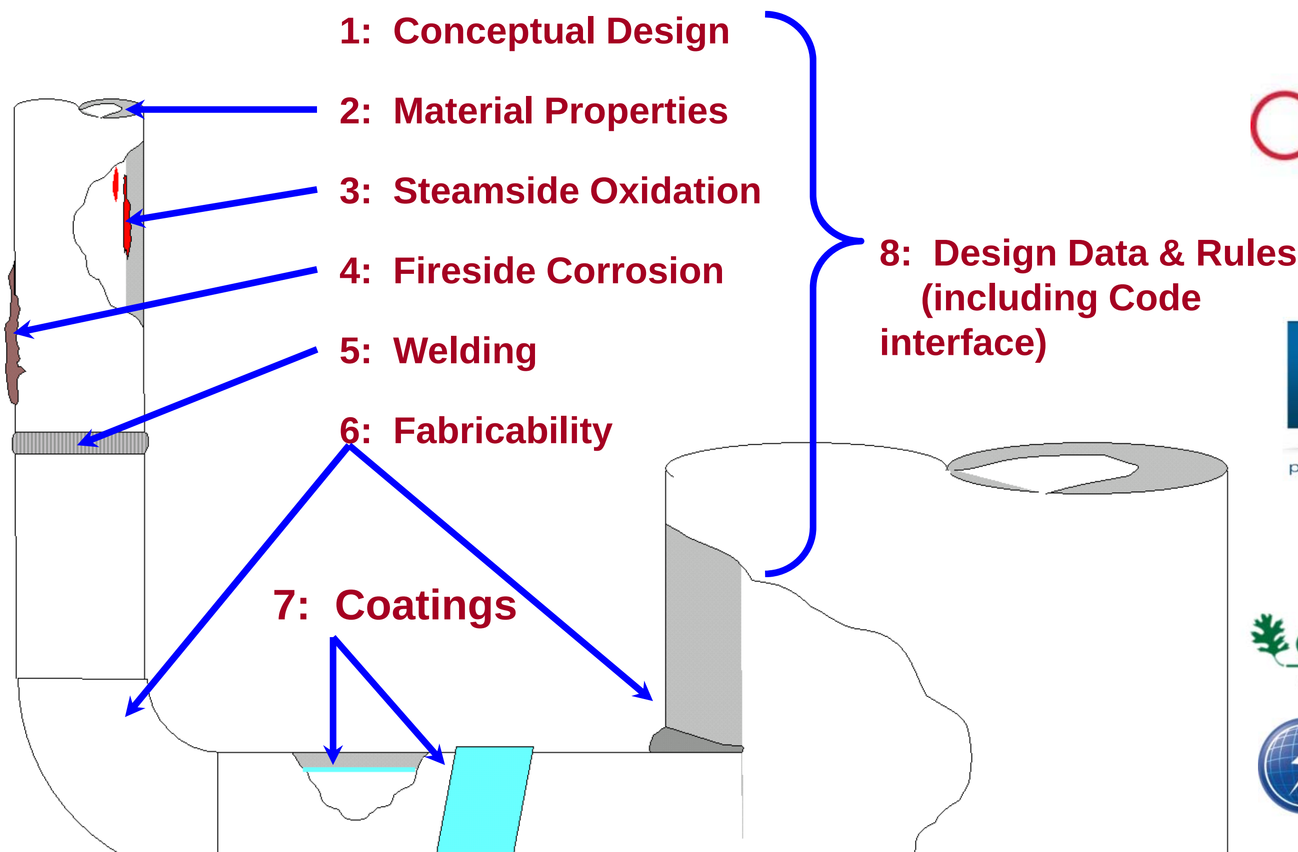
Why 1400°F (760°C)?
Best Approach to Achieving Good Economics

- Materials will limit the maximum achievable temperature
- Economics will dictate the optimum temperature
- For Example: a material suitable for 1400°F will have economic advantages at 1300°F over other materials because components will have *thinner walls*
  - Lower weight = lower material cost
  - Thinner sections = easier to weld/erect
  - Reduced thermal gradients = improved cycling



If you have to pay for nickel, make the most of it!

U.S. DOE/OCDO: A-USC Steam Boiler Consortium



Develop the materials technology to fabricate and operate an A-USC steam boiler with steam parameters up to 1400°F (760°C)

U.S. DEPARTMENT OF ENERGY

Ohio Coal Development Office

Energy Industries Of Ohio

B&W power generation group

NETL

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OAK RIDGE NATIONAL LABORATORY MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

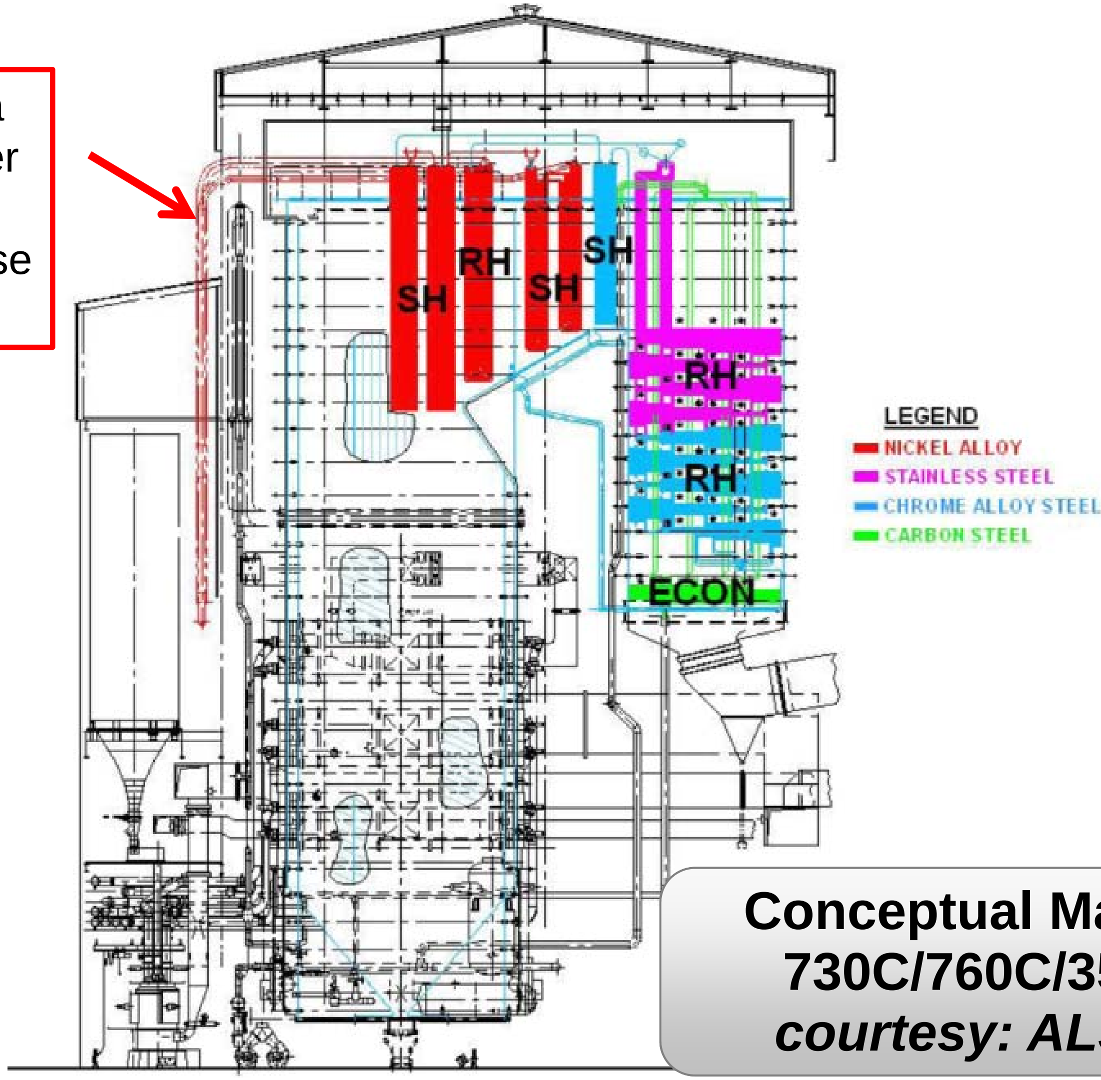
Riley Power

ALSTOM

FOSTER WHEELER

A-USC Steam Boiler Highlight: A-USC Design

Piping is a major driver for overall cost increase in plant



Conceptual Material Layout: 730C/760C/35MPa A-USC *courtesy: ALSTOM Power*

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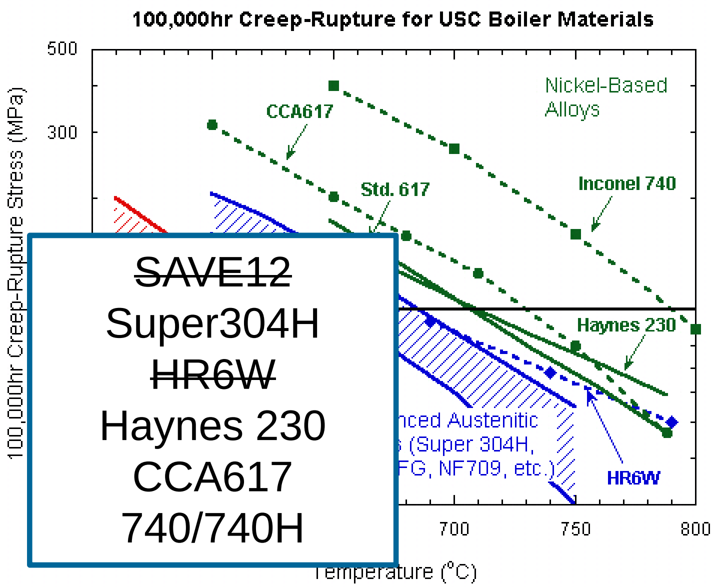
Boiler materials selection based on strength and stability



~~SAVE12~~
Super304H
~~HR6W~~
Haynes 230
CCA617
740/740H

- Long-term strength
- Fabrication Effects
- Weldment behavior
- Testing for code case

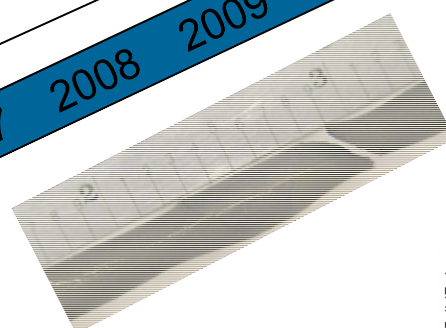
- Codes & Standards Interface
- Long-term weldment strength
- 40,000 hr + testing

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

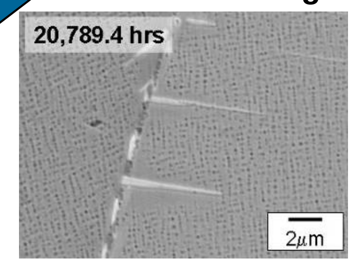
- Materials Selection
- Procurement of Materials (6 alloys)

- Initial creep testing (10,000hr)
- Microstructure & Aging Studies

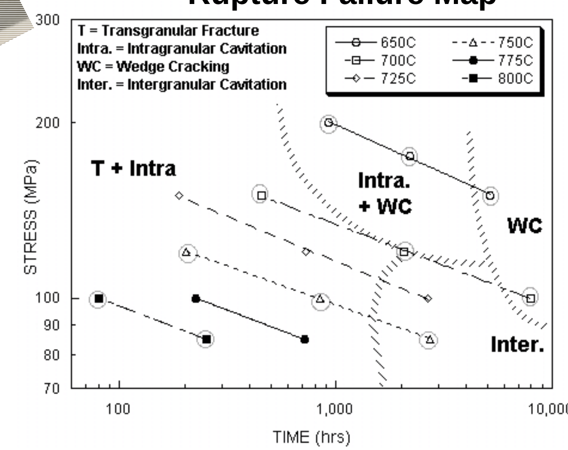
- Vendor Discussions/Literature Search



SEM Image



Rupture Failure Map



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A-USC Steam Boiler Highlight: Steam-Side Oxidation Tests

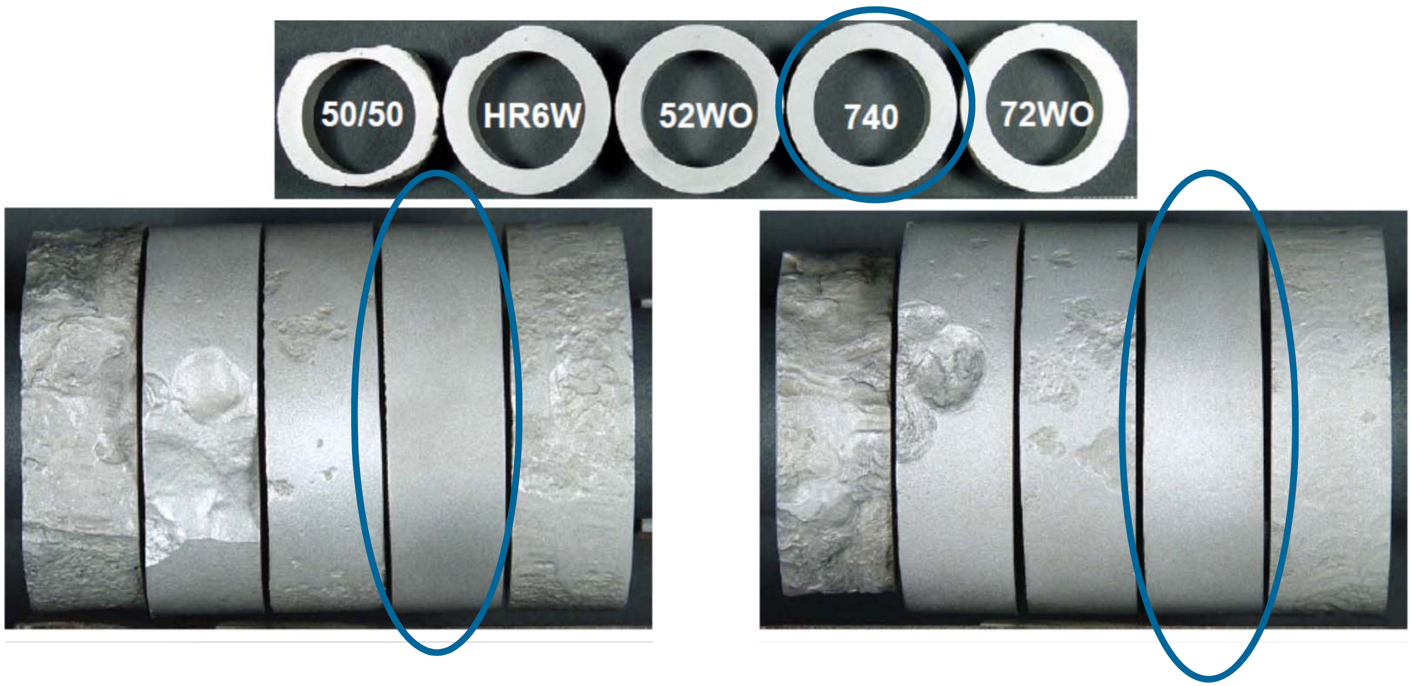
- Steam-side exfoliation being studied in first-of-a-kind test rig being developed
- Long-term testing (up to 10,000 hours) has validated earlier results for materials selection

Macroscopic appearance of steam oxidation samples after 3,000 hours at 620°C (1148°F)

Note good performance of shot-peened, higher alloyed & fine-grained materials

A-USC Steam Boiler Highlight: Fireside Corrosion – Air Cooled Probes

Cleaned surface of an air-cooled probe exposed for 2 years in a coal-fired boiler at A-USC temperatures



Inconel 740 shows lower wastage than a high chromium cladding (50/50), a 23% Cr wrought alloy (HR6W), and weld overlays (WO)

Fabrication

- **Evaluation of fabrication processes for new alloys**
  - Bending, machining, swaging, forming
  - Cold work and recrystallization
  - Testing of tube bends to evaluate cold-work limits

- Cold-work effects on creep properties and recrystallization

Basic fabrication processes

Aging & recrystallization

Pressurized tube bend tests and analysis

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Demonstration articles

- **Demonstration articles were produced to showing multiple processes being put together**

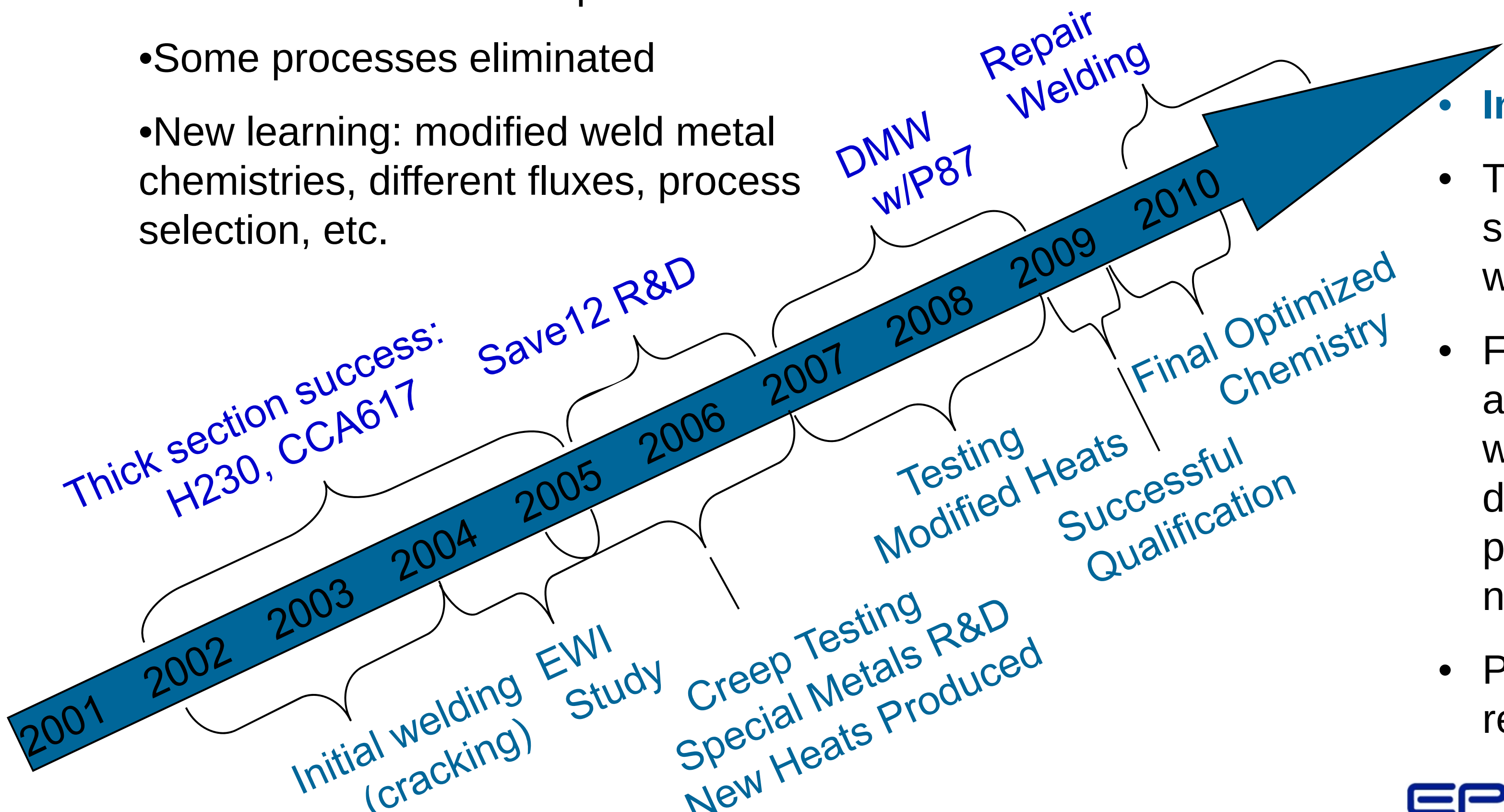
Successes

- No significant changes to fabrication techniques were required
- Initial R&D was used to make changes to ASME Section I Table PG-19 for H230 & 617
- Initial tests on Inconel 740 led to additional phase 2 work (ongoing) on cold-work effects on creep (how the bends will perform in service)

Weldability

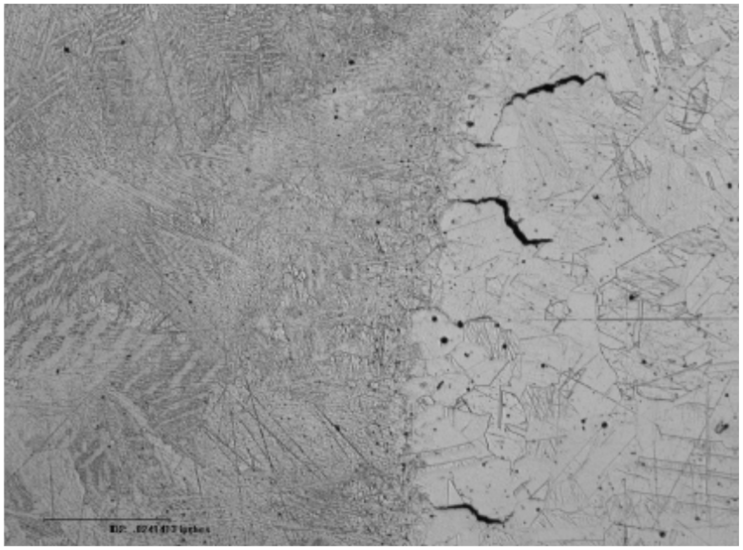
- **Welding**
  - •7 alloys, multiple processes, thin & thick section
  - •Over 20 combinations qualified
  - •Some processes eliminated
  - •New learning: modified weld metal chemistries, different fluxes, process selection, etc.

- Additional mechanical property testing of welds
- Report on dissimilar metal welds
- Repair welding



- **Inconel 740**
- Tube-to-tube successfully welded
- For thick section an extensive welding development program was needed
- Process is now repeatable

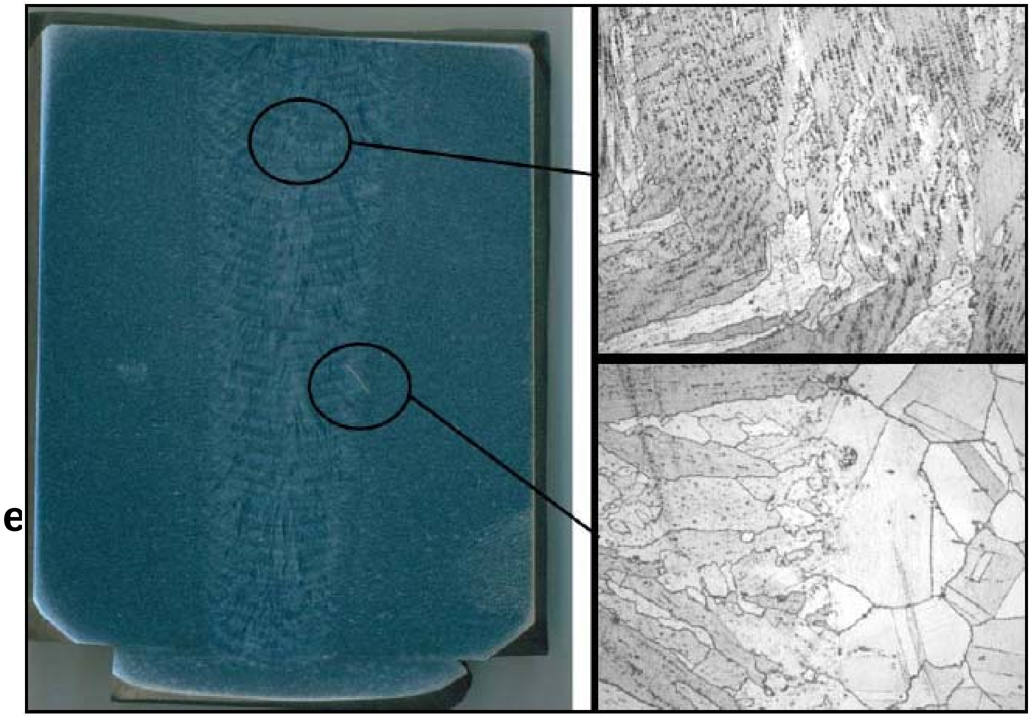
Successes



Original Inconel 740 weld trials
(Liquation cracking in heat affected zone)

Consortium Research

Today: Repeatable 3” (75mm) thick Inconel 740 welds without cracking



Consortium research has demonstrated revolutionary progress in nickel-based alloy welding

Recent Results: In-Plant Testing at 760°C (1400°F) Operating Steam Corrosion Test Loop

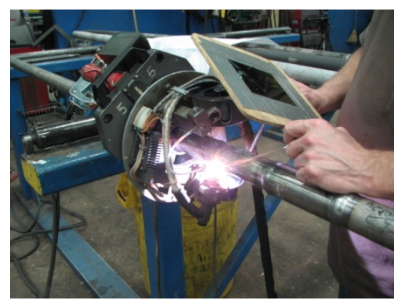
- Phase 1
  - Extensive laboratory testing &air-cooled probes in boiler
  - Steam-cooled loop (high S coal)
- 2nd Steam Loop now installed and operating (8,000hrs+).
  - Planned duration extended until late 2014
  - **World's first steam loop operating at 760°C (1400°F)**
  - Initial evaluations = little to no wastage

Materials include:

740H, CCA617, HR6W, Super 304H, Coating, Overlays, and Others

Fabrication in Alstom Chattanooga TN shop

Prior to Welding



Being Welded

After Assembly

Highlights: World's First Inconel®740H Pipe Extrusion

- Special Metals (Huntington, WV) & Wyman-Gordon (Houston, TX) Project

not consortium funded

- 15-inch (381mm) O.D. X 8-inch (203mm) I.D. X 34-1/2 feet (10.4m) long
- **Larger forging window for Inconel 740H compared to CCA617** (same size pipe extrusion was shorter, 8.9m)

Inconel®740H Pipe after Extrusion at Wyman-Gordon

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Major Step: Code Case 2702 (Inconel®740H) now Approved (2011) 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

CASES OF ASME BOILER AND PRESSURE VESSEL CODE

CASE
2702

Approval Date: September 26, 2011

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case 2702
Seamless Ni-25Cr-20Co Material
Section I

Inquiry: May precipitation-hardenable Ni-25Cr-20Co alloy (UNS N07740) wrought sheet, plate, rod, seamless pipe and tube, fittings and forgings material conforming to the chemical requirements shown in Table 1, the mechanical properties listed in Table 2, and otherwise conforming to the applicable requirements in the specifications listed in Table 3 and in this Case be used in welded construction under Section I rules?

Reply: It is the opinion of the Committee that precipitation-hardenable Ni-25Cr-20Co alloy (UNS N07740) wrought sheet, plate, rod, seamless pipe and tube, fittings and forgings as described in the Inquiry may be used in welded construction complying with the rules of Section I, provided the following rules are met:

(a) Material shall be supplied in the solution heat treated and aged condition. Solution heat treatment shall be performed at 2,010°F (1100°C) minimum for 1 hr per 1 in. (25 mm) of thickness but not less than ½ hr. Aging shall

(d) Postweld heat treatment for this material is mandatory. The postweld heat treatment shall be performed at 1,400°F to 1,500°F (760°C to 815°C) for a minimum of 4 hr for thickness up to 2 in. (50 mm), plus an additional 1 hr per additional 1 in. (25 mm) of thickness. If a longitudinal weld seam is required in the construction of a component, a weld strength reduction factor of 0.70 shall apply in accordance with rules in PG-26 for applications at temperatures above 1,112°F (600°C).

(e) After cold forming to strains in excess of 5%; after any swages, upsets, or flares; or after any hot forming of this material, the component shall be heat treated in accordance with the requirements specified in (a). No local solution annealing may be performed. The entire affected component or part that includes the cold-strained area and transition to unstrained material must be included in both heat treatments. The calculations of cold strains shall be made as described in Section I, PG-19.

(f) The maximum use temperature is 1,472°F (800°C).

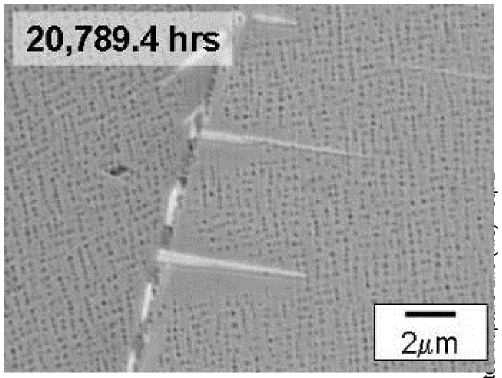
(g) S_u and S_y values are listed in Tables 5 and 5M and Tables 6 and 6M, respectively.

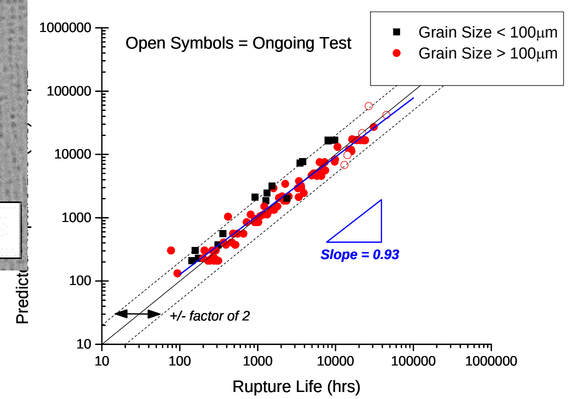
(h) Physical Properties. See also Tables 7 and 7M, Physical Properties.

Additional Research Continues to Extend the Maximum Use Temperature

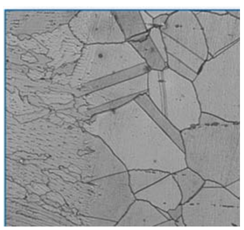
Code Case 2702 (Inconel®740/740H) Timeline & History

Extensive Testing and Data Analysis





Microstructure Development



ASME Section I (2011)

B31.1 (2012)

2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

Initial welding

EWI Study

Creep Testing
Special Metals R&D
New Heats Produced

Testing
Modified Heats

Successful
Weld
Qualification

Final Optimized
Chemistry

Ongoing:

Long-time validation

Higher Temp. Operation

In-Plant Testing

Next: ComTest

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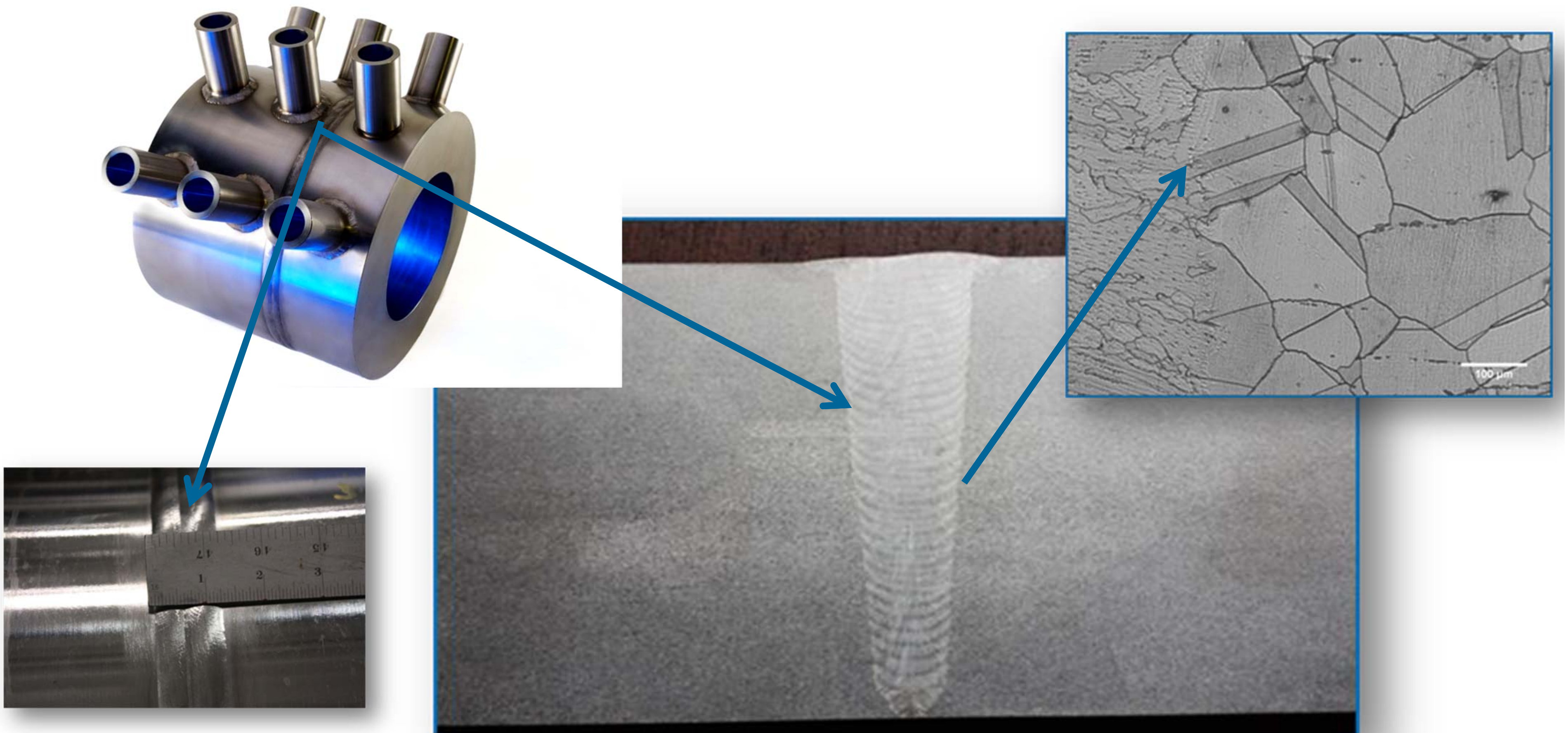
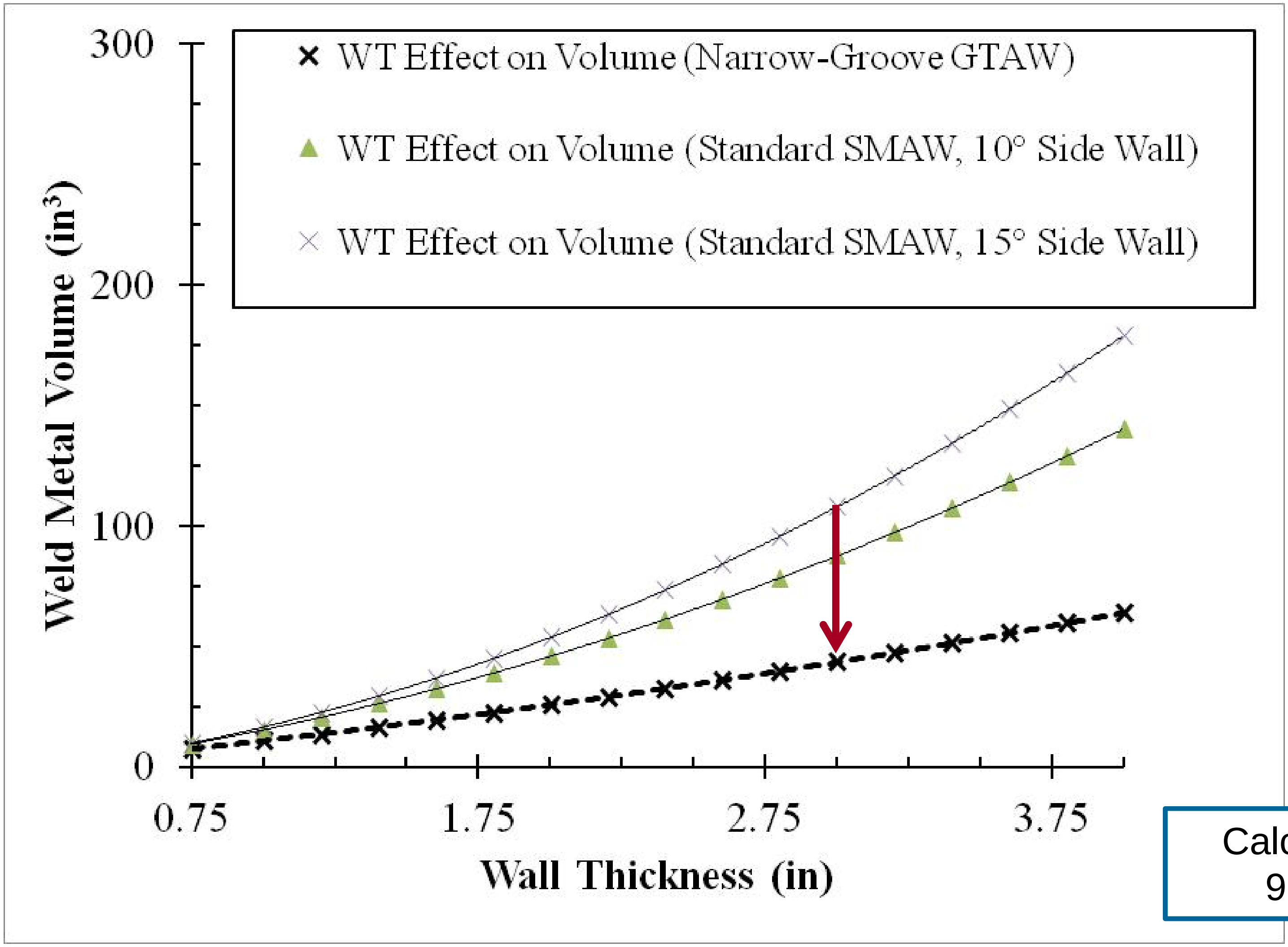
Welding Advancements for Age-Hardenable Alloys



76mm (3”) wall thickness full circumferential pipe weld in Inconel 740H

B.A. Baker, et al. Welding and Repair Technology for Power Plants, Tenth International EPRI Conference. June 26-29, 2012 Marco Island, FL USA.

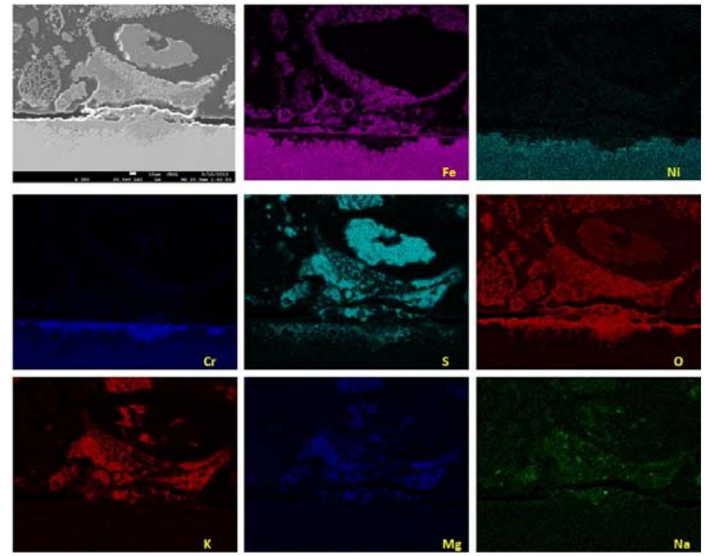
Use of Narrow-Groove Reduces Weld Metal Volume and Increases Productivity for Heavy Section Welds

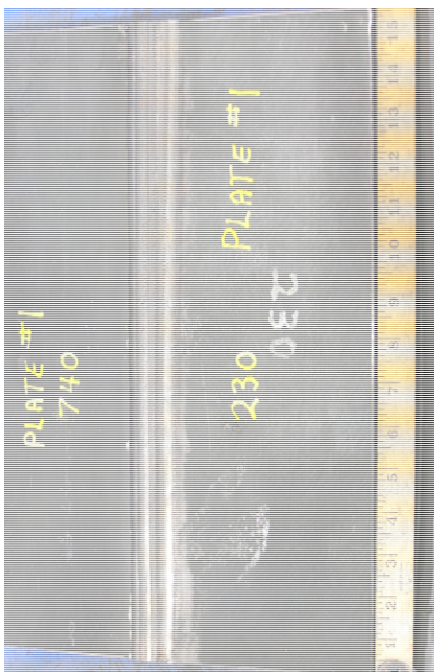


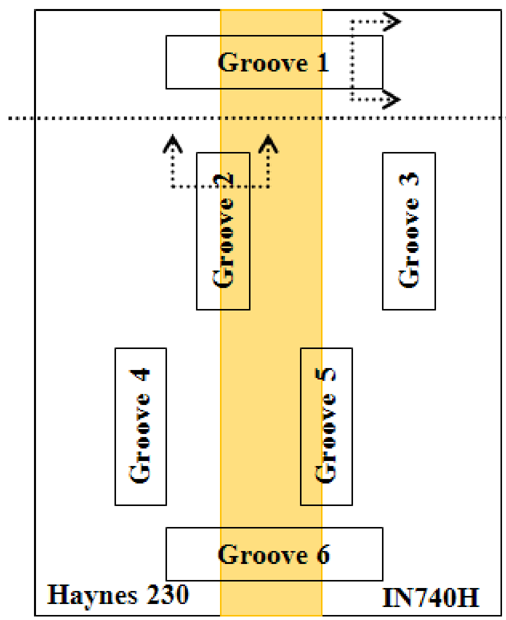
Calculation for 9.84” I.D.

Other ongoing activities

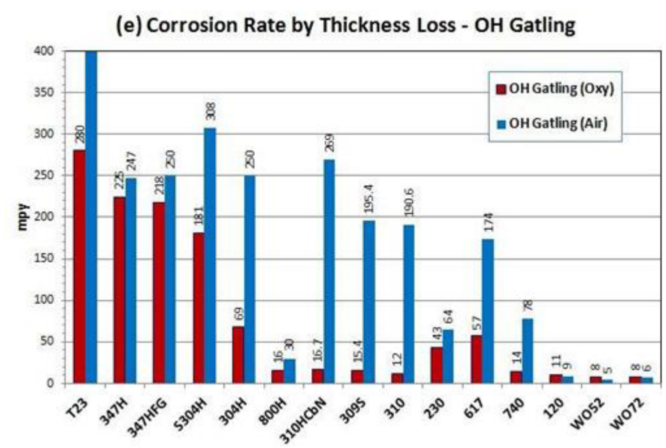
740H to H230 Weld Repair Study: Simulated Aging and Weld Repairs on 38mm Plates







A-USC Oxycombustion Testing



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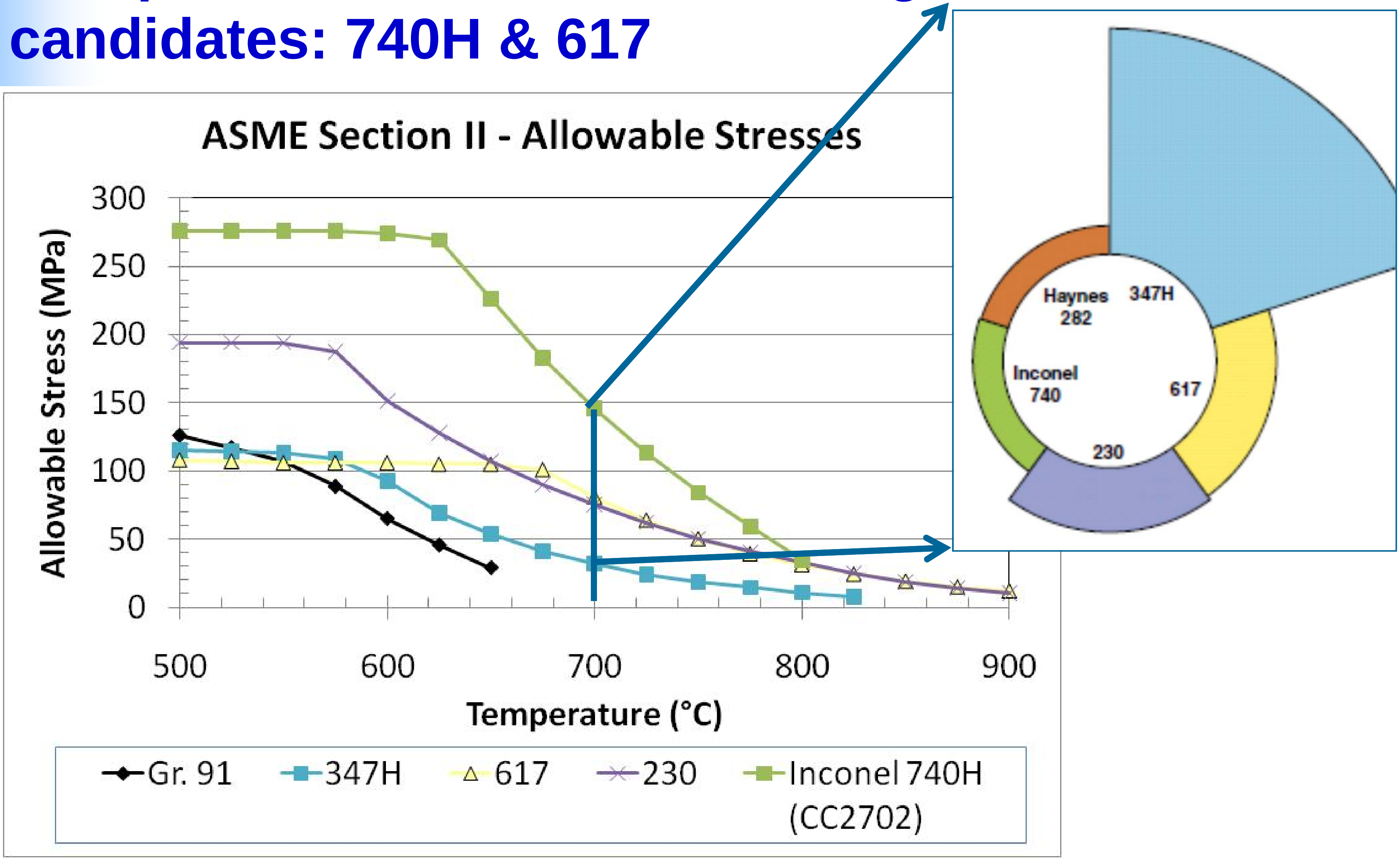
A-USC Economics…

Comparison between two leading candidates: 740H & 617



Higher Allowable Stress for Inconel 740H = Thinner Pipe Walls

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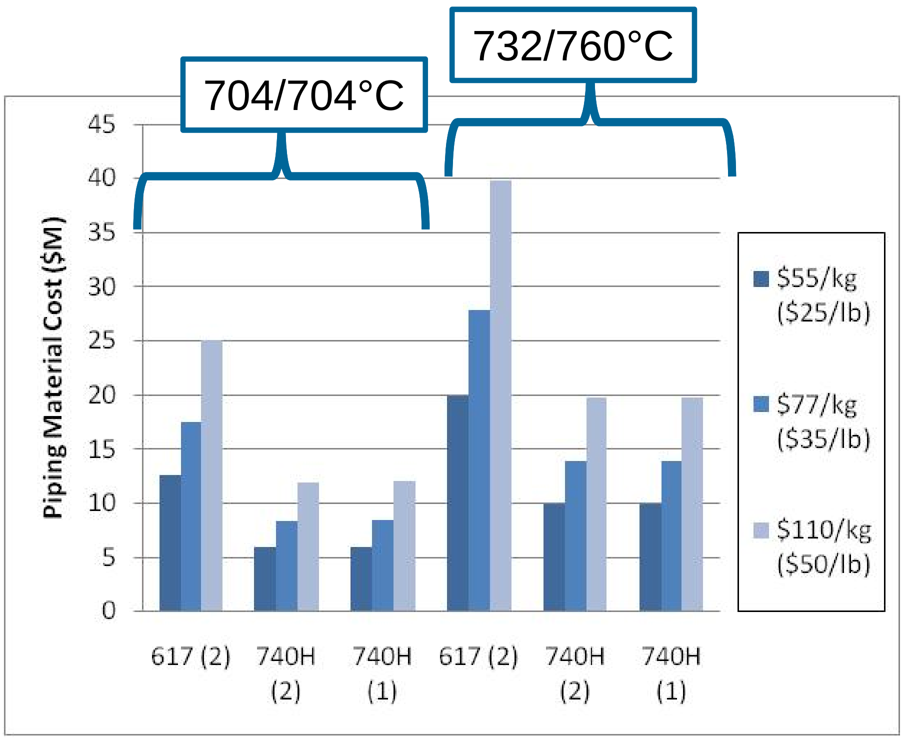
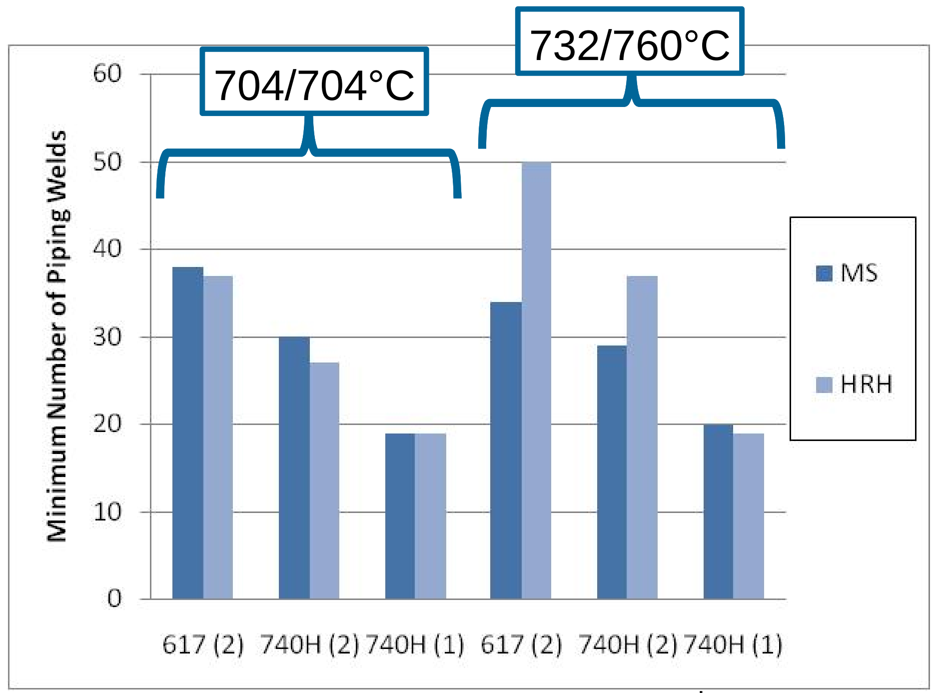
Higher-strength alloys provide an avenue for cost savings

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

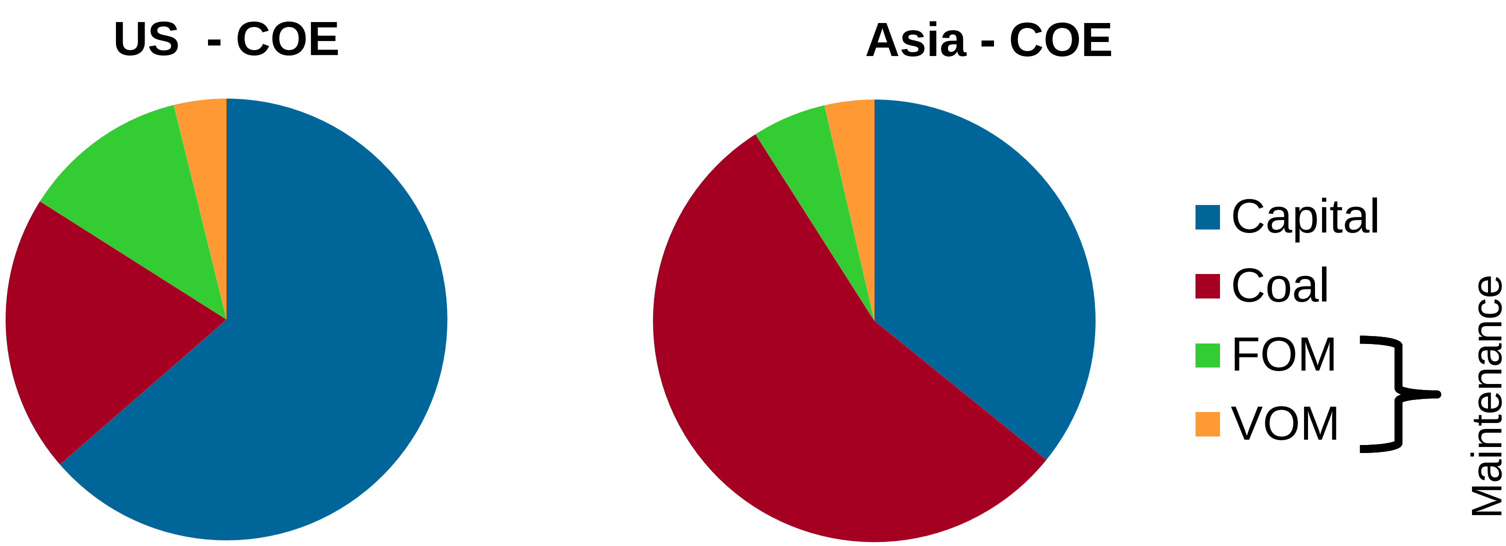
- A-USC plant design study showed using 740H compared to alloy 617 for a main steam and hot-reheat piping system:
  - Reduced piping material cost (less material) by a factor of ~2
  - Reduced welding cost (less welds)
  - Provided a buffer for nickel-based alloy price fluctuations





Business Case – International Comparison

- A-USC is expected to cost 5-10% more than USC. What is the business case that drives development?
  - US - Low fuel cost, higher labor and construction costs.
  - Asia – High fuel cost, lower labor and construction costs.
  - Europe – High fuel cost, higher labor and construction costs.



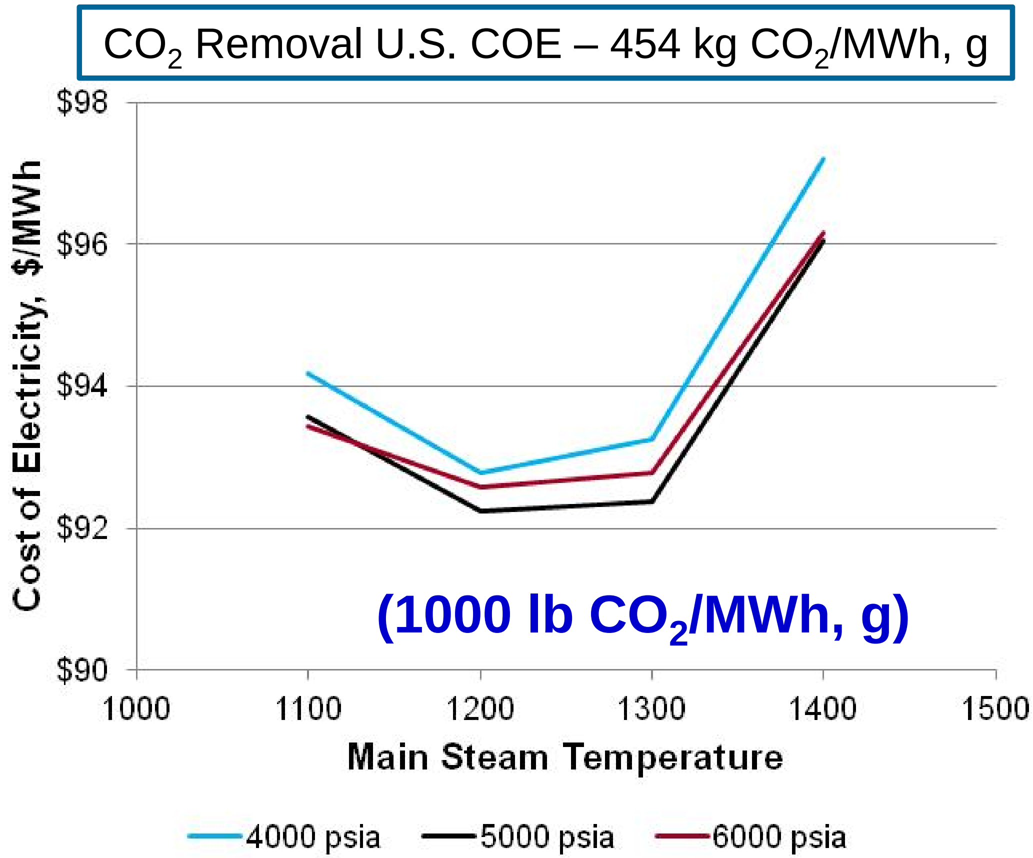
The higher efficiency of A-USC is important in Asia.

Business Case (U.S.) – CO_2 Removal

- **Uncontrolled CO_2 emissions are about 10% lower from A-USC than USC due to the higher efficiency**:
  - USC - ~1740 lb CO_2/MWg
  - A-USC - ~1530 lb CO_2/MWg
  - *U.S. limits for new plant are 1100 lb CO_2/MWg*
- Adding any Post Combustion CO_2 removal system should cost less for A-USC and have a smaller impact on performance.
- Comparison of 90% removal of CO_2 using 30 wt% MEA showed that even if the capital cost of A-USC was 10% higher than USC, the COE of the A-USC unit would be lower. (Reference report 1026645).

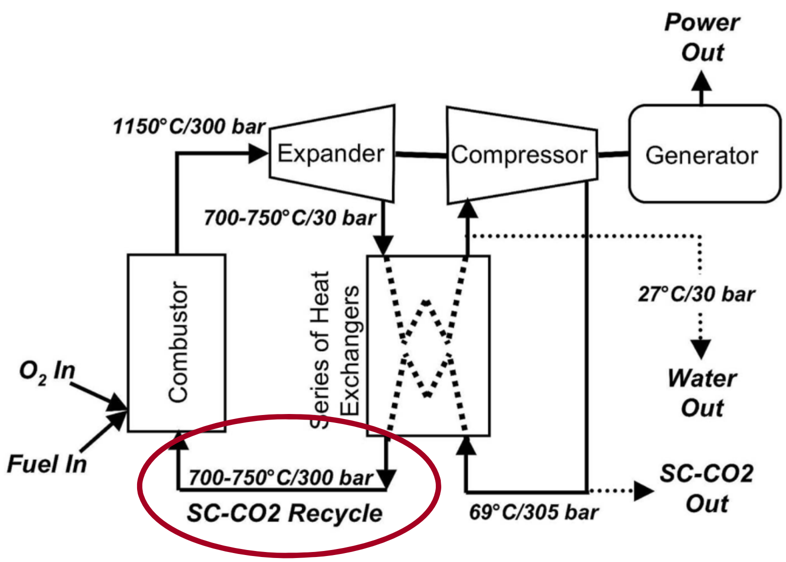
A-USC Economics: more work is needed

- EPRI modeling suggests an economic optimum temperature & pressure
  - Location (U.S. versus Asia)
  - Material cost uncertainty
  - Boiler design – current piping system length skews cost
- There is a need for larger scale deployment (ComTest) to help reduce uncertainty



Alternative Power Cycles Need Advanced (A-USC) Materials Technology

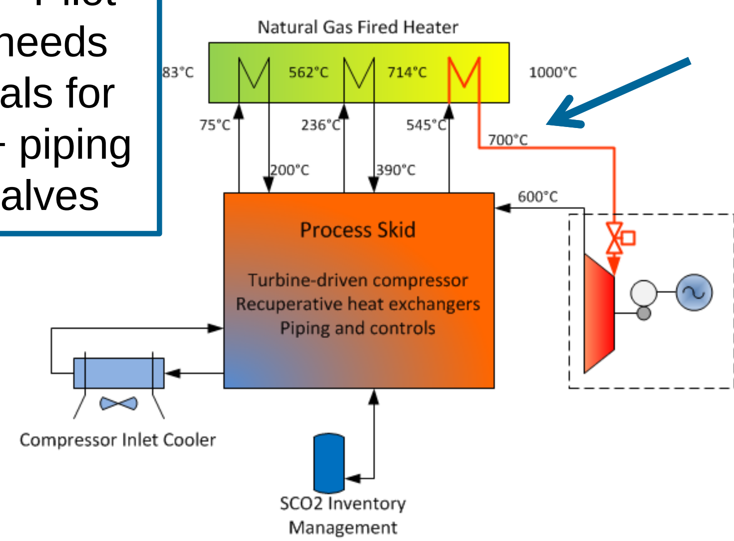
NET Power Cycle 25MW Demo (2014-15)
Gas-Fired 100% Carbon Capture Modified CO_2 Brayton Cycle is planning to use Inconel 740H for High-Temperature CO_2 piping



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

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

DOE Sun-Shot Solar Powered CO_2 Brayton Cycle – Pilot plant needs materials for 700°C+ piping and valves



Partners: NREL, Echogen, Dresser Rand, Abengoa Solar, Sandia, Unv. of Wisc., EPRI, Barber-Nichols

Summary

- U.S. Program continues to make progress on the materials technology for A-USC Boilers
  - Materials technology continues to advance with most work complete
  - In plant testing for corrosion ongoing
  - Welding technology successes
- Economics:
  - Higher-strength alloys provide an economic benefit
  - Drivers for A-USC differ depending on the region of the world
- Cross-cutting nature of materials
  - Oxycombustion work looks promissing
  - Alternative power cycles can (and will) benefit from this technology
- **A component test facility is needed to validate lab findings, prove out new materials, and reduce cost uncertainty**

Together…Shaping the Future of Electricity