Update on U.S. DOE/OCDO Advanced Ultrasupercritical (A-USC) Steam Boiler and Turbine Consortium

DE-FG26-01NT41175
OCDO Grant: CDO-D-05-02(A)
DE-FE0000234
OCDO Grant: CDO-D-05-02(B)

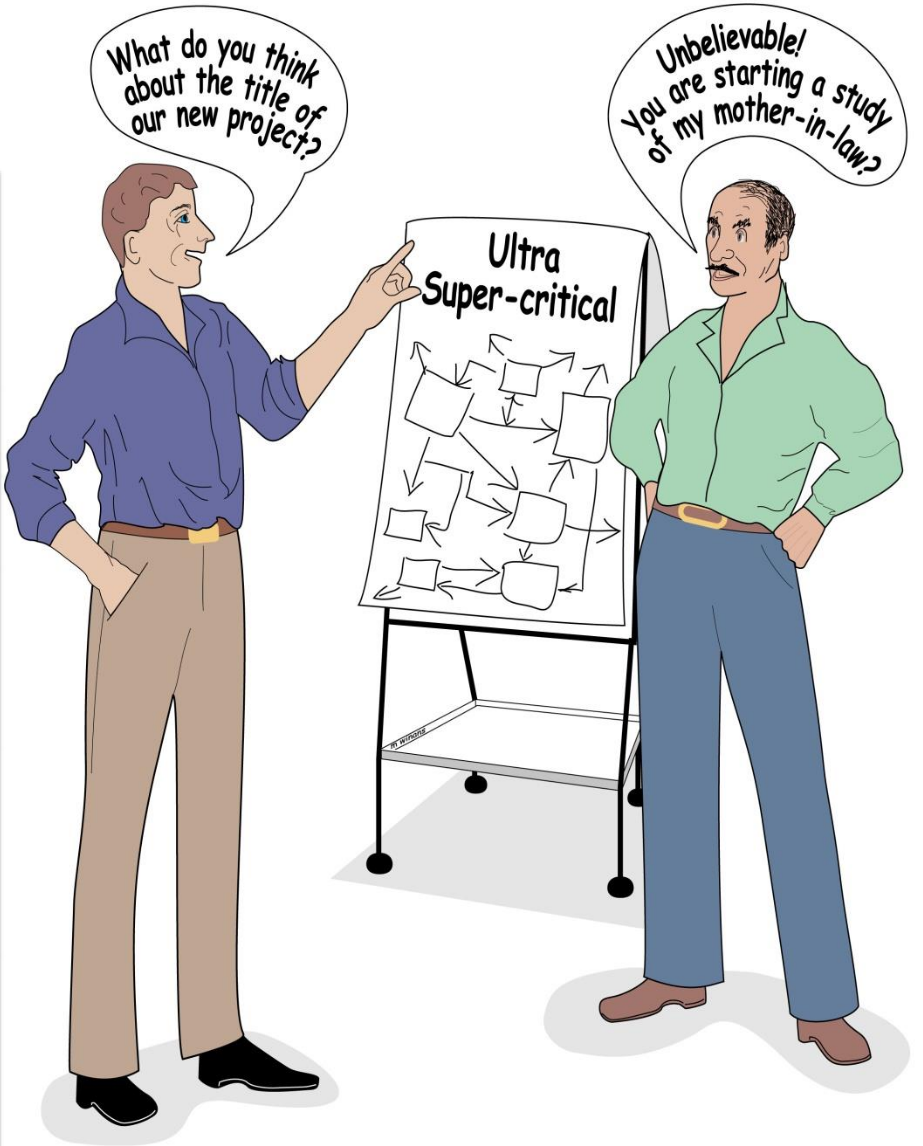
Bob Purgert
President, Energy Industries of Ohio

John Shingledecker, Ph.D
Program Manager, EPRI Fossil Materials & Repair Program

DOE-FE Cross-Cutting Review Meeting
April 29, 2015:
Pittsburg, PA USA

Nomenclature

Nomenclature	Steam Conditions	Net Plant Efficiency (HHV)
Subcritical	2400psig 1000 to 1050ºF	35%
Supercritical (SC)	>3600psig ~1050ºF (550ºC) and above	38%
Ultrasupercritical (USC)	>3600 psig ~1100ºF (600ºC) and above	>42%
Advanced-UltraSupercritical (A-USC)	4000-5000psig 1300-1400ºF (700-760ºC)	>45%



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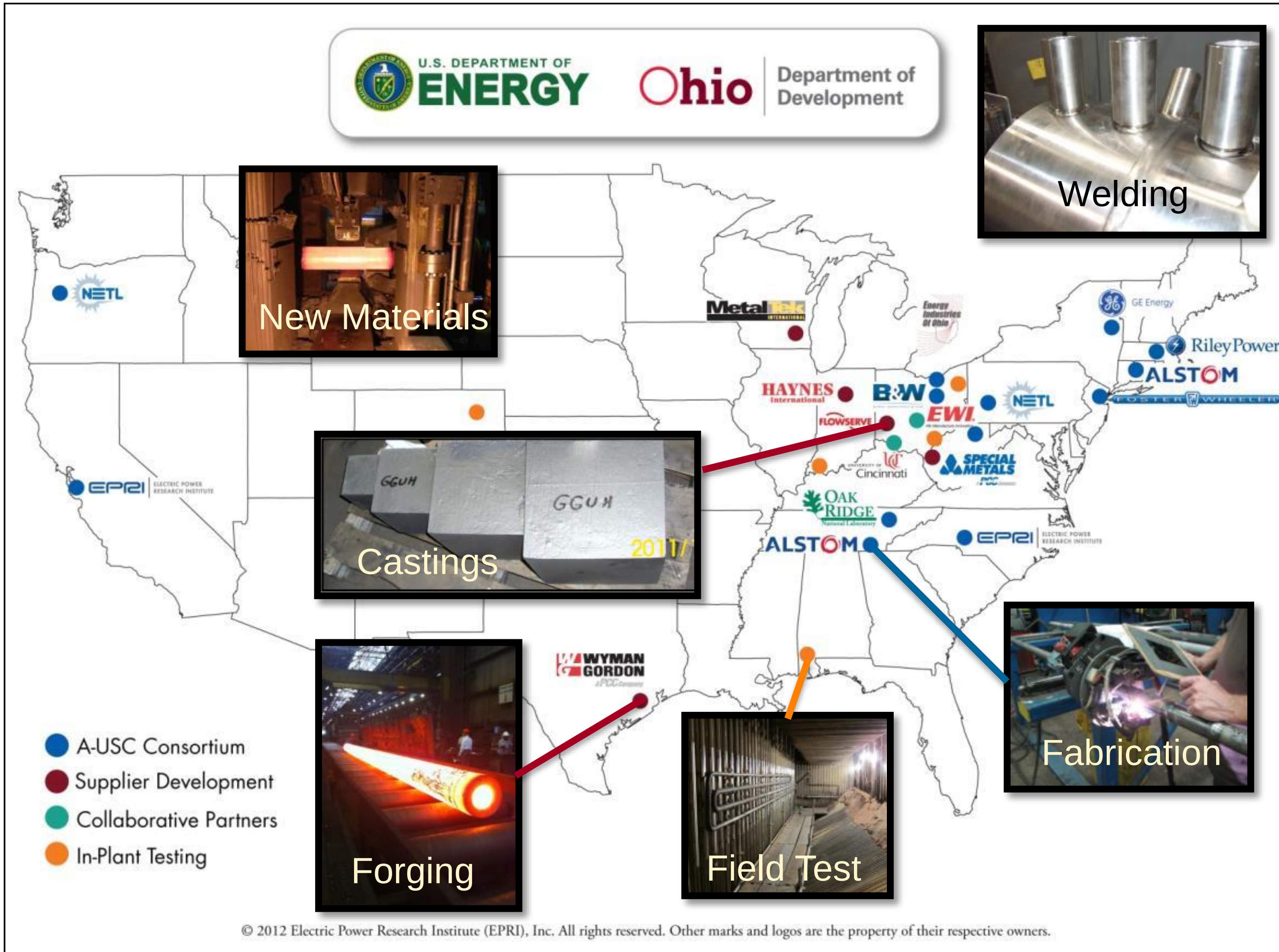
U.S. Department of Energy (US DOE) / Ohio Coal Development Office (OCDO) A-USC Steam Boiler and Turbine Consortia

Federal – State – National Laboratory

Non Profit – For Profit

Cost Sharing Consortium



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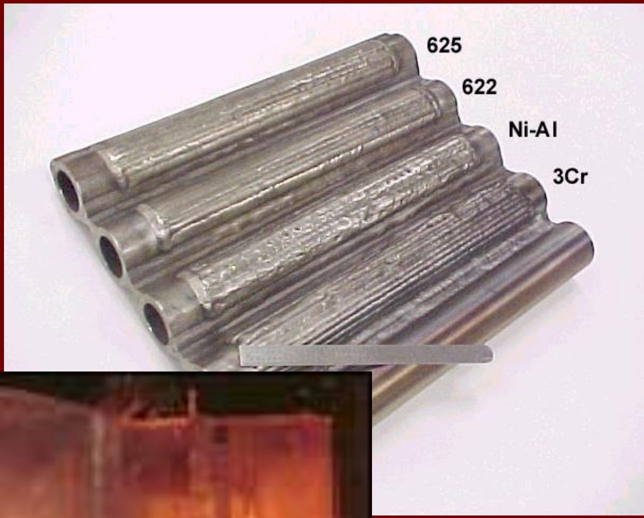
UltraSuperCritical Advanced Materials for Coal Fired Power Generation

- New Materials needed to achieve 1400˚ F and 5,000PSI
- Will increase efficiency from ~35% to ~ 50% (LHV)
- Reduce Emissions
- <u>Success Story</u> for Leveraging
  - State-Ohio Coal Development Office
  - Industrial
  - Non-Profit
- Consortium of All U.S. Boiler and Turbine Mfgrs and EPRI



Management Approach

- Year 15 of 1st Time public/private/non-profit team
- Separate Business and Technical Management
- Identified and dealt with Unique Issues
  - Memo of Understanding amongst Consortium
  - IP Sharing/Patent Rights
  - Reporting Formats and Integration
  - Communication Protocols
  - Budgeting Issues
    - Differing Fiscal Years
    - Differing Accounting Regulations & Rqmts
    - Differing Invoice formats
  - Subcontract Grant Administration

USC Program Management

- EIO Prime Contractor
  - EIO is Administrative Lead
    - w/OMB-133 System Approval
  - EPRI is Technical Lead Organization
  - Industry Teams are Task Leaders
  - Oak Ridge National Lab Leads Task 2
  - NETL/ARL assisted in casting tasks
- Technical Program Steering Committee
- Program Management Oversight Committee

Team Issues

- First Time for Collaboration between U.S. Boiler Industry
- Lead(s) for Each Task Differ
- EPRI Role
- Decision Matrix

- Competitors
- Anti-Trust Analysis
- One or Two Organizations working with Other Members
- Technical Oversight
  - Non Endorsing
  - Independent
- Consortium Driven
- 1 Vote per member

Team Issues Cont.

- SOW and Task Definition
- Teams composed of competing members
- Subtasks and Subcontracts within Tasks
- Release of Information

- Severable and distinct work definitions
- Task Leaders – Access to proprietary information
- Direct and Indirect Management
- Different Missions-Cost Shared

Major Issues that were Addressed and Resolved

- Intellectual Property
- Multi Funding Sources
- National Lab Participating
- Differing Reporting Requirements

- Different Clauses
  Non- Profit and For-Profit Organizations
- One Organization fully funded by OCDO
- Another by both OCDO and DOE
- Rest by DOE
- Fiscal Years differ
- Adjusted Report formats

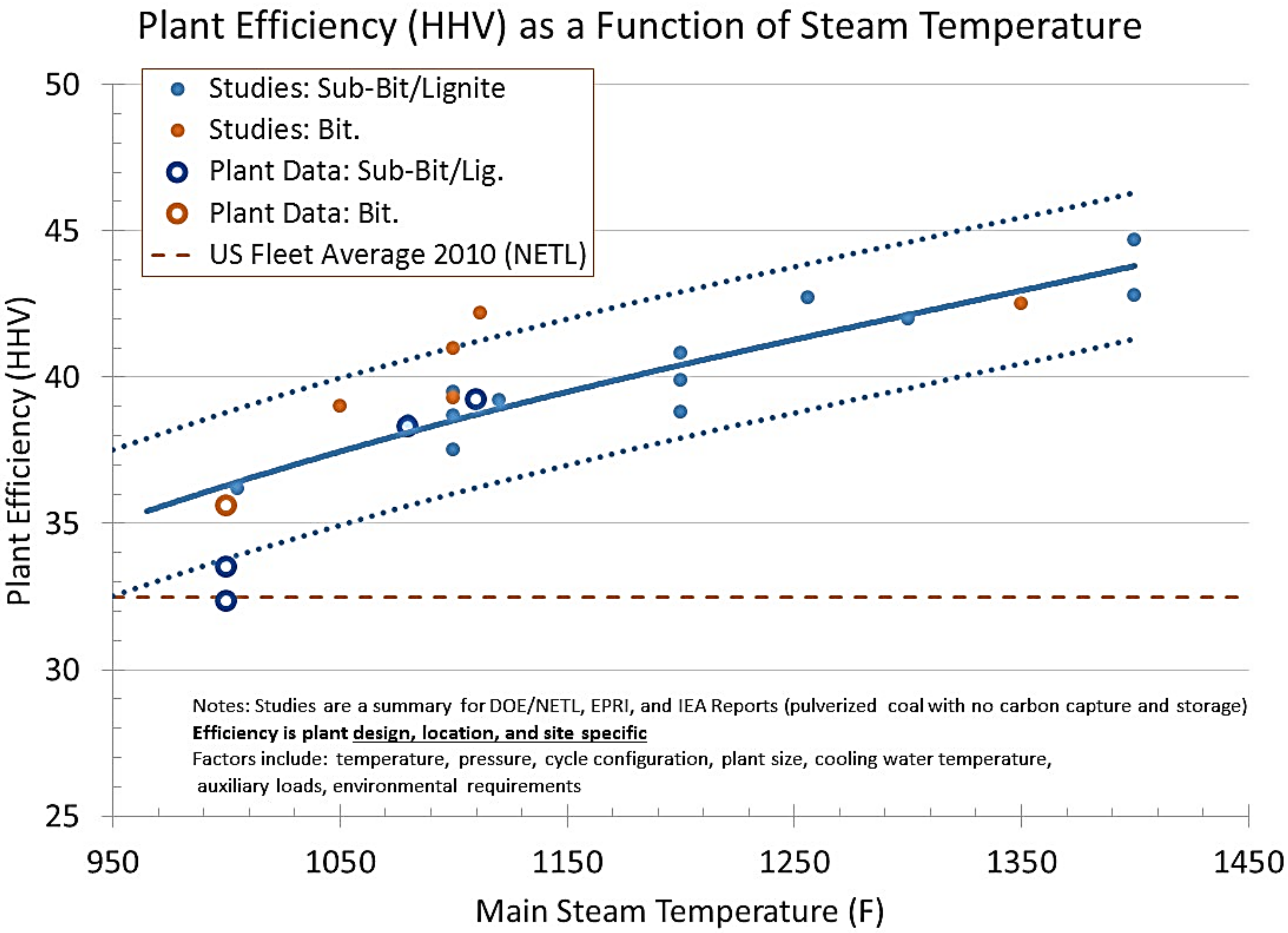
Lessons Learned

- Open Communication a Must
  - Contact Roster Needs to be published
- Invoicing as soon as possible
- Budget Updates and projections seem like a moving target but necessary
- TSC and PMOC for Oversight
- Defined Communication i.e. Monthly telecons
- Reporting due dates must be adhered to
- Publishing needs protocol for team approval

Progress to Date and Future Goals

- Initial technical effort completed per funding schedule
- Costs were per budget (managed through increases for test materials with other savings)
- Project materials identified and base testing almost completed--ready to begin Component Testing
- Component Testing scheduled to be completed by 2020 with Demonstration as the next phase

Increasing Steam Conditions Dramatically Improve Efficiency (Summary of EPRI, NETL, IEA Studies)



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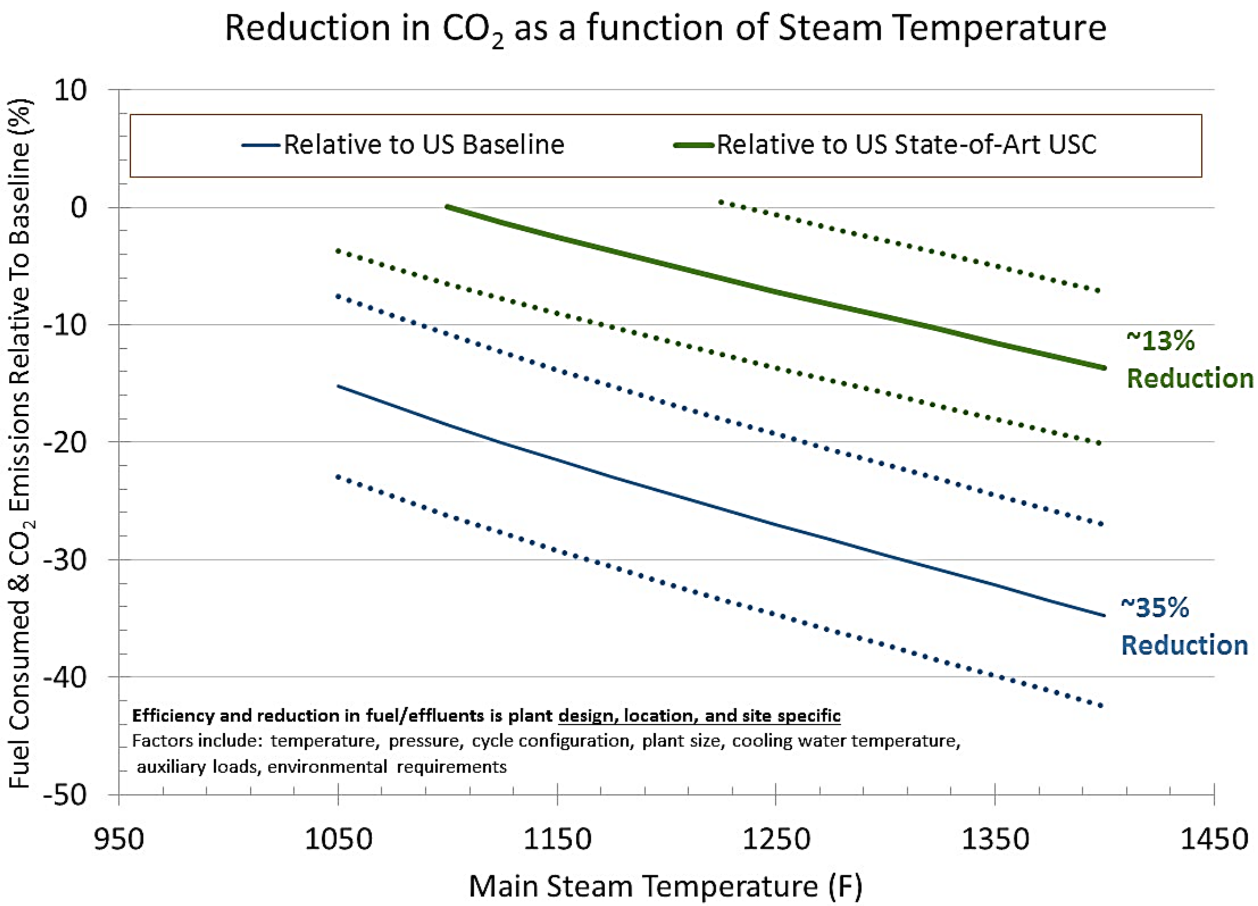
Increasing Steam Conditions Dramatically Reduce CO2 emissions (less coal burned)



<u>Increased Efficiency is a Least Regret Strategy for CO_2 Reduction</u>

Studies show A-USC = 10-35% reduction in CO_2 compared to current plants

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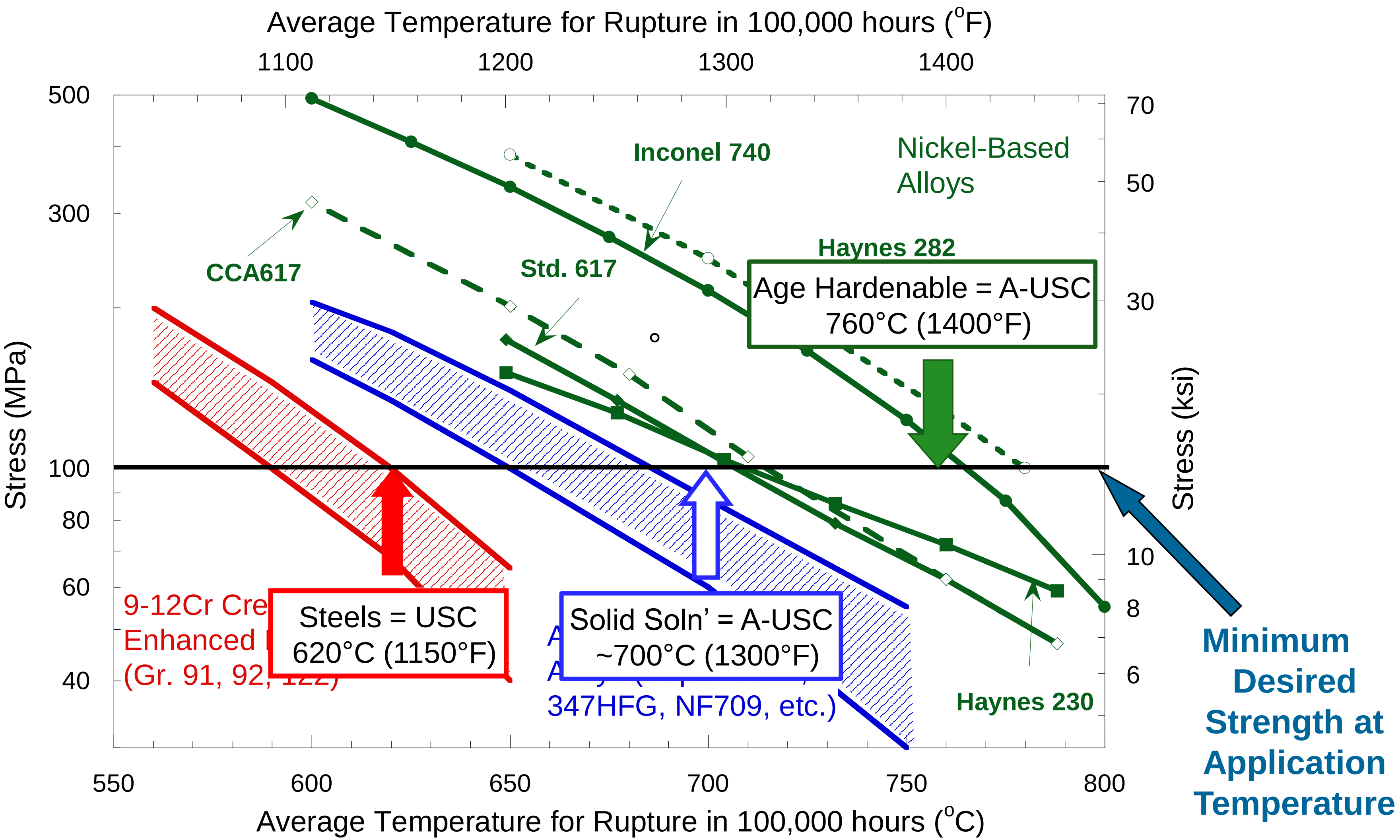
Materials Limit the Current Technology:

Today's State-of-the-Art (USC) are defined by steel technology



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Primary Technical Goals of US A-USC Materials Programs

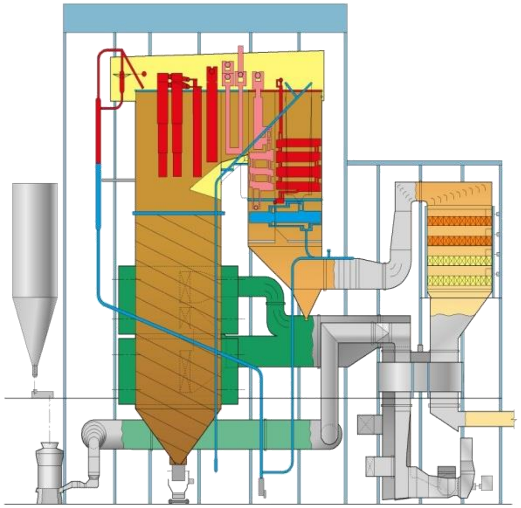
- Materials Technology Evaluation
  - Focus on **nickel-based alloys**
  - Development of fabrication and joining technology for new alloys
- Unique Conditions for US Program Considerations
  - Higher-temperatures than Other International Programs (760°C versus 700°C) means **additional alloys** are being evaluated
  - For Boiler:
    - Corrosion resistance for **US coals**
    - Data for **ASME code** acceptance of new materials
    - Evaluate the effect of combining technology with other carbon capture technologies such as **Oxycombustion**

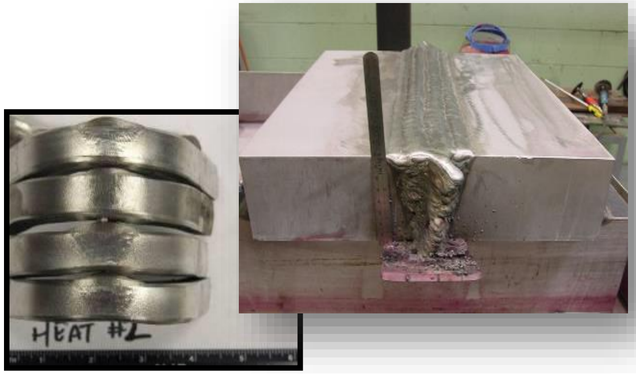
Precompetitive Research & Development on Materials will Enable the Future Power System

Accomplishments
A-USC Fact Book - EPRI 1022770

(download free at: www.epri.com)

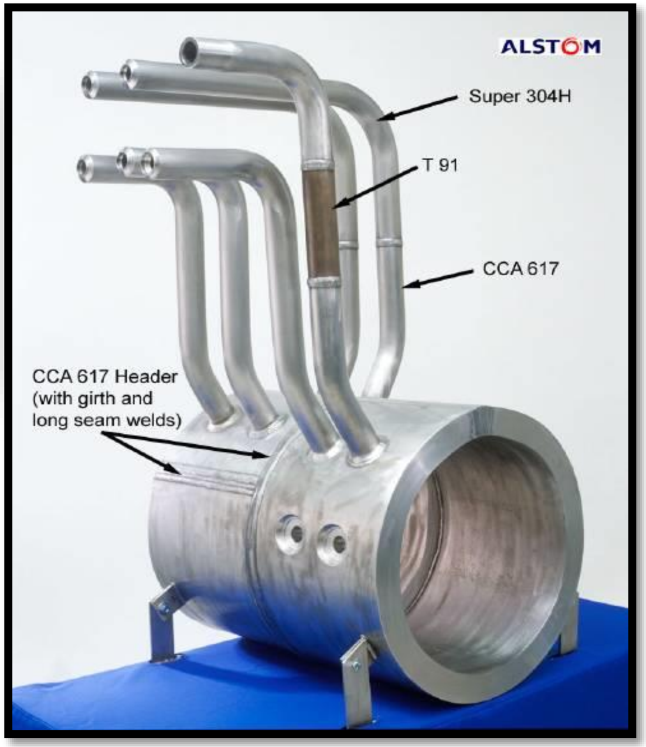
General design studies show favorable economics





Welding Technology Developments

Fabrication Processes



Steam-Side Oxidation

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

Turbine Component Scale-up

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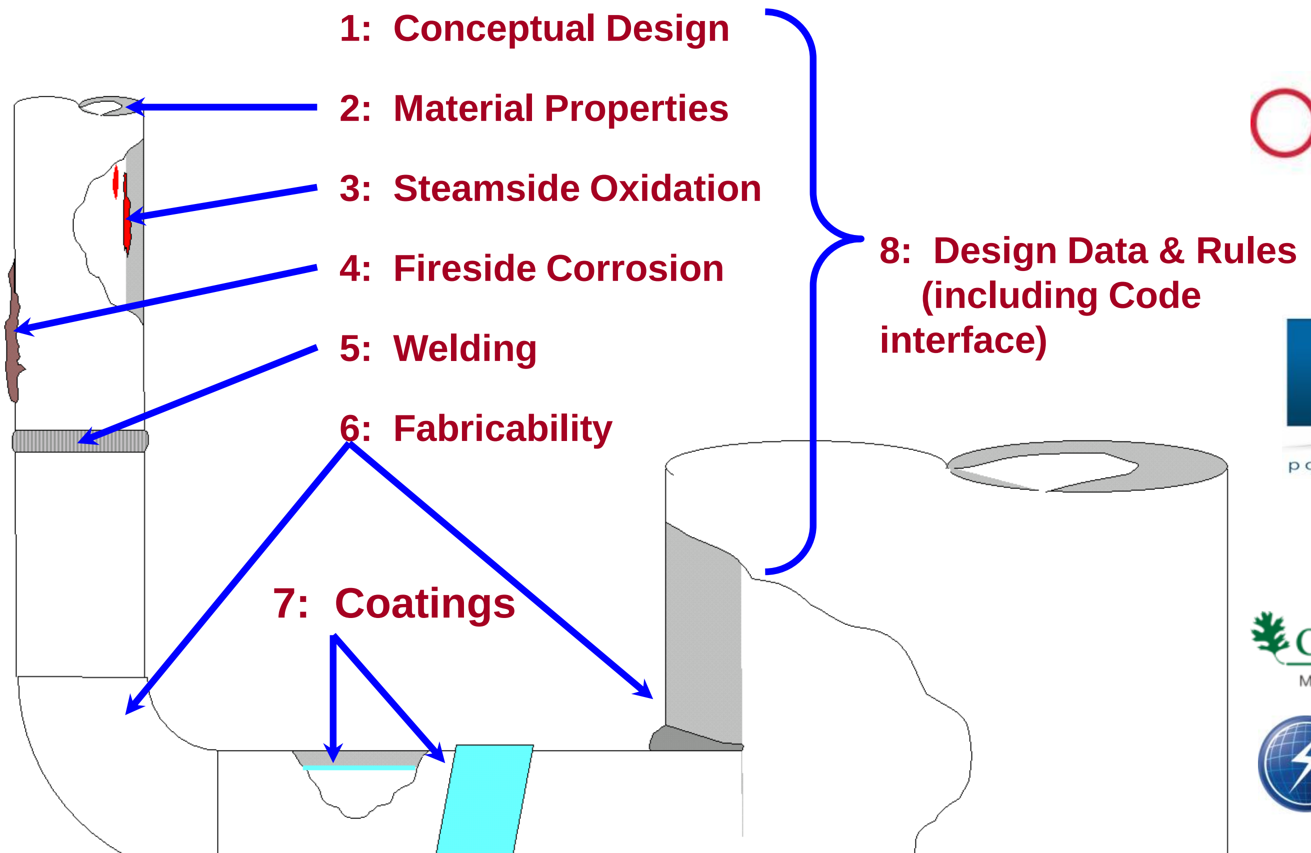
U.S. DOE/OCDO: A-USC Steam Boiler Consortium



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

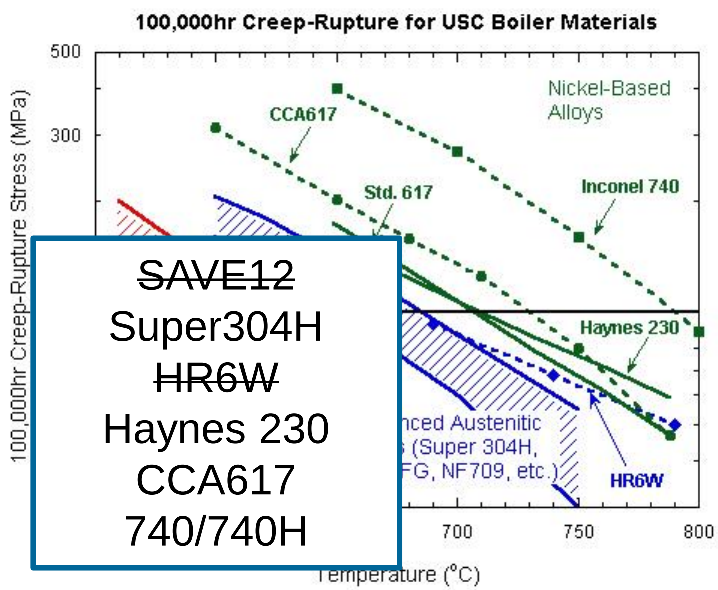
Riley Power

ALSTOM

FOSTER WHEELER

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

Boiler materials selection based on strength and stability

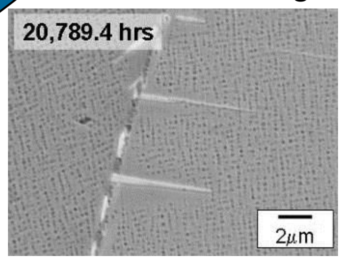


~~SAVE12~~
Super304H
~~HR6W~~
Haynes 230
CCA617
740/740H

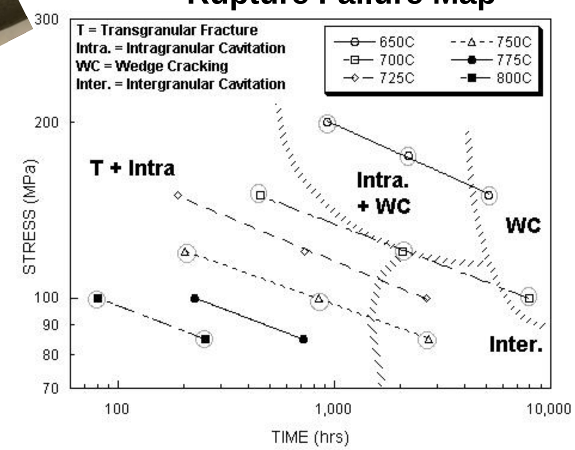
- Long-term strength
- Fabrication Effects
- Weldment behavior
- Testing for code case

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

SEM Image



Rupture Failure Map



2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

- Materials Selection
- Procurement of Materials (6 alloys)

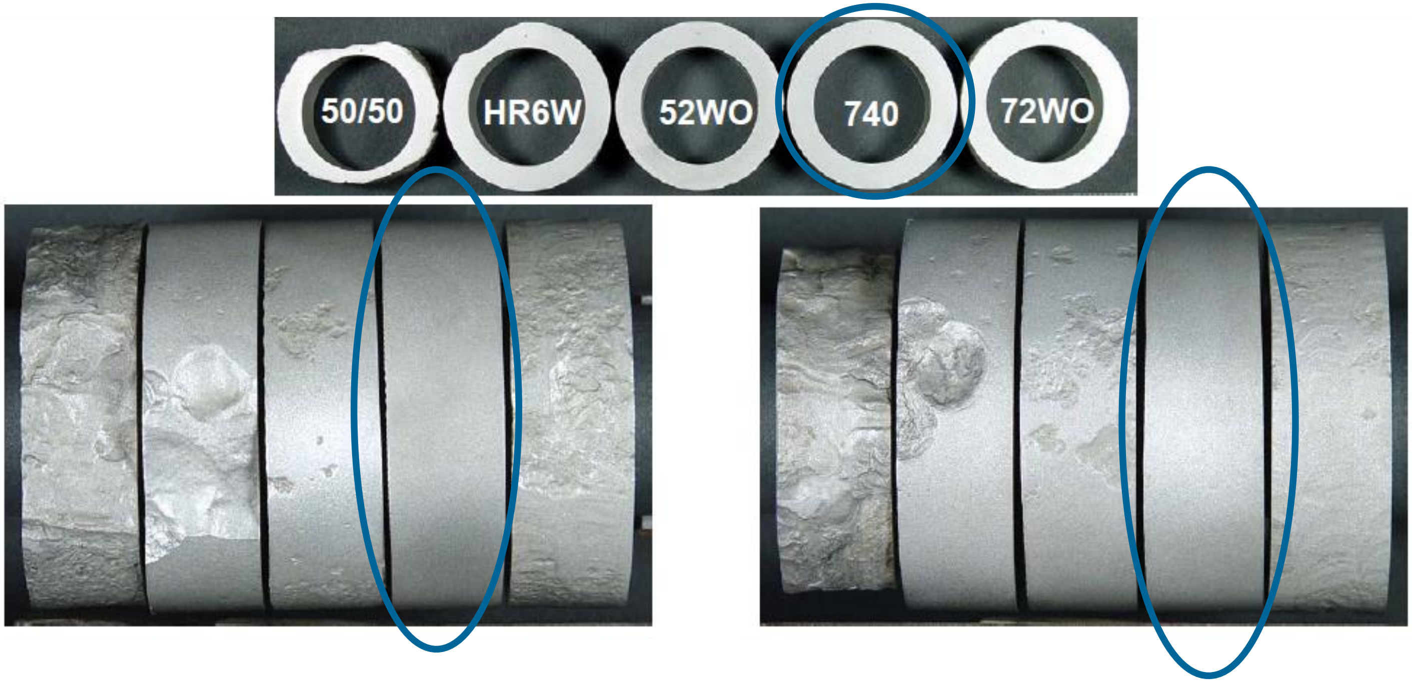
- Initial creep testing (10,000hr)
- Microstructure & Aging Studies

- Vendor Discussions/Literature Search

ORNL (Tortorelli) talk this am

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)

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

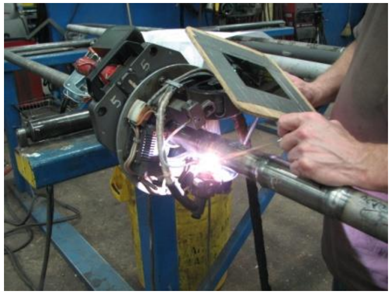
- Phase 1
  - Extensive laboratory testing &air-cooled probes in boiler
  - Steam-cooled loop (high S coal)
- 2nd Steam Loop
  - **World's first steam loop operating at 760°C (1400°F)**
  - **Removed from service after 33months with >16,000hrs in operation**
  - **Evaluations = little to no wastage**

Materials include:

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

Fabrication in Alstom Chattanooga TN shop

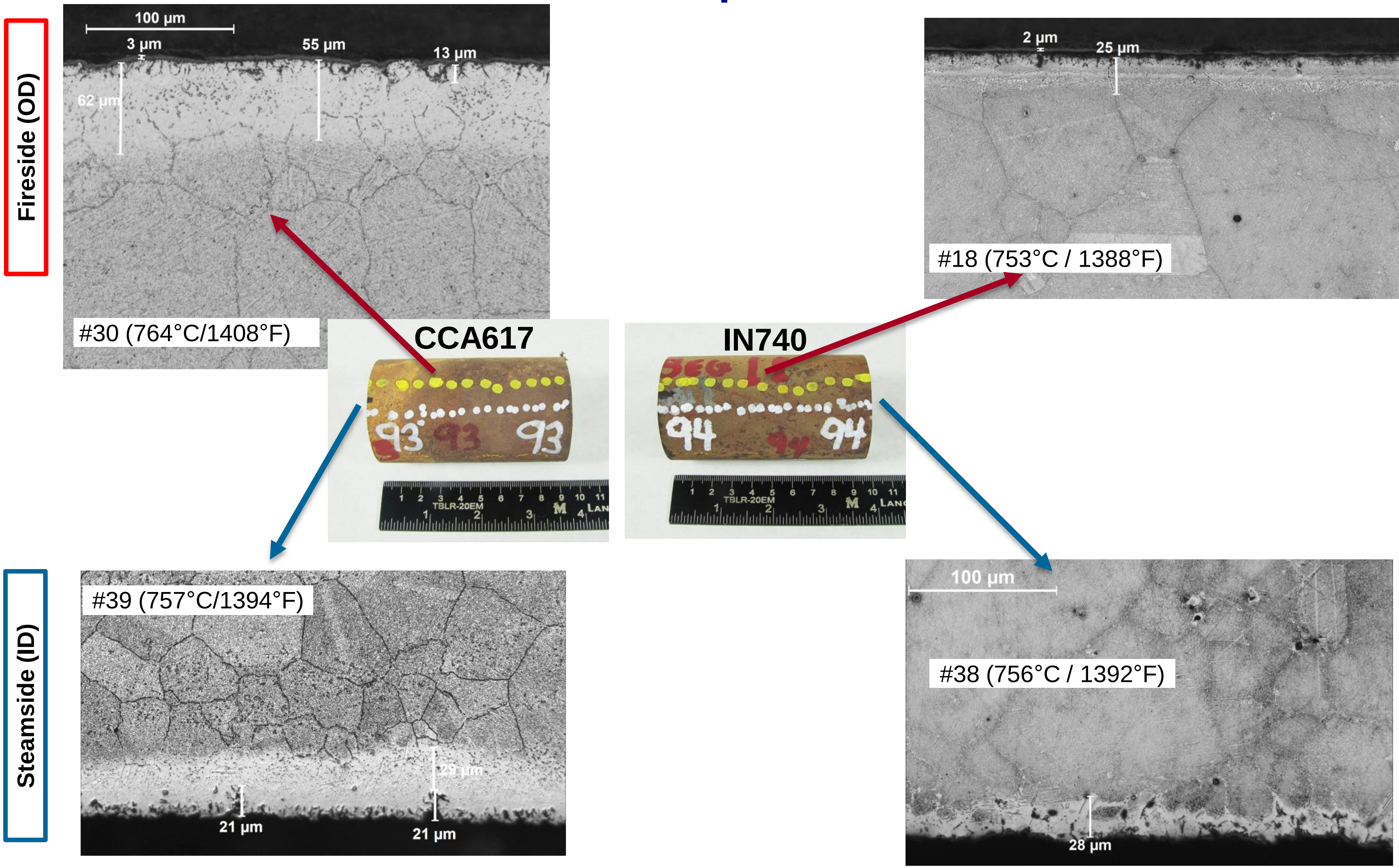
Prior to Welding



Being Welded

After Assembly

Example: Steam-side oxidation/exfoliation and fireside corrosion from steam cooled loop



Boiler Fabrication Successes

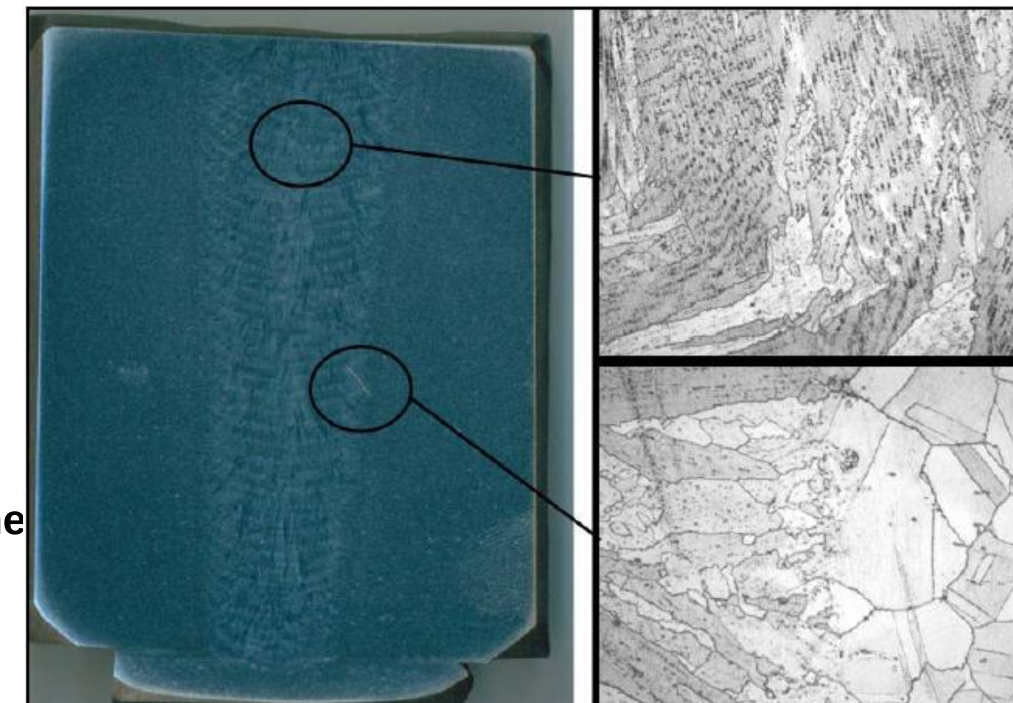
- No significant changes to fabrication techniques were required
- R&D was used to make changes to ASME Section I Table PG-19
- Full-size laboratory testing
- Initial tests on Inconel 740 led to additional phase 2 work on cold-work effects on creep which was needed for the code case

Welding Successes

- 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.

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

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



Consortium Research

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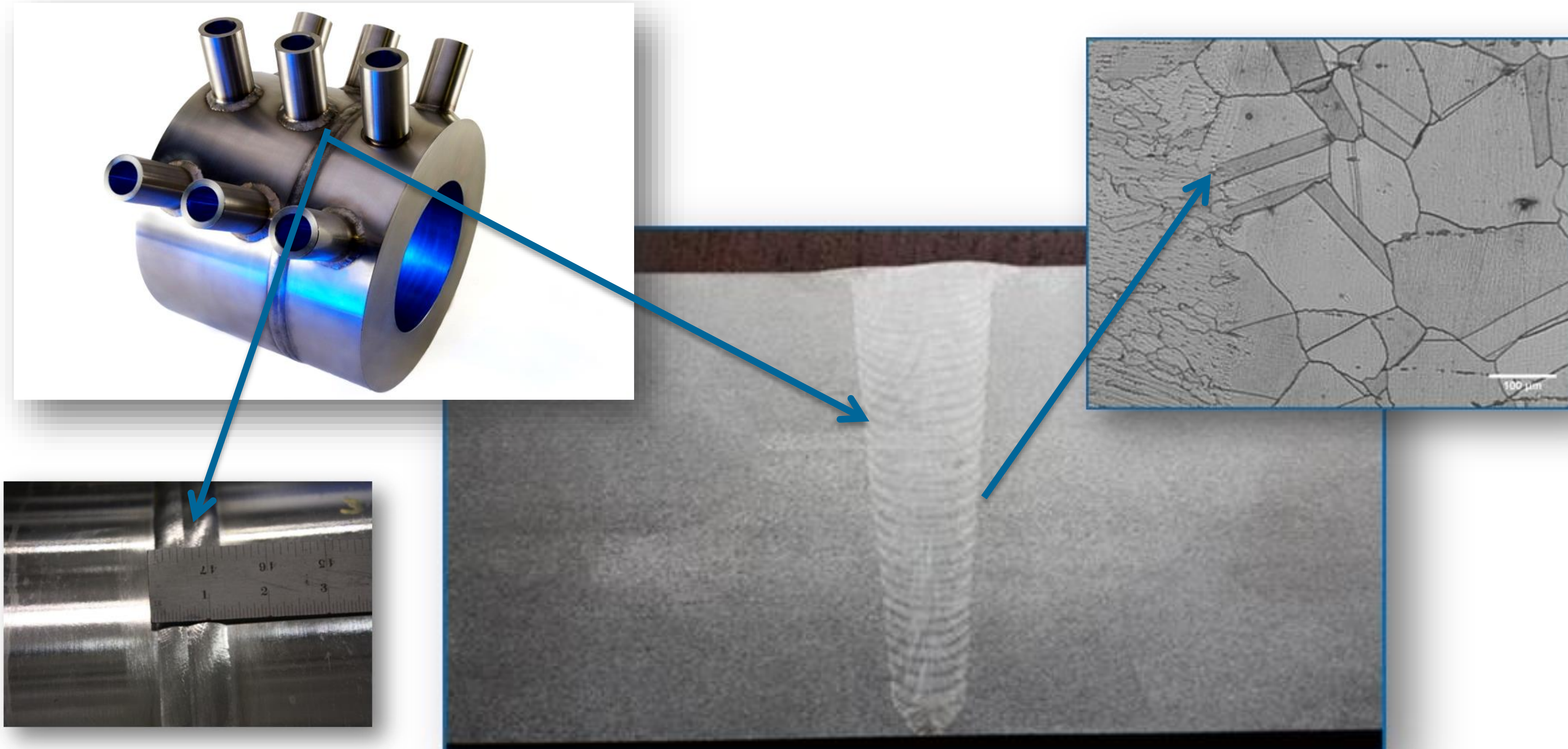
Welding Advancements for Age-Hardenable Alloys



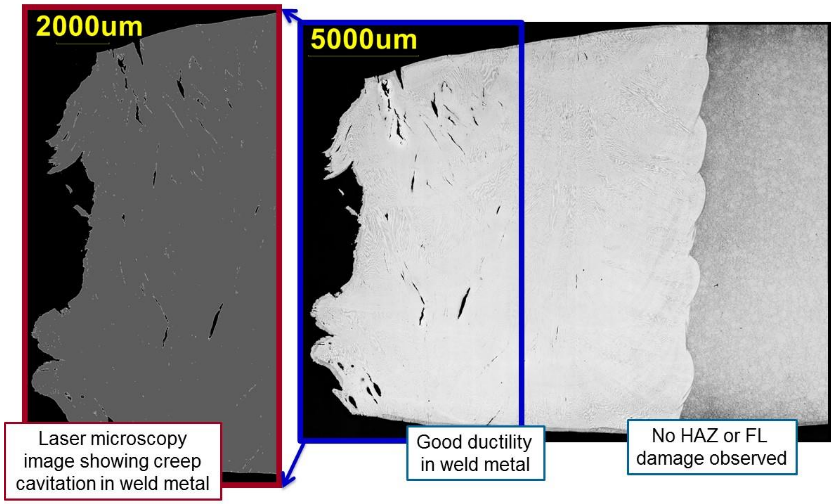
76mm (3”) wall thickness full circumferential pipe weld in Inconel 740H

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

Understanding performance of weldments is critical to design and life management of future A-USC plants

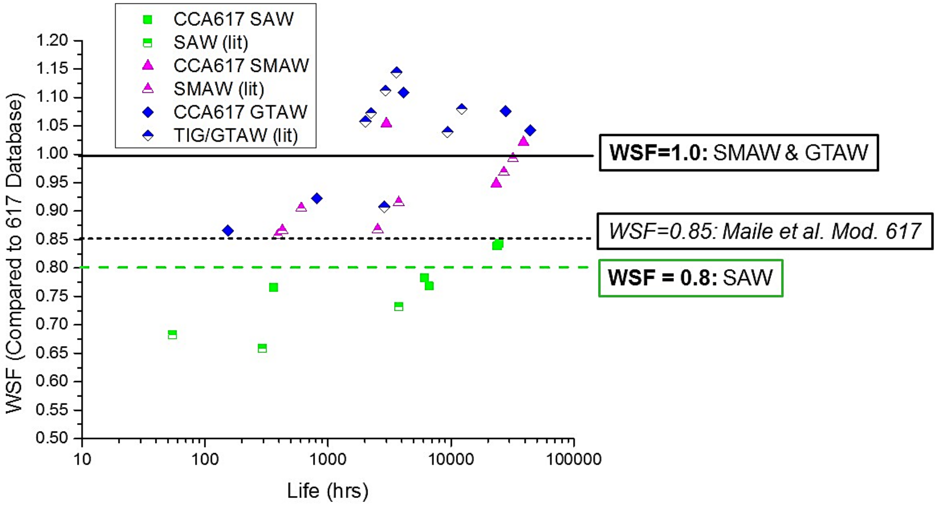
- Long-term creep testing of full-size weldments
- Development of Weld Strength Reduction Factors

SMAW Weld Metal Failure: 750°C, 38960 hours



Metallurgical failure analysis of 38mm (1.5”) thick CCA617 Weldment Creep Samples

Comparison of long-term creep test on CCA617 with various welding processes showing WSRFs



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

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

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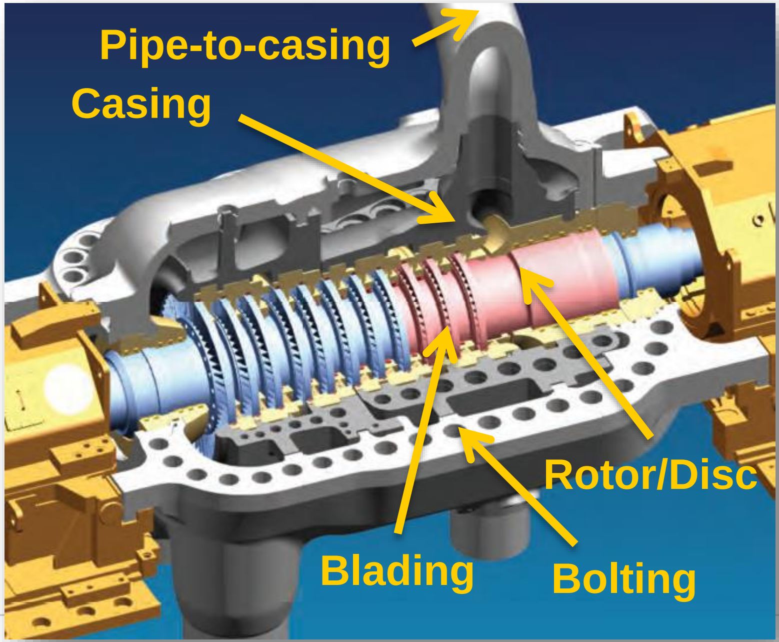
DOE/OCDO A-USC Steam Turbine Consortium

- Selected Materials from Phase I
- Rotor/Disc Testing (full-size forgings, environmental interaction)
- Blade Alloy Testing (and erosion resistant coatings)
- Cast Casing Scale-Up Alloy Testing
- Casing Welding and Repair

1400°F (760°C) Steam Turbine Conceptual Design (HP) – *Bolted Construction*



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Ohio Coal Development Office
Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY
GE Energy
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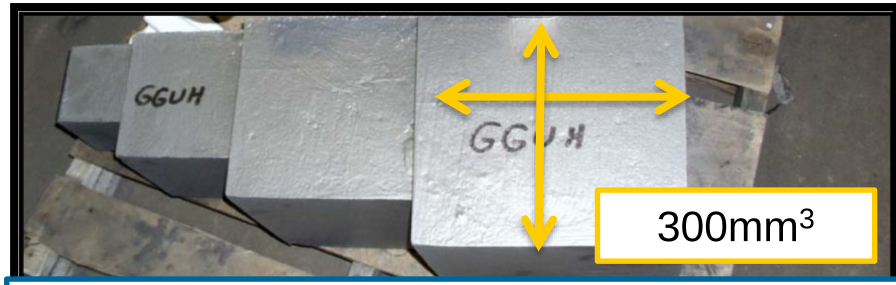
Energy Industries Of Ohio
NETL

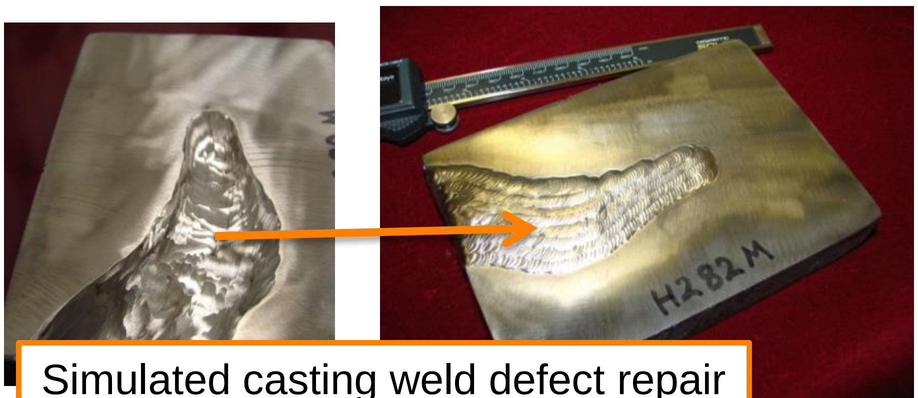
Casting scale-up and turbine casing welding is progressing with supply chain development (3 Foundries Qualified)



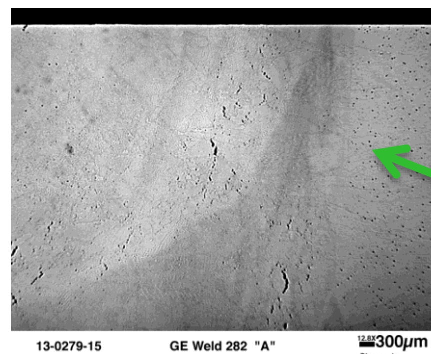
Haynes 282 and **Alloy 263** Step Castings
135-450kg sizes (300 to 1,000 lbs)

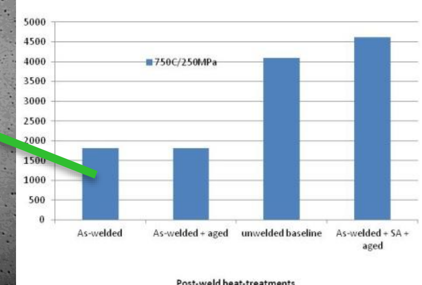
Haynes 282 centrifugal casting: 635kg (1,400lbs)

Long-term creep of weldments & microstructural assessment



Simulated casting weld defect repair





740H Pipe to 282 Casting Weld

ORNL (Maziasz) and NETL (Jablonski) presentations later today

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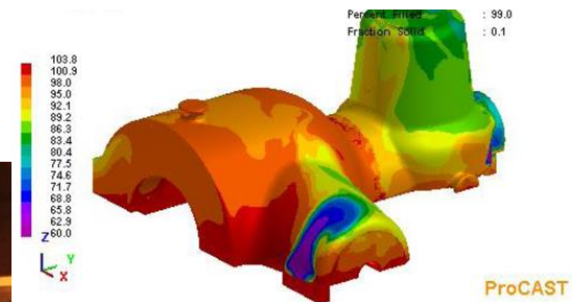
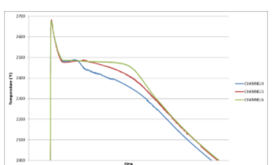
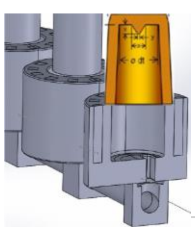
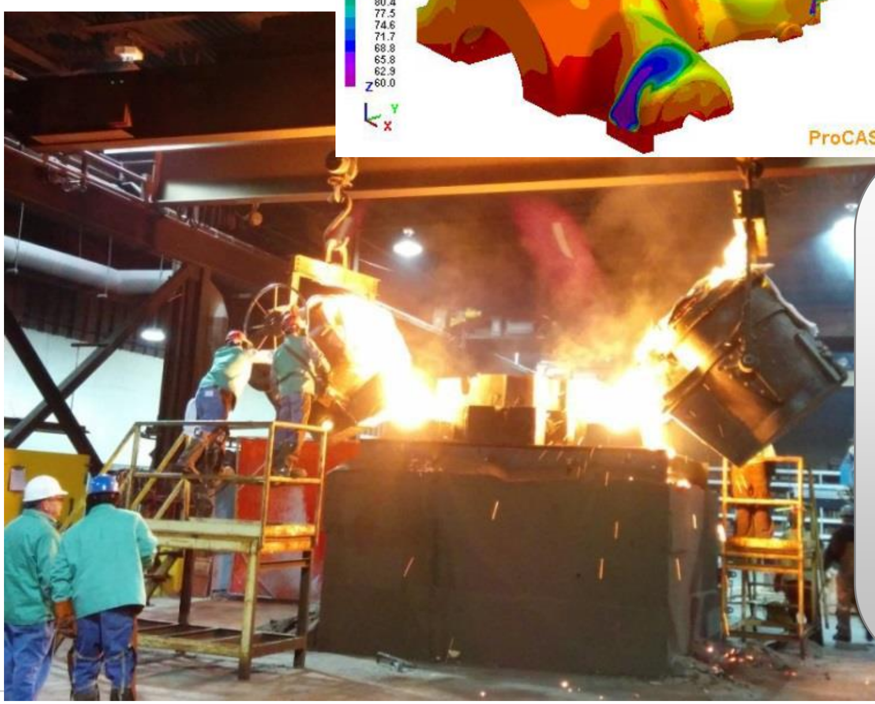
Modeling and World's Largest Age-Hardenable Alloy Casting

- Casting simulation developed
- Cooling rate and secondary dendrite arm spacing predictions validated
- Modeling used to design valve body casting









~2700kg (6,000lb)
½ Valve body

(simulate full-size valve)

Casting successful
Nov. 2014 (17,500lb pour)

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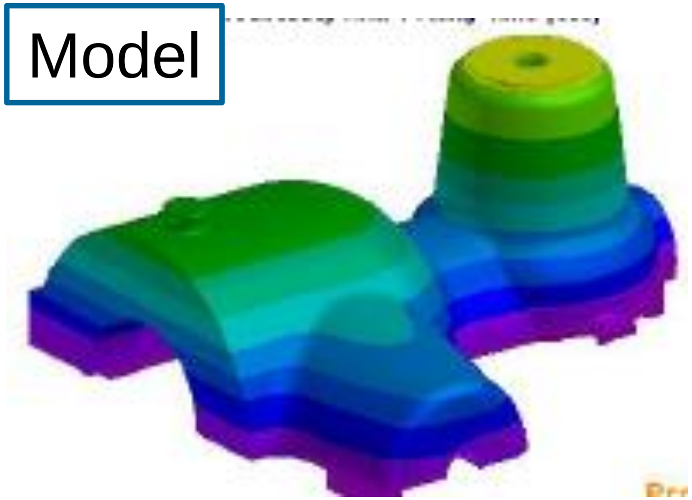
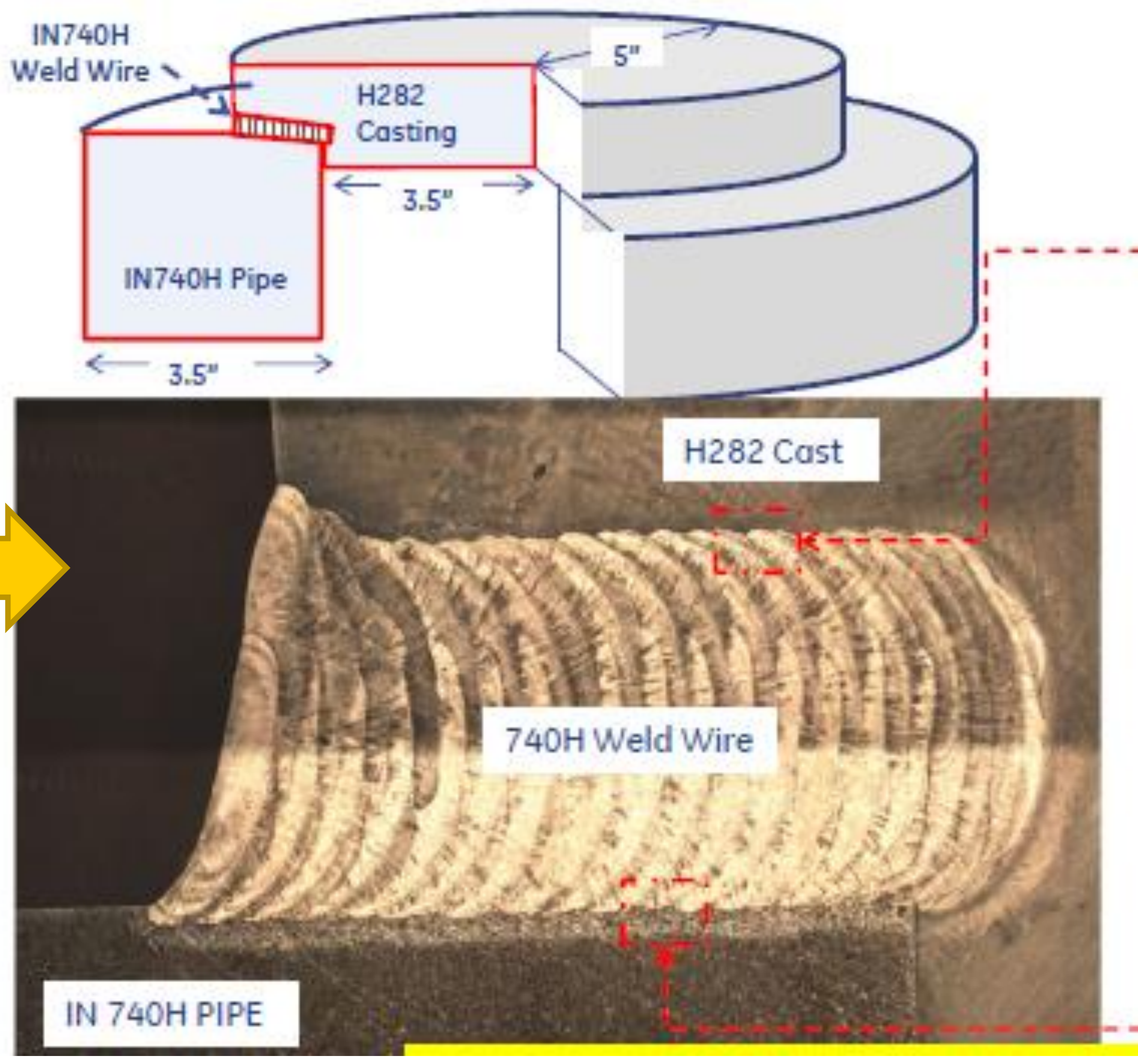
½ Valve Body Casting



Casing to Pipe Weld

- Boiler to turbine connection
- Leverage A-USC boiler knowledge from Inconel 740H welding
- Successful weld completed
- **2nd Trial with new casting planned**



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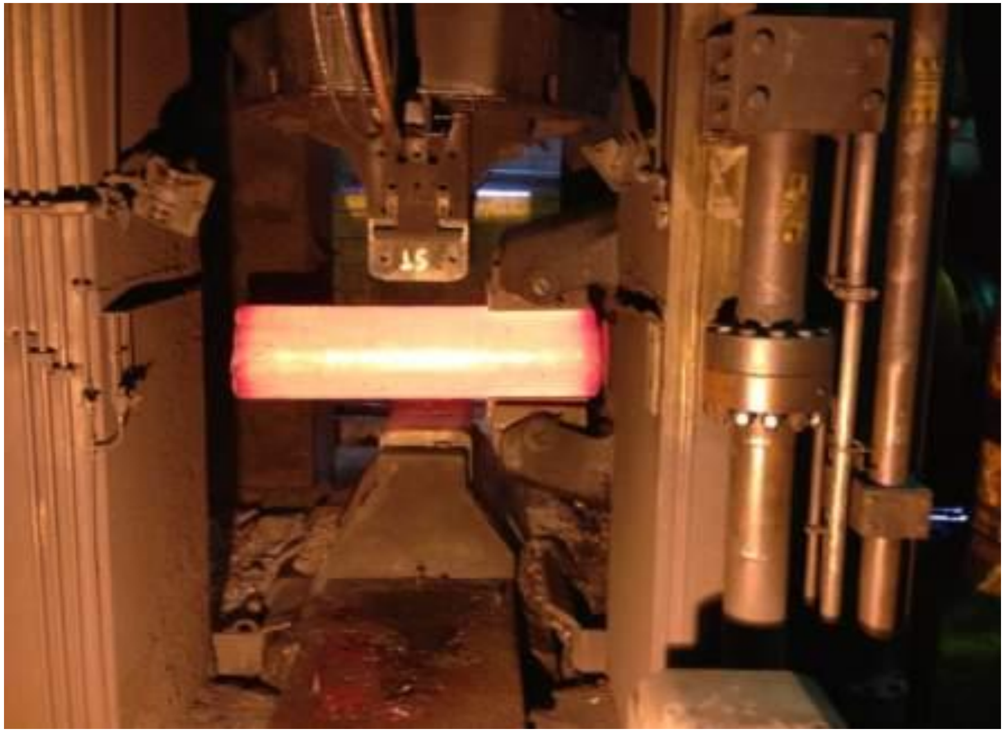
A-USC Turbine Highlight
Haynes 282 Rotor Scale-Up

Two ingots now produced:

1. Chemical homogeneity / grain size / defects evaluation
2. Disc forging



World's First Haynes 282 Triple Melt Ingot

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Haynes 282 (Triple Melt) has been successfully forged into a disc for detailed evaluations

Diameter (Top) = 44”
Diameter (Bulge) = 49.5”
Thickness = 9.5”

Disc meets criteria for largest
A-USC forging needed
(IP turbine)

Characterization Plan:
Tensile, Creep, LCF, HCF, FCGR and Toughness + fatigue in steam (ORNL)

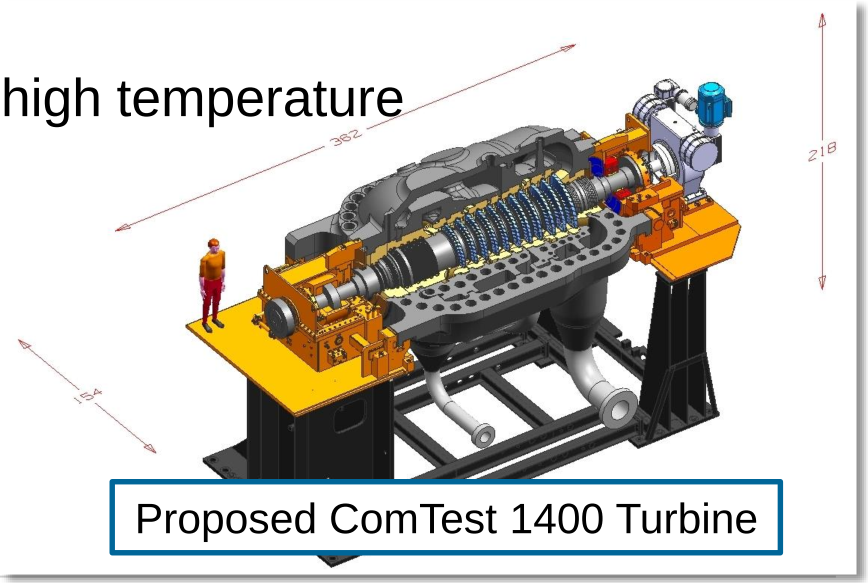
Next Steps: ComTest 1400

- Evaluation of advanced materials and components under coal fired, A-USC conditions.
- Minimize risk for a utility desiring to build an A-USC Plant.
  - Demonstrate turbine operation
  - Demonstrate reliability and safety
  - Understand manufacturing and cost
- Evaluation of the constraints in the supply chain
- Validation of fabrication techniques, and the ability to construct, install and repair ComTest with on-site labor.

Need and definition for ComTest was Developed through a focused <u>Utility Workshop</u> on the Development of A-USC Technology

Specific Goals (Defined by Utilities and Consortium)

- Boiler: Design, install, start-up, operate and **cycle** high temperature nickel components (740H & others)
  - Large diameter piping
  - Header and tubes (gas fired heater)
  - Superheater materials exposure (at pressure)
- Turbine: Design, install, start-up, operate and cycle **full size** Steam Valves & COMTEST steam turbine for 760°C (1400°F).
  - – Periodic testing of steam valves at high temperature
  - – Materials & coatings
  - – Turbine architecture
  - – Oxidation, deposits, SPE
  - – NDE/NDT
- Fabrication methods & supply chain for super-alloys



Proposed ComTest 1400 Turbine

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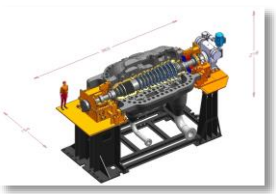
Transformational technologies will need A-USC materials and components demonstrated in ComTest



A-USC Materials R&D Consortium
(Boiler and Turbine)

A-USC ComTest

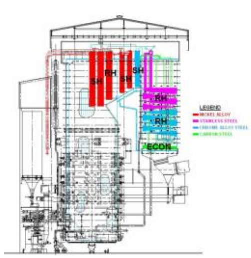
sCO2 R&D

sCO2 PILOT

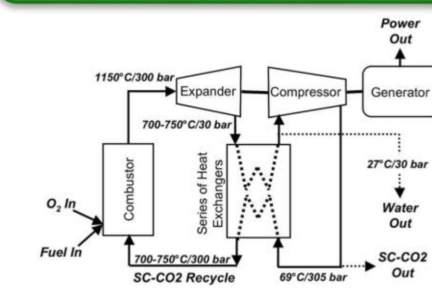
A-USC DEMO Plant

A-USC DEMO Topping/Retrofit/Repowering

sCO2 DEMO



ComTest Provides Options to Enable Transformational Technologies



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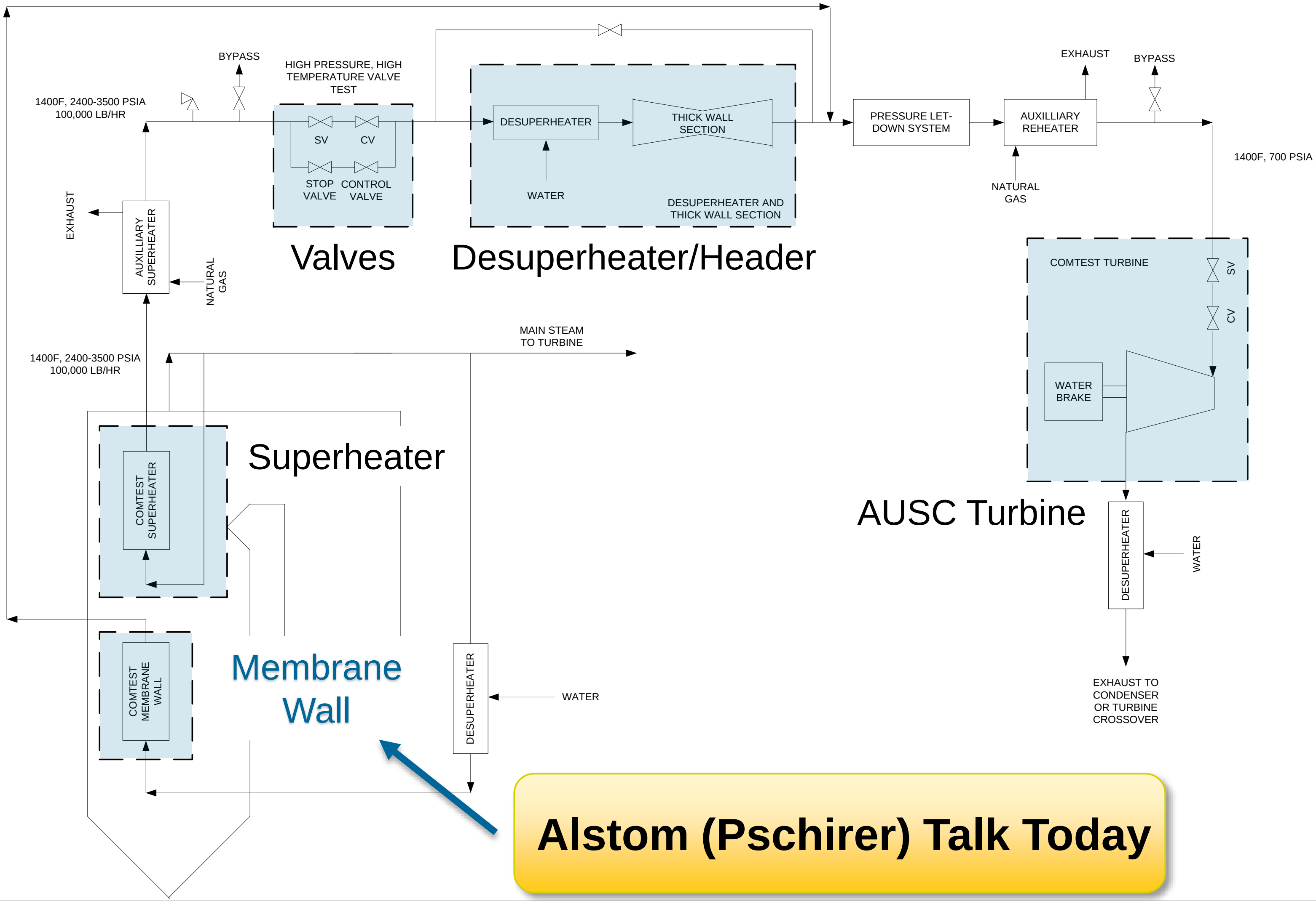
A-USC ComTest Advisory Committee

- Envisaged and formed in 2014 to primarily support the development of a U.S. based A-USC Component Test Facility
- Current Membership:
  - AEP
  - Duke
  - First Energy
  - Southern
  - Tri-State

- **Prioritize needs and provide critical input for a ComTest to build confidence in using A-USC Technology**
- **Ensure A-USC Technology is Ready when needed**
- **Support project through defining technology needs, justifying technical approach, providing potential host site(s), collaborating with the project team, and informing stakeholders**

ComTest Program (General Concept)
- Have explored options with various potential host sites to achieve overall goals



Alstom (Pschirer) Talk Today

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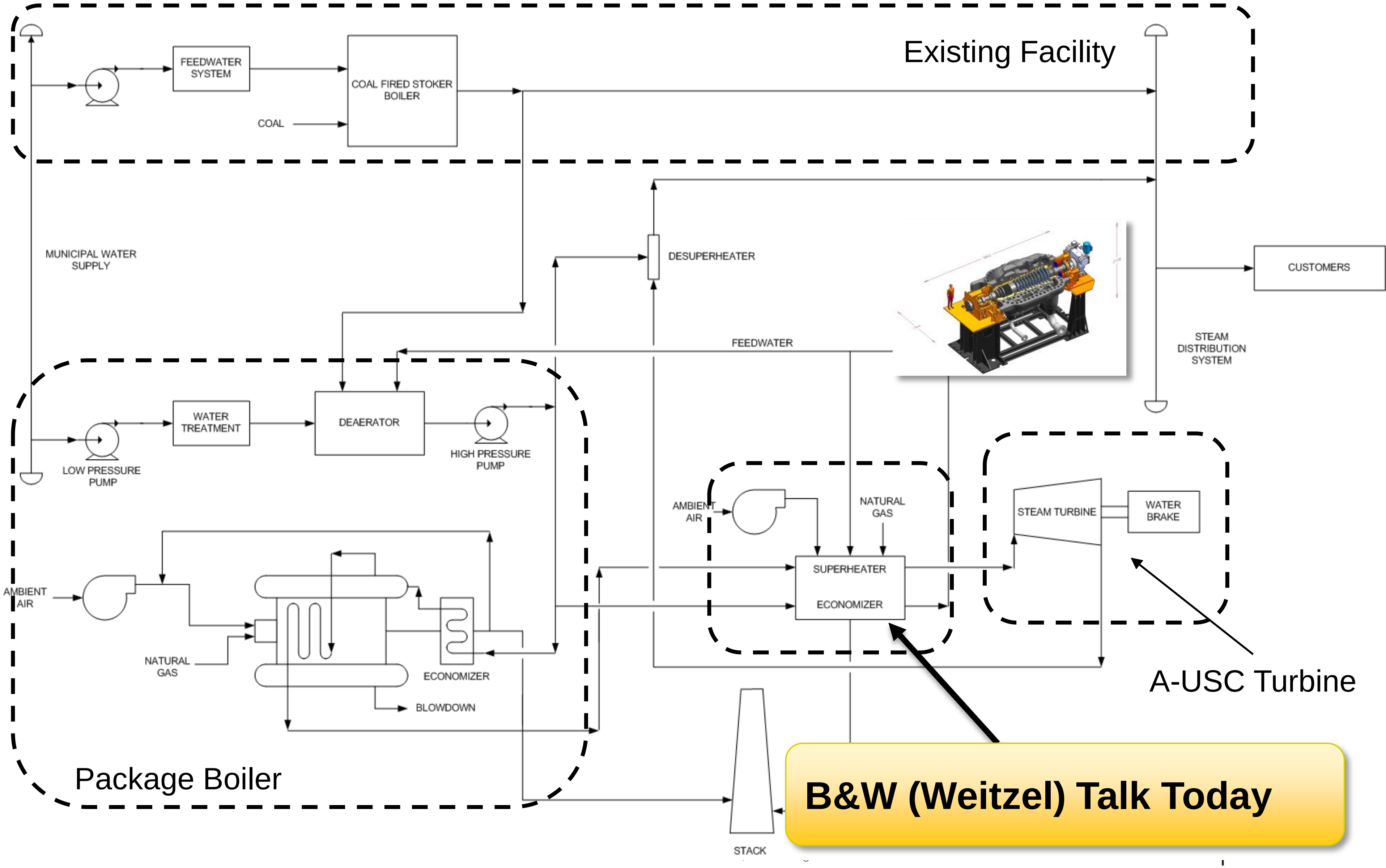
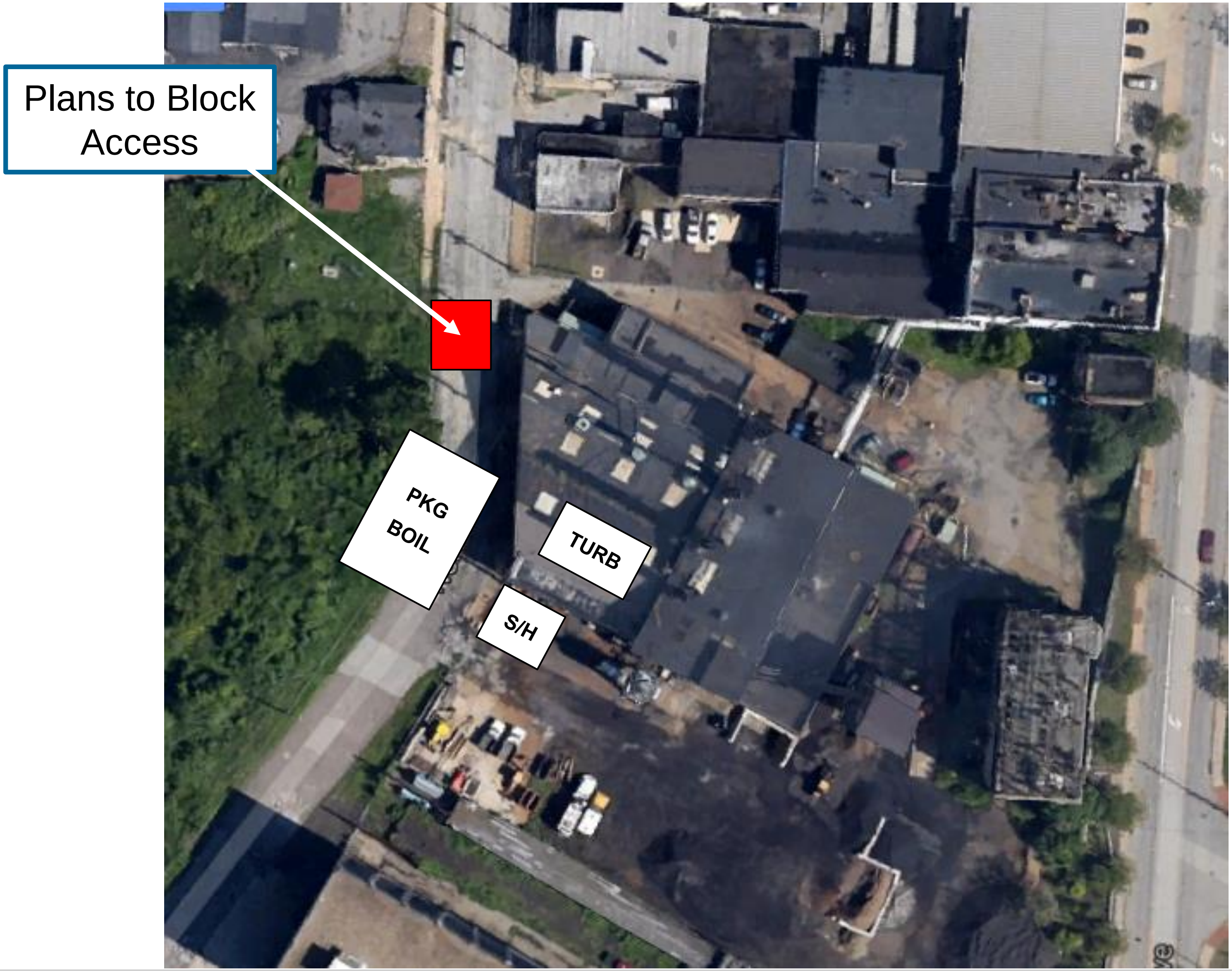
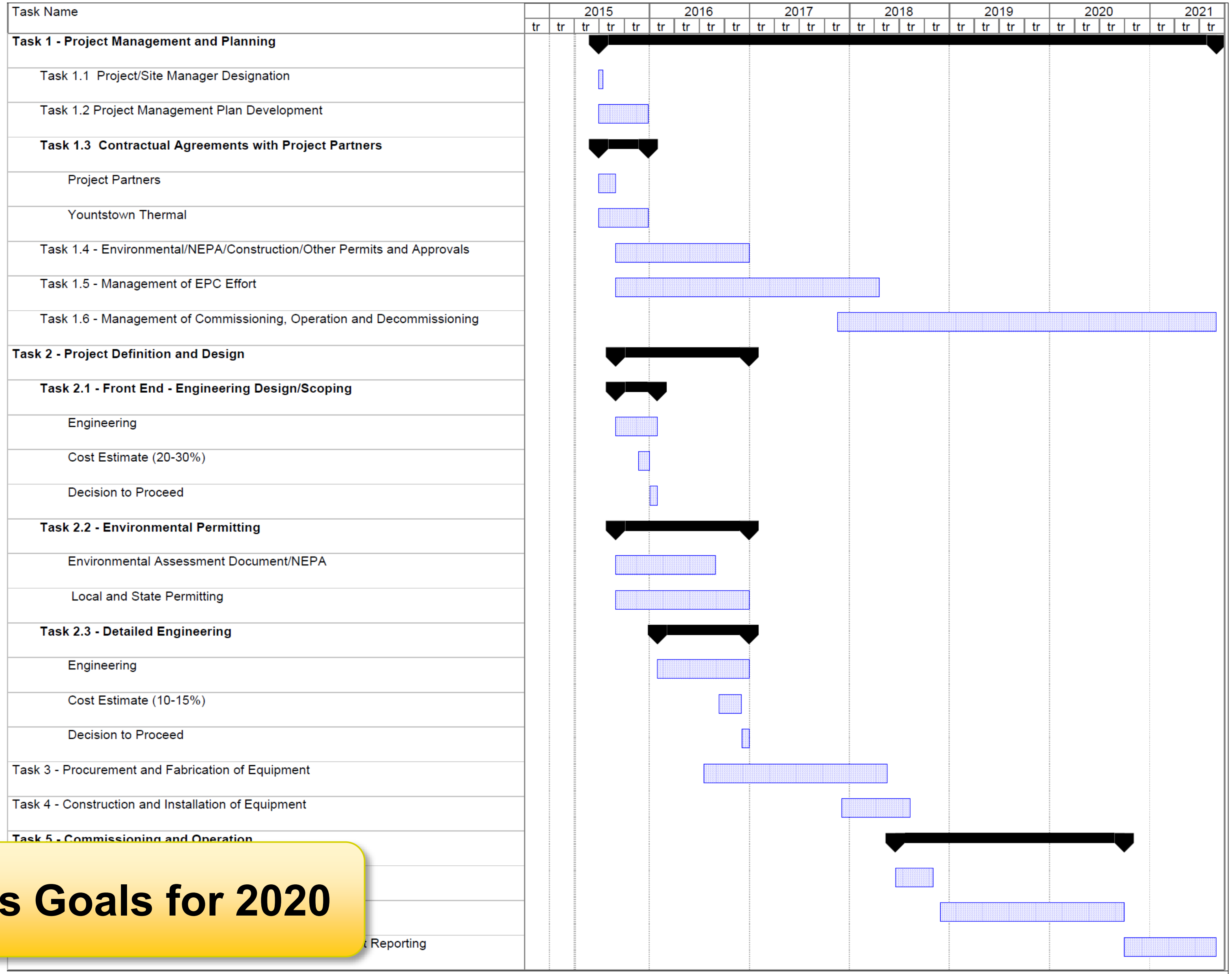
Youngstown Thermal ComTest Proposed Concept



Youngstown Site Layout (very preliminary)

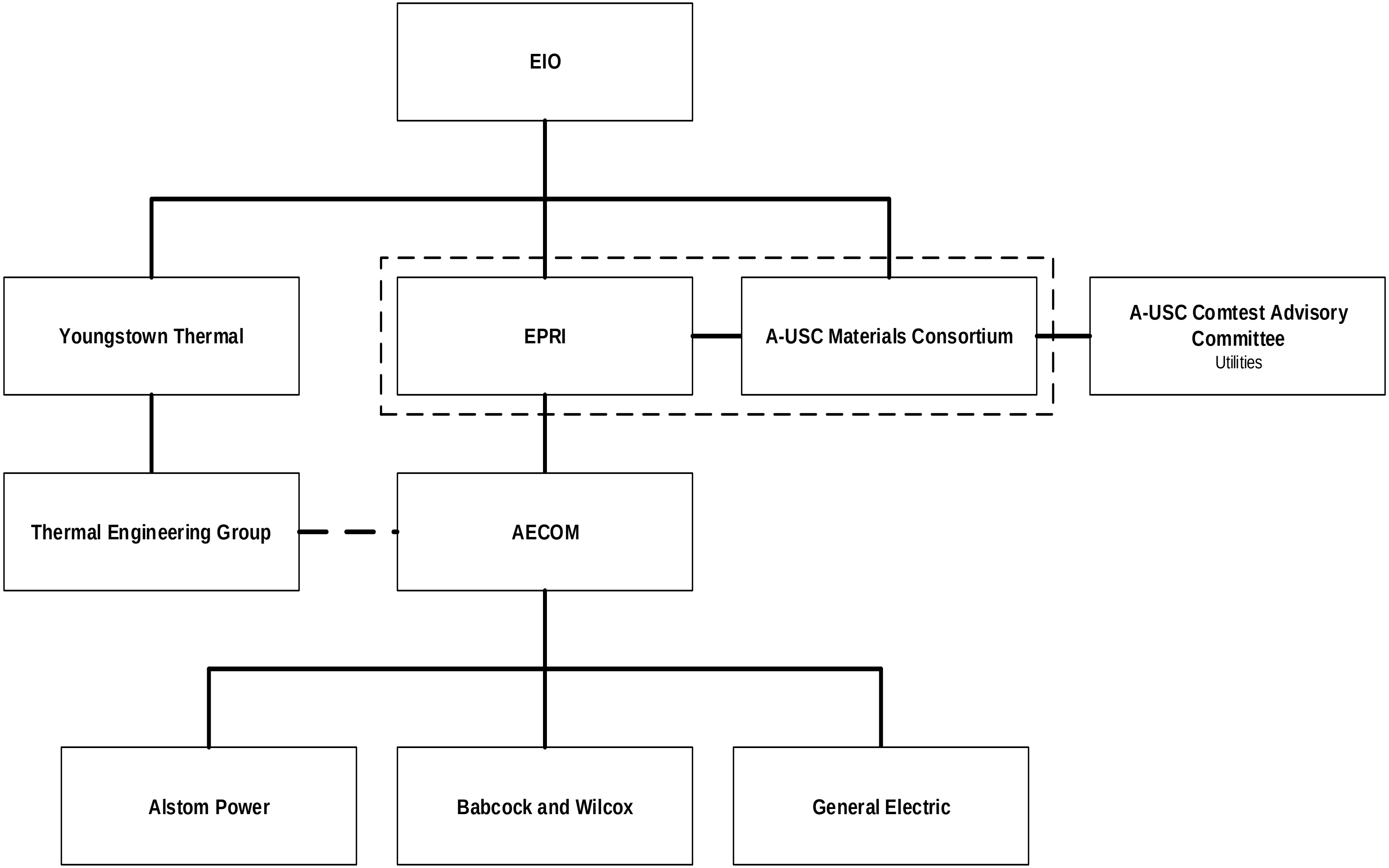


Youngstown Proposal Tasks and Timeline



Meets DOE's Goals for 2020

Project Team Proposed for Youngstown ComTest



Summary for Youngstown Site

For utilities to consider A-USC retrofit it is imperative to test a steam turbine under A-USC conditions.

- Addresses most of the overall goals for the ComTest Program
  - A-USC Turbine
  - Piping, valves, 'boiler' with membrane construction at A-USC Conditions
  - Onsite installation and operation
  - Exercises supply chain
- Benefits of the Youngstown Thermal ComTest Project
  - Existing site with needed infrastructure and a **willing host**.
  - Steam exhausting the turbine has value (their product).
  - Nearly complete control over testing conditions (cycling of unit does not affect test).
  - Excellent project team.
  - Testing could be complete by 9/2020 (if we begin in 2015).
  - "Shovel ready" project in Ohio (State support for the project)
- Limitations:
  - Low pressure in current concept form limits research on high-pressure valves and thick section components

Summary: US DOE/OCDO A-USC Consortium

- Unprecedented success in developing the materials technology to enable A-USC Steam cycles up to 760°C (1400F)
  - Extensive laboratory and shop R&D
  - Field applications for fireside corrosion
- Next Steps:
  - Component Test (ComTest) → end of precompetitive research and consortium activities
- Future for these materials <u>if a ComTest operates:</u>
  - A-USC steam cycles (enables economic oxycombustion, post combustion capture, etc.)
  - Supercritical CO_2 cycles (need 700°C+ for efficiency)
  - Existing plant retrofits to improve efficiency and reduce CO_2

2008 EPRI Study: Sub, SC, USC, and A-USC Plant Study
EPRI Report 1015699 => Not Retrofits, New Plants Only

Quantity	Sub-critical	Super-critical	600ºC USC	700ºC A-USC	760ºC A-USC
Coal Cost, $/GJ	3.42	3.42	3.42	3.42	3.42
Main Steam Temperature, °C	541	582	604	680 (3)	732 (4)
Main Steam Pressure, bar	179	262	276	352	352
Net heat rate, Btu/kWh (HHV)	9,430	8,860	8,700	7,990	7,633
Efficiency, % HHV	**35.5**	**38.5**	**39.2**	**42.7**	**44.7**
LCOE, $/MWh (1)	71.0	69.2	69.4	69.7	69.7
CO_2, kg/MWh from plant	900	851	836	763	729
Relative CO_2 emissions vs Subcritical	**100**	**94.5**	**92.9**	**84.8**	**81.0**

- Source: *Engineering and Economic Evaluation of 1300F Series Ultra-Supercritical Pulverized Coal Power Plants: Phase 1.* EPRI Report 1015699, Palo Alto, CA: September 2008.
- Footnotes:

1. Mid-2007 dollars, 30-year book life, carrying charge = 0.121, capacity factor = 85%, no CO_2 emissions cost
2. LCOE assumed to be same as for 700°C design
3. EPRI study reduced main steam temperature because of turbine material limitations. 60 Hz operation imposes more stress than European 50 Hz operation. DOE program expects to identify how this limitation can be lifted to raise efficiency by 0.7% points.
4. Conditions chosen to match current US DOE/OCDO Consortium designs with 732°C main steam and 760°C reheat

A-USC Improves Heat-Rate by up to 19%

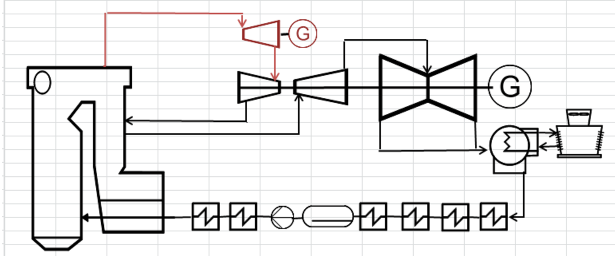
Repowering with USC/AUSC Topping Cycles

Suitable for sub-critical steam-electric power plants

- Demolish the existing sub-critical steam generator
- Build a new USC or AUSC steam generator
- Install a new USC or AUSC steam turbine-generator which exhausts at the temperature, pressure, and flow of the existing sub-critical steam turbine
- Options:
  - Reblade existing sub-critical steam generator to increase capacity/efficiency at existing design inlet temperature/pressure
  - Upgrade AQCS

The Applicability of Supercritical Topping Cycles for Repowering Subcritical Steam-Electric Power Plants. 2010. 1019676.

2010 EPRI Topping Cycle Study
Note: Max Cycle Temperature = 682C (1260F)



Base Plant Size	120 MW	160 MW	250 MW	500 MW
Base Cycle	Non-reheat	Reheat	Reheat	Reheat
Base Main Steam Temp.	538°C, 1000°F	538°C, 1000°F	538°C, 1000°F	538°C, 1000°F
Base Main Steam Press.	124 bar, 1800 psi	124 bar, 1800 psi	165 bar, 2400 psi	165 bar, 2400 psi
Base Cycle Effcy	33.50%	35.30%	35.90%	36.40%
Base Cycle Heat Rate, Btu/kWhr	10185	9666	9504	9374
USC Topping Steam Temp.	604°C, 1120°F	604°C, 1120°F	604°C, 1120°F	604°C, 1120°F
USC Topping Effcy	35.50%	37.50%	37.20%	38.00%
USC Topping Heat Rate, Btu/kWhr	9611	9099	9172	8979
USC Topping Heat Rate Reduction	**5.6%**	**5.9%**	**3.5%**	**4.2%**
A-USC Topping Steam Temp.	682°C, 1260°F	682°C, 1260°F	671°C, 1240°F	671°C, 1240°F
A-USC Topping Effcy	37.10%	38.90%	38.90%	39.20%
A-USC Topping Heat Rate, Btu/kWhr	9197	8771	8771	8704
A-USC Topping Heat Rate Reduction	**9.7%**	**9.3%**	**7.7%**	**7.1%**

A-USC 'Topping Cycles' can improve heat-rate by 3.5 to 9.7% (or greater)

Supercritical Retrofit to an Existing Subcritical Plant

- UK's DTI Project 407 based on Ferrybridge Unit
- Current subcritical unit cycle efficiency 36.7% (LHV)
  - Replacement of boiler, within existing boilerhouse
  - Pipework and turbine modifications
  - Add FGD and SCR to new plant standards
  - Reuse bulk of ancillary equipment
  - Maximize use of existing infrastructure
  - Designed to be CO2 capture ready

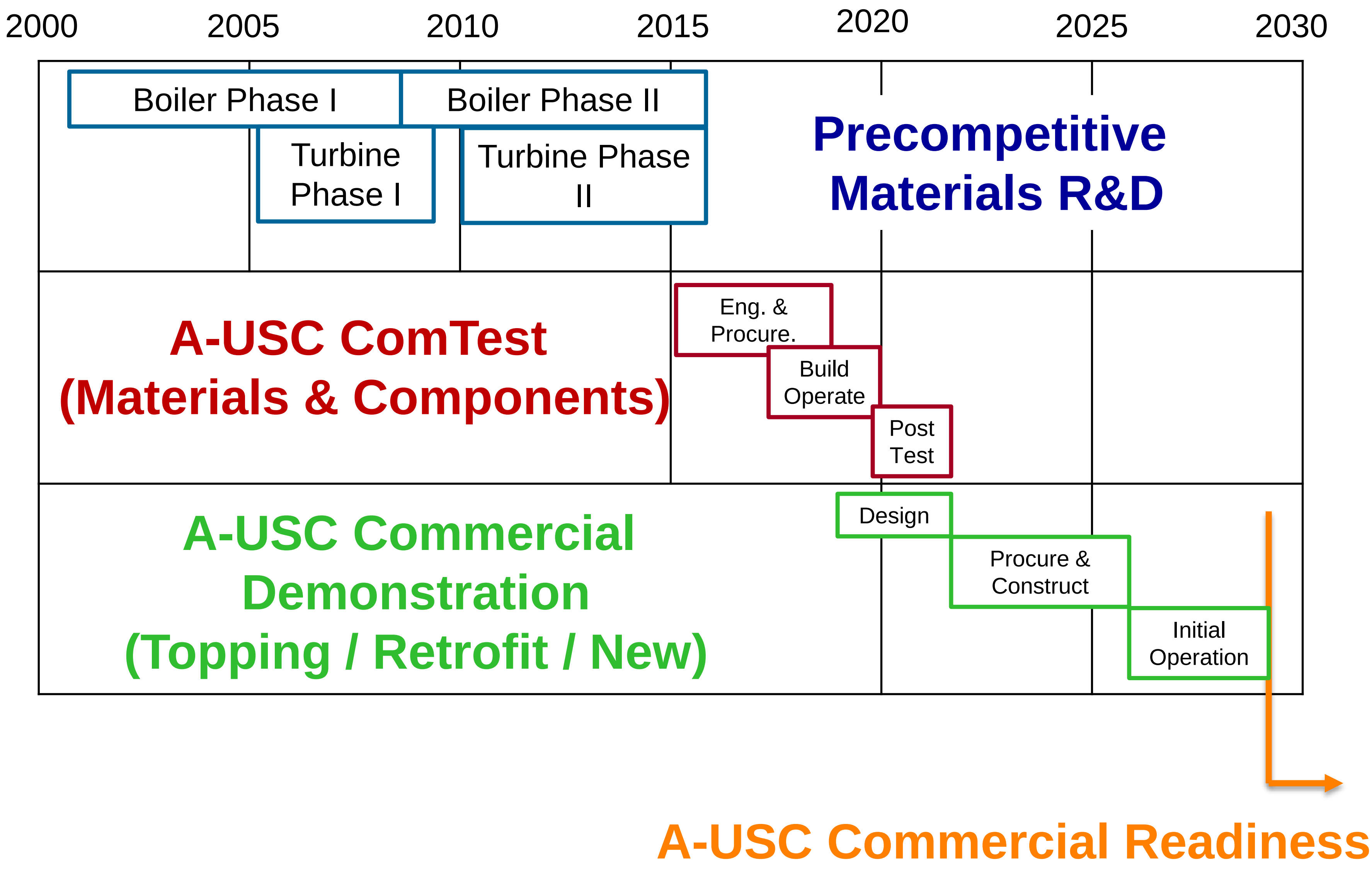
- AUSC retrofit, SCR & FGD, cycle efficiency 44.7% (LHV)
  - 22% increase in overall efficiency
  - Significant improvement despite SCR / FGD penalty
  - CO_2 reductions, at a load factor of 70%, are 483,500 te/yr (18%)

***Doosan Babcock Energy Limited* "Coal-Fired Advanced Supercritical Retrofit with CO2 Capture" DTI Project 407**

Research on A-USC and Heat-Rate

- A-USC Technology could offer significant heat-rate advantages compared to today's US baseline data
  - The data vary significantly because studies are specific to: baseline comparison, specific steam conditions, size & location of plant, fuel, etc…
- A limited amount of work has been done to evaluate retrofits, but the data are encouraging
  - Cost data (which will be unit specific) will be needed to assess this fully
- No power plant owner has implemented an A-USC retrofit yet
  - Next step in US DOE program is the deployment of a component test facility (ComTest) to build confidence in the technology and to establish the supply chain

Timeline for U.S. A-USC Development



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