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)

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

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Steam Conditions</th>
<th>Net Plant Efficiency (HHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcritical</td>
<td>2400psig 1000 to 1050°F</td>
<td>35%</td>
</tr>
<tr>
<td>Supercritical (SC)</td>
<td>&gt;3600psig ~1050°F (550°C) and above</td>
<td>38%</td>
</tr>
<tr>
<td>Ultrasupercritical (USC)</td>
<td>&gt;3600 psig ~1100°F (600°C) and above</td>
<td>&gt;42%</td>
</tr>
<tr>
<td>Advanced-UltraSupercritical (A-USC)</td>
<td>4000-5000psig 1300-1400°F (700-760°C)</td>
<td>&gt;45%</td>
</tr>
</tbody>
</table>

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
- Success Story 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)

Plant Efficiency (HHV) as a Function of Steam Temperature

- Studies: Sub-Bit/Lignite
- Studies: Bit.
- Plant Data: Sub-Bit/Lig.
- Plant Data: Bit.
- US Fleet Average 2010 (NETL)

Notes: Studies are a summary for DOE/NETL, EPRI, and IEA Reports (pulverized coal with no carbon capture and storage)

Efficiency is plant design, location, and site specific

Factors include: temperature, pressure, cycle configuration, plant size, cooling water temperature, auxiliary loads, environmental requirements
Increasing Steam Conditions Dramatically Reduce CO2 emissions (less coal burned)

Reduction in CO$_2$ as a function of Steam Temperature

Efficiency and reduction in fuel/effluents is plant design, location, and site specific. Factors include: temperature, pressure, cycle configuration, plant size, cooling water temperature, auxiliary loads, environmental requirements.

Increased Efficiency is a Least Regret Strategy for CO$_2$ Reduction

Studies show A-USC = 10-35% reduction in CO$_2$ compared to current plants
Materials Limit the Current Technology:

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

- Steels = USC 620°C (1150°F)
- Solid Soln’ = A-USC ~700°C (1300°F)
- 9-12Cr Creep-Strength Enhanced (Gr. 91, 92, 122)
- Nickel-Based Alloys
  - Inconel 740
  - CCA617
  - Std. 617
  - Haynes 282
  - Haynes 230
  - Advanced Austenitic Alloys (Super 304H, 347HFG, NF709, etc.)

Minimum Desired Strength at Application Temperature

Minimum Desired Strength at Application Temperature
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
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

- Materials Selection
- Procurement of Materials (6 alloys)
  - Initial creep testing (10,000hr)
  - Microstructure & Aging Studies
  - Vendor Discussions/Literature Search

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

SEM Image

Rupture Failure Map

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 33 months with >16,000 hrs 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

Fireside (OD)

#30 (764°C/1408°F)

CCA617

#18 (753°C / 1388°F)

Steamside (ID)

#39 (757°C/1394°F)

#38 (756°C / 1392°F)
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

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

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

• 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.

Consortium Research
Welding Advancements for Age-Hardenable Alloys

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

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

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

Metallurgical failure analysis of 38mm (1.5”) thick CCA617 Weldment Creep Samples
Highlights: World’s First Inconel®740H Pipe Extrusion

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

Additional Research Continues to Extend the Maximum Use Temperature
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
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)

Simulated casting weld defect repair

740H Pipe to 282 Casting Weld

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

Long-term creep of weldments & microstructural assessment

ORNL (Maziasz) and NETL (Jablonski) presentations later today
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)
½ Valve Body Casting

Model

Pouring

After mold shake-out

Risers removed, ready for homogenization
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
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
Haynes 282 (Triple Melt) has been successfully forged into a disc for detailed evaluations.

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

Disc meets criteria for largest A-USC forging needed (IP turbine)
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 Utility Workshop 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
Transformational technologies will need **A-USC materials** and components demonstrated in ComTest
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

VALVES

DESUPERHEATER/HEADER

SUPERHEATER

MEMBRANE WALL

AUSC TURBINE

Alstom (Pschirer) Talk Today
Youngstown Thermal ComTest Proposed Concept

Existing Facility

Package Boiler

A-USC Turbine

B&W (Weitzel) Talk Today
Youngstown Site Layout (very preliminary)

Plans to Block Access

PKG BOIL

TURB

S/H
Youngstown Proposal Tasks and Timeline

Meets DOE’s Goals for 2020
Project Team Proposed for Youngstown ComTest

- Youngstown Thermal
- Thermal Engineering Group
- EPRI
- AECOM
- A-USC Materials Consortium
- A-USC Comtest Advisory Committee
- Utilities
- Alstom Power
- Babcock and Wilcox
- General Electric

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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 if a ComTest operates:
  - A-USC steam cycles (enables economic oxycombustion, post combustion capture, etc.)
  - Supercritical CO₂ cycles (need 700°C+ for efficiency)
  - Existing plant retrofits to improve efficiency and reduce CO₂
### 2008 EPRI Study: Sub, SC, USC, and A-USC Plant Study

**EPRI Report 1015699 => Not Retrofits, New Plants Only**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Sub-critical</th>
<th>Super-critical</th>
<th>600°C USC</th>
<th>700°C A-USC</th>
<th>760°C A-USC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Cost, $/GJ</td>
<td>3.42</td>
<td>3.42</td>
<td>3.42</td>
<td>3.42</td>
<td>3.42</td>
</tr>
<tr>
<td>Main Steam Temperature, °C</td>
<td>541</td>
<td>582</td>
<td>604</td>
<td>680 (3)</td>
<td>732 (4)</td>
</tr>
<tr>
<td>Main Steam Pressure, bar</td>
<td>179</td>
<td>262</td>
<td>276</td>
<td>352</td>
<td>352</td>
</tr>
<tr>
<td>Net heat rate, Btu/kWh (HHV)</td>
<td>9,430</td>
<td>8,860</td>
<td>8,700</td>
<td>7,990</td>
<td>7,633</td>
</tr>
<tr>
<td>Efficiency, % HHV</td>
<td>35.5</td>
<td>38.5</td>
<td>39.2</td>
<td>42.7</td>
<td>44.7</td>
</tr>
<tr>
<td>LCOE, $/MWh (1)</td>
<td>71.0</td>
<td>69.2</td>
<td>69.4</td>
<td>69.7</td>
<td>69.7</td>
</tr>
<tr>
<td>CO₂, kg/MWh from plant</td>
<td>900</td>
<td>851</td>
<td>836</td>
<td>763</td>
<td>729</td>
</tr>
<tr>
<td>Relative CO₂ emissions vs Subcritical</td>
<td>100</td>
<td>94.5</td>
<td>92.9</td>
<td>84.8</td>
<td>81.0</td>
</tr>
</tbody>
</table>

- **Footnotes:**
  1. Mid-2007 dollars, 30-year book life, carrying charge = 0.121, capacity factor = 85%, no CO₂ 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

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**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 = 682°C (1260°F)

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

**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
  - CO₂ reductions, at a load factor of 70%, are 483,500 te/yr (18%)
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
Together…Shaping the Future of Electricity