Advanced
Ultrasupercritical Update
Rankine Cycles above 1200°F

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It’s All About Thermal Efficiency

- According to Sadi Carnot
  - Thermal Efficiency = 1 – $T_L/T_H$
- To get higher efficiencies, we must minimize the value of $T_L/T_H$
- We cannot do much to reduce $T_L$, but we can increase $T_H$ by operating at higher temperatures

http://www.wikiwand.com/fr/Sadi_Carnot_(physicien)
US Coal Power Plant Thermal Efficiency Through the Years

- Efficiency grew significantly and rapidly from 1920 to 1960
- Has plateaued since 1960s
- Steam turbine inlet temperatures rose from 600°F (315°C) in 1920 to between 1000°F and 1100°F (538°C and 600°C) in the 1960s
- Moving beyond today’s efficiency level will require moving beyond ferritic steels
14-year DOE-Ohio AUSC Materials Program

- Initiation of A-USC boiler materials program
- Validation of boiler component fabrication techniques
- Long-term creep testing of full-size weldments (50,000+ hours)
- Alabama Power Plant Barry steam loop at 760°C (1400°F)
- Long-term creep testing of full-size weldments (50,000+ hours)
- Initiation of steam turbine materials program
- Long-term creep tests on Inconel 740H
- ASME Code Case 2702 Inconel 740H approved
- Haynes 282 casting demonstration turbine valve body (17,000 pounds)
- DOE final report submitted
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 >16,000hrs 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

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Conclusions – Fireside corrosion of IN740

- In general, the depth of attack at Barry seems to be smaller than those in previously tested steam loops & probes in other boilers
  - Lower-sulfur coal used at Plant Barry is benign
- Corrosion rates from lab tests are varying over a wide range (>1 order of magnitude)
- Corrosion rates from recent Alstom testing (green triangles) are close to corrosion rates experienced in Barry Steam Loop
DOE/OCDO A-USC Steam Turbine Consortium

- Selected Materials from Phase I
- Rotor/Disc Testing (full-size forgings)
- Blade/Bucket Alloy Testing
- Cast Casing Scale-Up Alloy Testing
- Casing Welding and Repair
- A-USC Economics

1400°F (760°C) Steam Turbine Conceptual Design (HP) – Bolted Construction
Modeling and Large-Scale Casting Development

- 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)
Haynes 282 Steam Turbine Valve Casing

- Large Casting Material Evaluation Test Results

- Worlds first large Haynes 282 casting with poured weight 17000 lbs.
  - Casting wall thicknesses range 3.5 to 8 inches
  - SDAS values in the range of 215µ to 275µ
  - Met VT, RT and LPT, NDT Inspection and acceptance criteria
- Chemical analysis, tensile, LCF, stress rupture, Charpy and fracture toughness test results of cast on coupons, trepan and chilled cast sections were summarized
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

- Future for these materials:
  - A-USC steam cycles (enables economic oxy-combustion, post-combustion capture, etc.)
  - Supercritical CO₂ cycles (need >700°C for efficiency)
  - Existing plant retrofits to improve efficiency and reduce CO₂
## USC vs A-USC Performance & Cost Comparisons

<table>
<thead>
<tr>
<th></th>
<th>USC Plant</th>
<th></th>
<th>A-USC Plant</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without PCC</td>
<td>With PCC</td>
<td>without PCC</td>
<td>With PCC</td>
</tr>
<tr>
<td><strong>Main and Reheat Steam Temperature, °F</strong></td>
<td>1100/1100</td>
<td>1100/1100</td>
<td>1350/1400</td>
<td>1350/1400</td>
</tr>
<tr>
<td><strong>CO₂ Emissions lb/MWh-gross</strong></td>
<td>1758</td>
<td>1400</td>
<td>1592</td>
<td>1400</td>
</tr>
<tr>
<td><strong>Net Power Output, MW</strong></td>
<td>749.6</td>
<td>709.0</td>
<td>754.2</td>
<td>734.3</td>
</tr>
<tr>
<td><strong>Net Efficiency, % (HHV)</strong></td>
<td>38.8</td>
<td>36.7</td>
<td>41.4</td>
<td>40.3</td>
</tr>
<tr>
<td><strong>% of Flue Gas to Capture</strong></td>
<td>0</td>
<td>24</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total Plant Cost, $/kW</strong></td>
<td>2,637</td>
<td><strong>3,306</strong></td>
<td>2,933</td>
<td><strong>3,190</strong></td>
</tr>
<tr>
<td><strong>LCOE, $/MWh (including CO₂ T&amp;S cost)</strong></td>
<td>80.0</td>
<td><strong>98.9</strong></td>
<td>84.7</td>
<td><strong>93.3</strong></td>
</tr>
<tr>
<td><strong>Cost of CO₂ Avoided, $/tonne (relative to USC w/o PCC)</strong></td>
<td>124</td>
<td>84</td>
<td>96</td>
<td></td>
</tr>
</tbody>
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Both plants firing Powder River Basin sub-bituminous coal

**USC at 1400 lb CO₂/MWhr extrapolated from DOE/NELT-2015/1720 results**

**Estimate $5/MWh advantage for A-USC at 1400 lb CO₂/MWhr**
The Next Step: AUSC ComTest (Component Test)

- **Boiler:** Design, install, start-up, operate and **cycle** high temperature nickel components (740H & others)
  - Large diameter piping (commercial-scale)
  - Header and tubes
  - Superheater materials exposure
- **Turbine:** Design, install, start-up, operate and cycle 760°C (1400°F) 8 MW steam turbine & **full size** steam valves
  - Materials & coatings
  - Turbine architecture
  - Oxidation, deposits, SPE
  - NDE/NDT
- Fabrication methods & supply chain for super-alloys
ComTest Schematic

- Plan 8,000 hours at high temp., press.
- Steady state and ramping conditions
- Complete by 2020

Testing of full scope may require testing at additional facilities in the future.

Superheater Header

Membrane Wall / Superheater

STEAM FROM HOST

HIGH PRESSURE, HIGH TEMPERATURE VALVE TEST

SV
CV

THICK WALL SECTION

PRESSURE LET-DOWN SYSTEM

REHEATER

NATURAL GAS

EXHAUST

TEMPERATURE, PRESSURE ADJUSTMENT

RETURN TO HOST

EXHAUST

SUPERHEATER

NATURAL GAS

EXHAUST

NATURAL GAS

THICK WALL SECTION

SV
CV

HIGH PRESSURE, HIGH TEMPERATURE VALVE TEST

Turbine Inlet Conditions
1400°F, 600 psig, ~130,000 lb/hr

A-USC Turbine

WATER BRAKE

TEMPEPROURE, PRESSURE ADJUSTMENT

RETURN TO HOST

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Proposed A-USC Test Site Youngstown, Ohio (Former Ohio Edison Generation Plant)
A-USC ComTest Preliminary Schedule

- Pre-FEED
- NEPA
- FEED
- Detailed Engineering
- Procurement & Construction
- Operation
  - Membrane Wall & SH
  - Cycling Header & Valves
  - Steam Turbine
- Evaluation & Reporting

Key:
- Milestone (i.e. meeting, presentation)
- Deliverable (i.e. report)
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