State-of-the-Art Ultra-Supercritical (USC) and readiness for Advanced Ultra-Supercritical (AUSC) Steam Power Plants

John Marion
Director Boiler Technology and R&D

International Conference on Advanced Technologies and Best Practices for Supercritical Thermal Plants, New Delhi, India

22 November 2013
Agenda

• Introduction Alstom Power
• Industry Evolution of Steam Conditions
• Today’s State-of-the-art SC and USC power plants
• AUSC power plant development
• Next steps
Group – Power, Grid, Transport

Thermal Power
- 9.2 €bn

Renewable Power
- 1.8 €bn

Grid
- 3.8 €bn

Transport
- 5.5 €bn

- Total sales 2012/13 = 20.3 €bn
- Total orders 2012/13 = 23.8 €bn

GAS

COAL

OIL

BIOMASS

NUCLEAR

HYDRO

TIDAL

GEOTHERMAL

SOLAR

WIND (off + onshore)
Steam product range - Power plants, systems, components

Full turnkey Steam Plants  Boiler Islands (incl. AQCS)  Turbine Islands  Components

ALSTOM Boiler Projects
in design, construction, commissioning or recent operation

SC, Sub SH or RH < 600 °C
Ultra SC, SH or RH ≥ 600 °C
Economics continue to drive efficiency improvements. This will be achieved by several technological steps including higher steam conditions enabled by cost effective materials advances.
## Current maximum steam conditions by region

<table>
<thead>
<tr>
<th>Steam conditions</th>
<th>Europe</th>
<th>China</th>
<th>India</th>
<th>Japan</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure - bar /psig</td>
<td>293</td>
<td>4292</td>
<td>293</td>
<td>4307</td>
<td>254</td>
</tr>
<tr>
<td>SH Temp. - °C/°F</td>
<td>603</td>
<td>1117</td>
<td>605</td>
<td>1121</td>
<td>603</td>
</tr>
<tr>
<td>RH Temp. - °C/°F</td>
<td>621</td>
<td>1150</td>
<td>623</td>
<td>1153</td>
<td>613</td>
</tr>
</tbody>
</table>

**Source:** Alstom analysis

## Current Alstom References (ST or Boiler) (including Licensees)

<table>
<thead>
<tr>
<th>Steam conditions</th>
<th>Europe</th>
<th>China</th>
<th>India</th>
<th>Japan</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure - bar /psig</td>
<td>292</td>
<td>4292</td>
<td>276</td>
<td>3990</td>
<td>242</td>
</tr>
<tr>
<td>SH Temp. - °C/°F</td>
<td>603</td>
<td>1117</td>
<td>605</td>
<td>1120</td>
<td>600</td>
</tr>
<tr>
<td>RH Temp. - °C/°F</td>
<td>621</td>
<td>1150</td>
<td>603</td>
<td>1117</td>
<td>600</td>
</tr>
</tbody>
</table>

**Source:** Alstom analysis
Alstom experience in advancing steam conditions

• Pioneered World’s First Utility Scale Ultra-Supercritical Steam Plant
  • 1954 design phase to 1960 startup
  • Initial steam conditions: **365 bar** (5293 psig), 1200/1050/1050°F (649/566/566°C)
  • Tempered steam conditions: **340 bar** (5000 psig), 1135/1050/1050°F (613/566/566°C)

• Retired in 2011 after more than **50 years** of operation
  • Operated at most advanced steam conditions of any coal-fired boiler in the world

Philadelphia Electric Co. (now Excelon) Eddystone Station

325 MW Eddystone Boiler
Alstom tangential fired-type
Alstom is a world leader in supercritical boiler design

Supercritical Experience:

- **113** Alstom directly executed supercritical boilers in operation or under construction, worldwide
  - Over **70,000 MWe**
  - Most units in operation for over 30 years

- **200** boilers supplied by licensees, using Alstom technology
  - **132,000 MWe**
State-of-the-Art Steam Power Plant
Example: TNBJ Manjung Unit 4 - Malaysia

OWNER: TNB JANAMANJUNG

PLANT OUTPUT = 1,000 MWe (net)

BOILER DESIGN PARAMETERS

MAIN STEAM: 282.4 bar (4095 psi)
600 °C (1112 °F)
3,226 t/hr (7,112,000 lb/hr)

REHEAT STEAM: 60.6 bar (879 psi)
605 °C (1121 °F)
2,687 t/hr (5,924,000 lb/hr)

FEEDWATER: 304 °C (579 °F)

FUEL: Sub-bituminous coal

All data at BMCR, operating data
# Manjung Unit 4

## Boiler design features

**Design Features**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler type</td>
<td>Two pass, sliding pressure supercritical</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Base load and two-shift</td>
</tr>
<tr>
<td>Circulation system</td>
<td>Once-through</td>
</tr>
<tr>
<td>Start-up system</td>
<td>Pump recirculation (≤ 35% load)</td>
</tr>
<tr>
<td>Furnace walls</td>
<td>Vertical tube (Combined Circulation Plus™)</td>
</tr>
<tr>
<td>Firing system</td>
<td>Two-fireball with improved tangential firing (LNTFS)</td>
</tr>
<tr>
<td>Furnace cleaning</td>
<td>Steam sootblowers</td>
</tr>
<tr>
<td>Economizer</td>
<td>Bare tube</td>
</tr>
<tr>
<td>Coal mills</td>
<td>8 x Alstom HP mills with dynamic classifiers</td>
</tr>
<tr>
<td>Air Fans</td>
<td>2 x 60% PA, 2 x 60% FD</td>
</tr>
<tr>
<td>Air Heaters</td>
<td>2 x Alstom regenerative tri-sector</td>
</tr>
</tbody>
</table>

**Alstom Scope**

<table>
<thead>
<tr>
<th>Scope</th>
<th>Turnkey Plant</th>
</tr>
</thead>
</table>

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State-of-the-Art Steam Power Plant
Example: RDK8 - Germany

OWNER: EnBW

PLANT OUTPUT = 912 MWe (net)

BOILER DESIGN PARAMETERS

MAIN STEAM: 292 bar (4292 psi)
603°C (1117 °F)
2,419 t/hr (5,334,000 lb/hr)

REHEAT STEAM: 61 bar (897 psi)
621 °C (1150 °F)
2,007 t/hr (4,425,000 lb/hr)

FEEDWATER: 307 °C (584 °F)

FUEL: Bituminous coal

All data at BMCR, operating data
## RDK8
Boiler design features

### Design Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler type</td>
<td>Tower type, sliding pressure supercritical</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Base load and two-shift</td>
</tr>
<tr>
<td>Circulation system</td>
<td>Once-through</td>
</tr>
<tr>
<td>Start-up system</td>
<td>Pump recirculation (≤ 35% load) optimized ≤20% load</td>
</tr>
<tr>
<td>Furnace walls</td>
<td>Spiral Wound</td>
</tr>
<tr>
<td>Firing system</td>
<td>Single-fireball with improved tangential firing (LNTFS)</td>
</tr>
<tr>
<td>Furnace cleaning</td>
<td>Water lance</td>
</tr>
<tr>
<td>Economizer</td>
<td>Fin tube</td>
</tr>
<tr>
<td>Coal mills</td>
<td>4 x Alstom SM mills with dynamic classifiers</td>
</tr>
<tr>
<td>Air Fans</td>
<td>1 x 100% PA, 1 x 100% FD, 1 x 100% ID</td>
</tr>
<tr>
<td>Air Heaters</td>
<td>1 x Alstom regenerative quad-sector</td>
</tr>
</tbody>
</table>

### Alstom Scope

| Scope                        | Turnkey Plant                                      |
### State-of-the-Art Steam Power Plant

Example: NTPC – Barh II, India

<table>
<thead>
<tr>
<th><strong>BOILER DESIGN PARAMETERS</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN STEAM:</strong></td>
<td><strong>REHEAT STEAM:</strong></td>
</tr>
<tr>
<td>255 kg/cm²</td>
<td>54.7 kg/cm²</td>
</tr>
<tr>
<td>568 °C</td>
<td>596 °C</td>
</tr>
<tr>
<td>2120 t/hr</td>
<td>1708 t/hr</td>
</tr>
<tr>
<td>(3628 psi)</td>
<td>(778 psi)</td>
</tr>
<tr>
<td>(1054 °F)</td>
<td>(1105 °F)</td>
</tr>
<tr>
<td>(4,674,000 lbs/hr)</td>
<td>(3,765,000 lbs/hr)</td>
</tr>
</tbody>
</table>

**OWNER:** NTPC, Ltd.

**PLANT OUTPUT = 2 x 660 Mwe**

**FUEL:** Domestic Unwashed Coal

All data at BMCR, operating data
## Barh II, Units 4 & 5
### Boiler design features

<table>
<thead>
<tr>
<th>Design Features</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler type</td>
<td>Two pass, sliding pressure supercritical</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Base load and two-shift</td>
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<tr>
<td>Circulation system</td>
<td>Once-through</td>
</tr>
<tr>
<td>Start-up system</td>
<td>Pump recirculation (&lt; 40% load)</td>
</tr>
<tr>
<td>Furnace walls</td>
<td>Spiral Wall</td>
</tr>
<tr>
<td>Firing system</td>
<td>Improved tangential firing (LNTFS)</td>
</tr>
<tr>
<td>Furnace cleaning</td>
<td>Steam sootblowing</td>
</tr>
<tr>
<td>Economizer</td>
<td>Bare tube</td>
</tr>
<tr>
<td>Coal mills</td>
<td>9 x Alstom HP mills</td>
</tr>
<tr>
<td>Air Fans</td>
<td>2 x 60% PA, 2 x 60% FD</td>
</tr>
<tr>
<td>NOx reduction</td>
<td>LNTFS</td>
</tr>
<tr>
<td>Air Heaters</td>
<td>2 x Alstom regenerative bi-sector primary air and 2 x Alstom regenerative bi-sector secondary air</td>
</tr>
</tbody>
</table>

### Alstom/BHEL Scope

| Alstom/BHEL scope | Boiler island supply plus construction - boiler, mills, air fans, air heater, bottom ash, etc. |

Barh II 2 x 660 Mwe
Bituminous coal
OWNER: M/S Andra Pradesh Power Development Company, Ltd.

PLANT OUTPUT = 2 x 800 Mwe

**BOILER DESIGN PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAIN STEAM:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>255 kg/cm²</td>
<td>(3628 psi)</td>
</tr>
<tr>
<td>Temperature</td>
<td>568 °C</td>
<td>(1054 °F)</td>
</tr>
<tr>
<td>Flow</td>
<td>2600 t/hr</td>
<td>(5,720,000 lbs/hr)</td>
</tr>
<tr>
<td><strong>REHEAT STEAM:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>54.7 kg/cm²</td>
<td>(778 psi)</td>
</tr>
<tr>
<td>Temperature</td>
<td>596 °C</td>
<td>(1105 °F)</td>
</tr>
<tr>
<td>Flow</td>
<td>2052 t/hr</td>
<td>(4,514,000 lbs/hr)</td>
</tr>
<tr>
<td><strong>FEEDWATER:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>307 °C</td>
<td>(585 °F)</td>
</tr>
<tr>
<td><strong>FUEL:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Domestic washed + imported Coal</td>
<td></td>
</tr>
</tbody>
</table>

All data at BMCR, operating data
Krishnapatnam, stage 1, Units 1 & 2
Boiler design features

### Design Features

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<td>Bare tube</td>
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<tr>
<td>Coal mills</td>
<td>6 x Alstom HP mills</td>
</tr>
<tr>
<td>Air Fans</td>
<td>2 x 50% PA, 2 x 50% FD</td>
</tr>
<tr>
<td>NOx reduction</td>
<td>LNTFS</td>
</tr>
<tr>
<td>Air Heaters</td>
<td>2 x Alstom regenerative tri-sector air heaters</td>
</tr>
</tbody>
</table>

### Alstom/BHEL Scope

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<td>Boiler island supply plus construction - boiler, mills, air fans, air heater, bottom ash, etc.</td>
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</tbody>
</table>
Reliability with SC / USC units

• Design
  – Materials selection and margin
  – Predictable gas temperatures and heat transfer
  – PP component design

• Fabrication / Construction
  – Stringent QA purchased materials
  – Process specification and management
  – Personnel training
  – Strict on-site inspection

• Operations
  – Adherence to OEM operation guidance
  – Routine maintenance

ASME allowable stresses for advanced boiler materials

“Advanced” ferritic alloys - precipitation hardened

Care to avoid, example; internal oxidation, stress corrosion cracking, microstructure changes in bending
Jumping to A-USC

- A-USC refers to steam cycles with steam temps of 700-760°C (1300-1400°F)
- A-USC steam cycles increase net plant efficiency by ~ +9% vs. USC (600°C or 1100°F)
- A-USC reduces emissions (including CO2) and flue gas volumes making equipment smaller
A-USC Development Required

- Achieving 700/760°C steam temps requires:
  - New materials
  - New fabrication techniques

- New materials include:
  - Ni-based alloys for SH/RH tubing/piping and turbine forgings/castings
    - 617, 263, Sanicro 25, 740, 625

- New fabrication techniques include:
  - Membrane wall tube panels from high-Cr ferritic alloy (T91/92)
  - Dissimilar welds in turbine rotor
A-USC Development Programs

- Alstom is strongly involved in A-USC development:

  - For 700-760°C steam temperatures
    - In collaboration with various groups in Europe and USA
    - Material tests completed and also on-going
    - Component tests completed
    - Component tests (thick walled) under cyclic conditions on-going
    - Detailed 550 MW Tower boiler design
    - 550 MW steam turbine design
    - 1000 MW reference Two Pass boiler design
    - 1100 MW reference Tower boiler design
    - 1100 MW steam turbine design
    - 1100 MW steam plant concept design
Alstom involvement in A-USC Development
Europe (700C)

AD 700-2
Amager Test Rig

Water Wall Panels
Manufacturing

COMTES 700
Components Test Facility

Esbjerg Test Rig
720°C Test Loop

In 817 Welding for Large Wall Thicknesses

In the framework of the Marck of D62
Program, welding tests of pipes were
successfully performed in ALSTOM Power
Boiler in Stuttgart.

MARCKO 700
Header from Alloy 817 mod.

Header: OD 400 x 80 mm
Nozzles: 38 x 6.3 mm
Header-Nozzle-Welds:
Inside-ﬁt
Outside-ﬁt

725 HTW GKM
Steam Flow Diagram
Alstom involvement in A-USC Development
USA (760°C)

- DOE, the State of Ohio Office of Coal Development and Industry have teamed to develop next generation technology which will provide efficiency and environmental gains

- A uniquely qualified industry team - Energy Industry of Ohio, all the major US boiler manufacturers, US steam turbine manufacturers, Oak Ridge National lab, Ohio organizations, and EPRI

- An aggressive goal – 760C (1400F) steam temperature
  - Exploit strength
  - Cost is justified

Cost of (precipitation strengthened) nickel-based alloys for 760°C applications is predicted to be similar to their weaker (solution strengthened) counterparts for 700°C applications - More nickel alloy for 760°C, but not more expensive.
Alstom involvement in A-USC Development USA (760°C)

1: Conceptual Design
2: Material Properties
3: Steamside Oxidation
4: Fireside Corrosion
5: Welding
6: Fabricability
7: Coatings
8: Design Data & Rules (including Code interface)
A-USC – USA (760 C)  
Barry Steam Loop

Candidate materials for A-USC steam conditions have been installed in an operating coal fired boiler. Field exposure testing at A-USC steam temperature (1400°F) will validate laboratory corrosion and oxidation testing.

Loop in operation since early 2012 and planned through September 2014

Super304H, HR3C, HR6W, Haynes 230, Haynes 230 with an Amstar thermal spray, Inconel 617, Inconel 617 with EN33 laser cladding, Inconel 617 with EN622 laser cladding, Haynes 282, and Inconel 740
Conceptual Design – 1000MW A-USC two pass boiler

730C/760C/350bar
1350F/1400F/5500 psi
AUSC Boiler Design – Materials Considerations

**Membrane Walls**
- Alloy 617
- T91*/T92*
- T23/T24
- T12

**Considering:**
- Creep strength
- Oxidation in steam
- *Post-weld heat treatment

**RH & SH Tubes**
- Alloy 740
- Alloy 617
- Sanicor25
- 25% Cr-Steel e.g. HR3C
- 17% Cr-Steel (shot blasting) e.g. Super304H (SB)
- 17% Cr-Steel (fine grained) e.g. TP347HFG

**Considering:**
- Creep strength
- Oxidation in steam
- Fatigue
- Consideration of load change rate (wall thickness & physical properties)

**HP Headers & Piping**
- Alloy 263
- Alloy 617

**Considering:**
- Creep strength
- Oxidation in steam
- High-temperature corrosion in flue gas

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Alstom Concept for 700°C +

1000 MW arrangement

Example of single reheat arrangement

ALSTOM standard design tools:
Thermodynamic calculations
Steam path design
Rotor dynamics

Adaptation by material selection:
Blade materials:
nickel base alloy
austenitic steel
12% Cr steel

Rotors and casing sections:
nickel base alloy & ferritic steel

No change in standard procedures and design rules for a safe introduction of advanced technologies
Turbine Design

- Shrink ring design used by Alstom since 1960
- Excellent design for very high pressures and temperatures
  - Very low casing distortion for sustainable efficiencies
  - Relatively thin structure allows good transient behavior

ALSTOM’s 700°C turbines stay with proven design adaptation is done by material selection

Ni base alloy
Ferritic steel
Welded Rotor Design

• Alstom has over 70 years experience in in rotor weld technology - Several thousand welded rotors in operation

• Not a single case of a ruptured welded rotor

• Excellent material testing conditions, good access for ultrasonic testing

• Successful test welds carried out at Alstom:
  - Full-scale test block weld between alloy 617 and ferritic steel
  - Full-scale test block weld between alloy 625 and ferritic steel

ALSTOM has longest experience in welded rotor technology
Boiler to Turbine Pipe arrangement

- Live and Reheat steam piping for A-USC plant requires application of Nickel Alloys

- Piping is a significant cost increase in a A-USC plant

- Solutions to reduce piping volume (through thickness decrease) and piping routing (improved plant arrangement) are key drivers to manage A-USC plant costs

Example of improved plant arrangement (elevated HP turbine)

Options for Ni alloy pipe
USC Deployment and A-USC Development
Key Next Steps

• Today’s state-of-the-art steam power plants are being successfully deployed with care in the application of advanced steels

• Looking forward to A-USC steam conditions, major development work is done and the general feasibility has been demonstrated

• Design work is complete based on proven architecture and experience

• A demonstration project is needed to prove:
  - Performance and operational characteristics
  - Supply chain for advanced nickel alloy components
  - Cost and economics