BOILER MATERIALS FOR USC PLANT

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EIO Project Manager:  R. Purgert
OCDO Project Manager:  H. Johnson
Improvements in heat rate (efficiency) achieved by increasing steam temperature and pressure using single and double reheat cycles (Ref. 1), compared to the base case of 535°C/18.5 MPa
Steam Turbine Pressure versus Temperature
Current Situation of USC

- 1100°F (593°C)/4300 psi (30MPa) single reheat plants are SOA. About dozen plants exist in Europe and in Japan.

- The EU has an ambitious R&D project aimed at 1300°F(700°C)/5400 psi (37.5MPa) steam condition.

- Phase 1 - 6 yrs/21 million Euro/40 companies/10 countries has been completed. EU contributes 40%.

- Phase 2 - 4 yrs/11.2 million Euro/EU 50% started in January 1, 2002.

- Demo plant envisaged for 2007. Funding being sought.

- National programs in Germany.
Goals of the DOE/OCDO Project

The GOALS include:

• Identify advanced materials that achieve cost competitive, environmentally acceptable coal based electric power generation that includes the use of high sulfur coals;

• Enable domestic boiler manufacturers to globally compete for the construction and installation of high efficiency coal fired power plants.
Specific Objectives of the USC Materials Project

The OBJECTIVES of the Ultra Supercritical Materials Program are to:

- Identify materials performance issues that limit operating temperatures and thermal efficiency of coal-fired electricity generating plants;
- Identify improved alloys, fabrication processes and coating methods that will permit boiler operation of steam temperature up to 760°C or 1400°F and steam pressures up to 5500 psi;
Specific Objectives of the USC Materials Project
(cont’d.)

• Work with alloy developers, fabricators, equipment vendors and power generators to develop cost targets for the commercial deployment of alloys and processes developed;
• Define issues impacting designs that can permit power generation at temperatures greater than or equal to 870°C or 1600°F;
• Lay the groundwork for ASME Code approval.
Benefits of the USC Materials Project

This program will have an impact on

• Ultrasupercritical coal combustion systems, ensuring fuel flexibility and coal based power generation.
• Integrated gasification combined cycle plants
• Hybrid cycles incorporating partial gasification and fluid bed combustion
• Gasification fuel-cell/turbine systems.
• The near term benefits could solve high-temperature materials problems in present power generation systems.
• The long term benefit would be the development of new high temperature materials capable of providing for higher efficiency cycles critical to the success of the Vision 21 concept. Higher efficiencies result in reduced fuel costs, BOP costs and emissions.
Schedule and Funding

• Duration: October 2001 – September 2006
• Funding:
  – USDOE/National Energy Technology Labs $15.2MM
  – Ohio Coal Development Office/Ohio Dept. of Development $2.0MM
  – Cost share by members $2.7MM
The Tasks

• Task 1 Conceptual Design—EPRI/Others
• Task 2 Mechanical Properties—EPRI/ORNL
• Task 3 Steamside Oxidation—B&W
• Task 4 Fireside Corrosion—Foster Wheeler
• Task 5 Welding Development—Alstom
• Task 6 Fabricability—B&W
• Task 7 Coatings—Alstom
• Task 8 Design Data Codes—Alstom
• Task 9 Project Management—EIO/EPRI
## Estimated Plant Efficiencies for Various Steam Cycles
*(Ref. P. Weitzel and M. Palkes)*

<table>
<thead>
<tr>
<th>Description</th>
<th>Cycle</th>
<th>Reported at European Location (LHV/HHV)</th>
<th>Converted to U.S. Practice&lt;sup&gt;(4)&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>Subcritical</td>
<td>16.8 MPa/538°C/538°C</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>Supercritical</td>
<td>24.5 MPa/565°C/565°C/565°C&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td></td>
<td>40.9</td>
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<tr>
<td>ELSAM (Nordjylland 3)</td>
<td>28.9 MPa/580°C/580°C/580°C</td>
<td>47/44</td>
<td>42</td>
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<tr>
<td>Thermie</td>
<td>38 MPa/700°C/720°C/720°C</td>
<td>50.2/47.7</td>
<td>46.0</td>
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<tr>
<td>DOE/OCDO</td>
<td>38.5 MPa/760°C/760°C</td>
<td></td>
<td>46.5</td>
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<tr>
<td>USC Project</td>
<td>38.5 MPa/760°C/760°C/760°C</td>
<td></td>
<td>47.5 - 48</td>
</tr>
</tbody>
</table>

3. Eastern bituminous Ohio coal.
4. Reported European efficiencies are generally higher compared U.S. due to differences in reporting practice (LHV vs HHV), coal quality, auxiliary power needs, condenser pressure and ambient temperature and many other variables. Numbers in this column for European project numbers are adjusted for U.S. conditions to facilitate comparison.
Plant Efficiency (Europe vs US)

- Boiler efficiency
  - Presentation in LHV in Europe gives higher value compared to HHV in USA (2% difference)
  - Lower S content in European coal permits lower flue gas exit temperature (105°C (221°F) in Europe vs 133°C (272°F) in US)
- Turbine Efficiency
  - Colder latitudes and cold sea water cooling permits lower condenser back pressure in Europe (0.62” HgA in Europe vs 2.0” Hg in US) (0.7% difference)
  - Number of reheat stages: double vs single (1.7%)
- Auxiliary Power
  - Lower auxiliary power consumption in Europe

These factors can increase heat rate for US plant by as much as 1055kJ/kWh or 1000 Btu/kWh or 3-5% difference in efficiency.
Conclusions

• If the USC plant efficiency can be improved to 45 to 48%, then the USC Total Plant Cost can be allowed to be 12 to 15% higher at the same cost of electricity as a subcritical PC Plant
  - Based on EPRI TAG financial parameters, 20 year plant life, 80% capacity factor, and a coal cost of $1.50/MMBtu

• USC BOP cost can be 13 to 16% lower
  - Smaller coal handling, pollution control, and other BOP costs for the same net plant output

• USC Boiler/Steam Turbine cost can be allowed to be 40 to 50% higher

• Emissions are reduced by 15 to 22%
Issue Related to Three Major Boiler Components Are Being Addressed

• Waterwalls

• Superheater/reheater tubing

• Headers and piping
Historic Evolution of Materials in Terms of Increasing Creep Rupture Strength
Evolution of Ferritic Steels for Boilers

10^5h Creep Rupture Strength at 600°C

<table>
<thead>
<tr>
<th>35 MPa</th>
<th>100 MPa</th>
<th>140 MPa</th>
<th>180 MPa</th>
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<tbody>
<tr>
<td>First Generation</td>
<td>Second Generation</td>
<td>Third Generation</td>
<td>Fourth Generation</td>
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<tr>
<td>2.25Cr-1Mo</td>
<td>2.25Cr-1MoV</td>
<td>HCM2S</td>
<td>2.25Cr-1.6M VNb</td>
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<td>ASME T22 (STBA24)</td>
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<td>(ASME T23 STBA24J1)</td>
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<td>+Mo</td>
<td>9Cr-0.5Mo-1.8W VNb</td>
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<td>HCM9M</td>
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<tr>
<td>(STBA 27)</td>
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<td>9Cr-2MoV Nb</td>
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<td>EM12</td>
<td>+V</td>
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<tr>
<td>(NFA 49213)</td>
<td>+Nb</td>
<td>(ASME T91 STBA28)</td>
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<td>V, Nb</td>
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<td>Tempaloy F-9</td>
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<tr>
<td>12Cr</td>
<td>+Mo</td>
<td>12Cr-0.5Mo</td>
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<td>12Cr-1MoV</td>
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<td>+W</td>
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<td>12Cr-1MoWV</td>
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<tr>
<td>HT9 (DINX20CrMoW121)</td>
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<tr>
<td>12Cr-1MoW Nb</td>
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<tr>
<td>HCM12</td>
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<tr>
<td>(SU5410J 2TB)</td>
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<td>12Cr-0.5Mo</td>
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<td>(ASME T122 SU5410J3T3)</td>
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<td>2W CuV Nb</td>
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<td>W CoV Nb</td>
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<td>SAVE12</td>
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<tr>
<td>12Cr- W CoV Nb</td>
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</table>
Alloy Design for HCM12A
Development Progress of Austenitic Steels for Boiler

- C
  + Ti
  + Nb
  + Mo
  + Cr
  + Ni
  18Cr9Ni (AISI 302)
  18Cr10NiTi (AISI 321)
  18Cr10NiNb (AISI 347)
  18Cr12NiMo (AISI 316)

Heat Treatment

18Cr10NiNb (ASME TP347H/FG)
18Cr10NiNbTi (SUS321J1HTB)

Cu Addition

18Cr9NiCuNbN

Super 304H
(SUS304J1HTB)

Chemistry Optimization

18Cr10NiNbTi

17Cr14NiCuMoNbTi

SUS310J1HTB

SAVE 25

22Cr20NiNb (AISI 310)

HR3C
(ASME TP310Cbn/
SUS310J1TB)

22Cr15NiNbN

Tempaloy A-3
(SUS309J4HTB)

23Cr43NiWNbTi

HR6W

20Cr25NiMoNbTi

NF709
(SUS310J2TB)

21Cr32NiTiAl
(Alloy 800H)

( ) designates 10⁵h creep rupture strength (MPa) at 600°C.
Comparison of Allowable Stresses of Ferritic Steels for Boiler
Figure 2: Preliminary Allowable Stress Levels
Boiler Materials for USC Plant

[Graph showing stress-temperature relationships for different alloys, categorized into Ferritic and Austenitic, with various alloy names and maximum allowable stresses indicated.]
Relationship Between Hot-Corrosion Weight Loss and Chromium Content for Various Alloys

Test Condition: 650°C x 5h
Ash: 1.5M K₂SO₄ - 1.5M Na₂SO₄ - 1M Fe₂O₃
Gas: 1% SO₂ - 5% O₂ - 15% CO₂ - Bal. N₂

Note saturation of Cr effect above 30%
Comparison of Fire-side Corrosion Resistance of Various Alloys

![Graph showing weight loss vs. temperature for different alloys.](image)

- **Weight Loss (mg/cm²)**
- **Temperature (°C)**

1. TP 316H
2. TP 321H
3. TP 347H
4. TP 310
5. 17-14CuMo
6. Esshete 1250
7. Incoloy 800H
8. AISI 314
9. Tempaloy A-2
10. HK 4M
11. YUS 170 mod
12. Inconel 617
13. In 671
14. Incoloy 807
15. Chromized 17-14CuMo
Fig. 4 Laboratory test results of high-Cr, high-Ni steels and alloys reacted with 100% steam at 700°C (1292°F) for 1000 h.
Conclusions from Design Study

• The feasibility of designing an ultra supercritical 750W boiler operating at 732/760°C (1350/1400°F) and 35 MPa (5000 psig) with existing material technology is encouraging. This design would be capable of achieving a net plant efficiency of 45.5% HHV based on US design practice and as high as 50.5% when expressed in European format with alternative European boundary conditions.

• Throttle temperature increase is much more advantageous than throttle pressure increase for improvement of efficiency at minimal cost impact.

• The original project goal for throttle pressure and temperature produced excessively thick pressure parts. A 50°F reduction to 732°C (1350°F) in temperature from the original goal was required to obtain a design that would prove acceptable for current boiler operating expectations. Reheat inlet temperature is 760°C (1400°F).
Conclusions from Design Study (cont’d.)

• Nickel based super alloys are required for major portions of the superheater and reheater. Economizer sections can be fabricated with currently available carbon steel materials. Enclosure walls can be fabricated from SA213T23 material. T92 is an alternative.

• The USC boiler has a capital cost approximately 28% higher than the comparable subcritical boiler. This is well below the 40% increase permitted by EPRI to breakeven on a cost of electricity basis. It was noted that unknowns in fabrication and erection costs with the new materials could skew the results somewhat.
Progress To Date

• Conceptual design and economic analysis have been completed.

• Materials and coatings selection and procurement is nearly completed.

• Equipment calibration and testing, specimen design and other preliminaries for corrosion and mechanical tests are complete.

• Utility sites for field tests have been identified.

• Limited mechanical tests have been started at ORNL.
Progress To Date (cont’d.)

• Topical Reports have been issued.
  – Conceptual Design and Material Solution
  – Economic Analysis
  – SOA of Coatings
  – SOA of Steamside Oxidation
  – 4-volume report on materials nearly complete at ORNL