Background

Boilers have not changed much since the 19th century, except...

- More and more are fueled by natural gas
- Emissions regulations are much tougher
- Fuel costs more than ever

Boilers burn a lot of fuel in the U.S.

- 8.8 quads, or 40% of all industrial energy use
- Natural gas contributes about 3.5 quads (40%) of that amount
- Major steam users: chemicals, paper, steel, food
Genesis of the project

- DOE - with industry support - proposed to develop a new generation of boilers
  - 1998-1999 *Vision* and *Roadmap* documents issued

- 1999 DOE Super Boiler solicitation
  - Define a new steam generation "platform"
  - Demonstrate 1st-Generation Super Boiler
    - Improve efficiency
    - Reduce emissions
    - Reduce size

- GTI began work Oct 2000
  - Teamed with Cleaver-Brooks in 2002
Project team

> Performers
  - Gas Technology Institute
  - Cleaver-Brooks Inc.
  - Media & Process Technology
  - Pacific Northwest National Lab
  - Specification Rubber Products
  - Clement Pappas & Co.

> Sponsors
  - U.S. DOE - ITP
  - Gas Research Institute
  - Southern California Gas
  - GTI SMP
  - Cleaver-Brooks Inc.
  - Utilization Technology Development Company
  - California Energy Commission
  - California Air Resources Board
  - South Coast Air Quality Management District
System approach

> Combustion
  - Super-low NOx
  - CO and VOC burnout
  - Low excess air

> Heat transfer
  - Extended surfaces
  - Space efficiency

> Heat recovery
  - Recover stack loss, including *latent* heat
  - Preheat water
  - Preheat air
Combustion: Two-stage boiler*

- Air staging
- Premixed fuel/air in both stages
- Forced internal recirculation insert
- Interstage heat removal via steam generation
- Familiar firetube configuration

* U.S. Patent No. 6,289,851 (Sept 2001)
# Combustion:
Two-stage emissions data

<table>
<thead>
<tr>
<th>Firing rate, million Btu/h</th>
<th>0.88 (light-off)</th>
<th>1.54</th>
<th>2.22</th>
<th>3.02</th>
<th>3.41</th>
<th>4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staging</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Steam pressure, psig</td>
<td>--</td>
<td>114</td>
<td>114</td>
<td>105</td>
<td>38</td>
<td>49</td>
</tr>
<tr>
<td>$O_2$, vol%</td>
<td>8.8</td>
<td>1.1</td>
<td>3.1</td>
<td>2.8</td>
<td>2.3</td>
<td>1.6</td>
</tr>
<tr>
<td>NOx, ppmv (ref 3%$O_2$)</td>
<td>3.8</td>
<td>3.0</td>
<td>4.1</td>
<td>4.4</td>
<td>4.2</td>
<td>5.0</td>
</tr>
<tr>
<td>CO, ppmv (ref 3%$O_2$)</td>
<td>25</td>
<td>13</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>THC, ppmv</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flue gas temperature, °F</td>
<td>152</td>
<td>326</td>
<td>343</td>
<td>351</td>
<td>309</td>
<td>332</td>
</tr>
<tr>
<td>Stack pressure, &quot;wc&quot;</td>
<td>0.1</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0.4</td>
<td>+2.1</td>
<td>+2.6</td>
</tr>
<tr>
<td>Turning box pressure, &quot;wc&quot;</td>
<td>0.3</td>
<td>0.4</td>
<td>1.1</td>
<td>1.8</td>
<td>3.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Windbox pressure, &quot;wc&quot;</td>
<td>5.4</td>
<td>4.6</td>
<td>10.4</td>
<td>16.6</td>
<td>20.6</td>
<td>25.6</td>
</tr>
</tbody>
</table>

**NOTES:**
- NOx ≤ 5 ppm at all loads
- Excellent burnout at low excess air
- 4.5 to 1 turndown
- Able to fire up to 4 million Btu/h (33% overfire)
- No noise, pulsation, or instability
Combustion: Stable secondary flame

3.5 ppmv NOx
3 ppmv CO
1.5% O2
Heat transfer

- Shorten convective passes
  - Firetubes with internal extended surfaces
  - Heat transfer up to 18 times more intensive than rifled tubes
  - 2-pass boiler can deliver efficiency of 4-pass design with smaller size and lower cost

<table>
<thead>
<tr>
<th>% relative to base case</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footprint</td>
<td>61</td>
<td>75</td>
<td>70</td>
</tr>
<tr>
<td>Cross-section</td>
<td>71</td>
<td>56</td>
<td>50</td>
</tr>
<tr>
<td>Volume</td>
<td>51</td>
<td>56</td>
<td>49</td>
</tr>
<tr>
<td>Weight</td>
<td>51</td>
<td>59</td>
<td>51</td>
</tr>
</tbody>
</table>
Heat recovery*

- Economizers remove sensible heat
- *Transport membrane condenser (TMC)* uses nanoporous membrane to dehumidify flue gas
- *Humidifying air heater (HAH)* cools and recycles TMC condensate
- Advanced controls to maintain optimal conditions

*U.S. Patent No. 7,066,396*
Heat recovery: Transport Membrane Condenser*

- Selective transport of water vapor from flue gas to boiler feed water
- Cools and dries flue gas
- Transfers latent and sensible heat directly back to boiler energy loop
- Flue gas exits below 130°F with no condensation
- Feed water remains uncontaminated

* U.S. Patent No. 6,517,607 (Feb 2003)
Heat recovery:
Humidifying Air Heater

- Microporous ceramic membrane tubes
- Hot water first transfers heat to combustion air
- Partly cooled water passes through membrane to humidify combustion air
- HAH cools water for TMC and improves performance
## Heat recovery:
### Energy Efficiency from Model

<table>
<thead>
<tr>
<th>Case</th>
<th>Plant condensate return</th>
<th>Conventional boiler no heat recovery</th>
<th>Super Boiler with TMC/HAH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wt% of total feed water</td>
<td>Stack temp/ dew point</td>
<td>Boiler efficiency*</td>
</tr>
<tr>
<td>1</td>
<td>None</td>
<td>440/137</td>
<td>80.2</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>440/137</td>
<td>81.3</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>440/137</td>
<td>81.0</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>440/137</td>
<td>81.4</td>
</tr>
</tbody>
</table>

— Natural gas: 93.7%CH₄, 2.8%C₂H₆, 0.6%C₃H₈, 2%N₂, 0.9%CO₂
— ISO combustion air (60%RH at 59°F)
— 10% excess air combustion
— 60°F makeup water
— 180°F condensate return
— 440°F flue gas from boiler vent
— Surface loss = 0.77% of steam output

* Efficiency calculations:
\[ \eta_{\text{boiler}} = \frac{H_{\text{fuel}} - H_{\text{stack}}}{H_{\text{fuel}}} \]
\[ \eta_{\text{fuel-to-steam}} = \frac{H_{\text{steam}}}{H_{\text{fuel}}} \]
Super Boiler Comparison

- Efficiency
- Emissions
- Footprint

* Not all in the same boiler
Field demonstration

- Scaled up from 90 to 300 horsepower
- Industrial sites in Alabama, California, & Utah
- 6 to 12 months testing & monitoring

Alabama – single-stage boiler with TMC/HAH heat recovery

California – two-stage boiler with TMC/HAH heat recovery

Utah – retrofit TMC to conventional firetube boiler
Field demonstration: Alabaster, Alabama

> Specification Rubber Products
  - Manufactures rubber gaskets
  - Single-stage 300-HP boiler with TMC/HAH heat recovery system
  - Boiler installed Mar 2006
  - Long-term testing under way

Pre-testing boiler at CB plant

Boiler & economizers on site

Transport membrane condenser

Humidifying air heater
Progress

- Testing started Apr 2006
- 93-95% efficiency
- 7 ppmv NOx at full load
- Began 24/5 on-demand operation July 21
- Over 2400 hrs logged
Field demonstration: Ontario, California

- Clement Pappas & Co.
  - Fruit juice bottling plant
  - Uses steam for pasteurization and sterilization
  - Two-stage 300-HP boiler with TMC/HAH heat recovery
  - Signed agreement and began engineering in May 2006
Field demonstration: Ontario, California continued

Progress
- Boiler and burner fabricated at Cleaver-Brooks facilities
- Combustion setup and acceptance testing under way
- Delivery slated for Dec 2006
Third Dimension, Inc.
- Packaging company
- New facility near Salt Lake City
- Uses steam in manufacture of special packaging for KraftMaid kitchen cabinets
- 100% makeup water

Retrofit of economizer and TMC to conventional 250-HP firetube boiler
- Introduces new upflow version of TMC
- Estimated delivery March 2007
What’s next...

> Complete current field demonstrations
> Additional heat recovery work
  > Retrofit applications
  > Improve design and economics
> Demonstration and deployment
  > Federal and/or military facilities
  > Broader range of boiler sizes
> 2nd Generation Super Boiler
  > Extend performance improvements to watertube boilers including larger sizes and high-pressure superheated steam
Acknowledgment

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- Media & Process Technology: Rich Ciora, Paul Liu
- PNNL: Greg Whyatt
- Dr. Jacob Korenberg
Thank you!

> Questions?