Waste Heat Recovery for Pipeline Compressor Stations
2009 Gas/Electric Partnership
Houston, TX

Presented By
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Agenda

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Mechanical Efficiency
System Yield
What to do With Power
Equipment Cost
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Case Study III – Private power Generation
Acknowledgments and References

International Natural Gas Association of America (INGAA),
  - ORMAT Technologies Inc.
  - Kinder Morgan Energy Partners / Knight INC. presented at the spring 2008 INGAA foundation meeting.
  - Energy and Environmental Analysis Inc.

TurboThermal

El Paso Corporation

Advanced Engine Technology Corporation, technical advisor.

National Gas Machinery Laboratory, Kansas State University

Energy Information Administration (www.eia.org).

Opportunity

15 Million Hp in pipeline compression
Fleet average heat rate is ~ 7500 Btu/hp-hr
1 Hp = 2545 Btu/hr
Fleet average efficiency is ~33%
Approximately 2/3 of the fuel energy is lost to waste heat.

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Typical Heat Rate</th>
<th>Efficiency</th>
<th>Rated Hp</th>
<th>Waste Heat BTU/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper Bessmer</td>
<td>GMVA-10</td>
<td>8000</td>
<td>32%</td>
<td>1350</td>
<td>7,364,250</td>
</tr>
<tr>
<td></td>
<td>GMWC-10</td>
<td>7700</td>
<td>33%</td>
<td>3400</td>
<td>17,527,000</td>
</tr>
<tr>
<td></td>
<td>16-V250</td>
<td>7000</td>
<td>36%</td>
<td>5500</td>
<td>24,502,500</td>
</tr>
<tr>
<td></td>
<td>16-W330</td>
<td>6500</td>
<td>39%</td>
<td>8000</td>
<td>31,640,000</td>
</tr>
<tr>
<td>Clark</td>
<td>HBA-10T</td>
<td>8350</td>
<td>30%</td>
<td>2600</td>
<td>15,093,000</td>
</tr>
<tr>
<td></td>
<td>TLA-10</td>
<td>7500</td>
<td>34%</td>
<td>3400</td>
<td>16,847,000</td>
</tr>
<tr>
<td></td>
<td>TCV-16</td>
<td>7400</td>
<td>34%</td>
<td>5500</td>
<td>26,702,500</td>
</tr>
<tr>
<td>Solar</td>
<td>Centar - 50</td>
<td>8500</td>
<td>30%</td>
<td>6130</td>
<td>36,504,150</td>
</tr>
<tr>
<td></td>
<td>Taurus - 70</td>
<td>7310</td>
<td>35%</td>
<td>10310</td>
<td>49,127,150</td>
</tr>
<tr>
<td></td>
<td>Mars - 100</td>
<td>7490</td>
<td>34%</td>
<td>15000</td>
<td>74,175,000</td>
</tr>
</tbody>
</table>

The Potential Fuel Value of the Waste Heat is $6.6 Billion / Year
Waste Heat
Benchmarking

Modern combined cycle power plants achieve thermal efficiencies in excess of 50%.

- Steam is used to capture waste heat from gas turbine generator sets
- Superheat and other efficiency improving techniques are employed
- Plants can be very large > 500 MW

Combined heat and power plants can achieve 90% efficiency.

- Need a use for low temperature heat
- Radiators for home heating
- Other processes needing modest temperatures (digesters at waste water plants)
- Limited applications for low temp heat

An Appropriate Efficiency Target is the Combined Cycle Efficiency of 50%
Availability in the Exhaust Stack

Practical limits for pipeline applications include:

- Steam should not condense in exhaust stack (300F min temperature)
- Cooling will be by radiator / aerial fin fan
- Assume no use for low temperature waste (JW and CW streams)

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Air Flow SCFM</th>
<th>Air Flow #/hr</th>
<th>Exhaust Temp</th>
<th>Cp</th>
<th>Total Waste Heat BTU/HR</th>
<th>Available Exhaust Energy (to 300 F) BTU/hr</th>
<th>Available as % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper</td>
<td>GMVA-10</td>
<td>5400</td>
<td>24300</td>
<td>750</td>
<td>0.256</td>
<td>7,364,250</td>
<td>2,793,893</td>
<td>38%</td>
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<tr>
<td></td>
<td>GMWC-10</td>
<td>13600</td>
<td>61200</td>
<td>700</td>
<td>0.254</td>
<td>17,527,000</td>
<td>6,217,920</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>16-V250</td>
<td>22000</td>
<td>99000</td>
<td>650</td>
<td>0.253</td>
<td>24,502,500</td>
<td>8,749,125</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>16-W330</td>
<td>32000</td>
<td>144000</td>
<td>650</td>
<td>0.253</td>
<td>31,640,000</td>
<td>12,726,000</td>
<td>40%</td>
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<tr>
<td>Clark</td>
<td>TLA-10</td>
<td>13600</td>
<td>61200</td>
<td>700</td>
<td>0.254</td>
<td>16,847,000</td>
<td>6,217,920</td>
<td>37%</td>
</tr>
<tr>
<td></td>
<td>TCV-16</td>
<td>22000</td>
<td>99000</td>
<td>650</td>
<td>0.253</td>
<td>26,702,500</td>
<td>8,749,125</td>
<td>33%</td>
</tr>
<tr>
<td>Solar</td>
<td>Centar - 50</td>
<td>33196</td>
<td>149,380</td>
<td>960</td>
<td>0.263</td>
<td>36,504,150</td>
<td>25,968,817</td>
<td>71%</td>
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<tr>
<td></td>
<td>Taurus - 70</td>
<td>46851</td>
<td>210,830</td>
<td>920</td>
<td>0.262</td>
<td>49,127,150</td>
<td>34,221,082</td>
<td>70%</td>
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<tr>
<td></td>
<td>Mars - 100</td>
<td>73678</td>
<td>331,550</td>
<td>905</td>
<td>0.261</td>
<td>74,175,000</td>
<td>52,393,520</td>
<td>71%</td>
</tr>
</tbody>
</table>
Rankine Cycle Efficiency

Example

- A basic closed loop system
- The boiler (EGHG) and pump will be sized to provide 400°F steam and 300 °F exhaust outlet temperature
- The steam at the outlet of the boiler will be saturated
- The condenser will be sized to provide 150 °F condensate on a 100 degree day

The best achievable efficiency is defined by Carnot cycle:

\[
    n_{\text{thermal}} = 1 - \frac{T_L}{T_H} = 1 - \frac{607}{860} = 29\%
\]

Best Achievable Efficiency is 29%
Rankine Cycle Efficiency

Example

Pump input power = 118 Btu/lbm

Boiler input heat = 1084 Btu/lbm

Turbine output = 284 Btu/lbm

Condenser output = 801 Btu/lbm

Actual efficiency for the described application is:

\[
\eta_{th} = \frac{w_{net}}{q_H} = \frac{283.6 - .74}{1084} = 26.1\% 
\]

Actual Efficiency for Cycle is 26.1% (90% of Theoretical Best)
Mechanical System Efficiency

Steam turbine isentropic efficiency ranges with size
- ~60% for 750 KW
- ~70% for 3 MW

Speed reducers are ~95% efficient

Generator in this size range are ~95% efficient

For 1MW steam generator set overall mechanical efficiency is ~54%

Total System Efficiency for 1MW Steam Generator System is ~14%
WHR System Yield

Expect modest amounts of power from most applications

Combined efficiencies still not near combined cycle levels

- Pick up 10% over baseline for Recips
- Pick up 20% over baseline for Turbines

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Energy Output of Gen / Comp Btu/hr</th>
<th>Hp Equivalent</th>
<th>KW Equivalent</th>
<th>Waste heat Recovered (%)</th>
<th>Combined Energy Efficiency (%)</th>
<th>Efficiency Improvement from Baseline (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper</td>
<td>GMVA-10</td>
<td>391,145</td>
<td>154</td>
<td>115</td>
<td>5%</td>
<td>35%</td>
<td>11%</td>
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<tr>
<td></td>
<td>GMW C-10</td>
<td>870,509</td>
<td>342</td>
<td>255</td>
<td>5%</td>
<td>36%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>16-V250</td>
<td>1,224,878</td>
<td>481</td>
<td>359</td>
<td>5%</td>
<td>40%</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>16-W330</td>
<td>1,781,640</td>
<td>700</td>
<td>522</td>
<td>6%</td>
<td>43%</td>
<td>9%</td>
</tr>
<tr>
<td>Clark</td>
<td>TLA-10</td>
<td>870,509</td>
<td>342</td>
<td>255</td>
<td>5%</td>
<td>37%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>TCV-16</td>
<td>1,224,878</td>
<td>481</td>
<td>359</td>
<td>5%</td>
<td>37%</td>
<td>9%</td>
</tr>
<tr>
<td>Solar</td>
<td>Centar - 50</td>
<td>3,635,634</td>
<td>1,429</td>
<td>1,066</td>
<td>10%</td>
<td>37%</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>Taurus - 70</td>
<td>4,790,952</td>
<td>1,882</td>
<td>1,404</td>
<td>10%</td>
<td>41%</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Mars - 100</td>
<td>7,335,093</td>
<td>2,882</td>
<td>2,150</td>
<td>10%</td>
<td>41%</td>
<td>19%</td>
</tr>
</tbody>
</table>
What to do With WHR Generated Power

Most of the companies currently pursuing WHR seek to sell power to the grid for a profit

- Prices for interruptible power from “non” electrics are as low as 1¢/KWH
- Need guaranteed delivery to approach 5¢/KWH
- Politics come to play as WHR power competes with other “green” energy for funding
- Utilities aren’t inclined to compete with generators who get “free” fuel

Local power displacement offers best opportunity for small generation

- Average industrial rate is 7.3¢/KWH
- Rhode Island is 18¢/KWH

Current Market is not Very Attractive for Commercial Sale of WHR Power
Equipment Cost

Equipment cost is very site specific

- Skidded steam turbine generator sets of 1 – 3 MW $150 - $600/KW
- Supporting equipment will drive majority of installed cost
- Current WHR system operators report installed costs of $2500 - $4000 / KW depending on size

<table>
<thead>
<tr>
<th>Traditional steam generator set (skidded)</th>
<th>Approximate Delivered Cost New</th>
<th>Approximate Delivered Cost New</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MW single stage steam turbine generator set on skid, includes turbine, governor, gear box, synchronous</td>
<td>$150,000</td>
<td>$300,000</td>
</tr>
<tr>
<td>generator, coupler, base plate and lube oil system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 MW multi stage steam turbine generator set on skid, includes turbine, governor, gear box, synchronous</td>
<td>$750,000</td>
<td>$1,500,000</td>
</tr>
<tr>
<td>generator, coupler, base plate and lube oil system.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Notes on Real Systems

Steam is not a practical choice for small plants
- Operator requirements
- Make up water

Organic fluids are common in WHR
- Hydrocarbon or Freon based
- Lower vaporization temperatures
- Superheat at lower temperatures
- Less drop liquid out during expansion

The Commercial Market Is Limited By Regulations, Lobbying And Politics
Case Study I – Current Technology

Northern Border Pipeline – ORMAT

Driver is Rolls Royce RB211

WHR delivers 6.5MW of power

Remote operation

Operating costs (including capital recovery) 3.5 – 4.5 ¢/KWH

Revenues 3.5 – 5 ¢/KWH

Make or break on run hours

Installed cost ~$2500 / KW

Operational Cost Are In The Range Of Generated Revenue
Case Study II – Emerging Technology

TurboThermal – Applications sized for modern 4 stroke engines

Unique turbo expander is efficient at lower outputs

Technology is optimized for 250 – 750 KW range

Operating cost forecast < 1¢ / KWH

Installed cost is $2000 - $2500 / KW

At 10 ¢/KWH value IRR is ~30%

Emerging technology not in pipeline service to date

With Size Range Of 250KW-750KW Attractive Option for Local Use
Case Study III – Private power Generation

Combined cycle power generation with thermal efficiencies in excess of 50% offer the highest potential fuel utilization rate for compression application.

Key is to minimize transmission and distribution losses

Installed cost includes generation and compression

Total capital and operating costs to be considered along with any incentives GHG reductions may make an attractive option

The Next Step In The Process Lies With The Operators
Thank You