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Waste Heat Recovery Drivers

- Increased focus on economic benefits of energy & fuel conservation
  - need to remain competitive drives focus on energy costs
  - Converting waste energy to usable energy / power has a high value

- Availability of distributed energy and the need for more energy
  - need for less reliance on grid power / distributed energy
  - adoption of more self generated / sustaining sources of energy

- Climate change & environmental legislation
  - energy efficiency and reduction targets
  - emissions legislation, including CO₂ emissions
  - More power output for a given environmental impact

Generating Usable Energy from Waste Heat Reduces Energy Consumption and Reduces CO₂ Emissions

Opportunity for Low Temperature Waste Heat Recovery

- Recovery of high temperature waste heat (>300°C) is common
  - Low temperature (50-250°C) waste heat recovery is less common
  - Perception that it is un-recoverable / un-economic to recover

- Huge opportunity for low vs. high temperature waste heat recovery
  - Estimated >2 x 10¹³ mega joules industrial waste heat
  - >$20BN low temp heat recovery opportunity in large industrial space
  - High value of recovered energy - higher temperature heat and electricity

- Perceptions changing
  - Low Temp heat recovery technologies proving performance
  - Improving technologies & Improving economics – KEY TO GROWTH

Converting Waste Heat to Energy is Good Business and Good for the Environment
Heat Pump and ORC – Low Temperature Waste Heat Recovery

**High Temperature Heat Pumps**

- Waste Heat to Thermal Power
  - Sources (40-70°C)
    - Geothermal
    - Waste Hot Water / Low Temp Steam
  - Applications (90-140°C)
    - Industrial Process Heat
    - District Heating
    - Onsite / localized heating
- Waste Heat to Electricity
  - Sources (80-250°C)
    - Geothermal
    - Waste Hot Water / Steam
    - Solar Thermal
    - Waste streams from boilers, generators, power plants, industrial processes

**ORC**

- Heat Source Temp °C
  - 250
  - 210
  - 180
  - 150
  - 120
  - 90
  - 60
  - 30

**What is ORC?**

**Waste Heat Sources**
- Waste streams from boilers, generators, power plants, industrial processes
- Geothermal
- Waste Hot Water / Steam
- Solar Thermal

**Applications**
- Prime power generation
- Industrial plants
- Buildings
- Homes

**Key benefits**
- Power from waste heat and renewable heat sources
  - Reduces specific fuel consumption
  - Increases the extent of renewable energy / offset grid consumption
  - Reduce per unit emissions (CO₂, NOₓ, Soₓ)
- Are built to last > 20 years
- Are leak tight – elimination of working fluid emissions

Schematic of a typical ORC Configuration
Refrigerants Comparison

The shape of the saturation curves, hence the choice of the working fluid will impact cycle performance.

- **Negative Slope Saturation curve**
  - Wet fluid at exit from turbine
  - Risk of damage to turbine blades
  - Example: Water, R22, R134a

- **Isentropic Saturation curve**
  - Preferred characteristic
  - Expansion parallel to saturation curve
  - Example: R11, R123, R245fa

- **Positive Slope Saturation curve**
  - Superheated turbine exit conditions
  - Possibility to use a regenerator
  - Example: R113, n-pentene, Toluene

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Genetron 245fa Properties

Genetron 245fa is an HFC specifically designed as a working fluid for 'green' energy systems.

- Thermodynamic properties that maximize low temperature waste heat recovery cycle performance
  - Very suitable for low temperature heat recovery (source heat of 80-250°C)
  - Maximizes system efficiency / performance economics
- Non-flammable / Non-Corrosive
- Favorable toxicological profile

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Name</td>
<td>1,1,1,3,3-pentafluoropropane</td>
</tr>
<tr>
<td>Molecular Formula</td>
<td>CF₃CH₂CHF₂</td>
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<tr>
<td>Flash Point</td>
<td>Non-by ASTM</td>
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<tr>
<td>Flammability range in air</td>
<td>None</td>
</tr>
<tr>
<td>Boiling point °C at 1.01 bar</td>
<td>15.3 °C / 59.5 °F</td>
</tr>
<tr>
<td>Critical Temperature K</td>
<td>154 °C / 309 °F</td>
</tr>
<tr>
<td>Liquid Heat Capacity kJ/kg K</td>
<td>1.36</td>
</tr>
<tr>
<td>Vapor Heat Capacity at constant pressure 1.01 bar kJ/kg K</td>
<td>0.8831</td>
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</tbody>
</table>

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### Comparative assessment of potential working Fluids

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Atmospheric lifetime</th>
<th>CDP</th>
<th>GWP</th>
<th>Slope of saturation vapour line</th>
<th>Critical point</th>
<th>Heat of Vaporization at 100°C</th>
<th>Boiling temp at 1 atm</th>
<th>Flammability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0</td>
<td>Wet</td>
<td>0</td>
<td>0</td>
<td>171°C - 220 bar</td>
<td>2236.4 kg/m³</td>
<td>100 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-114</td>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>199°C - 64.1 bar</td>
<td>167.1 kg/m³</td>
<td>23.5 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-22</td>
<td>12</td>
<td>3.5x</td>
<td>1719</td>
<td>0</td>
<td>200°C - 49.9 bar</td>
<td>-11.1 kg/m³</td>
<td>41.5 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-113</td>
<td>85</td>
<td>3.5</td>
<td>3338</td>
<td>Dry</td>
<td>214°C - 58.4 bar</td>
<td>315.4 kg/m³</td>
<td>47.8 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-123</td>
<td>1.3</td>
<td>0</td>
<td>15</td>
<td>Isentropic</td>
<td>164°C - 36.7 bar</td>
<td>134 kg/m³</td>
<td>27.7 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-134a</td>
<td>14</td>
<td>0</td>
<td>1320</td>
<td>Wet</td>
<td>107°C - 63.6 bar</td>
<td>34.4 kg/m³</td>
<td>26.4 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-245fa</td>
<td>7.6</td>
<td>0</td>
<td>1604</td>
<td>Isentropic</td>
<td>154°C - 36.4 bar</td>
<td>125.5 kg/m³</td>
<td>15.3 kg/m³</td>
<td>Non-Flammable</td>
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<tr>
<td>R-365mfc</td>
<td>10.2</td>
<td>0</td>
<td>915</td>
<td>Isentropic</td>
<td>189°C - 27.5 bar</td>
<td>146 kg/m³</td>
<td>46.2 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>R-410a</td>
<td>17.1</td>
<td>0</td>
<td>1766</td>
<td>Dry</td>
<td>185°C - 22.9 bar</td>
<td>215.7 kg/m³</td>
<td>54.5 kg/m³</td>
<td>Non-Flammable</td>
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<tr>
<td>R-7110a</td>
<td>4.5</td>
<td>0</td>
<td>330</td>
<td>Dry</td>
<td>195°C - 22.3 bar</td>
<td>239.5 kg/m³</td>
<td>60.5 kg/m³</td>
<td>Non-Flammable</td>
</tr>
<tr>
<td>n-pentane</td>
<td>0</td>
<td>20</td>
<td>280</td>
<td>Dry</td>
<td>196°C - 33.8 bar</td>
<td>264.4 kg/m³</td>
<td>35.5 kg/m³</td>
<td>Flammable</td>
</tr>
<tr>
<td>isopentane</td>
<td>0</td>
<td>26</td>
<td>280</td>
<td>Dry</td>
<td>187°C - 33.7 bar</td>
<td>275 kg/m³</td>
<td>27.5 kg/m³</td>
<td>Flammable</td>
</tr>
<tr>
<td>Benzene</td>
<td>0-10</td>
<td>0</td>
<td>280</td>
<td>Dry</td>
<td>200°C - 49 bar</td>
<td>378.7 kg/m³</td>
<td>79.8 kg/m³</td>
<td>Flammable</td>
</tr>
<tr>
<td>Toluene</td>
<td>2</td>
<td>0</td>
<td>280</td>
<td>Dry</td>
<td>319°C - 41 bar</td>
<td>388.4 kg/m³</td>
<td>110.4 kg/m³</td>
<td>Flammable</td>
</tr>
<tr>
<td>n-xylene</td>
<td>&lt;5</td>
<td>0</td>
<td>280</td>
<td>Dry</td>
<td>345°C - 32 bar</td>
<td>388.3 kg/m³</td>
<td>110.4 kg/m³</td>
<td>Flammable</td>
</tr>
</tbody>
</table>

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### Low Temperature ORC Heat Recovery Opportunity in Thermal Power in India

- Several opportunities to recover low temp heat
  - Bottoming of steam cycle
  - Flue gas from boiler exhaust
  - Exhaust gas from Flue Gas Pre-heater
- In Thermal Plants in India recovery of flue gas waste heat is a potentially attractive opportunity
  - Accessible
  - Suitable Temperature (150-250°C)
  - High uptime

**Recovery of Gaseous Waste Heat Potentially Attractive Opportunity**
Benefits of ORC in Thermal Power Plants

- Improve efficiency of power generation in existing coal power plants
  - ORC typically converts 10-15% of waste heat stream to electrical power
  - Estimated ~2.5 MW of electrical power recovery possible just from post-ESP gaseous heat stream of 210 MW unit before ID fan
  - No fuel or water consumption for this additional power
- Reduce environment impact per unit output
  - Lower per unit generation of fly ash and consumption of water and fuel
  - Reduction of CO₂ emissions - possibility of carbon credits
- Defer capital investment in additional power generation plant
- Typically modular systems: minimize process interruption for installation and commissioning

Geothermal Power Plant – Sauerlach, Germany

- Plant type: Geothermal ORC turbogenerator unit
- Total electric power: 5+ MWel plus thermal decoupling for district heating
- Working Fluid: 245fa
- ORC Unit to be supplied by: Turboden S.r.l.
- End Customer: SWM - StadtWerke München (public utilities company)
- Location: Bavaria, Germany
- Commissioning expected: end 2011
- Heat source: geothermal fluid at 140°C
- Cooling device: air condensers

New 5MW plant under construction
Heat Recovery from Biomass Boiler – Trevisio, Slovenia

- ORC system manufactured & supplied by Calnetix Power Solutions (CPS)
- Working Fluid Genetron 245fa
- 125KW electrical power output
- Running on steam from a sawdust fired boiler
- Indirect condensing using cooling tower
- Commissioned Q1, 2010

EDF Industrial Heat Pump Development

- Project at EDF R&D, France
- Working Fluid Genetron 245fa
- Pilot size unit running
- 400KW energy output at condenser
- 100°C water temperature at condenser exhaust
- Potential applications in industrial waste heat recovery
Genetron 245fa in High Temperature Heat Pumps

- Thermal energy from low temperature sources can be recovered and boosted to a more valuable temperature
  - Process usage, pre-heating, site usage
  - Offset existing thermal energy / fuel consumption
- Genetron 245fa critical temperature enables 120°C output / sink temperature
- Higher source temperatures greatly improve Efficiency (COP)

High Temperature Heat Pump developed for Dairy Industry.

Further Working Fluid Developments

**Auto Exhaust Gas WHR**
- Heavy duty trucks
- ORC – exhaust gas heat to power
- Safe, efficient working fluid solutions

**Low Enthalpy Geothermal**
- Large developing application
- ORC technology evolving
- Fluids to meet needs / performance improvement

**New Molecules**
- HBA-2
  - Lower GWP
  - Excellent performance

**Tailored fluids**
- Evolving needs of ORC / HTHP
- Specific high growth applications
- Solutions of commercially available / new molecules

*Honeywell is working with industry to meet heat recovery needs*
Commercial Status / The Future

• ORC
  – Genetron 245fa has been selected by numerous ORC OEM’s as a preferred working fluid
  – ORC moving from Feasibility to Commercial (3KW to 10MW)
  – 40 ORC systems using Genetron 245fa in 2010
  – Substantial market growth over 2010-2015 period

• Heat Pumps
  – Recovery of low temperature industrial waste heat in development phase
  – Several development projects running with Genetron 245fa
  – Piloting and commercial implementation over next 2-3 years