Mechanical Energy Systems for Low Grade Waste Heat Recovery

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**Low Grade WHR to Cooling - ARPA-e ARID Project**

- Utilizing ~100°C power plant waste heat to reduce dry-cooling load
- Low cost system, high COP
- Reduction in dry-air heat exchanger size
- 250 kW\textsubscript{th} demonstration early 2017
PRESENTATION OUTLINE

- Fundamental Thermodynamic Considerations
- Overview of Mechanical System Technology Options
- Challenges for WHR Commercialization
- Potential “ARPA-e Hard” Challenges for Mechanical Systems
**Waste Heat from Representative Engines**

**CAT 3516B Engine:**
- $1.6 \text{ MW}_e$
- $1.6 \text{ MW}_\text{th}$ exhaust
  - (517°C to 15°C, ~3 kg/s)
- $1.2 \text{ MW}_\text{th}$ coolant/other

**Saturn 20PG Gas Turbine:**
- $1.2 \text{ MW}_e$
- $3.3 \text{ kW}_\text{th}$ exhaust
  - (504°C to 15°C, 6.5 kg/s)

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*Higher temperature heat in exhaust gases, must be cooled to extract heat*
As heat is removed, "reservoir" temperature is reduced – even infinite reversible engines below inlet Carnot limit
**Finite Devices: Heat Exchangers**

Exhaust gases: large $A$ required for cycle “reservoir” to approach waste heat temperature.

**Equations**

\[ Q_H = \varepsilon (mC_p)_{\text{min}} (T_H - T_{H,c}) \]

\[ \varepsilon = 1 - \exp \left[ \frac{UA}{(mC_p)_{\text{min}}} \right] \]

\[ UA = \left[ \frac{1}{(hA)_H} + R_{\text{wall}} + \frac{1}{(hA)_{H,c}} \right]^{-1} \]
**HEAT EXCHANGER EFFECTIVENESS**

- NTU increases, effectiveness increases
- Larger UA: more heat transfer, but diminishing rate of return

*Extracting more heat can cost $$$*

\[
\text{NTU} = \frac{U/A}{(mC_p)_{\text{exhaust}}}
\]

Incropera and Dewitt, 1996
Overview of Mechanical WHR Systems
**Organic Rankine Cycle**

- Largest and most mature technology
- Similar to steam cycle, but (typically) with carbon containing fluid
- Examples: n-pentane, R245fa, ethanol, others (siloxaneses)
  - Low flammability fluids tend to decompose at low temperatures
  - High flammability fluids tend to survive higher temperatures

![Diagram of Organic Rankine Cycle](image-url)
Majority of installed capacity >50 kW are geothermal installations

http://orc-world-map.org/analysis.html
GROWTH IN ORC MARKETS

Large number of biomass and heat recovery installations in last decade, geothermal capacity still dominates

http://orc-world-map.org/analysis.html
DOE SUPERTRUCK EFFORT

- U.S. Department of Energy SuperTruck program
  - Goal: Raise engine efficiency to 55%
  - WHR used by majority of participants

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Cummins</th>
<th>Daimler</th>
<th>Navistar</th>
<th>Volvo</th>
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<tbody>
<tr>
<td>Engine downsizing</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Engine downspeeding</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Transmission</td>
<td>Automated manual</td>
<td>Automated manual</td>
<td>Dual-mode hybrid</td>
<td>Dual-clutch automated manual</td>
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<tr>
<td>Hybridization*</td>
<td>No</td>
<td>Mild</td>
<td>Full (series/parallel)</td>
<td>No</td>
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<tr>
<td>Organic Rankine cycle</td>
<td>Yes (mechanical)</td>
<td>Yes (electric)</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Turbocompounding</td>
<td>No</td>
<td>No</td>
<td>Yes (electric)</td>
<td>Yes (mechanical)</td>
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</tbody>
</table>

3.6 BTE % pt. improvement

Delgado and Lutsey, 2014

http://social.cummins.com/
Maloney-Robertson/Kalina Cycle

- Maloney and Robertson (1953) investigated absorption power cycle, similar performance to ORC
- Kalina (1983) proposed similar cycle, adjusted concentration in ammonia-water system to match temperature glide of exhaust stream
- System efficiency higher, cost likely higher than ORC
# Kalina Cycle Case Studies

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Commissioned</th>
<th>Output (MW)</th>
<th>Heat source</th>
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<tbody>
<tr>
<td>Canoga Park</td>
<td>USA</td>
<td>1992</td>
<td>6.5</td>
<td>Nuclear waste heat</td>
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<tr>
<td>Fukuoka</td>
<td>Japan</td>
<td>1998</td>
<td>4</td>
<td>Waste incineration</td>
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<tr>
<td>Sumitomo Metals</td>
<td>Japan</td>
<td>1999</td>
<td>3.5</td>
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<tr>
<td>Husavik</td>
<td>Iceland</td>
<td>2000</td>
<td>2</td>
<td>Geothermal</td>
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<tr>
<td>Fuji Oil</td>
<td>Japan</td>
<td>2005</td>
<td>3.9</td>
<td>Waste heat</td>
</tr>
<tr>
<td>Bruschal</td>
<td>Germany</td>
<td>2009</td>
<td>0.6</td>
<td>Geothermal</td>
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<tr>
<td>Unterhaching</td>
<td>Germany</td>
<td>2009</td>
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<tr>
<td>Shanghai Expo</td>
<td>China</td>
<td>2010</td>
<td>0.05</td>
<td>Solar hot water</td>
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<tr>
<td>Quingshui</td>
<td>Taiwan</td>
<td>2011</td>
<td>0.05</td>
<td>Geothermal</td>
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</tbody>
</table>

STIRLING (AND ERICSSON) CYCLES

- Many years of development (DOE solar since 1980)
- Some early stage commercial development ongoing for both cycles (including for ARPA-e GENSETS program – High T)
- Compact systems at high efficiency at low grade waste heat a challenge due to gas recuperation
- Costs, volume likely higher for low grade waste heat

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>( P_e (\text{kW}) )</th>
<th>( P_i (\text{kW}) )</th>
<th>( P_l (\text{kW}) )</th>
<th>( n_e )</th>
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<tbody>
<tr>
<td>ICE</td>
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<td>3.3</td>
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<td>ICE</td>
<td>ASIN SEIKI</td>
<td>CECC46A2</td>
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<td>10.55</td>
<td>18.0</td>
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<td>ICE</td>
<td>Senertec (DACHS)</td>
<td>HIKA G 5.0</td>
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<td>MGT</td>
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<td>15.0</td>
<td>18.75</td>
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<td>mRC Energy</td>
<td>Genlec</td>
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<td>JX Crystal</td>
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<td>1.5</td>
<td>9.4</td>
<td>12.2</td>
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</table>

Barbieri et al., 2012

EPRI, 2002
**BRAYTON CYCLE**

- Not typically used for low grade waste heat
- High grade waste heat projects for ARPA-e GENSETS
- DOE investing a significant amount for large scale (10 MW) sCO$_2$ systems
- Likely to suffer same limitations as Stirling due to large HEX volumes for gas recuperators

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*Moran and Shapiro, 2000*
Low Grade WHR Target?
Size and Weight Targets Needed
(Need $\eta$ and Temperature Target Too – perhaps sliding scale?)
Heat Exchanger Cost and Volume Limitations

- Cost of heat exchangers can be >50% of overall system
- Substantial reductions needed to achieve lower overall system cost
- Example: Electratherm 35 kWe unit

Differential cost for air cooled unit: $2200/kWe (not all HX, probable volume discount, but still significant)
Most of Normally Discharge Exhaust Heat is Rejected in HX \( \sim 3 \times \) Core Face Area of Radiator
Complexity: Speed Synchronization

- High speed, high efficiency turbomachines
- Low speed engines
- Need intermediate device to link performance of two system (battery, transmission, etc.)
Summary and Conclusions
**SUMMARY AND CONCLUSIONS**

- ORCs are well established and mature technology, but cost reduction needed at low power outputs and low waste heat temperatures.

- Stirling, Brayton cycles: need to address volume, weight, and efficiency challenges at low temperature.

- Cost target <$500/kW (or lower), efficiency of ~50% of Carnot at 10 kW might be a good target for low grade waste heat (Need TEA for different markets!)

- Potential “ARPA-e Hard” challenges
  - Extreme cost reduction of heat exchangers
  - Inert (and low cost) working fluids without adverse environmental impact, flammability, or other implementation issues (e.g., freezing)
  - Transportation: improved gas heat exchange per unit volume
REFERENCES

- Koeberlein, D, 2015, Cummins SuperTruck Program, DOE Project ID: ACE057.
Thank you! Questions?