U.S. DEPARTMENT OF ENERGY
Northwest Clean Energy Application Center
Promoting CHP, District Energy, and Waste Heat Recovery

Overview of Waste Heat Recovery Technologies for Power and Heat

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A Brief and Broad Overview Of Waste Heat Recovery Technologies

- Later presentations will provide more detail.
- Weblinks in this PPT provide more information.

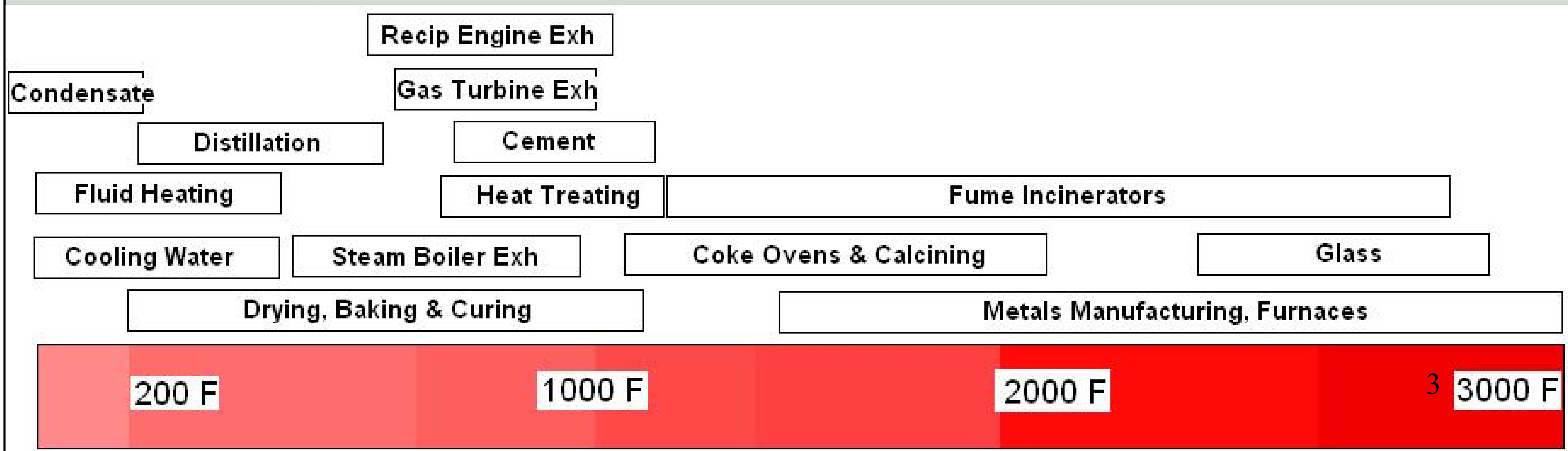
- Outline of this presentation
  - Where Do You Look for Opportunities?
  - What Can You Do With the Heat?
  - How Do You Do It?
    - Basic Concepts of Waste Heat Recovery and WHTP
  - What Equipment Is Used?
    - System Components
    - High Temperature CHP
    - Low to Medium Temperature CHP

Where Do You Look?
Examples of Waste Heat Sources

Waste heat opportunities at a wide range of projects

- Many industrial, but also commercial and institutional sites
- From low to high temperatures:

  ~200°F to 3000°F (~90°C to 1600°C)



High Temperature Opportunities

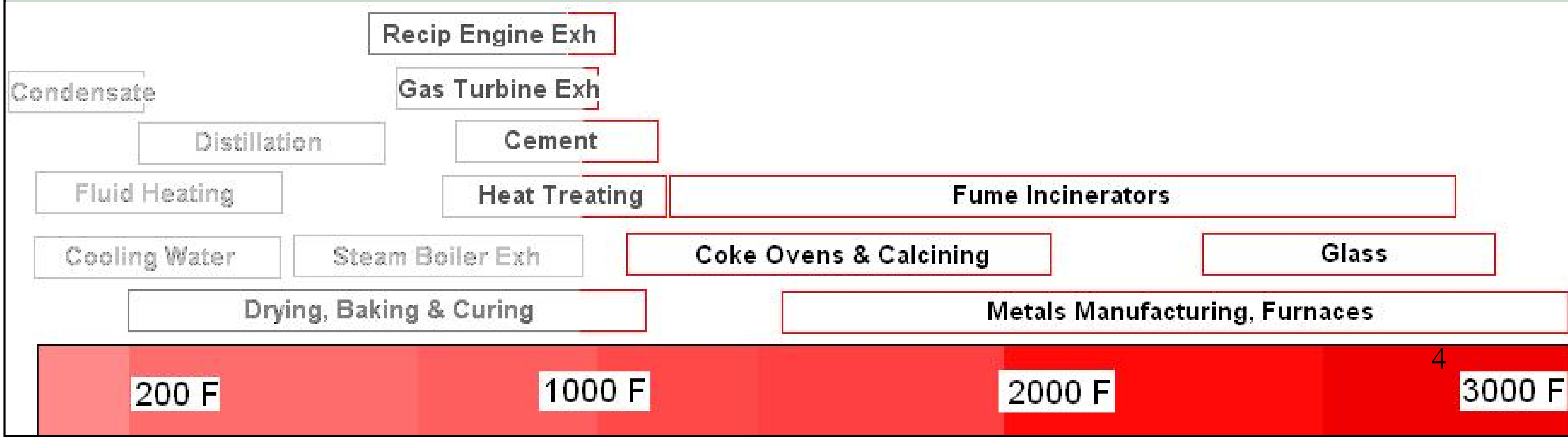
About 1000ºF and Greater

Examples:

- Metals Manufacturing and Reheating (Steel, Al, Ni, Cu, Zn, Si…)
- Glass
- Coke Ovens and Calcining
- Fume Incinerators

Plus high ends of

- Turbine & engine exhausts, heat treating furnaces, drying & baking ovens, cement kilns



Low & Medium Temperature Opportunities

Up to About 1000ºF

Examples:

- Turbine, Engine and Boiler Exhausts
- Distillation Columns
- Drying, Baking and Curing Processes
- Cooling Water from Industrial Processes

Plus low ends of

- Heat treating furnaces and cement kilns

What Do You Do With It?
Examples of End Uses

- Steam Generation and Process Heating for Industrial Processes
  - e.g. Steam use at paper mill or refinery
- Plant or Building Heating
- Electricity Generation
- Hot Water Heating
  - Commercial, Industrial & Institutional
- Cooling and Chilling
  - Commercial, Industrial & Institutional

How Do You Do It?

Basic Concepts: Passive vs. Active Systems

- Heat naturally flows from high to low temperature.
- Passive Systems
  - Do not require significant mechanical or electrical input for their operation
  - Transfer heat from a higher temp source to a lower temperature sink.
  - Example: Heat exchanger to transfer heat from exhaust air to preheat supply air
- Active Systems
  - Require the input of mechanical or electrical energy
  - “Upgrade” the waste heat to a higher temperature or to electricity
  - Examples: Industrial heat pumps and combined heat and power systems.

Basic Concepts

Analysis Strategy

In evaluating a project, consider <u>in order</u>

1. Energy efficiency

   e.g. Insulation, reducing leaks, high efficiency burners, etc.

2. Passive heat recovery strategies

   i. Recycling energy back into the <u>same</u> industrial process.
      e.g. using a kiln's exhaust to preheat its load

   ii. Recovering energy for <u>other on-site</u> uses
      e.g. using a furnace's exhaust as a heat source for a nearby dryer.

3. Heat recovery by active systems

   e.g. CHP, heat pumps, and absorption technologies.

Why this order? Consider most cost effective and simplest first.

Basic Concepts

What to Look For in Screening & Analysis

- Factors affecting cost effectiveness and feasibility include
  - Temperature (i.e. Quality)
  - Flow rate of heat source
  - Availability over the course of the day and year
  - Exhaust composition
    - Clean or particulate laden, corrosive, abrasive, slagging, sticky, or oily
  - Matching heat source and end uses
    - Heat source is available at times when it can be used
    - Quantity of heat source and uses are similar
  - Proximity of heat source and end uses
    - e.g. Exhaust duct is located near supply duct
  - Opportunity to "cascade" recovered heat through more than one end use

The Importance of Temperature

- Cost effectiveness generally improves with temperature
- Temperature largely determines the most appropriate technology and end use.
  - For example, in CHP systems
    - Steam cycle is conventional at high temperatures
    - But other technologies must be used at lower temps
- Temperature ranges often classified as
  - High - 1100^{o}F and greater
  - Medium – 400^{o}F to 1100^{o}F
  - Low – 80^{o}F to 400^{o}F

(Others sometimes define ranges differently.)

Turner, Wayne, "Chapter 8: Waste Heat Recovery", *Energy Management Handbook ,* 5th Edition, 2005, by Wayne Turner

The Importance of Exhaust Characteristics

- Many waste heat sources pose challenges:
  - Particulate-laden
  - Corrosive
  - Abrasive
  - Slagging
  - Sticky
  - Oily
- Don’t rule these out out of hand.

….strategies→

Survey of Gas-side Fouling _www.moderneq.com/documents/whitepapers/NASA_Recuperation_study.pdf

The Importance of Exhaust Characteristics

- Difficult exhausts do pose financial and technical issues.
- But consider possible strategies:
  - Filtration Systems
  - Material Selection
    e.g. corrosion resistant "duplex steels" or TFE coatings
  - Heat Exchanger Design
    e.g. provide access to heat transfer surfaces for cleaning
    e.g. ensure passages are large enough to minimize blockages
  - Surface Cleaning with Soot Blowers, Acoustic Horns & Pulse Detonation
  - Mechanical Surface Cleaners
  - Automatic Wash Cycles
    e.g. Used in heat recovery from sticky exhaust of apple dryers
- Example: Port Arthur Steam Energy's CHP system at calcining plant uses acoustic horns to handle particulate-laden exhaust

PASE : www.integralpower.com/portarthursteam.html
TFE and other coatings: http://www.haward.com/xylanandtfe/

Waste Heat Recovery System Components

For low to high temperature heat sources:

- Heat exchangers
- Power generation equipment
  - For example: ORC turbine, Steam turbine
- Auxiliary equipment
  - For example, pumps and fans
  - Equipment for handling difficult waste heat sources

For low temperature heat sources:

- Heat pumps & absorption units, also

Most Systems Have Heat Exchangers
Heat Exchanger Terminology

- There are two general ways of classifying heat exchangers.
  1. By physical configuration and fluid flows
  2. By typical use or function

- Intermixing these classifications is common, sometimes causing confusion.

… More →

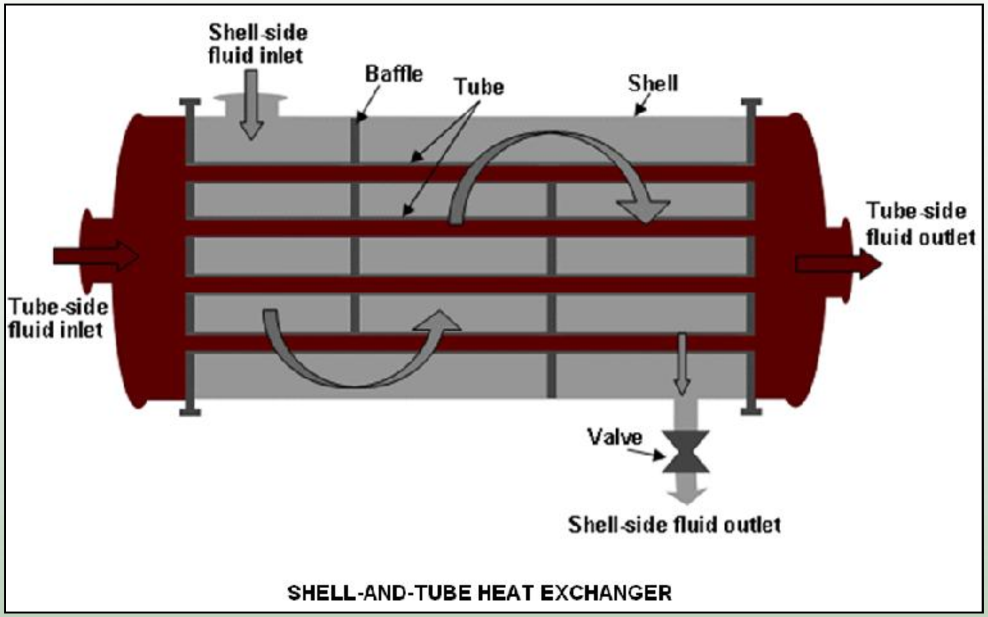
Classification of Heat Exchangers

One way of classifying heat exchangers is

- By physical configuration
  - Shell-and-Tube
  - Concentric Tube
  - Plate-and-Frame
  - Finned-Tube
- … and by fluid streams between which heat is transferred
  - Gas-to-Gas
  - Gas-to-Liquid
  - Liquid-to-Liquid

Example of Physical Configuration Terminology

Shell-and-tube air-to-water heat exchanger



"Shell-and-Tube"

- Bundle of tubes within a cylindrical shell

"Air-to-Water"

- Air is on one side
- Water is on the other side

Other terminology may indicate what fluid is on which side. For e.g.,

- "Fire Tube Boiler" – Water on shell side, gases on tube side
- "Water Tube Boiler" – Water on tube side, gases on shell side

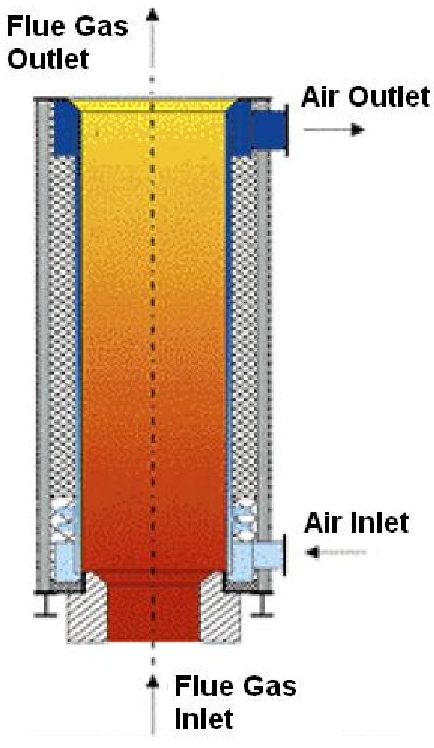
http://www.mckenziecorp.com/boiler_tip_8.htm

Heat Exchanger Terminology

- A second way of classifying heat exchangers is by typical use.
- These types can have various physical configurations.
- Examples:
  - **"Recuperators"**
    Typical Use: Recover heat from flue gases to preheat combustion air
  - **"Economizers"**
    Typical Use: Recover heat from flue gases to heat boiler feedwater
  - **"Regenerators"**
    Typical Use: Recover heat from exhaust to preheat air using thermal mass
  - "**Heat Recovery Steam Generators" (HRSG)**
    Typical Use: Recover heat for steam generation
  - **"Waste Heat Boilers"**
    Typical Use: Recover heat for hot water or steam generation.

Example of Classification by Typical Use
Recuperators

"Recuperators" are typically used to recover or "recuperate" heat from flue gas to heat air.



Concentric-Tube
Radiation Recuperator
(~1800F and Greater)

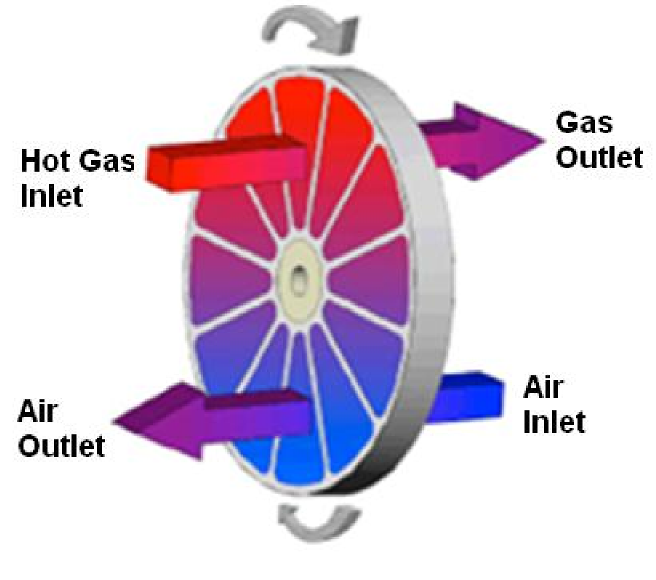
- **Example: "Metalic Radiation Recuperators":**
  - Concentric-Tube is common physical configuration
  - Used for high temperatures (>1800ºF)

- **Others recuperators include:**
  - **"Convective Recuperator"**
    - Physical configuration is often shell-and-tube
  - **"Radiation-Convective Recuperator"**

Example of Classification by Typical Use Regenerators

"Regenerators" are heat exchangers that use thermal mass (e.g. bricks or ceramic) in an alternating cycle to recover heat from exhaust to preheat supply air

- First, thermal mass is heated by the hot gas.
- Then, air to be preheated passes over the mass to extract its heat.



Rotary Regenerator

- **Example: "Rotary Regenerator"**
  - Mass is wheel that turns through adjacent exhaust and supply ducts

http://www.process-heating.com/Articles/Industry_News/BNP_GUID_9-5-2006_A_10000000000000255829

http://www.recair.nl/paginas/30-recuperator-or-regenerator.html

Active Heat Recovery

Waste heat can be “upgraded” by active systems

- Absorption Chillers and Heat Pumps
- Mechanical Heat Pumps
- Combined Heat and Power Systems

…More →

Mechanical Heat Pumps

- Technology:
  - Conventional refrigeration cycle, but with “high” temperature refrigerants
  - Heats supply air or water to a temperature greater than the temperature of the waste heat source (i.e. achieves a “temperature lift”)
  - Can achieve very high COPs when the temperature lift is small.

- Applications:
  - Heat recovery from waste heat streams up to about 200ºF
    - Drying, washing, evaporating, distilling and cooling.
  - Hot water and steam generation for space and process heating
  - Refrigeration and cooling
- Most cost effective applications:
  - Serving simultaneous heating and cooling needs
  - Recovery from moist exhausts to recover both latent and sensible heat
    - “Sensible heat” – heat associated with temperature
    - “Latent heat” – heat associated with humidity

Photos from Nyle Corporation: www.nyle.com

Absorption Chillers & Heat Pumps

- Technology:
  - Absorption chiller uses heat to produce chilled water.
  - Absorption heat pump uses a heat source to "upgrade" a second lower temperature stream to an intermediate temperature.
- Heat source can be low pressure steam, hot gas or hot liquid stream.
- Most cost effective applications:
  - Heat source of about 200ºF to 400ºF,
  - Need for simultaneous heating and cooling.

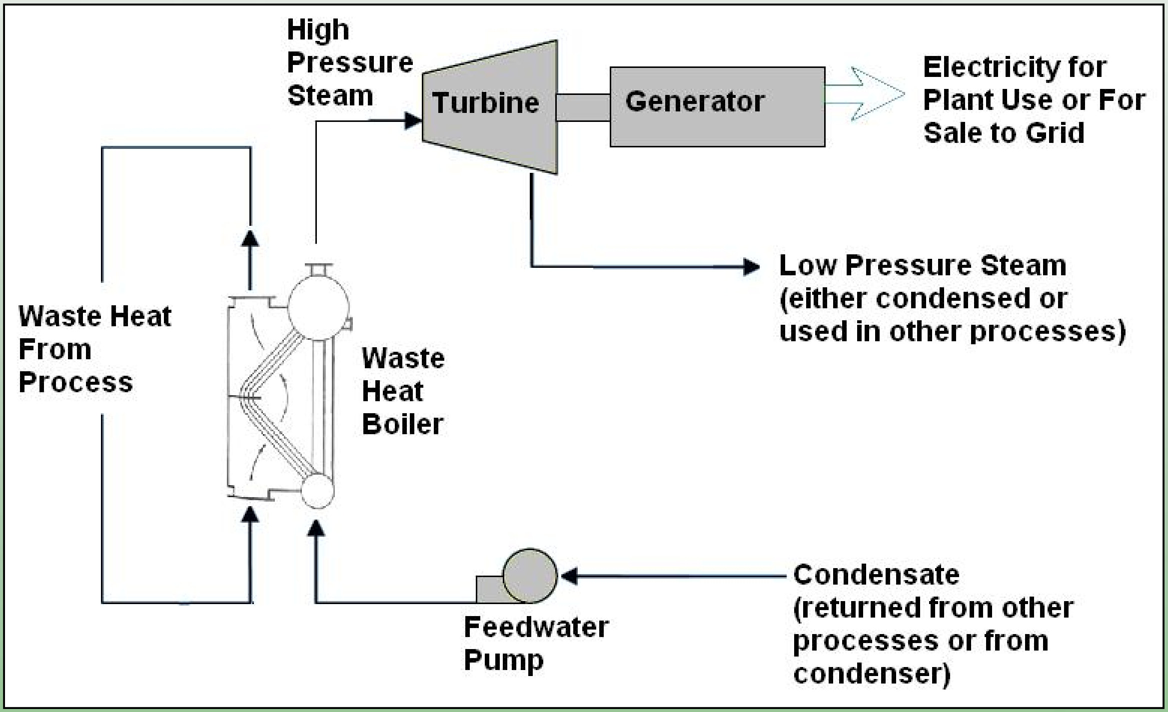
Weblinks

http://www.energytechpro.com/Demo-IC/Gas_Technology/Absorption_Chillers.htm
http://www1.eere.energy.gov/industry/bestpractices/pdfs/steam14_chillers.pdfhttp://www.leonardo-energy.org/webfm_send/180

http://www.northeastchp.org/nac/businesses/thermal.htm#absorb

Heat Recovery for Power Generation at Temperatures of ~1000°F and Above

- Steam Rankine cycle is conventional for high temps
  - Waste heat boiler recovers heat to generate steam
  - Steam is expanded in a steam turbine to generate electricity
  - Low pressure steam can be used in other processes or condensed.



Other CHP Technologies for High Temperatures

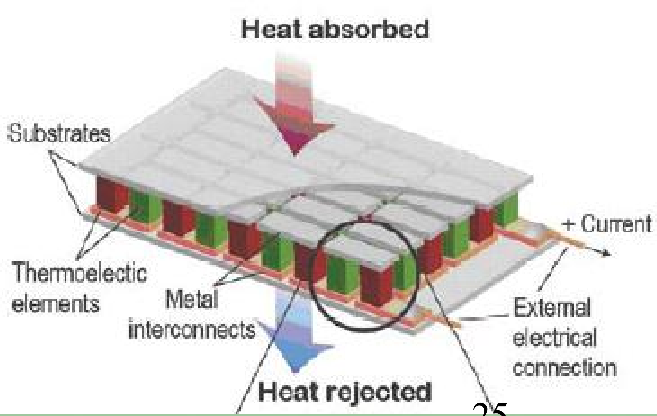
- Other less conventional technologies exist.
- Reasons for being less common include:
  - Under development, cost concerns, lack of track record for the application
- Examples:
  - Stirling engine
    - Old technology that is reemerging
    - Long used in solar applications
    - Newer application: Micro-CHP (e.g. WhisperGen)
  - "Heat Recovery Gas Turbine" (Brayton Cycle)
    - Just like a conventional gas turbine, except uses waste heat rather than combustion.
    - Heat exchanger replaces combustion chamber

Stirling Animation at http://en.wikipedia.org/wiki/Stirling_engine

WhisperGen - http://www.whispergen.com/

Other CHP Technologies for High Temperatures

- Examples (cont.)
  - Thermoelectric Generator – Under development
    - Direct conversion of temperature differences to electric voltage. Creates a voltage when there is a different temperature on each side.
    - Similar physics to thermocouple and photovoltaics.
    - Can be used to recover disparate source by running wires instead of pipes or ducts
    - Takes up very little space
    - Major R&D is for vehicle heat recovery



http://en.wikipedia.org/wiki/Thermoelectric_generator
http://www.electrochem.org/dl/interface/fal/fal08/fal08_p54-56.pdf

Power Generation at Low to Medium Temperatures

- Commercialized technologies for power generation at low to medium temperatures:
  - Organic Rankine Cycle
  - Kalina Cycle

…More →

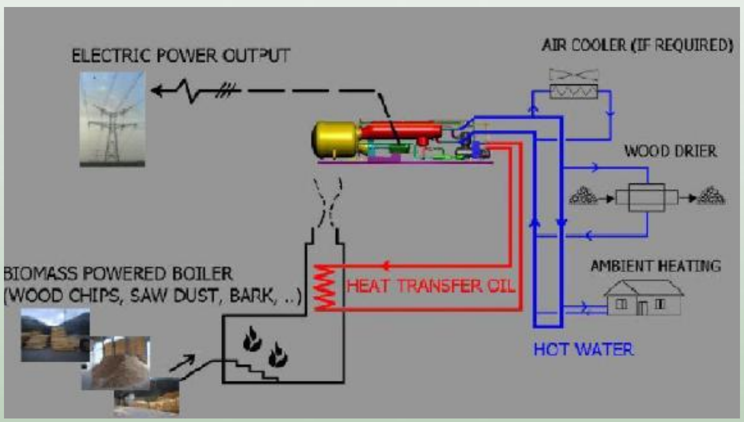
Organic Rankine Cycle

- Similar to steam cycle, except working fluid is a refrigerant instead of water.
- Temperatures vary depending on design:
  - Heat sources may range between 300ºF and about 750ºF
  - With some designs, source temperature can be as low as ~150ºF to 200ºF, if low temperature cooling is available.

- ORCs have a 40 year track record.
  - Geothermal applications
  - Bottoming cycle for steam power plants
- Track record back to 1999 for industrial heat recovery
  - Cement kilns
  - Compressor stations

Organic Rankine Cycle For District Heating

- District heating is a new application of ORCs
- Example: Grand Marais Biomass District Heat & CHP
  - ORC heat source is 630°F oil heated in low pressure thermal oil heater.
  - Cooling water for ORC is 160°F return water from district heating loop
  - 175°F hot water leaving ORC's condenser is recovered for district heating



- Advantages over district heating with steam turbine include:
  - Thermal oil heater operates at 150 psig.
    - Does not require boiler operator, reducing labor costs
  - ORCs are packaged units or skid-mounted for easy installation.

See: http://www.cookcountylep.org/Feasibility_Biomass_7_14_09.pdf

Kalina Cycle

- Temperature range of about 200ºF to 1,600ºF
  - Fills temperature gap between maximum for ORC and cost effective temperature of steam cycle.
- More efficient than either steam cycle or ORC.
- An example project:
  - Sumitomo Steel in Kashima, Japan,
  - Generates 3.1 MW using 208ºF hot water as its heat source
  - Operating since 1999 with 98% availability
  - More at: http://media.wotnews.com.au/asxann/01079928.pdf

http://www.exorka.com/tl_files/pdf/An_Introduction_to_the_Kalina_Cycle.pdf

Up and Coming for
Low to Medium Temperatures

- Others technologies are under development.
- Examples:
  - **Variable Phase Turbine**

    http://www.energent.net/technology/variable-phase-cycle.html
  - **Piezoelectric Generator**

    http://www.cleanpowerresources.com/content.php?sub_section=thermoenergyconversion&name=the_thermocoustic_alternator

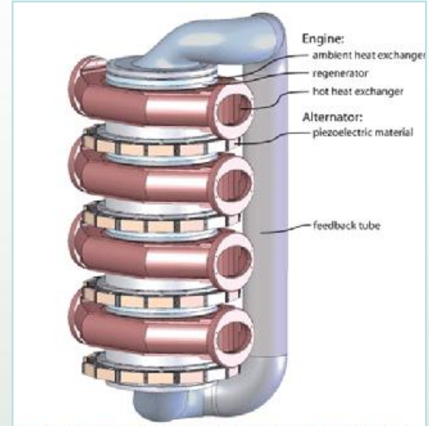


Figure 1. Thermoacoustic piezoelectric generator, consisting of four thermoacoustic Stirling engines driving four piezoelectric alternators.

Figure 12. Variable Phase Turbine operating in pilot plant.

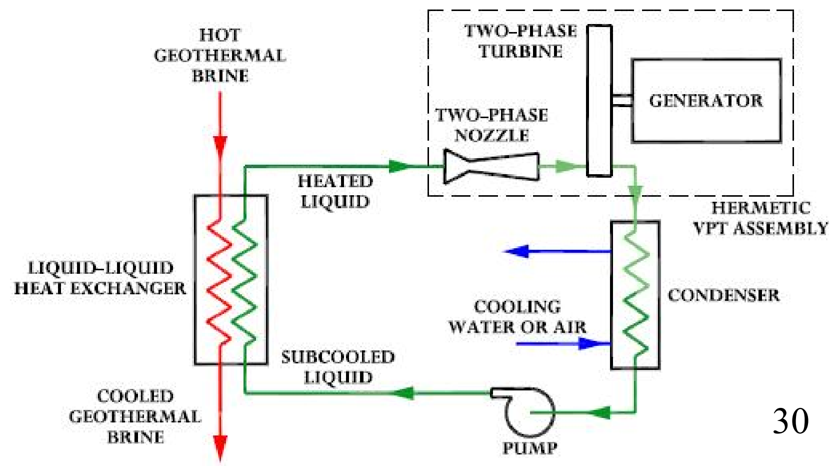


Figure 15. Variable Phase cycle process flow diagram.

Wrap Up

- Where Do You Look for Opportunities?
  - Industrial, commercial, and institutional
  - Low to high temperature sources
  - Consider both dirty and clean heat sources
- What Can You Do With the Heat?
  - Steam and process heating, space heating, electricity, hot water, cooling & chilling
- How Do You Do It?
  - Energy Efficiency
  - Passive heat recovery
  - Active heat recovery
    - Absorption chillers and heat pumps
    - Combined heat recovery

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