



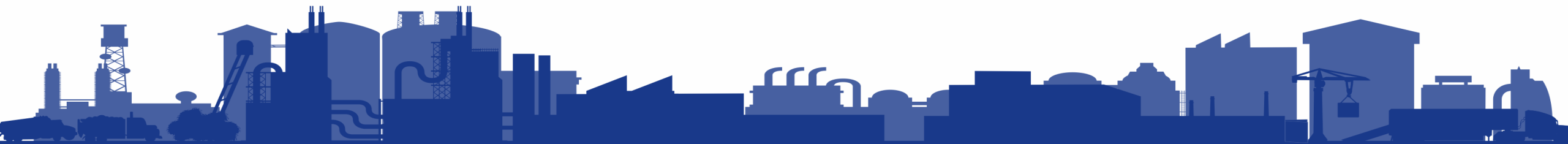
VIRTUAL PROCESS HEATING INPLT

Session 7



Training Module # 7

Waste Heat Recovery for Process Heating Equipment



Outline

- Drivers for Industrial Waste Heat Management
- Waste Heat Management – 3Rs
- Sources of Waste Heat and Where Can We Use It?
- Barriers to Waste Heat Management
- Waste Heat Recycling Options
 - Combustion Air Preheating Considerations
- Waste Heat Recovery Options
 - Waste Heat to Power Options
 - Waste Heat Recovery Emerging Technologies
- Waste Heat Management Summary

Drivers for Industrial Waste Heat Management

Example – Dry-off Oven Waste Heat



- Typically, gas fired and can have a high exhaust rate - up to 50% of total oven heat load
- Generally, operate between 200 and 650°F, the potentially large amount of heat lost in the exhaust

- Waste heat = NO FOSSIL FUEL (capturing wasted energy)
- Reduction in fuel energy use in process heating equipment
- Reduced electricity purchase and/or export to grid
- Waste heat = NO incremental EMISSIONS
- Green projects = “sustainable development”...P.R. story
- Industrial WHR considered “renewable” now in some countries

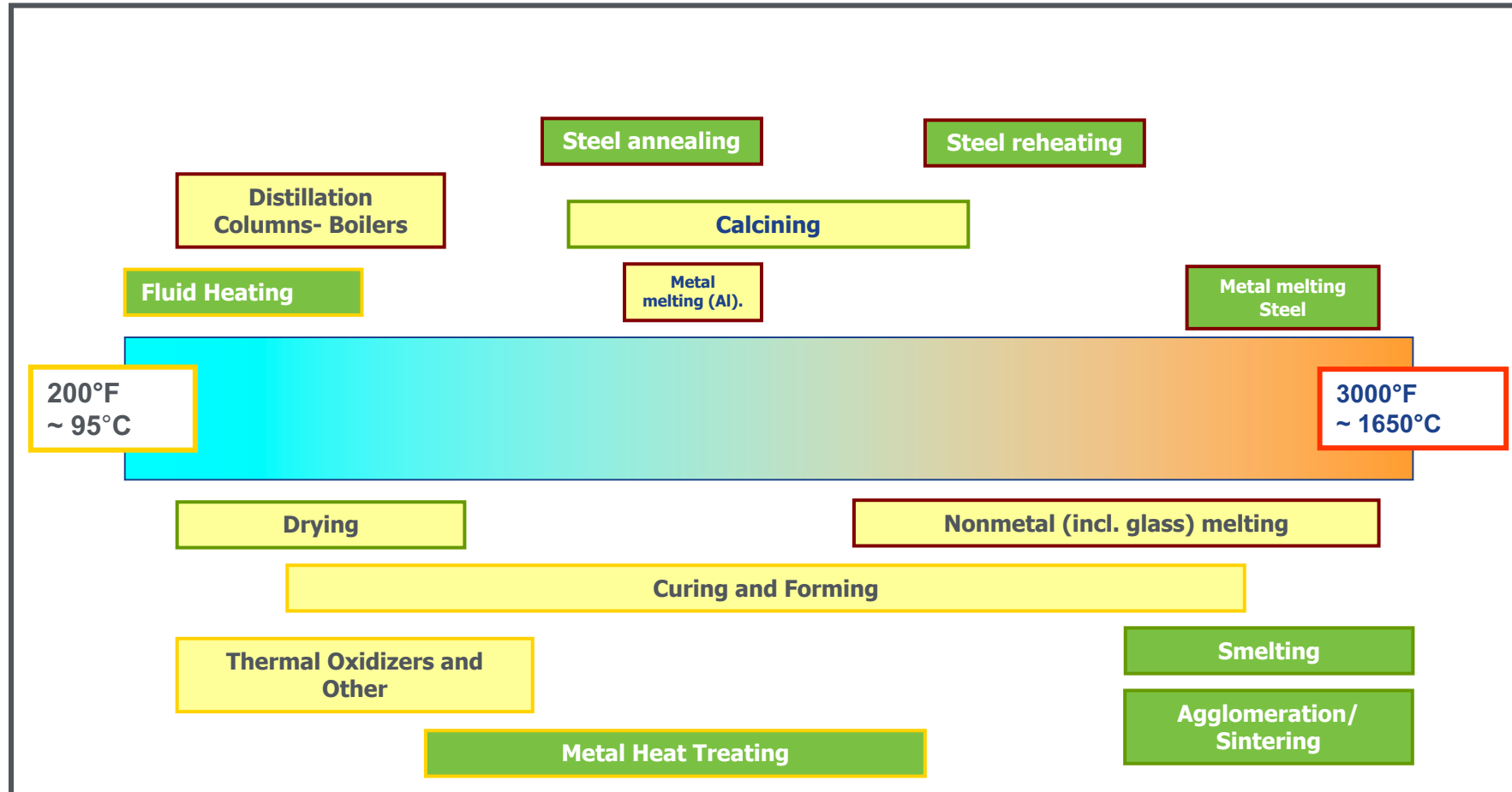
Options for Exhaust Gas Waste Heat



- Waste heat Reduction within the heating system itself
- Waste heat Recycling within the heating system itself
- Waste heat Recovery:
 - Use of waste heat outside the heating system – utilize heat in (or for) other systems within the plant or outside the plant.
 - Waste heat to power conversion

Range of Temperatures for Waste Heat

From Industrial Heating Processes



Sources of Waste Heat

- Exhaust or flue gases from:
 - Boilers, furnaces, heaters, kilns, combustion turbines, engines etc.
- Exhaust air from ovens, dryers etc.
- Hot liquids or water from processes
- Steam from various sources
- Hot products discharged from the heating equipment (i.e. hot steel, clinkers, glass ware, castings etc.)
- Radiation – convection heat from hot sources (i.e. ducts, conveyors etc.)
- Chemical reactors (heat of exothermic reactions)
- Other sources

Waste Streams, Industries of Origin, and their Characteristics Indicated by Color Code

Waste Heat Source	Steel	Aluminum	Glass	Paper	Pet. Refining	Mining	Chemical	Food	Cement	Coating	Steam generation	CHP/Gas turbine
1) The Exhaust gases or vapors												
a) High temperature combustion products - clean ...	Red	Orange			Orange	Yellow	Orange			Yellow		
b) High temperature flue gases or combustion products with contaminants	Red	Red	Red			Orange			Red			
c) Heated air or flue gases containing high (>14%) O2 without large amount of moisture and particulates.				Yellow						Yellow		Yellow
d) Process gases or by product gases/vapors that contain combustibles ...					Yellow		Yellow			Light Blue		
e) Process or make up air mixed with combustion products, large amount of water vapor or moisture						Light Blue		Light Blue		Light Blue		
f) Steam discharged as vented steam or steam leaks.	Light Blue			Light Blue	Light Blue	Light Blue	Light Blue	Light Blue			Light Blue	Light Blue
g) Other gaseous streams.												
2) Heated water or liquids												
a) Clean heated water discharged from indirect cooling systems...	Dark Blue						Dark Blue				Dark Blue	Dark Blue
b) Hot water that contains presence of large amount of separatable solids	Dark Blue			Dark Blue			Dark Blue	Dark Blue	Dark Blue	Dark Blue		
c) Hot water or liquids containing dissolved precipitable solids, dissolved gases.....					Dark Blue	Dark Blue	Dark Blue	Dark Blue			Dark Blue	
3) Hot products												
a) Hot solids that are air cooled after processing.		Yellow	Red	Light Blue	Light Blue	Yellow	Yellow	Light Blue	Red	Yellow		
b) Hot solids that are cooled after processing using water or air-water mixture.	Red					Yellow						
c) Hot liquids/vapors that are cooled after thermal processing.				Dark Blue			Dark Blue	Dark Blue				
4) High temperature surfaces												
a) Furnace or heater walls	Light Blue	Light Blue	Light Blue		Dark Blue				Light Blue			
b) Extended surfaces or parts used in furnaces or heaters.	Dark Blue	Dark Blue	Dark Blue									

The largest source for most manufacturing industries is exhaust / flue gases or heated air from heating systems.

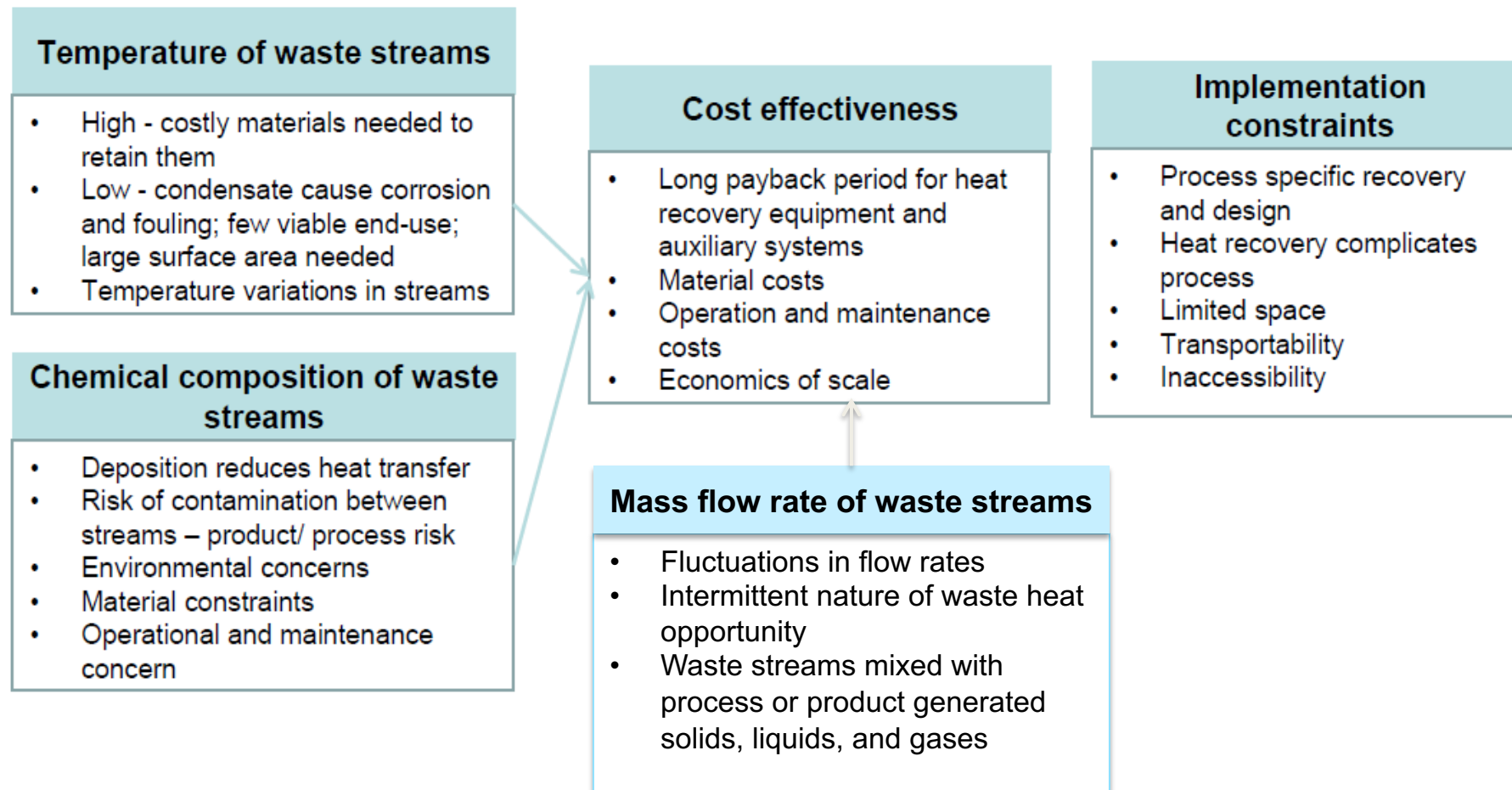
Waste Heat

Where Can We Use It?

- Combustion air or make-up preheating
- Fuel preheating in limited cases
- Charge – load – feed preheating
- Heat recovery for preheating the oven exhaust air upstream of the thermal oxidizer
- Steam generation for process or heating
- Electric power generation from high and low temperature gases
- Heat cascading using high temperature exhaust.
- HVAC in limited cases
- Chilled water system (absorption cooling) for certain plants
- Other in-plant demands??

Barriers to Waste Heat Management

- Barriers may be interrelated. Some technical barriers lead to cost barriers.



Outline

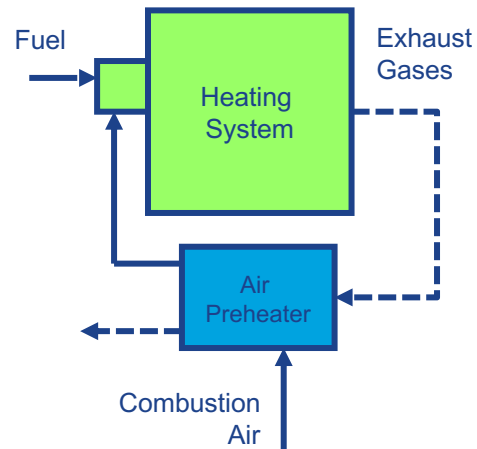
- Drivers for Industrial Waste Heat Management
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- **Waste Heat Recycling Options**
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Exhaust Heat Recycling – Recovery Issues to Consider

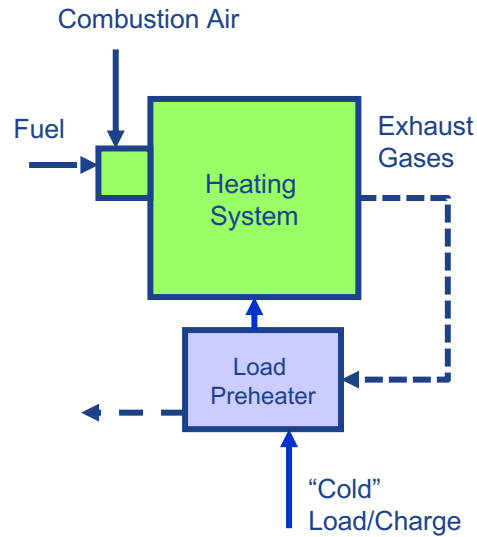
Before you decide on a method of waste heat recovery, consider the following issues:

- Temperature of flue gases: High, medium, low
- Mass or volume flow rate: High, low
- Availability: constant or variable
- Presence of particulates in flue gases: organic or inorganic
- Presence of corrosive gas compounds (chlorine, fluorine, sulfur)
- Presence of condensable vapors or gases (oil, light metals etc.)
- Presence of combustible gases or vapors (CO, H₂, organic solvent vapors)

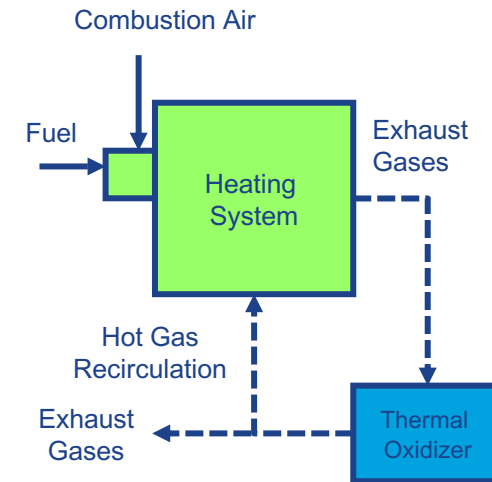
Waste Heat Recycling Options



1. Combustion Air Preheating



2. Load-Charge Preheating



3. Internal heat recycling - cascading

These other options: use similar technology and hardware as the systems 1,2 and 3:

- 4. Make up air heating
- 5. Water (liquid) heating

Advantages of Waste Heat Recycling

- Compatible with process demand and variations in operating conditions.
- Can be used as retrofit for existing equipment.
- Relatively easy and inexpensive to implement.
- Heat recovery – 30% to 90% of the waste heat.
- Implementation cost: \$30,000 to \$75,000 per MMBtu (\$28,500 to \$71,000 per GJ) recovered heat (includes normal installation). Very much dependent on technology, site and size of the system used.
- Typical payback periods – one year to three years
- Application temperature range – Typically it ranges from 440°F (225°C) and higher. Depends on specific process conditions.

Note: The implementation cost values are based on current for US market conditions. The values could be different for Ukraine. Use these values for comparison purpose only.

Waste Heat Recycling Economic Considerations

Saving:

- Energy savings based on average operating conditions
- Emission reduction
- Productivity gain
- Quality improvement
- Other (labor, waste disposal cost, etc.)

Cost:

- Equipment (i.e. recuperators, regenerators) cost
- Auxiliary equipment (i.e. burners, controls, piping, etc.) cost
- Added supplemental energy cost (for blower motor, pumps, etc.)
- Changes in emissions (increase??) and environmental permits
- Equipment relocation, etc.
- Other cost – penalties (if any)

Waste Heat Recycling Summary

Method	Exhaust Gas Temperature Range* (°F)	Energy savings potential* (%)	Typical Applications
Combustion air preheat:			
Recuperators	570 – 1650	10 – 30%	Furnaces, ovens, thermal oxidizers, heater, kilns etc.
Regenerators	1100 – 2000	10 – 40%	
Load/Charge preheating	>750	5 – 25%	Furnace, ovens, kilns etc.
Internal heat recycling	300 – 1000	10 – 20%	Ovens, dryers etc.
Make-up air heating	300 – 950	10 – 25%	Ovens, dryers, air heaters etc.
Water heating	>212	3 – 10%	Heat treating operations, metal coating, ceramic kilns, etc.

Note: The numbers for temperature and savings are for typical applications. There are lots of exceptions, use this with care!

Combustion Air Preheating Considerations

- Use of flue gas heat to preheat combustion (or make up) air is the most used method of heat recovery for furnaces and ovens
- Application of preheated air on existing equipment requires:
 - Installation of a heat recovery device such as a recuperator or a regenerator
 - Changing burners to allow use of higher-temperature air
 - Changing air piping and insulation of the pipes
 - Changing air-to-fuel ratio control system and other controls in some cases
- Using hot air can increase formation of NO_x in most current (pre-90's design) generation burners, however, newer burner designs with air/fuel staging and other techniques may actually result in much lower amounts of NO_x emissions

Combustion Air Preheating Savings

Use of Preheated Combustion Air

	Current	New	Comments
Furnace flue gas temp. (°F)	840	840	
Percent O ₂ (dry) in flue gases	4.25	4.25	
% Excess air	22.71	22.71	MEASUR
Combustion air temperature (°F)	82	540	
Fuel consumption (MMBtu/hr.) - Avg. current	3.00	2.61	
Available Heat (%)	71.30	81.99	MEASUR
Fuel savings (%)	----	13.04%	
No. of operating hours	5400	5400	
Energy used per year (MMBtu/year)	16,200	14,094	
Energy saved per year (MMBtu/year)	----	2,106	
Cost of Fuel (\$/MMBtu)	\$ 5.00	\$ 5.00	
Annual Energy Cost Savings	----	\$ 10,530	

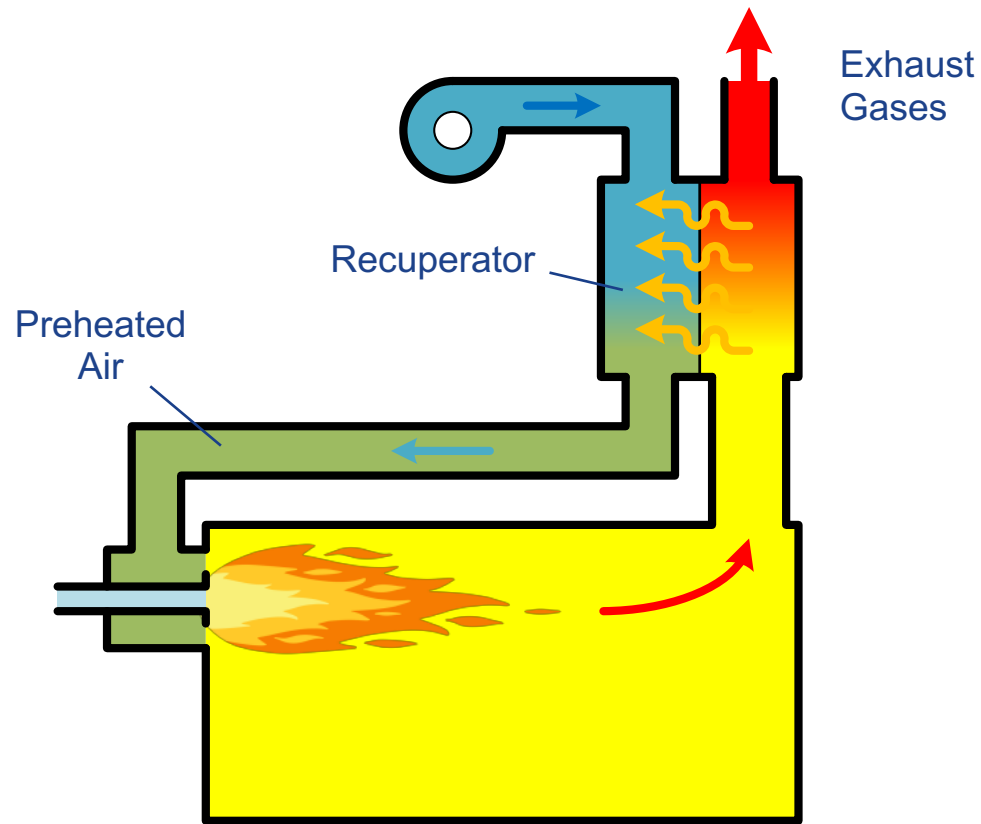
Heat treating furnace for an automotive parts supplier saves approx. \$10,530 per year

Combustion Air Preheating Equipment

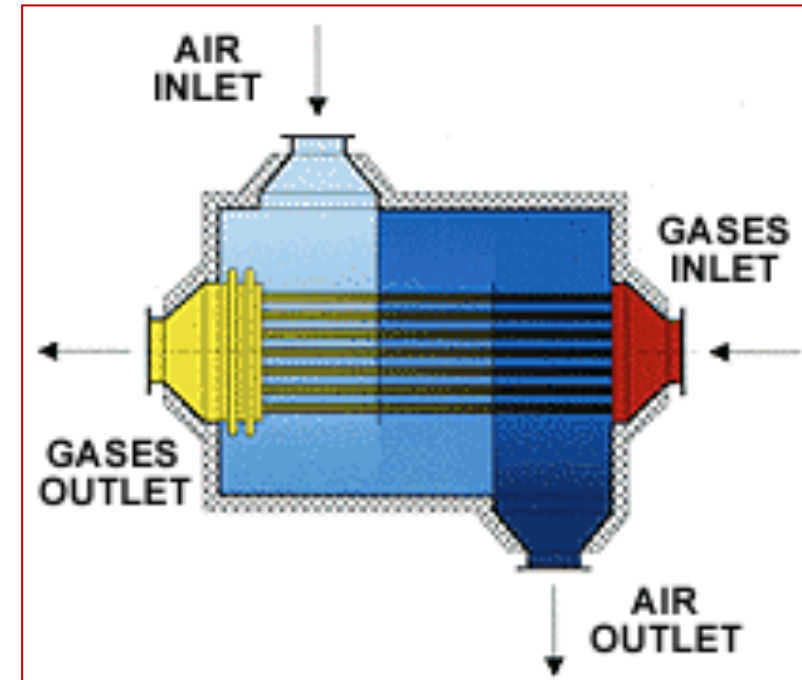
Recuperators

- Recuperators are extensively used for combustion air preheating for clean combustion products
- Recuperators are designed in many different configurations, such as parallel flow, counter flow, and cross flow (this designation indicates flow directions of air and flue gases)
 - Material for construction varies from simple carbon steel to high-temperature Ni-Cr alloys
- Flue gas temperature range for application: 480°F to 1600°F; combustion air temperature range: 300°F to 1000°F
- Maintenance problems arise when flue gases contain particles, condensable vapors or gases, combustibles, or corrosive gases
- Economically justifiable heat-recovery efficiency or effectiveness varies from 40% to 60%
- Unit size and cost increases significantly when the effectiveness exceeds 60%

Combustion Air Preheating Equipment Options

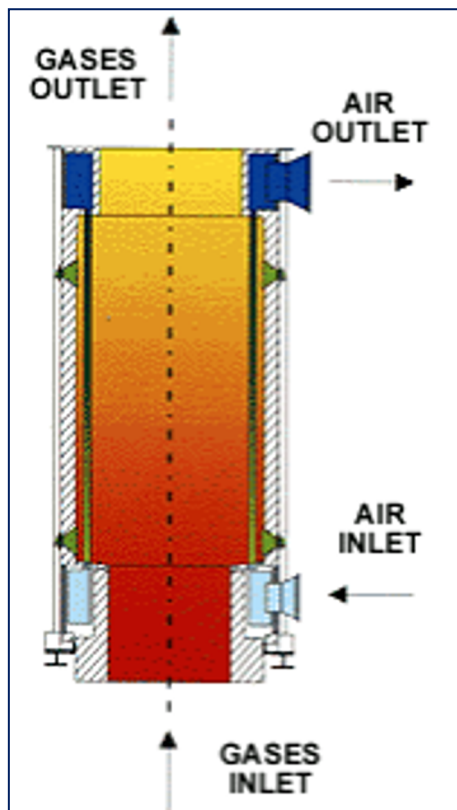


- Continuous, simultaneous flow of exhaust and combustion air
- A physical barrier separates air and exhaust flows



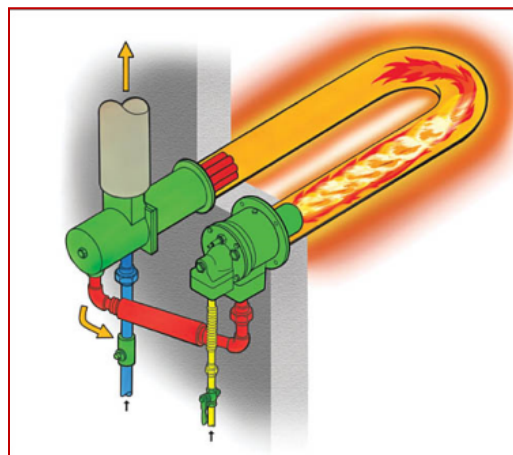
Courtesy HARDTECH Group

Combustion Air Preheating Equipment Options



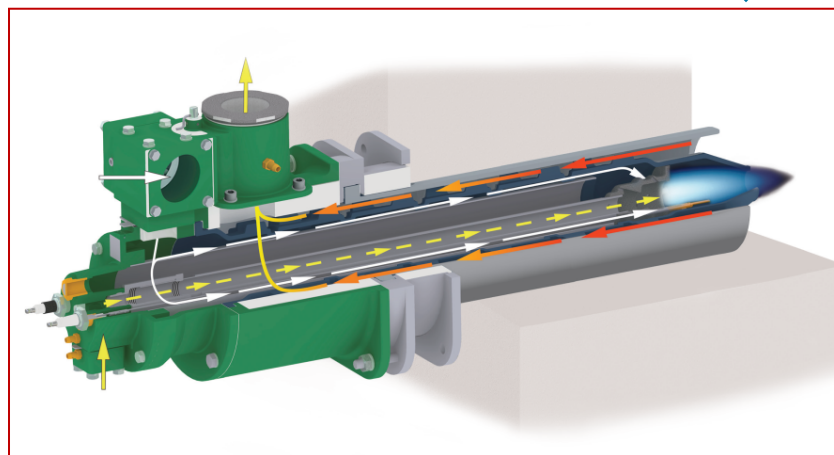
Radiation Recuperator

Courtesy HARDTECH Group



**Self recuperative radiant
tube burner**

**Self recuperative direct
fired burner**



Courtesy Eclipse Combustion - USA

Combustion Air Preheating Equipment Options

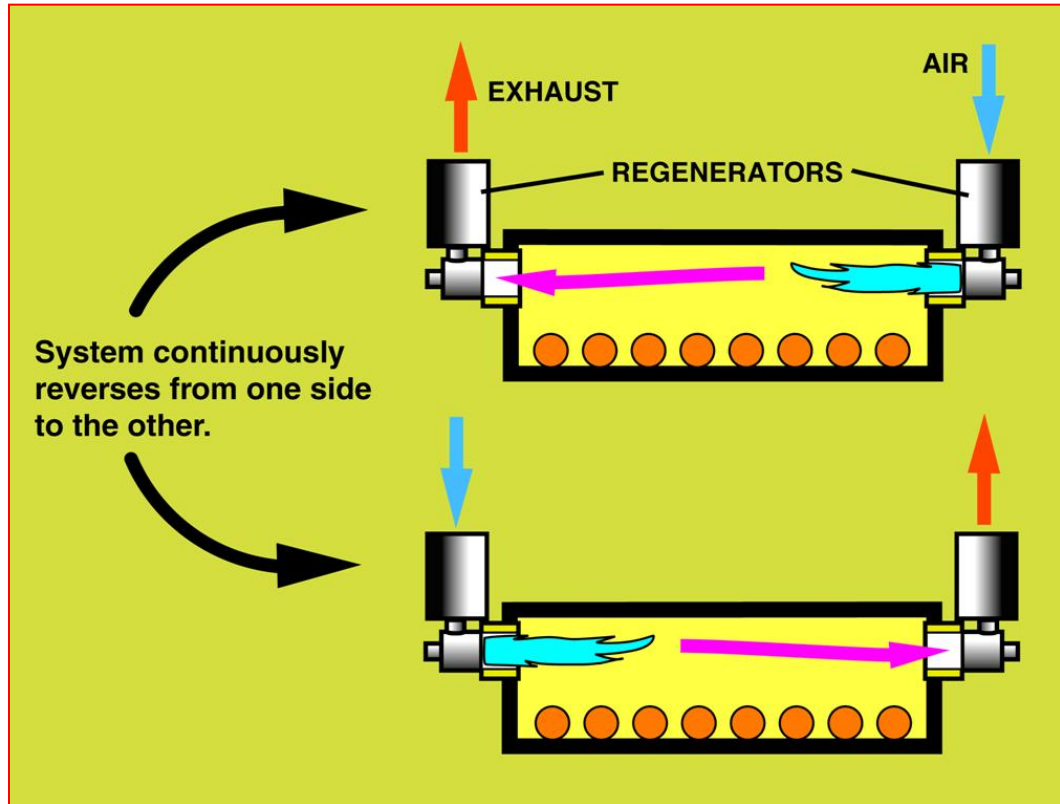
Regenerators

- Designs available to meet different temperature requirements.
- Regenerators offer much higher (65% to 85%) heat recovery ‘efficiency’ potential compared to recuperators.
- A regenerator designs include rotating matrix type design or a stationary unit. See examples in next slide.
- The rotary matrix units are generally used for lower temperature (<930 °F) exhaust gas applications while the stationary design is used for higher temperature (>1300°F) exhaust gas heating systems.
- Regenerative burners – It consists of a pair of burners each including its own heat transfer medium.

Regenerative Burners

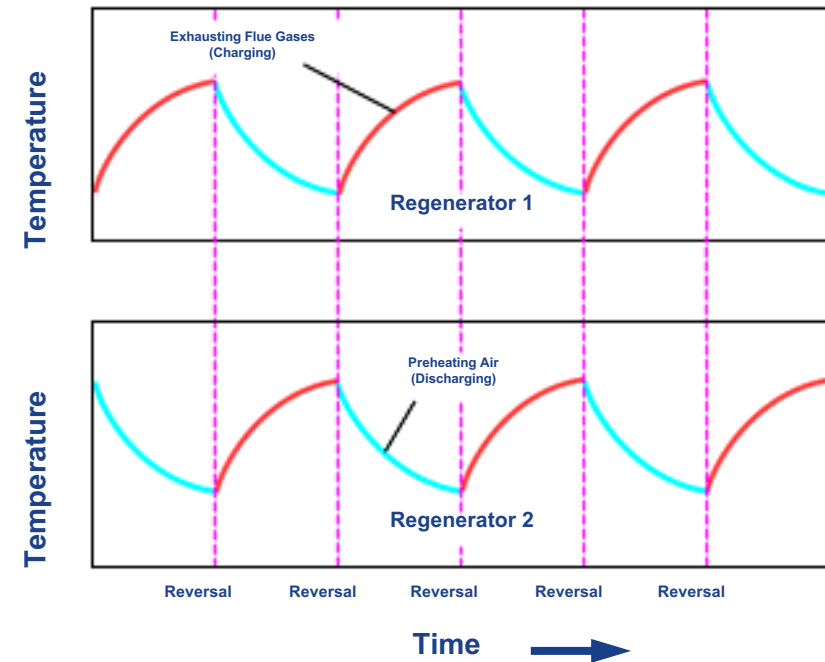
- The regenerative burner system includes a specially designed burner and associated regenerator
- The burners are always used in a pair
- The regenerative system is used for combustion air preheating
- The system is used for relatively high-temperature applications such as steel reheating, aluminum melting, and forging
- Overall heat-recovery efficiency is in the range of 60% to 85%
- Major issues for this type of system include: plugging of the bed resulting in frequent maintenance, furnace pressure control, size of the burner-regenerator system, space requirement around an existing furnace, and higher initial cost
- In most applications the payback period is 2 to 3 years

Regenerative Burners



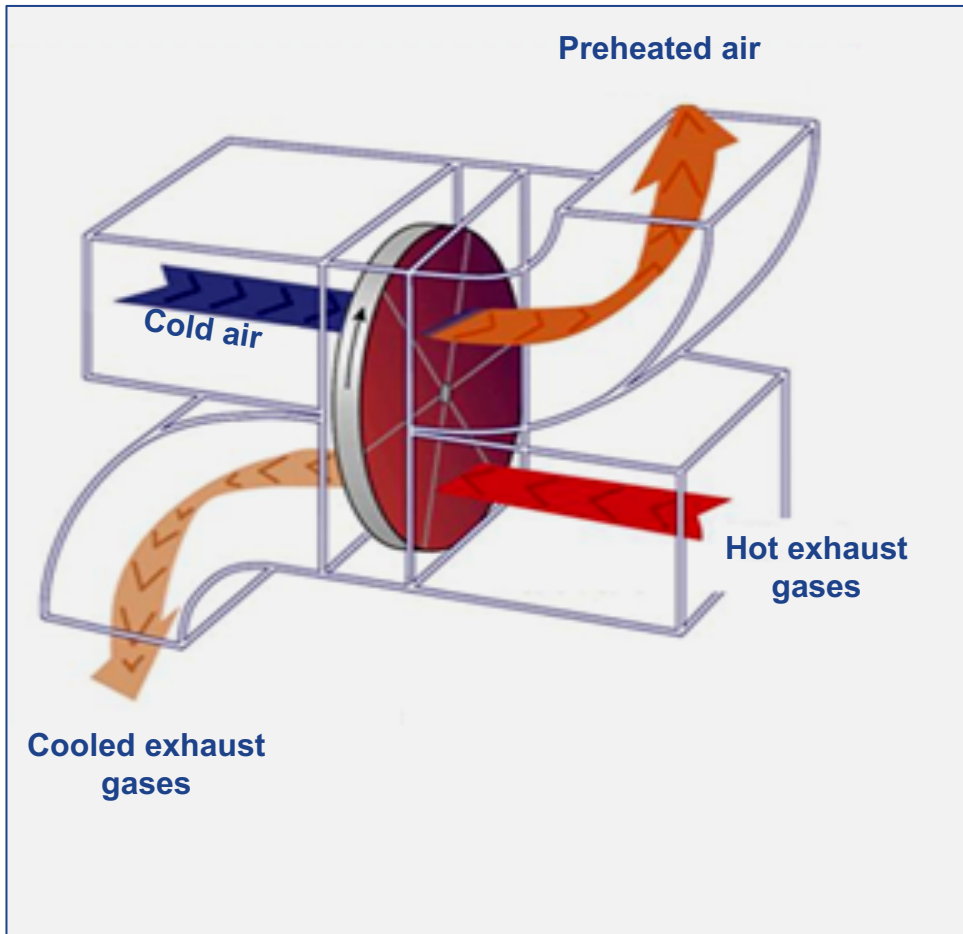
Note: Regenerators have been used to preheat low calorific value fuels such as blast furnace gas. Fuel preheating is rarely used for high calorific value fuels.

Time-Temperature Cycles in Regenerators



Courtesy Fives North American Mfg. Company

Other Regenerative Systems



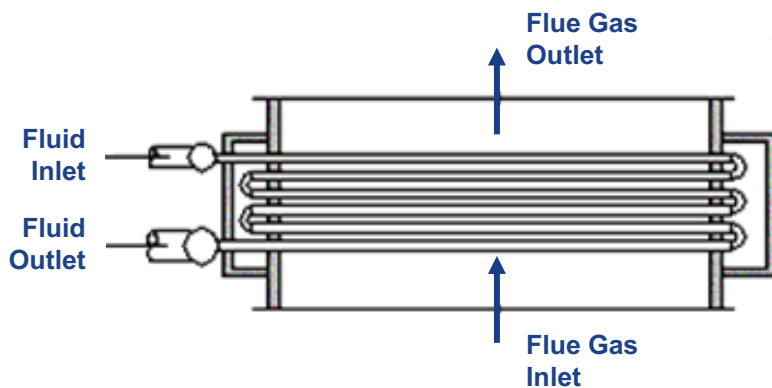
Rotary wheel type of units

- Most commonly used for boilers and HVAC applications.
- In some cases, the unit may include moisture removal materials coated on the heat transfer surfaces.

Stationary matrix units

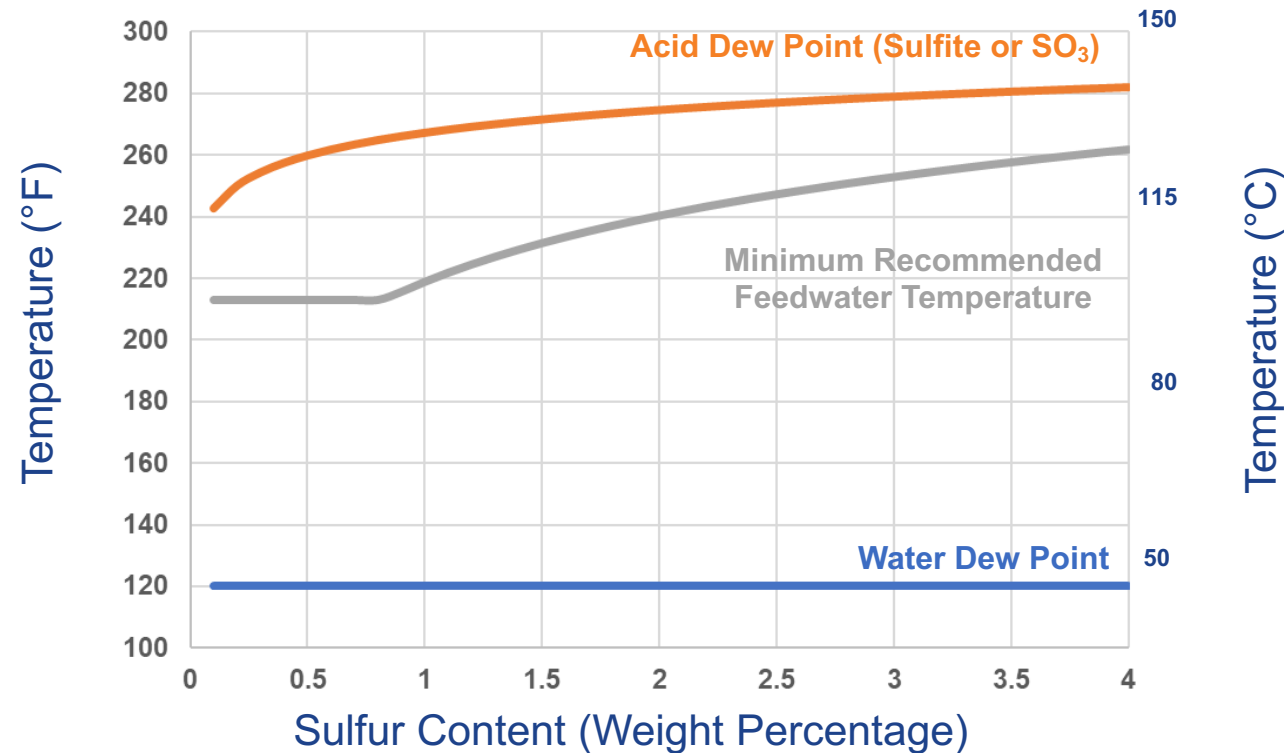
- Have been used for more than 100 years in steel and glass industry.
- Massive units with large space requirement.
- Offer long life and high efficiency but may require considerable maintenance.

Water or Fluid Heater



- Water heated by flue gases is used to heat process water or boiler feed water in the chemical, petroleum, paper, and food industries
- In some cases, process fluids such as crude oil are preheated by using heat from flue gases
- A water heater can be used to recover 40% to 60% of the flue gas heat
- Care should be taken to avoid cooling the flue gases below dew point
- Flue gas condensation temperature depends on the water content of the flue gases and the type of fuel (hydrogen content, sulfur content) used
- A condensing heat exchanger can be used to recover latent heat of water vapor from flue gases; in most cases a condensing heat exchanger is used to heat a once-through water stream

Flue Gas Temperature Limitations



Flue gas temperature is maintained above the dew point of acidic components.

- Fuels containing sulfur produce sulfuric acid.
- All hydrocarbon fuels can produce carbonic acid.

Outline

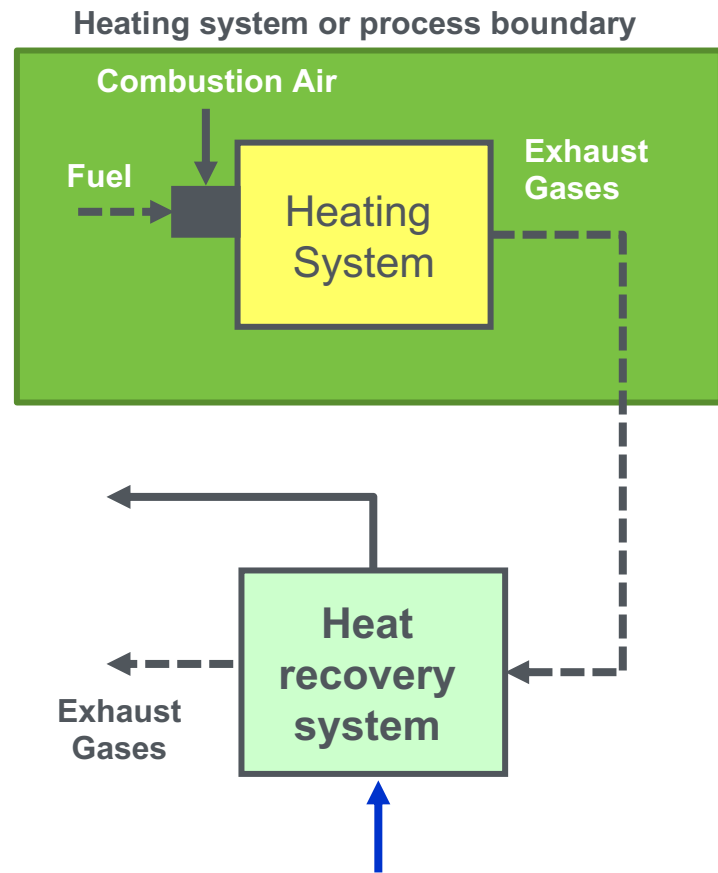
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Exhaust (Flue) Gas Heat Recovery

Commonly used options and equipment:

- Water (i.e. process, boiler feed water) or other fluid (i.e. heat transfer liquids) heating - use water to gas heat exchangers.
- Air heating for process or HVAC application – use gas to gas heat exchanger or regenerative systems.
- Steam generation – use waste heat recovery boilers.
- Heat cascading (using hot flue gases for lower temperature processes) – use direct injection of gases or heat exchangers.
- Other methods (i.e. absorption chillers) – use specialized equipment such as absorption chillers.
- Electrical power generation – use steam-based system or other low temperature systems discussed later.

In-Plant Waste Heat Recovery



- Use of waste heat to supplement the plant utility or auxiliary systems energy use in a plant to reduce the plant energy use.
- Can be used as retrofit for existing equipment or for new processes.
- Application temperature range:
 - As low as 250°F exhaust gas temperature
 - Higher temperature limit is usually 1650°F exhaust gas temperature.

Waste Heat Recovery Considerations



- Most important consideration is matching of heat supply to the heat demand for the selected utility within a plant or a neighboring plant.
- Moderately expensive to implement.
- Heat recovery – 10% to 75% of the waste heat.
- Installed cost varies with the type of system selected.
- Implementation cost:
 - Application and site specific.
 - Varies with the selection of the heat recovery method.
 - Typical cost could vary from \$50 to \$200 per kBTU recovered heat (includes normal installation)
- Typical payback periods: one-half year to five years.

Saving and cost considerations are same as in case of waste heat recycling.

Heat Recovery Systems - Summary

Heat recovery system	Waste heat Temperature	Typical applications	Typical installed cost
Steam generation	>660°F	Large furnaces with >25 MMBtu/hr.. firing rate. Reheat furnaces, process heaters, glass melting furnaces etc.	\$35,000 to \$60,000 per 1100 lb of steam generation
Hot water heating	>300°F	Heating equipment of all sizes. Heat treating, reheating, forging, ovens, dryers etc.	\$30,000 to \$50,000 per MMBtu heat transferred
Plant or building heating	>212°F	Mostly in cold climate areas. Can be used for medium to large size (5 MMBtu/hr. and larger size).	\$25,000 to \$50,000 per MMBtu transferred
Absorption cooling systems	>350°F	Low to medium temperature systems, large size furnaces, ovens, heaters etc.	\$750 to \$1,500 per ton of refrigeration capacity
Cascading to lower temperature heating processes	>750°F	For gases from medium to large size systems supplying heat to lower temperature heating systems.	\$40,000 to \$100,000 per MMBtu transferred

Note:

Costs are very preliminary and based on US conditions hence given in USD. They can be different for other countries and even vary by as much as 100%. DO NOT use the costs for economic analysis for site specific cases.

Waste Heat to Power

Options for Industrial Applications

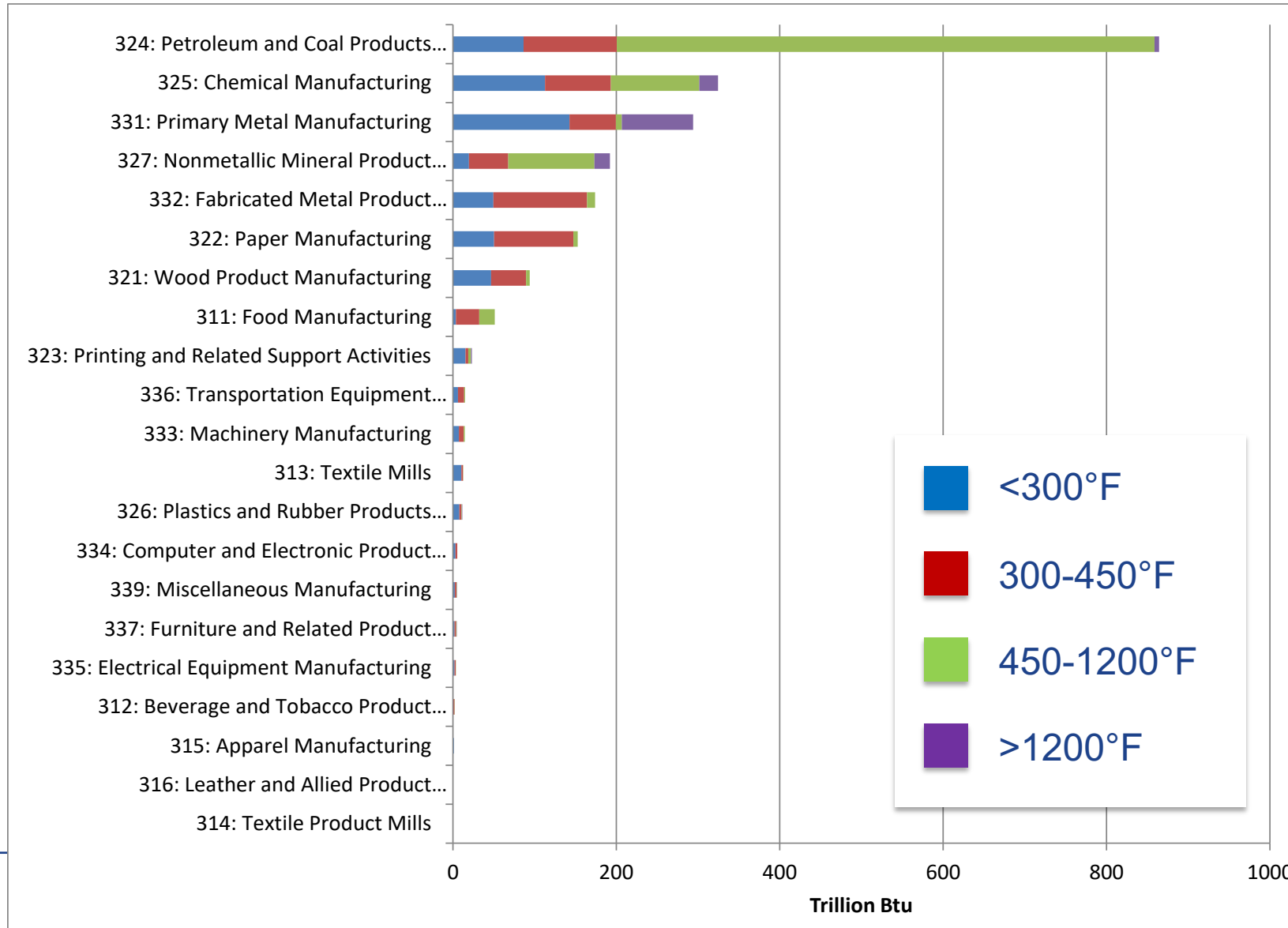
- “Conventional plant” using a steam boiler, steam turbine and generator
- Organic Ranking Cycle (ORC) plant
- Ammonia – water systems (i.e. Kalina system)
- Thermo-electric power generation (TEG)

Caution:

This is a fast-changing field. Technology, performance, and cost can vary significantly. Take the numbers as typical only.

Waste Heat Inventory by Industry and Temperature Range

(reference temp. at 120°F or 50°C)



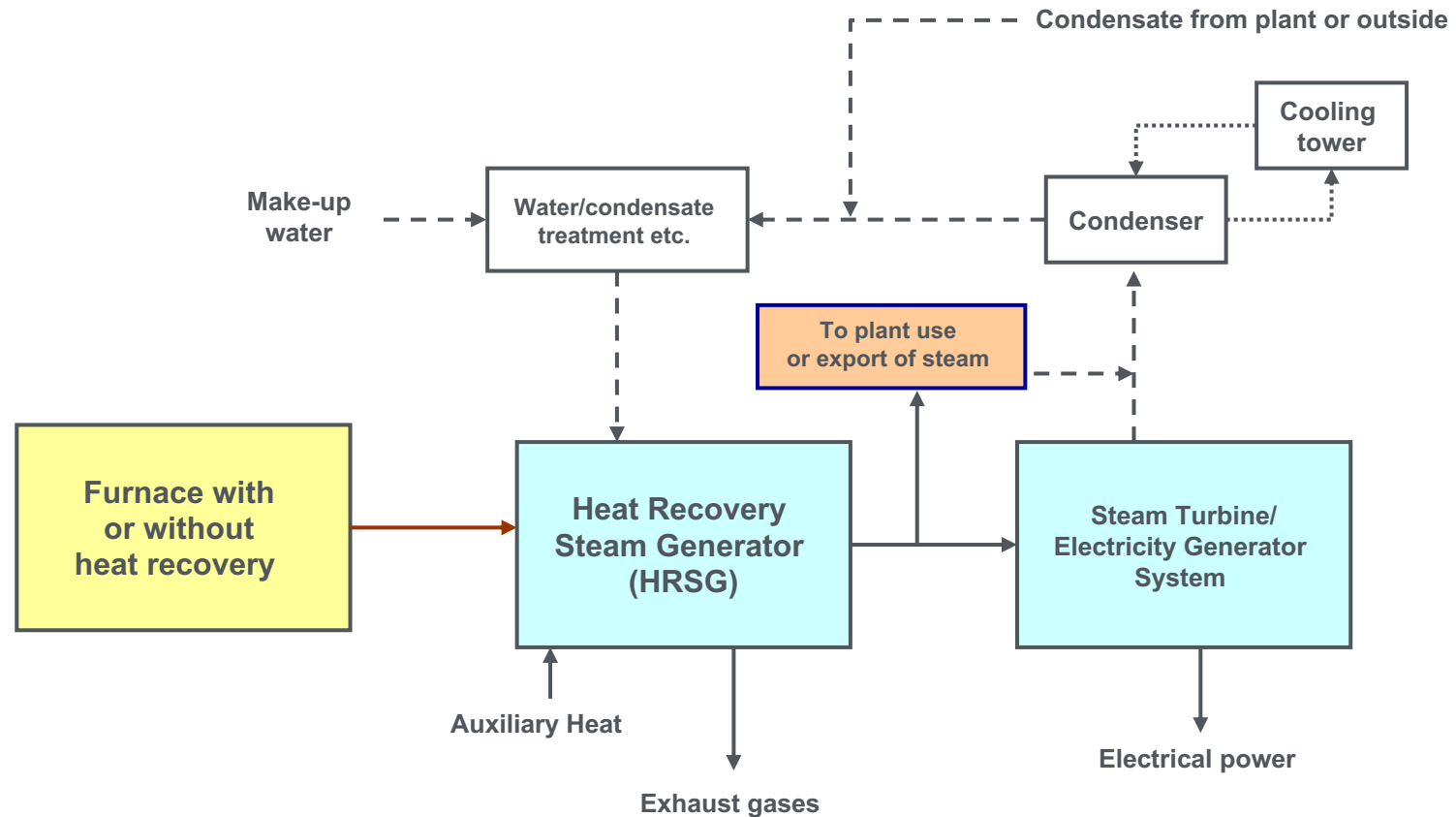
Waste Heat to Power

Application Considerations

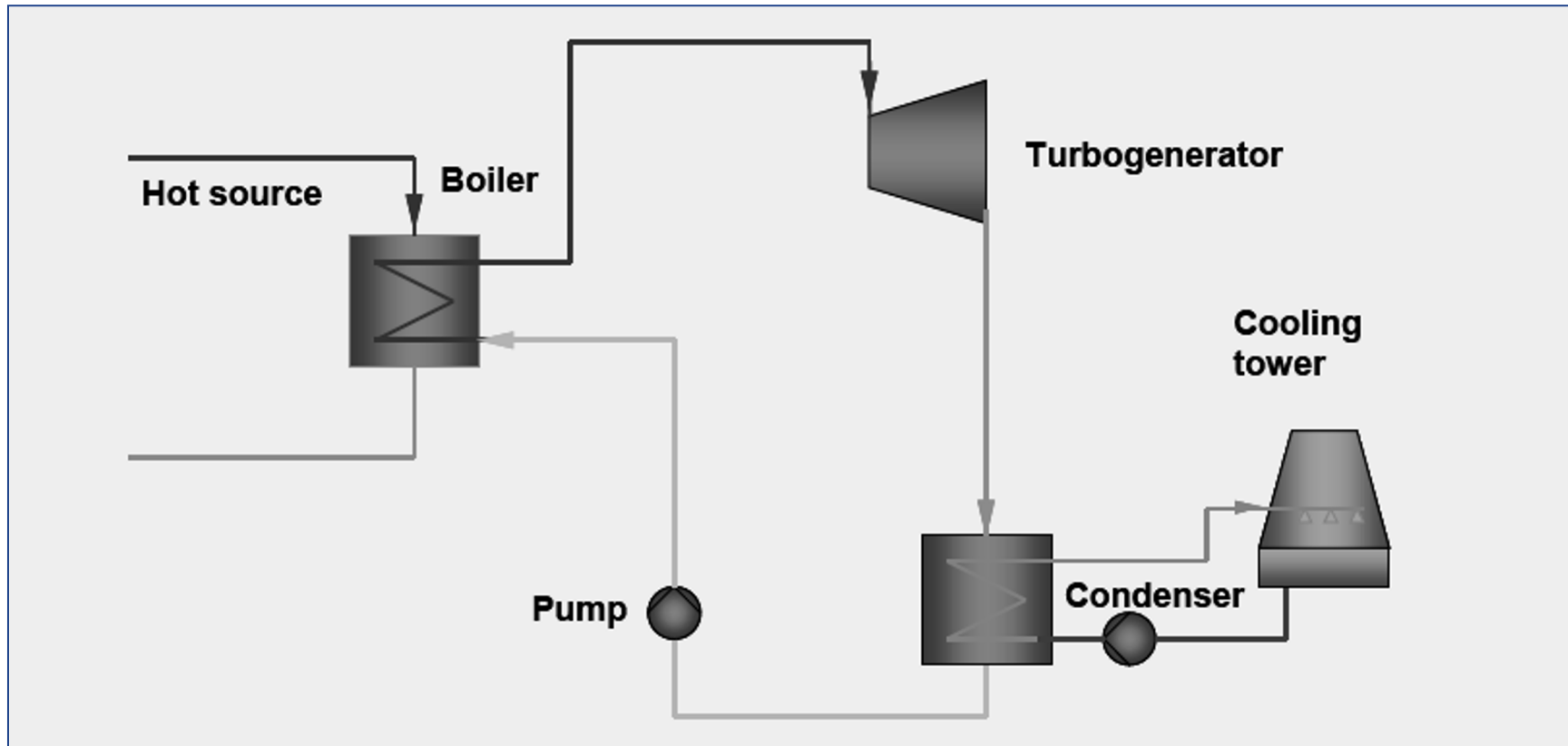
- Need relatively clean and contamination free source of waste heat (gas or liquid source). Avoid heavy particulate loading and/or presence of condensable vapors in waste heat stream.
- Continuous or predictable flow for the waste heat source.
- Relatively moderate waste heat stream temperature (at least 300°F, but >600°F is preferred) at a constant or predictable value.
- Cannot find or justify use of heat within the process or heating equipment itself.
- Cannot find or justify alternate heat recovery methods (steam, hot water, cascading, etc.) that can be used in the plant.
- Try to avoid or reduce use of supplementary fuel for power generation. It can have a negative effect on the overall economics unless the power cost can justify it.

Waste Heat to Power System

“Conventional” Steam – Power Generation



Typical Organic Rankine Cycle (ORC) for Power Generation



Several other variations of ORC have been are developed to improve its efficiency

Typical Organic Ranking Cycle (ORC) for Power Generation

How it works:

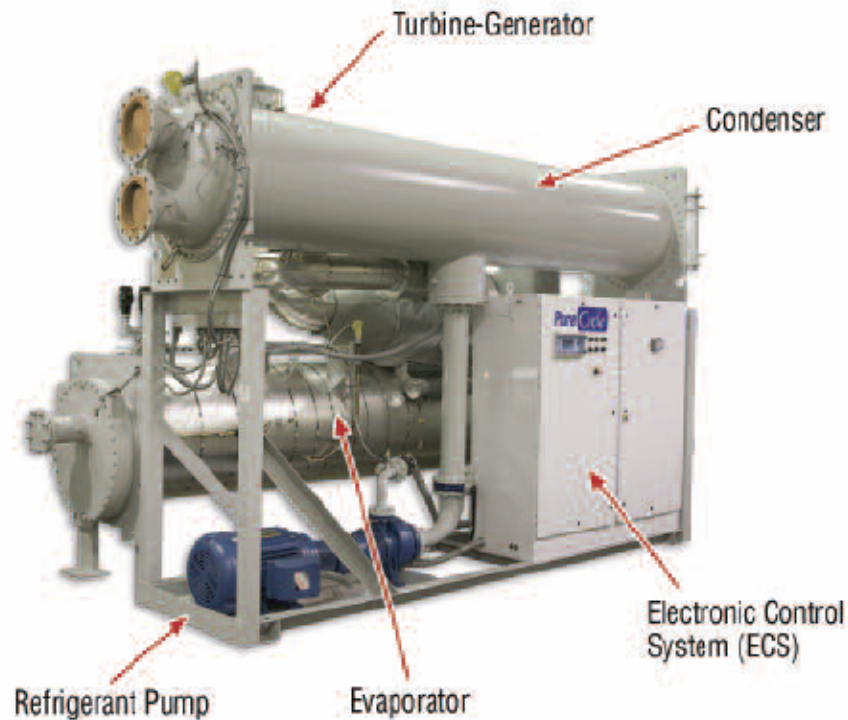
- A heat source heats thermal oil to a high temperature, typically about 570°F, in a closed circuit;
- The hot thermal oil is drawn to and from the ORC module in closed circuit. In the ORC it evaporates the organic working fluid of the ORC in a suitable heat exchanger system (pre-heater and evaporator);
- Organic vapor expands in the turbine, producing mechanical energy, further transformed into electric energy through a generator;
- The vapor is then cooled by a fluid in a closed circuit and condensed. The water warms up at about 180 - 190°F and it is used for different applications requiring heat;
- The condensed organic fluid is pumped back into the regenerator to close the circuit and restart the cycle.

Waste Heat to Power Organic Rankin Cycle

- **Working medium:** variety of organic liquids such as Freon, butane, propane, ammonia, and the new “environmentally-friendly” refrigerants
- Waste heat temperature range is 300°F and up with proper temperature control for the evaporator heat exchanger
- Operating efficiency (~8% to 15%) for low (300°F) to medium (800°F) temperature range for waste heat
- Higher temperatures may create problems with the working fluid
- Relatively high cost (\$2,500 to \$4,000 per kW capacity)
- Most applications in geo-thermal and other non-heavy industrial areas

Note: The operating data and costs are derived from available literature and their accuracy cannot be guaranteed.

Waste Heat to Power

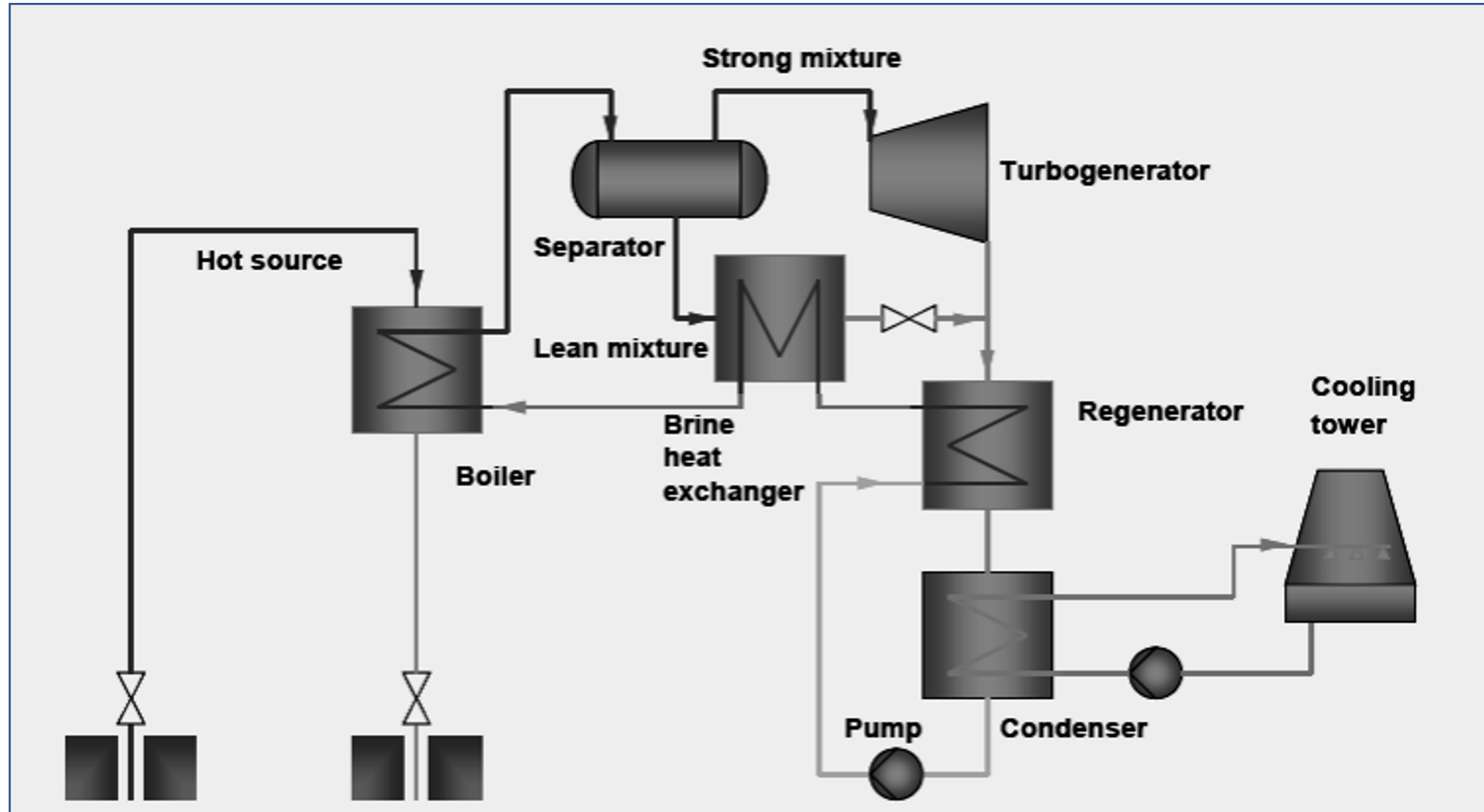


Example: UTC PureCycle Option

Current Status and Applications

- Several companies in the USA and other countries offer this technology.
- Size ranges from 30kW to as high as 22kW.
- Waste heat source temperature can be from 212°F and higher.
- In most cases the heat source has to be liquid which must be heated by using gases if the source is exhaust gases.
- Cost varies over a wide range. From \$3,500/kW and higher.

Kalina Cycle Using Ammonia-Water as Working Fluid



Kalina cycle system claims to be 15% to 25% more efficient than ORC cycle at the same temperature level

Waste Heat to Power Options for Industrial Application

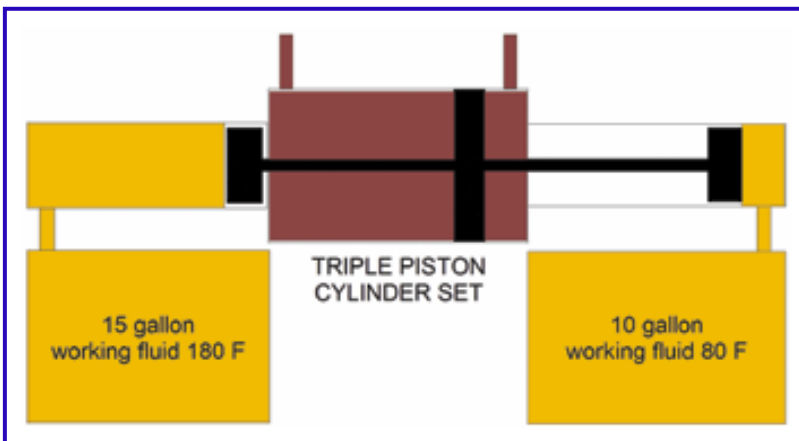
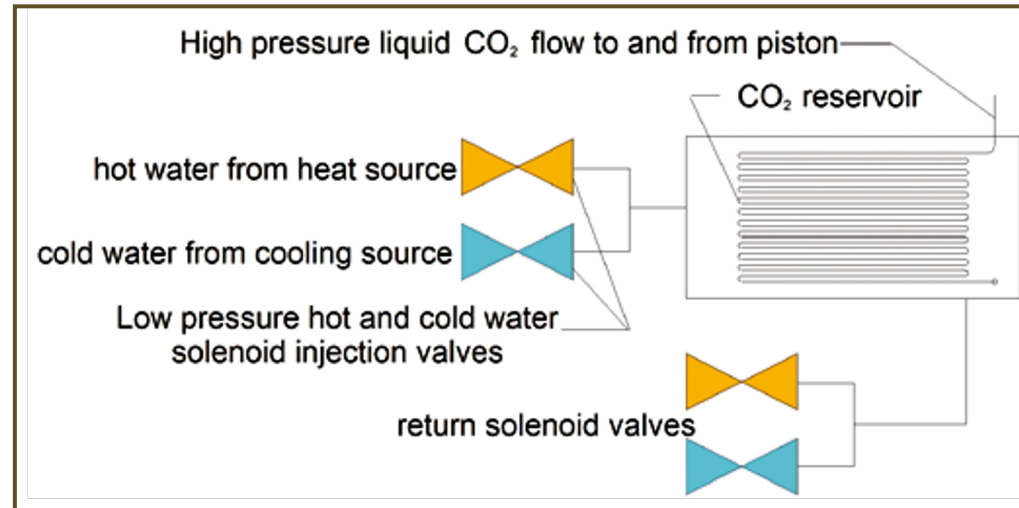
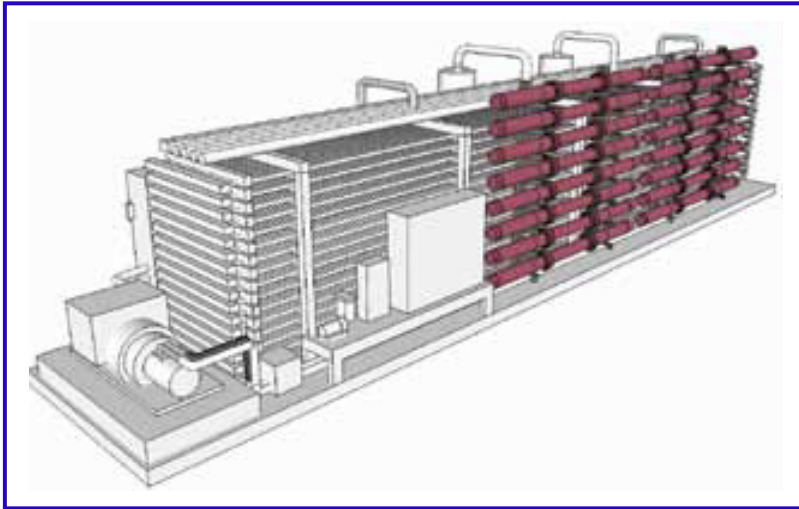


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Kalina Cycle Plant:

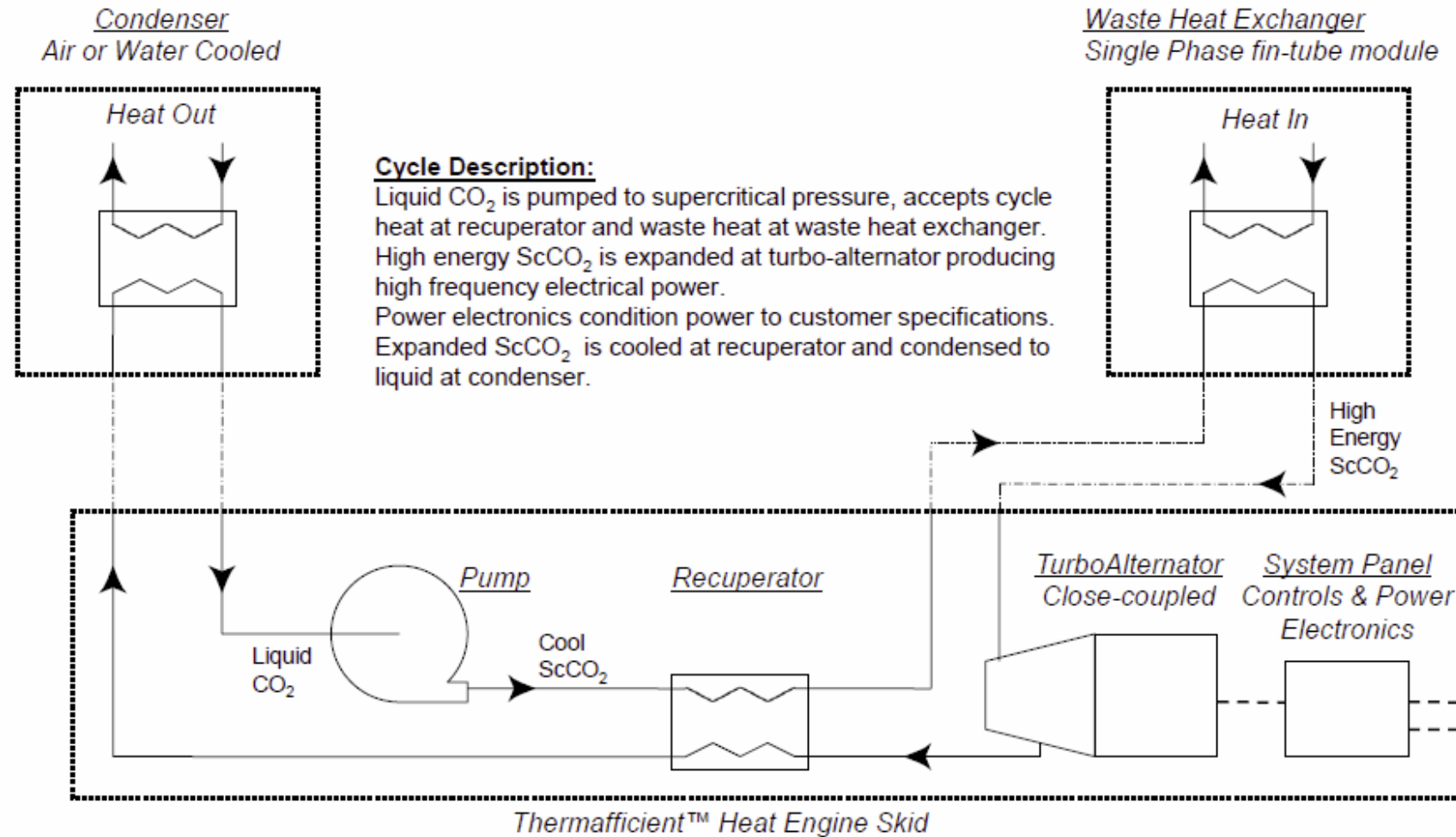
- Bottoming cycle – working medium: Ammonia – water vapor
- Operating temperature range: 250°F to as high as 1000°F waste heat with proper heat exchanger equipment.
- Operating efficiency (~15%) with waste heat temperature at a relatively low temperature. (~300°F)
- Relatively high cost: \$2,000 to \$3,000 per kW capacity.
- Large percentage of total cost (capital and maintenance) is in heat exchangers
- Most applications in geo-thermal and other non-heavy industrial areas.

Deluge Natural Energy Engine



1. Requires 180 + deg. F. water
2. Approximate cost (quoted) \$2,000/kW not including installation etc.
3. Maintenance and operating cost (other than hot water) - unknown
4. No operating unit for power production
5. Claimed efficiency: 23% (based on of the heat to power conversion)

Echo-Gen Super Critical Power Cycle



Power Cycle Comparison

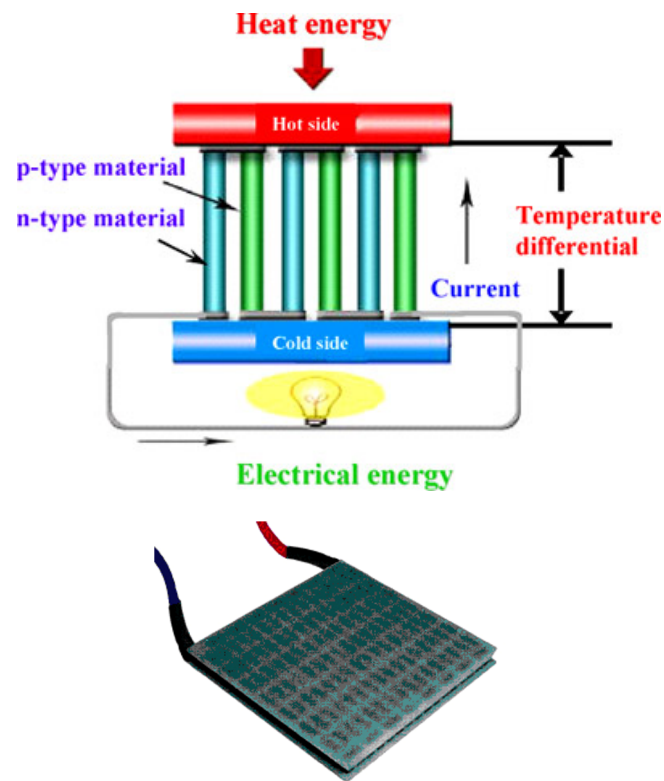
Comparison	Steam Rankine	Organic Rankine (ORC)	Ammonia (NH ₃) - Water	CO ₂ Power Cycle
Source Temperature Range (°F)	>750	300 – 570	212 – 840	440 – 1200
Working Fluid	Treated water	HCFCs or Hydrocarbons	Ammonia - water mixture	Carbon Dioxide
Working Fluid Attributes	Requires treatment to reduce corrosion and mineral deposition	Limited temperature range, flammability, thermally unstable at higher temperature	Limited temperature range, corrosive, ammonia leaks	Non-corrosive, non-toxic, non-flammable, thermally stable
Conversion Efficiency (%)	20% plus	8% to 12%	8% to 15%	13% to 17%
Reported Cost (\$/kW)	\$600 plus	\$2500 plus	\$2500 plus	\$2000 plus

Note: This is a fast-changing field. The efficiency values highly dependent on the source temperature. Cost could vary significantly with size, supplier and incentives from several sources.

Costs are preliminary and based on US conditions hence in USD. They can be different for other countries and even vary by as much as 100%

Waste Heat to Power

Thermo-Electric Power Generation (TEG)



Note: The operating data and costs are derived from available literature and their accuracy cannot be guaranteed.

- Technology in infancy and unproven for industrial application
- Waste heat temperature range from 440°C to 930°F.
- Relatively low efficiency – less than 5%.
- Very expensive [$> \$5,000$ per kW] and unproven for industrial use
- Will require considerable R&D and technology pilot demonstration before it can be used for waste heat to power applications.

Outline

- Drivers for Industrial Waste Heat Management
- Waste Heat Management – 3Rs
- Sources of Waste Heat and Where Can We Use It?
- Barriers to Waste Heat Management
- Waste Heat Recycling Options
 - Combustion Air Preheating Considerations
- Waste Heat Recovery Options
 - Waste Heat to Power Options
 - Waste Heat Recovery Emerging Technologies
- **Waste Heat Management Summary**

Waste Heat Options Summary

Recycling and Recovery:

- Three possible options should be considered and evaluated for use of waste heat from a heating system.
 - Use waste heat within the process or system itself. This is the most economical and effective method of using waste heat.
 - Use waste heat within the plant boundary itself. Options include use in or for plant utilities or use in other processes.
 - Waste heat to power conversion.
- Very few options are available for recycling or recovery of “contaminated” waste heat streams, particularly at higher temperatures.

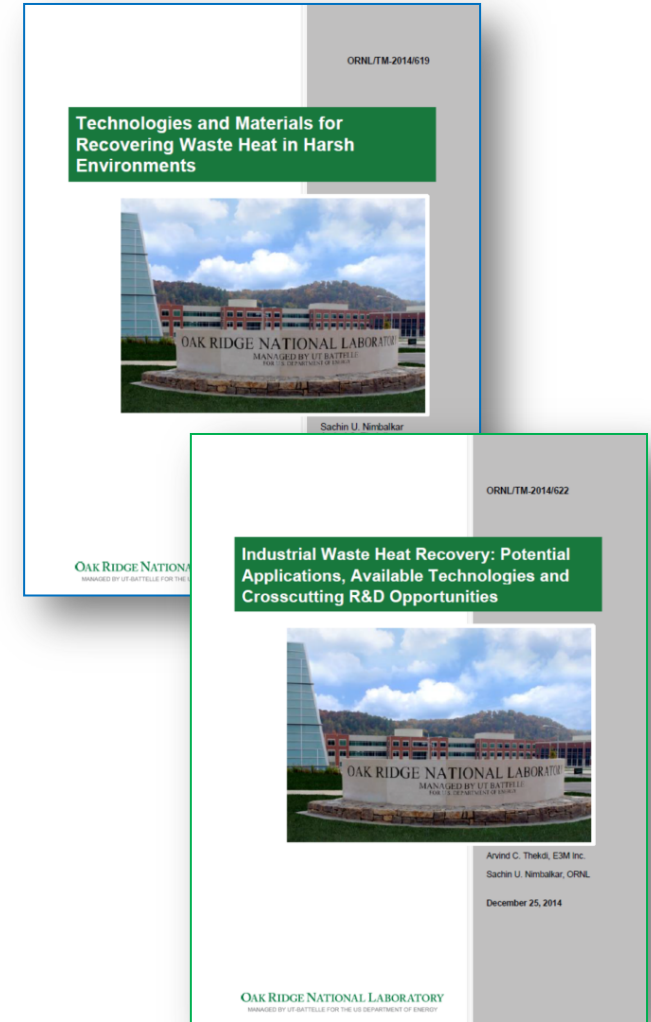
Waste Heat Options Summary

Power Generation:

- Conventional steam turbine-generator option is the most attractive option for clean, contamination free waste heat at higher ($>800^{\circ}\text{F}$) temperature.
- Three options are available for lower temperature waste: ORC, Ammonia-water based systems and CO_2 based systems. However, none of these have a long and “proven” history in industrial applications to offer economically justifiable power generation as of today.
- Waste heat to power projects are difficult to justify for low ($\sim 480^{\circ}\text{F}$ or lower) temperature waste heat, especially if the waste heat supply is not continuous and auxiliary energy is required.
- Thermo-electrical systems are in early development stage and their use cannot be economically justified at this time.

For More Information

- **“Technologies and Materials for Recovering Waste Heat in Harsh Environment”,** ORNL Report, ORNL/TM-2014/619.
- **“Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities”,** ORNL Report, ORNL/TM-2014/622.
- **“Electric Arc Furnace Off-gas Enthalpy Modeling – Preliminary Results”,** the Association for Iron & Steel Technology’s AISTech 2015 conference, May 2015.
- **“Waste Heat Recovery from High Temperature Off-Gases from Electric Arc Furnaces”,** the Association for Iron & Steel Technology’s AISTech 2014 conference, May 2014.



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Information used in the presentation is derived from several sources including equipment manufacturers' websites, published literature, and handbooks.

- Fives North American Mfg. Co.
- Bloom Engineering
- Echogen Power
- Thermal Transfer Company
- Eclipse Combustion
- U.S. Department of Energy
- Industrial Heating magazine
- G.C. Broach Company
- Air products and Chemical Inc.

Questions and Answers

