Better Plants
U.S. DEPARTMENT OF ENERGY

VIRTUAL PROCESS HEATING INPLT
Session 7

Training Module # 7
Waste Heat Management for Process Heating Equipment

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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

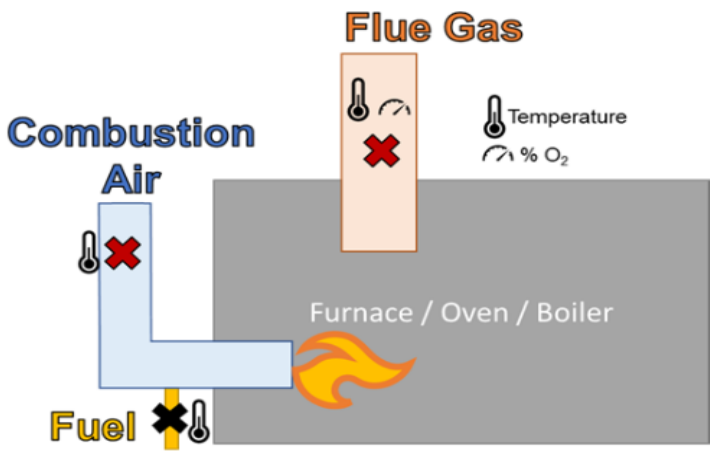
Example – Dry-off Oven Waste Heat

- 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

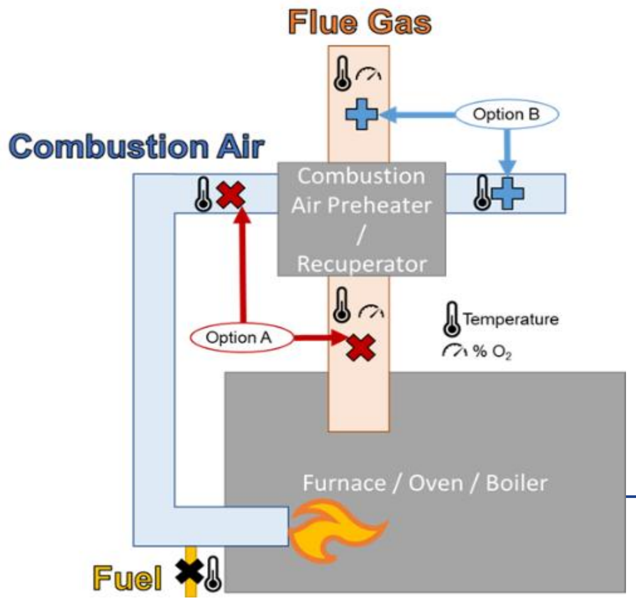
- Waste heat = NO FOSSIL FUEL (capturing wasted energy)
- Reduction in fuel energy use in process heating equipment
- Reduced electricity purchase and/or export to grid
- Waste heat = NO incremental EMISSIONS
- Green projects = “sustainable development”…P.R. story
- Industrial WHR considered “renewable”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

Energy Saving Measures Exhaust Gases or Flue Gases

Measurement location without recuperator



Measurement location with recuperator



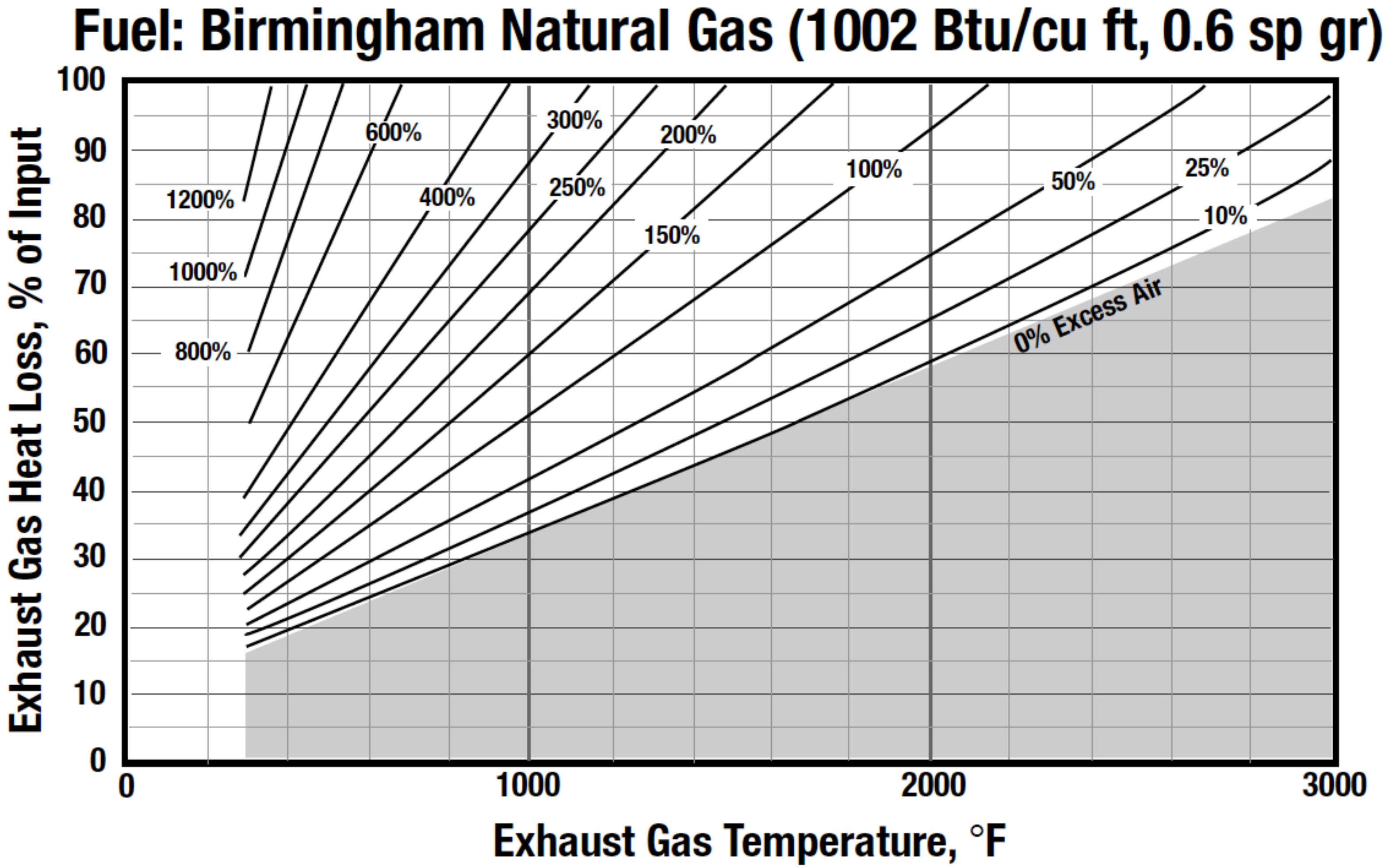
- Flue gases from a furnace may contain:
  - Combustion products
  - Water vapor
  - Liquid vapors
  - Volatiles
  - Condensable solids
  - Non-condensable particles
  - Furnace “atmosphere” or gases
- Flue gas analysis (FGA) such as percentage of O_2 and percentage of CO_2 given by most commonly used analyzers is affected by the presence of non-condensable gases
- Care must be taken to correct the analysis for the presence of these gases, if any, in using FGA results for thermal calculations

Factors Affecting Flue Gas Heat Loss

$$\Delta H = M \times C_p \times \Delta T$$

	Flue Gas Temperature Heat Loss	Mass Flow of Flue Gases	Specific Heat	Temperature Rise
Determined by:		Excess Air (or Oxygen) in Flue Gases	Type of Fuel (Flue Gas Composition)	$\dfrac{\text{Flue Gas Temperature}}{\text{Combustion Air Temperature}}$

Reduce Flue Gas Losses



Flue losses increase with: Temperature of flue gases; O_2 level in flue gases

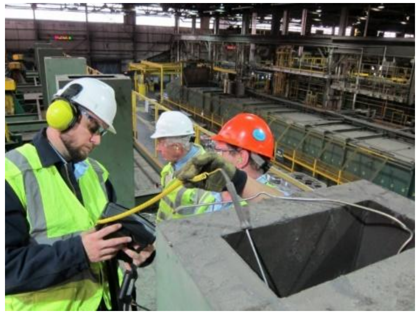
Options for Exhaust Gas Waste Heat

- 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

Exhaust Gas Waste Heat Reduction

Reduce mass flow rate

- Reduce/control excess air for burners
- Control make-up air
- Reduce/eliminate air leaks
- Reduce moisture content of exhaust gases where possible
- Process specific actions (i.e. pretreatment of charge material)
- Use of oxygen enriched air
- Use of air and/or fuel preheating



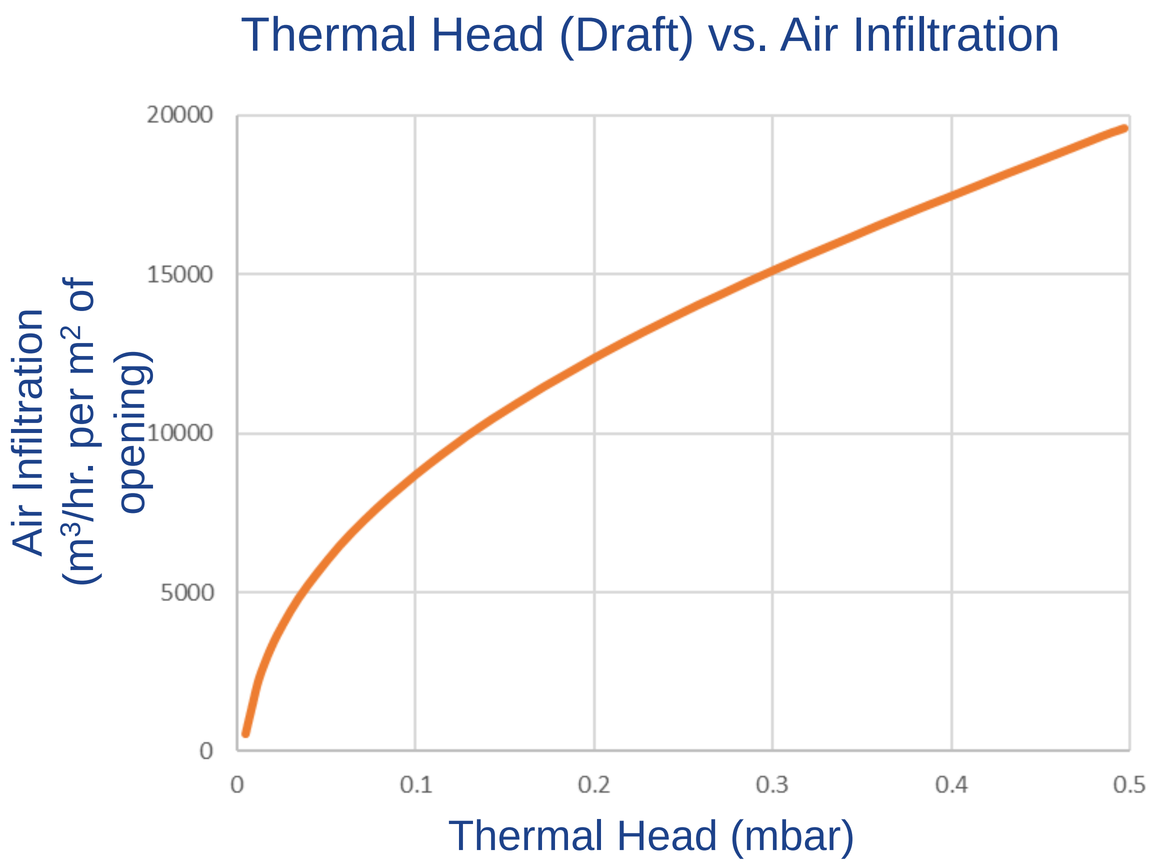
Reduce temperature of exhaust gases

- Use of proper temperature controls Use of advanced controls to optimize zone temperature (i.e. on-line process modeling)
- Avoid over-firing of burners
- Control air-fuel ratio to avoid sub-stoichiometric (rich) combustion

Waste Heat Reduction Air Leakage Control

- Air leaks into the furnace through openings, large and small, visible or invisible, and at unsuspected locations when the furnace pressure is lower than the ambient pressure
- Most common areas of air leaks include gaps at door seals, fully or partially open doors, cracks in furnace walls, and seals at the tubes, burner mounting, and conveyor rollers
- Pressure in the furnace varies from top to bottom and, in some cases, from side to side or at local spots; measurement at one point or level does not mean the same pressure at all levels within the furnace
- Pressure could become negative (with respect to ambient pressure) due to:
  - Draft generated due to "chimney" effect when the exhaust gas temperature is higher than the ambient temperature
  - Use of an induced draft (ID) fan
  - Jet effect of flame or other air jets, if used

Air Leakage vs. Pressure (Draft)

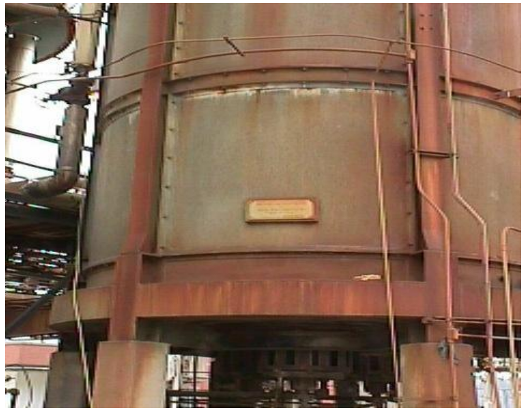


Conversion Factor

0.1 mb = 1 mm of H_2O

Common Areas of Air Leaks for Process Heaters

Tube Penetrations

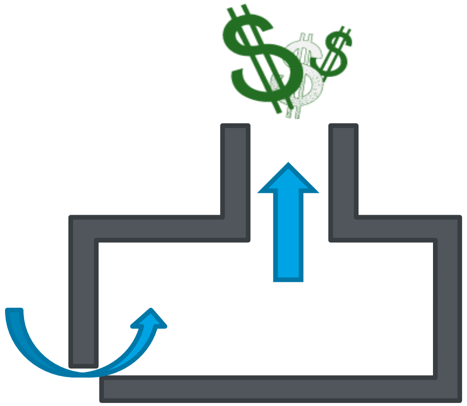


Door Seal

Tired Gasket

Explosion Door

Cost of Air Leakage



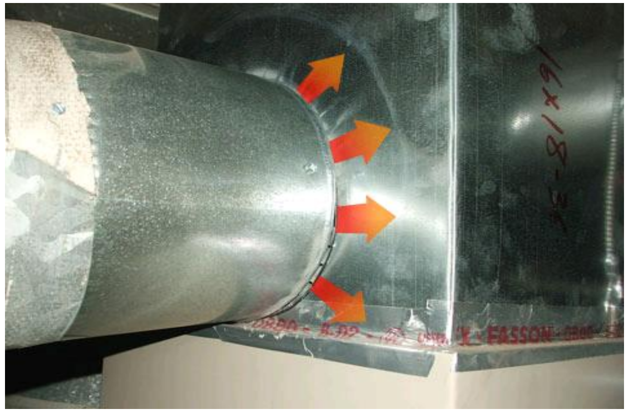
Cost of Air Infiltration in Oven or Furnace	
Furnace draft (neg. pressure) inch. W.C.	0.050
Opening size - area ft^2	1.00
Combustion air temperature (F)	70
Temperature of flue gases (F)	400
Excess air used in burners (%) **	10
Available heat for burners (%)	84.6
Fuel cost $/Million Btu	$ 9.00
Operating hours/year	8000
Heat reqd. (net) to heat air Btu/hr.	273,278
Gross heat reqd. btu/hr	323,072
Air infiltration from the opening (SCFH)	40,188
Cost of fuel wasted per year	$ 23,261

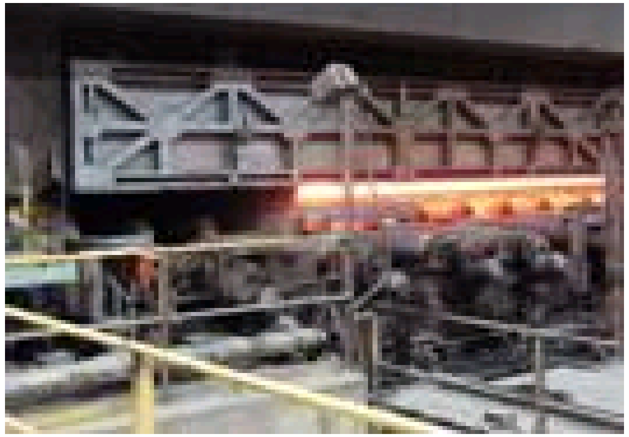
* Note: This is NOT oxygen in stack gases.
It represents how the burners are adjusted for air-fuel ratio
In many cases the users are advised to adjust burners to give
2% to 4% Oxygen (10% to 20% excess air) in combustion products

** Default value for burner excess air is 10%

Developed by E3M, Inc.

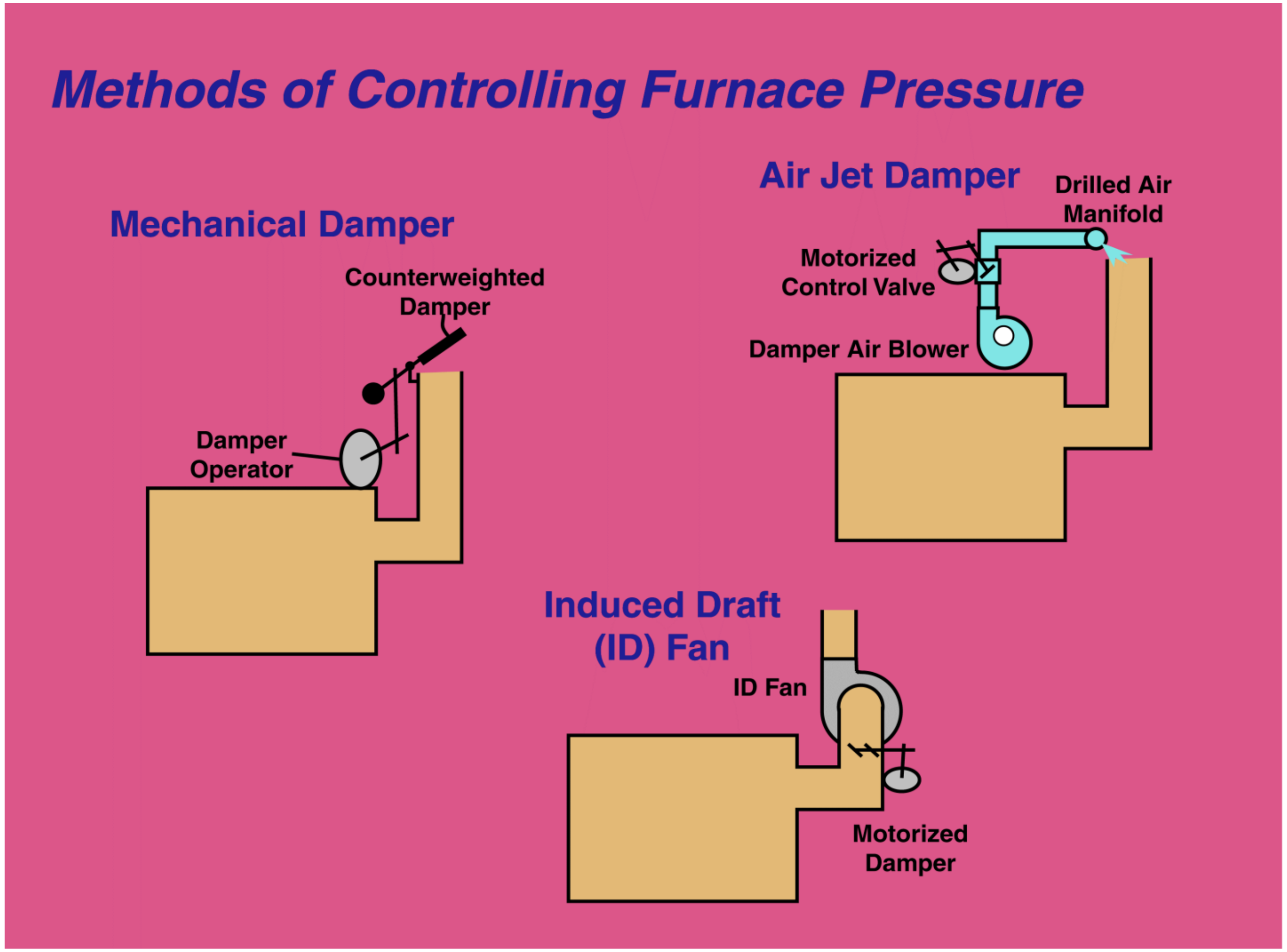
Hot Gas Leakage





Density corrected flow (nm^3/hour)	1,075
Ambient temp (°C)	35
Heat loss in hot gases kJ/hr.	1,102,961
Number of operating hours per year	8,000
Total energy loss GJ/year	8,824
Heat recovery efficiency for the system (if used) - %	55%
Loss in heat recovery GJ/year	4,853
Cost of fuel ($/GJ)	$ 6.00
Potential cost savings $/year	$ 29,118
Potential Annual Cost Savings ($/year)	**$29,120**

Furnace Draft Control



Summary for Exhaust Gas Reduction Related Measures

Actions	Potential energy savings*
Reduce excess air used for fuel combustion in burners	2% to 10%
Control and minimize the amount of make-up air, if used, in ovens and dryers	5% to 20%
Minimize air leakage by reducing the size and number of openings	1% to 5%
Use pressure control to reduce/eliminate air infiltration or hot gases exfiltration	1% to 5%
Use proper controls for zone temperature and furnace firing rate to avoid excessively high exhaust gas temperature	2% to 10%
Avoid discharge of excessive moisture or process gases if possible, by pre-processing the load/charge material	0% to 2%

Options for Exhaust Gas Waste Heat

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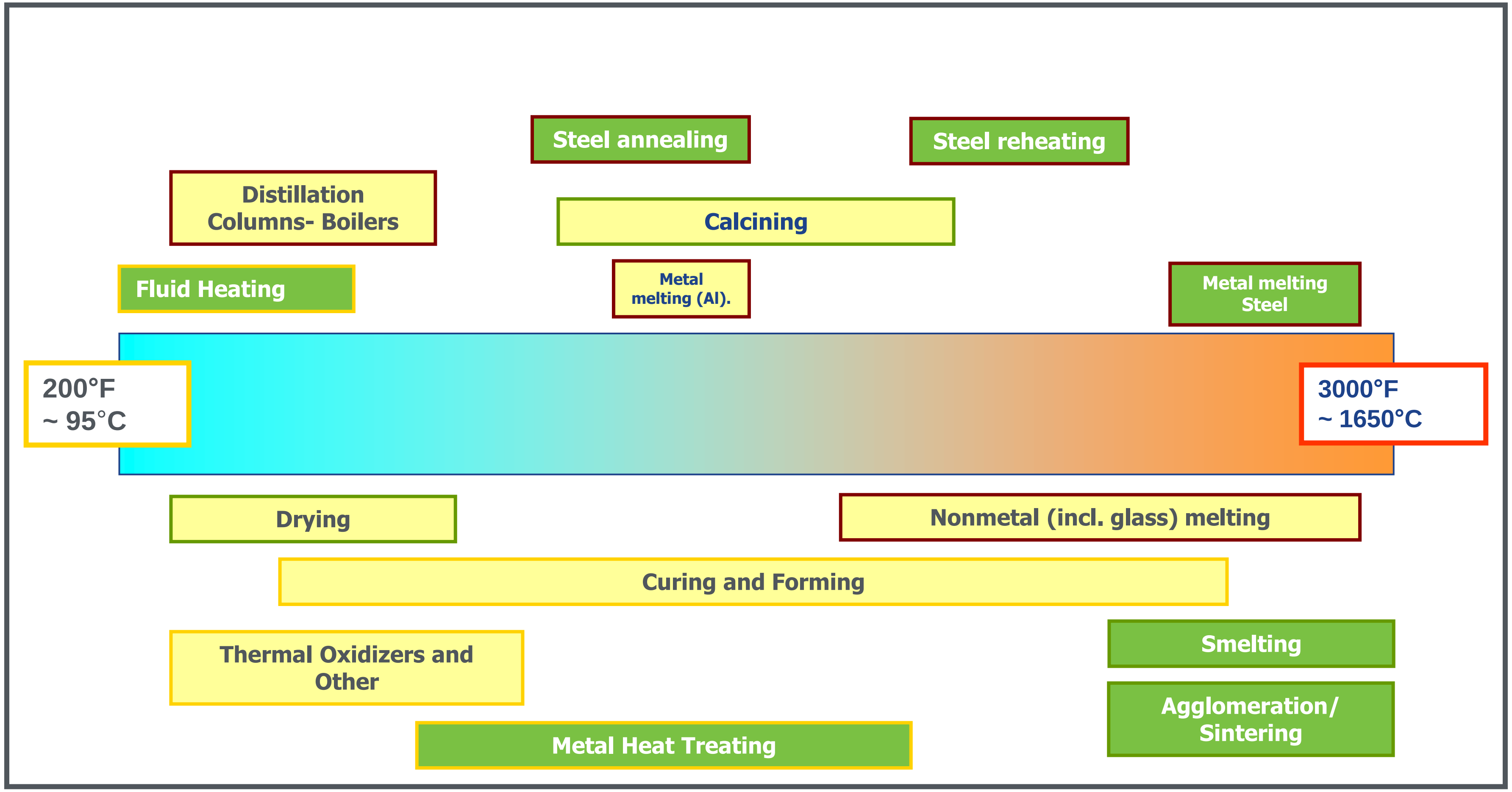
Range of Temperatures for Waste Heat

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 ...												
b) High temperature flue gases or combustion products with contaminants												
c) Heated air or flue gases containing high (>14%) O2 without large amount of moisture and particulates.												
d) Process gases or by product gases/vapors that contain combustibles ...												
e) Process or make up air mixed with combustion products, large amount of water vapor or moisture												
f) Steam discharged as vented steam or steam leaks.												
g) Other gaseous streams.												
2) Heated water or liquids												
a) Clean heated water discharged from indirect cooling systems...												
b) Hot water that contains presence of large amount of seperatable solids												
c) Hot water or liquids containing dissolved precipitatable solids, dissolved gases........												
3) Hot products												
a) Hot solids that are air cooled after processing.												
b) Hot solids that are cooled after processing using water or air-water mixture.												
c) Hot liquids/vapors that are cooled after thermal processing.												
4) High temperature surfaces												
a) Furnace or heater walls												
b) Extended surfaces or parts used in furnaces or heaters.												

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.

Temperature of waste streams

- High - costly materials needed to retain them
- Low - condensate cause corrosion and fouling; few viable end-use; large surface area needed
- Temperature variations in streams

Chemical composition of waste streams

- Deposition reduces heat transfer
- Risk of contamination between streams – product/ process risk
- Environmental concerns
- Material constraints
- Operational and maintenance concern

Cost effectiveness

- Long payback period for heat recovery equipment and auxiliary systems
- Material costs
- Operation and maintenance costs
- Economics of scale

Implementation constraints

- Process specific recovery and design
- Heat recovery complicates process
- Limited space
- Transportability
- Inaccessibility

Mass flow rate of waste streams

- Fluctuations in flow rates
- Intermittent nature of waste heat opportunity
- Waste streams mixed with process or product generated solids, liquids, and gases

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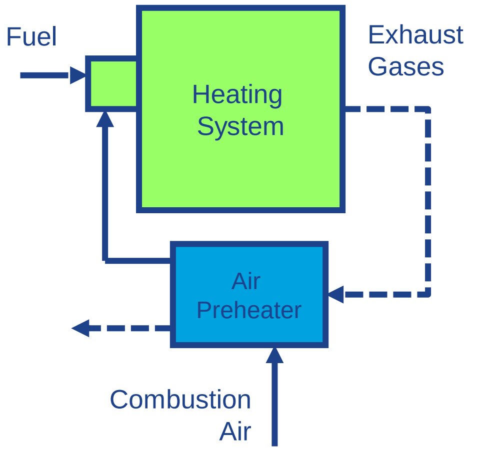
Exhaust Heat Recycling – Recovery Issues to Consider

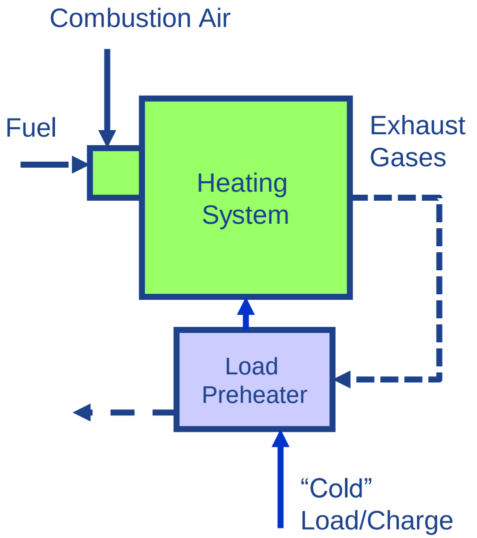
Before you decide on a method of waste heat recovery, consider the following issues:

- 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, H_2, organic solvent vapors)

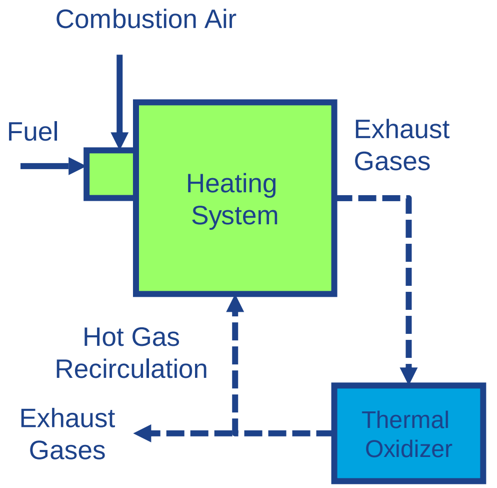
Waste Heat Recycling Options



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 <u>most used method</u> 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 NOx 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 NOx 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	

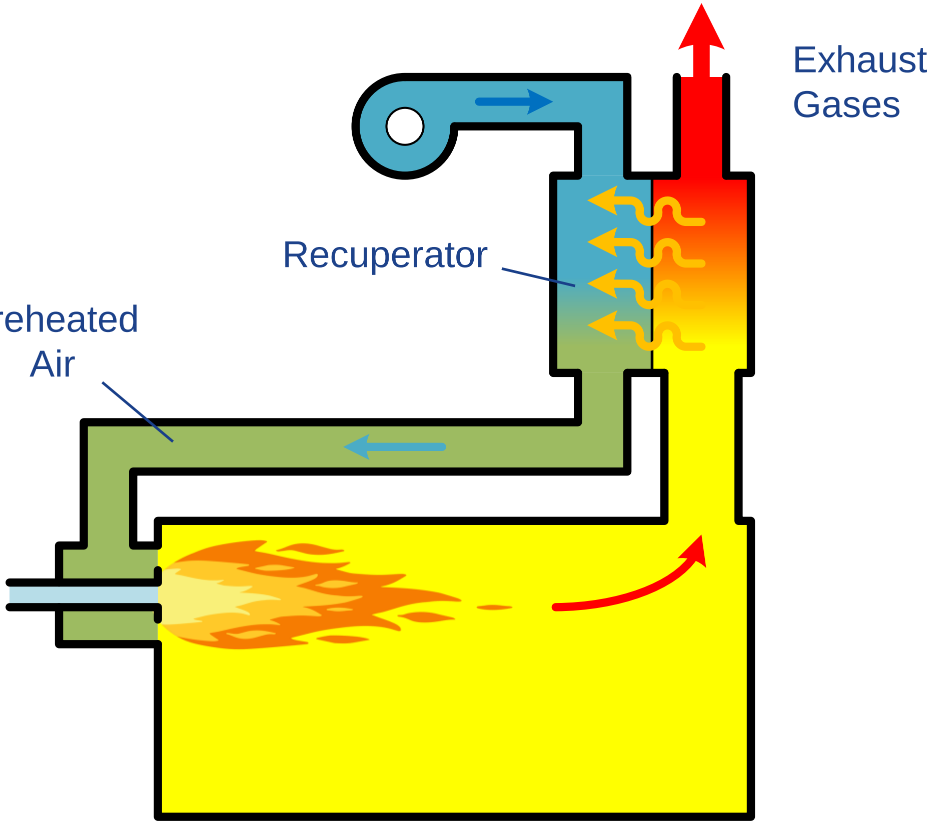
Heat treating furnace for an automotive parts supplier saves approx. $10,530 per year

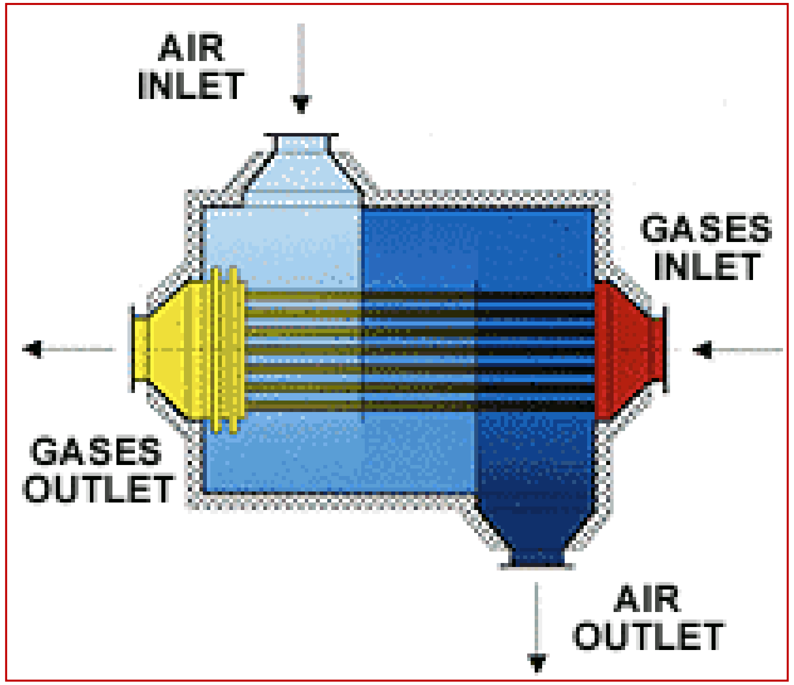
Combustion Air Preheating Equipment

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

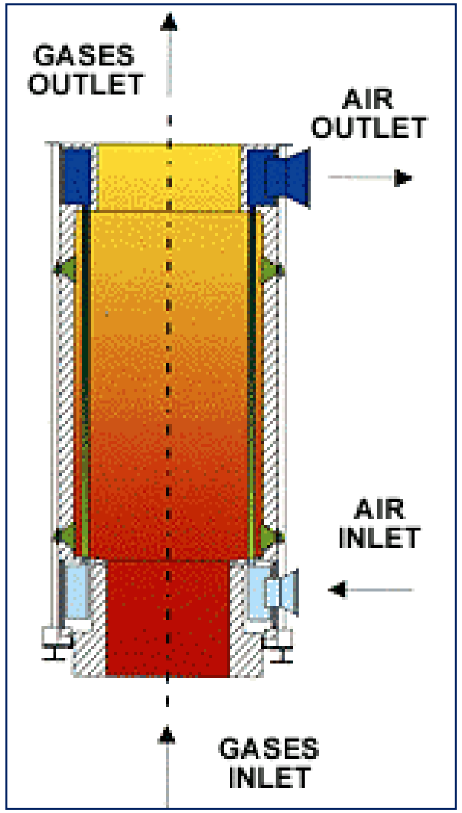




Courtesy HARDTECH Group

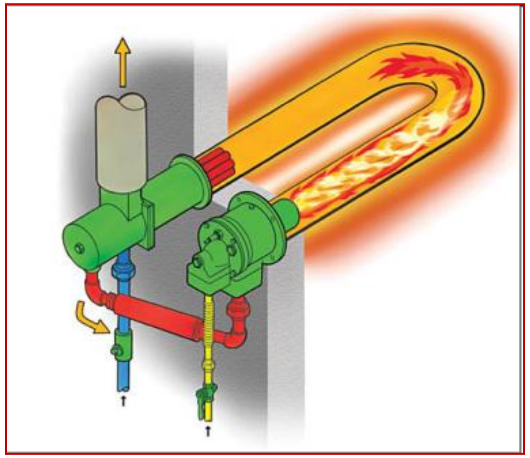
- Continuous, simultaneous flow of exhaust and combustion air
- A physical barrier separates air and exhaust flows

Combustion Air Preheating Equipment Options



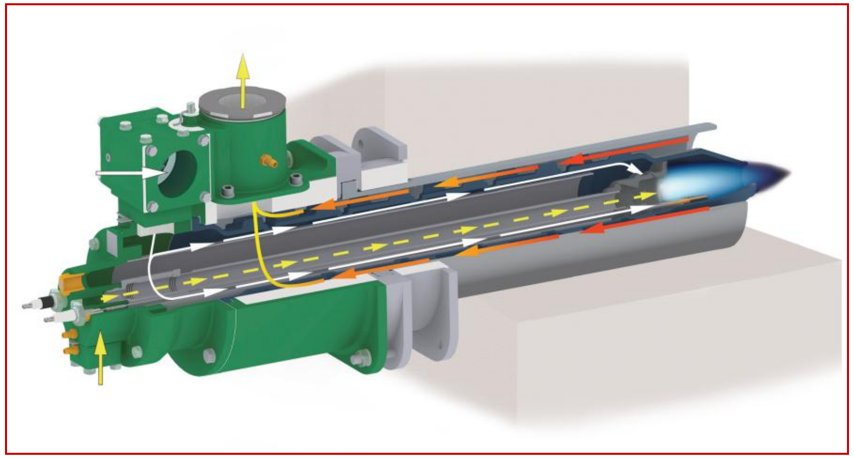
Radiation Recuperator

Courtesy HARDTECH Group



Self recuperative radiant tube burner

Self recuperative direct fired burner



Courtesy Eclipse Combustion - USA

Combustion Air Preheating Equipment Options

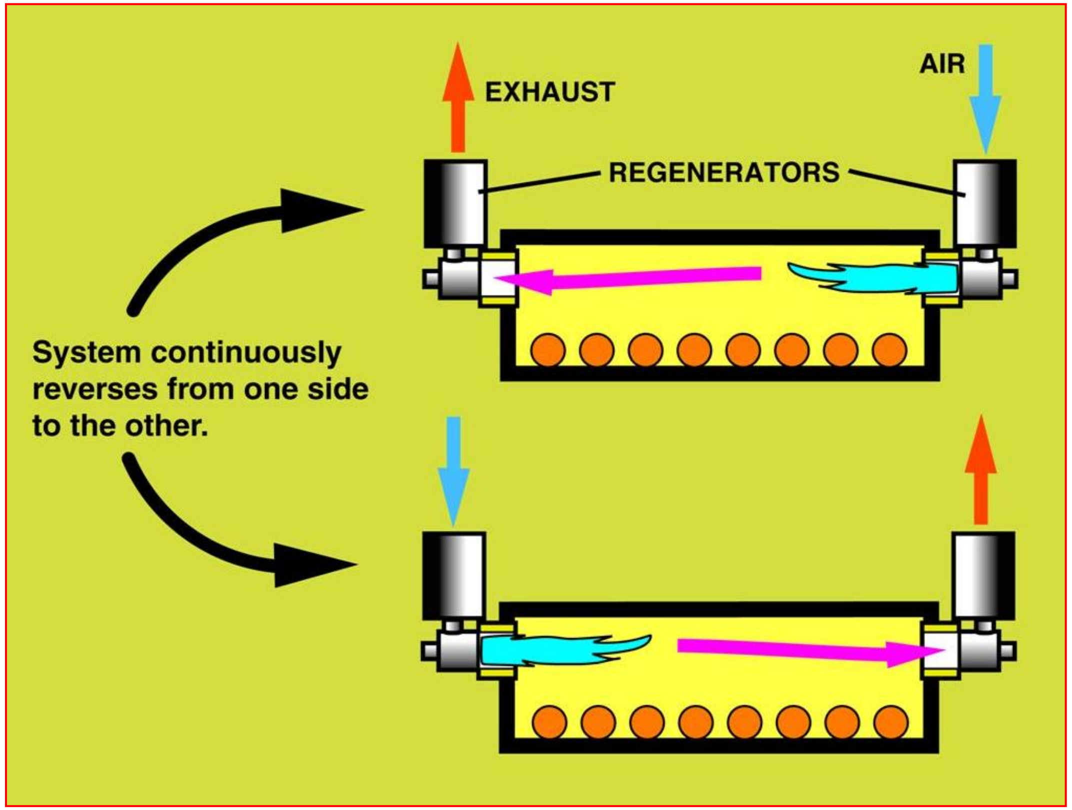
Regenerators

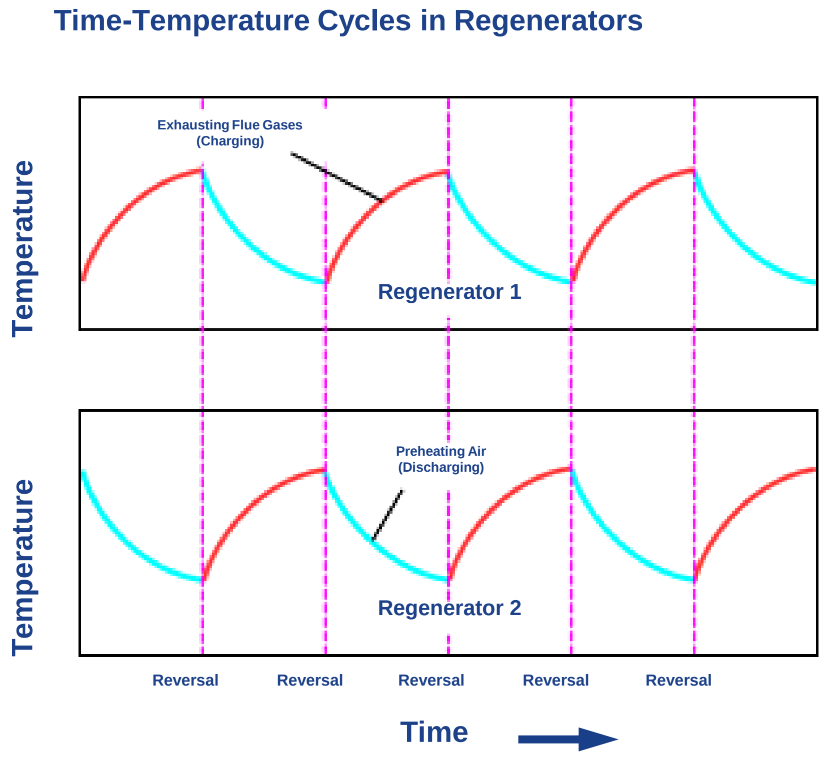
- Designs available to meet different temperature requirements.
- Regenerators offer much higher (65% to 85%) heat recovery ‘efficiency” potential compared to recuperators.
- A regenerator designs include rotating matrix type design or a stationary unit. See examples in next slide.
- The rotary matrix 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

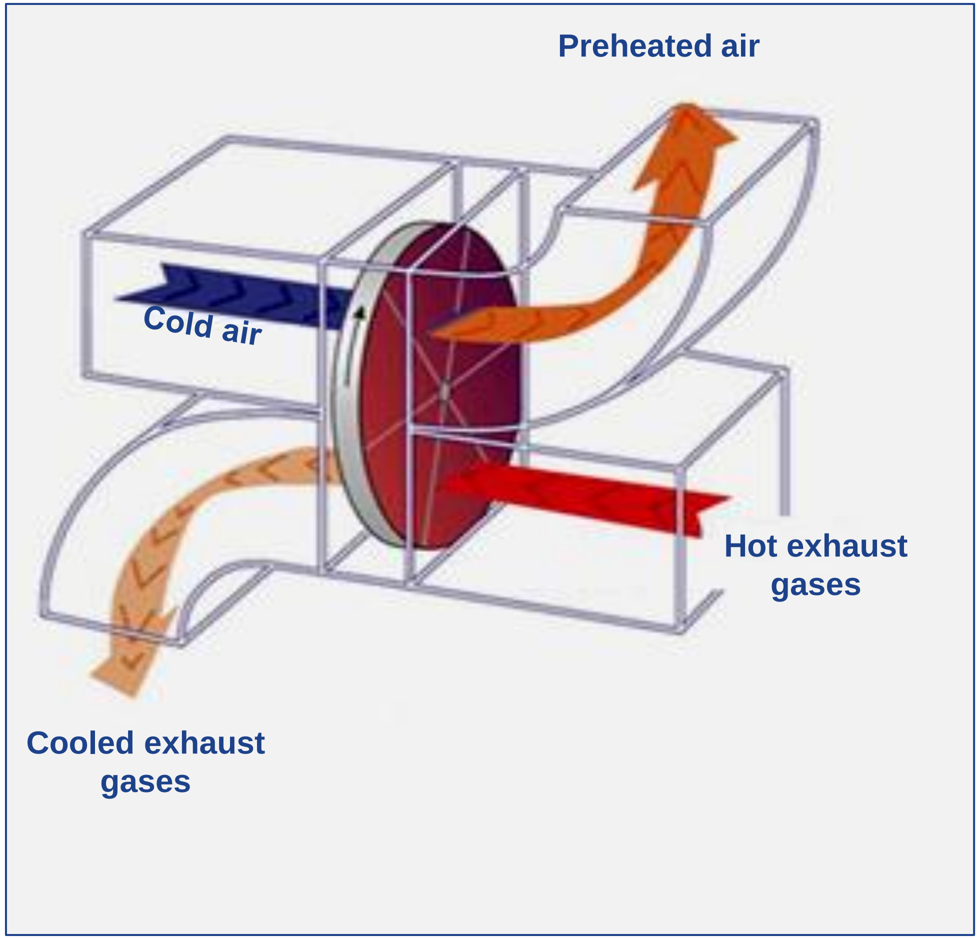




Note: Regenerators have been used to preheat low calorific value fuels such as blast furnace gas. Fuel preheating is rarely used for high calorific value fuels.

Courtesy Fives North American Mfg. Company

Other Regenerative Systems



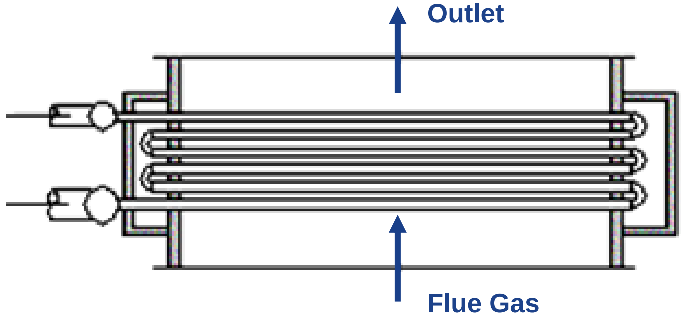
Rotary wheel type of units

- 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

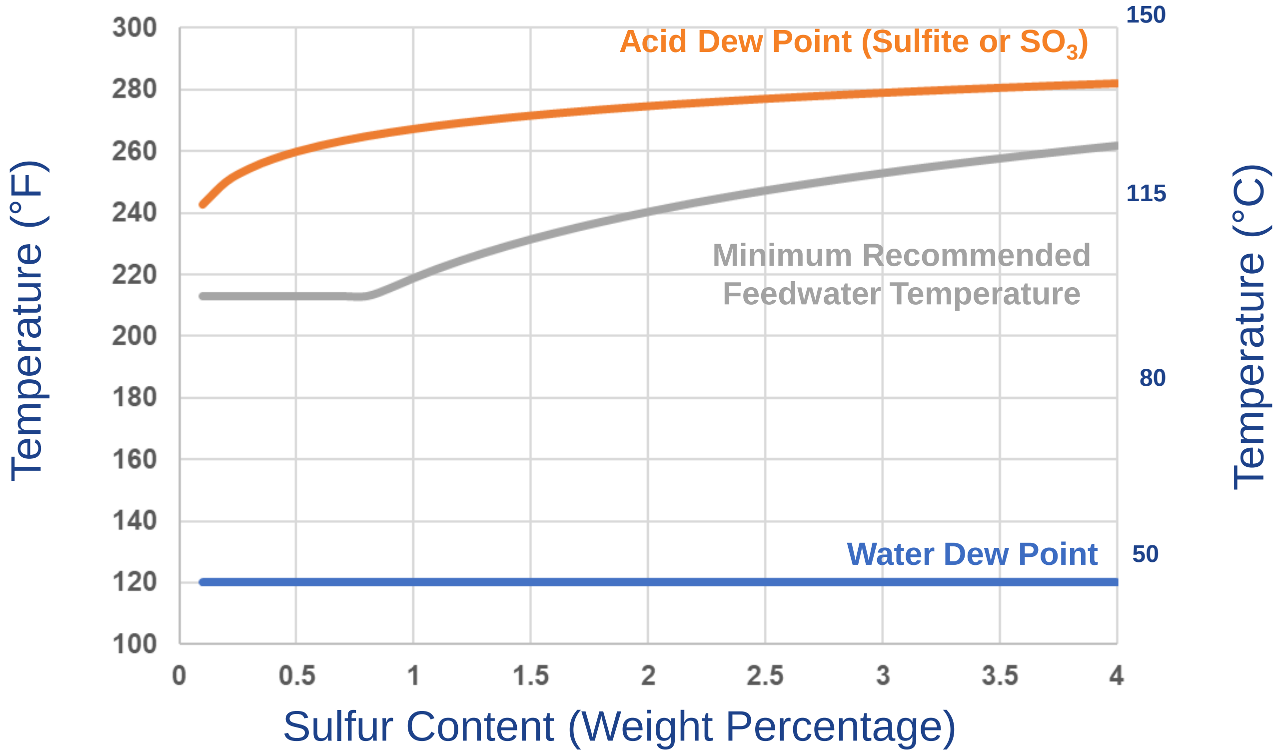
- Have been used for more than 100 years in steel and glass industry.
- Massive units with large space requirement.
- Offer long life and high efficiency but may require considerable maintenance.

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.

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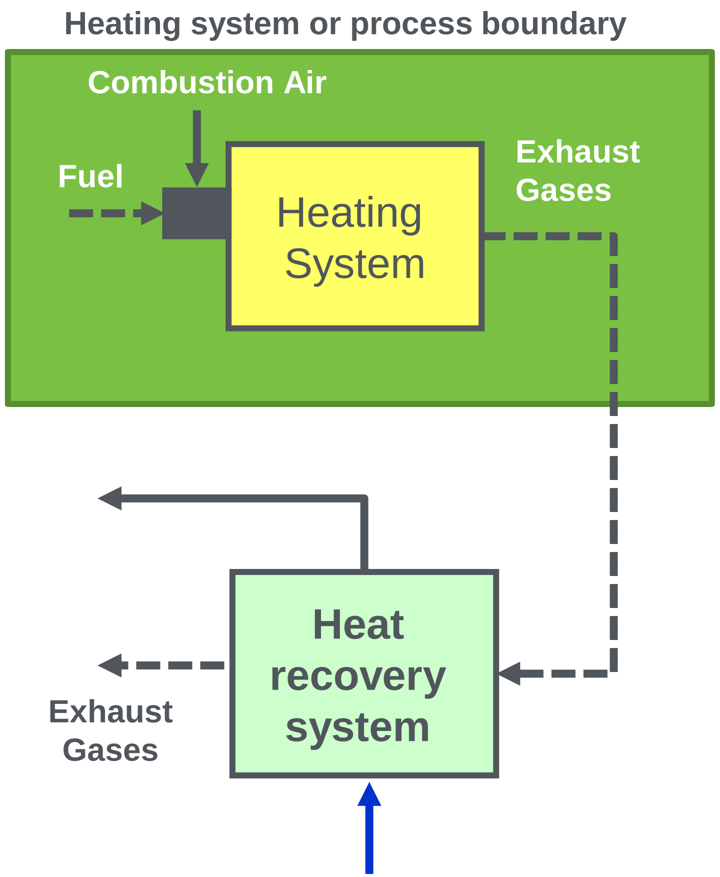
Exhaust (Flue) Gas Heat Recovery

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:

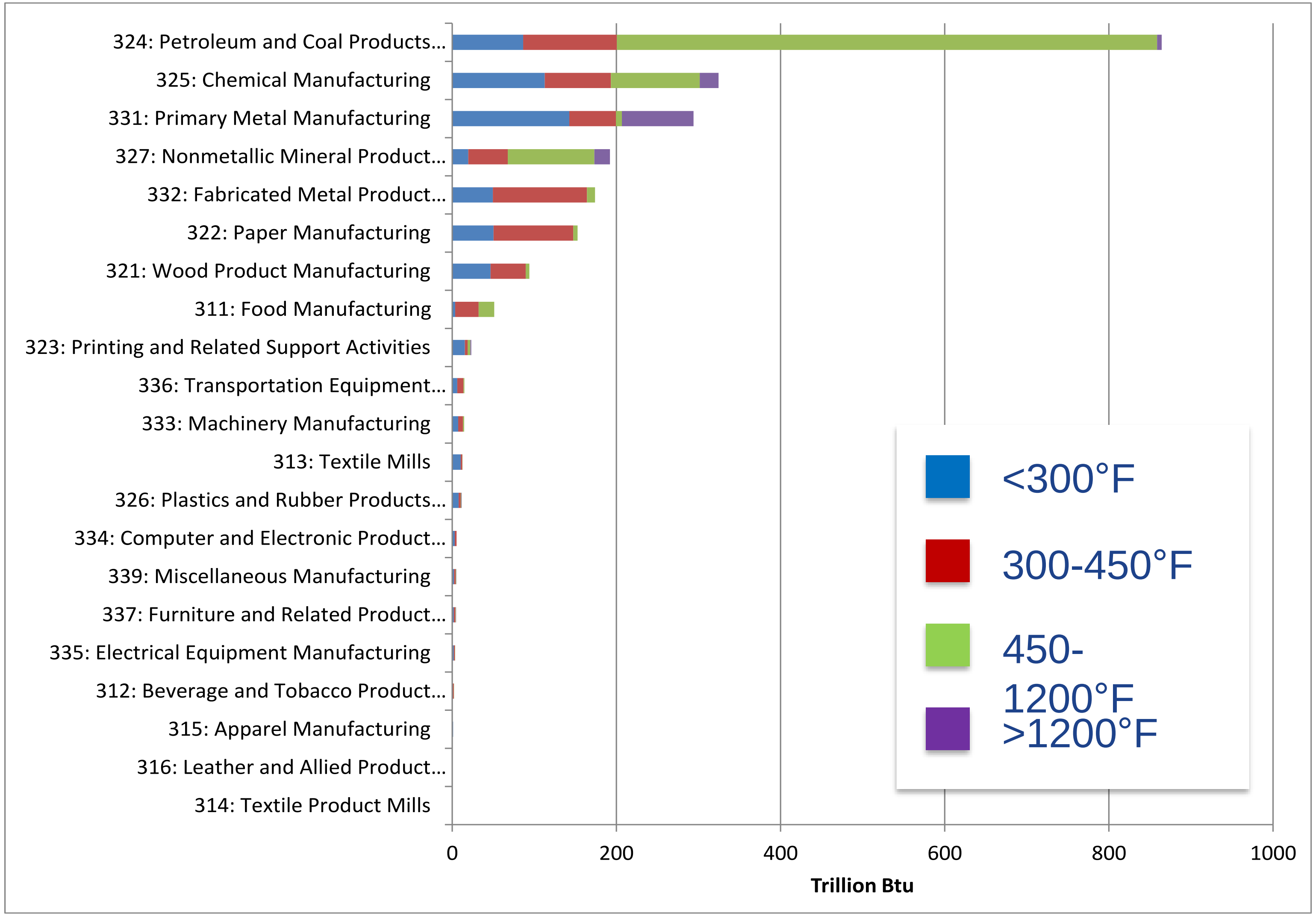
This is a fast-changing field. Technology, performance, and cost can vary significantly. Take the numbers as typical only.

Benefits of WHP

- Utilize heat from existing thermal processes, which would otherwise be wasted to produce electricity.
- Important resource for increasing industrial energy efficiency.
- Improving the competitiveness of the U.S. industrial sector.
- Source of carbon-free power

Waste Heat Inventory by Industry and Temperature Range

(reference temp. at 120ºF or 50ºC)



Reference: Waste Heat to Power Market Assessment, ICF/ORNL, 2015

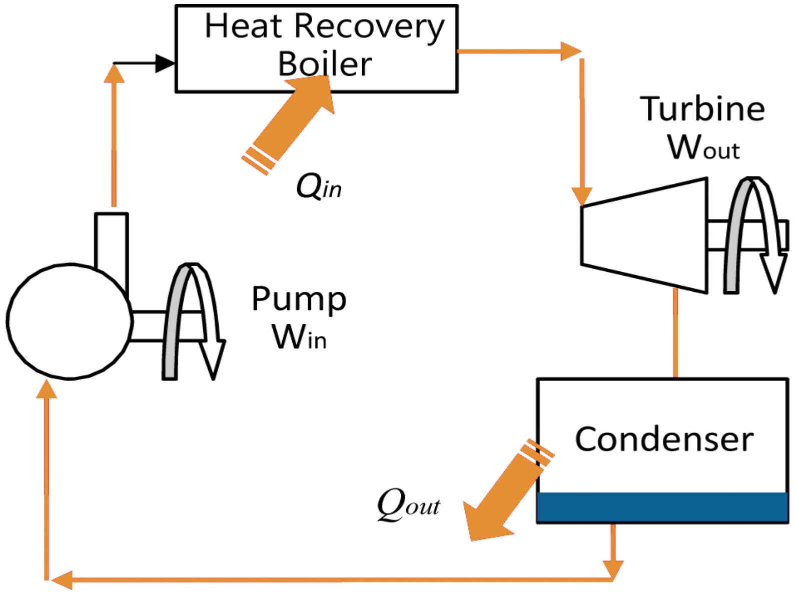
Waste Heat to Power

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.

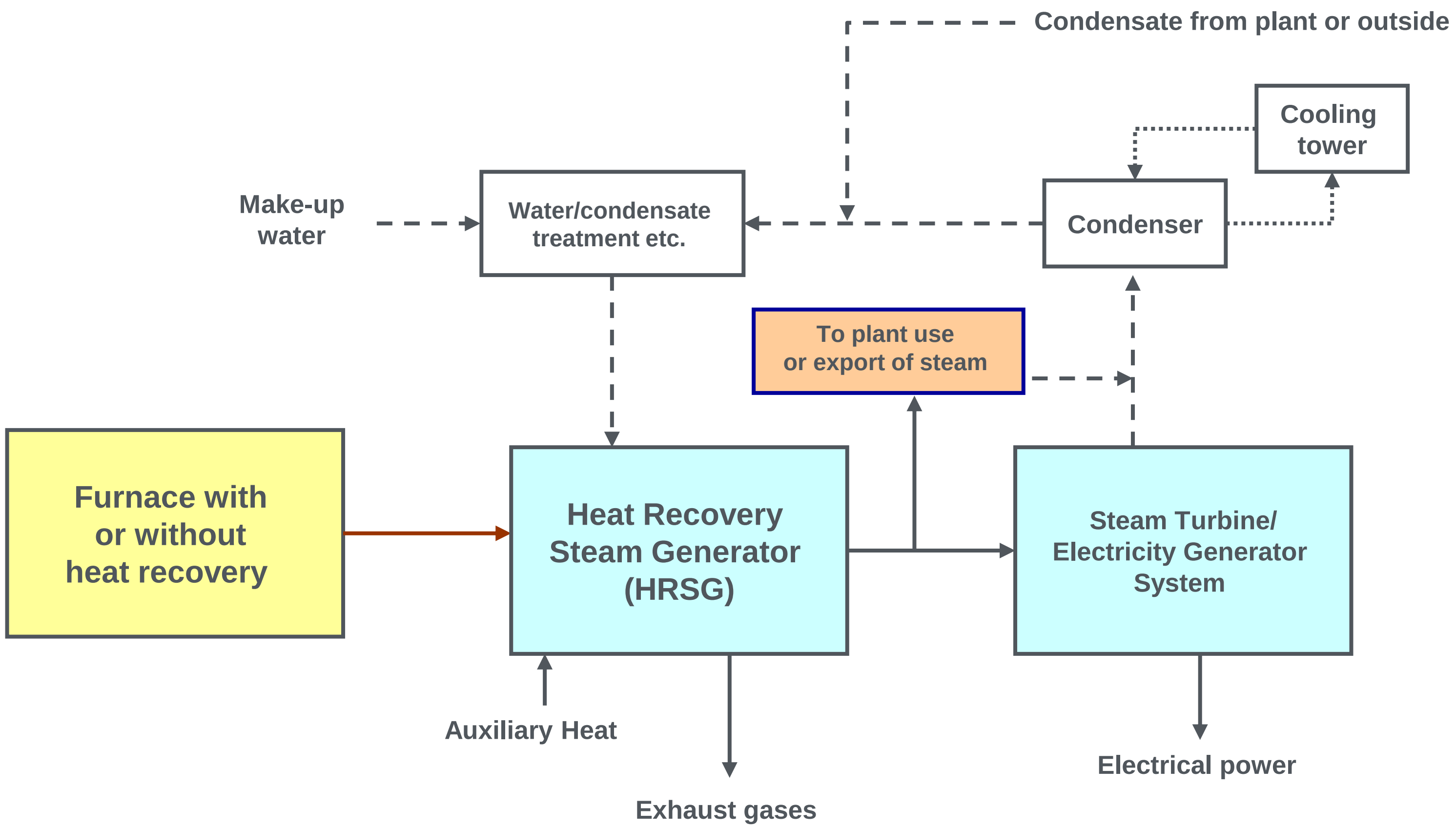
WHP Power Generation Technologies

- Steam Rankine Cycle (SRC)
- Organic Rankine Cycle (ORC)
- Emerging Technologies
  - Kalina Cycle
  - sCO2 Power Cycle
  - Thermoelectric Generation

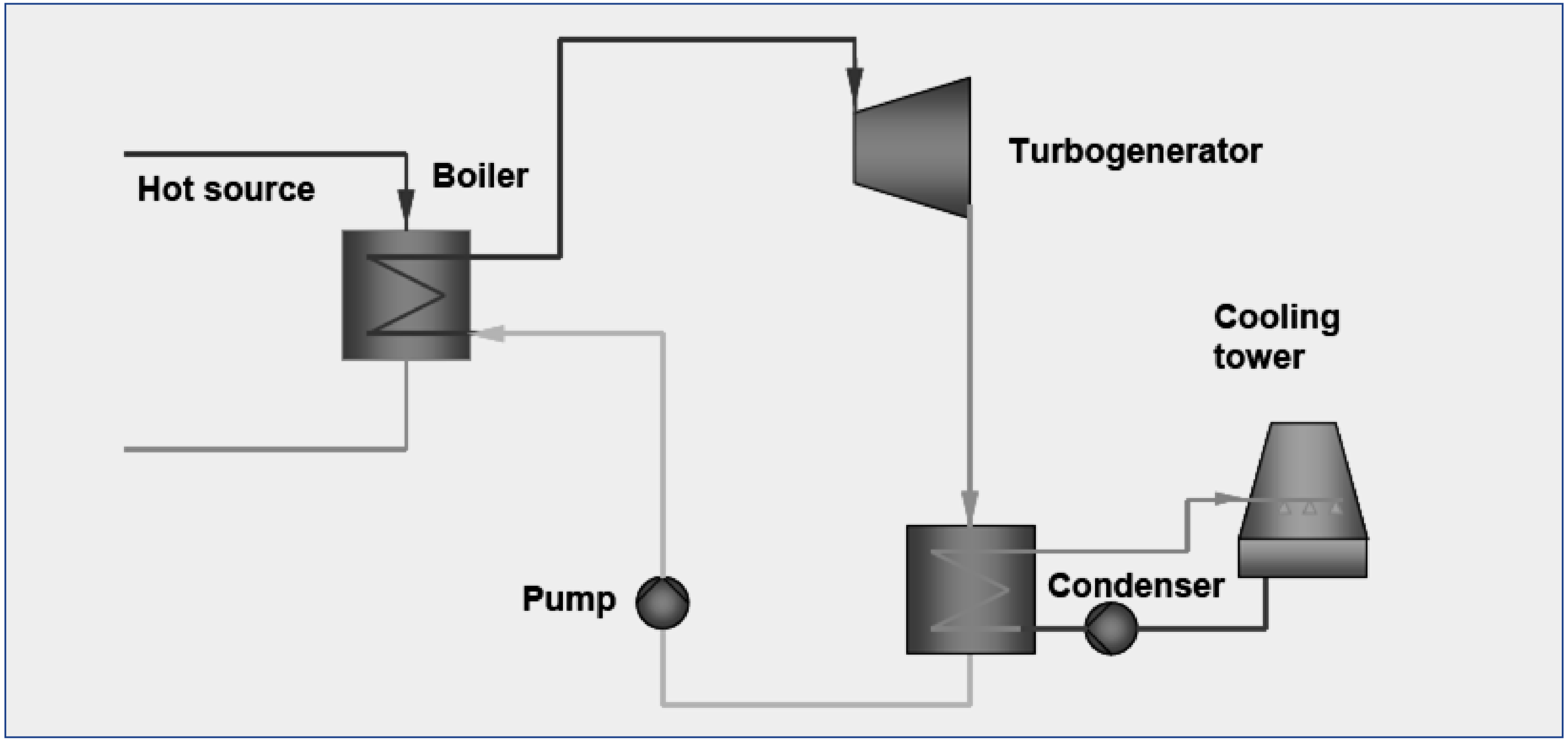


Waste Heat to Power System

"Conventional" Steam – Power Generation



Typical Organic Ranking Cycle (ORC) for Power Generation

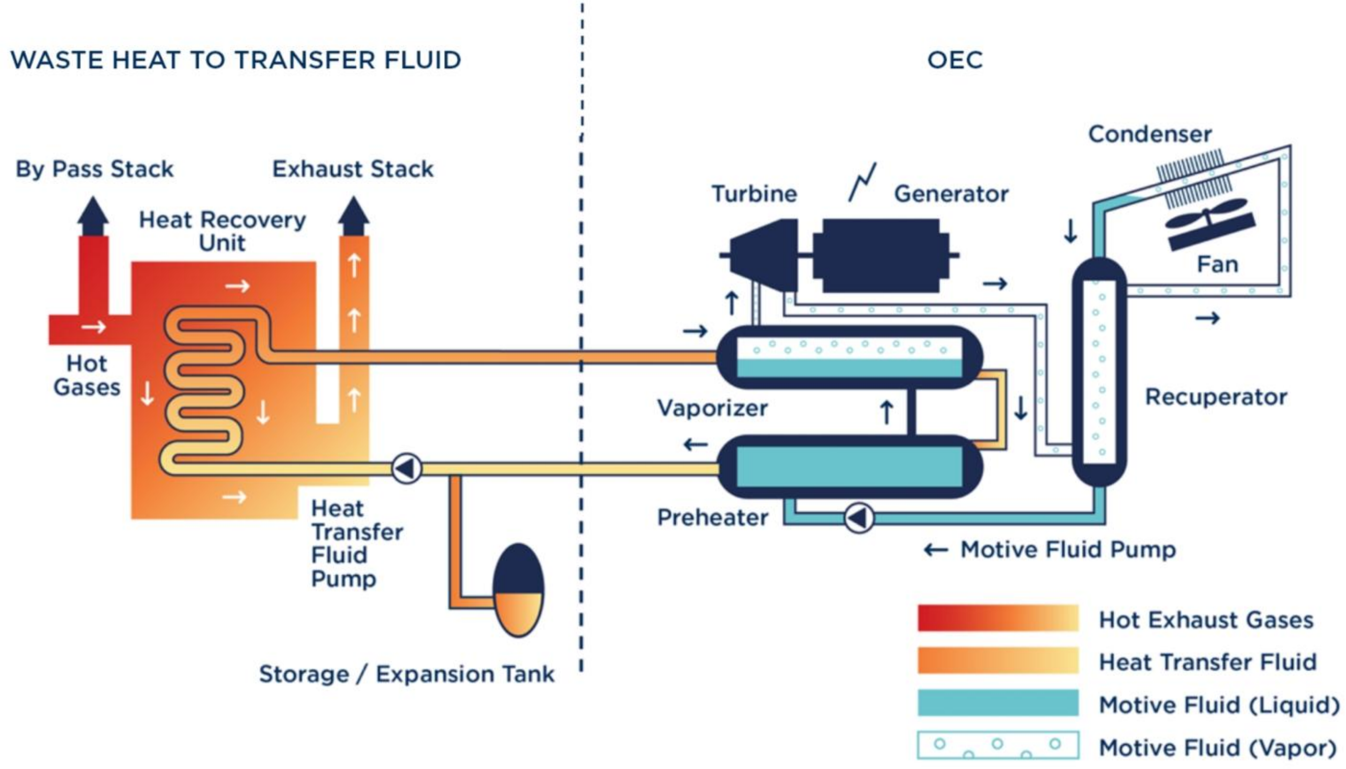


Several other variations of ORC have been are developed to improve its efficiency

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.



Source: Ormat WHP Technologies

Waste Heat to Power Organic Rankin Cycle

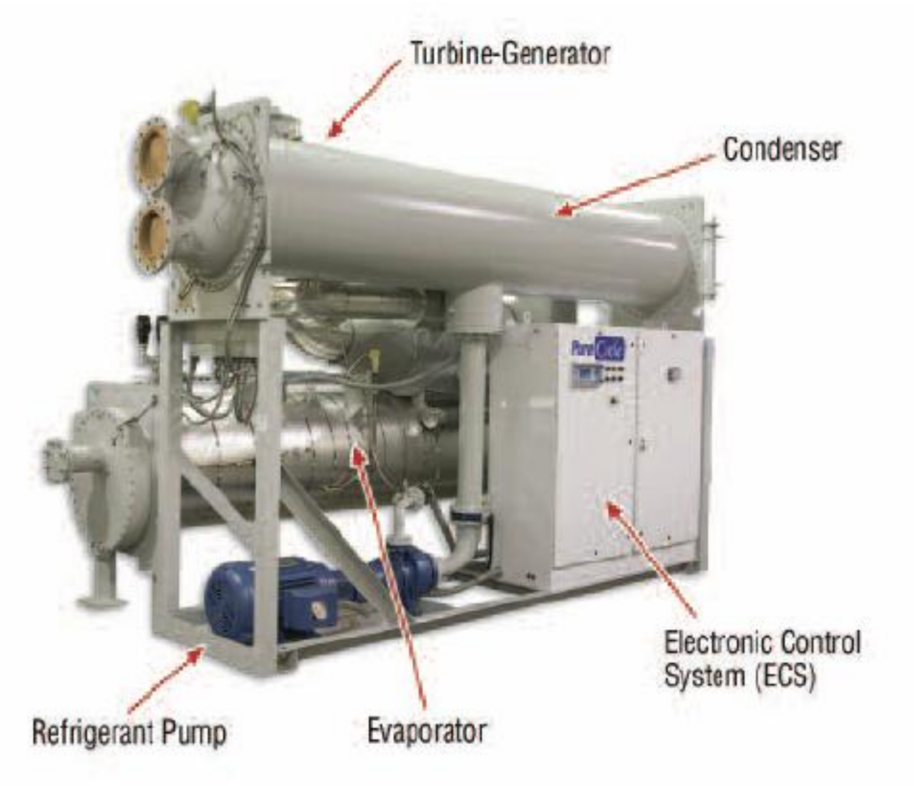
- **Working medium:** variety of organic liquids such as Freon, butane, propane, ammonia, and the new “environmentally-friendly” refrigerants
- Waste heat temperature range is 300°F and up with proper temperature control for the evaporator heat exchanger
- Operating efficiency (~8% to 15%) for low (300°F) 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.

Steam Cycle vs ORC

	Advantages	Disadvantages
ORC	• Applicable to medium-low temperature applications (heat source <300°C) • Better choice for small installations (<2-5 MW power output) • Very high turndown ratio (power production is possible at ratios as low as 10% of nominal heat input) • Better choice if water is not easily and abundantly available • Unattended operation (no dedicated supervision or operators required) • Low turbine maintenance requirements	• Less efficient than SRC in medium-high temperature applications (heat source >350°C) • Higher capital cost on a USD/kW basis • Higher auxiliary power requirements due to increased pump and fan power • Organic fluids can be expensive and require more attention than water when handled (they may be harmful to environment or flammable) • Leakage detection is a must, to avoid losses of expensive fluid • Emerging technology with limited installations worldwide
SRC	• Well-known and reliable technology, with many installations worldwide • Lower CapEx for systems of equal size; • More efficient than ORC in medium-high temperature applications (heat source >350°C) • Better choice for large installations (>5 MW power output) • Water is normally easily available and environmentally friendly	• Requires large amounts of water • Requires expensive equipment and chemicals for water treatment • Less flexible and efficient at part load operation (at input loads <60-70%) • Turbine more prone to maintenance requirements (for the effects of corrosion or erosion

Waste Heat to Power

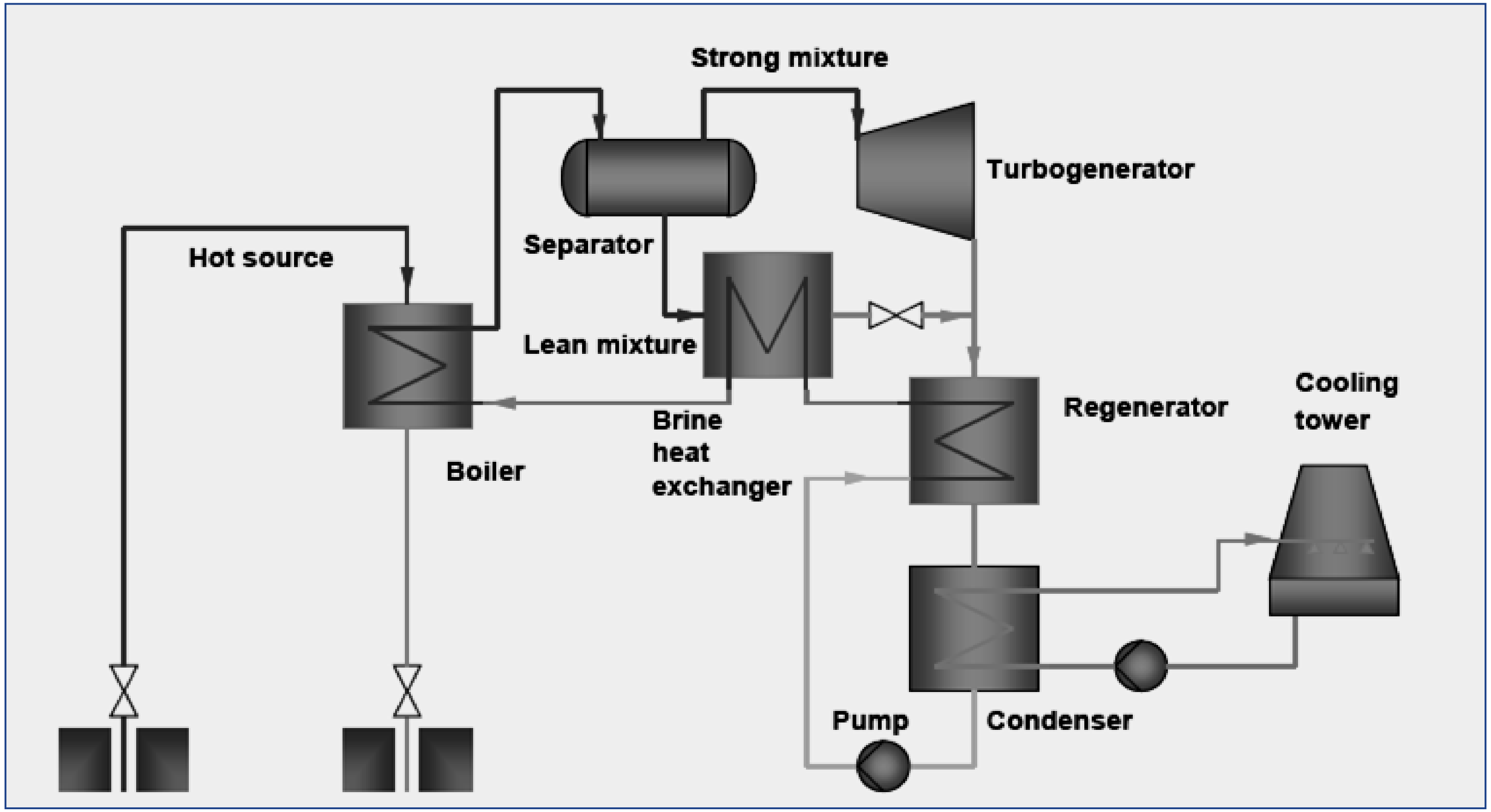


Example: UTC PureCycle Option

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

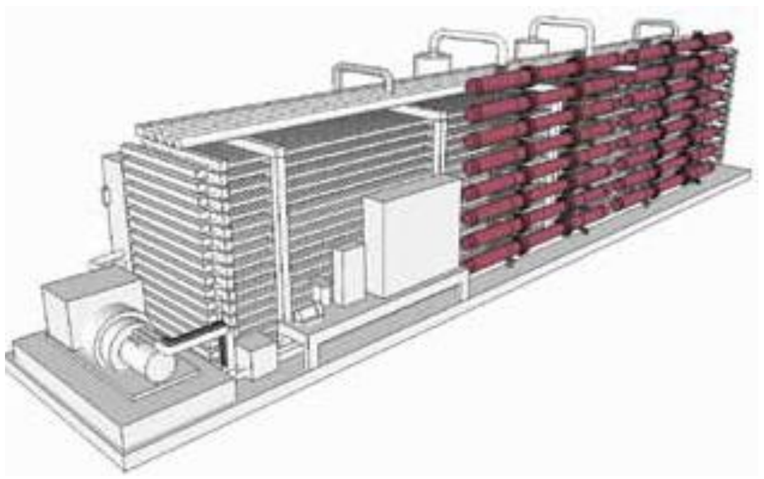
Waste Heat to Power Options for Industrial Application

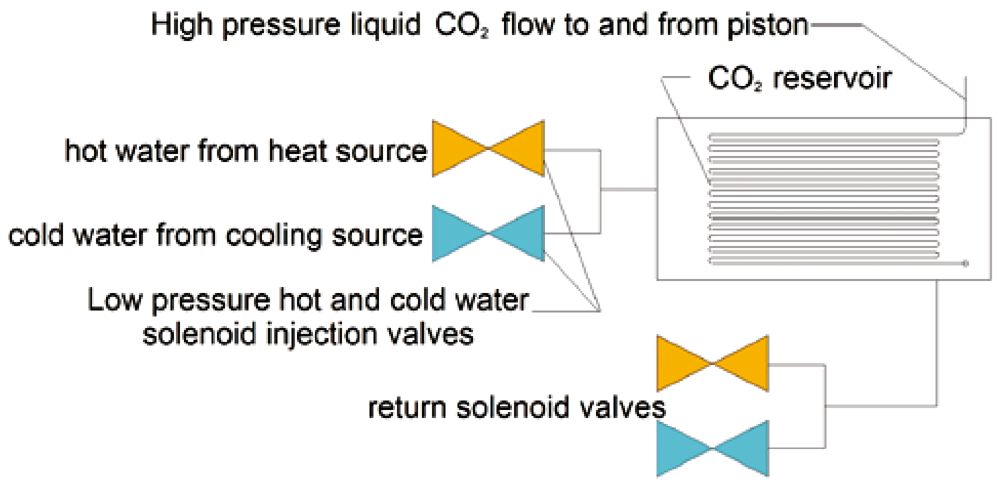
Note: The operating data and costs are derived from available literature and their accuracy cannot be guaranteed.

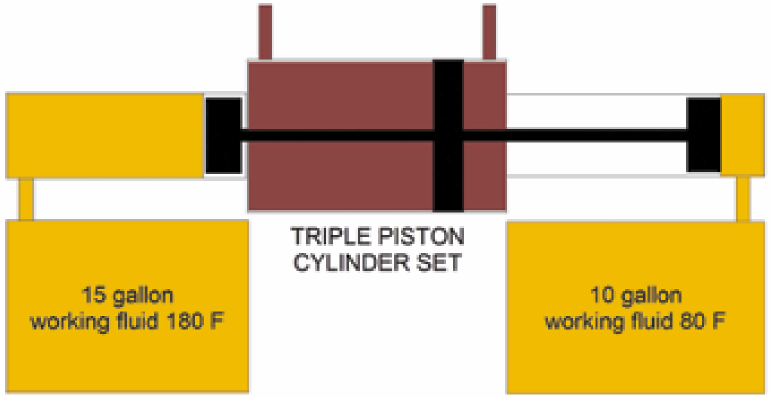
Kalina Cycle Plant:

- 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

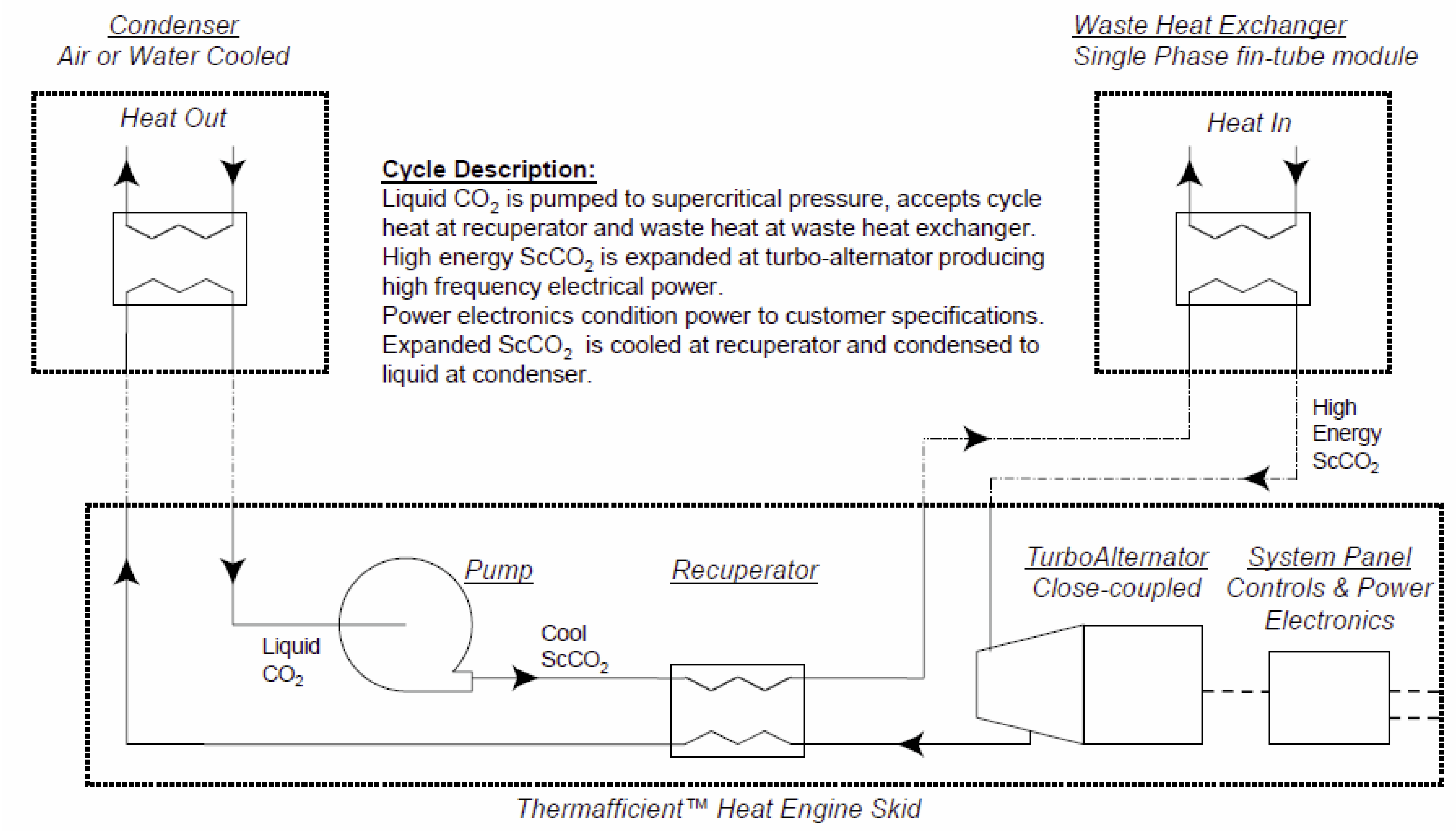






1. **Requires 180 + deg. F. water**
2. **Approximate cost (quoted) $2,000/kW not including installation etc.**
3. **Maintenance and operating cost (other than hot water) - unknown**
4. **No operating unit for power production**
5. **Claimed efficiency: 23% (based on of the heat to power conversion)**

Echo-Gen Super Critical Power Cycle



Power Cycle Comparison

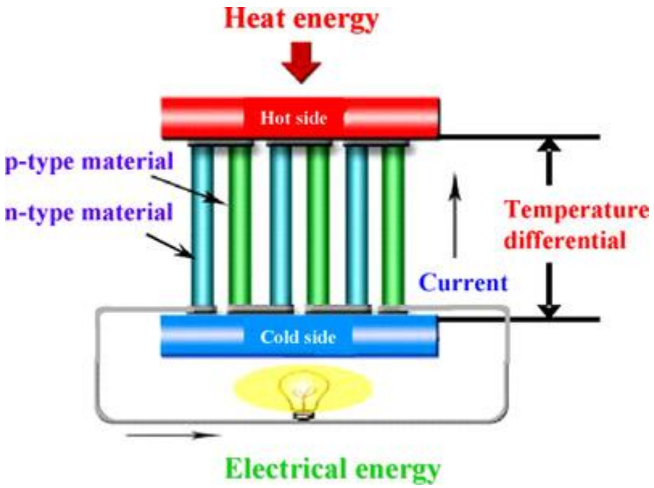
Comparison	Steam Rankine	Organic Rankine (ORC)	Ammonia (NH_3) - Water	CO_2 Power Cycle
Source Temperature Range (°F)	>750	300 – 570	212 – 840	440 – 1200
Working Fluid	Treated water	HCFCs or Hydrocarbons	Ammonia - water mixture	Caron Dioxide
Working Fluid Attributes	Requires treatment to reduce corrosion 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

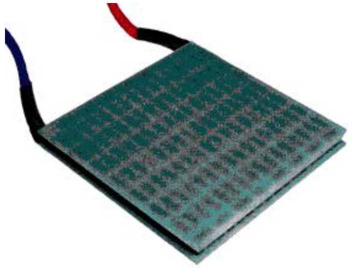
Note: This is a fast-changing field. The efficiency values highly dependent on the source temperature. Cost could vary significantly with size, supplier and incentives from several sources.

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.

Technical Factors to Consider

- Is the waste heat source a gas or a liquid stream?
- What is the temperature of the waste stream and does it vary over time?
- What is the availability of the waste heat—is it continuous, cyclic, or intermittent?
- What is the load factor of the waste heat source—are the annual operating hours sufficient to amortize the capital costs of the WHP system?
- What is the flow rate of the waste stream, and does it vary?
- Is the waste stream at a positive or negative pressure, and does this vary?
- What is the composition of the waste stream?
- Are there contaminants that may corrode or erode the heat recovery equipment?
- Is there space available in or close to the waste heat stream for recovery and generation equipment?

Economic Factors to Consider

- Waste heat recovery options – can the waste heat be used elsewhere at the facility (always the most cost effective option)
- Characteristics of the waste heat stream
- Cost of grid electricity
- Integration of WHP
  - Site factors impacting cost and performance
- Availability of financial incentives

Case studies

Project Snapshot 1:

Waste heat to power and process heat, Port Arthur, TX

Application/Industry: Petroleum Refining

Capacity: 5 MW

Equipment: Waste heat recovery boilers; back pressure steam turbine

Fuel Type: Waste heat

Thermal Use: Steam and electricity generation

Installation Year: 2005

Environmental Benefits: CO2 emissions reduced by 159,000 tons/year

Testimonial: “Through the recovery of otherwise-wasted heat to produce high pressure steam for crude oil processing, Port Arthur Steam Energy LLP has demonstrated exceptional leadership in energy use and management.”

- U.S. Environmental Protection Agency, in giving the 2010 Energy Star Award

Project Snapshot 2:

Williams Ignacio Gas Plant

Durango, CO

Application/Industry: Oil and Gas Extraction

Capacity (MW): 6.2 MW

Power Output: 43,800 MWh per year

Prime Mover: Steam turbine

Fuel Type: WHP

Electrical Use: Waste heat from turbines drives centrifugal compressors

Installation Year: 1984, upgraded 2014

Emissions Savings: 2,480 tons per year

- Nitrogen oxides (NOx) reduced 88%
- Carbon oxides (CO) reduced 48%
- Volatile Organic Compounds (VOC) reduced 82%
- Particular matter (PM) reduced 59%

Steam Turbine Waste Heat Recovery
Facility provides compression, dehydration and natural gas liquids recovery and produces liquefied natural gas (LNG) as part of the company's San Juan Gathering System. A recycled energy system captures waste heat from the compression process and uses it to generate electricity.

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.

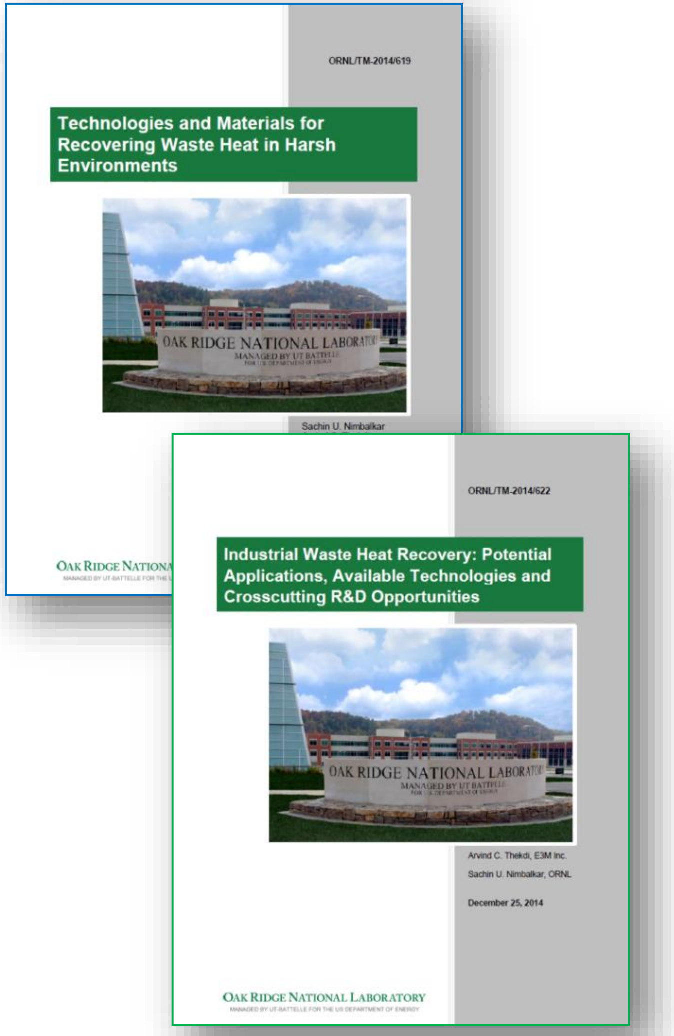
Waste Heat Options Summary

Power Generation:

- Conventional steam turbine-generator option is the most attractive option for clean, contamination free waste heat at higher (>800°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 (~480°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.



Acknowledgement

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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