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Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division (ETSD)

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About This Report

The purpose of this report was to explore key areas and characteristics of industrial waste heat and its generation, barriers to waste heat recovery and use, and potential research and development (R&D) opportunities. The report also provides an overview of technologies and systems currently available for waste heat recovery and discusses the issues or barriers for each. Also included is information on emerging technologies under development or at various stages of demonstrations, and R&D opportunities cross-walked by various temperature ranges, technology areas, and energy-intensive process industries.

Disclaimer

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Executive Summary

Industrial energy use in all of its forms (such as fuel, electricity, and steam) accounts for approximately one-third of total U.S energy usage. Energy used in a typical industrial plant is distributed over a large number of subsystems, which can be divided into the following three major categories:

- Onsite generation of power and other utilities—such as steam, water, and air—that is distributed and used in the plant
- Process energy use that is distributed over several systems within a plant such as process heating, process cooling and refrigeration, electrochemical, machine drive, and other uses
- Non-process energy use such as facility heating, ventilating, and air conditioning; lighting; support services; and onsite transportation

Energy use analysis indicates that more than 80% of total plant energy usage comes from onsite generation and process energy applications. Onsite generation and process energy uses are also areas of large energy losses; for example, process heating energy losses represent 25%–55% of the total energy use. Almost all losses from onsite generation and process energy applications are lost as heat in many forms—such as sensible and latent heat, radiation, or convection—which is discharged from the system and lost in the ambient. Recovering this waste heat and using it as an energy source in industrial systems is one of the best methods of reducing energy intensity in manufacturing plants.

The Department of Energy's Industrial Technologies Program (ITP) has previously conducted several studies to identify heat losses from industrial energy systems. In addition to using information from those reports, this report explores key sources and characteristics of industrial waste heat and its generation for major industrial sectors, focusing on low-temperature heat in particular. Past studies have indicated that low-temperature waste heat is a large percentage of total industrial waste heat; however, the amount of heat recovered is small compared to the amount of heat recovered from higher temperature sources.

The report also discusses barriers and limitations for commonly used and emerging waste heat recovery technologies, with the appendix providing a detailed overview of many technologies and systems currently available and a few emerging technologies under development or in demonstration. Using input from industrial users and waste heat recovery equipment suppliers, where available, information is presented on the performance of and limitations in the use of these technologies and systems.

The report also identifies potential research and development (R&D) opportunities. The list of R&D opportunities was based on information gathered from available reports and discussions with industrial users, equipment suppliers, and research workers in the area of industrial waste heat recovery. In the report, R&D opportunities are cross-walked by various temperature ranges, technology areas, and energy-intensive process industries as shown in the following table.

R&D Opportunities by Category		
Heat Source	**Technology Area**	**Major Industries**
• High-temperature waste heat • Medium-temperature waste heat • Low-temperature waste heat	• Basic research • Advanced materials • Advanced concepts and designs • Sensors and controls • Advanced high-efficiency power generation	• Aluminum • Cement • Chemicals and petroleum refining • Coatings • Food (snack) manufacturing • Glass • Iron & steel • Paper

Key conclusions are as follows:

- The economic justification of heat recovery systems depends on the temperature and quality or cleanliness of the waste streams; the magnitude of waste heat; the system's cost-benefit ratio; and, most importantly, the cost of energy—particularly fuels, natural gas, and coal.
- A large number of technologies and systems are available to recover heat from medium (600°–1,200°F or 316° - 650°C) and high-temperature (>1,200°F or 650°C) clean gases discharged from industrial processes. In most cases, there is an upper temperature limit (>1,600°F or 870°C) that restricts use of the available equipment.
- Several systems are available to recover heat from lower temperature clean gases and liquids; however, current energy prices prevent their wide-scale use.
- Next to the cost of energy, the equipment performance of waste heat recovery technologies is the most important issue preventing use of waste heat systems in all temperature ranges. For example, a large amount of waste heat is available in high-temperature processes; however, the waste heat streams contain many contaminants that severely limit use of existing waste heat recovery systems. On the other hand, thermodynamic limitations and the lack of economically justifiable, efficient energy conversion systems prevent wide-scale use of heat recovery from low-temperature waste heat streams.
- In many cases, the available technologies and hardware can economically recover large amounts of heat in the form of hot air (gas), liquid (water), or steam. However, in most cases there is very little use of such energy sources in the plant. The best form of energy conversion seems to be electricity that is easily transportable or can be exported to the utility company. Currently available technologies and systems need several improvements before they are accepted by the industry. Additional R&D efforts in this area could offer large returns.
- Addressing a number of technical issues and pursuing R&D efforts could allow further wide-scale use of waste heat recovery from high-temperature streams. Many technical issues and R&D efforts are related to materials and are designed to extend equipment life, reduce maintenance or cleaning time intervals, and provide consistent and reliable performance over an acceptable lifetime (usually several years).
- Specifically for low-temperature waste heat streams, cost, system size limitations, and the lack of use of low-grade heat within the plant are major barriers to waste heat recovery. The very low temperature of the heat source places severe limitations on heat transfer rates and requires large surface areas, resulting in large footprints and unjustifiable economics. Development of micro-size heat exchangers, designs that offer large area-to-volume ratios (smaller footprint), and materials that can withstand the corrosive properties of low-temperature streams (condensed liquids from flue gases) are required for wide-scale adoption of low-temperature heat recovery systems. Usage of recovered waste heat within the plant remains a substantial hurdle and presents a cost justification issue for plant management.

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Introduction and Background

Waste heat in manufacturing is generated from several industrial systems distributed throughout a plant. The largest sources of waste heat for most industries are exhaust and flue gases and heated air from heating systems such as high-temperature gases from burners in process heating; lower temperature gases from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. While waste heat in the form of exhaust gases is readily recognized, waste heat can also be found within liquids and solids. Waste heat within liquids includes cooling water, heated wash water, and blow-down water. Solids can be hot products that are discharged after processing or after reactions are complete, or they can be hot by-products from processes or combustion of solid materials. Other less apparent waste heat sources include hot surfaces, steam leaks, and boiler blow-down water. Exhibit 1 shows typical major waste heat sources along with the temperature range and characteristics of the source.

Exhibit 1: Temperature Range and Characteristics for Industrial Waste Heat Sources

Waste Heat Source	Temperature Range °F	Temperature Range °C	Cleanliness
Furnace or heating system exhaust gases	600 – 2,000	316 – 1,100	Varies
Gas (combustion) turbine exhaust gases	900 – 1,100	480 – 600	Clean
Reciprocating engines			
Jacket cooling water	190 – 200	90 – 100	Clean
Exhaust gases (for gas fuels)	900 – 1,100	480 – 600	Mostly clean
Hot surfaces	150 – 600	65 – 316	Clean
Compressor after or inter cooler water	100 – 180	38 – 82	Clean
Hot products	200 – 2,500	100 – 1,370	Mostly clean
Steam vents or leaks	250 – 600	120 – 316	Mostly clean
Condensate	150 – 500	65 – 260	Clean
Emission control devices – thermal oxidizers, etc.	150 – 1,500	65 – 816	Mostly clean

Previous Studies

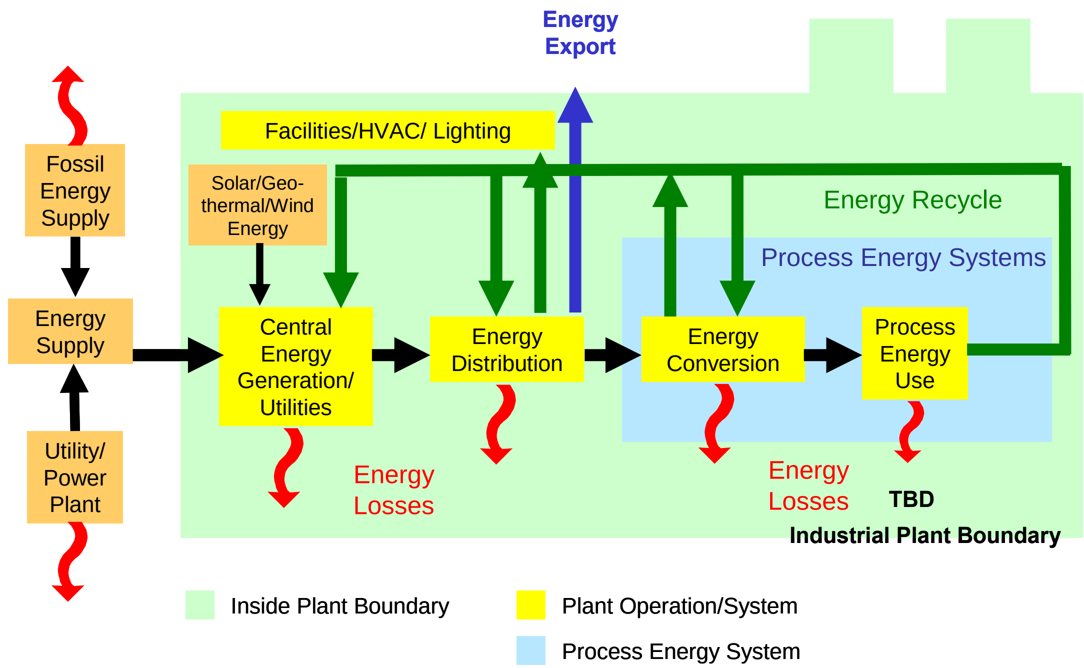
A number of reports prepared for the Department of Energy (DOE) and other organizations studied sources of waste heat, primarily from industrial heating systems. The scope of these reports varied from estimating losses from various industrial heating systems in Btus per year to reviewing waste heat from various industries and identifying general R&D opportunities. Following is an overview of several waste heat reports that were used as references in this study.

Energy Use and Loss Analysis

The "Energy Use and Loss Analysis" report, prepared by Energetics Incorporated, describes total energy used by major manufacturing sectors identified by North American Industry Classification System (NAICS) codes, using Manufacturing Energy Consumption Survey (MECS) data published by the Energy Information Agency. The MECS data was used to estimate major areas of energy use in a plant as well as losses from the subsystems, as shown in Exhibit 2.

The losses were based on estimated percentages of losses for the major areas of energy use. The loss factors for each area are shown in Exhibit 3. Based on the loss factors and energy use, an estimate was made for the energy losses in various industrial sectors, as seen in Exhibit 4. The report did not attempt to identify specific areas of waste heat for the energy systems.

Exhibit 2: Major Areas of Energy Use in a Manufacturing Plant



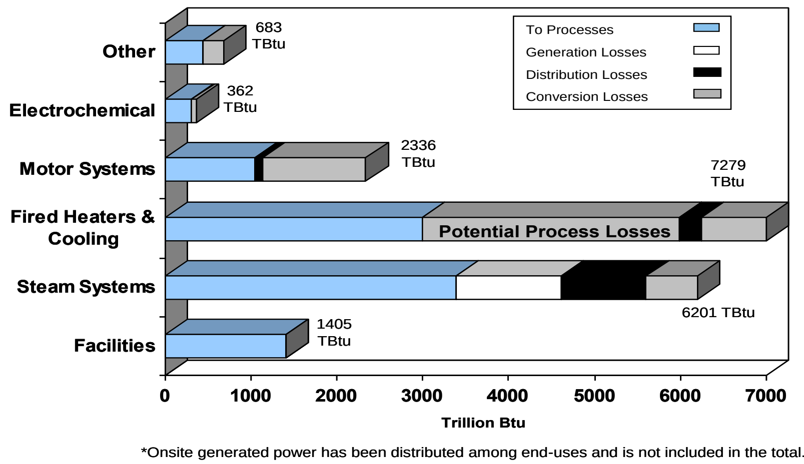
Source: Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining, Energetics Incorporated and E3M, 2004.

Exhibit 3: Energy Loss Factors for Major Energy Systems in a Manufacturing Plant

Energy System	Percent Energy Lost
Steam systems	Boilers – 20% Steam pipes and traps - 20% Steam delivery/heat exchangers – 15%
Power generation	Combined heat and power – 24% (4500 Btu/kWh) Conventional power – 45% (6200 Btu/kWh)
Energy distribution	Fuel and electricity distribution lines and pipes (not steam) – 3%
Energy conversion	Process heaters – 15% Cooling systems – 10% Onsite transport systems – 50% Electrolytic cells – 15% Other – 10%
Motor systems	Pumps – 40% Fans – 40% Compressed air – 80% Refrigeration – 5% Materials handling – 5% Materials processing – 90% Motor windings – 5%

Source: Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining, Energetics Incorporated and E3M, 2004.

Exhibit 4: Estimates of Energy Losses for Major Energy Use Areas in Manufacturing



Source: Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining, Energetics Incorporated and E3M, 2004.

Waste Heat Recovery: Technology and Opportunities in U.S. Industry

ITP issued a detailed report prepared by BCS Incorporated titled “Waste Heat Recovery: Technology and Opportunities in U.S. Industry” that provides information on waste heat sources in major industrial sectors; the nature of waste heat; available waste heat recovery equipment currently used by the industry; and research, development, and demonstration (RD&D) needs. The report classifies waste heat sources in three categories: high temperature (>1,200°F or 650°C), medium temperature (450°–1,200°F or 230° - 650°C), and low temperature (<450°F or 230°C).

The BCS report provides a waste heat profile that describes the type of waste heat discharged from industrial plants, general observations related to waste heat sources, the nature of waste heat, and waste heat recovery practices. It outlines RD&D opportunities to extend the economic operating range of conventional technologies and conduct RD&D in emerging and novel technologies.

The report also identifies uncovered waste heat in different temperature ranges, concluding that the amount of heat wasted above 77°F (or 25°C) reference temperature is 1,478 trillion Btu per year and lowers to 256 trillion Btu per year if the reference temperature is raised to 300°F (or 150°C). This indicates significant heat recovery opportunities in the 77°–300°F (or 25°-150°C) temperature range, which represents more than 80% of the total estimated waste heat and emphasizes the need for R&D in this range.

A summary of key RD&D opportunities identified in the BCS report cross-walked against barriers these opportunities address are shown in Exhibit 5.

Exhibit 5: RD&D Opportunities and Barriers Addressed

	Barriers Addressed									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-Use	Heat Transfer Rates	Environmental Concerns	Process Control and Product Quality	Process-Specific Constraints	Inaccessibility
Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures		X	X							
Economically scale down heat recovery equipment	X	X		X						
Develop economic recovery systems that can be easily cleaned after exposure to gases with high chemical activity			X	X		X				
Develop novel manufacturing processes that avoid introducing contaminants into off-gases in energy-intensive manufacturing processes		X	X				X	X	X	
Develop low-cost dry gas cleaning systems		X	X			X	X	X		
Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation		X			X					
Develop alternative end-uses for waste heat					X					
Develop novel heat exchanger designs with increased heat transfer coefficients	X	X				X				
Develop process-specific heat recovery technologies				X		X	X	X	X	X
Reduce the technical challenges and costs of process-specific feed preheating systems	X			X		X		X	X	
Evaluate and develop opportunities for recovery from unconventional waste heat sources (e.g., sidewall losses)									X	X
Promote new heat recovery technologies such as solid-state generation										X
Promote low-cost manufacturing techniques for the technologies described above	X	X	X	X	X	X	X	X	X	X

Source: Waste Heat Recovery: Technology and Opportunities in U.S. Industry, BCS, 2008.

Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions

A Pacific Northwest National Laboratory (PNNL) report titled "Opportunity Analysis for Recovering Energy from Industrial Waste Heat and Emissions" discusses waste energy availability. The report analyzes barriers and pathways to recovering chemical and thermal emissions from U.S. industry, with the goal of more effectively capitalizing on such opportunities.

A primary part of this study was characterizing the quantity and energy value of these emissions. The authors surveyed publicly available literature to determine the amount of energy embedded in the emissions and identify technology opportunities to capture and reuse this energy. The authors identify U.S. industry as having 2,180 petajoules (PJ), or 2 Quads (quadrillion Btu), of residual chemical fuel value. As landfills are not traditionally considered industrial organizations, the industry component of these emissions has a value of 1,480 PJ, or 1.4 Quads—approximately 4.3% of total energy use by U.S. industry.

The report discusses the advanced materials (e.g., thermoelectric, thermionic, and piezoelectric) and other technologies (e.g., solid oxide fuel cells) that, in the authors' opinion, are the most promising technologies for re-utilizing chemical and thermal emissions. The authors recommend additional research and development as well as industry education to make these technologies sufficiently cost effective and widely commercialized.

Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery

PNNL and BCS, Incorporated prepared a report titled "Engineering Scoping Study of Thermoelectric Generator (TEG) Systems for Industrial Waste Heat Recovery" that was issued in November 2006. This report evaluated the TEG system with the intent to accomplish the following:

- Examine industrial processes in order to identify and quantify industrial waste heat sources that could potentially use TEGs.
- Describe the operating environment that a TEG would encounter in selected industrial processes and quantify the anticipated TEG system performance.
- Identify cost, design, and engineering performance requirements needed for TEGs to operate in the selected industrial processes.
- Identify the research, development, and deployment needed to overcome limitations that discourage the development and use of TEGs for recovery of industrial waste heat.

Three industrial waste heat processes were selected to investigate applicability of TEGs: glass furnaces (905°–2,550°F or 485°–1,400°C), aluminum Hall-Hèroult cells (1,760°F or ~960°C), and reverberatory furnaces (1,400°F or ~760°C). Based on the analysis of opportunities, the report concludes that TEG application in glass furnaces would generate more than $25 million in annual sales, assuming that higher efficiency TEGs with a dimensionless figure of merit ZT ~2 could be built for $5/watt and assuming that 5% of the market buys TEGs per year.

The report suggests pursuing R&D work in thermal transfer technologies and engineering studies to interface TEG systems with existing process equipment, as well as studies of possible exhaust system modifications (e.g., duct length and residence times) that could lead to greater opportunities for integrating TEG systems in more industrial applications.

Analysis of waste heat sources and recovery is greatly affected by the waste heat temperature−therefore it is necessary to clearly identify the temperature regimes for waste heat related discussions. The BCS report identifies three temperature ranges to classify waste heat sources and opportunities; however, there is no general agreement on or basis for this definition of the temperature range. In this report, the temperature ranges have been expanded on both sides (high and low) of the spectrum. This expansion allows for the exploration and identification of R&D opportunities in the temperature ranges below 250°F (or <120°C) (ultra-low temperature) and higher than 1,600°F (or >870°C) (ultra-high temperature), in which it is difficult to identify cost-effective waste heat recovery methods or equipment. Hence, this report recognizes the following five temperature ranges:

- Ultra low temperature: below 250°F (or <120°C). The lower temperature for this range is usually the ambient temperature or the temperature of a cooling medium such as cooling tower water or other water used for cooling systems. The upper limit is based on several considerations, such as the condensation temperature of combustion products or flue gases (usually below 180°F or 82°C for natural gas combustion products); the applicability of low-temperature, non-oxidizing materials such as aluminum or non-metallic materials such as polymers or plastics; or the usage of low-temperature waste heat recovery systems such as heat pumps.

- Low temperature: 250°–450°F (or 120°–230°C), as defined in the BCS report.
- Medium temperature: 450°–1,200°F (or 230°–650°C), as defined in the BCS report.
- High temperature: >1,200°F (or >650°C), as defined in the BCS report. However, based on contacts with the industry and waste heat recovery equipment suppliers, it is suggested that this range be divided into two temperature ranges. The normal definition of the "high" temperature range, based on availability of equipment and material, is 1,200°–1,600°F (or 650°–870°C).
- Ultra high temperature: >1,600°F (or >870°C). Waste heat recovery from streams above 1,600°F (870°C) requires use of special high-temperature materials that can be metallic or nonmetallic, such as ceramics. Selection of material and equipment design becomes very critical in many cases, as such streams contain a large amount of contaminants.

<u>Other Reports</u>

The Lawrence Berkeley National Laboratory Industrial Energy Study group has prepared several reports that describe energy use and energy efficiency improvement opportunities such as the "Energy Efficiency Improvement and Cost Savings Opportunities for Petroleum Refineries: An ENERGY STAR Guide for Energy and Plant Managers." These reports were published for several industries, including steel, cement, and food processing, and include discussion of waste heat recovery and suggestions on using certain technologies to recover waste energy for industrial processes.

A July 2009 report prepared by McKinsey & Company, "Unlocking Energy Efficiency in the U.S. Economy," examines, in detail, the potential for greater efficiency in non-transportation energy uses and assesses the barriers to this goal. The report suggests formulating an overarching strategy that includes recognizing energy efficiency as an important energy resource, as well as formulating and launching approaches to foster innovation in the development and deployment of next-generation energy efficiency technologies. The report does not provide specific suggestions regarding R&D program areas.

In September 2009, an industry-government forum on Energy Intensive Processes was held at the ITP-sponsored "Energy Intensive Processes Workshop." The goal of the workshop was to collect feedback on ITP's Energy-Intensive Processes R&D portfolio and strategy, as well as obtain guidance on future efforts. The workshop included a session on waste heat minimization and recovery and discussion on reducing fuel demands of steam boilers and furnaces by utilizing waste heat recovery. Workshop participants were asked to evaluate platforms, R&D focus areas, and project selections, and to provide recommendations on future topic areas. Participants were interested in the following areas of waste heat minimization and recovery:

- Ultra-high efficiency steam generation, with one project including the "super boiler"
- High-efficiency process heating equipment, with priority R&D opportunities including the following:
    - Ultra-high efficiency combustion
    - Insulation and refractory systems
- Waste energy recovery, with top R&D opportunities including the following:
    - Low-temperature heat utilization

  - Advanced energy conversion (e.g., solid-state and mechanical)
  - Heat recovery from high-temperature contaminated flue gases
  - Deployment of novel, waste-heat-to-electricity in a series of industrial demonstrations
- Waste energy minimization, with top R&D opportunities including the following:
  - Develop high-efficiency compressors, motors, and variable speed drives
  - Implement heat transfer improvements, such as coatings, and other ways to resist corrosion
- Process intensification and integration, with top R&D opportunities including the following:
  - Integrate industrial control system components (e.g., valves, actuators, and sensors)
  - Replace batch operations with continuous ones
  - Develop predictive modeling and simulation for combustion

Findings from Previous Reports

Analysis of previous studies along with direct contact with industry and equipment suppliers have shown that a large amount of waste heat is not recovered in two temperature ranges: ultra-low (<250°F or 120°C) and ultra-high (>1,600°F or 870°C). The lack of wide-scale heat recovery in these two temperature ranges appears to be primarily due to issues associated with technology, materials, and economics, such as the lack of economically justifiable measures and equipment to recover the low-grade heat, as well as heat contained in very high temperature and contaminated waste heat streams.

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Waste Heat in Major Industry Sectors

This study analyzes the following industrial sectors for sources and availability of waste heat, possible applications of the waste heat inside and outside the plant, experience in waste heat recovery activities, and barriers to waste heat recovery:

- Aluminum – Primary Production
- Aluminum – Recycling and Secondary Melting
- Steel – Integrated Steel Mill
- Steel – Mini Mill or EAF Mill
- Glass – Fiberglass Manufacturing
- Chemicals and Petroleum Refining – Major Operations
- Paper – Paper Mill
- Food – Food (Snack) Manufacturing
- Cement – Dry Process and Shaft Furnaces
- Coatings – Vinyl Coating Mill

The following factors were taken into consideration within each sector:

- The plant's processes, operations, sources of waste heat, and current use or discharge of waste heat streams
- The energy used for utilities and other areas where waste heat or its converted form of energy (i.e., electricity) can be used
- Activities in waste heat management (reduction, recycling, and recovery)
- Requirements and economic criteria needed to justify and subsequently implement waste heat management projects

Issues that affect activities in waste heat management at the plant and within each industrial sector. The following is an overview of representative waste heat sources, characteristics, and recovery efforts, as well as possible waste heat uses within a typical plant for each sector. This provides a summary of the issues related to waste heat in each industry.

Aluminum – Primary Production

Refining

Calciners

A large percentage of the total energy required to produce aluminum is used during the calcination process. Waste heat exhaust from calciners is a target for heat recovery. The exhaust contains considerable moisture (about 50% water by volume) and contaminants such as alumina particulates at a relatively low temperature (365°–392°F or 185°–200°C). The challenge of recovering heat from exhaust gases and hot alumina is that the low temperature and presence of particulates result in severe fouling of any type of heat exchanger. The industry is considering several technologies to recover latent heat of the water vapor and is working with several organizations to investigate other options.

Heat from hot alumina discharged at a very high temperature is another source of heat recovery. Despite the higher temperature, the presence of particulates still presents a challenge. Attempts are being made to recover heat from hot alumina to produce hot water that can be used as a heat source for the Kalina cycle or in other processes within the plant. However, there is a limit on how much hot water can be used for the plant processes. Excess heat may also be used in the Kalina cycle to produce electricity. Large plant owners can consider building a cogeneration facility.

There is also an opportunity to recover heat from coke calciner afterburner waste gas streams at 1,900°–2,000°F (1,040°–1,090°C) to produce steam or electricity, but this is a business case and economic decision rather than an R&D need.

Smelting

Electrolysis – Pots

There is good potential for heat recovery in this area. The sidewalls and endwalls represent a 15%–20% heat loss while the off gases represent about a 15% energy loss. There is a band around the circumference of the pot about 500 mm high where the heat flux is 10–15 kW/m^2 and temperatures range from 570°–1,020°F (or 300°–550°C) (with a normal temperature around 842°F or 450°C). Higher temperatures are achieved when production is pushed. It would be possible to attach a thermoelectric device on the wall, which is covered with a steel shell. Accessibility depends on the age of the pots and geometry. Some smelters are more accessible than others—for example, Warwick smelting pots are difficult to access. Some trials on heat recovery have been done in other countries; results are proprietary.

The pots operate with a crust or "ledge" a few centimeters thick. A heat sink is needed to maintain the crust; however, too much cooling can result in a ledge that is too thick, reducing the pot's capacity. Alcoa wants to recover heat while keeping a thermal balance in the pot. There may be some additional benefits from heat recovery if hot air generated by natural convection around the pots is able to be captured and removed, such as a more stable operation and improved work environment.

Thermoelectric (TE) devices are considered an emerging technology. With ZTs[1] hopefully approaching 1.5, there may be more opportunities for TE device application. It is assumed that the technology will continue to improve. There may be an opportunity for applied R&D that focuses on managing the heat sink; scaling and transforming modules to workable devices; process integration and infrastructure development; power management and quality of power; handling thermal expansion, attach panels, and durability; and overall control of the system, as well as cold side heat recovery considerations.

Off gases from the pot are 212°F (or 100°C) after the scrubbers and only 212°–266°F (or 100°–130°C) before the scrubbers. Alcoa is interested in capturing waste heat before the scrubbers because there are issues with build-up and particulate fouling. Make-up air is used to prevent fugitive emissions and the duct system needs to be open for periodic maintenance. Cleaning the gases remains a challenge. The fouling problem is covered in available literature. An Installation in Europe utilizes a heat exchanger on exhaust gas stream to recover heat from the aluminum smelting cells or reactors, commonly known as pots. A heat exchanger (gas to water) upstream of the scrubber is used to get hot water to supply heat to a district heating system at a location in Iceland. As of July 2010 the system has been operating for a few months [Martin Fleer 2010].

The industry is monitoring improvements to the organic Rankine cycle using a portfolio approach in which there is initial tolerance for long payback periods of up to 5 years, with efforts to identify improvements

[1] ZT is an indicator of thermodynamic efficiency of the TE device and is a convenient figure for comparing the potential efficiency of devices using different materials. Values of ZT equaling one are considered good, and values of at least three to four are considered essential for thermoelectric to compete with mechanical generation and refrigeration in efficiency.

that will reduce payback periods to 2–3 years. Besides the value of heat, other values are considered, such as process benefits and avoidance of investments in downstream equipment.

Anode Baking

Anode baking processes generate hot exhaust gases from fuel combustion. These gases represent substantial heat loss. The exhaust gases contain a fair amount of volatiles and tar vapors. Dealing with fouling from tars is also an issue. Exhaust temperatures are 390°–750°F (or 200°–400°C) and contain large amounts of excess air. “Pitch Burn technology” is getting cleaner and could provide further opportunities.

Researchers should revisit work that was done in the 1970s and 1980s. The Norwegian Research Council and Norwegian Technology University are working on fundamental areas of research. There may be an opportunity to work with the European institutes to develop applied technology to reduce and recover waste heat.

Melting

On the primary cast side, holding furnaces use a cold charge to cool down the superheated metal or increase production. The furnaces operate in semi-continuous or batch mode and result in variable exhaust gas flows and temperatures. Most furnaces are gas fired; however, there are a few plants with electric furnaces. Exhaust gases may have some hydrogen fluoride—usually less than 1 ppm—but in some cases it could be 5–10 ppm. This limits the use of conventional heat exchangers to recover heat. Wall losses and opening losses could be a good percentage of the total heat input; however, these losses are reduced by using best practices in furnace design and operations. Heat loss from these furnaces can be considered a low-impact, high-complexity category.

On the secondary side, melting furnaces discharge a large amount of heat as exhaust gases. They are at a high temperature—usually greater than 1,600°F (870°C) —and can contain particulates, organic vapors, and flux material vapors and can be classified in the same category as flue gases from gas melting furnaces. Separating these contaminants at higher temperatures can be considered a cross-industry need. Another possibility that should be considered is treating the gases with absorbents to neutralize the “bad actors.” This will eliminate the need to cool the gases and creates cleaner gases that can be used for heat recovery in currently available heat recovery systems. The possibility of pre-cleaning or pre-treating the hot flue gases to remove the contaminants should be considered an R&D need.

Use of submerged combustion devices to promote better heat transfer has been considered and tried. Direct immersion heaters are of interest; however, the challenge is in selecting materials that can survive the highly corrosive nature of molten aluminum with acceptable lifetimes and minimum risk of failure. This is a materials issue. Induction heating is a possibility; however, the limitations are in its efficiency and size, as it is difficult to get units in the energy supply size range required for aluminum melters.

Other Operations

Other operations under the “semi-fabrication” category use a relatively small percentage of the total energy used in aluminum plants. In most cases the waste heat is discharged in the form of clean exhaust gases, which can be recovered using conventional heat recovery systems such as recuperators, regenerators, or regenerative burners. This can be considered an established best practice.

Aluminum – Recycling and Secondary Melting

The following is a list of the types of waste heat sources typically found in secondary aluminum melting:

- Waste heat in clean exhaust gases from reverb furnaces, gas generators, and crucible heaters: These gases range from 1,450°F (790°C) in the crucible heaters to 2,000°F (1,090°C) in reverb furnaces, contain combustion products of natural gas, and do not contain any major contaminants. They are prime candidates for heat recovery for preheating combustion air. These gases contain as much as 60% of the total heat input for the heating systems. Possible options for heat recovery include combustion air preheating using recuperator or regenerative type units, or low-temperature power generating cycles such as an organic Rankine-cycle based system. There is very little use for hot water, hot air, or a cooling system, which could be used for heat recovery.
- Waste heat from rotary furnaces: These gases are relatively cold and contain a large amount of contaminants. The mass flow rate is cyclic and often unpredictable. There is no industry accepted method of recovering sensible heat from these gases. Development of a low-pressure drop filter or higher temperature fabric material for baghouses can help clean up the gases so they can be used for heat recovery.
- Waste heat from delacquering systems: These systems remove volatile materials from the UBCs and preheat them to about 900°F (480°C) before they are discharged from a rotary kiln. The preheated but partially cooled UBCs are charged in the reverb furnace. Delacquering systems use a gas generator that incinerates volatiles from the paint coating on UBCs. The exhaust gases from the unit are relatively clean and are discharged at about 650°F (340°C). There is no heat recovery from these gases.
- Waste heat from crucible heaters: These are relatively small units used to preheat crucibles before pouring hot aluminum metal from rotary furnaces or reverb furnaces. The burners are relatively small and fired in an uncontrolled fashion. The gases are discharged at about 1,450°F (790°C) and the heat is not recovered.

Steel – Integrated Steel Mill

This section discusses the following three areas of waste heat in an integrated steel plant and addresses primary and secondary sectors of the steel industry:

- Blast furnaces and the iron-making process, including power generation at the site
- Coke ovens and coke oven gas processing equipment
- Reheating and heat treating furnaces at a rolling and finishing area

Blast Furnace, Iron Making, and Power Generation

This area includes iron making in blast furnaces, power plants that include gas-fired boilers and steam turbine generators, and steel making using a Basic Oxygen Process (BOP) system. This section details areas in which waste heat is available and comments on its characteristics and use.

Blast Furnaces (BF)

A blast furnace uses a hot air blast with oxygen enrichment to increase production. In some plants, natural gas injection and coal injection have been used. The preheated blast air is used at 1,950°–2,050°F (or 1,066°–1,122°C) and includes 5%–10% added oxygen. The waste heat discharged from the blast furnace is in the form of sensible and chemical heat from the blast furnace gas (BFG), which is used as fuel at several locations within the plant. The BFG, as it is discharged from the top of the blast furnace, contains several contaminants including particulates, sulfur, and other compounds, and must be cleaned using a scrubber and then dehumidified.

Following are the waste heat sources from blast furnaces:

- Hot BFG with a considerable amount of sensible heat: The gas contains particulates and condensable materials that need to be addressed if any type of sensible heat recovery is to be achieved.
- Moisture removal from the BFG itself with a heating value of approximately 90 Btu/cu ft: At this low heating value moisture content becomes an important consideration, as it will suppress "flame" temperature when used as a fuel. An innovative method of reducing or eliminating water vapor will improve the combustion characteristics of the gas.
- Recovery of heat from flared BFG when not in use: Recovery or conversion of this heat in a usable form such as independent electricity production, if economically justifiable, would save energy.

Blast Furnace Stoves
BF stoves are direct-fired regenerators used to preheat the blast air used in the BF. These stoves use BFG and coke oven gas (COG) with an injection of natural gas to achieve the required temperature in the stoves, and hence for the air.

Following are the areas of waste heat, heat recovery, and performance improvement in BF stoves:

- Dehumidifying or drying BFG prior to its use in the stoves.
- Recovering heat from the stove's exhaust gases at approximately 600°F (316°C); as these gases are relatively clean and free of particulates or other contaminants.
- Adding O_2 in combustion air used for combustion of the blast furnace gas in the stoves to increase flame temperature and increase heat transfer as well as to reduce stove exhaust gas volume. This is an option for a possible replacement for natural gas mixing with the blast furnace gas to enhance its heating value. In either one of these cases the net result is improved heat transfer and delivery of hotter temperature for the blast air used in the blast furnace. The economics depend on the relative cost of natural gas versus oxygen. In most cases, availability of on-site O_2 may favor use of O_2.

Power Plant (Boilers – Steam System)
Boilers in an integrated steel plant normally use BFG and COG as fuel. The exhaust gas temperature for the boilers varies with the boiler's age and the controls used. Temperatures could be fairly high (650°–840°F or 340°–450°C) to average (700°F or 370°C), with O_2 content varying from 3%–7.5%. The waste heat is in the form of clean, contamination-free gases and does not require further conditioning.

The areas of waste heat and recovery from boilers and steam systems include the following:

- Using exhaust gases to preheat BFG and COG
- Using low-temperature power generation if economically justifiable

- Preheating service water or river water for use in the plant, if possible and required (may be useful during the colder months)
- Venting low-pressure (5 psig) steam, which may be condensed and reused for the boiler water system

Steel Making – Basic Oxygen Process Area

In this area, the main source of waste heat is exhaust gases from the basic oxygen process (BOP) vessel. Mass flow of the gases and the amount of heat leaving the system is variable. The gases are at very high temperatures (>2,000°F or 1,090°C) and contain all types of contaminants, including particulates. The flow is periodic, with large peaks during a short time period of the total cycle time. Most BOPs have a non-steaming hood to collect exhaust gases. The hoods are non-water cooled and the gases are cooled before being taken to a scrubber.

Possible waste heat recovery opportunities include the following:

- Recovery of heat for production of steam with the use of large accumulators
- Capture of CO_2 for use in the water system

Caster area

The de-gasser in this area uses 250 psig steam that is de-superheated before its use. Areas of waste heat include the following:

- Heat from the de-superheating process
- Heat from the de-superheater degasser steam that is discharged at the end of the de-superheater and unable to be returned because it produces contaminated steam and condensate

Coke Plant

Coke facilities can include several coke oven batteries. A large facility includes extensive process equipment for recovering by-products from the coke-making process. The plants use large boilers that produce steam at 600 psig or higher. The boilers are fired by using COG with natural gas as supplementary fuel. The steam is used to produce power for process uses. A small amount (approximately 10%) of the steam is returned. In many cases, an incinerator is used for final “cleaning” of gases from the plant.

The following sources of waste heat were identified for the plant:

- Hot coke discharged from batteries: The hot coke contains approximately 1 MMBtu/ton heat that is lost due to quick quenching of coke. This is the single largest source of waste heat. Some companies are considering the use of a dry quench system to recover the heat and produce power. The system is commercially proven technology and has been used by several facilities.
- Hot coke oven gas, which is discharged from the batteries at about 1,500°F (815°C): This gas contains many different constituents, including particulates, condensable liquids, and sulfur compounds. The gas is quenched to 180°F (82°C) and then cooled to 85°F (30°C). The hot gases contain 0.3–0.4 MMBtu/ton of coke. This heat is wasted as hot water from the COG cooling system.
- Exhaust gases from the coke oven batteries: The batteries include regenerative heat recovery for the hot gases; hence the exhaust gases are at 400°–600°F (200°-320°C). They contain some

particulates, which can be considered relatively clean, and are discharged into the atmosphere from stacks. There is no simple method of recovering heat from these gases. It is likely that the heat can be used for power generation using low-temperature power generation systems; however, at this stage the economics do not look favorable due to the long payback time.

- Clean boiler flue gases at low temperatures: These may be used for heating water in direct or indirect heat exchangers. Carbonic acid condensation could be a concern unless the water is used as "once-through water" or a slight increase in acidity does not affect the system. The economics of this may be marginal.
- Energy used in the incinerator is relatively low: It is possible to use a recuperator or regenerator for heat recovery; however, the payback time could be long.

Rolling Mill and Finishing Area

Rolling and finishing typically include reheat furnaces, annealing furnaces, and continuous annealing lines. The furnaces use natural gas, COG, and BFG as mixed fuel. The slabs' drop-out temperature is 2,150°F (1,180°C), and the furnaces include a recuperator to preheat combustion air. For older installations (pre-1980s), air temperature can be very low (less than 700°F or 370°C), while the exhaust gas temperature varies from 1,000°–1,250°F (540°-680°C), with a large percentage of O_2 (sometime higher than 8%).

Areas of waste heat include the following:

- Exhaust gas from furnaces: The gases are relatively clean (free of particulates or condensable vapors); however, in some cases, they contain large amounts of excess air. Reducing O_2 and recovering heat using better recuperators will be of great benefit.
- Radiation heat from furnace openings: Radiation heat usually comes from the charge and discharge end as well as from other areas, including the roof and parts of the furnace shell or walls.
- Heat from rolled steel shapes: The industry normally does not recover heat from rolled shapes, thus it may be beneficial to consider heat recovery.

Steel – Mini Mill or EAF Mill

The following are types of waste heat sources typically present at almost all EAF steel-making plants:

- Waste heat in clean exhaust gases from reheat furnaces, tundish heaters, and ladle heaters: These gases are in the range of 1,000°F (540°C) from the heat furnace respirators to 1,800°F (980°C) from ladle and tundish heaters. These gases contain combustion elements of natural gas and do not contain any major contaminants. They are prime candidates for additional heat recovery as they contain as much as 35% of the total heat input for the heating systems.
    - Possible options for heat recovery include higher efficiency heat recovery system charge or load preheating, either recuperator or regenerative; load or charge preheating; steam and power generation; and the use of low-temperature power generation cycles, such as an organic Rankine cycle based system. There is very little need for heat recovery for hot water, hot air, or cooling systems.

- Waste heat from gases discharged from EAF: These gases are hot and contain large amounts of contaminants, and the mass flow rate is cyclic and often unpredictable. Currently, there is no industry-accepted method of recovering chemical and sensible heat from these gases.
- Waste heat from hot surfaces or reduction of heat from the walls of ladle and tundish heaters.

Glass – Fiberglass Manufacturing

The following discusses waste heat discharged from the major energy use systems in the fiberglass industry; however, most energy-use systems are very similar in other glass plants, particularly as they relate to waste-heat discharge and their characteristics:

- Glass melters: The melters can use natural-gas-fired burners with preheated air or oxy-fuel burners or electricity as a source of heat used in glass melting. The fuel-fired systems may use electric boost to supplement heat supplied from gas-fired burners. The melters include channels that are gas-fired and discharge large amounts of hot gases vented directly into the building. Energy consumption of the melters varies depending on the type of heating system used.
    - Sources of waste heat include exhaust gases from the furnace and channels. These gases are at very high temperatures (in excess of 2,500°F or 1,370°C) and contain a large amount of contaminants, such as inorganic particles and vapors of elements that condense in a certain temperature range. The nature of the elements depends on the type of glass and operating practices. These gases are quenched by blending a large amount of air. For some glass plants, a recuperator or regenerative system is used. The gases from the system can be from 450°–900°F (230°-480°C). The gases discharged from the baghouses used for collecting the particulates can be as high as 450°F (230°C).
- Fiberizing process: The fiberizing process uses a large quantity of natural gas for maintaining the required temperature conditions. The heating system can be very complex and has to be "tuned" to give the desired quality specifications for the fibers. The plants are continually looking at methods to reduce energy use in the system. The waste heat is in the form of hot gases; however, due to blending with lots of air or steam, the temperature is low (sometimes less than 500°F or 260°C) and collection of the gases is very difficult.
- Curing ovens: The curing ovens use natural-gas-fired burners with recirculation fans. The oven's operating temperature varies with the type of process and product going through, ranging from 450°–550°F (230°-290°C). It is likely that the exhaust gas volume is much higher than the volume of combustion products from the burners due to large air leaks into the ovens. The exhaust gases are usually incinerated to remove the organic contents of the exhaust gases. In many cases, the incinerators use regenerative heat recovery systems, and the exhaust gases are discharged at or below 375°F (190°C). The waste heat source is low-temperature clean gases.
- Space heating: Space heating is a major area of energy use for plants in cold weather areas. In such areas, space heating of a building can require 25% or higher of the total plant energy use during the colder months. This heat is supplied by placing gas-fired unit heaters at several locations within the plant, particularly in the finishing, packaging, and shipping areas where there is no heat available from the furnaces and the curing oven.

Chemicals and Petroleum Refining – Major Operations

Chemical industry companies manufacture a wide variety of products from a number of different raw materials, mostly hydrocarbons, and use a large amount of fuel to supply heat to process heating systems. Due to this variability, it is difficult to discuss waste heat recovery on a plant-by-plant, equipment, or process basis. However, a discussion of broad categories of waste heat sources and issues related to waste heat recovery in a "typical" petrochemical industry plant is possible. The following areas of waste heat are representative of major petrochemical operations:

- Exhaust gases from boilers, fired heating systems (i.e., crackers), and power generation (combustion turbine plus HRSG) equipment: In most cases, when natural gas is used as fuel, the gases are clean and the plants use currently available technologies for heat recovery. The waste heat discharged ranges from 200°–350°F (95°-180°C). The waste gas stream temperature could be higher for equipment using by-product fuels.
- Exhaust gases from thermal oxidizers (TO): TOs are often used for process heating equipment. The temperatures of exhaust gases from TOs range from 1,400°–1,800°F (760°-980°C) and may include chlorinated gases, or gases with other non-organic contaminants that are highly corrosive. Use of heat recovery equipment can be challenging. Higher temperatures and the presence of corrosive gases do not allow use of economically justifiable heat exchangers and, in many cases, it is necessary to quench the gases, resulting in loss of heat to scrubbing liquids. This presents additional problems with the need for additional water and, in some cases, cooling capacity. In generic terms, the issue is heat recovery from high-temperature gases containing corrosive components.
- Use of hydrogen from chlorine process: A by-product of hydrogen, RCL, can be a very good source of fuel; however, its use presents problems. Many plants face problems in recovering or using this by-product since RCL turns into HCL, which limits burning of this valuable by-product in power plants. Proper treatment to remove chlorinated components would increase use of this valuable fuel in power plants.
- Use of heat from exothermic processes in reactors: It may be possible to produce steam at high pressures (600–1,500 psig) for power generation. Quenching of some products produces hot water from which heat can be recovered. No simple method of recovering this heat is available at this time.
- Logistics of collecting stack gases and using them to heat liquids or gases: In most plants, there are multiple stacks and a collection of gases that present major hurdles. In addition to this use of heat exchangers, it is difficult to retrofit such units due to limits on available space. Compacting footprints will definitely encourage increased use of stack-gas heat recovery. Use of micro-channel heat exchangers has been considered; however, their availability and history of use in industrial installations is almost non-existent.
- Heat from gases containing water vapors discharged from evaporators and other units: These gases contain a large percentage of their heat in vapors and need cooling below condensation temperature to recover latent heat. In many cases, available water temperature, size of the units, and quality of vapors (contaminations) limit use of convention heat exchangers. Development of condensing heat exchangers in smaller footprint sizes would be useful in recovering a large percentage of heat wasted in these types of streams. These heat exchangers would result in water conservation. Some companies have considered use of permeable membranes and other similar vapor heat recovery systems without much success.
- Heat from hydrocarbon processing units: In the hydrocarbon processing units, heat is wasted in massive volumes of low-pressure steam. Recovering heat from this source is a challenge for the plant. In many cases, this is limited by availability and cost of pumping cooling water as well as

limited uses for the resulting hot water. Technologies that allow the use of heat from the steam source directly or from water would allow a large amount of heat recovery.

- Energy used for pumping water used in cooling streams: Development of air-cooled units would save a large amount of energy used for pumping water. This will also reduce water use. Water is a very valuable resource that is hard to obtain in some of the plants. It is expected that water shortages and increased costs could be major economic issues for many plants in the future.
- Flared gases: Development of reliable disposal of excess gases that are flared could result in energy savings. The periodic and unpredictable nature of this waste heat source is a major challenge.

Paper – Paper Mill

The following provides an overview of waste heat sources, their characteristics, and issues for a typical paper mill using the Sulfite process to produce paper. Although Kraft process is more commonly used in typical paper mills, we are discussing the Sulfite process in this section mainly because we visited the paper mill that used sulfite process and the report mostly deals with the plants we visited. We did not attempt to cover all processes/mills:

- Waste heat in the form of hot water from various processes: This water, which includes water discharged from a water treatment plant, contains several contaminants and impurities. The heat recovery from this water does not present any major technology challenges. Current technology for chemical treatment, filtration, and heat exchangers can meet the plant's heat recovery requirements.
- Exhaust air from paper machine dryers: This stream is at a relatively low temperature (140°–180°F or 60°-82°C), contains a large amount of water vapor, and may contain small, but variable and unpredictable, amounts of fibers and other contaminants that are hard to remove. Moisture with solid contaminants presents serious concerns for performance reliability due to the potential buildup of solids on heat transfer surfaces and the plugging of gas passages. Hence, this presents an opportunity for developing systems that may contain existing components or a novel system for heat recovery.
- Need for technologies for dehumidifying hot air that includes a very small amount of solids from the plant sources: The temperature range (140°–180°F or 60°-82°C) is too high for use in conventional dehumidifying systems such as desiccant systems. Membrane-type latent heat recovery systems, such as those offered by the Gas Technology Institute (GTI), that can be used for temperatures in this range could have operational and maintenance problems due to the presence of contaminants in the form of solids in the air carrying water vapor.

Food (Snack) Manufacturing

The following is an overview of typical waste heat sources and their characteristics for food processing, in particular for snack manufacturing and similar operations:

- Waste heat in the form of clean exhaust gases such as boiler flue gases, gases from product dryers, and toast ovens: These gases range from 300°–600°F (150°-316°C) and may contain varying amounts of moisture. Heat recovery from these gases for conventional uses such as combustion air preheating or make-up air heating is possible; however, several issues such as the economics of combustion air preheating (e.g., the cost of recuperator-regenerator and hot air piping), the type of burners used (premix burners), and the distances and long piping, could be challenging. It is possible that a plant may consider using direct contact heat exchangers (condensing units) for heating water for process use or wash water if sufficiently large holding capacity is available. As far as the technology of heat recovery from such gases is concerned, it could be considered mature technology with several vendors offering heat exchangers. The primary issues include the economics, logistics, and scheduling of the use of recovered waste heat in the plant. R&D in this area should be considered a low priority.

- Waste heat in the form of exhaust gases with high moisture content and oil vapors, such as exhaust gases from fryers: These gases are at 350°F (180°C) and require "pretreatment" to remove oil vapors before heat recovery. There is no simple method of recovering this heat due to its lower temperature and the presence of condensable oil vapors—even after using filters or demisters that remove large amounts of, but not all, oil vapors from the gases. Cooling of these gases during a heat recovery process, such as in low-temperature power generation systems (if economically justifiable), could result in condensation of the residual oil vapors, resulting in heat transfer issues in conventional heat exchanger equipment used for such systems.
- Waste heat in heated water used as wash water: This heat is at a very low temperature (usually less than 100°F or 37°C) and can be used for preheating make-up water during colder months. Applicability of this option depends on the geographic location of the plant and can be an attractive option for plants located in colder weather areas, such as the northern United States.
- Low-temperature waste heat: Many progressive plants are considering several options for low-temperature heat recovery systems such as organic Rankine cycle systems (i.e., UTC, Ormat). However, there are limiting issues such as the low temperature of the heat source (as previously discussed), the requirement of low-temperature heat sink in the form of water used for the condenser section of these systems, and low energy conversion (heat to electric power) efficiency levels that severely limit economic justification for use of such systems. At least one company is considering use of CO_2-based power conversion devices that allow use of lower temperature (<200°F or 94°C) heat sources.

Cement – Dry Process and Shaft Furnaces

Typical sources of waste heat for both old and small-sized shaft furnace types of units and plants that use the dry process are as follows:

- Clinker cooling air from cooling bed: The air temperature varies from 350°–900°F (180°-480°C). Waste heat recovery technologies used are preheating air from coal- and fuel-fired boilers to raise steam for power generation and for other auxiliary heating. No special R&D is required for heat recovery.
- Exhaust gases from the system, usually from the preheaters: These gases contain a high percentage of CO_2 generated from the calcining reaction and products of combustion from fuels used in the kiln and precalciner. The gas temperature can vary from 300°–500°F (150°-260°C). In most cases, the exhaust gases are mixed with clinker cooling air and the heat is recovered in boilers or other heat recovery units.
- Hot shell or surfaces of kilns and precalciner: The surface temperature can vary from 500°–800°F (260°-430°C). There is no practical way to recover this heat yet. The best solution is to redesign the insulation-refractory system to reduce the kiln shell temperature.

Coatings – Vinyl Coating Mill

The following are representative of typical waste heat sources for medium-sized coating plants producing flooring and other products:

- Ovens: Ovens are used to heat vinyl or other material coated with different substances and to cure the material. The ovens have several (typically 10–14) zones, each with its own burners, recirculating fans, and discharge ducts. The ducts from several zones are combined into a single common duct that is connected to one or more regenerative thermal oxidizers. During the heating process, volatile organic compounds (VOCs) are generated that get mixed with make-up air or air leaking into the ovens. The material is heated to 300°–400°F (150°-200°C) and then cooled before it is discharged. It is necessary to maintain a minimum amount of air flow into the oven to meet safety regulations. The regulations require use of enough air to maintain a minimum of 25% LEL value for the VOCs inside the oven. The ovens use infrared (IR) zones as supplemental heat supply. The waste heat is in the form of chemical heat of VOCs and sensible heat of air. These gases are required to be incinerated to remove air pollutants; hence, they are not considered a direct waste heat source.
- Dryers: The production process requires printing of the product using non-solvent-based ink. Two dryers are used to dry ink. The dryers, which are on the roof of the plant, use recirculating air flow that is heated by air heaters also located on the roof. The air heaters use ratio-type burners and recirculating fans. A certain amount of exhaust air is discharged from a single duct. The air flow is required to maintain proper humidity that allows an efficient drying process for the air being recirculated. The exhaust air at 300°F (150°C) and higher contains clean heat that represents a large percentage (in excess of 50%) of the total heat input to the dryer.
- Regenerative thermal oxidizers (RTOs): These plants use RTOs to destroy VOCs generated in the ovens. There could be one or more RTOs for each oven. The RTOs are designed to recover heat from the incineration or combustion chamber section of the system to preheat incoming exhaust air from the ovens. The RTOs discharge clean exhaust air at about 350°–400°F (180°-200°C). They seem to be very efficient in recovering heat from the exhaust gases. It is necessary to operate the RTOs at a temperature higher than 1,500°F (816°C) to meet the local air emission regulations. These units are tested regularly to assure their regulatory compliance. Waste heat from these units is discharged at about 350°–400°F (180°-200°C) and can be recovered to supply heat in the ovens or to provide hot water or make-up air for the plant.
- Steam boilers: The boilers are used to supply steam to the processes and for plant space heating during the colder winter months where it is required. Typically, the boilers discharge flue gases at about 500°F (260°C) and they do not have any type of heat recovery for the exhaust gases. The boiler drum blow-down is continuous and manually controlled. No heat recovery system exists for the blow-down water. The amount of boiler blow-down water is unknown. The steam is distributed over fairly long distances through a network of steam piping and condensate returns to the boiler house. Waste heat sources are exhaust gases at 500°F (260°C) and boiler blow-down water at the operating pressure (150 psig and higher). The waste heat can be recovered using commercially available heat recovery systems.
- Oil heater: Some of the ovens use a hot oil recirculation system to supply hot air to the ovens. The oil heater uses natural-gas-fired burners to produce hot gases that are used to heat recirculating oil. This unit discharges exhaust gases at relatively low temperatures (350°F (180°C) or lower). The waste heat in exhaust gases can be recovered by using commercially available equipment.

- Space heating: Space heating can be a major area of energy use for the plant during the colder months. Space heating is done mostly by using steam produced in the boilers mentioned above. The heat demand depends on the time of year as well as the time of the day. During the colder months—November through March—space heating can consume as much as 50% of the total natural gas used by the plant. There is no waste heat associated with this heating system.

Typical Waste Heat Streams in Plant Operations

Several studies have documented waste heat from other industries. Information from these references was used to prepare a summary of waste heat types and their characteristics.

The waste streams from almost all industries are primarily in the form of exhaust (flue) gases or vapor, cooling water or other liquid, heated products (solids and liquids) or by-product waste, and high-temperature surfaces of the heating equipment including utility (i.e., primarily steam, hot water, hot gases) distribution system. The waste streams vary in temperature, composition, and content, which may include particulates, vapors, or condensable materials. Following are the types of waste heat streams:

Exhaust Gases or Vapors

The exhaust gases or vapors can be classified in the following categories:

- High-temperature combustion products or hot flue gases that are relatively clean and can be recovered using commercially viable heat recovery equipment to produce high-temperature air, steam, or water for use in processing equipment or other uses such as direct discharge for building heating. Examples include a large number of directly fired and indirectly fired heating processes that are widely used by all major industries.
- High-temperature flue gases or combustion products with contaminants such as particulates and condensable vapors. In many cases, these contaminants would present problems due to condensation of vapors in liquids or solids, which can foul the surfaces of the heat transfer equipment. Examples include exhaust gases from melting furnaces, dryers, kilns, and coal-fired boilers.
- Heated air or flue gases containing high (>14%) O_2 without a large amount of moisture and particulates. This stream does not have as many restrictions on condensation temperature as the combustion precuts due to the absence of acid-forming gases (e.g., CO_2) and can be cooled to a lower temperature without having the major detrimental effect of corrosion. Examples include indirectly used cooling air from processes, gas turbine exhaust gases, some product cooling systems, and air coolers used in refrigeration or chiller systems.
- Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form requiring further treatment before their release into the atmosphere. Examples are exhaust from coating ovens and process reactors.
- Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amounts of particulates but no condensable organic vapors. Examples include exhaust air from paper machines, ceramic dryers, and food dryers.
- Steam discharged as vented steam or steam leaks.
- Other gaseous streams.

Heated Water or Liquid

Heated water or liquid can be classified in the following categories:

- Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants.

- Hot water that contains large amounts of contaminants, such as solids from the process or other sources, but does not contain organic liquids or vapors. The solids can be filtered out without further treatment of water. Examples include quenching or cooling water used to cool hot parts in the metals industry, paper industry, or cement industry.
- Hot water or liquids containing dissolved solids, dissolved gases (e.g., CO_2, SO_2), or liquids. These liquids (water) require further treatment before their use or discharge in the streams. Examples include scrubber water; wash water from chemical processes or from the food, paper, or textile industries.

Heated Products or By-Products

Heated products or by-products can be classified in the following categories:

- Hot solids that are cooled after processing in an uncontrolled manner. Examples are hot slabs, mineral products, paper or textile web, and food cereals. These products are usually cooled by natural or forced cooling using air, but the heat is not recovered. Hot solids that are cooled after processing using water or an air-water mixture. Examples include hot coke, ash, slag, and heat-treated parts.
- Hot liquids and vapors that are cooled after thermal processing. Examples include fluids heated in petroleum refining, chemical, food, mining, and paper industries.
- By-products or wastes that are discharged from thermal processes. These materials contain sensible, latent, and chemical heat that is not recovered prior to its disposal. Examples include ash from coal- or solid-waste-fired boilers, slag from steel melting operations, dross from aluminum melters, and bottom waste from reactors or sludge.

High-Temperature Surfaces

High-temperature surfaces can be classified in the following categories:

- Furnace or heater walls where a large amount of heat is lost due to convection and radiation.
- Extended surfaces or parts used in furnaces or heaters.

Exhibit 6 lists the different types of waste streams, the industries in which they are generated, and the temperature regimes for their waste stream, which is coded by color. This table does not give additional details on composition or other characteristics of the waste stream. These are discussed in separate tables for each of the industries examined in this study.

Exhibit 6: Waste Streams, Industries of Origin, and Characteristic Temperatures Coded by Color

Waste Heat Source	Steel	Aluminum	Glass	Paper	Pet. Refining	Mining	Chemical	Food	Cement	Coating	Steam generation
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%) O_2 without large amount of moisture and particulates.											
d) Process gases or by-product gases and vapors that contain combustibles.											
e) Process or make-up air mixed with combustion products, large amounts 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 or 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 and 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.											

Temperature Color Code Key

Ultra High temperature (>1,600°F)

High temperature – between 1,200°F and 1,600°F

Medium temperature – between 450°F and 1,200°F

Low temperature – between 250°F and 450°F

Ultra low temperature – below 250°F

Barriers to Waste Heat Recovery

The following section summarizes the barriers to waste heat recovery in the major industries analyzed in this report. These barriers are presented by type of waste heat stream and by industry.

Barriers by Type of Waste Heat Stream

The following is a summary of waste heat by type and associated barriers:

- High-temperature combustion products or hot flue gases that are relatively clean.
  - Reduced thermodynamic potential for the most efficient heat recovery due to materials limitations (particularly metallic) that require gases to be diluted.
  - Heat transfer limits on the flue gas side in steam generation or other power generation (i.e., organic Rankine cycle) heat exchanger systems applications.
  - Seal issues for heat exchanger designs with metallic and nonmetallic (ceramics) components (due to dissimilar thermal expansions).

- High-temperature flue gases or combustion products with contaminants such as particulates or condensable vapors.
  - Availability or cost of materials that are designed to resist the corrosive effects of contaminants.
  - Lack of design innovation that will allow self-cleaning of the heat recovery equipment to reduce maintenance.
  - Lack of cleaning systems (similar to soot blowing) that allow easy and on-line removal of deposits of materials on heat transfer surfaces.
  - Heat transfer limitations on the gas side of heat exchange equipment.

- Heated air or flue gases containing high (>14%) O_2 without large amounts of moisture and particulates.
  - Limitations on the heat exchanger size that prevent use on retrofit, which may be due to heat transfer limitations or design issues such as size and shape of heat transfer surfaces (e.g., tubes or flat plates).
  - Lack of availability of combustion systems for small (less than 1 MM Btu/hr) to use low O_2 exhaust gases as combustion air for fired systems.

- Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form.
  - Lack of available, economically justifiable vapor concentrators for recovery and reuse of the organic-combustible components, which would avoid the need for heating a large amount of dilution air and the resultant large equipment size. The concentrated fluids can be used as fuel in the heating systems (ovens).
  - Lack of availability of compact heat recovery systems that will reduce the size of the heat exchangers (large regenerators).

- Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amount of particulates but no condensable organic vapors.
  - Rapid performance drop and plugging of conventional heat exchanger. Unavailability of designs that allow self cleaning of heat transfer surfaces on units such as recuperators.

- Lack of innovative designs that allow use of condensing heat exchangers (gas-water) without having the corrosive effects of carbonic acid produced from CO_2 in flue products.

- Steam discharged as vented steam or steam leaks.
  - No major technical barriers. The major barriers are cost and return on investment for the collection of steam, the cooling system, condensate collection and, in some cases, the cleaning system.
- Other gaseous streams.
  - Application-specific barriers.
- Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants.
  - Lack of use of low-grade heat within the plant. Lack of economically justifiable heat recovery systems that can convert low-grade heat into a transportable and usable form of energy, such as electricity.
- Hot water that contains large amounts of contaminants such as solids from the process or other sources, but does not contain organic liquids or vapors mixed with the water.
  - No major technical barriers for cleaning the water (removing the solids).
  - Lack of use of low-grade heat within the plant or economically justifiable energy conversion systems.
- Hot water or liquids containing dissolved perceptible solids, dissolved gases (e.g., CO_2 and SO_2) or liquids.
  - No major technical barriers for filtering the water (removing the solids).
  - The presence of SO_2, CO_2, and other dissolved gases presents problems of high PH values for water use within a plant. There is no simple method of neutralizing the water.
  - Lack of use of low-grade heat within the plant or economically justifiable energy conversion systems.
- Hot solids that are cooled after processing in an uncontrolled manner.
  - Economically justifiable cooling air collection system.
  - Lack of use of low-temperature heat within the plant or economically justifiable energy conversion systems.
  - Variations in cooling air temperatures and the presence of microscopic particulates prevent their use in combustion system (burners).
- Hot solids that are cooled after processing used water or air-water mixture. Examples include hot coke, ash, slag, and heat treated parts.
  - No major technical barriers for filtering the water (removing the solids).
  - Lack of use of low-grade heat within the plant or economically justifiable energy conversion systems.
- Hot liquids and vapors that are cooled after thermal processing. Examples include fluids heated in petroleum reefing or the chemical, food, mining, or paper industries.
  - No major technical barriers for recovering heat if there is sufficient temperature “head.”
  - Lack of use of low-grade heat within the plant or economically justifiable energy conversion systems.

- By-products or waste that is discharged from thermal processes. These materials contain sensible, latent, and chemical heat that is not recovered prior to their disposal. Examples include ash from coal or solid waste fired boilers, slag from steel melting operations, dross from aluminum melters, bottom waste from reactors, and sludge.
    - Economically justifiable collection system for hot material.
    - Economics of processing the material to recover recyclable or useful materials, or combustibles for use of chemical heat.
    - Materials are often classified as hazardous materials and need special treatment.
    - Cost of recycling or cleaning the residues and treatment of gases or other materials that are produced during the recovery or treatment process.
    - Variations in the amount of recoverable materials.

- High-temperature surfaces.
    - No practical way of recovering this heat, especially for systems such as rotary kiln or moving surfaces (i.e. conveyors).
    - Low efficiency and cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems.

- Extended surfaces or parts used in furnaces or heaters.
    - No practical way of recovering and collecting this heat, especially for systems such as rolls used for a furnace.
    - Low efficiency and cost for advanced surface-mounted energy conversion technologies such as thermoelectric systems.

Barriers by Major Industry

Details of the barriers or limitations to waste heat recovery, along with waste heat sources and recovery opportunities, are summarized in Exhibits 7 to 13 for the major industries analyzed.

Exhibit 7: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Iron and Steel Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Blast furnace gas (BFG)	Maintaining heating value to reduce or eliminate use of supplementary fuel, such as natural gas.	Moisture removal method for BFG at relatively high temperature.
Coke oven gas (COG)	Use of sensible heat and chemical heat of COG—elimination of need to cool or quench the COG as discharged from the coke oven batteries.	Presence of particulates, vapors of condensable material, and certain gaseous impurities (e.g., SO_2 and CO_2) that present problems of condensation and corrosion in transmission and use of hot gases.
Steam from liquid steel refining area	Recovery of steam heat and condensate return.	Presence of gases and particulates that need to be removed before its use in heat exchangers to condense the steam and collect clean and reusable condensate to be returned to the boiler water system.
Hot coke discharged from coke ovens	Recovery of high-grade (temperature) sensible heat from hot coke.	Highly combustible material and the need to be cooled to a fairly low temperature without ignition. Need for fast cooling (quenching) using inert gas.
Hot products discharged from various furnaces such as reheat furnaces, annealing furnaces, and heat treating furnaces	Recovery of heat from high-temperature (1,300°–2,200°F) (700°–1,200°C) steel products.	Design of a cooling system that can cool a product without affecting its surface or other qualities. Economically justifiable method of collection and use of a low- to medium-temperature (as previously defined) cooling medium such as air, mist, or water.
Waste heat from recuperator or a regenerative burner system used on various heating or heat treating furnaces	Recovery of sensible and latent heat from fly-use gases.	Use of low-grade heat usually in the form of hot air or water. Economically justifiable energy conversion from hot gases to electricity, a transportable energy form.
Low-grade heat available in the form of hot water used in cooling systems for various operations (e.g., caster, reheat furnaces, and roll cooling)	Recovery of heat from low-temperature water (usually less than 125°F or 52°C).	Use of low-grade (less than 100°F or 37°C) recovered heat, economic justification for use of systems such as thermally driven heat pumps.
Radiation – convection heat loss from furnace walls	Recovery of heat for use within the plant.	Low temperatures and large surface areas present economic and logistical problems. Potentially usable systems such as TEGs are prohibitively expensive at this time.
EAF exhaust gases	Recovery of chemical and sensible heat.	High temperatures, variable flow rates and temperatures of gases, and the presence of contaminants (e.g., particulates, condensable vapors, and combustible gases).

Exhibit 8: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Paper Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Paper machines	Low-temperature (<600°F or 316°C) heat recovery for heating water, air, or power generation. The gases contain some particulates and large amount of water vapor—wet steam.	Materials for heat exchanger. Corrosion of materials is a big issue for gases containing acidic constituents (e.g., CO_2 and SO_2) that can tolerate presence of small particulate or fibrous materials and variable amount of water vapor.
		Availability and cost of reliable and efficient low-temperature condensing heat exchangers.
Boilers fired with hog fuel or other waste material	Use of exhaust gas heat and heat recovery from residual (ash) material that may contain some combustible material.	Materials for heat exchanger. Corrosion of materials is a big issue for gases containing acidic constituents (CO_2, SO_2, etc.) that can tolerate presence of small particulate or fibrous materials and variable amount of water vapor.
Waste material with organic content or having heat value	Recovery and use of heating value content of the waste material.	Economic justification and availability of combustion equipment that can burn such waste economically.

Exhibit 9: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Cement Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Hot clinker	Recovery of sensible heat.	No major technological barriers. The use of available waste heat within the plant presents a logistical barrier.
Exhaust gases from pre-heaters and other areas	Recovery of sensible heat.	No major technological barriers. The use of available waste heat within the plant presents a logistical barrier.
Hot surfaces - kiln shell	Heat recovery in the form of electricity using TEG devices.	Availability of materials and method of their use for the kiln walls to reduce surface temperature. There is no simple recovery of heat without affecting temperature profile within the kiln.

Exhibit 10: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Food (Snack) Manufacturing Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Clean exhaust gases from boilers, corn products dryers, oil heaters, and other sources	Low-temperature (<500°F or 260°C) heat recovery from combustion products with moisture content of 20%–40%.	No major technical barriers. Economics of heat recovery system installation and use of recovered heat within the plant are two major barriers. Electricity generation using heat from these sources using low-temperature systems (i.e. ORC) is uneconomical at the current state of technology.
Exhaust gases from fryers. These gases contain moisture and oil vapors.	Recovery of sensible heat, use of heating value content of oil vapors and latent heat of moisture.	Presence of oil vapors prevents use of conventional heat recovery (e.g., recuperates, heat wheels, condensing heat exchangers).
Hot wash water (120°–180°F or 50°–82°C) from various sources.	Sensible heat of water	Presence of particulates, economics of heat recovery, and lack of use of low-grade heat in the forms of warm water or air in the plant.
Waste material with organic content or heat value and moisture	Recovery and use of heating value content of the waste material.	Economic justification, availability of combustion equipment that can burn or process such waste economically.

Exhibit 11: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Glass Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Melting furnace flue gases with regenerators	Medium-temperature (<900°F or 480°C) heat recovery for power generation. The gases may contain some particulates but no condensable components.	Availability of reliable and efficient heat exchangers, small size boilers and steam turbine power generation system that can be used for relatively small and low-temperature waste heat sources.
Melting furnace flue gases with oxy-fuel systems	Cleaning or filtering particulates from high-temperature (>1,600°F or 870°C) exhaust gases containing corrosive components. This will allow recovery of heat from exhaust gases at higher temperatures without pre-cooling them.	Availability of reliable and efficient heat exchangers, small size boilers, and steam turbine power generation system that can be used for relatively small and low-temperature waste heat sources.
All fuel-fired melting systems	Using heat of low-temperature clean exhaust gases (<400°F or 204°C) discharged from ESPs or baghouses.	Cost, reliability, and industrial installation demonstration of currently available low-temperature power generation systems (ORC and others).
Melters and forehearth outer surfaces or casing	High-temperature (>400°F or 204°C) furnace walls.	Cost, reliability, and industrial installation demonstration of currently available low-temperature power generation systems (ORC and others).
Annealing lehrs (temperature controlled kilns), tempering furnaces, or drying ovens	Reducing air leakage from inlet-outlet sections or areas.	The equipment design and operational components that require flexibility of operation. Availability of low-temperature heat recovery systems, cost of combustion system using preheated air.

Exhibit 12: Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Aluminum Industry

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Calciner exhaust gases at 350°–400°F (180°–200°C) containing more than 50% moisture and particulates	Recovery of sensible and latent heat of moisture.	High moisture content, presence of particulates (alumina), and low temperature. Lack of use of low-grade heat in the form of hot water or air within the plant.
Hot alumina from calciner operation	Hot alumina from calciner operation	Easy and convenient method of recovery and use of this heat within the plant.
Smelting—heat from side walls that vary in temperature from 550°–750°F (290°–400°C).	Heat recovery in the form of electricity using TEG devices.	Recovery of heat without affecting temperature profile within the pots.
Off gases from smelting operations before entering a scrubber. The gases are at about 212°F (100°C)	Recovery of low-grade (temperature) sensible heat from hot gases.	Low temperature and presence of particulates.
Products of combustion from anode baking operations. These gases are at 400°–600°F (200°–316°C).	Recovery of chemical and sensible heat from low-temperature exhaust gases.	Presence of condensable tar vapors and particulates at low temperature.
Exhaust gases from melting furnaces	Recovery of sensible and latent heat from flue gases.	High-temperature (1,600°–2,000°F or 870°–1,100°C)., variations in temperature, and presence of particulates in gases. In some cases the gases need to be cooled for particulate collection in a baghouse.
Low- to medium-temperature (or grade) heat available in the form of exhaust gases from heating and heat treating furnaces (usually batch operations).	Recovery of heat from low- and medium-temperature combustion products.	Low-temperature, variable flow, and temperature die to batch operations, lack of use of low-grade heat in the plant.

Exhibit 13: Waste Matrix of Waste Heat Sources, Recovery Opportunities and Barriers for the Chemical and Petroleum Refining Industries

Waste Heat Source	Heat Recovery Opportunities	Barriers or Limitations – Currently Available Equipment
Clean exhaust gases from boilers, crackers, fired heaters, combustion turbines, and other sources	Low-temperature (<500°F or 260°C) heat recovery from combustion products with moisture content of 15%–20%.	No major technical barriers. Economics of heat recovery system installation and use of recovered heat within the plant are two major barriers. Electricity generation using heat from these sources using low-temperature systems (i.e., ORC) is uneconomical at current state of technology.
Exhaust gases from thermal oxidizers	Heat recovery from high-temperature gases – sensible and latent heat.	The gases are at high temperature and are highly corrosive, containing chlorinated gases and other gases. At this time they need to be quenched, hence loss of useful energy.
Hydrogen from chlorine process	Heat content of hydrogen.	The gas contains chlorine and it can turn into hydrochloric acid (if it reacts with H_2 and dissolves in aqueous condensate), which will be corrosive to the heating systems. Proper treatment is required.
Heat from various exothermic processes	Recovery of heat of reaction to produce steam at high pressure with end goal of using steam in processes or for electric power generation.	Simple method of integrating steam generation within the process reactors.
Heat from hot products from reactors	Sensible heat recovered from hot products.	No simple method of recovering the heat (heat recovery equipment for solid or liquid to air or gas) that can fit into existing footprint of the plant.
Exhaust gases from multiple stacks	Use of sensible heat and latent heat of liquid – water vapor. Reduction in water use at the plants.	Logistics of collecting stack gases and using them in conventional heat exchanger poses available space in existing footprint. Microchannel heat exchanger with small size has no history of use in the chemical industry and may pose maintenance problems.
Heat from gases containing water vapors discharged from evaporators and other units.	Use of sensible heat and latent heat of liquid – water vapor. Reduction in water use at the plants.	Quality of water vapor, which may contain gaseous and solid contaminants. Currently available heat exchangers (condensers) are too big. Need smaller size heat exchangers to fit into the existing footprint of the plant. Vapor filtration or water purification system availability.
Low-pressure steam	Latent heat of steam and water.	Dry coolers to eliminate use of water, which is scarce in many areas of the plant location.
Low-temperature cooling water	Sensible heat of water.	Availability of water at low temperatures. Lack of availability of indirect dry (air) coolers that can replace cooling towers or conventional water to water heat exchangers.
Flared gases with high hydrocarbon content.	Heating value of gases or feedstock recovery.	Periodic and unpredictable nature of the source of gases.
Byproduct solids or residues	Sensible heat and heat content of the material.	Material handling and combustion systems for contaminated solids.

Current Status of Waste Heat Recovery Technologies

Industry uses a wide variety of waste heat recovery equipment offered by a number of suppliers in United States and from other countries. Much of this equipment is designed for specific crosscutting industrial applications. There is no standard method for classifying this equipment; in many cases the manufacturers offer application-specific designs.

Commonly Used Waste Heat Recovery Systems

A summary of conventional or commonly used waste heat recovery technologies for various temperature ranges is found in Exhibit 14.

Exhibit 14: Commonly Used Waste Heat Recovery Systems by Temperature Range

Ultra-High Temperature (>1600°F or 870°C)	High Temperature (1200° to 1600°F OR 650° to 870°C)	Medium Temperature (600° to 1200°F OR 315° to 650°C)	Low Temperature (250° to 600°F OR 120° to 315°C)	Ultra-Low Temperature (< 250°F or 120°C)
• Refractory (ceramic) regenerators • Heat recovery boilers • Regenerative burners • Radiation recuperator • Waste heat boilers including steam turbine-generator based power generation • Load or charge preheating	• Convection recuperator (metallic) – mostly tubular • Radiation recuperator • Regenerative burners • Heat recovery boilers • Waste heat boilers including steam turbine-generator based power generation • Metallic heat wheels (regenerative system) • Load or charge preheating	• Convection recuperator (metallic) of many different designs • Finned tube heat exchanger (economizers) • Shell and tube heat exchangers for water and liquid heating • Self recuperative burners • Waste heat boilers for steam or hot water condensate • Load-charge (convection section) preheating • Heat pipe exchanger • Metallic heat wheel	• Convection recuperator (metallic) of many different designs • Finned tube heat exchanger (economizers) • Shell and tube heat exchangers for water and liquid heating • Heat pumps • Metallic heat wheel • Condensing water heaters or heat exchangers • Heat pipe exchanger • Direct contact water heaters	• Shell and tube type heat exchangers • Plate type heat exchangers • Air heaters for waste heat from liquids • Heat pumps • HVAC applications (i.e., recirculation water heating or glycol-water recirculation) • Direct contact water heaters • Non-metallic heat exchangers

The commonly used systems listed in this table are available from several suppliers and are used on industrial waste heat sources. In most cases, the systems are proven; however, they are continuously being improved in one of the following areas to offer better performance:

- Design changes to offer higher thermal efficiency in smaller footprint or size
- Cost reduction through use of better design and manufacturing techniques
- Improved seals to reduce maintenance or extend the life of the seals
- Use of different materials to improve heat transfer performance or maintenance cost
- Design changes to meet customer demands for different or previously untested applications

Emerging or Developing Waste Heat Recovery Technologies

Exhibit 15 lists emerging technologies that may be used in a few cases, or are in some stage of development and demonstration.

Exhibit 15: Emerging or Developing Waste Heat Recovery Technologies by Temperature Range

Ultra-High Temperature (>1600°F or 870°C)	High Temperature (1200° to 1600°F OR 650° to 870°C)	Medium Temperature (600° to 1200°F OR 315° to 650°C)	Low Temperature (250° to 600°F OR 120° to 315°C)	Ultra-Low Temperature (< 250°F or 120°C)
• Regenerative burners • Systems with phase change material • Advanced regenerative systems • Advanced load or charge preheating systems	• Recuperators with innovative heat transfer surface geometries • Thermo-chemical reaction recuperators • Advanced design of metallic heat wheel type regenerators • Advanced load or charge preheating systems • Systems with phase change material • Self recuperative burners	• Recuperators with innovative heat transfer surface geometries • Advanced design of metallic heat wheel type regenerators • Self recuperative burners • Systems with phase change material • Advanced heat pipe exchanger • Advanced design of metallic heat wheel • Thermoelectric electricity generation systems	• Convection recuperator (metallic) of many different designs • Advanced heat pipe exchanger • Advanced heat pumps • Membrane type systems for latent heat recovery from water vapor • Low temperature power generation (i.e., ORC, Kalina cycle, etc.) • Thermally activated absorption systems for cooling and refrigeration • Systems with phase change material • Thermoelectric electricity generation systems • Condensing water heaters or heat exchangers	• Non-metallic (polymer or plastic) corrosion resistant heat exchangers of many different designs • Systems with phase change material • Desiccant systems for latent heat recovery from moisture laden gases • Membrane type systems for latent heat recovery from water vapor • Condensing water heaters or heat exchangers • Thermally activated absorption systems for cooling and refrigeration

Emerging or developing technologies are being developed and tested at the laboratory or pilot scale. Development work is being carried out in many countries. The current status of the technology or product development depends on the local energy situation (cost and availability) and support from the local governments or funding agencies. In general, the following areas are getting the most attention:

- Conversion of waste heat into a flexible and transportable energy source such as electricity
- Heat recovery from high-temperature gases with large amounts of contaminants such as particulates, combustibles, and condensable vapors (organic, metallic, or nonmetallic materials)
- Heat recovery from low-temperature sources, primarily lower than 250°F (or 120°C)
- Heat recovery from low- to medium-temperature exhaust gases or air with high moisture content to recover the latent heat of water vapor

All of these areas of development are discussed in the R&D opportunities section of this report.

Limitations of Currently Available Technologies

Exhibits 16 and 17 depict limitations and barriers of currently available waste heat recovery technologies for ultra-high, high, and medium temperature ranges.

Exhibit 16: Limitations of Currently Available Waste Heat Recovery Technologies, High and Ultra High Temperature Ranges

Equipment	Limitations and Barriers
Metallic recuperators	• Upper temperature limit of 1,600° to 1,800°F (or 870° to 980°C) • Economically justifiable heat recovery efficiency – 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Life expectancy in applications where the mass flow and temperature of the fluids vary or are cyclic • Fouling and corrosion of heat transfer surfaces • In some cases, difficulty in maintaining or cleaning the heat transfer surfaces
Ceramic recuperators	• Life expectancy due to thermal cycling and possibility of leaks from high-pressure side • Initial cost • Relatively high maintenance • Size limitations – difficult to build large size units
Recuperative burners	• Lower heat recovery efficiency (usually less than 30%) • Temperature limitation – exhaust gas temperature less than 1,600°F (870°C) • Limited size availability (usually for burners with less than 1 MM Btu/hr) • Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Stationary regenerators	• Large footprint • Declining performance over the lifetime • Plugging of exhaust gas passages when the gases contain particulates • Chemical reaction of certain exhaust gas constituents with the heat transfer surfaces • Possibility of leakage through dampers and moving parts • Cost can be justified only for high-temperature (>2,000°F or 1,100°C) exhaust gases and larger size (>50 MM Btu/hr firing rate)
Rotary regenerators	• Seals between the high-pressure and low-pressure gases (air) • Plugging of exhaust gas passages when the gases contain particulates • High pressure drop compared to recuperators • Maintenance and operation reliability for rotary mechanism
Regenerative burners	• Large footprint for many applications • Complicated controls with dampers that cannot be completely sealed • Difficult pressure control for the furnace • Cost competiveness • Plugging of the bed when the gases contain particulates. Require frequent cleaning of the media and the bed.
Heat recovery steam generators - boilers	• Can be used for large size systems (usually higher than 25 MM Btu/hr) • Can be used only for clean, particulate free, exhaust gases • Need to identify use of steam in the plant • Initial cost is very high compared to other options such as recuperators

Exhibit 17: Limitations of Currently Available Waste Heat Recovery Technologies, Medium Temperature Ranges

Equipment	Limitations and Barriers
Metallic recuperators	• Economic justification for exhaust gas temperature below about 1,000°F (540°C) • Economically justifiable heat recovery efficiency – 40%–60% • High maintenance for use with gases containing particulates, condensable vapors, or combustible material • Fouling of heat transfer surfaces • In some cases, difficulty in maintaining or cleaning the heat transfer surfaces
Recuperative burners	• Lower heat recovery efficiency (usually less than 30%) • Limited size availability (usually for burners with less than 1 MM Btu/hr) • Cannot be applied to processes where exhaust gases contain particles and condensable vapors
Rotary regenerators	• Seals between the high-pressure and low-pressure gases (air) • Plugging of exhaust gas passages when the gases contain particulates • High pressure drop compared to recuperators • Maintenance and operation reliability for rotary mechanism
Shell and tube heat exchanger for heating liquid (water)	• Fouling of heat transfer surfaces when the gases contain particulates or condensable liquids • Condensation of moisture at selected cold spots and resulting corrosion

Another approach would be to develop a matrix according to the type of equipment available in the market. Considerations would include its application range, in terms of temperatures and heat source characteristics; performance level; and limitations with respect to industrial applications.

R&D Opportunities

R&D opportunities are presented in three formats: by temperature range, by major industry, and by research category.

R&D Opportunities for Various Temperature Ranges

The following are lists of R&D opportunities categorized in temperature regimes at which waste heat is available.

Opportunities for High-Temperature Waste Heat Sources

This section includes two different categories of high temperatures: 1,200°–1,600°F (650°-870°C), and >1,600°F (or 870°C).

- Heat recovery systems that can handle high-temperature gases with solids and condensable contaminants. These systems can also have internal cleaning systems that allow long-term continuous operation without major maintenance time for cleaning or rebuilding. The systems can be recuperative or regenerative.
- Materials that can withstand high temperatures and chemical reactions with the waste heat source and the cyclic nature of waste heat in terms of mass flow rates, temperature, or composition.
- Development of high-temperature phase change materials that can be used by high-temperature heat recovery systems to reduce the size of the system and allow tolerance of the cyclic nature of the waste heat source.
- Development and testing of selective coatings or laminations that are compatible with base materials of construction and can withstand specific contaminants and combustibles in the waste gas streams.
- Systems with smaller footprints that allow installation as a retrofit for existing systems, which are usually located in limited space in the plants.
- Secondary heat recovery systems that can be used as supplementary or secondary recovery systems to enhance the performance of the existing systems. These systems should be compatible with the performance of the primary systems.
- A hot gas cleaning system to remove particulates from high-temperature gases.
- Electrical power generation systems integrated with high-temperature waste heat sources or existing primary heat recovery systems. The electric power generation system must be able to handle variations in heat sources and the cyclic nature of the waste heat source. In most cases, the system must be able to tolerate some contaminants present in the waste heat source.
- Catalysts for reforming fuel gases or liquid fuel vapors for use in endothermic heat recovery units.

Opportunities for Medium-Temperature Waste Heat Sources

This section includes temperatures from 600°–1,200°F (315°-650°C).

- Compact heat exchangers or micro-channel heat exchangers for clean gases that reduce the size or footprint of the heat recovery system.
- High-performance heat recovery systems that integrate burners and eliminate the need for hot air piping and space for external heat recovery systems. This may require development and integration of micro-channel heat exchangers.

- Heat transfer systems for gases containing condensable vapors or combustible gases such as solvent vapors in coating ovens.

Opportunities for Low-Temperature Waste Heat Sources

This section includes two different categories of low temperatures: <250°F (120°C) and 250°–600°F (120°-315°C).

- Innovative condensing heat exchangers for gases containing high moisture levels with particulates, as discharged from paper machines, food drying ovens, or other sources.
- Nonmetallic materials (polymers) that can withstand condensed water from combustion products containing acid gases. These must be cost competitive and used for low-temperature condensing heat exchangers.
- High-efficiency, liquid-gas heat exchangers for low-temperature flue gases or exhaust air from dryers.
- Liquid-to-liquid heat exchangers for heat recovery from waste water containing particulates and other contaminants.
- Dry coolers for cooling liquids that reduce or eliminate water use in heat exchangers.

A special category of heat recovery systems includes use of low- and medium-temperature waste heat for electric power generation and absorption cooling. R&D needs for this category of waste heat recovery systems require further development of components or sub-systems. These developments to enhance performance of the currently used waste to power systems include the following:

- Condenser units (heat exchangers) that replace water with air to reduce the cost of cooling towers and liquid cooling systems.
- Waste heat exchangers designed for fast startup, low-thermal stresses, low cost, and compact size.
- Evaporator section heat exchangers with "de-fouling" for glass and other particle-laden exhaust streams.
- Turbo machinery with variable area inlet nozzles for high turndown.
- A working fluid pump design with optimized efficiency for vapor compression. The exact design features will vary with the commonly used working fluids used in Rankine cycle systems. The unit may include alternates to the pump design, and could potentially crossover into CO_2 compression for sequestration.
- Heat recovery recuperators—advanced design and analysis methods to improve thermal stresses for fast startup.

R&D Opportunities by Major Industry

The following opportunities have been identified where R&D could impact waste heat recovery in the major industries analyzed in this report.

Opportunities for the Aluminum Industry

- Cleaning high-temperature contaminated gases without cooling them to lower (<570°F or 300°C) temperatures.
- Thermoelectric system infrastructure to prepare for higher ZT value materials and for their use in recovering low- to medium-temperature heat, particularly for surface heat losses such as in electrolysis pots.

- Improved efficiency or lower initial costs for lower temperature power generation systems, such as the Kalina cycle. The developments can include reducing the number of components (such as gas-liquid heat exchangers) or using alternate fluids for the cycle.
- Removal of tars and organic vapors from the exhaust gases without dropping their temperature to allow heat recovery from the “cleaner” gases.
- Materials and components that offer reliability and longer life for submerged heating devices for corrosive surroundings, such as molten aluminum or molten glass.

Opportunities for Food (Snack) Manufacturing

- Development of heat recovery or energy conversion systems for low-temperature (<200°F or 93°C) heat sources, such as exhaust gases, that may contain water vapor and other contaminates, such as small amounts of oil vapors.
- Development of heat recovery from low-temperature water (<100°F or 37°C) for plant use.
- Development of efficient heater systems to reduce energy intensity.

Opportunities for Integrated Steel Industry

- Secondary heat recovery devices that can supplement and enhance performance of the currently used systems, and are capable of recovering part (less than 50%, in most cases) of the waste heat available.
- Recovery of waste heat or increasing the value of available heat from blast furnace gas (removal of moisture).
- Recovery of waste heat in hot products such as hot slabs, rolled steel shapes downstream of the rolling mill, heat treated steel processed in furnaces, and coke discharged from coke oven batteries. In some cases, the technologies exist but are too difficult to implement due to space requirements in existing operations, cost, or lack of use of the low-grade heat produced after heat recovery. The industry has not considered this notion, perhaps due to its nature (low- to medium-grade) and difficulty in recovering and using the heat.
- Recovery and use of waste heat from highly contaminated hot gases such as hot COG from the ovens. No technology exists or is commercially used in similar cases.
- Energy recovery through cleaning and recycling steam heat from degasifying systems used for liquid steel refining area.
- Recovery or utilization of radiation−convection heat from furnace walls or openings, or hot products such as hot steel shapes after rolling.
- Use of low-grade heat in the form of cooling water used in casters or in rolling operations.

Opportunities for the Glass Industry (Fiberglass and others)

- Heat recovery from very high temperature gases (2,200°F or 1,200°C) that contain condensable vapors and produce solid particles that need to be removed. Possible methods include fluidized bed or solid particle-gas heat transfer with a proper material handling system.
- Rapid quenching methods of hot gases to avoid generation of sticky solids, and subsequent use of these gases in conventional boilers or air heaters.
- Electricity generation through direct contact or radiation from moderate temperature (300°–900°F or 1500°–480°C) surfaces with economically justifiable paybacks. Possible methods are thermoelectric and photovoltaic devices under development.

- Use of advanced heat exchangers for evaporators and condensers that use direct gas-air heating for the evaporators and air for condensers. This would eliminate secondary heat exchanger loops such as producing hot water or steam for the evaporators as well as the need for cooling towers for the condenser. This would reduce costs as well as eliminate inefficiencies introduced with the use of secondary heat exchanger circuits.
- Secondary heat recovery systems for flue gases discharged from regenerators. These gases are at temperatures from 800°–1,200°F (430°–650°C). The gas temperature is cyclic and, in some cases, the gases contain very small amount of particulates, which are easy to remove.
- Glass batch drying and preheating systems using exhaust gases from the melting furnace or refining forehearth section exhaust gases. Previously developed systems have not been used by the industry due to a variety of issues related to operations and maintenance. A new approach or design is required.
- Hot gas cleanup systems for use by medium- to low-temperature gases prior to secondary heat recovery.
- Use of CHP systems for generating hot gases for use in annealing ovens. The system will deliver electricity as well as hot air with reduced but sufficient oxygen for use as combustion air.
- Use of heat from annealed products. The heat is available at temperatures below 500°F.

Opportunities for the Paper Industry

- Development of heat recovery or energy conversion systems for low-temperature (<140°F or 60°C) heat sources, such as exhaust gases, that may contain water vapor and other contaminates, such as small amount of fibers or duct.
- A system for dehumidifying high-temperature (≥140°F or 60°C) air containing fibers or dust.
- Development of heat recovery from low-temperature water (<100°F or 37°C) for use in the plant.
- Development of a drying system for solids, using waste heat from the exhaust gases.

Opportunities for Steel Mini-mills (EAF Furnaces and Rolling Mill)

- Heat recovery from EAF exhaust gases. Options could include hot gas clean up, controlled combustion of combustibles to manage reaction temperatures while avoiding melting of steel oxides and other solid contaminants, and heat recovery from highly contaminated (e.g., particulate and condensable oil vapors) gases.
- Recovery of heat from surfaces of hot ladles. The heat is in the form of radiation and convection and the ladles are moved from one location to another during the day.
- Heat recovery from cooling water used in the continuous casting process and reheat furnace cooling (e.g., walking beam furnaces or thin-slab reheating roller hearth furnaces)
- Secondary heat recovery from reheat furnaces downstream of conventional heat recuperators to recover additional heat. One option is preheating the product entering the furnace. Issues to be addressed include the location of the heat source and heat use, available space, and the infrastructure or logistics of transporting heat to the desired location.
- Heat recovery from hot cooled products. This could be medium- or low-grade heat.

Opportunities for Coating Plants

- Secondary heat recovery from regenerative thermal oxidizers (RTOs) exhaust gases that are available from 350°–400°F (180°–200°C).

- Control system for ovens to regulate the amount of make-up air used. This will require development of a system that controls the amount of make-up air, and hence the amount of heat wasted from the oven.

Opportunities for Aluminum Recycling Operations

- Cleaning of hot gases from rotary furnaces to allow heat recovery from exhaust gases.
- A heat recovery system for hot (>1,800°F or 980°C) exhaust gases containing materials such as flux material and aluminum oxide particles.
- Secondary heat recovery from gases discharged from recuperators used for combustion air preheating. The gases could be in the temperature range of 400°–800°F (200°–430°C).

Opportunities for the Cement Industry

- Heat recovery from hot surfaces or kiln shell surfaces.
- Cleaning (particulate removal) of heated clinker cooling air prior to its use in boilers or other heat recovery systems.
- Moisture control or reduction for the raw materials using exhaust gases from heat recovery systems.
- Use of an alternate (conventional steam boiler or generator) CHP system for generating power using hot air from cooling beds as well as exhaust gases from the system.

Opportunities for the Chemicals and Petroleum Refining Industries

- Heat recovery from low-temperature (<200°F or 95°C) but relatively clean gases, such as combustion products, from natural gas-fired heaters or boilers. Compact heat exchangers that allow condensation of water vapor and use mediums that use no or minimal water are needed.
- Treatment of high-temperature gases containing corrosive gases such as HCL from TO gases that includes removing (or reacting) these compounds while allowing heat recovery using conventional heat exchanger equipment.
- Equipment to recover heat from exothermic processes. The system must be compact and reliable and deliver recovered heat in the form of high-pressure steam or another compact usable form.
- Development of compact heat exchangers such as micro-channel heat exchangers for use in industrial environments. A major requirement is tolerance of the minor and unpredictable presence of solids or other materials that may adversely affect heat exchanger performance.
- Development of air-cooled heat exchangers that can replace water-cooled units. This will reduce water and associated energy use.
- Economically justifiable energy recovery from flared gases.

R&D Opportunities by Research Category

The industry requirement-based R&D lists have been consolidated to identify crosscutting R&D that could meet requirements of many different industries and at the same time fill the gaps in capabilities or performance of the currently available systems. While there are many ways the R&D areas could be presented, the following employs the method of dividing R&D activities into specific programs that can be pursued by equipment suppliers to advance the technology or performance of the currently offered systems:

Opportunities in Basic Research

- Heat transfer
  - Enhancement of heat transfer for air or other gases to reduce the size of heat exchangers. This could include advancements in heat transfer surfaces in shape, configuration, coatings, and changes in fluid flow patterns through innovative flow patterns, changes in gas compositions, or other methods that could make significant improvements in convection heat transfer for the gases.
  - Radiation heat transfer enhancement to take advantage of thermal radiation emission properties of gases such as CO_2 and H_2O that are present in combustion products of commonly used fossil fuels. This may include using reradiation surfaces or geometrical modifications.
- Particulate removal or gas cleaning
  - Particulates filtering of particulate laden gases in all temperature ranges through innovative methods of increasing filtering efficiency with minimized pressure drop. Of particular interest is cleaning or filtering of high-temperature gases encountered in industries such as EAF (mini-mills), glass, cement and lime kilns, aluminum melting, and steel melting.
  - Innovative methods of avoiding or reducing particulate deposition on heat transfer surfaces. This can be used to retard or remove deposits of organic materials (e.g., oil vapors) or inorganic materials (e.g., boron vapors) present in glass melting furnaces, ash in coal fired boilers, and oxides in steel or aluminum melting furnaces.
  - Particulate removal methods for high-temperature heat transfer surfaces, particularly materials deposited at high temperatures.
- Gas or vapor separation
  - Selective separation of water vapor or steam, CO_2, oil, or organic liquid vapors from exhaust gases at high temperatures (greater than the condensation temperature of the selected materials) without the need for cooling the entire gas mass. This may include membranes or other methods such as high-temperature desiccant or molecular sieves to absorb or adsorb water vapor or other gases selectively.
  - Reactive systems (i.e., controlled combustion for organic vapors) to remove or collect organic vapors and combustible gases or vapors with controlled reaction rates and temperature increases.

Opportunities in Advanced Materials

- Corrosion-resistant coatings for low-temperature applications.
- High-temperature (>1,600°F or 870°C) corrosion resistant materials for heat exchangers (recuperators).
- Heat storage materials with high latent heat, thermal capacity (specific heat), and thermal conductivity for all temperature ranges.
- Seal materials for high-temperature heat exchanger designs with moving parts (e.g., heat wheels or regenerators). The seal can be for metal-to-metal interface or metal-to-non-metallic materials (e.g., ceramics).
- Polymers or plastics with improved thermal conductivity for use in low-temperature corrosive environments (e.g., combustion products of fossil fuels).

- Cost-effective thermoelectric or thermo-ionic materials capable of producing electricity from heat with 15%–20% thermal efficiency.
- Working fluids for low-temperature power generation cycles that can withstand broader temperature ranges for use in ovens and furnaces.
- Advanced materials to increase temperature lift in absorption cycles and improve overall heating and cooling performance.
- Catalysts to support lower temperature "reforming" reactions for use in medium- to high-temperature (≥800°F or 430°C) waste heat applications.
- Higher temperature materials to be used for "bag-houses," or gas cleaning systems. This will allow use of lower temperature electricity generation cycles.

Opportunities in Advanced Concepts and Designs

- Innovative heat transfer methods and heat exchanger geometries to reduce heat exchanger size (see the Basic Research section).
- Heat exchangers or regenerators with continuous surface cleaning to remove surface deposits resulting from particulates or fibers in waste gas streams.
- Air cooled (dry) heat exchangers to be used to replace or supplement currently used water cooled condensers or heat exchangers (see the Basic Research section for heat transfer improvement).
- New concepts for recovering and collecting heat from gases containing particulates and high-temperature condensable materials as encountered in the glass, steel, cement, and aluminum industries.
- New regenerator designs to reduce the volume of high-temperature particulate laden gases, such as using a high surface-area-to-volume ratio or high thermal capacity materials that are easy to clean.
- Improved design of "generator" or waste heat "boilers" that can utilize lower temperature (≥100°F or 37°C) heat source. This allows use of "low grade" waste heat for thermally-activated refrigeration and heat pump systems to replace or supplement direct gas firing.
- Pumps and turbo-expanders with high turndown capability for use in low-temperature power generation systems.
- Self-cleaning filters for gases with relatively low particulate loading.
- Advanced heat exchangers for evaporators and condensers that use direct gas – air heating for the evaporators and air for condensers.
- Methods to seal ends of a continuous furnace or oven to reduce or eliminate air leaks that result in excessive energy use in heating equipment; increased size for exhaust gas handling systems; and gas treatment, if necessary for meeting local environmental regulations.

Opportunities in Sensors and Controls

- Reliable sensors and controls for high-temperature (>400°F or 200°C) applications to measure and monitor humidity or lower explosion limits (LEL) in dryers and ovens to allow recycling of exhaust gases and reduce the amount of make-up air.

- Systems for monitoring heat exchanger performance to detect performance degradation and alarms for maintenance.
- A low cost reliable system for monitoring O_2 and CO in small applications (<5 MM Btu/hr fired systems).
- Continuous monitoring of energy intensity (Btu or kWh per unit of production) to identify performance problems.

Opportunities in Advanced High Efficiency Power Generation Systems

- High turndown systems for use in applications where the waste fired stream heat content (in terms of Btu/hr) changes significantly.
- Systems with non-water cooled condensers to avoid the need for water and cooling towers.

Report Summary

This study identifies key RD&D opportunities to increase application of waste heat recovery in various industries. Analysis of the information obtained during this study provides the basis for determining crosscutting opportunities and specific R&D program areas for wider application of waste heat recovery in industrial plants.

There are several barriers to reducing and recovering waste heat, including the following:

- Specific process and operations requirements
- Design limitations of the heating systems
- Lack of availability of waste heat recovery equipment that can be used for waste heat streams containing contaminants
- Unavailability of heat recovery systems for low-temperature heat recovery
- Poor economics or long payback periods for waste heat recovery projects

This report gives an overview of a large variety of equipment and systems currently available for waste heat recovery, as well as issues or barriers for these systems. This study also attempted to collect information on emerging technologies under development or in various stages of demonstrations.

This report lists R&D opportunities in several categories of project activities, such as basic research, advanced materials, concepts and design, sensors and controls, and advanced power generation systems. These R&D projects are identified based on the information derived from typical plant operations and reviews of currently available technologies and systems as well as emerging technologies and their technology gaps.

Appendix A: Waste Heat Recovery Equipment and Systems

This appendix provides an overview of equipment and systems currently available for waste heat recovery and the critical issues or barriers associated with their use. Following the equipment overview is a description of a special category of heat recovery systems that use waste heat for electric power generation. The appendix concludes with an overview of emerging waste heat recovery technologies currently under development.

Commonly Used Waste Heat Recovery Equipment and Systems

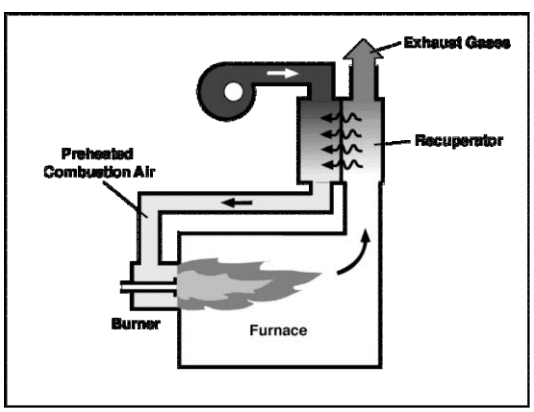
Waste heat recovery equipment is divided into the following categories: high to ultra-high temperature (1,200° to 1,600°F or 650° to 870°C), low to medium temperature (250° to 1,200°F or 120° to 650°C), or low temperature (below 250°F or 120°C). Due to special interest in low-temperature applications, the equipment used for waste streams below 600°F are described in greater detail.

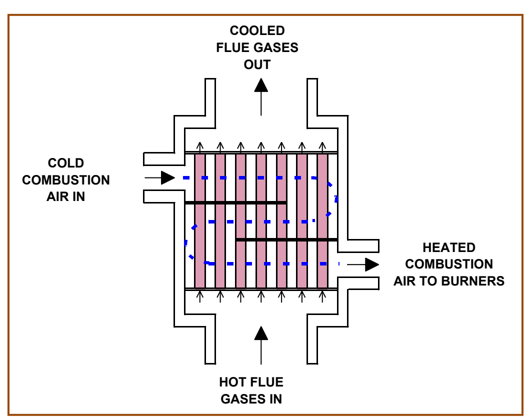
High- to Ultra-High-Temperature Heat Recovery Equipment

Recuperators
In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Ducts or tubes carry the air to be preheated in the combustion chamber; the other side contains the waste heat stream. A recuperator for recovering waste heat from flue gases is shown in Exhibit A-1. Five types of recuperators are described: convective, metallic, hybrid, ceramic, and a special class known as self-recuperative burners.

Convective Recuperator
A common configuration for recuperators is called the tube type or convective recuperator. As seen in the exhibit below, the hot gases are carried through a number of parallel small diameter tubes, while the incoming air to be heated enters a shell surrounding the tubes and passes over the hot tubes one or more times in the direction normal to their axes. If the tubes are baffled to allow the gas to pass over them twice, the heat exchanger is termed a two-pass recuperator; if two baffles are used, the heat exchanger is termed a three-pass recuperator, etc. Although baffling increases both the cost of the exchanger and the pressure drop in the combustion air path, it increases the effectiveness of heat exchange. Shell and tube type recuperators are generally more compact and have a higher effectiveness because of the larger heat transfer area made possible through the use of multiple tubes and multiple passes of the gases.

Exhibit A-1: Metallic Convection Recuperator Design and Application





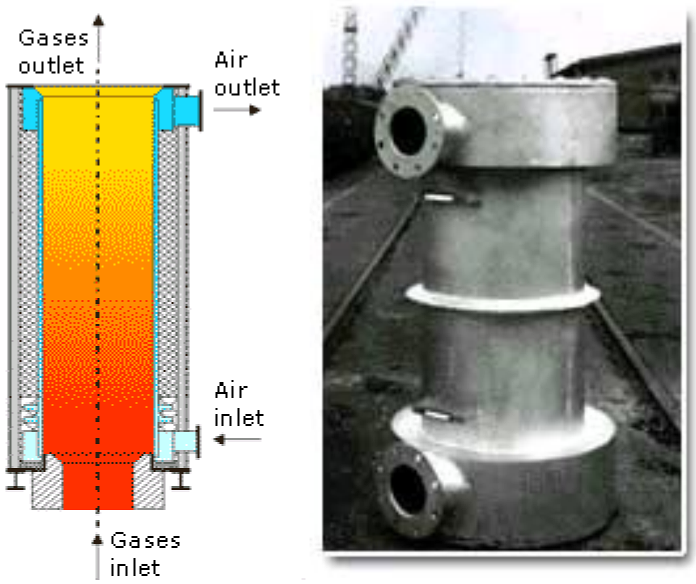
Metallic Radiation Recuperator

The radiation recuperator consists of two concentric lengths of metal tubing, as shown in Exhibit A-2. The inner tube carries the hot exhaust gases, while the external annulus carries the combustion air from the atmosphere to the air inlets of the furnace burners. The hot gases are cooled by the incoming combustion air, which now carries additional energy into the combustion chamber.

The radiation recuperator gets its name from the fact that a substantial portion of the heat transferred from the hot gases to the surface of the inner tube takes place by radiative heat transfer from the exhaust gases, such as carbon dioxide and water vapor, that radiate energy in the infrared region of the spectrum. Radiation heat transfer depends on the gas temperature and the “path length,” that is, the diameter of the inner tube carrying the exhaust gases. The radiation heat transfer is most effective at high temperature--usually above 1,400°F (760°C); therefore, this type of recuperator is used only for high-temperature process applications. The cold air in the annulus is almost transparent to infrared radiation so that only convection heat transfer takes place to the incoming air.

As shown in the diagram, the two gas flows are usually parallel; however, the configuration would be simpler and the heat transfer more efficient if the flows were opposed in direction (or counter flow). The reason for the use of parallel flow is that recuperators frequently serve the additional function of cooling the duct that carries away the exhaust gases to extend its service life.

Exhibit A-2: Typical Radiation Recuperator



Hybrid Recuperator

For maximum effectiveness of heat transfer, hybrid recuperators are used. These are combinations of radiation and convective designs, with a high-temperature radiation section followed by a convective section. These are more expensive than simple metallic radiation recuperators, but are less bulky.

Ceramic Recuperator

Ceramic tube recuperators have been developed to overcome the temperature limitations of metal recuperators as metal recuperators are normally used for temperatures from 1,600°–1,800°F (870° to

980°C) due to limitations (technical and economical) of the material used in the recuperators. Early ceramic recuperators were built of tile and joined with furnace cement; however, thermal cycling caused cracking of joints and rapid deterioration of the tubes. Recent developments in ceramic recuperators use silicon carbide tubes, which can be joined by flexible seals located in the air headers. These designs require good seal design to avoid leakage of combustion air which is at a higher pressure. The new designs are available in many different configurations and now offer much improved performance in terms of heat recovery and life.

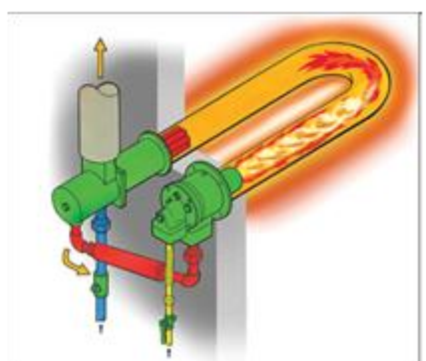
External recuperators are among the most widely used heat recovery devices; however, their use is limited due to several factors:

- Temperature limit for metallic recuperators. The limit depends on the material used for the recuperator construction. Modern recuperators that use high-temperature alloys can be used with flue gas temperatures up to 1,600°F (870°C).
- Cost of high-temperature recuperators. The alloys used for gases above 1,200°F (650°C) can be very expansive. For example, the cost of a recuperator used for exhaust gases at 1,600°F (870°C) can be in the range of $10,000–$15,000 per MM Btu recovered.
- The recuperators cannot be used for gases that contain particulates, corrosive gases, and condensable vapors.
- Ceramic recuperators require high maintenance due to potential for air leaks and and for material damage during thermal cycling.

Self-recuperative Burners

A special class of recuperators, known as self-recuperative burners, is now offered by several burner suppliers. In this system, the recuperator is integrated with the burner itself, so there is no need to have hot air piping from the recuperator to the burners resulting in substantial cost advantage. Exhibit A-3 shows commonly used designs for direct fired burners and radiant tube type heating systems.

Exhibit A-3: Self-Recuperative Burner Designs (Direct Fired and Radiant Tube Application)

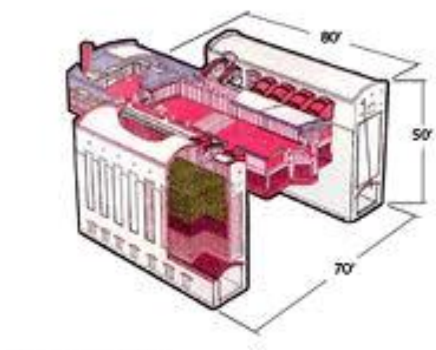


The self-recuperative burners cannot give the same heat transfer rate or heat transfer efficiency; hence the fuel savings are limited to 30%–60% of that normally available from an external recuperator.

Regenerators

Regenerators have been widely used in glass and steel melting furnaces to recover heat from high-temperature exhaust gases, normally above 2,500°F (1,370°C). They are made from high-temperature refractory bricks or specially designed ceramic shapes. The efficiency of the regenerator depends on the size of the regenerator; the time span between reversals; and the thickness, conductivity, and heat storage ratio of the brick. The time span between the reversals is especially important because long periods would mean higher thermal storage and hence higher cost as well as lower average temperature of preheat and consequently reduction in the fuel economy. Accumulation of dust and slag on the surfaces reduce efficiency of heat transfer as the furnace becomes old. Heat losses from the walls of the regenerator and air in-leaks during the gas period and out-leaks during the air period also reduce the heat transfer.

Exhibit A-4: Large Regenerative Heat Recovery System Used in Glass and Steel Industries

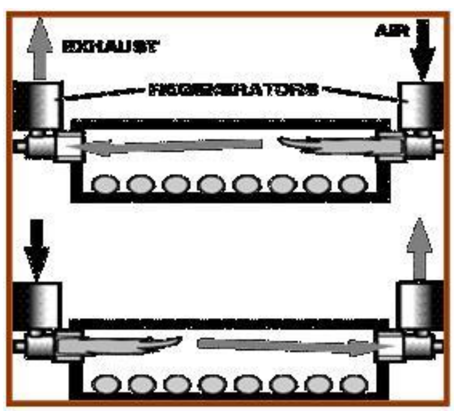


Regenerators offer higher heat recovery efficiency compared to recuperators. However, they use considerably larger surface area, are much more bulky, and require more frequent maintenance.

Regenerative Burners

Regenerative burners are a special class of regenerator that is attached to a pair of burners. The regenerator attached to a burner is much smaller in size, uses small ceramic pebbles or shapes, and requires more frequent cycling than that for a large regenerator. Typically, these systems offer 60%–80% heat recovery efficiency and require cycling every 20 seconds or less. This is almost 50 times more frequent than that of the large recuperators.

Exhibit A-5: Regenerative Burners for Medium to Small Furnaces



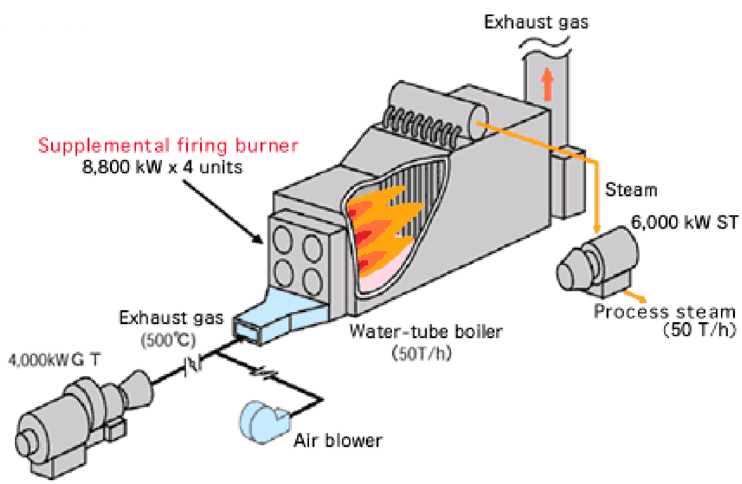
These burners are used for high-temperature furnaces, such as aluminum melting furnaces, forge furnaces, or steel reheating furnaces. Cost of these units is 2–3 times higher than the normal recuperator itself. However, it can be as cost effective as a normal heat recovery system using a recuperator because the regenerative burners do not have added cost of hot air piping or preheated air burners, for example.

These systems are not recommended for use where the flue gases contain large amount of particulates, condensable vapors, combustibles, or other type of contaminants.

Waste Heat Recovery Boilers

Waste heat boilers are ordinarily water tube boilers in which the hot exhaust gases from gas turbines, incinerators, etc., pass over a number of parallel tubes containing water. The water is vaporized in the tubes and collected in a steam drum from which it is drawn out and used as heating or processing steam. Because the exhaust gases are usually in the medium temperature range and to conserve space, a more compact boiler can be produced if the water tubes are finned in order to increase the effective heat transfer area on the gas side. Exhibit A-6 shows a waste heat boiler system used to recover heat from a gas turbine exhaust.

Exhibit A-6: Waste Heat Boiler (HRSG) Application for Gas Turbine Exhaust Gases



The gases, ranging from 900°–1,100°F (480°-590°C) are used in a water tube boiler with supplementary fuel. The steam is used for process heating or power generation in the plant. The boilers are fairly efficient (65%–70%) in recovering heat. A similar arrangement can be used for recovering waste heat from furnaces or heaters.

The pressure of the generated steam and the rate at which steam is produced are limited by the temperature of waste heat. The pressure of a pure vapor in the presence of its liquid is a function of the temperature of the liquid from which it is evaporated. The steam tables tabulate this relationship between saturation pressure and temperature. If the waste heat in the exhaust gases is insufficient for generating the required amount of process steam, auxiliary burners, which burn fuel in the waste heat boiler, or an after-burner in the exhaust gas flue, are added.

Before pursuing use of waste heat boilers, consider that these boilers are only economically justified when exhaust gas streams contain a relatively large (>10 MM Btu/hr) amount of heat. Also consider the following barriers as well:

- Size limitations – good for large size systems

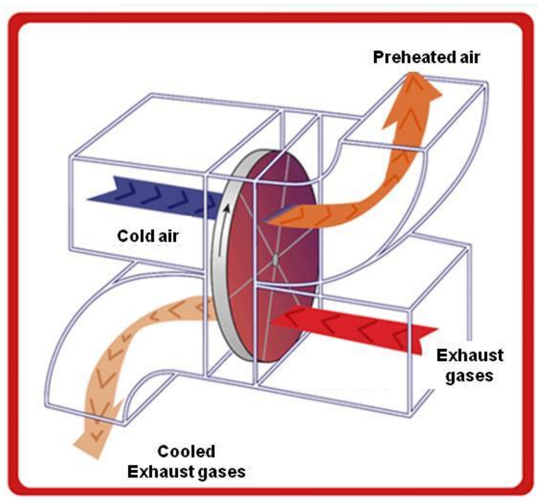
- Cleanliness of exhaust gases– they should not be used when the gases contain large amounts of particles or condensable vapors
- They cannot be used if there is no need for steam in the plant
- They are not recommended when the gas mass flows vary over a period of time – use of auxiliary heat can be expensive and economically unjustifiable

Low- to Medium-Temperature Heat Recovery Equipment

Heat Wheels

A heat wheel is finding increasing applications in low- to medium-temperature waste heat recovery systems, usually limited to about 600°F (315°C). The wheel itself is a sizable porous disk, fabricated with material having a fairly high heat capacity that rotates between two side-by-side ducts: one is a cold gas duct, the other a hot gas duct. The axis of the disk is located parallel and on the partition between the two ducts.

Exhibit A-7: Typical Heat Wheel Type Waste Heat Recovery Unit



As the disk slowly rotates, hot air transfers sensible heat (moisture that contains latent heat) to the disk by the hot air and from the disk to the cold air. The overall efficiency of sensible heat transfer for this kind of regenerator can be as high as 85%.

A variation of the heat wheel is the rotary regenerator where the matrix is in a cylinder rotating across the waste gas and air streams. The heat or energy recovery wheel is a rotary gas heat regenerator, which can transfer heat from exhaust to incoming gases. Its main area of application is where heat is exchanged between large masses of air having small temperature differences.

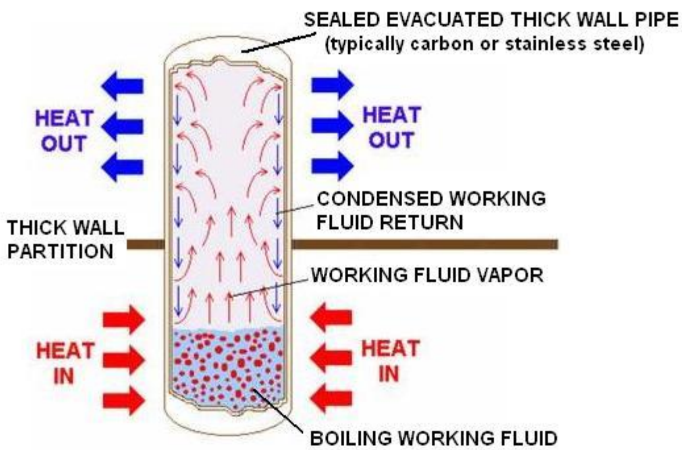
The heat wheel system requires good seals between the higher pressure air being heated and the lower pressure exhaust gases. Reliability of seals and plugging up of the gas passages have been the major draw backs of a heat wheel. These systems are most commonly used for preheating combustion air for boiler. Their use is very limited for industrial furnaces other than low temperature ovens.

Heat Pipe

A heat pipe is a thermal energy absorbing and transferring system that has no moving parts and therefore requires minimal maintenance. It can transfer up to 100 times more thermal energy than copper—the best-known conductor.

As shown in Exhibit A-8, the heat pipe is comprised of three elements: a sealed container, a capillary wick structure, and a working fluid. The capillary wick structure is integrally fabricated into the interior surface of the container tube and sealed under vacuum. Thermal energy applied to the external surface of the heat pipe is in equilibrium with its own vapor as the container tube is sealed under vacuum, and causes the condensed working fluid near the surface to evaporate instantaneously. Vapor thus formed absorbs the latent heat of vaporization and this part of the heat pipe becomes an evaporator region. The vapor then travels to the other end the pipe where the thermal energy is removed causing the vapor to condense into liquid again, thereby giving up the latent heat of the condensation. This part of the heat pipe works as the condenser region. The condensed liquid then flows back to the evaporated region.

Exhibit A-8: Typical Heat Pipe Used for Waste Heat Recovery



The heat pipe exchanger (HPHE) is a lightweight compact heat recovery system that is not only mechanical-maintenance-free — because there are no moving parts that wear out— but it also does not need input power, cooling water, or a lubrication system. It also lowers the fan horsepower requirement and increases the overall thermal efficiency of the system. Heat pipe heat recovery systems are capable of operating with 60%–80% heat recovery capability.

Heat pipes are typically used in the following industrial applications:

- Processing space heating – The heat pipe heat exchanger transfers the thermal energy from process exhaust for building heating. The preheated air can be blended if required. The requirement of additional heating equipment to deliver heated make up air is drastically reduced or eliminated.
- Process to process – The heat pipe heat exchangers recover thermal energy waste from the exhaust process and transfer this energy to the incoming process air. The incoming air thus becomes warm and can be used either for the same process/other processes and hence, reduce process energy consumption.

- Cooling – Heat pipe heat exchanger pre-cools the building makeup air in the summer and thus reduces the total tonnes of refrigeration, apart from the operational saving of the cooling system. Thermal energy is recovered from the cool exhaust and transferred to the hot supply makeup air.
- Heating –The above process is reversed during winter to preheat the makeup air.

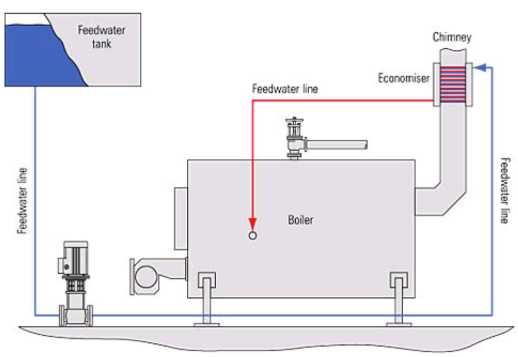
Following are other applications of heat pipes in industry:

- Preheating of boiler combustion air
- Recovery of waste heat from furnaces
- Reheating of fresh air for hot air driers
- Recovery of waste heat from catalytic deodorizing equipment
- Reuse of furnace waste heat as heat source for other oven
- Cooling of closed rooms with outside air
- Preheating of boiler feed water with waste heat recovery from flue gases in the heat pipe economizers.
- Drying, curing, and baking ovens
- Waste steam reclamation
- Brick kilns (secondary recovery)
- Reverberatory furnaces (secondary recovery)
- Heating, ventilating, and air-conditioning systems

Economizers

An economizer can be used with a boiler system to pre-heat the boiler feedwater with the flue gas heat or, in an air pre-heater, to pre-heat the combustion air. In both the cases, there is a corresponding reduction in the fuel requirements of the boiler. For every 428°F (220°C) reduction in flue gas temperature by passing through an economizer or a pre-heater, there is a 1% saving of fuel in the boiler. In other words, for every 140°F (60°C) rise in feedwater temperature through an economizer, or 392°F (200°C) rise in combustion air temperature through an air pre-heater, there is 1% saving of fuel in the boiler.

Exhibit A-9: Feedwater Economizer – Typical Unit and Installation on a Boiler

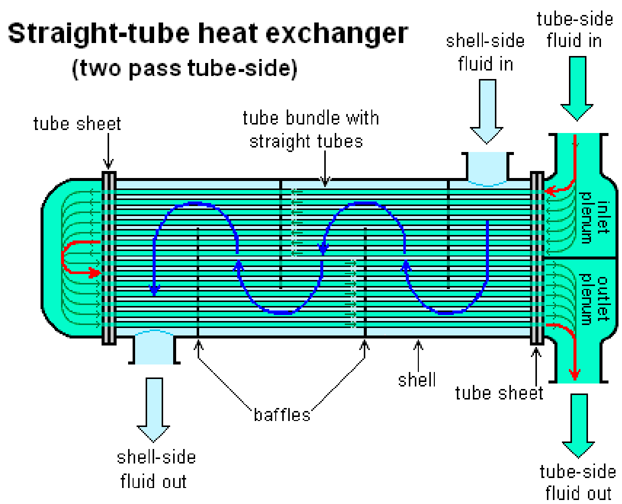


Shell and Tube Heat Exchangers

A shell and tube heat exchanger must be used when the medium to contain waste heat is a liquid or a vapor which is used to heat another liquid. This is because both paths must be sealed to contain the pressures of their respective fluids. The shell contains the tube bundle and usually internal baffles to direct the fluid in the shell over the tubes in multiple passes. The shell is inherently weaker than the tube, so that the higher pressure fluid is circulated in the tubes while the lower pressure fluid flows through the shell. When a vapor contains the waste heat, it usually condenses, giving up its latent heat to the liquid being heated. In this application, the vapor is almost invariably contained within the shell. If the reverse is attempted, the condensation of vapors within small diameter parallel tubes causes flow instabilities.

Tube and shell heat exchangers are available in a wide range of standard sizes with many combinations of materials for the tubes and shells. A shell and tube heat exchanger is illustrated in Exhibit A-10 below.

Exhibit A-10: Commonly Used Shell and Tube Type Heat Exchanger for Fluid Heating



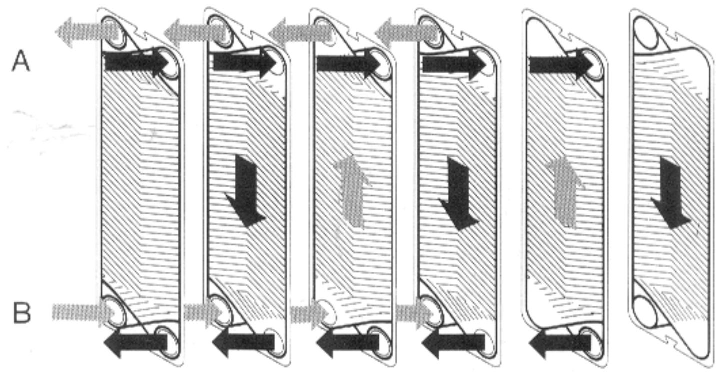
Shell and tube heat exchangers are typically used in the following applications:

- Refrigeration and air-conditioning systems
- Process steam
- Engines, air compressors, bearings, and lubricants
- Distillation processes

Plate Heat Exchanger

The cost of a heat exchange surface is a major factor when the temperature differences are not large. One way of meeting this problem is the plate type heat exchanger, which consists of a series of separate parallel plates forming a thin flow pass. Each plate is separated from the next by gaskets and the hot stream passes in parallel through alternative plates while the liquid to be heated passes in parallel between the hot plates. To improve heat transfer, the plates are corrugated. Hot liquid passing through a bottom port is permitted to pass upward between every second plate while cold liquid at the top is permitted to pass downward between the odd plates. When the directions of hot and cold fluids are opposite, the arrangement is described as counter current. A plate heat exchanger is shown in Exhibit A-11.

Exhibit A-11: Commonly Used Plate Type Heat Exchanger for Fluid (Mostly Liquid) Heating



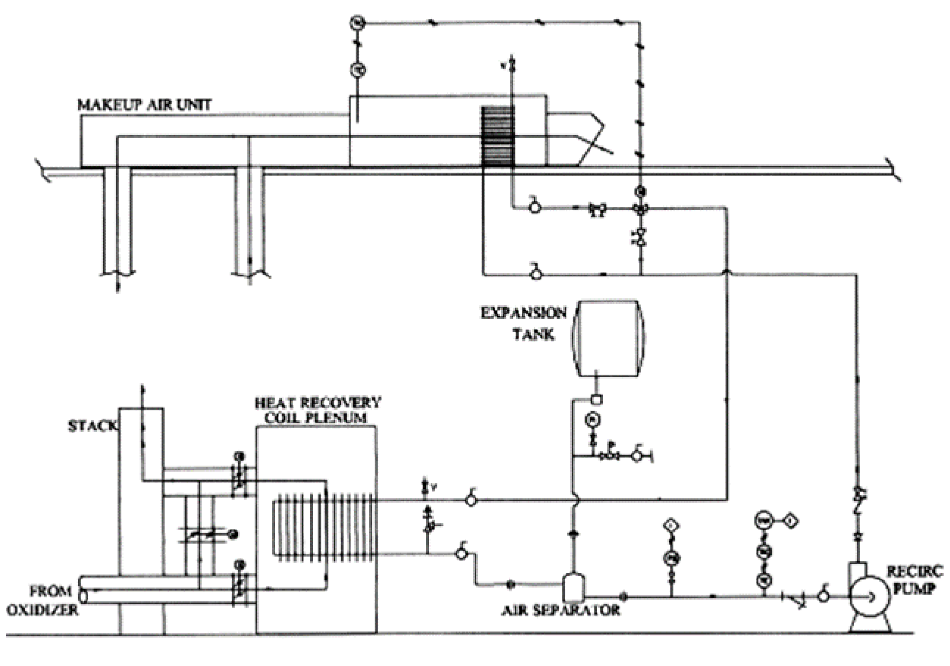
Typical industrial applications of the plate heat exchanger are as follows:

- Pasteurization section in a milk packaging plant
- Evaporation plants in the food industry
- Petroleum-refining industry for heat recovery
- Chemical industry for heat recovery

Run Around Coil Exchangers

Run around coil exchangers are similar in principle to heat pipe exchangers. The heat from hot fluid is transferred to the colder fluid via an intermediate fluid known as the “heat transfer fluid.” One coil of this closed loop is installed in the hot stream, while the other is in the cold stream. Circulation of this fluid is maintained by means of a circulating pump. It is more useful when the hot and cold fluids are located far away from each other and are not easily accessible.

Exhibit A-12: Heat Recovery for HVAC Application Using Recirculating Liquid



Typical industrial applications are heat recovery from ventilation, air conditioning, and low-temperature heat recovery.

Low-Temperature Waste Heat Recovery Systems

With a few notable exceptions, most low-temperature heat exchangers are constructed from copper tubing with aluminum fins soldered or press-fitted on the outside surface of the copper tubes. The tubes are bent in the hairpin shape to provide longer residence time for the fluid flow inside the tube. Both of these design features improve heat transfer. In addition, low-temperature waste heat recovery systems have several new features that offer higher heat transfer rates, such as special fin designs for finned tube heat exchangers and redesigned tube-on-plate condensers with Coanda-effect louver designs that allow the air to flow in wave form.

Plastic Heat Exchangers

New plastic heat exchangers developed by several suppliers offer an alternative to metal heat exchangers as metal exchangers are subject to corrosion, oxidation, and microbiological attack and experience slow degradation and loss in heat transfer capacity when used in chemical water treatment.

Use of specialized plastics for heat exchanger tubing provides effective energy transfer in most applications. Some suppliers claim that the heat transfer capacity of this plastic tubing is comparable to that of copper heat exchangers, and that transfer rate remains consistent for both heating and cooling. These heat exchangers are not subject to corrosion, oxidation, microbiological attack, or galvanic action. This allows the plastic heat exchangers to function effectively under conditions in which conventional systems would not survive. Additionally, friction or contact between coils during operation is not an issue because: 1) the coils naturally dampen the vibrations in the system and 2) the surface is smoother, permitting little friction between tubing rows even if they do come in contact. Also, plastic is lightweight and its surface is smoother than copper and resists the buildup of material deposits, which can restrict both fluid and airflow through and around the coils. If an internal buildup does occur, it can be removed by flushing the plastic at moderate pressure.

Despite their significant advantages, plastic heat exchangers are not suitable for all applications. They cannot be used with refrigerants or high-pressure or high-temperature systems. Plastic is not a suitable heat transfer media for systems with operating temperatures higher than 220°F (105°C) or pressures higher than 150 psi. Plastic additionally cannot be used with any gaseous systems because it does not serve as a sufficient vapor barrier.

Direct Contact Water Heaters

The direct contact water heaters are used to heat water using sensible and latent heat of exhaust gases. In many cases, the latent heat represents more than 10 times the sensible heat. A typical direct contact water heater, shown in Exhibit A-13, is used to recover heat from a boiler's exhaust gases.

Colder water from the process enters the top inlet of the water heater (economizer) and is sprayed over the heat transfer media. Simultaneously, the hot exhaust gas or boiler flue gas is directed to the flue gas inlet, at the base of the economizer. The water travels from the spray nozzle counterflow, from the rising flue gas through the stainless steel transfer media. As the water droplets travel through the media, the hot flue gas rises to the top of the economizer, preheating the water.

Exhibit A-13: Direct Contact Water Heater Used for Latent Heat Recovery from Flue Gases

Final heating of the water takes place in the direct contact chamber. Either a transfer pump or gravity move the preheated water to a hot water storage system, then onto the direct contact water heater.

The hot water contains carbonic acid, since the flue gas CO_2 is dissolved in water. Therefore, the water can only be used in selective applications. It is not advisable to recycle this water. In some cases, it is possible to use a secondary heat exchanger designed with proper materials to recover heat from the hot water in a recirculating media.

Direct contact water heaters are highly effective in recovering a large percentage (as much as 90%) of the total heat content of flue gases. The efficiency depends on the temperature of flue gases and, more importantly, the inlet water temperature that controls the outlet (colder) gas temperature from the unit. The exhaust gas from the unit is saturated and carries water vapor. Higher outlet temperatures would reduce the heat recovery efficiency significantly.

Primary barriers to using this technology include limited temperature rise for the water, acidic nature of the heated water, and issues associated with plugging up the media in the unit. The hot water is used for cleaning or as process water for some industries.

The industrial applications of these systems include the food industry, cement industry, automotive industry, and laundry, and textile industry.

Heat Pumps

In the various commercial options previously discussed, waste heat is transferred from a hot fluid to a fluid at a lower temperature. Heat must flow spontaneously "downhill," that is, from a system at high temperature to one at a lower temperature. When energy is repeatedly transferred or transformed, it becomes less and less available for use. Eventually, energy has such low intensity (resides in a medium at such low temperature) that it is no longer available to function.

It has been a general rule of thumb in industrial operations that fluids with temperatures less than 248°F (120°C) **(**or, better, 300°F or 150°C to provide a safe margin), are set as the limit for waste heat recovery because of the risk of condensation of corrosive liquids. However, as fuel costs continue to rise, even such waste heat can be used economically for space heating and other low-temperature applications. It is possible to reverse the direction of spontaneous energy flow by using a thermodynamic system known as a heat pump. The majority of heat pumps work on the same principle as the vapor compression cycle. In this cycle, the circulating fluid (such as a refrigerant) is physically separated from the heat source (i.e. waste heat, at a higher temperature) and the fluid is re-used in a cyclical fashion, therefore being called "closed cycle." In the heat pump, the following processes take place:

- In the evaporator, the heat is extracted from the heat source to boil the circulating substance.
- The compressor compresses the circulating substance, thereby raising its pressure and temperature. The low-temperature vapor is compressed by a compressor, which requires external work. The work done on the vapor raises its pressure and temperature to a level where its energy becomes available for use.
- The heat is delivered to the condenser.
- The pressure of the circulating substance (working fluid) is reduced back to the evaporator condition in the throttling valve, where the cycle is repeated.

The heat pump was developed as a space heating system where low-temperature energy from the ambient air, water, or earth is raised to heating system temperatures by doing compression work with an electric motor-driven compressor. Heat pumps have the ability to upgrade heat to a value more than twice the energy consumed by the device. The potential for application of heat pumps is growing and a growing number of industries have benefited by recovering low grade waste heat, upgrading it, and using it in the main process stream.

Heat pump applications are most promising when both the heating and cooling capabilities can be used in combination. One such example of this is a plastics factory where chilled water from a heat pump is used to cool injection-molding machines, while the heat output from the heat pump is used to provide factory or office heating. Other examples of heat pump installations include product drying in which the dry atmosphere for storage is maintained and compressed air is dried.

Thermo-Compressor

In many cases, for lack of a better option for reuse, very low-pressure steam is reused as water. However, it is feasible to compress this low-pressure steam by very high-pressure steam and reuse it as a medium-pressure steam. The major energy in steam is in its latent heat value, thus, thermo compressing would largely improve waste heat recovery.

A thermo-compressor is simple equipment with a nozzle where high pressure (HP) steam is accelerated into a high velocity fluid. This entrains the low pressure (LP) steam by momentum transfer and then recompresses it in a divergent venturi. It is typically used in evaporators where the boiling steam is recompressed and used as heating steam.

Thermally Activated Technologies (TAT)

TAT consists of equipment use thermal energy for heating, cooling, humidity control, and power (mechanical and electric). These technologies include absorption chillers or refrigerating equipment, desiccant systems for humidity control, and organic Rankine type power generation systems. Many of the systems known as Combined Heat and Power (CHP) can be considered thermally activated technologies when they use waste heat for power generation.

Absorption Chillers

Absorption chillers transfer recovered waste heat to a heat sink through an absorbent fluid and a refrigerant. There are two primary systems using two different types of working fluids: ammonia–water and lithium bromide-–water. Ammonia–water is used in a number of applications, such as small refrigerators and large heat-recovery machines installed with power plants. Ammonia is an excellent refrigerant with a high latent heat and excellent heat transfer characteristics. However, because of its toxicity, it is often restricted to applications in which the equipment is located outside to allow for the natural dilution of any leaks.

Aqueous lithium bromide is used for all types of systems and is being widely used to avoid concerns about the toxicity of ammonia-based systems. These systems use a low-temperature liquid refrigerant that absorbs heat from the heat source (usually hot water) to be cooled and converted to a vapor (in the evaporator section). The refrigerant vapor is then compressed to a higher pressure by a compressor or generator and converted back into a liquid by rejecting heat to the external surroundings in the condenser section. Next, it is expanded to a low-pressure mixture of liquid and vapor (in the expander valve), which boils in the evaporator section, absorbing heat and producing the cooling effect. Then the cycle is repeated.

Ammonia–Water Absorption System

Ammonia–water absorption chillers and heat pumps are designed for 2–10 RT (Refrigeration Tons) and can be modularized into larger systems. Compared with the lithium bromide single-effect absorption water cycle, the ammonia–water single-effect absorption cycle requires two additional components: a rectifier, which is needed because the absorbent (water) is volatile at generator conditions, and a condensate precooler. The rectifier is designed to strip some of the water out of the vapor stream.

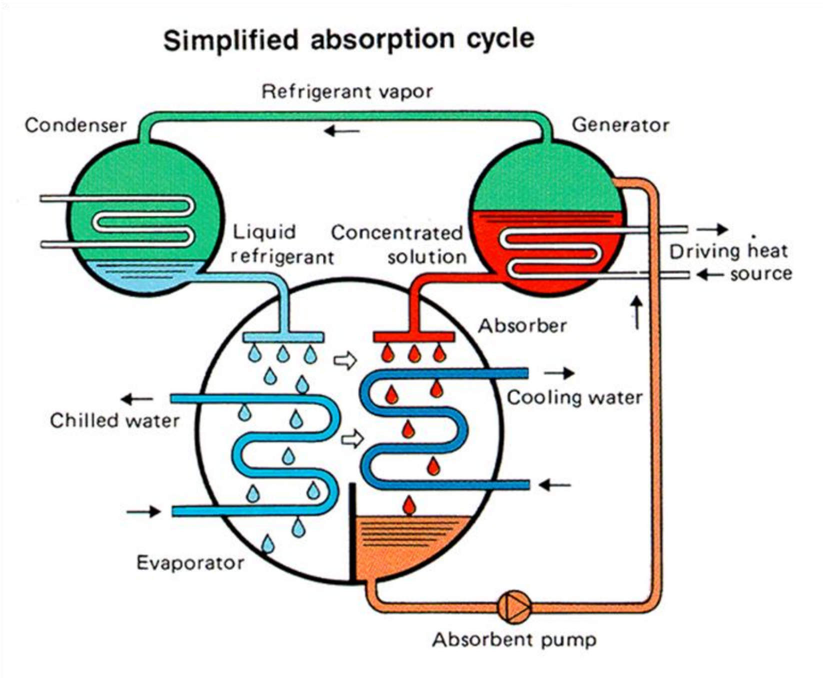
One design option for increasing the coefficient of performance (COP) that is available when ammonia-–water is the working fluid is the generator-absorber heat exchanger (GAX). GAX is not possible in lithium bromide systems because of the crystallization characteristics. The basic feature of GAX is an internal heat exchange. This allows the heat to be input at a higher temperature such that it is then reused internally. A temperature overlap between the generator and the absorber can be used to move some of the heat normally rejected by the absorber back to the generator, thereby reducing the heat input required and increasing efficiency. This overlap will only exist if the temperature difference between the condenser and evaporator is relatively low, which occurs in most air-conditioning applications.

Lithium Bromide Systems

A lithium bromide (Li-Br) system uses a solution of water and lithium bromide as working fluid instead of an ammonia and water mixture. The system uses waste heat in the form of low-pressure steam to supply the necessary energy to “drive” the system. The thermal system replaces a compressor used in electrically driven vapor compression systems commonly used by the industry.

As shown in Exhibit A-14, a typical absorption cooling system using fluids such as lithium bromide/absorption includes two vessels or shells. The upper shell contains the generator and condenser; the lower shell, the absorber and evaporator. Heat supplied in the generator section is added to a solution of $LiBr/H_2O$. This heat causes the refrigerant, in this case water, to be boiled out of the solution in a distillation process. The water vapor that results passes into the condenser section where a cooling medium is used to condense the vapor back to a liquid state. The water then flows down to the evaporator section where it passes over tubes containing the fluid to be cooled. By maintaining a very low pressure in the absorber-evaporator shell, the water boils at a very low temperature. This boiling causes the water to absorb heat from the medium to be cooled, thus lowering its temperature. Evaporated water then passes into the absorber section where it is mixed with a Li Br/H_2O solution that is very low in water content. This strong solution (strong in Li Br) tends to absorb the vapor from the evaporator section to form a weaker solution. This is the absorption process that gives the cycle its name. The weak solution is then pumped to the generator section to repeat the cycle.

Exhibit A-14: Simplified Absorption Cycle Using Heat



Efficiency of cooling system or chillers is indicated by the term “coefficient of performance (COP)” and is defined as cooling output divided by the required heat input. For a single effect unit that does not include extensive heat recovery heat exchangers, COP is in the range of 0.45–0.7. A comparable electrically operated system would have a COP of 4.5–6.0. However, for the absorption units that use waste heat, the operating cost is very small compared to the electrical units.

The cost (operating and capital or investment) should include the cost of the unit as installed at the location plus cost for auxiliary condenser equipment (cooling tower, cooling water pumps and cooling water piping). In most cases the cost of absorption system could be 50% higher than the equivalent electrical system. The auxiliary system cost is approximately 33% of the total cost of the system.

Power Generation Systems

A special category of heat recovery systems use waste heat for electric power generation. This section describes several of these power generation systems that are options for industrial applications and provides a comparison of these technologies.

- “Conventional plant" using a steam boiler, steam turbine, and generator
- Organic Rankine Cycle (ORC) plant
- Ammonia–water systems (i.e., Kalina, Neogen systems)

- Supercritical carbon dioxide systems
- Thermo-electric power generation (TEG)

The conventional systems for high-temperature waste heat applications use a heat recovery steam generator (HRSG) or boiler, steam turbine, and a generator to produce electricity. Other options are now available that can be used for lower temperature heat sources, including Organic Rankine Cycle (ORC), ammonia–water systems (i.e., Kalina, Neogen systems), Supercritical carbon dioxide systems, and Thermo-Electric Generators (TEG). This area is a fast-changing field. Technologies, performance, and costs can vary significantly.

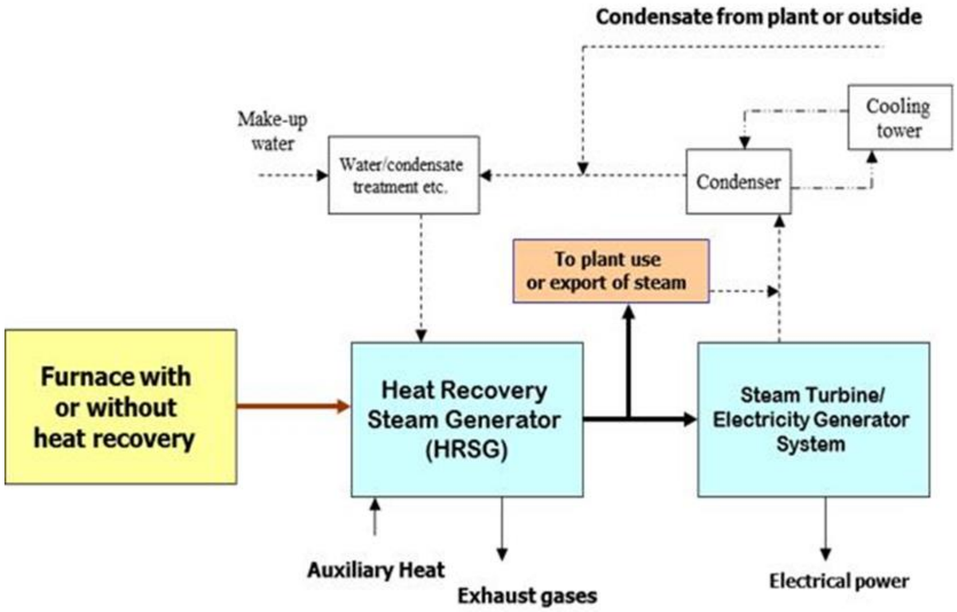
"Conventional Plant" Using a Steam Boiler, Steam Turbine, and Generator
The steam-based systems require heat source (usually exhaust gases) higher than 600°F (315°C) to produce high-pressure steam. The gases have to be relatively clean without the presence of particulates, condensable vapors, or corrosive gases that would affect performance and life of the boiler interiors. Efficiency, defined as the ratio of electrical energy produced to the total heat input (sensible and chemical heat of exhaust heat source, plus auxiliary heat input if used), is in the range of 25%–30%. Most of these systems are available in large sizes (higher than 2 MW electrical output or total heat input of 25 MM Btu/hr). Therefore, they are used only for very large fired systems such as steel reheating furnaces, process heaters, cement or lime kilns, and certain steel melting furnaces.

Following are other issues or barriers associated with conventional, steam-based, power generation systems:

- Need a 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
- Need continuous or predictable flow for the waste heat source
- Need relatively moderate waste heat stream temperature (at least 300°F (150°C), but >600°F (315°C) is preferred) at 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 as it can have a negative effect on overall economics—unless the power cost can justify it

As mentioned before, conversion efficiency of waste heat to electricity is low; therefore, it should only be considered when the heat cannot be used directly within the process or when other recovery methods are not practical within the plant. Overall economics of the system depends on the cost of electricity and, in some cases, on the benefits of reducing peak demand if the demand charges are high. It is advisable to avoid or reduce the use of supplementary fuel for power generation since this has negative effects on the overall economics.

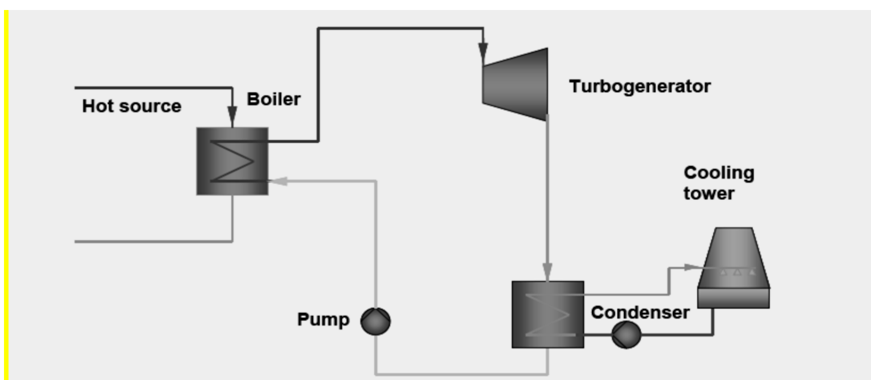
Exhibit A-15: Schematic for Electrical Power Generation System Components



Organic Rankine Cycle (ORC)

Organic Rankine Cycle is a generic name used for a number of systems where waste heat is used to generate electrical power. The variations in the systems are attributed to the working fluid used and types of critical companies used. Exhibit A-16 shows a schematic of a typical ORC system.

Exhibit A-16: Organic Rankine Cycle (ORC) System Components



A heat source, such as hot water or steam (flue gases in some cases), is used to heat and evaporate high-pressure working fluid (typically refrigerants, such as R124, R134a, or R245fa or light hydrocarbons such as isoButane, n-Butane, isoPentane, and n-Pentane); a turbo generator is used to expand pressure of the vapors of the working fluid and generate mechanical work; a condenser is used to cool and liquefy the cooled vapors; and a pump is used to increase pressure of the liquid. The turbo generator is connected to an electrical generator to convert mechanical energy into electricity. It is necessary to supply a cooling medium, usually water, for the condenser. Heated water from the condenser is cooled in a cooling tower.

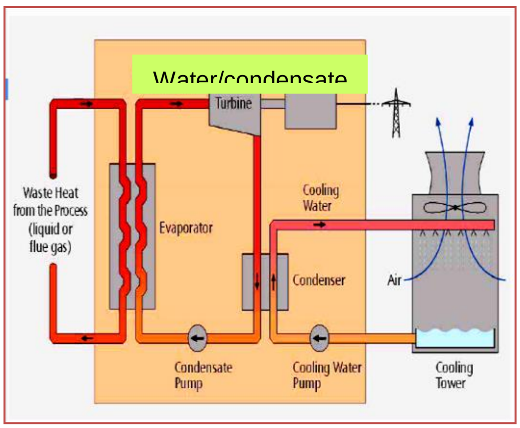
Waste heat is supplied at a temperature of approximately 300°F (150°C) as a minimum temperature to the evaporator, and the cooling water in the condenser can be between 60°–90°F (15°–32°C). Several variations of the ORC system are offered by a number of suppliers; however, the general performance of the ORC system is within a narrow range due to thermodynamic limitations of the system.

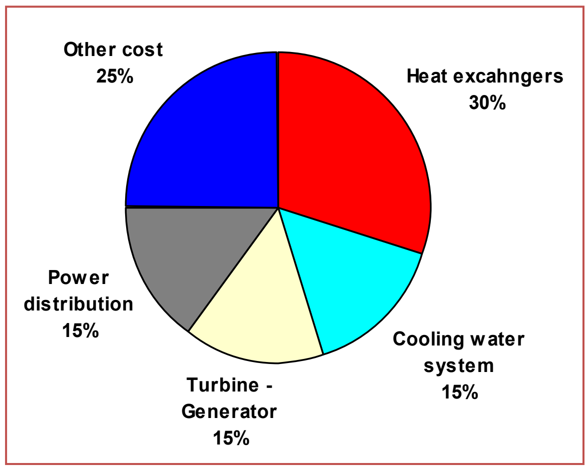
The term “efficiency” of the system is defined in many different ways and it is important to fully understand the meaning of the term “efficiency.” The efficiency represents the percentage of the supplied energy in the heating medium and recovered as electricity (converted to Btu/hr). The efficiency ranges from 8%–15%, depending on the heating source temperature. The efficiency ranges for heat source temperature are from 300°–800°F (150°–430°C).

Cost of the system varies from $2,500–$3,500 per kW design capacity. The cost distribution of a typical system is provided in Exhibit A-17. It shows that a large percentage is used for heat exchangers, and cost reduction efforts should be directed towards the development of improved—compact heat exchangers to reduce the cost as well as the footprint of the system.

In the past, most of the applications of the ORC system have been in the geothermal field and non-industrial areas. Only recently are ORC systems being tested for industrial applications.

Exhibit A-17: Organic Rankine Cycle (ORC) System Components and Cost Distribution



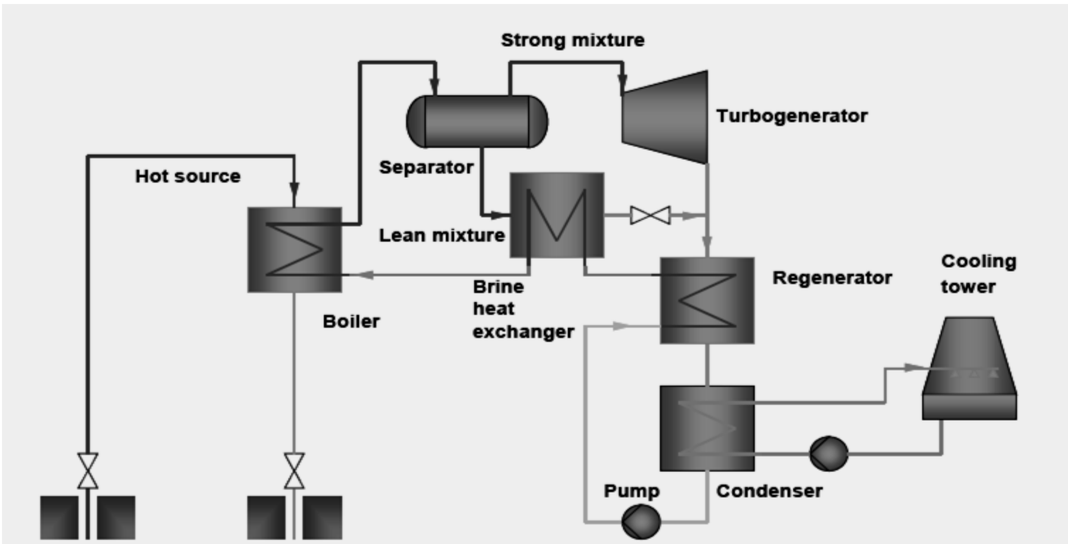


Ammonia–Water System: The Kalina Cycle

The Kalina cycle, which uses a mixture of 70% ammonia–30% water as the working fluid, has the potential of achieving significant efficiency gains over the conventional Rankine cycle. The general arrangement of components is very similar to the ORC system with several additional heat exchangers to improve heat recovery and enhance overall performance of the system. The system can be used for the heat source temperature range from 250°F (120°C) to as high as 1,000°F (540°C) with proper heat exchanger equipment. Operating efficiency is higher than the ORC system, about 15% with waste heat temperature in the range of 300°F (150°C), which improves at higher heat source temperature. The main reason for the improvement in efficiency is that the boiling of the ammonia–water mixture occurs over a range of temperatures, unlike other fluids; therefore, the amount of energy recovered from the gas stream is much higher. The condensation of ammonia–water also occurs over a range of temperatures, permitting additional heat recovery in the condensation system, unlike Rankine cycle, where the low-end temperature (affected by ambient conditions) limits the condenser back pressure and power output of system.

Total cost of the system is relatively high ($2,000–$3,000 per kW capacity) compared to the ORC system. A large percentage of total cost (capital and maintenance) is, again, in heat exchangers. Most applications for this system have been in geothermal and other non-heavy industrial areas.

Exhibit A-18: Kalina Cycle System Components



Supercritical Carbon Dioxide Cycle

Use of supercritical carbon dioxide for low-temperature power generation is a relatively new development. These systems are discussed under the emerging technology section of this appendix.

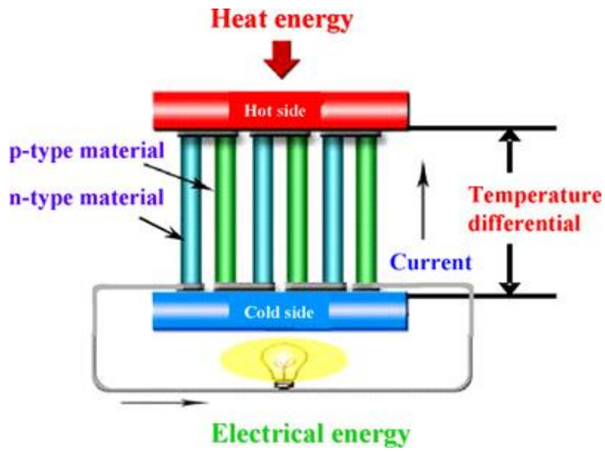
Thermo-Electric Power Generation (TEG)

Thermoelectric (TE) technologies have been considered potential candidates for direct conversion of waste heat into electricity. TE materials are semiconductor solids that produce an electric current when joined together and subjected to a temperature difference across the junction. The principle of operation is the same that is used in thermocouples. The material properties make it possible to generate direct current electricity by applying waste heat on one side of a TE material, while exposing the other side to lower or ambient temperature surroundings. The conversion efficiency from waste heat to electricity depends on the material properties and the temperature difference between the hot side and the cold side. The systems have been developed to be used for a temperature range from 400°–900°F (200°–480°C). Typical efficiency with the use of advanced material is from 5%–7% with a potential of reaching 15% as innovative materials, such as nano materials, are further developed.

As shown in Exhibit A-19, a TE power generation system consists of four unit operations:

- A TE module consisting of an array of several or hundreds of TE material junctions
- A hot-side heat exchanger
- A cold-side heat exchanger
- A power electronic module to provide the desired volt and ampere output

Exhibit A-19: Thermo-Electric Generator (TEG) System Components



Design and operation of each of these operations is critical to determining and realizing the anticipated TEG performance in industrial waste energy recovery.

At this time, the cost of TEG units is approximately $5,000 or higher on a per kW power production basis. Systems for industrial application are in the early development stage and are not proven for industrial use. Industrial-scale application of TE technology will require considerable R&D and technology pilot demonstration before it can be used for waste heat-to-power applications.

As shown in the following table, the most attractive option for clean, contamination-free waste heat >800ºF (425ºC) is the conventional steam turbine-generator option. Of the three options available at lower waste heat temperatures, ORC, ammonia–water based systems, and CO_2-based systems, none currently have a long and proven history in industrial applications to offer economically justifiable power generation. Waste heat-to-power projects are difficult to justify for <400ºF (200ºC) waste heat, especially if the waste heat supply is not continuous and an auxiliary energy is required.

Thermo-electrical systems are in an early development stage and their use cannot be economically justified at this time, except in special cases. This technology is being used for a temperature range of 400°–900ºF (200°–480ºC). The reported efficiency has been less than 5%, with a very expensive cost of >$5,000 per kW. The technology will require considerable R&D and technology pilot demonstration before it can be used for waste heat-to-power applications.

Exhibit A-20: Comparison of Low Temperature Electric Power Generation Systems

Comparison	Steam Rankine	Organic Rankine (ORC)	Ammonia (NH_3)–Water	Supercritical CO_2 Power Cycle
Source Temperature Range °F (°C)	800°F+ (430°C+)	200 to 500°F (90 to 260°C)	200 to 800°F (90 to 430°C)	400 to 1,200°F (200 to 650°C)
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	Corrosive, non-toxic, non-flammable, thermally stable
Conversion Efficiency	20%+	8 to 12%	8 to 15%	13 to 17%
Reported Cost ($/kw)	$600+	$2,500+	$2,500+	$2,000+

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

Emerging Waste Heat Recovery Technologies

Several new developments are underway for improving performance of the existing systems or advancing the waste heat recovery technology. At this time, there are many technologies already in use and many suppliers of these technologies are making incremental progress towards improving current technologies for their current market or expanding the application areas. There are only a few truly new technologies being developed.

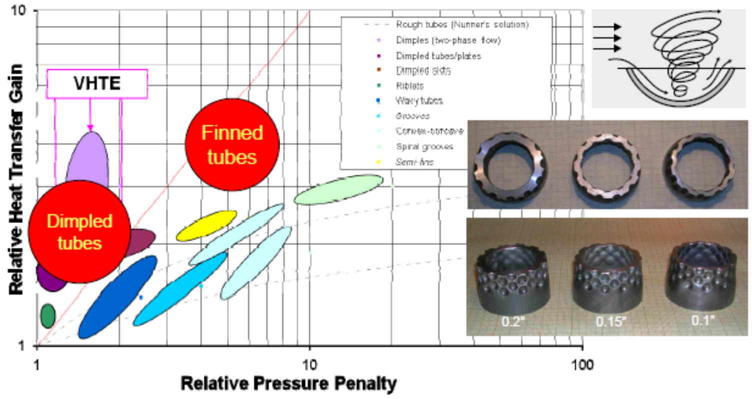
In many cases, it is difficult to get detailed information on the technologies that are being developed or being advanced as this information is highly proprietary. The following section gives a brief overview of the technologies and their benefits. Information for the following technologies was obtained from the Gas Technology Institute (GTI).

Advanced Heat Transfer Enhancement

This technology is being developed to increase the convection heat transfer coefficient for heat exchangers used in low- to medium-temperature applications where radiation is very small, and convection heat transfer from gases controls the overall performance of a heat exchanger. The development offers increased heat transfer relative to the increased pressure drop, which affects energy use in blowers and compressors used with the heat recovery systems.

In this system, a dimpled tube is substituted for traditionally used finned tubes. As shown in Exhibit A-21 below, the dimpled tube configuration increases heat transfer by 2 to 3 times that for the bare tube while increasing the pressure drop by 50% or so. The exact values of improvement depend on the size of the dimple. The equipment, like an economizer, offers several additional advantages, such as reduced cost, fewer chances of surface deposits that deteriorate the performance, lower maintenance, and lower cost of tube replacement. In general, the system cost is reduced by 20%–30%.

Exhibit A-21: Convection Heat Transfer Enhancement by Using Dimpled Tubes



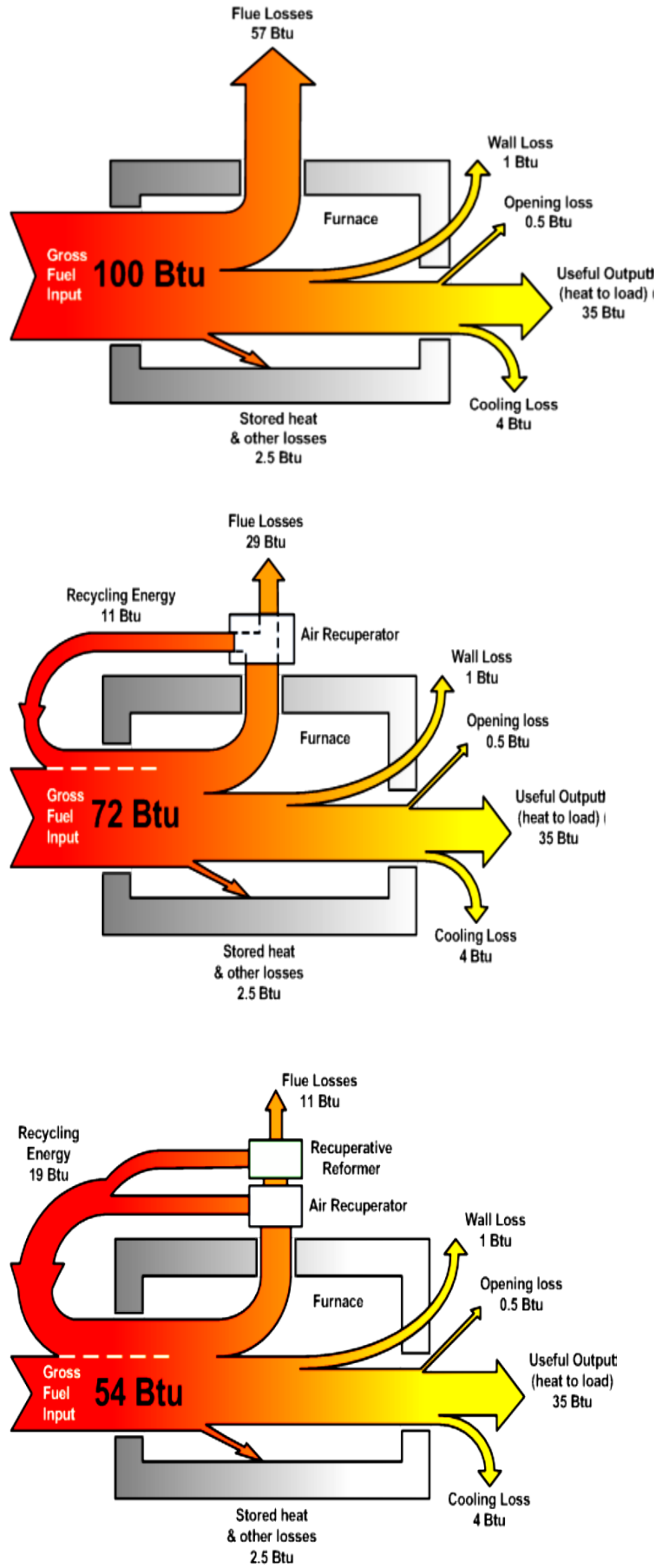
At this time, the technology is not widely used due to lack of availability of the tubes and unwillingness of the tube manufacturers to gear up to manufacture these tubes. GTI is working with several heat transfer equipment suppliers to make them aware of the technology and its benefits.

Thermochemical Recuperation of Fuel Gas

This technology can be used for medium- and high-temperature waste heat streams for natural gas fired burners or other similar equipment where gaseous flues are used. This technology uses waste heat to drive an exothermic natural gas reforming reaction that would result in production of CO and H_2 and increase the overall heating value of natural gas. The system uses air, oxygen, or steam for the reforming reaction. According to the developer of this technology, GTI, use of this technology results in overall energy reduction of 6%–10% for a gas-fired internal combustion engine. Similar benefits can be derived for other fired equipment.

A group of Sankey diagrams for a gas fired system (shown in Exhibit A-22) show that energy use would reduce from a base value of 100 to 72 with use of a conventional recuperator to preheat combustion air. The energy use can be reduced further to 54, an additional 18%, with the use of thermochemical recuperation. The technology has been demonstrated for IC engine application. According to GTI, payback for this system is less than one year for most high-temperature applications when the system is used on a continuous basis.

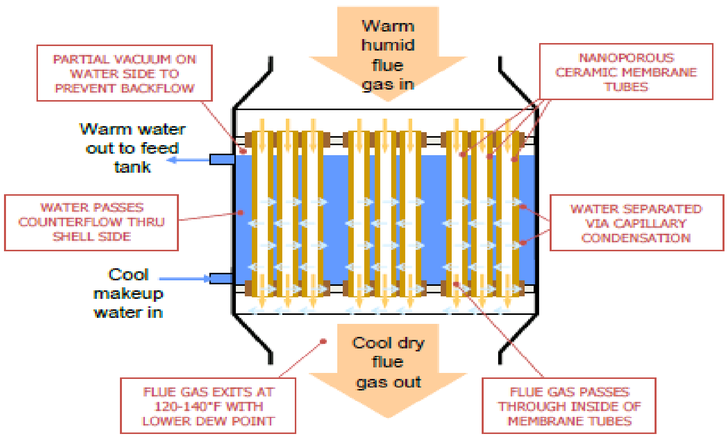
Exhibit A-22: Heat Balance (Sankey Diagrams) Showing Energy Savings with Use of Thermochemical Recuperative (TCR) System



Water Vapor Condensation in Exhaust

Heat recovery from combustion products and gases containing high moisture can be increased by at least 10% when latent heat of water vapor is recovered. GTI has developed an advanced Heat Recovery System (AHRS) package featuring the Transport Membrane Condenser (TMC). TMC bundles include hundreds of porous ceramic membrane tubes. As shown in Exhibit A-23, combustion products from boilers and other heating systems flow through the TMC where latent and sensible heats are recovered along with water vapor. This is accomplished by dehumidifying the flue gas and recovering the condensed water vapor. The cold water, or boiler feedwater in case of boilers, flows through the tubes, thereby drawing the heat-laden moist effluent into the membrane structure by first condensing inside the inner separation membrane layer employing a slight vacuum as the motive force for extraction. Pure water is recovered while other gas components in the flue gas pass by, due to their larger molecular size. The condensed water along with its latent heat joins with the cold boiler feedwater, transferring its heat to the feedwater and thus reducing fresh water requirements commensurately.

Exhibit A-23: Transport Membrane Condenser (TMC) System Components



Use of AHRS results in 95% fuel-to-steam efficiency for boiler applications. This amounts to 15%–20% decrease in fuel consumption, 30%–50% recovery of water from flue gas, and 15%–20% reduction in greenhouse gas emissions.

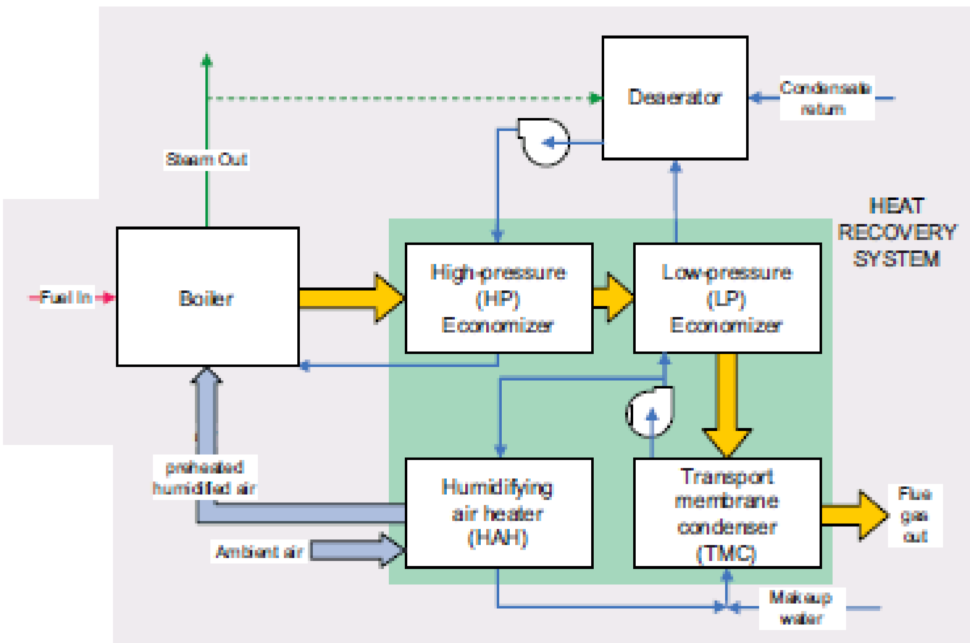
The AHRS has been in operation for over 15,000 hours at a rubber plant in Alabama and at varying hours at several other locations at food processing plants, pharmaceutical plants, and a military base. .

Super Boiler

Super boiler, although technically not a waste heat recovery system, provides an example of integration of a number of waste-heat-related (reduction and recovery) technologies to improve performance of one of the most widely used systems for industries,

A "super boiler" program was initiated by the U.S. Department of Energy in collaboration with several industrial partners to make a quantum jump in energy efficiency of a boiler for high-pressure steam systems. The super boiler combines a boiler design with footprint reduction, extended heat transfer surface, ultra low NO_x combustion system, and Advanced Heat Recovery System (AHRS) featuring the Transport Membrane Condenser (TMC), all in a single offering. The system is comprised of a two-pass, high-pressure steam fire tube boiler with AluFer tubes and NO refractory, an ultra low NO_x/high turndown burner, state-of-the-art controls, and an AHRS. The AHRS is comprised of a high-temperature economizer, a low- temperature economizer, state-of-the-art control system, and the transport membrane condenser—all integrated into a single system. As shown below, the modules of the systems include a boiler, high pressure and low pressure economizers for feedwater heating after and before the deaerator unit, a Transport Membrane Condenser to condense part of the water contained in exhaust gases, and a humidifier air heater.

Exhibit A-24: Super Boiler System Components



The super boiler design offers of AHRS results in 50% reduction in boiler footprint, 15%–20% reduction in fuel use, 30%–50% recovery of water from flue gases, and 15%–20% reduction in greenhouse gas emissions with less than 9 ppm NO_x.

The major issues for the technology are the cost and payback period for the investment in the super boiler design and fragile nature of ceramic membrane (TMC) tubes.

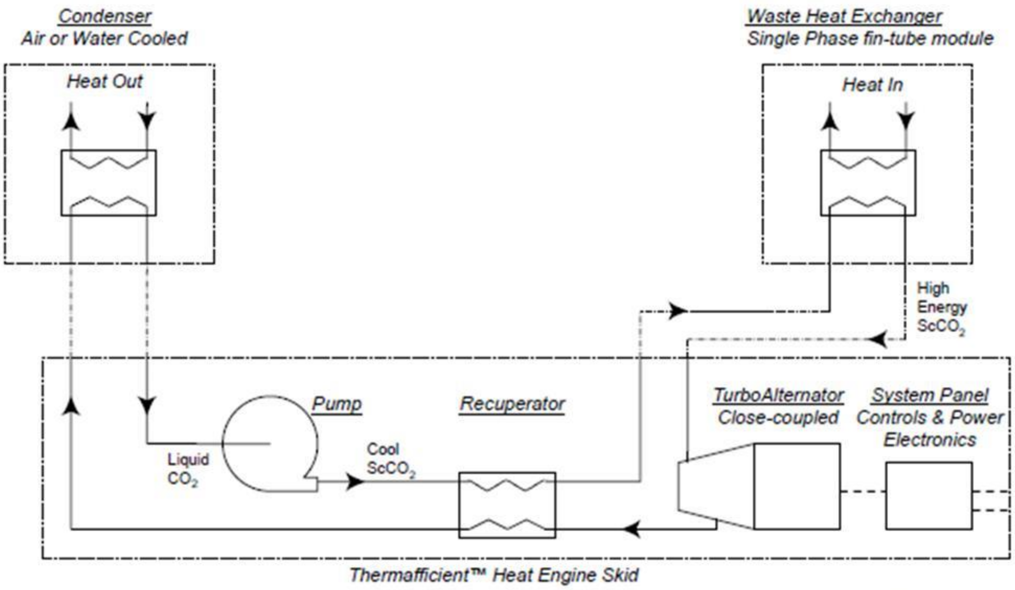
Super Critical CO_2-based Power Generation Technology

At least two low-temperature waste heat-to-power systems are in the development stage. Each of these systems uses supercritical CO_2 as working fluid. However, the technology and approach taken for the system is quite different. These systems are discussed below.

EchoGen System – Thermal Engine

This system uses liquid CO_2 as a working fluid. As shown in Exhibit A-25, liquid CO_2 is pumped to supercritical pressure and then passed though a recuperator where it is preheated before going to a heat exchanger, where it is heated and vaporized at supercritical pressure using heat from a source of waste heat. The waste heat source can be at any temperature between 400°F and 1,200°F (200 to 650°C). This high-energy $ScCO_2$ is expanded in a turbo-alternator producing high-frequency electrical power. The low-pressure vapors are taken to a condenser where colder air or water is used to condense the $ScCVO_2$ in the liquid state. The system uses power electronics to condition power to customer specifications.

Exhibit A-25: Electrical Power Generation System that Uses Supercritical Carbon Dioxide – Echogen System



The developer claims to achieve 13.6%–17.5% efficiency, which is defined based on the heat transferred and supplied to the system and electrical power generation.

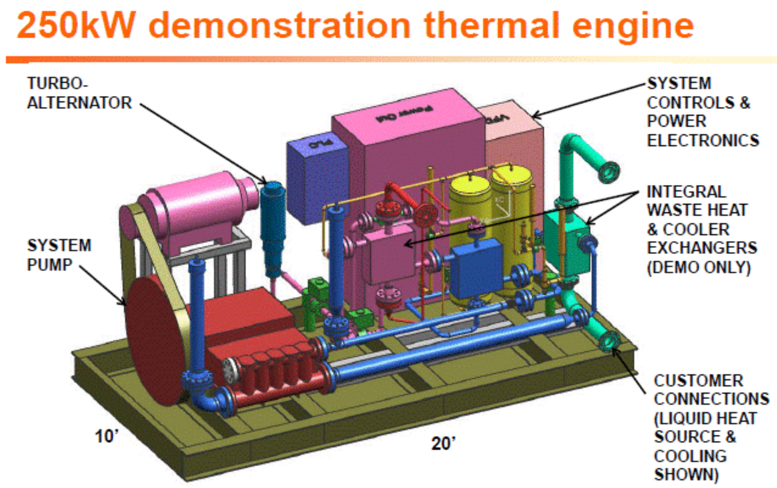
Following are the major advantages of this system:

- Since fluids lose distinct liquid and vapor phase above "critical pressure," the waste heat exchanger temperature "pinch" limit for steam is eliminated.
- Thermal stability provides a key advantage over ORC refrigerant-based working fluids. Also, thermal breakdown of HCFC and HFC's at ~500°F (260°C) eliminates the need for a bypass stack, which is required for conventional ORC systems.
- CO_2 being non-flammable, it permits direct heat transfer from gases to the working fluid. The working fluids used in ORC systems are hydrocarbon-based fluids and they are extremely flammable. Safety considerations, in this case, require external heat transfer fluid loop for stack applications. Elimination of intermediate heat exchangers reduces cost and the overall size of the unit or the footprint.

Performance of the technology has been tested on a 5 kW laboratory-scale system that has been built and demonstrated. Following this, a 15 kW pilot-scale system was built and tested as a pilot unit at the laboratory facilities. The company has collaborated with a utility company in building and testing a 250 kW demonstration system which is currently under construction. This unit became operational during the year 2010.

An artist's view of the skid-mounted, 250 kW unit with overall dimensions is shown in Exhibit A-26.

Exhibit A-26: 250 kW Demonstration Unit – Echogen System



Projected cost of the unit with normal installation is $2,100 per kW. Cost of this system is 15%–25% lower compared to similar ORC systems.

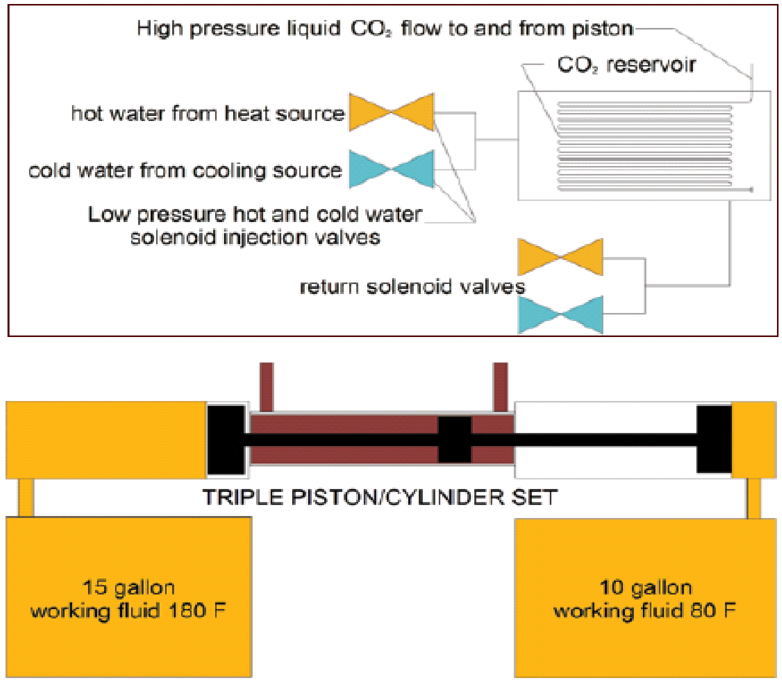
Natural Energy Engine (NEE) – Deluge Inc.
This waste heat recovery system uses reciprocating cylinders and CO_2 as a working fluid to convert thermal energy into mechanical work. As shown in Exhibit A-27, the source of heat is hot water which is heated in a separate heat exchanger by using waste heat. The hot water heat is transferred to the working fluid. In this case, the working fluid is liquefied CO_2 because of its high coefficient of expansion. As the working fluid expands, it pushes a piston located inside the engine's cylinder. Water for cooling next enters the heat exchanger, causing the working fluid to contract thus preparing the piston for another revolution. The piston's motion is then harnessed to operate a hydraulic motor or perform other work.

The calculated engine efficiency for producing mechanical work is about 23%. Efficiency for electricity generation would be lower, estimated to be about 20%.

The engine does not require high-speed turbo machines or expanders and offers the following advantages: relatively little heat losses, fewer moving parts, fully hydraulic transmission, and low noise level. The engine can use heat at or above 200°F (95°C) water temperature and can be operated at a temperature differential of 100°F (37°C), from 80°F cold water supply to 180°F (26 to 82°C) heated water supply.

The system has been used to operate reciprocating engines in oil fields. At this time, a 250 kW unit has been built and is being tested to collect data on the electrical performance using water from geothermal energy.

Exhibit A-27: Natural Energy Engine – a Liquid Carbon Dioxide (CO_2) Based Power Generation System



Estimated cost of the unit is approximately $2,000 per kW. This could vary considerably depending on the application and location.

Major barriers to the technology is unproven design, issues related to maintenance of the cylinder and pistons with seals, and cost of CO_2 replacement. The field tests of the pilot unit should be able to address some of these issues.

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