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Technologies and Materials for Recovering Waste Heat in Harsh Environments

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December 15, 2014

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AIST	Association for Iron and Steel Technology
BFG	blast furnace gass
BF	blast furnace
BOF	basic oxygen furnace
DOE	Department of Energy
EAF	electric arc furnace
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU-27	European Union with 27 member countries
HRSG	heat recovery steam generator
HVAC	heating, ventilation, and air-conditioning
MECS	Manufacturing Energy Consumption Survey
ORC	organic Rankine cycle
rpm	revolutions per minute
R/R	regenerative & recuperative
scf	standard cubic foot
TRG	thermoelectric generators
tonne	metric ton (1,000 kilogram)
US	United States
USGS	US Geological Survey
WHR	waste heat recovery

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1. INTRODUCTION

1.1 WASTE HEAT IN EXHAUST GASES AND HEAT RECOVERY ISSUES

A large amount (7,204 TBtu/year) [1] of energy is used for process heating by the manufacturing sector in the United States (US). This energy is in the form of fuels—mostly natural gas with some coal or other fuels—and steam generated using fuels such as natural gas, coal, by-product fuels, and some others. Combustion of these fuels results in the release of heat, which is used for process heating, and in the generation of combustion products that are discharged from the heating system. All major US industries use heating equipment such as furnaces, ovens, heaters, kilns, and dryers. The hot exhaust gases from this equipment, after providing the necessary process heat, are discharged into the atmosphere through stacks.

The temperature of the exhaust gases discharged into the atmosphere from heating equipment depends on the process temperature and whether a waste heat recovery (WHR) system is used to reduce the exhaust gas temperature. The temperature of discharged gases varies from as low as 200°F to as high as 3000°F. Combustion products themselves, generated from well-designed and well-operated burners using gaseous and light liquid fuels, are relatively clean and do not contain particles or condensable components that may require "cleanup" before discharge into the atmosphere. However, during the heating process, the combustion products may react or mix with the product being heated and may pick up constituents such as reactive gases, liquid vapors, volatiles from low-melting-temperature solid materials, particulates, condensable materials, and the like. Some or all of these constituents, particularly at high temperatures, may react with materials used in the construction of downstream heat WHR equipment and create significant problems. Potential issues include chemical reaction of exhaust gases and their solid or vapor content with the materials used in the WHR equipment; deposit of particulates in or on surfaces of WHR equipment; condensation of organics such as tars and inorganic vapors such as zinc oxides and boron on heat exchanger surfaces; and erosion of heat exchanger components by the solids in the exhaust gases. Many of these problems are compounded by the high temperature of the exhaust gases, uneven flow patterns of the hot gases inside the heat exchanger, and operating variations such as frequent heating and cooling of the heat exchanger.

This project deals with identification of industries and industrial heating processes in which the exhaust gases are at high temperature (>1200°F), contain all of the types of reactive constituents described, and can be considered as harsh or contaminated. It also identifies specific issues related to WHR for each of these processes or waste heat streams.

1.2 METHODOLOGY USED FOR SHORT-LISTING INDUSTRIES AND INDUSTRIAL HEATING PROCESSES

As shown in Figure 1.1, a large percentage (approximately 36%) of the total energy used for process heating is discharged as process losses. Waste heat contained in exhaust gases from a fuel fired or electrically heated heating systems such as furnaces, ovens, heaters, and boilers is the single largest heat loss from manufacturing plants [2].

Some of these hot gases are clean, or contamination free, and can be used in properly designed WHR equipment without major problems. However, in many processes, the exhaust gases are at high temperature and/or contain reactive constituents, and it is difficult to recover heat from them. These types of gases are termed "harsh environments" in this report. This section further defines harsh environments based on their characteristics and identifies specific industries and processes in which such environments are present. Heat recovery from these harsh gases using commercially available WHR systems such as recuperators, regenerators, heat recovery steam generators (boilers), water heaters, economizers, and heat pipes may result in excessive maintenance, short equipment life, or in some cases, safety risks.

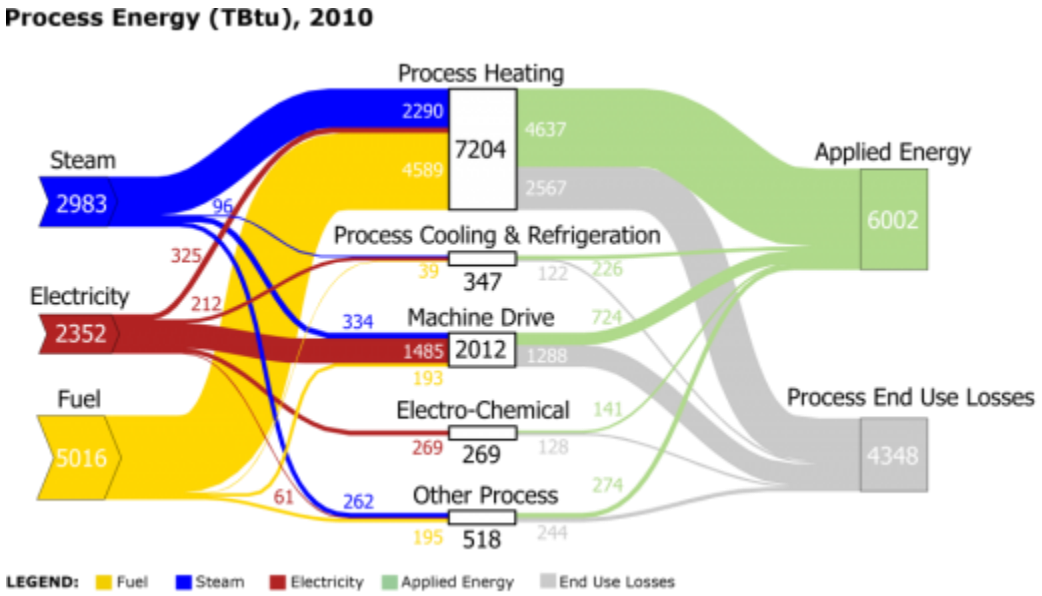

Figure 1-1. Sankey diagram of process energy flow in the US manufacturing sector [1].

Previous studies [3 and 4] have shown that WHR from combustion products at temperatures lower than 1,600°F and containing no harmful constituents can be achieved using many commercially available WHR systems. Several different types of WHR systems are used for many heating processes discharging clean exhaust gases without any major issues. (Specific types of WHR equipment and their performance are discussed in refs. 3, 5, and 6.) However, because of the limitations of the available equipment and technologies, attempts to recover heat from exhaust gases in harsh environments from a number of industrial processes that use large amounts of energy have been unsuccessful. To identify industries and specific processes in which such harsh environments are encountered, it is necessary to define the characteristics of gases that fall into this category.

One of the most important parameters used to define waste gas streams is the temperature of the gases. Several definitions have been used in the past. A report prepared by BCS in 2008 [3] used the following definitions:

- High temperature: 1,200°F (649°C) and higher
- Medium temperature: between 450°F (232°C) and 1,200°F (649°C)
- Low temperature: 450°F (232°C) and lower

More recently, two reports related to waste heat from industrial heating processes have been prepared for the US Department of Energy (DOE) [3 and 4]. In 2011, Thekdi [4] conducted an extensive survey of US industries for the DOE by visiting manufacturing plants in various industries. Discussions with industry representatives and the industry organizations suggested that the definitions of exhaust temperatures need to be expanded to identify gases in two more categories, one on each end of the temperature spectrum (i.e., lower and higher). Hence this report uses the following five temperature regimes for classification of waste heat sources:

- **Ultra-low temperature:** below 250°F. The lower temperature for this range is usually 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 for natural gas combustion products); the applicability of low-temperature, materials such as

aluminum or non-metallic materials such as polymers or plastics; or the use of low-temperature WHR systems such as heat pumps.

- **Low temperature:** between 250 and 450°F, as defined in the BCS report [3].
- **Medium temperature:** between 450 and 1,200°F, as defined in the BCS report [3].
- **High temperature:** between 1,200 and 1,600°F.
- **Ultra-high temperature:** greater than 1,600°F. WHR from streams above 1,600°F requires the use of special high-temperature materials that can be metallic or nonmetallic, such as ceramics. The selection of material and equipment design is very critical in many cases; as such streams contain a large amount of contaminants.

The exhaust gas temperature from industrial heating systems is primarily related to process temperatures that range from as low 150°F to as high as 3,000°F. Figure 1.2 [6] shows typical process temperatures for commonly used heating processes in various industries. References [3] and [4] provide detailed information for the estimated amount and quality of heat wasted as exhaust gases from many of these processes.

Typically, the primary considerations for selecting WHR methods and equipment are exhaust gas temperature and chemical composition. In most fuel-fired industrial heating processes, combustion of fuel (mostly natural gas in the United States) generates relatively clean combustion products for use in many different types of WHR systems. However, during a heating process, combustion gases come into contact with product/charge materials being heated, resulting in the addition of various solid and gaseous constituents that could damage or interfere with WHR equipment. (Specific issues related to material corrosion are discussed in detail in Section 2 of this report.)

The quantity and quality of exhaust gases from industrial heating processes depend on many factors related to the operation and design of heating equipment. Exhaust gases can be classified in many different categories based on their temperature, reactivity with WHR equipment materials, and ease or difficulty in recovering heat from these gases. Thekdi [4] developed a classification system based on visits to several industrial plants in different industries, contacts with personnel during the visits, and communication with engineering and operating personnel during conferences and discussions. Table 1.1 provides descriptions and examples for each waste heat category.

Several documents [2, 3, and 7] and representatives from industrial plants identified the waste heat sources shown in Table 1.5. It provides details regarding how much energy is used in these sectors and the quantity of the heat losses. During this project, a detailed study was conducted to contribute to this knowledge base by identifying waste heat sources in the form of high-temperature exhaust gases with a variety of contaminants. The shortlisted industries are

- steel
- petroleum
- chemicals
- glass
- aluminum (secondary)
- cement
- lime

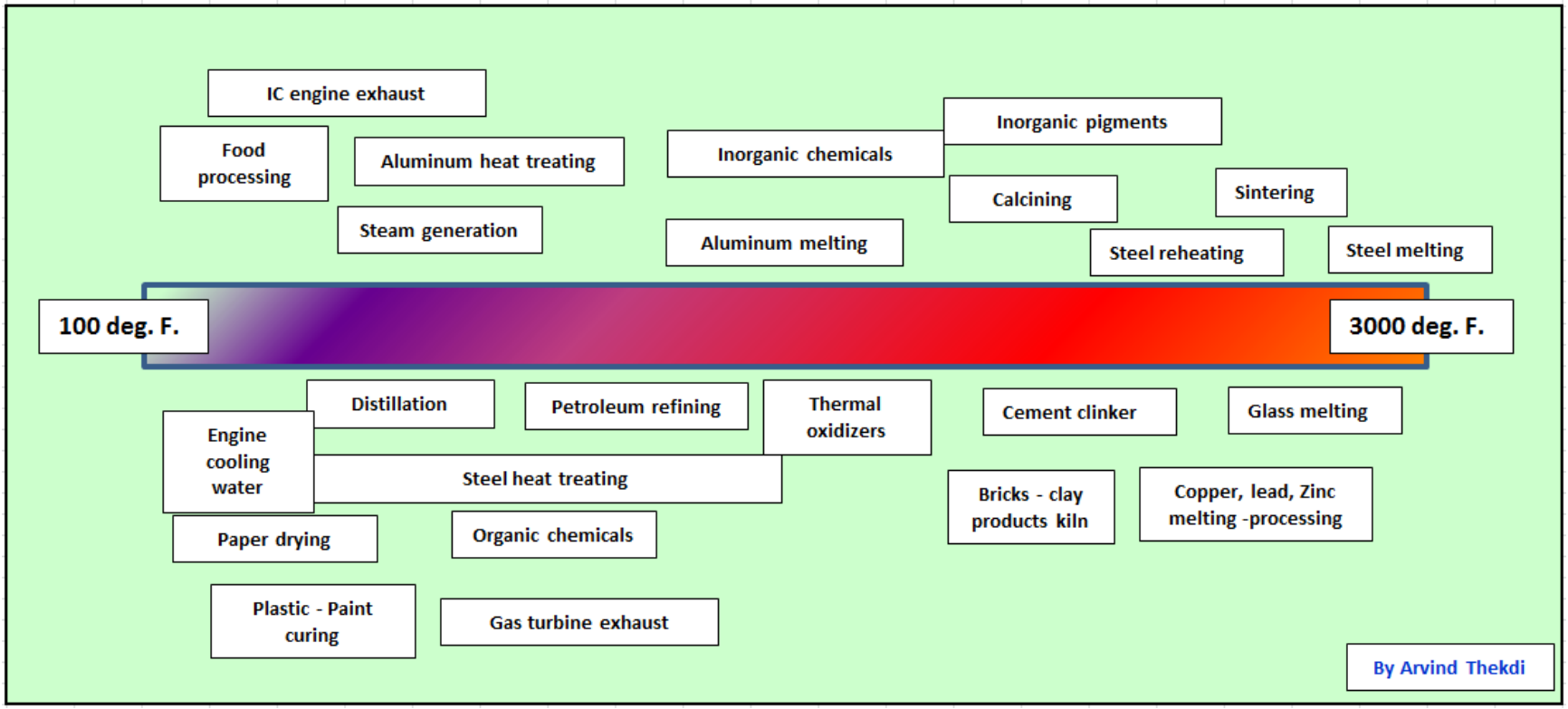

Figure 1-2. Range of process temperatures for some commonly used heating processes in manufacturing [6].

Table 1.1. Characteristics and descriptions of waste heat streams (exhaust gases) from process heating systems

Category	Waste heat stream characteristic	Description and examples of sources
1	Clean combustion products [a]	Waste gases from natural gas–fired heating systems (e.g., steam generators, furnaces, ovens, process heaters)
2	Combustion products with presence of relatively large proportion (>1%) of combustible gases [b]	Waste gases from gas- or oil-fired heating systems in which the combustion process is not controlled properly, resulting in sub-stoichiometric combustion or reactions in selected areas of the heating system Examples: furnaces, ovens, process heaters
3	Combustion products containing fuel-based corrosive gases (e.g., SO_2, HCl)	Waste gases from heating systems fired byproduct gases (e.g., refinery gases, coke oven gas, blast furnace gas) Examples: heating systems including boilers used in chemical, petroleum refining, paper industry
4	Combustion products containing fuel-based ash, unburned carbon, soot, and so on	Waste gases from fuel-fired equipment using coal and other solid fuels, byproduct liquid fuels and some untreated gaseous streams. Examples: boilers, steel reheating furnaces; mostly used outside North America
5	Combustion products (categories 1–4) mixed with process- or product-generated solids, liquids volatiles, and vapors (contaminants)[c]	Waste gases from heating processes in which charge materials are in solid, liquid, sludge or slurry form and in direct contact with combustion products. These may use clean gaseous fuels such as natural gas or other types of fuels (mostly fuel oil) Examples: glass melting furnaces, secondary aluminum melting furnaces, cement and lime kilns
6	Other types of process equipment in which the process and/or fuels generate combustible material (gases, volatiles, using mostly solid fuels	Waste gases from process equipment in which the "fuel" is a process reactant and produces waste gases containing combustible gases, solids, and condensable vapors Examples: blast furnaces, coke ovens, cokers, coke calciners

[a] Containing CO_2, H_2O, N_2, O_2 with very small (<0.1%) amount of combustibles (e.g., CO, H_2, CH_4).
[b] CO, H_2, CH_4 and gaseous hydrocarbons.
[c] Product-generated contaminants include solids, liquid vapors, or vapors of organic or inorganic materials generated or entrained from the product or process.

The analysis includes a list of major heating processes, exhaust gas temperatures for those processes, and exhaust gas characteristics (Table 1.1). The analysis results are provided in Appendix A (Tables A1.1 to A1.6).

Table 2.2 gives examples from the steel industry. The temperature ranges for exhaust gases are from widely used heating equipment at the heating system exit. For example, the temperature range of exhaust gas (commonly known as off-gas) at the fourth hole of an electric arc furnace (EAF) is 2,700 to 3,000°F (1,500 to 1,700°C). This range is observed before the gases are used in any WHR system, such as a scrap preheater, or mixed with dilution or cooling air.

Information from Tables A1.1 to A1.6 in Appendix A is used to identify exhaust gas streams that can be classified as harsh environments, those that present technical challenges and economic issues. Specific examples of harsh environments where recovery of sensible and chemical heat has been difficult or absent are EAF off-gases, basic oxygen furnace (BOF) exhaust, flue gases from aluminum melting furnaces, some cement and lime kilns, and blast furnace exhaust.

Table 1.2. Exhaust gas temperatures and characteristics from steel industry heating processes—equipment

Waste heat source [a]	Temperature (°F)	Temperature (°C)	Exhaust gas characteristics (as defined in Table 1.1)
Blast furnace stove exhaust gases	400 to 600	200 to 320	6
EAF exhaust gases	2,700 to 3,000	1,500 to 1,700	5
Ladle preheater exhaust gases [a]	1,650 to 2,300	900 to 1,250	1
Tundish heaters [a]	1,650 to 2,300	909 to 1,250	1
Basic oxygen process	2,300 to 3,000	1,250 to 1,700	5
Reheat furnace (with recuperator) [a]	850 to 1,000	450 to 550	1
Reheat furnace (with regenerative burners) [a]	400 to 750	200 to 400	1
Annealing furnace [a]	1,100 to 1,300	600 to 750	1
Galvanizing—galangal furnace [a]	750 to 1,100	400 to 600	1
Other heat treating [a]	575 to 1,475	300 to 800	1
Gas (combustion) turbine exhaust gases [a]	1,650 to 1,830	900 to 1,100	1
Boiler flue gases	350 to 575	175 to 300	1

[a] Assumes natural gas or other gaseous fuel or light oil is used as fuel for the burners.

The following are common characteristics of the gases classified as harsh environments.

1. High gas temperature (>1,600°F): Although the process temperature might be less than 1,600°F, the presence of combustible components such as CO, H_2, or hydrocarbons in flue gases, and their combustion in the presence of air that could leak into the flue gas ducts or into a WHR system such as a recuperator, could increase the localized temperature that may exceed temperature limit of the heat recovery system component. Examples include EAF and BOF exhaust gases and flue gases from "over-fired" aluminum melting furnaces.

2. Presence of highly corrosive fluxing agents (e.g., chlorides, fluorides, etc.): The types and amounts of fluxing agents or their compounds depend on the heating process and the final product specifications. These fluxing agents can remove oxide layers from metal parts (or surfaces) that may promote degradation of materials in WHR equipment. For example: due to the presence of fluxing agents, chemical reactions between the corrosive atmosphere and metal tubes in a recuperator could result in an extremely short life for the recuperator. The use of advanced or exotic materials that would extend the recuperator life is uneconomical for most applications.

3. Presence of particulates (e.g., metal oxides, carbon or soot particles, fluxing materials, slag, aluminum oxide, magnesium oxide, manganese): Fine particles entrained in flue gases may react with the heat exchanger materials (metallic or nonmetallic), resulting in reduction of heat transfer and in damaging reactions with heat exchanger materials. The net effect of these reactions is a shorter life for recuperator parts and, often, premature failure of metals at critical locations. In some cases, such as in boilers, it is possible to remove the material buildup by soot blowing, but this is not possible for all types of heat recovery systems.

4. Presence of combustibles (e.g., CO, H_2, hydrocarbons): The presence of combustibles in flue gases could result in higher-than-design temperatures for heat exchangers owing to air leaks or the addition

of diluent or cooling air to flue gases. In cases where no cooling or diluting air is used, the presence of combustibles still presents severe problems. The combustibles may react with constituents (such as nickel) of high-temperature alloys to form soot that deposits on heat transfer surfaces and reacts with metal leading to shortened life of equipment components.

5. Presence of combustible volatiles from charge material such as scrap used for aluminum melting furnaces and EAF: The scrap is obtained from a variety of sources and the plants use separation processing of scrap to remove combustible materials such as oils, paint, paper, plastic, and rubber. However, some of these materials end up in the charge material. Incomplete combustion, or breakdown of these organic materials results in the presence of combustible gases or solids, and they have the same effects on heat recovery equipment as the combustible materials described in item 4.

6. Variations in flow, temperature and composition of gases: Most heating equipment using a large amount of energy, such as EAFs, BOFs, and many aluminum melting furnaces, operates in a batch or semi-continuous mode. This results in variations in temperature, flow, and the composition of flue gases leaving the furnace. Variations in flue gas temperature could result in thermal fatigue of metals, which reduces the lifetime of the heat recovery equipment. Additionally, these variations could result in cyclic thermal expansion and the premature failure of welds or other metal-joints within the heat exchanger. These conditions could lead in turn to air leakage from the higher-pressure combustion side to the flue gas side and affect metal–gas or gas–gas reactions on the flue gas side. Using a heat exchanger to preheat combustion air could also change the air-fuel ratio for the burner and result into sub-stoichiometric combustion that forms combustible gases or soot in the flue gases.

At this time the industry uses several practices for managing or dealing with exhaust gases classified as harsh environments:

1. No heat recovery but treating (scrubbing, cooling by blending with cold air or mist cooling) exhaust gases to meet regulatory requirements. Examples are EAF and BOF exhaust gases.

2. Partial WHR due to materials limitations, design issues and space considerations. An example is preheating of glass melting furnace combustion air using regenerators.

3. Partial heat recovery due to other limitations such as safety, maintenance, lifetime. Examples are use of scrap preheaters for EAFs and use of steam generation for BOF installations.

4. Partial or no heat recovery due to high capital cost, limited operating hours, or other operating and economic reasons. Examples are small glass and aluminum melting furnaces and cement and lime kilns.

5. Loss of sensible heat and loss of certain condensable organic materials (e.g., tar, condensable liquids, volatiles) during treatment of exhaust gases, and use of chemical heat after drying the gases as fuels. Examples are blast furnaces and coke ovens.

Information from Tables A1.1–A1.6 in Appendix A was used to identify exhaust gas streams that can be classified as harsh environments. For this report, the following parameters were used to define a harsh environment.

- Waste heat stream temperature in the high or ultra-high category—at least 1,200°F.
- Waste heat characterization category 3 to 6 with a strong inclination toward categories 5 and 6 (see Table 1.1).

Information from Tables A1.1 to A1.6 was used to select five major industries in which large amounts of waste heat are available but are not being recovered at this time because of the quality of the heat and the difficulty of using WHR equipment to recover it. The selection was based on quantity of recoverable heat, possibilities for recovering considerably more heat than is recovered currently, and lack of availability of acceptable WHR options. Selection of these industries does not mean that all their waste heat is or can be recovered without any technical or economic hurdles.

These industries are

1. iron and steel—blast furnaces, BOF and EAF operations
2. glass—melting furnaces
3. aluminum—secondary melting furnaces
4. cement
5. lime

Table 1.3 summarizes information about the waste heat in exhaust gases identified as harsh environments resulting from selected processes in those industries.

Calculations were performed for recoverable waste heat from harsh environment gases for each of these industrial sectors. The calculations were based on available information from various sources identified in the report. The results from the calculations and the data used for arriving at the results are provided in Appendix B. The total amounts of recoverable heat from the exhaust gases listed in Table 1.3 are shown in Table 1.4.

An example of the calculation methodology used to estimate recoverable waste heat for EAF operations in the steel industry is given below.

- Temperature of off-gases from an EAF: 2,700 to 3,000°F (1,500 to 1,600°C) [8]
- Steel production in the United States (March 2013–March 2014): 8,000 tons/month (average, or 96,000 tons/year [9]
- EAF steel production as percentage of total US steel production: 67% [10]
- Energy input: 742 kWh/ton or 2.535 MM Btu/ton of billet (or molten steel)
- Sensible heat: 16.7% or 0.423 MMBtu/ton
- Chemical heat: 21.4% or 0.542 MMBtu/ton
- Total waste heat: 0.423 + 0.542 = 0.965 MMBtu/ton
- Total recoverable heat for US EAF industry: $0.965 \times 96{,}000 \times 0.67 = 62{,}068.8$ MMBtu/year or approximately 62.1 TBtu/year

These calculations used information from Evenston et al. [11]. Note that there is an error in the summation in that document, and this report uses the corrected figure.

Table 1.3. Exhaust gases identified as harsh environments from selected industrial processes

Criteria: Exhaust gases considered either >1200°F (650°C) and/or containing combustibles and contaminants						
Industry	**Waste heat source**	**Temp. range (°F)**	**Characteristics**	**WHR technology/system status**	**Production (MM tons/year)**	**Exhaust gas flow**
Steel	Blast furnace gases	400 to 600	Contain combustibles, particulates, etc.	Available and widely used–partial WHR	30	Constant
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	64.32	Varying
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	31.68	Varying
Glass	Flat glass	800 to 2,600	Contain particulates, etc.	Available for air-fuel combustion only and widely used–partial WHR	5.00	Constant
	Container glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and widely used—partial WHR	10.00	Constant
	Glass fiber (all types)	1,800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and partially used–partial WHR	3.00	Constant
	Specialty glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for partial heat recovery but rarely used	2.00	Constant
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Contain combustibles, particulates, etc.	Available, not widely used– partial WHR	10.00	Constant
	Anode baking	570 to 930	Contain combustibles, particulates, polycyclic organic matter, etc.	Available but NOT demonstrated	2.22	Constant
	Calcining	570 to 930	Particulates, fuel combustion products, etc.	Available but NOT demonstrated	–	–
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	390 to 750	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	69.3	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	390 to 1,100	Contain particulates, etc. Relatively easy to handle	Available, not widely used– partial WHR	20.9	Constant

A similar method was used to calculate total recoverable waste heat from other waste heat sources listed in Table 1.4 for which harsh environments are present. The details for these calculations are provided in Appendix B.

Table 1.4. Total recoverable heat estimate for exhaust gases from selected industrial processes

Criteria: Exhaust gases considered either >1200°F (650°C) and/or containing combustibles and contaminants						
Industry	**Waste heat source**	**Temp. range (°F)**	**Recoverable—potential TBtu/year[a]**			**Exhaust gas flow**
			Sensible	**Chemical**	**Total**	
Steel	Blast furnace gases	400 to 600	15.49	172.69	188.2	Constant
	EAF exhaust gases	2,700 to 3,000	27.21	34.86	62.1	Varying
	Basic oxygen process	2,250 to 3,000	4.47	25.22	29.7	Varying
Glass	Flat glass	800 to 2,600	12.38	Negligible	12.4	Constant
	Container glass	800 to 2,600	19.30	Negligible	19.3	Constant
	Glass fiber (all types)	1,800 to 2,600	3.65	Negligible	3.7	Constant
	Specialty glass	800 to 2,600	7.60	Negligible	7.6	Constant
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	15.88	Small/site-specific	15.9	Constant
	Anode baking	570 to 930	1.88	Small/site-specific (unknown)	1.9	Constant
	Calcining	570 to 930	–	–	–	–
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	390 to 750	53.02	Negligible	53.0	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	390 to 1,100	40.7	Negligible	40.7	Constant

[a] In few cases, a small quantity of waste heat is already being recovered using the existing WHR technologies.

Waste heat source	Temperature range (°F)	Characteristics	Production (MM tons/year)	Unit energy use (MM Btu/ton)	Percentage in waste gas (sensible + chemical)	Heat in waste gas /ton of steel (MM Btu/ton of iron) sensible	Heat in waste gas /ton of steel (MM Btu/ton of iron) chemical	Energy in waste gases (TBtu/ year)
EAF exhaust gases**	2,700 to 3,000	Contain combustibles, particulates, etc.	64.32	2.535	38.1%	0.423	0.542	62.1

Table 1.5 summarizes information about the recoverable waste heat from the processes listed in Table 1.4.

The total recoverable heat (the sum of sensible and chemical heat) from 11 short-listed high-temperature waste heat sources is approximately 430 TBtu/year. At present, some of this waste heat is recovered by using the available WHR equipment—in spite of major issues with maintenance and frequent replacement costs—even when the heat recovery for a few selected cases is less than 40% of the total recoverable heat. Note that even with the development of advanced materials and innovative designs, and even in light of the justifiable cost of WHR systems, it may be possible to recover only about 70% of the heat identified as recoverable. The level of recoverability is based on the results of a parallel program at Oak Ridge National Laboratory (ORNL) that addresses the novel design of heat recovery system for EAF exhaust gases. The value of potentially recoverable heat—about 300 TBtu/year—is about $1.2 to $1.5 billion per year based on $4 to $5 per MMBtu for a replaced fuel source such as natural gas.

Table 1.5. Recoverable waste heat from selected harsh environment waste gas streams

Criteria: Exhaust gases considered either >1200°F (650°C) and/or containing combustibles and contaminants

Industry	Waste heat source	Temp. range (°F)	Characteristics	WHR technology/system status	Production** (MM tons/year)	Waste Heat Recovery Potential TBtu/year*			Exhaust gas flow
						Sensible	Chemical	Total	
Steel	Blast furnace gases	400 to 600	Contain combustibles, particulates, etc.	Available and widely used–partial WHR	30	15.49	172.69	188.2	Constant
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	64.32	27.21	34.86	62.1	Varying
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	31.68	4.47	25.22	29.7	Varying
Glass	Flat glass	800 to 2,600	Contain particulates, etc.	Available for air-fuel combustion only and widely used–partial WHR***	5.00	12.38	Negligible	12.4	Constant
	Container glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and widely used–partial WHR***	10.00	19.30	Negligible	19.3	Constant
	Glass fiber (all types)	1,800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and partially used–partial WHR***	3.00	3.65	Negligible	3.7	Constant
	Specialty glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for partial heat recovery but rarely used.	2.00	7.60	Negligible	7.6	Constant
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Contain combustibles, particulates, etc.	Available, not widely used–partial WHR	10.00	15.88	Small - site specific	15.9	Constant
	Anode baking	570 to 930	Contain combustibles, particulates, polycyclic organic matter, etc.	Available but NOT demonstrated	2.22	1.88	Small/site specific (unknown)	1.9	Constant
	Calcining	570 to 930	Particulates, fuel combustion products, etc.	Available but NOT demonstrated		Data not available at this time			
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operation	390 to 750	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	69.3	53.02	Negligible	53.0	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operation	390 to 1,100	Contain particulates, etc. Relatively easy to handle	Available, not widely used–partial WHR	20.9	40.7	Negligible	40.7	Constant
				Total				**434.4**	

* For few waste heat sources (particularly in steel, aluminum, and glass industry), a small quantity of waste heat is already being recovered using the existing WHR technologies.
** Production data for steel industry is from 2013, glass industry 2002, aluminum industry 2012, and for cement and lime industry production data is from 2013.
*** WHR technologies currently not available/used for oxy-fuel fired systems.

A large number of heat recovery systems and items of equipment based on various technologies have been proposed, and some of them have been used for recovery of waste heat from exhaust gases identified as harsh environments in the past. Available heat recovery systems and issues associated with their use are discussed in Section 3.

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2. EXISTING TECHNOLOGIES USED FOR RECOVERING WASTE HEAT FROM HIGH TEMPERATURE EXHAUST GASES

2.1 EXISTING WHR TECHNOLOGIES FOR HIGH-TEMPERATURE HARSH ENVIRONMENTS

Many technologies and much equipment are available to recover waste heat from high-temperature exhaust gases discharged by industrial heating systems. Selection of heat recovery technology and equipment largely depends upon the category of exhaust gases. A review of available literature [1–3] indicates that heat recovery from gases at low to high temperatures is cost-effective. However, based on communications with industry contacts and their feedback, it is difficult to obtain equipment that offers a long life at a justifiable cost to recover a large percentage (>50%) of the heat contained in high-temperature and ultra-high-temperature exhaust gases (as defined in Section 1). Heat recovery systems for harsh environments use high-temperature materials (alloys and in some cases ceramic or refractory materials) with a high capital cost. They also present operation–maintenance issues that require frequent attention and much expense. For category 4 and 5 exhaust gases, these issues are difficult to manage; as a result, there is little or no WHR from exhaust gases from systems that are large energy users, such as EAF, BOF, and secondary aluminum melting furnaces.

The most commonly used items of WHR equipment (not all) are

- recuperators
- regenerators
- economizers—non-condensing and condensing
- direct-contact or indirect water heaters
- air heaters for heating, ventilation, and air-conditioning (HVAC) or process applications
- waste heat boilers for steam generation
- steam-based electrical power generation systems
- organic Rankin cycle–based electrical power generation systems
- cascade systems to recover heat from high-temperature gases for lower-temperature processes
- load or charge preheating

There are many other systems, such as heat pipes, heat pumps, and thermoelectric generators, that are used only in a very few cases for industrial applications. A detailed review of these devices is available in refs.4–6.

All of this equipment has been used for heat recovery from clean gases and combustion products in the temperature range from 400°F up to 1,600°F. Depending upon design and maintenance practices, some equipment such as radiation recuperators, steam generators, and water heaters can handle small amounts of combustibles and particulates. However, attempts to use any of these types of equipment for high-temperature gases containing contaminants such as particulates, corrosive gases, or condensable compounds have resulted in a short life (less than one year) and frequent maintenance (often every few months). Hence use of such equipment for the exhaust gases from processes listed in Table 1.5 is very limited.

2.2 EXISTING WHR TECHNOLOGIES FOR HIGH-TEMPERATURE APPLICATIONS AND THEIR LIMITATIONS

The commonly used WHR systems shown in Table 2.1 [7] are available from several suppliers and are used with industrial waste heat sources. In most cases, these systems are proven; however, the equipment

used in high-temperature and ultra-high temperature ranges needs significant improvement to offer better performance and longer lives. The needed improvements are in the following areas:

- Use of advanced materials to improve heat transfer performance, increase performance life, or reduce maintenance cost
- Design changes to enable survival in harsh conditions for different or previously untested applications
- Design changes to offer higher thermal efficiency with a smaller footprint or size
- Cost reduction through better design and manufacturing techniques
- Improved seals to reduce maintenance or extend seal life

Some plants have used tubular metallic recuperators to preheat combustion air using heat from exhaust gases for aluminum melting furnaces. An investigation of the use of recuperators at a large aluminum plant [4] indicated that these recuperators have very short lives because of corrosion of metals, localized high temperatures resulting from the combustion of combustible gases in exhaust gases, deposits of dross and other flux material particles, and other issues. The life expectancy has been less than 2 years, and they require frequent maintenance (see Figure 2.1). Overall heat recovery efficiency (recovered heat as percentage of recoverable heat) is in the range of 45–55%, so a large amount of heat is left in exhaust gases from a furnace. In a few cases, small specialty glass furnaces use recuperators.

The glass industry has used radiation recuperators to preheat combustion air for glass melting furnaces in the glass fiber and specialty glass sectors. These recuperators have large passages for flue gases and can withstand relatively heavy particulate content in exhaust gases. In harsh environments, radiation recuperators experience metal corrosion and fouling-related issues. "Fouling" refers to the deposition of material on a heat transfer surface, usually resulting in increased resistance to heat transfer and subsequent loss of thermal exchange capacity in the heat transfer equipment. The heat recovery efficiency of recuperators is in the range of 45–55%, so that percentage of the heat in the gases leaving the recuperator remains unrecovered.

Figure 2-1. Recuperator used on an aluminum melting furnace. Note bent and broken tubes in the first row and missing refractory on the upper end of the tubes [4].

Table 2.1. Commonly used primary WHR systems [5]

Commonly used primary waste-heat recovery systems				
Temperature range				
Ultra-high temperature (>1600°F)	**High temperature (1,200–1600°F)**	**Medium temperature (600–1,200°F)**	**Low temperature (250–600°F)**	**Ultra-low temperature (<250°F)**
Refractory (ceramic) regenerators	Convection recuperator (metallic)—mostly tubular	Convection recuperators (metallic) of many different designs	Convection recuperators (metallic) of many different designs	Shell and tube type heat exchangers
Heat recovery boilers	Radiation recuperator	Finned tube heat exchangers (economizer)	Finned tube heat exchangers (economizer)	Plate type heat exchangers
Regenerative burners	Regenerative burners	Shell and tube heat exchangers for water or liquid heating	Shell and tube heat exchangers for water or liquid heating	Air heaters for waste heat from liquids
Radiation recuperator	Heat recovery boilers	Self-recuperative and regenerative burners	Heat pumps	Heat pumps
Waste heat to power using boilers and steam turbine-generators	Waste heat to power using boilers and steam turbine-generators	Waste heat boilers for steam or hot water-condensate	Metallic heat wheels	HVAC applications (i.e. recirculation water heating or glycol-water recirculation)
Load or charge preheating	Ceramic heat wheels (regenerative system)	Load-charge (convection section) preheating	Condensing water heaters or heat exchangers	Direct contact water heaters
	Load or charge preheating	Heat pipe exchanger	Heat pipe exchangers	Non-metallic heat exchangers
		Metallic heat wheel	Direct contact water heaters	

Several regenerator designs are used to preheat combustion air using waste heat in exhaust gases. Stationary regenerators using refractory shapes (bricks and crucibles) are widely used for glass melting furnaces that use air-fuel combustion. They have a long history—over 100 years of use in the glass industry. The regenerator system consists of two regenerator units located on the side of a melting furnace. At any one time, exhaust gases flow through one of the units and heat the refractory shapes while combustion air is preheated using heat contained in the refractory shapes. This operation lasts for about 20 minutes and then the flows of exhaust gases and combustion air are switched from one unit to the other. More than 80% of melting furnaces in the flat glass sector, 55% of furnaces for container glass, and 26% of furnaces for specialty glass use stationary regenerators. These regenerators cannot be used for furnaces that use oxy-fuel firing systems. Their main applications are in the flat glass and container glass sectors. These regenerators can withstand very high or ultra-high temperatures and can recover 60–70% of the furnace exhaust gases, which may contain large amount of particulates and corrosive–reactive gases. They have very long lives—in the range of 10 to 20 years with periodic maintenance. They are massive and occupy a large volume of space, often two to three times that of the melting section of a furnace. The industry has made several advancements in materials, construction, and cleaning methods during its long history of using regenerators. At this time, the glass industry is the only industry using stationary regenerators. Generally these regenerators experience fouling or deposition-related (sodium sulfide and ash) issues.

Another application of a similar regenerator design, commonly known as a blast furnace stove, is preheating blast or combustion air for blast furnaces. In this case, the refractory material is heated by firing fuel in one unit while the other unit is being cooled by blast air used in the blast furnace. These units are switched at a lower frequency. Since these regenerators use clean fuels such as cleaned blast furnace gas, cleaned coke oven gas, natural gas, or in some cases fuel oil, the degradation of materials is not as much an issue as in glass furnace regenerators.

Another form of regenerator system, the regenerative burner, is comparatively small and a relatively new development. Regenerative burners, which include a regenerator section as an integral part, are used on aluminum melting furnaces to preheat combustion air. The burners are used in pairs and are switched frequently (usually every 20 seconds) The regenerator section contains small (about 1 in. diameter) ceramic balls or media (high-alumina spheres) packed loosely to avoid a large pressure drop for the gas and air flows. These regenerators can recover 65–75% of the exhaust gas heat, resulting in an exhaust gas temperature of less than 400°F from the regenerators. In many cases, part of the combustion products at a high temperature, close to the furnace interior temperature, must be discharged from an axillary stack to maintain the mass balance for the gases passing through the regenerative sections. In these cases, the overall heat recovery is lower than for gases passing through the regenerator. These units present the same problems of plugging and a need for frequent cleaning of the media. Other limitations are a need for cycling hardware and limited operating temperatures due to hot-side valving [7]. To extend the use of regenerative burners, investigation of extended-temperature-range valving—such as ceramic or specialty alloys flappers and special bearing designs—is needed [7]. The cost of a regenerative burner system, particularly for retrofit situations, is quite high—as much as twice that of recuperators, considering the energy savings for the furnace.

Rotary regenerators are rarely, if ever, used for harsh environments or exhaust gases from high-temperature furnaces.

Almost all integrated steel mills in the United States use clean blast furnace gas mixed with coke oven gas (where available) and natural gas in steam boilers. Steam from these boilers is used for process heating in the plant and for electrical power generation. Recently, as a result of lower natural gas costs, environmental and economic issues related to treatment and transportation of blast furnace gases, and lack of coke oven gas availability, many plants are discontinuing the use of blast furnace gas in their furnaces

and seeking alternate uses of blast furnace gas. One example is the use of blast furnace gas for electrical power generation at ArcelorMittal's Indiana plant [8]. This project, supported by DOE is using 46 billion ft^3 of waste blast furnace gases to generate 350,000 lb of steam per hour and 333,000 MWh of power per year [8].

Heat recovery steam generators (HRSGs) or boilers are used to recover heat from BOF exhaust gases in several integrated steel plants. The challenges of high temperature, variability in available waste heat, and particulates and corrosive gases make it very difficult to justify the use of such systems. Several installations outside the US use blast furnace gas in combustion turbines, followed by a waste heat boiler to generate electrical power [9]. The use of waste heat boilers to recover waste heat from cement and lime kilns is common in countries such as China and India. In those cases, the gases are at a relatively lower temperature, usually below 1200°F, and contain particulates of alkaline compounds, coal ash, SO_2, HCl, and other reactive gases. At lower temperatures, sulfuric acid corrosion in the boiler is very common. All these issues require high maintenance and frequent replacement of boiler interior parts. Use of waste heat boilers in the US cement industry is almost nonexistent. The relatively lower cost of electrical power and fossil fuels (e.g., coal, natural gas) and the requirement for shorter payback periods, usually less than 2 years, makes it difficult to justify the use of WHR boilers on cement or lime kilns.

The use of economizers (other than on fuel-fired boilers), heat pipes, heat pumps, water heating using direct or indirect water heaters, or organic Rankine cycle (ORC) -based power generation from high-temperature gases containing several contaminants is practically nonexistent in the United States.

The use of exhaust gas waste heat for load or charge preheating is an area of interest and activity for high-temperature industrial heating systems. "Charge" refers to materials such as scrap, mixed batch, or raw materials introduced into a furnace or kiln. This heat recovery method offers several advantages, such as reduced energy use (electricity and fuel), reduced melting or processing times, increased productivity, and in some cases reduced emissions. However, in the past, several issues related to installation cost, safety, production equipment downtime, high maintenance costs, and process controllability have prevented wide use of this WHR method [10]. Many of the problems are related to unavailability of appropriate materials at an affordable cost and performance unpredictability due to the variability and lack of consistency or control of incoming charge material, which makes it difficult to design and operate the equipment. A prime example is use of scrap preheaters for EAFs: charge preheaters offer many economic advantages, but the issues mentioned limit their application to about 10% of EAF installations in the US. Similar situations exist for the glass and aluminum industries.

The use of raw material preheating in cement plants, using four to six preheaters and a precalciner, is becoming standard throughout the world. Scrap preheating for EAFs and aluminum melters, cullet and batch preheating for glass-melting furnaces, and raw material preheating for cement plants are other examples of this type of WHR. Preheating of charge material is increasing in small to medium size melters (2000 to 5000 lb/h molten metal tap rate) [5]; furnace flue gases are commonly used to dry and preheat aluminum charge material (mostly purchased or in-house scrap). Results show that scrap preheating using exhaust gases from a melting furnace, directly or after a combustion air preheater, results in productivity and safety gains for the plant.

As shown in Table 1.5, total recoverable heat is approximately 430 TBtu/year for the heating processes described for the steel, glass, aluminum, and cement-lime industries. Some portion of this heat is already recovered using the equipment or methods discussed. It is difficult to estimate exactly how much of this heat is currently recovered, but a best estimate is that approximately 35% of total recoverable heat is recovered. This heat recovery is achieved using equipment that may have substantial issues related to maintenance and life expectancy. If a potential for an additional 35% heat recovery is assumed, total recoverable heat is about 300 TBtu/year. Given a potential heat recovery efficiency of 70% using

appropriate and innovative materials and heat recovery systems, and an energy cost of $5 per MM Btu, potential cost savings from WHR could be over a billion dollars per year.

At this time the industry uses several practices for managing or dealing with exhaust gases classified as harsh environments:

1. No heat recovery, but treatment (scrubbing or cooling by blending with cold air or mist cooling) of exhaust gases to meet regulatory requirements. Example: EAF and BOF exhaust gases.

2. Only partial heat recovery because of materials limitations, design issues, and space considerations (as in the case of glass melting furnaces using regenerators)

3. Only partial heat recovery because of other limitations such as safety, maintenance, and lifetime, as in the use of scrap preheaters for EAFs and steam generation for BOFs

4. Partial or no heat recovery because of high capital cost, limited operating hours, or other operating and economic issues, as in case of small glass and aluminum melting furnaces and cement and lime kilns

5. Loss of sensible heat and loss of certain condensable organic materials (e.g., tars, condensable liquids, volatiles) during treatment of exhaust gases, and use of chemical heat as fuel after drying of the gases, as in the case of blast furnaces and coke ovens

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3. CURRENTLY USED MATERIALS AND THEIR LIMITATIONS

This section describes materials used for various types of heat recovery equipment in WHR systems. WHR systems employ both metallic and nonmetallic materials with a variety of technical limitations. The discussion includes descriptions of material properties required to enable optimum heat recovery from harsh environment gases. The descriptions include knowledge gaps regarding (1) the characteristics of harsh environments (e.g., issues related to variability in scrap and charge material) and (2) materials properties such as the effects of certain gas constituents on the lifetimes of materials. Unfortunately, the lack of available information limits the depth of the discussion of this topic.

3.1 SELECTING MATERIALS FOR HIGH-TEMPERATURE HARSH ENVIRONMENTS

Materials for WHR equipment are selected on the basis of service requirements, notably strength, and corrosion resistance (stability). WHR equipment must be strong and resilient against the unique stresses imposed on them, which include those arising from significant temperature changes and thermal gradients in many high-temperature applications. Choosing appropriate materials requires knowing what materials are available and the extent to which they are suited to the specific application. The decisions are complex, and the choice is significantly affected by the use environment and the intended use, whether for recuperators, boiler tubes, fluidized beds surfaces, regenerator bricks, crucibles, shields, ducts, or other equipment types. The user or designer must properly understand that the off-gas environment dictates the materials selection approach at all stages of the process or application. For example, an alloy that performs well at the service temperature may corrode because of dew point corrosion (condensation of water vapor) at lower temperatures during off-load periods, or because faulty design details or poor maintenance procedures introduce local air drafts that cool the WHR system (e.g., at access doors or inspection ports) [1]. For optimum performance, a supplier must be aware of the application, and the user must be aware of the general range of available materials and the limitations of the design or operating conditions. Otherwise, severe problems can result. In considering traditional materials, it is important for the WHR equipment designer and user to be fully aware of the mechanical limits of a material. [2] For example, type 304 steel is intended for use in a pressure vessel at up to 1,500°F (815°C). Based upon ASME tables, for a load of 17 MPa (2.5 ksi) at 1,400°F (760°C), the expected design life is 24 years; at 1,450°F (788°C), the life falls to 7 years; and at 1,500°F (815°C), it is only 2.2 years. Thus a short-term temperature excursion can have a significant effect on equipment life. [2]

3.2 HIGH TEMPERATURE MATERIALS

Figure 3.1 [3] shows high-temperature materials currently used by industry. They are

- high-temperature steels
- high-temperature, oxidation-resistant FeCrAl steels
- superalloys based on nickel, cobalt, iron, and chromium
- oxide-dispersion-strengthened alloys
- refractory metals and alloys
- intermetallic compounds for high-temperature use
- coatings
- metal matrix composites
- ceramic matrix composites
- ceramics

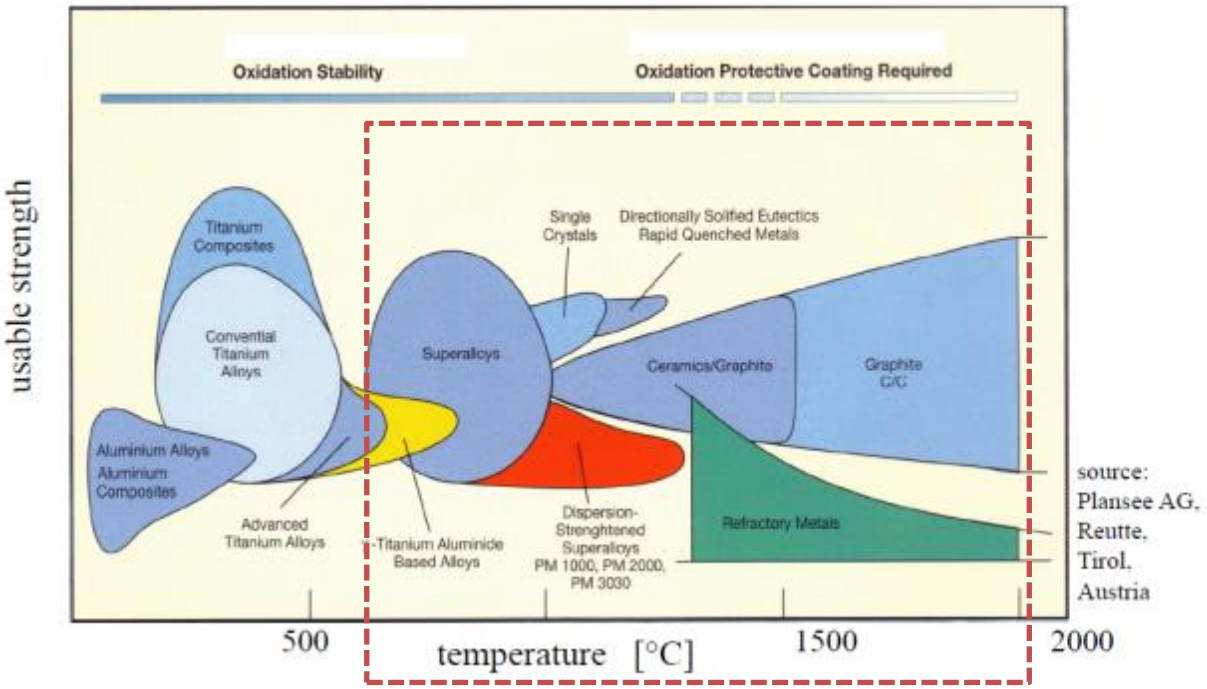

Figure 3-1. Selecting materials for high temperature harsh environments [3]

3.2.1 High-temperature Steels and Superalloys

High-temperature steels and superalloys demonstrate higher strength at higher temperatures than do conventional ferrous alloys (carbon steel, stainless steel, etc.). High-temperature alloys are typically based on iron, nickel, or cobalt and contain >20% chromium, which is sufficient to form a protective oxide against further oxidation. In general, oxidation protection in engineering materials is provided by chromia to about 1,470°F (800°C) and alumina above that temperature. The basic alloys include various additional elements that aid corrosion resistance, notably aluminum (typically >4% to develop an alumina scale), silicon (up to 5% to develop an amorphous [glass-like] scale that is complementary to chromia), and rare earth elements (typically <1%, e.g., yttrium, cerium, and lanthanum to improve scale adhesion). Other additions, such as reactive and refractory metals and carbon, primarily improve mechanical properties. However, at higher levels of strengthening alloying elements, the alloys must be cast rather than wrought. The latest advance to avoid high-temperature creep by grain boundary sliding is the development of directionally solidified and single-crystal alloys. [4] Typically, the temperature capability of these alloys has risen by 570°F (300°C) over the past 30–40 years (Figure 3.1). Newer developments are oxide-dispersion alloys, which are strengthened by oxide particles that are insoluble in the matrix and thus stable to higher temperatures than directionally solidified or single-crystal alloys. However, oxide-dispersion-strengthened alloys generally are anisotropic, are not weldable, and have limited tensile strength up to 1,830°F (1,000°C) and poor thermal fatigue characteristics.

3.2.2 High-temperature Refractory Metals

Refractory metals provide attractive high-temperature strength but are handicapped by their very poor oxidation resistance, which is mainly due to volatile or molten oxides. All of the refractory metals (tungsten, tantalum, niobium, and molybdenum) may experience catastrophic oxidation as temperatures exceed about 1,300°F (700°C). Catastrophic oxidation rapidly renders a metal into a useless powdery

oxide. Damage is worse in stagnant conditions and appears to be exacerbated when sodium oxide is present (e.g., from insulation). Silicide coatings have shown to offer some resistance to this catastrophic ("pest") oxidation; but should the coating become damaged, the consequences of allowing the environment to access the underlying metallic component are disastrous.

3.2.3 High-temperature Ceramic Materials

Monolithic ceramics, particularly silicon nitride (Si_3N_4) and silicon carbide (SiC), show potential for application as high-temperature structural materials. They are stronger than the nickel superalloys discussed 1000°C (1,830°F), have superior creep strength and oxidation resistance, and are potentially cheaper. In addition, they are less than half as dense as the superalloys (typically 3.2 gm/m^3 compared with 7.9 gm/m^3 for superalloys). The Achilles heel of these materials is their intrinsic flaw sensitivity, brittleness, and consequent lack of reliability.

Fiber-reinforced ceramic matrix composites have recently received a great deal of attention for use in high-temperature structural applications. The reason is the assumption that strong ceramic fibers can prevent catastrophic brittle failure in ceramics by providing various energy-absorbing processes during a crack advance and thus can provide some defect tolerance.

Figure 3-2. Regenerator chamber used in recovering waste heat from glass melting furnaces [5]

3.2.4 Refractory Bricks and other Shapes

The refractory materials include Si_3N_4, SiC/$Al2O_3$ composites, high-alumina silicates, and high-magnesia silicates, among others. (Table 3.5 lists high-temperature refractory and ceramic materials.) Although refractory materials are not commonly used to construct traditionally used heat exchangers or WHR equipment, they are widely used for a special class of heat recovery system—the stationary regenerator (Figure 3.2)—used in high-temperature gases exhausted from glass melting and iron making systems. These large regenerators are used for exhaust gases classified under harsh environments and can withstand very high temperatures, up to 3,400°F (1,870°C). Refractory materials retain their high compressive strength at high temperatures. However, these materials are not normally used in tensile stress circumstances as they have less tensile strength. Hence they are used in applications with relatively low loads and little or no thermal cycling, such as in glass melting furnaces. Thermal cycling effect is related to their thermal expansion and possible changes in crystal structure. If the coefficient of thermal expansion is low to very low and there is limit to no crystal structure changes, then these materials can withstand thermal cycling. These types of designs offer special advantages for harsh environments but are a poor choice for relatively clean and lower-temperature (<1,800°F) exhaust gases. Recent developments in use of ceramics in WHR equipment include regenerative burners used for high temperature furnaces and internal recuperators. Regenerative burners

use ceramic matrix made from high alumina material. The matrix includes ceramic "balls" or spheres of 1 to 2 inch diameter packed in a refractory lined container. These units are used to recover 75% to 80% heat discharged from high temperature furnaces such as steel reheating, forge furnaces, aluminum melters, etc. The internal recuperators used in radiant tubes are specially shaped recuperators using sintered Silicon Nitride.

3.2.5 High-temperature Coatings

High-temperature coatings or surface modifications are generally based on chromium, aluminum, or silicon, which, at high temperatures, form protective oxides rich in chromia, alumina, or silica, respectively. In more recent years, there have been developments in applying "alloy coatings," for example, the use of MCRALY (metal, chromium, aluminum, and yttrium) on steels or other high-temperature alloy substrates. Research also is continuing on weld overlaying, in which a strong base metal supports a corrosion-resistant surface-coated layer.

3.3 TYPES OF HIGH-TEMPERATURE CORROSION

High-temperature corrosion is a chemical attack upon solid functional or structural materials that results in degradation of the desired properties. [6] Typically the material reacts with a gaseous environment, often forming undesirable reaction products. There are certain distinguishing features of high-temperature corrosion that aid in determining the cause of damage. Some typical indications are thick scales, grossly thinned metal, burnt (blackened) or charred surfaces, molten phases, deposits of various colors, distortion and cracking, and magnetism in what was first a nonmagnetic (e.g., austenitic) matrix.

Damage varies significantly based upon the

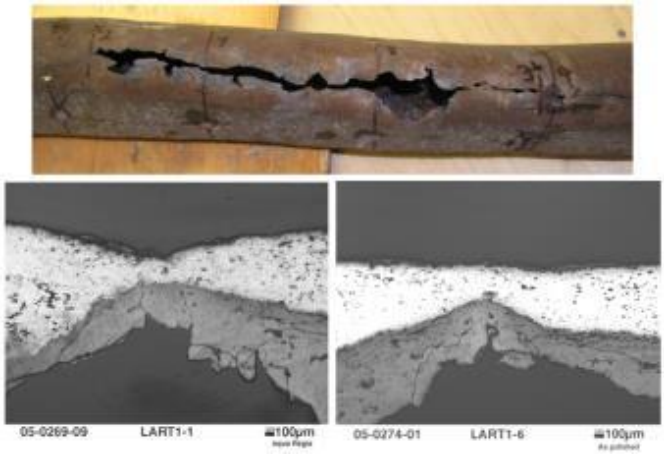

Figure 3-3. High temperature oxidation of recuperator tubes exposed to aluminum melting furnace exhaust gases (*Cross-sections showing significant wall thinning and thick internal oxide)* [7].

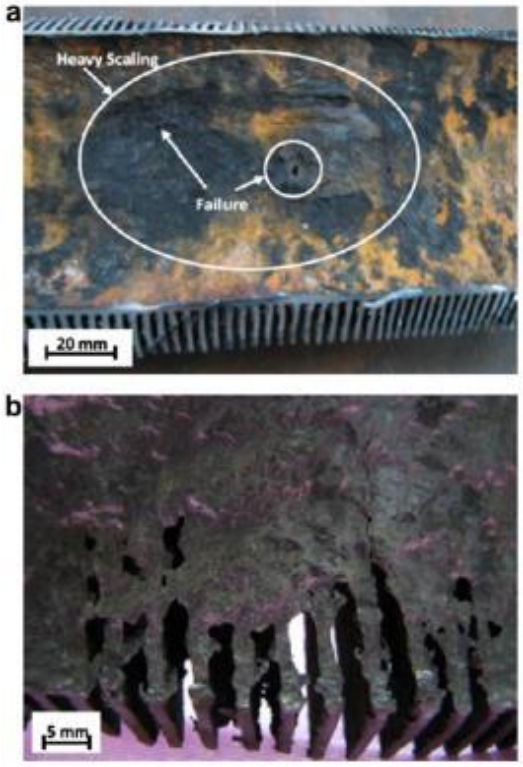

Figure 3-4. Internal surface of the failed reboiler heater tubes due to sulfidation, (a) corrosion products as heavy scaling and (b) dramatic wall thinning of the tube from process side and subsequent failure [10].

environment and will be most severe when an alloy sustains breakaway attack by oxygen/sulfur, halogen/oxygen, oxidant/low-melting fluxing salts, molten glasses, or molten metals.

3.3.1 Oxidation

Oxidation is the most common high-temperature corrosion reaction [8]. Much WHR equipment is exposed to oxidation, a process by which a metal in an off-gas environment containing oxygen species forms and sustains a protective oxide [9]. There are many possible oxide products, some of which are less desirable; for example, wustite (FeO), an oxide of iron, forms rapidly at about 1,000°F (540°C) on steel. Most high-temperature alloys are oxidation-resistant (depending on the environment), so price, availability, experience, and the type of application usually dictate the choice. Oxidation presents significant problems at temperatures above about 1,470°F (800°C) and the choice of successful alloys is somewhat limited [2, 8]. Simple iron-chromium (or iron-chromium-molybdenum) alloys are less useful as service temperatures increase; this is where the type 300 series austenitic stainless steels, (304, 309, 310, 314, 330, 333, etc.) and certain ferritic stainless steels (410 and 446) find many applications. Note that ferritic stainless steel 410 has less Chromium percentage than 300 series. Hence, oxidation resistance is not as good as the 300 series. For more arduous service conditions at higher temperatures, the latter alloys are surpassed by nickel-based formulations, including many of the more robust alloys that are mechanically alloyed to improve strength and to control (that is, minimize) grain growth at elevated temperatures.

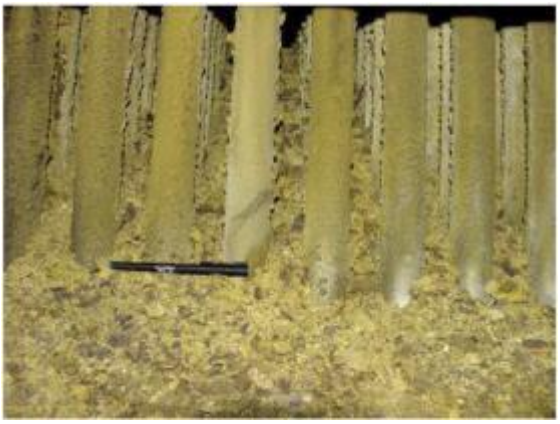

Figure 3-5. Sulfidation of the tubes as well as the recuperator floor on the exit side of a recuperator installed on a slab-reheating furnace combusting mixed gas (BFG + COG + BOF gas) as a fuel [10].

3.3.2 Sulfidation:

Sulfidation is a reaction of a metal or alloy with some form of sulfur to produce a sulfur compound that forms on or under the surface of a metal or alloy [11].

Sulfurous gases are common to many applications, including fuel combustion products or atmospheres, petrochemical processing, gas turbines, and coal gasification. Sulfides (e.g., sulfur vapor, hydrogen sulfide) can be very damaging, because metal sulfides form at faster rates than do metal oxides. Sulfides have low melting points and produce voluminous scaling (which can lead to scale spallation).

Mixed sulfur-and-oxygen gases can cause very high corrosion rates as a result of breakaway attack, typically at temperatures above 1,110°F (~600°C) for nickel-based, and 1724°F (940°C) for iron-based formulations. Break-away attack is commonly associated with sulfur and excess air. Once the initially formed oxide is lost or destroyed, the oxide will continue to re-form in the air or oxygen environment until the chromium or aluminum at the near surface is depleted below some critical level. Time to achieve this critical level is controlled by events that lead to oxide destruction, Cr and/or Al chemical activity in the alloy and its diffusion rate, which is dependent on temperature. Once the oxide formation ability is lost, sulfides can invade the chromium-depleted substrate, causing accelerated attack to occur. For example, Figure 3.5 shows premature failure of stainless steel tubes inside a recuperator used to preheat combustion air inside a slab-reheating furnace in a hot strip mill [10].

Iron-based alloys are preferred over high-nickel alloys, because nickel is prone to form a low-melting nickel-nickel sulfide eutectic, Ni-Ni_3S_2 that melts at 1,175°F (635°C). Eutectics of iron occur at higher

temperatures 1,805°F (985°C) [2]. Alloys containing aluminum and silicon are useful in sulfidizing environments. Many alloys classified as candidates for sulfidation do well only if oxides are able to form first.

3.3.3 Halogenation

Halogen (e.g., chlorine, fluorine, bromine) attack commonly manifests as a combination of scale spallation with internal alloy damage, including voids that form as a result of highly volatile species (e.g. chlorine or hydrogen chloride, fluorine or hydrogen fluoride) [12]. Halogens are readily soluble and diffuse rapidly into metals at high temperatures, and they can cause high-temperature corrosion. The solubility-diffusivity product (NxDx) for fluorine in nickel is about five times that for oxygen in nickel and about twice that for chlorine in nickel at 1,380°F (750°C) [12]. Oxidizing chlorine environments (e.g., air and 2% chlorine) are more damaging at 1,650°F (900°C) than reducing environments (e.g., Ar-25% H_2-10% HCl-5% CO-1% CO_2). Alumina-forming alloys are often the best choice overall; but acid-resistant alloys—rich in chromium and refractory metal—show reasonable performance in reducing atmospheres, unlike pure iron, for example [12].

3.3.4 Carburization

Carburization is a high-temperature corrosion phenomenon caused by the unwanted ingress of carbon into alloys used in the process and heat-treating industries. It occurs as a result of the presence of CO_2, methane, and hydrocarbon gases in off-gases. Damage usually manifests as internal carbides, notably in grain boundaries, and is generally worst above 1,922°F (1,050°C). When carburizing conditions alternate with oxidizing ones, carbides can become oxidized to form oxides, yielding carbon monoxide that can weaken the grain boundaries in an alloy. Such an alloy fails by "green rot," a name for the green fractured surface that results (chromium oxide). Strongly carburizing atmospheres (i.e., those that have a carbon activity >1) can cause a metal to form coke-like layers, often of a dusty form. This form of attack, termed "metal dusting," commonly occurs between 790°F and 1,470°F (425-800°C) and can be very rapid (occurring in days, not months). Damage is either general or localized, as dictated by the ability of the alloy to form a surface oxide. Carbon steels and alloy steels are normally uniformly thinned by metal dusting; more highly alloyed materials usually display localized outgrowths of coke that broaden with time. Cast iron-nickel-chromium alloys are widely used for carburizing applications, including more recently developed alloys containing 1–2% silicon and 1.5% niobium (the HP Mod alloys) [2, 12]. High-nickel alloys (with low solubility for carbon) find many applications in carburizing conditions. Stronger nickel-based alloys with high chromium and silicon contents are useful in more demanding environments. Highly alloyed ferritic stainless steels (which are able to more rapidly form a thin oxide film) tend to outperform austenitic steels.

3.3.5 Nitriding

Due to nitridation, performance of certain materials gets weakened (e.g. embrittlement) as a result of the formation of internal nitrides in the alloy. It is common to expect damage with nitrides at the elevated temperatures [1,290–1,650°F (700–900°C)]. Nitrides appear generally as needle-like precipitates in the alloy matrix. Nickel- and cobalt-rich alloys appear to be primary candidates for resisting nitride attack because of the low solubility of nitrogen in these base metals. Iron tends to be detrimental, as do aluminum and titanium in low concentrations. Silicon forms a brittle intermetallic compound with nitrogen and can contribute to scale spallation, especially in applications at low oxygen concentrations (potentials), in which thin oxides can form, and during thermal cycling [2].

3.3.6 Molten Product Corrosion

The mechanisms of molten product corrosion are complex. Deposits are a common product in many high-temperature applications, including boilers, waste incinerators, fluidized-bed combustors, and gas turbines. A whole series of reactions is possible should deposits become molten, and no single mechanism can be applied generally to characterize such damage. The types of damage include fuel-ash corrosion (sulfates, including acid and basic fluxing reactions, and vanadic slag attack), molten salt corrosion (chlorides, nitrates, and carbonates), and molten glass corrosion. Liquid metal attack is yet another special category. An example of molten product corrosion is the rapid degradation of alumina and silicon carbide refractories at very high temperature (probably > 1,800°F) due to the presence of zinc (likely from the galvanized material included in the scrap) in electric arc furnace systems.

Table 3.1. High-temperature waste heat sources and typical process conditions causing corrosion

Industry	Waste heat source	Temp. range (°F)	Characteristics	Type(s) of corrosion							
				O	S	C	Cl/F	N	Slag	Melt	Other
Steel	Blast furnace gases	750 to 1,100	Contain dust, sulfur, cyanide compounds, and other contaminants		X	X					
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	X	X	X	X	X	X	X	
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	X	X	X	X	X	X	X	
Glass	Regenerative system	750 to 1,100	Contain particulates; HCl, HF, boron vapors can be expected	X	X			X		X	X
	Oxy-fuel system	2,700 to 2,820	Contain particulates, condensable vapors, etc.	X	X			X		X	X
	Nonregenerative + other systems	2,700 to 2,820	Contain particulates, condensable vapors, etc.	X	X			X		X	X
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Combustibles, particulates, polycyclic organic matter, fluxing agents (chlorine, fluorine, etc.).	X	X		X	X	X	X	X
	Anode baking	570 to 930	Particulates, fuel combustion products, etc.	X	X	X	X				X
	Calcining	570 to 930	Particulates, fuel combustion products, etc.								
Cement	Cement kiln exhaust gases from modern clinker making operations	390 to 750	Exhaust gases contain particulates, etc. Relatively easy to handle	X	X		X				X
Lime	Lime kiln exhaust gases from commonly used rotary kiln type operations	390 to 1,100	Exhaust gases contain particulates, etc. Relatively easy to handle	X	X		X				X

Table 3.2. High-temperature waste heat sources and off-gas composition

Industry	Waste heat source	Temp. range (°F)	Characteristics	Off-gas composition (% by volume)								
				O_2	CO	H_2	CO_2	H_2O	CH_4	N_2	Other	Source
Steel	Blast furnace gases	750 to 1,100	Contain dust, sulfur, cyanide compounds, and other contaminants	–	20–28	1–5	17–25	–	–	50–55	–	[13]
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	–	22	5	8	2	3	60	–	[14]
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	–	70	2	13	2	1	13	–	[15]
Glass	Regenerative system	750 to 1,100	Contain particulates; HCl, HF, boron vapors can be expected	4–10	–	–	7–11	4-10	–	73-76	–	[16]
	Oxy-fuel system	2,700 to 2,820	Contain particulates, condensable vapors, etc.	1–2	–	–				–	–	Calculations – ESC
	Nonregenerative + other systems	2,700 to 2,820	Contain particulates, condensable vapors, etc.	4–10	–	–	7–11	4–10	–	73–76		
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Combustibles, particulates, polycyclic organic matter, fluxing agents (chlorine, fluorine, etc.)	4–10			50–55	42–49	–	0–2		Calculations
	Anode baking	570 to 930	Particulates, fuel combustion products, etc.	6–10	~0.2	~0.1	6–7	11–12		80–84		O_2 from [3.3] and calculations
	Calcining	570 to 930	Particulates, fuel combustion products, etc.									
Cement	Cement kiln exhaust gases from modern clinker making operations	390 to 750	Particulates, combustibles, NOx and SO_2	1.8	–	–	27.4	–	–	70.8	–	[17]
Lime	Lime kiln exhaust gases from commonly used rotary kiln type operations	390 to 1,100	Particulates, combustibles, NOx and SO_2	4–10	–	–	7–11	4–10	–	73–76	4–10	Combustion calculations based on O_2 content and different fuels

Table 3.3. Currently used waste heat recovery equipment and materials

Industry	Waste heat source	Temp. range (°F)	Characteristics	WHR related equipment
Steel	Blast furnace gases	750 to 1,100	Contain dust, sulfur, cyanide compounds, and other contaminants	Scrubbers, top gas pressure recovery turbines, and recuperator hot blast stoves
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	Consteel scrap preheaters, Bucket types scrap preheaters, Twin-shell furnaces, Fuchs shaft furnaces, and Evaporative Cooling (ECS) technology
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	Boiler or HRSGs, BOF gas cooling devices, dedusting devices, etc.
Glass	Regenerative system	750 to 1,100	Contain particulates; HCl, HF, boron vapors can be expected	Stationary regenerators, cullet preheaters, HRSGs, Organic Rankine Cycle (ORC) equipment
	Oxy-fuel system	2,700 to 2,820	Contain particulates, condensable vapors, etc.	Batch/Cullet preheaters, HRSGs, ORC equipment
	Nonregenerative + other (approx. values)	2,700 to 2,820	Contain particulates, condensable vapors, etc.	
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Combustibles, particulates, polycyclic organic matter, fluxing agents (chlorine, fluorine, etc.).	Conventional recuperators, regenerative burners, charge preheaters, HRSGs
	Anode baking	570 to 930	Particulates, fuel combustion products, etc.	Thermoelectric generators, sidewall heat exchangers, combustion air preheaters
	Calcining	570 to 930	Particulates, fuel combustion products, etc.	Cyclones and fluidized bed alumina coolers
Cement	Cement kiln exhaust gases from modern clinker making operations	390 to 750	Particulates, combustibles, NOx and SO_2	Waste heat recovery boilers, shaft type charge preheaters
Lime	Lime kiln exhaust gases from commonly used rotary kiln type operations	390 to 1,100	Particulates, combustibles, NOx and SO_2	Waste heat recovery boilers, shaft type charge preheaters

Table 3.4. High-temperature metal alloys

Alloy	Fe	Ni	Cr	Mo	Co	Al	C	Mn	Si	Zr	Ti	Other	Tensile at max use temp (ksi)	Yield at max use temp (ksi)	Max use temp (°F)
Carpenter															
Waspalloy	2.0 M	Bal	18–21	3.5–5.0	12–15	1.2–1.6	0.02–0.10	0.10 M	0.15 M	0.02–0.08	3.00		79	60	1600
Haynes Intl.															
Haynes 214	3.0	Bal	16			4.5	0.05	0.5 M	0.2 M	0.1 M	l		4.3	2.1	2200
Haynes 224	27.5	Bal	20			3.8									???
Haynes 230	3 M	Bal	22	2	5 M	0.3	0.10		0.40			14 W, 0.02 La	13.2	6.8	2100
Hastelloy X	18.0	Bal	22	9	2		0.10	1 M	1 M			0.6 W	14.0	6.4	2000
Rolled Alloys															
602CA	9.5	Bal	25			2.2	0.18	0.15 M	0.5 M	0.08	0.15	0.09 Y	5.8	5.0	2200
Sandvik Matl.															
353MA	Bal	35	25				0.05	1.50	1.60			0.05 Ce, 0.16 N			2100
APMT	Bal		21	3		5.0	0.08 M	0.4 M	0.7 M						2280
Sanicro 61		60	23			1.3	0.03	0.60	0.30				~7	~3	2100
Sanicro 70	9.5	72.5	16.5				0.06	0.80	0.40		0.15				NA
Special metals															
Inconel 601	14.0	62	23			1.4	0.05						~5	~3	2100
Inconel 617	3.0 M	44.5 M	20–24	8–10	10–15	0.8–1.5	0.05–0.15	1.0 M	1.0 M		0.6 M	0.5 Cu, 0.006 B	0.73	0.45	1800
Inconel 693	2.5–6.0	Bal	27–31			2.5–4.0	0.15 M	1.0 M	0.5 M		1.0 M	0.5 Cu	~7	~3	2000
Inconel 702	2.0 M	Bal	14–17			2.75–3.75					0.25–1.0				NA

Note: M – Maximum and Bal - Balance

Table 3.5. High-temperature ceramic/refractory materials

Material	Type	Producer	Chemistry										Physical properties				Service temp °F	Thermal conductivity (W/mK)		Cost and availability
			Al_2O_3	SiO_2	SiC	CaO	Fe_2O_3	MgO	TiO_2	P_2O_5	Alkali	Other	Density (g/cm3)	Porosity %	MOR MPa	Cc MPa		High	Low	
ALAKAST 85-ULC	High alumina, ULC	Riverside	85.71	9.27	–	1.39	0.76	0.01	2.33		0.09	0.44	2.85	15–16	17	95	3,100	3.47	2.91	
AlAKAST 95-LC-P	High alumina, LC	Riverside	90–95			5–10		<5												
Metpump C-192	High alumina, cement free	Magneco-Metrel	91.7	7.7	–	0.1	0.1	–	0.1		0.2	–	2.95	14	15	> 110	3,250	5	3.5	
Metpump Delta	High alumina, SiC	Magneco-Metrel	85.4	7.3	4.6	0.1	0.4	–	2		0.1	–	3.1	14	15	96.6	3,200			
F-1408	High magnesia	MinTeq	0.1	2.2	–	5	0.6	91.4	–	0.7	–	–	2.68	21	19	52	3,000			
Monofrax L	Fusion cast spinel	Monofrax	53.6	0.44	–	0.35	–	44.9	–		0.23	–	3.08	< 2			3,400	17.75	5.75	
Monofrax M	Fusion cast alumina	Monofrax	94	1	–	–	–	–	–		4	< 1	3.4	< 2	24	124	3,400		4.8	
MORCOCAST 85 LC	High alumina, LC	MORCO	84–86	9–10	–	< 2	< 2	–	< 3		–	< 1	2.8	14–16		93	3,250			
TCON TC1	SiC/Al2O3 composite	Fireline	37		50							(13% Al/Si)	2.93	9	25					
TCON TC2	SiC/Al2O3 composite	Fireline	33		55							(12% Al/Si)	3.05	4	21					

Note: MOR – Modulus of Rupture, Cc – Compression index, ULC – Ultra Low Carbon, and LC – Low Carbon.

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4. STEEL INDUSTRY

4.1 BLAST FURNACES

4.1.1 Background and Potential Opportunity

The purpose of a blast furnace is to convert iron oxides into liquid iron through a series of chemical reactions. Hot liquid metal production in a blast furnace is one of the most energy-consuming processes. In the US, the iron and steel industry account for 34% of energy use [1]. Blast furnaces that have been installed vary in size (working volume), ranging from less than 100 m^3 (3,531.5 ft^3) to more than 5000 m^3 (176.573 ft^3). [2] In 2014, there are total 22 blast furnaces installed in the US and their rated capacities vary between 1.2 to 2.8 million metric ton (tonne) per year. [3]

A blast furnace is a shaft that is charged from the top with a combination of iron ore sinter, coke and lime. The lime is used to remove impurities. [1] Hot compressed air is injected from the sides near the bottom end of the furnace using tuyeres (see Figure 4.1). The hot air entering the furnace is provided by several auxiliary hot blast stoves. Blast furnace gases and coke oven gases are combusted in these blast stoves to generate heat, which is transferred to a checker work regenerator. When the regenerator reaches a specific temperature, the flow of gases is reversed and cold air flows through the regenerator. This transfers the heat to the cold air, which can then be injected into the lower section of the blast furnace. [4] The charged materials work their way down the furnace through various zones, and the materials undergo a series of chemical reactions as they move down.

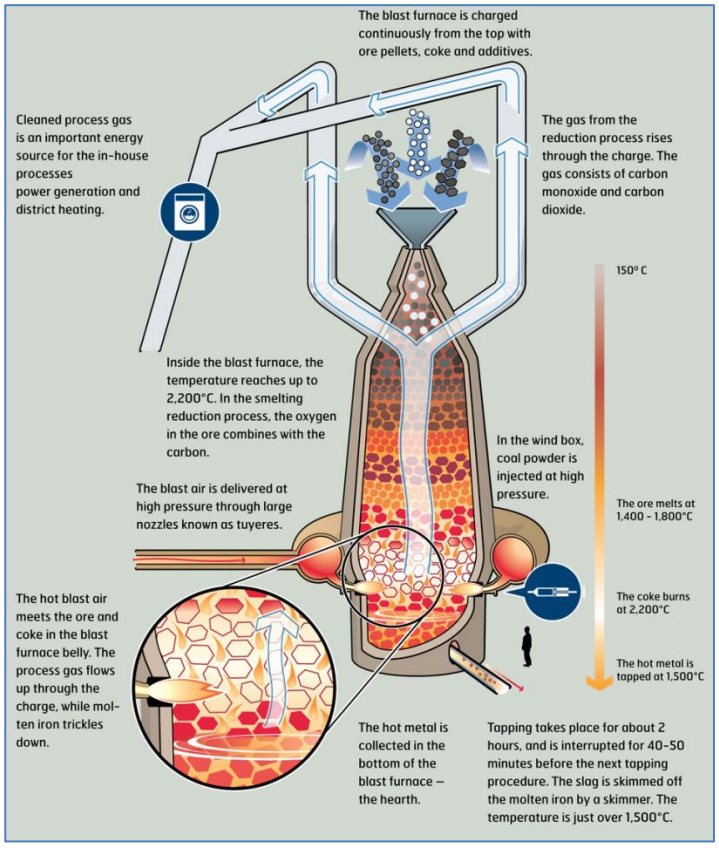

Figure 4-1. Inside the blast furnace. [5]

The bottom part of the furnace is the hottest zone; there the coke is gasified, creating high-temperature reducing gases that are necessary for the chemical reactions to reduce iron ore. The heat content of the gases decreases as they approach the top of the furnace. The gases exchange heat with the charge materials moving down the furnace.

Molten iron trickles down to the base of the furnace, forming a porous mass at 2,192°F (1200°C). Impurities in this molten iron are removed by a chemical reaction with fluxes such as calcium oxide. The reactions form a slag that floats on top of the molten iron because it is less dense. Silica that does not react with the calcium oxide is reduced by carbon. The coke chemical reactions produce carbon monoxide (CO) and other combustible gases as part of the gas mixture flowing toward the top section. After all the necessary reactions are complete, molten iron can be tapped and the slag removed. The final product is liquid iron, commonly known as pig iron, that can be tapped and used to make steel in a separate process vessel. [1]

Figure 4.2 shows an example of heat balance carried out in a blast furnace. As seen in the image, over 39% of the total heat input may be discharged as sensible and chemical heat in off-gases. In this case, the chemical heat is 29% of the discharged heat, higher than the percentage of sensible heat, indicating the presence of a large amount of combustible gases. These blast furnace gases are released through the top of the furnace if no recovery system is used. A typical blast furnace produces around 1,320–2,210 Nm^3 (46,615 to 78,045 ft^3) of furnace gas per ton of pig iron, containing 20–28% CO and 1–5% H_2 at an average gas temperature range of 400–600°F (200–320°C). [6] The practical minimum energy use for a blast furnace is 10.4 GJ/t (9.86 MMBtu/t). [3] Based on information obtained from six efficient hot blast stoves and blast stoves around the world, the average total primary energy requirement for a blast furnace system is reported to be 13.4 GJ/t of liquid iron. This energy use includes 1.8 GJ/t hot metal (1.71 MMBtu/t) for the hot blast stoves and 11.6 GJ/t-hot metal (11 MMBtu/t) for the blast furnace itself. [7].

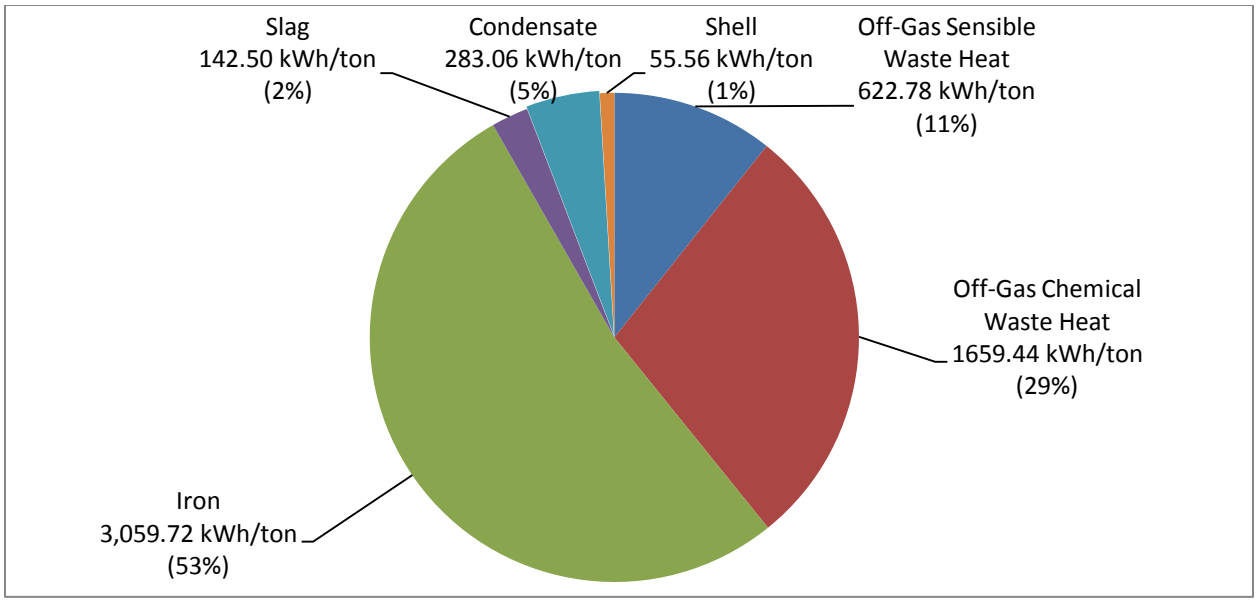

Figure 4-2. An example of heat balance carried out in a blast furnace. [8]

4.1.2 Current Methods of Waste Heat Recovery

In blast furnaces without recovery systems, a great deal of energy is wasted in the form of off-gases. Both chemical and sensible heat is lost. As mentioned earlier, 29% of the total input energy is wasted in the form of blast furnace gases (chemical heat). Another 11% is wasted as sensible heat. This is a significant amount of energy simply being released as waste. Many blast furnace plants today incorporate WHR systems that can recover some of the sensible and chemical heat for use in the steel making process. This not only reduces the amount of exhaust gases but also can potentially save a great deal of money and fuel. There are many existing WHR methods in use by the steel industry, which will be explored and analyzed in this section. Table 4.1 summarizes these methods and examines the advantages, disadvantages, and heat recovery potentials.

Recovery of chemical heat from blast furnace (BF) top gases: One major WHR method involves the recovery of blast furnace top gases. Most of the heat lost is in the form of chemical heat being released through the top of the blast furnace. A typical blast furnace produces about 1,320 to 2,210 Nm^3 (46,615–78,045 ft^3) of gas per ton of pig iron, [9] consisting of 20–28% CO, 1–5% H_2, 50–55% N_2, and 17–25% CO_2, as well as dust, sulfur, cyanide compounds, and other contaminants. [15] The gases being released have the potential to be used as fuel and/or used to generate electricity in a gas turbine. This method of recovery involves cooling or "washing" the blast furnace off-gases using a scrubber and then storing them. [7] Scrubbers remove about 60% of particulates from blast furnace gases. [9] Figure 4.2 shows a Venturi scrubber, a type of scrubber that can be used in this process. [10] After scrubbing, dry gases can then be distributed as fuel, mixed with other fuels (e.g., natural gas, coke oven gas) for the heating processes within the plant. The energy content in blast furnace gases ranges from 2.3–3.4 kBtu/Nm^3 (2.7–4.0 MJ/Nm^3). The amount of energy in these gases varies depending on the concentration of CO. The blast furnace gas usually has only about 10% of the energy content of natural gas (2.8 kBtu/m^3 vs. 28-38 kBtu/m^3); therefore, it is usually enriched by coke oven gases or natural gas before it is used in order to boost its energy content. [7] By recovering blast furnace top gases, cleaning them, and storing them for later use, it is possible to reduce emissions by 4.0 kg CO_2/t hot metal. [11]

The recovery technology for this method is currently available and widely used by many blast furnace plants in the US. The top-gas recovery system is fairly simple and well established. Site-specific variables

may affect costs. A top-gas recovery system has been installed on a furnace in the Netherlands at a cost of $0.43/ton ($0.47/tonne) of hot metal, and the energy savings have been estimated to be approximately 17 kWh/ton (0.066 GJ/tonne) (0.058 MMBtu/ton) of hot metal. [5] Clearly, this WHR method has several advantages; however, a few issues and barriers are associated with it. Although a significant amount of chemical heat is recovered, a great deal of the sensible heat is lost, so only a portion of the waste heat is being recovered. Sensible heat has the potential to be useful for preheating combustion fuels in several other recovery methods; however, it is lost because of requirement that particulates be removed through washing or scrubbing. Another issue with this recovery method is the disposal of scrubber water. In the wet scrubber, down-flow water sprays clean the dust from up-flowing gases. The wastewater contains 1000–10000 mg/l (0.0083–0.083 lb/gal) of suspended solids, [12] and its disposal may pose a challenge.

Top gas pressure recovery—use of turbines to generate electric power: Top gas pressure recovery, a second major WHR method, uses a turbine to recover energy from higher-pressure gases through pressure reduction. [7] The physical energy of high-pressure blast furnace top gases is converted into electricity by using an expansion turbine (Top pressure Recovery Turbine – TRT) [13]; electric power is generated by using the top gases to drive a turbine-generator as they expand from furnace top pressure to atmospheric pressure. Top gas pressures in most blast furnaces are approximately 6–36 psig (0.25–2.5 bar gauge). [7] The pressure differential between the furnace and the atmosphere is low, but the large volume of gas makes this method economical. [9] These systems can be either wet or dry, depending on the method used to remove the dust particles, which is necessary for proper turbine operation. [3] Dry system utilizes the BF gas heat and pressure energy to drive a turbine. Dry systems use less water and electricity and typically produce 25 to 30% more power, but they are more expensive than wet systems. Wet system utilizes only the BF gas pressure energy to drive a turbine. Wet systems are more common in the US. [9] Pressure recovery system is used for cooled gases. The gases must be cooled and "cleaned" to remove major particles content before they enter the pressure recovery turbine. Figure 4.3 shows a diagram of a Venturi scrubber (a wet scrubber), commonly used in blast furnace top pressure recovery. Wet scrubbers use water to remove very small dust particles. [17] Top pressure recovery systems have good operational reliability and are abrasive-resistant. [6] A wet turbine system of this type has the potential to produce approximately 14 to 36 kWh/ton (0.054 to 0.14 GJ/tonne) (0.048 to 0.123 MMBtu/ton) of hot metal. [6] Also, 40–60 kWh (0.136–0.205 MMBtu) of electricity can be produced per ton of hot metal. [9] This output can supply around 30% of all the electricity needs of all blast furnace equipment. [14]. Essentially, the waste gases at the top of a blast furnace are used to generate electricity rather than simply being exhausted into the atmosphere, reducing emissions as well as the cost of powering the blast furnace.

Cost is a significant issue to examine in considering use of top gas recovery. A typical investment for the turbine is approximately $28.4/ton hot metal ($31.3/tonne). Such a project would have an estimated payback time of 30 years. [6] Although that is a long period of time, many would argue that it is a good long-term investment because of the economic and environmental benefits. Another barrier associated with top gas pressure recovery is that blast furnaces do not operate at extremely high pressures, which can make top gas recovery somewhat difficult. [7] Although the top pressure in most US furnaces is too low for recovery, future furnace upgrades may result in pressures high enough to allow economic recovery. [6] For now, these systems are suitable only for large furnaces (in excess of 1 million tonne/year) and high-pressure gases. [6] This technology is available but is not widely used, especially in the US. [14] Dry type recovery turbines have already been commercialized; however, they are significantly more expensive than wet type systems and are not likely to be used in the US soon. [4] This technology is considered to have a high application potential for China, India, and the US, particularly for new plants. The final issue is that it is often difficult to retrofit existing blast furnaces to use top gas pressure recovery technology. [14]

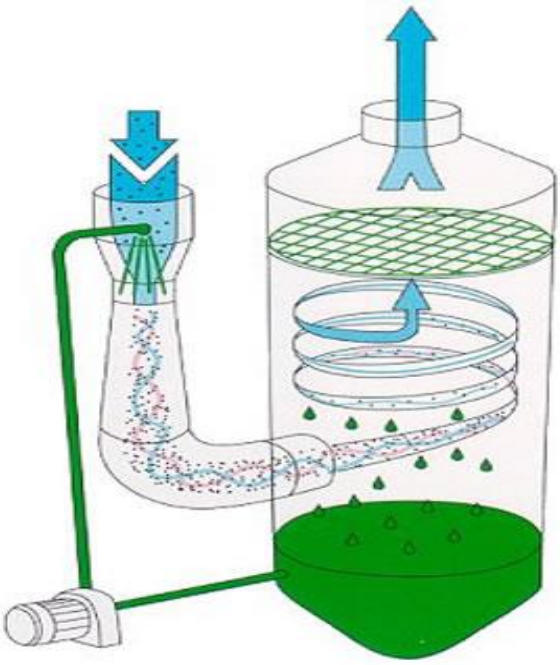

Figure 4-3. Venturi scrubber (wet type scrubber). [10]

Recuperator hot blast stove: A third WHR method uses a recuperator system to recover the heat from flue gases from the hot blast stove to preheat the blast furnace. The energy from the stove flue gases pre-heats the combustion fuel and air entering the blast stoves. The stove flue gases typically have a temperature of about 482°F (250°C). [7] Preheating can lead to an energy saving of approximately 87.92 kWh/ton (0.3 MMBtu/ton) of pig iron. Fuel savings can be from 20 to 21 kWh/ton (0.068 to 0.072 MMBtu/ton) of hot metal at a cost of approximately $19 to 21/MMBtu ($18 to $20/GJ) saved. This results in a payback period of about 8.7 years. [6] This method can allow an efficient hot blast stove to run without the need for natural gas. Another advantage of preheating is that the hotter combustion air results in a higher flame temperature. A higher flame temperature will result in a higher blast temperature of the blast furnace air. A specific medium-size WHR system located in Japan, consisting of two heat exchangers, achieved a recovery rate of sensible heat of 40–50%. This 1 tonne/year blast furnace system realized a savings of 0.125GJ/t of pig iron (0.118 MMBtu/ton) and a reduction in heat consumption of about 31.65 kWh/ton (0.108 MMBtu/ton) of pig iron. [15] An issue with this WHR method is that costs are high and depend considerably on the size of the blast furnace. [6] This technology has been installed at most steel plants in Japan. Candidate countries for this technology include China, India, Central/South America, and Eastern Europe countries [7]. Currently there is low potential for this technology in the US. [16]

BF gas preheating system using recuperator: A fourth WHR method uses a recuperator system to recover heat from blast furnace gases to preheat the combustion air for the blast furnace. This method is similar to the third method discussed, except that it uses recuperators to recover heat from the blast furnace gases leaving the top of the furnace rather than from the blast stove flue gases. The concept of preheating combustion fuel and air entering the stove are the same, but the heat is recovered from two different places using a system of recuperators. The two places are: (i) heat recovery from blast furnace top gases leaving the blast furnace; and (ii) exhaust gases or combustion products leaving the blast furnace stove itself. Blast furnace gas preheating systems use low- and medium-temperature waste heats 340 – 430°F (170–220°C). The heat exchange is difficult because of corrosion

Of working surfaces. An existing blast furnace gas preheating system at POSCO in South Korea was able to reduce fuel input by 102 kcal/kWh (0.30 kcal/Btu) (427.07 kJ/kWh) and increase the thermal efficiency of the furnace by 3.3%. Studies have shown that these systems are fairly reliable and stable. [9] A few barriers are associated with this method, mainly involving the recuperators. There are several different types of recuperators, each with their own set of barriers. Corrosion is very common because of chemical reactions that occur with the solid particulates suspended in the gases and the recuperator. To counter this problem, some companies, including POSCO in South Korea, have developed anti-corrosion systems. This method is currently considered an emerging commercial technology. [9]

Table 4.1. Existing and emerging waste heat recovery techniques/methods from blast furnace off-gases

Existing method of waste heat recovery	Brief description	WHR technology/system status	Advantage	Barrier/disadvantage	Waste heat recovery potential
Recovery of chemical heat from blast furnace (BF) top gases	Cooling or washing of BF off-gases using a scrubber and then storage and/or distribution of dry gases as fuel mixed with other fuels (e.g., natural gas, coke oven gas) [7]	Available and widely used [11]	Relatively simple and well established. Emissions can be reduced by 4.0 kg CO_2/t of hot metal [10]. Potential energy savings up to 17 kWh/t of hot metal (US EPA 2010) [6]	Loss of sensible heat [6], disposal of scrubber water [12]	Potential energy saving up to 17 kWh/t of hot metal [6]
Top gas pressure recovery—use of turbines to generate electric power	BF top gases are at higher pressure (0.1 to 0.25 MPa gage or 15.5 to 31 psig). Turbine recovers energy from higher-pressure gases through pressure reduction. [7]	Available but not widely used, particularly in US [6]	Electrical power generation [6]. Suitable for large furnaces and high-temperature gases. Good operational reliability, abrasion resistant [9]	US BFs do not operate at high pressure. Uneconomical, and retrofit is difficult [6]	Existing facilities using the technology have experienced net primary energy savings of 2,052,000,000 kWh (7 Tbtu) (as of 1997).[16] Turbine may produce ~14 to 36 kWh/ton (0.054 to 0.14 GJ/tonne) of hot metal [7]. 40–60 kWh of electricity can be produced per ton of hot metal and their output can meet around 30% of all electricity needs for the BF equipment [9]
Recuperator hot blast stove	Hot blast stove flue gases are used to preheat the BF [6].	Commercial status. Medium application potential in China and India, and low potential for the US. [15]	An efficient hot blast stove can run without the need for natural gas. Energy savings are ~0.3 MMBtu/ton pig iron. Fuel savings vary from 80–85 MJ/t hot metal [6]	Payback time is about 8.7 years [6]. Costs are high and depend heavily on the size of the BF [9]	Preheating can lead to energy savings of ~87.92 kWh/ton pig iron (0.3 MMBtu/ton pig iron or 0.35 GJ/tonne) [6]. Can reduce energy demand by 66.67 kWh/ton of hot metal (0.24 GJ/t) [15]

Table 4.1. Existing and emerging waste heat recovery techniques/methods from blast furnace off-gases (continued)

Existing method of waste heat recovery	Brief description	WHR technology/system status	Advantage	Barrier/disadvantage	Waste heat recovery potential
BF gas preheating system using recuperator	The exit temperature of the flue gases, ~480°F (250°C), can be recovered to preheat the combustion air of the stoves [9]	Emerging technology [9]	Economic recovery for low- to medium-temperature grade heat. 102 kcal/kWh reduction in fuel input; 3.3% thermal efficiency increase. Energy savings of 3–5% for boiler with payback period of within 1.5 years [9]	Recuperator corrosion is common [9]	102 kcal/kWh reduction in fuel input; 3.3% thermal efficiency increase of 3.3% Energy savings of 3–5% for boiler with payback period of within 1.5 years [9]

4.1.3 Limitations of Existing Methods of Waste Heat Recovery from Blast Furnaces

Despite the advantages attributed to blast furnace WHR methods, the use of some of these technologies is quite limited in the US, as well as in the rest of the world. The lack of use can be explained based on the following reasons:

- In each WHR method, only a portion of the waste heat is recovered. For example, during cooling or washing of off-gases in the recovery of chemical heat from top gases, most of the sensible heat is lost. Although a significant amount of chemical energy is recovered, a great deal of the sensible heat from the gases being recovered is lost to the atmosphere.

- US blast furnaces do not operate at extremely high pressures, which can make top gas recovery somewhat difficult and uneconomical. The gases leaving the top of the furnace are approximately 0.25–2.5 bar (25,000–250,000 N/m^2) and have a temperature of around 392°F (200°C). [2] This pressure and temperature are comparatively quite low. Top gas pressure recovery is suitable only for large furnaces and high-temperature gases.

- Retrofit may be difficult for some recovery methods, such as top pressure recovery methods. In such cases, the technology may have a higher application potential for new plants because of the difficulty of retrofitting existing plants. [3]

- It may be challenging to dispose of wastewater used to wash dirty off-gases to recover chemical energy. The wastewater in a wet scrubber contains 1000–10000 mg/l (0.0083–0.083 lb/gal) of suspended solids. [12]

- Recovery of sensible heat using heat exchangers is difficult because of a lack of suitable technology in the US. Recuperators, in particular, present a number of issues with preheating systems, depending on the type of recuperator used. [18] (Discussed in more detail in the paragraph following this list.)

- Recovery system components such as recuperators often experience corrosion as a result of high temperatures and the presence of particulates. Corrosion of recuperators can reduce the amount of heat transfer from the off-gases to the combustion air. [9]

Preheating systems, including hot blast stove and blast furnace gas preheating systems, are an excellent way to recover waste heat to preheat combustion air. The incorporation of recuperators in these recovery systems has resulted in reduced fuel consumption, increased cost effectiveness, and short payback periods. Although recuperators can be very beneficial, they also present many issues that create key barriers for the recovery systems in which they are used. Several different types of recuperators are available for use. They are classified according to the material of which they are made (metallic or ceramic) and the dominant mode of heat transfer. Each type of recuperator has its own set of drawbacks and issues that can prove to be significant barriers to a recovery system. The type of recuperator used in a recovery system depends on several variables, including the furnace size and temperature and the primary mode of heat transfer used. Convection recuperators are generally deployed when flue gas temperatures are fairly high. An air-type convection recuperator consists of a bundle of several hundred tubes outside which flue gas passes, guided by baffle plates. These recuperators are easily affected by dust, and their tubes are sensitive to abrasive wear caused by the solid suspended particles from the flue gases. In a gas-tube type convection recuperator, the diameter of the heating tubes is much larger than in an air-tube type; however, these recuperators experience more gas leaks than the air type. Ceramic recuperators are typically used for temperatures exceeding 2012°F (1100°C). Ceramic materials are better solutions for

durable heat exchangers; however, they are more prone to fouling. Fouling, a common problem for recuperators, is the deposition of material on a heat transfer surface. It results in an increase in the resistance to heat transfer. Fouling is primarily due to the variety of gaseous species present in combustion gases; many of those species are condensable and some are corrosive. [10]

4.1.4 Conclusions

The use of blast furnace off-gas heat to preheat combustion air, generate electricity, and recover chemical heat offers several benefits. The methods discussed can save energy, reduce emissions, and save money. Although there are many benefits, there are also several issues and barriers that should be considered for each method. The barriers depend on the WHR method being used, as well as the size of the blast furnace. Some plants cannot be retrofitted to accommodate some types of systems, and some WHR methods are suitable only for large furnaces and high-temperature gases. Costs and maintenance are issues for some blast furnace off-gas systems. Some of the methods discussed are currently being used by several companies, whereas others are still emerging technologies. New and existing WHR methods are still being developed and studied, and some of them have great potential to improve industrial processes.

4.2 ELECTRIC ARC FURNACES

4.2.1 Background and Potential Opportunity

The US steel industry has experienced significant growth in the production of liquid steel from recycled scrap using EAFs, which accounted for about 60.3% of US steel production in 2011. [19] The process uses electricity as well as fossil fuels, primarily natural gas and some carbon, to supply process energy requirements. Large amounts of exhaust gas at temperatures greater than 3,000°F (1,650°C) are discharged from a furnace during the EAF melting cycle. At different times during the melt cycle, these exhaust gases contain CO_2, water vapor (H_2O), CO, H_2, O_2, and hydrocarbons. The exhaust also contains small amounts of metallic and nonmetallic solid particles of varying sizes. The heat content of off-gases varies during a cycle, commonly known as the tap-to-tap time, which varies typically from 50 to 60 minutes. The exact heat content depends on a number of factors such as the fuel used, amount of oxygen present, scrap temperature, and type of charge material. Figure 4.4 shows an example of heat balance carried out on an EAF using electrical energy as well as carbon injection, oxy-fuel burners, and additional oxygen during the melting operation.

As seen in Figure 4.4, over 38% of the total heat input may be discharged as sensible and chemical heat in off-gases. In this case, chemical heat makes up 22% of the total; it is higher than the sensible heat, indicating the presence of a large amount of combustible gas. Although Figure 4.4 shows data for a specific operation, based on our literature review, off-gases often contain exhaust gases that are responsible for energy losses of about 25 to 35% of the total heat input.

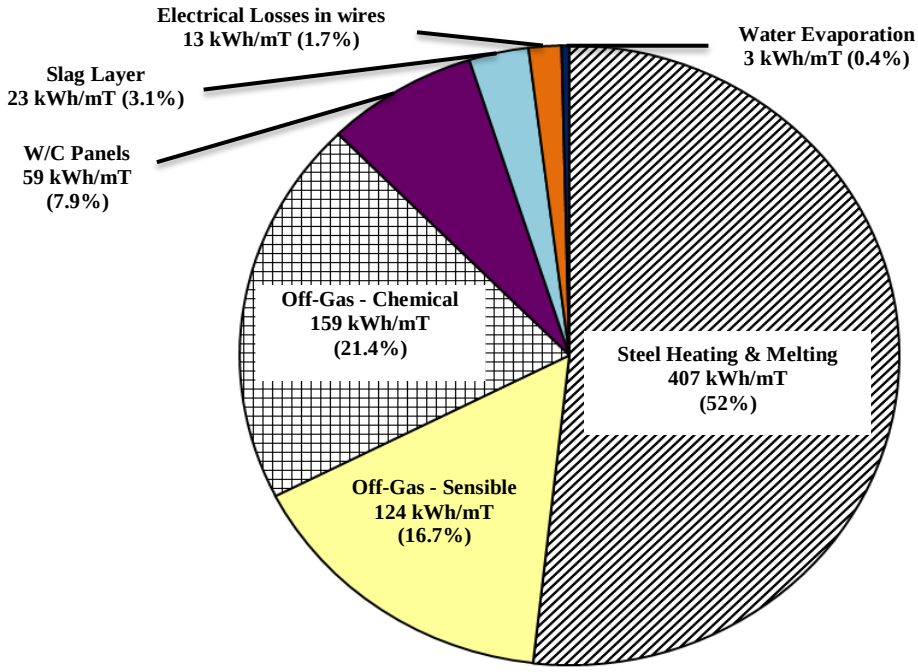

Figure 4-4. An example of heat balance carried out on an EAF using electrical energy as well as carbon injection, oxy-fuel burners and additional oxygen during the melting operation (mT= tonne).

Based on a conservative estimate of 30% off-gas heat loss; US steel production of 80.5 million tonne/year, 61.3% by EAF; and average energy use of 606 kWh/tonne of steel, the total heat loss from EAFs is estimated at 9.0 billion kWh or 31 trillion Btu/year using a 3,412 Btu/kWh conversion factor, or 95 trillion Btu/h using a conversion factor of 10,500 Btu/kWh that includes electricity generation,

transmission, and distribution losses. The actual number is somewhere between 31 and 95 trillion Btu/h and depends on the proportion of electrical and chemical energy used. The total sensible heat loss via exhaust gases would be approximately 14.0 petaJoule (or 13.3 trillion Btu/year).

According to an EAF roundup conducted by AIST [20], there are approximately 173 EAFs in the US. The characteristics of these 173 EAFs are shown in Figure 4.5. Approximately 42% of the EAFs were built before 1990, and over 56% are large furnaces with an average melting capacity ≥50 tonne. These numbers show there is a significant opportunity for replacing old EAFs with new energy-efficient EAFs and thus saving a significant amount of energy.

In the vast majority (>90% in the US) of installations [20], it is common practice to collect EAF exhaust gases, mix them with ambient air to oxidize the combustible materials, and then drop the temperature of the gases to less than 400°F (or 200°C). These relatively low-temperature gases are then passed through a pollution control device such as a baghouse before being discharged into the atmosphere. The capacity of these direct evacuation systems is typically 35,315 standard ft^3/h (or 1,000 Nm^3/h) per tonne of furnace capacity. The exhaust gas system may include a "drop out" box to drop out large particles, a quench or cold air mixing system, and an exhaust fan that uses hundreds of horsepower of electrical energy. The entire exhaust gas direct evacuation system requires frequent cleaning and other types of maintenance. In addition, fourth-hole direct evacuation systems do not always operate as designed. For example, a change in furnace pressure may cause fumes to escape through doors, ports, roof–sidewall joints, and electrode openings, bypassing the direct evacuation system. Hence many EAF operations also use a deep rectangular canopy hood over the furnace to capture the fumes generated during charging, tapping, melting, and refining. These types of systems typically have capacities of 12 to 30 million standard ft^3/h (or 340,000 to 850,000 Nm3/hour) per tonne and consume a significant amount of electrical energy.

In some cases (<10% of the total EAFs in the US), the waste heat from EAF off-gases is recovered and used for either scrap preheating or steam generation. According to the electric arc furnace roundup [20], there are total of nine EAFs (seven operational, one idled, and one under construction) with Consteel scrap preheating systems. There also are a total of nine EAFs (one EAF is not melting) with shaft, twin shaft, and twin shell types of scrap preheating systems. Among the WHR technologies used today, scrap preheating is a commonly used WHR method for EAFs. Therefore, this subsection focuses mainly on scrap preheating technologies and compares them with proposed concepts for advanced WHR. In the case of EAFs with scrap preheating technologies, exhaust gases from the furnace are passed through a scrap preheating system in which the gases supply heat to the charge material to raise its temperature before it is charged into the EAF vessel. Scrap preheating typically raises the temperature of the scrap several hundred degrees above the ambient temperature and thus reduces the amount of energy required for melting it. Several charge preheating system designs are used by the steel industry:

- CONSTEEL technologies
- scrap preheating in a charging bucket
- Fuch's shaft preheater
- Fuch's double shaft preheater, finger shaft furnace, etc.
- BBC-Brusa rotary tube-type scrap preheating furnace

Table 4.2 lists all major WHR techniques/methods currently available for recovering waste heat from high-temperature EAF off-gases, along with their advantages and disadvantages. Although several other WHR systems (e.g., chemical recuperators, evaporative cooling, steam or power generation) are available for recovering waste heat from EAFs, this section focuses mainly scrap preheating technologies, as they are commonly used and widely accepted.

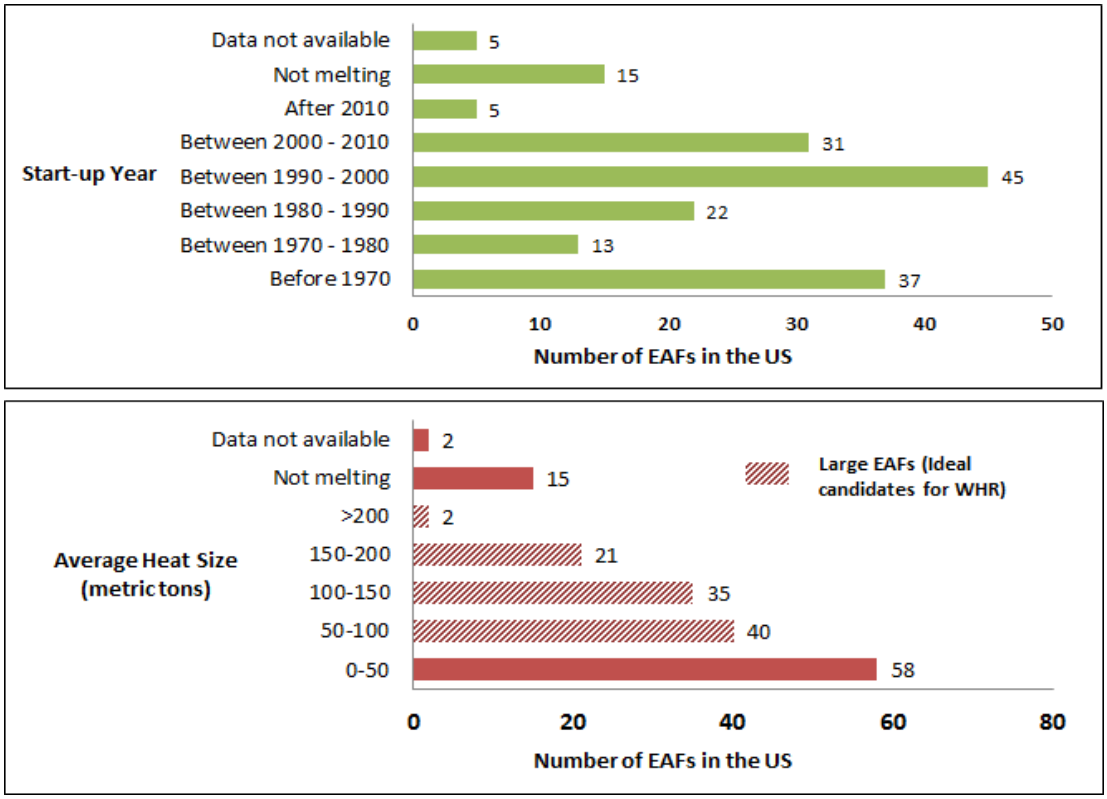

Figure 4-5. AIST 2014 EAF Roundup—startup year and average heat size (tonne)

Use of charge preheating offers several benefits, including reduced use of energy in EAFs (megawatts), reduced melt time, and increased productivity per megawatt (tonne/hour/MW). [21, 22, 23, and 24] The systems listed in Table 2.2 and used at a few plants include heating of scrap in buckets, in shafts, or on a conveyor specially designed to withstand high temperatures. In all cases, only a part of the exhaust gas heat is transferred to the charge material; a relatively large amount of heat is still left in the exhaust gases leaving the charge preheater (Figure 4.6). Users also have identified several issues with currently available scrap heating systems. Commonly used scrap preheating systems require frequent maintenance and may result in the uneven heating of scrap and localized melting of steel in the scrap preheater itself, resulting in operational problems. In many systems, operators prefer low to no preheating of the scrap material to avoid heat deformation of the charging bucket and resulting maintenance issues, or the occurrence of white smoke or a bad smell as a result of preheating certain types of scrap. Some scrap preheating systems may increase combustion gas pressure under the furnace roof. In those cases, a highly sensitive furnace pressure control is required to avoid unacceptable pressure in the furnace, which would lead to CO gas escaping through any gaps in the furnace and associated plant equipment. Many of these problems are due to uncontrolled gas temperatures and the presence of combustibles, together with unpredictable air flow patterns that may result in uncontrolled combustion of combustible gases. Hence there is a need for the development of systems that overcome issues and problems experienced with the use of currently available designs.

Table 4.2. Existing waste heat recovery techniques/methods from high temperature EAF off-gases

Existing method of waste heat recovery	Brief description	Advantage	Disadvantage	Waste heat recovery potential
Scrap preheating in charging bucket	Hot furnace off-gases are delivered to a scrap charging bucket from the fourth hole in the EAF through a special hood over the charging bucket. Typically the scrap is preheated to a range of 600 to 850°F (315 to 450°C) [21]	Recovery of waste heat and decreased electrical consumption to melt steel scrap, increased productivity, removal of moisture from the scrap, reduced electrode and refractory consumption. Some of the furnace dust is trapped by the scrap and returned to the furnace, thus reducing EAF dust generation and disposal [25]	Recovers only part of the sensible and chemical heat. Still requires large amounts of cooling/mixing air. Inconvenience of operation (e.g., scrap sticking to bucket, poor controllability of preheating due to cycling of the off-gas temperature and flow rate). Capital expense is not justifiable for tap-to-tap times of less than 70 minutes. If there are organic substances in the scrap, such as plastics, odors and/or dioxins may be formed. Many systems in the past have experienced operating issues and problems related to safety, maintenance, and localized melting	Can recover 30 to 45% of the waste heat leaving the furnace [21]. The medium mass temperature of heated scrap ranges from 600–840°F (315 to 450°C). Scrap preheating reduced tap-to-tap time by 9–10% and the electrical energy consumption of the furnace by 72–78 kWh/tonne [26]; double shaft furnace: 100–120 kWh/tonne [25]
Fuchs shaft preheater	In a batch type preheater situated on top of the EAF, scrap is preheated in the shaft by low-velocity off-gases and then dropped into the EAF. It can reduce electricity consumption by up to 18%, increase production by 17 to 20%, and reduce dust by ~20%			
Fuchs double shaft preheater	Two furnaces each with a shaft and one common electrode mast and set of electrodes to serve both furnaces. Tap-to-tap cycles have been reported to be as low as 40 minutes			
Fuchs finger shaft furnace	The finger shaft design uses a unique scrap retaining system with fingers, allowing the preheating of 100% of the scrap [27]	Through utilization of the furnace off-gas during the heat cycle, scrap can be preheated to ~800°C (1,472°F) before the final melting in the furnace vessel. This means considerable energy and cost savings with a substantial reduction in tap-to-tap times	Energy savings depend on the scrap used and the degree of post-combustion of off-gases	Fuchs systems make almost 100% scrap preheating possible, leading to potential energy savings of 90–110 kWh/tonne [28]

Table 4.2. Existing waste heat recovery techniques/methods from high-temperature EAF off-gases (continued)

Existing method of waste heat recovery	Brief description	Advantage	Disadvantage	Waste heat recovery potential
BBC-Brusa (Italy) rotary tube-type scrap preheating furnace	A rotary kiln inclined 12º to the horizontal and positioned so that the scrap exiting the kiln drops into the EAF through the roof.	Decreased energy, electrode, and refractory consumption	Can operate only using properly prepared, fragmented scrap. At higher temperatures, the scrap sticks, making it difficult to move the scrap through the kiln. Large equipment	Can heat scrap to 450°C (or 850°F) [21]
CONSTEEL technology for scrap preheating	Counter-flow heat exchanging conveyor tunnel, continuous scrap feeding. Consteel technology is perhaps the most widely used method of scrap preheating worldwide	Decreased energy and tap-to-tap times, low electrode consumption, reduced harmonic and flicker problems, reduction in dust generation (20 to 30%), reduced shop noise	Uses radiation as major mode of heat transfer in a tunnel and heats only the top layer of scrap on a conveyor, in some cases localized melting of scrap on the conveyor belt	Can recover up to 50% of the waste heat leaving the furnace [6]. Electricity use can be reduced to approximately 335–355 kWh/tonne [26]
Tenova's cvaporative cooling (ECS) technology	ECS technology uses off-gas waste heat to generate steam for vacuum degassing system and/or power generation [29]	ECS is a proven technology (e.g., BOFs, walking beam reheat furnaces). Steam can be used for many purposes (i.e. process steam, heating, compressor operation, and power generation) [29]	Because of the extremely high dust load of EAF waste gas, the design of the waste heat boiler must be planned very carefully. Recovers only part of the sensible and chemical heat [29]	High-pressure steam generation— average 20 tonne/hour at 13 bar/192°C and 28 bar/230°C [29]

Table 4.2. Existing waste heat recovery techniques/methods from high-temperature EAF off-gases (continued)

Existing method of waste heat recovery	Brief description	Advantage	Disadvantage	Waste heat recovery potential
Continuous optimized shaft system (COSS) by Fuchs Technology	Combines the benefits of the SHAFT systems—high scrap preheating—with those of the CONSTEEL process—continuous scrap feeding.	The COSS EAF can operate with or without the shaft, which is connected to the EAF by means of a removable car. Scrap can be charged into the shaft without interrupting the power input. Less maintenance cost compared with the CONSTEEL process and Fuchs Shaft. The short power-off time, the high energy input due to the flat bath operation, and the much higher scrap preheating temperatures compared with the shaft furnace systems and CS guarantee very low conversion cost figures and higher productivity [32].	Recovers only part of the sensible and chemical heat. To control preheating temperature, off-gases are routed through a bypass off-gas regulation system	100% scrap preheating possible with reduced electrical energy consumption by 80–100 kWh/tonne. Average productivity 114 tonne per hour [28]
Telescopic roof furnace for single-charge EAF operation by Fuchs Technology	Innovative EAF concept for single bucket application, telescope principle for gantry and roof lifting minimizes electrode length [30]	The telescopic roof allows for a larger furnace volume, depending on the scrap density that is currently available without the need of longer electrodes. Productivity increases due to a reduced power-off time (single bucket charge) and less required power-on time (energy savings due to scrap preheating).	Recovers only part of the sensible and chemical heat. Inconvenient to operate. Capital expense cannot be justified	Energy savings compared with standard EAFs in the range of 20–30 kWh /tonne [10] or 30–40 kWh/tonne [30] are possible

4.2.2 Limitations of Existing Technologies of Waste Heat Recovery from EAFs

Compared with using the heat of off-gases to deliver hot water or steam or electricity, scrap heating can be a much more attractive option, since the return of lost heat directly to the heating and melting process ensures not only reduced energy consumption but also a significant increase in the productivity (tonne/h/MW) of the EAF. Figure 4.6 shows enthalpy or heat content as kWh/tonne (expressed as kWh/t) of solid and liquid iron at temperatures for the melting process in an EAF. Approximately 294 kWh/tonne of energy is needed to heat scrap to the melting point of 1,530–1,540°C (2,780–2,800°F), 75 kWh/tonne is needed for melting, and about 25 kWh/tonne is needed to heat molten steel from the melting point to the tapping temperature. Thus 75% of all the required heat is used to heat the scrap to the melting point and only 25% to melt and heat liquid to the tapping temperature.

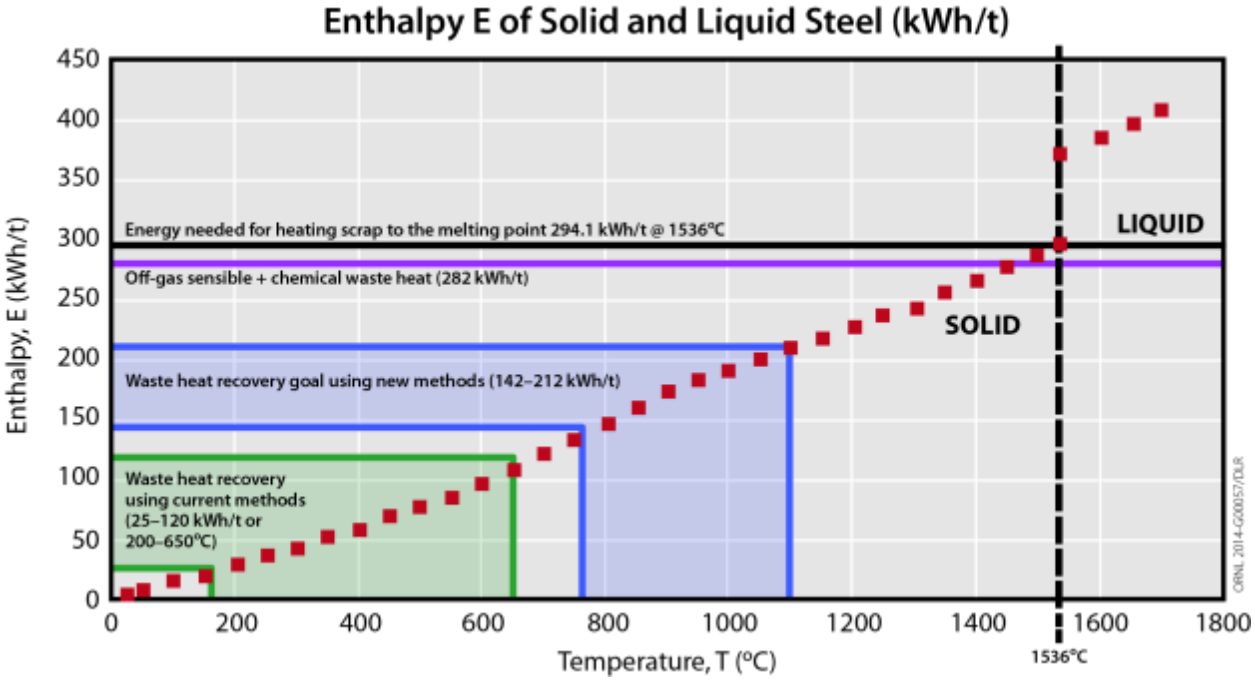

Figure 4-6. Comparison of consumption of useful heat for scrap heating, scrap meltdown, and heating of metal to tapping temperature.

Despite the advantages attributed to scrap preheating, use of scrap preheating technologies is quite limited in the US and in the rest of world. This can be explained based on the following reasons:

- Use of currently available scrap preheating systems can recover only a portion of the heat recovery potential from the total heat of off-gases. As shown in Figure 4.6 (green band), existing scrap preheating technologies can recover between 25 and 120 kWh/tonne (390–1,200°F [200–650°C]), depending upon technology, size, and scrap quality.

- Many systems in the past have experienced operating issues and problems related to safety, maintenance, and localized melting.

- Oil and other flammable contaminants present in the scrap emit a lot of heat while burning out. This results in undesirable consequences. Even when moderate-temperature (1,800–2,200ºF or 1,000–1,200°C) gas is used to preheat scrap, pockets of burning and melting of small fractions can be formed in the heated layer. When this occurs, the separate scrap lumps

are welded together, forming "bridges" that obstruct normal charging of preheated scrap into the furnace.

- At temperatures higher than 1,470–1,650°F (800–900°C), the fine scrap is oxidized intensely because of its very large surface area. This decreases the yield and can create dangerous situations during charging of scrap into the furnace. Charging of large quantities of fine, highly oxidized scrap into the liquid bath can cause an explosion-like release of CO.

- When scrap is preheated, it is likely that highly toxic compounds of halogens with hydrocarbons of varying composition, known under the general name of dioxins, may form.

- The Consteel technology, which uses a conveyor in a tunnel to heat scrap, uses radiation as a major mode of heat transfer (and a negligible amount of convection on the scrap top layer) that heats only the top layer of scrap on a conveyor. Using Consteel, the average preheating temperature of scrap in the tunnel is 750–1,100°F (400–600°C) resulting in potential savings of 80–120 kWh of sensible heat energy per liquid ton of steel. [31] As shown in Figure 4.6, the total enthalpy (sensible + chemical) of EAF off-gases may go up to 282 kWh/tonne. Hence, at best, Consteel recovers less than 50% of the total available waste heat, and about 50–70% of the off-gas energy remains untapped.

- According to data from Tenova studies, the optimal hot heel weight in Consteel furnaces comprises 50–60% of the total capacity [23], which exceeds the general practice for many EAFs by two to three times. The necessity to keep an enormous hot heel in Consteel furnaces may increase the heat losses. [26]

- Although the hourly productivity per megawatt (tonne/h/MW) of Consteel furnaces is higher than that of EAFs, the rate of scrap melting (ton/h) is approximately 1.4 times lower than in EAFs. [26] The productivity defined by tonne/h/MW is higher only because the power (megawatts) is lower.

4.2.3 Approach for Effective Scrap Preheating

During the last few decades, researchers have attempted to implement different practices for WHR, including preheating scrap using EAF off-gases. Nevertheless, the practices did not yield results that, compared with EAF without scrap preheating, could justify the use of sophisticated equipment requiring additional maintenance and attention. Hence it may be necessary to rethink and potentially redesign EAF WHR, including scrap preheating systems. Scrap preheating is definitely an attractive option, and Figure 4.7 clearly shows the benefits of effective scrap preheating. If the scrap temperature is increased from 200 to 600°C (390 to 1,110°F), the amount of electric energy needed to melt the scrap drops by over 15%. But to achieve effective, controlled scrap preheating, the following guidelines should be considered:

- Achieve maximum possible heat recovery with minimum exhaust gas volume.

- Achieve complete, controlled combustion of off-gas combustibles at a controlled temperature.

- Produce relatively clean gases.

- Use convection heating of scrap using clean, combustible free moderate temperature (800–900°C [1,470–1,650°F]) gases.

- Provide supplemental fuel heat using burners to maintain a constant scrap temperature entering the EAF.
- Attain better control and predictable scrap preheating process conditions and uniform heating of scrap across the scrap "depth," and avoid localized scrap overheating or melting.
- Effectively clean scrap preheater gases if necessary.
- Provide flexibility to allow use of different types of scrap.

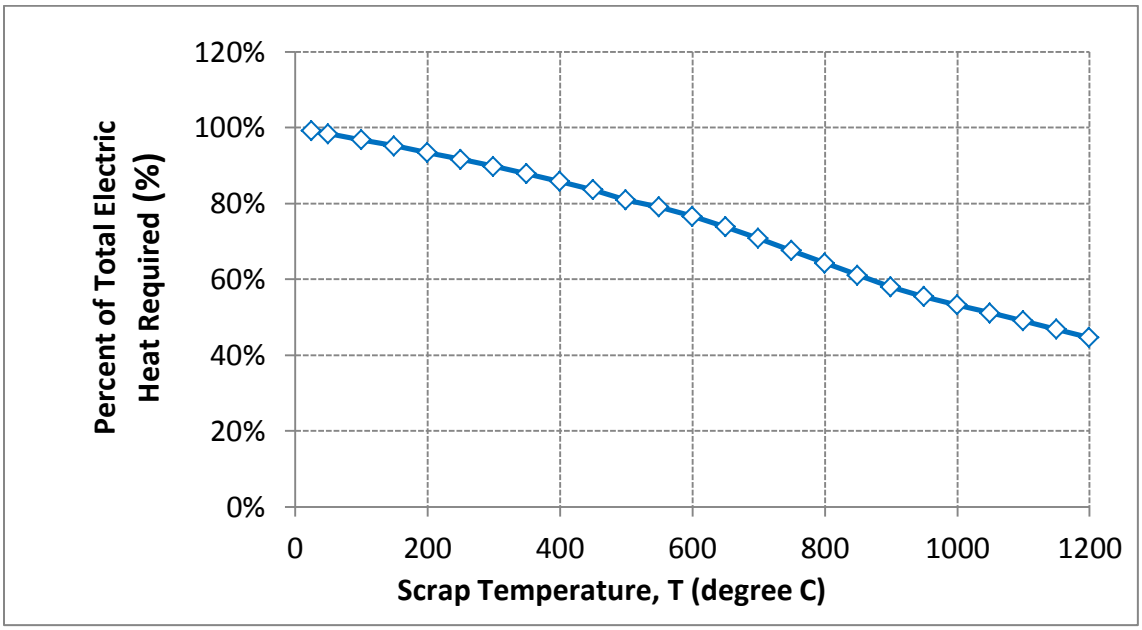

Figure 4-7. Benefits of effective scrap preheating—percentage of total electric heat required vs scrap temperature

Current research at ORNL is aimed at developing and testing new concepts and materials that allow maximum cost-effective recovery of sensible and chemical heat from high-temperature contaminated gases discharged from EAFs. The remainder of this section explains new concepts that follow the guidelines and may enable maximum recovery of total waste heat from EAFs.

4.2.4 EAF Waste Heat Recovery—Advanced Concepts

The goal of the research at ORNL is to develop innovative WHR concepts to preheat scrap when required and justifiable, generate steam if it is required in the plant, and produce electrical power simultaneously. The proposed heat recovery systems discussed in this section aim to eliminate many problems associated with currently used practices and provide an opportunity to recover sensible and chemical heat through controlled oxidation of combustibles in the EAF off-gases. The proposed WHR systems include controlled combustion of the combustible content of EAF exhaust gases and removal of a large percentage of the particulates, resulting in relatively clean hot gases. These gases can be used for scrap or charge preheating and to produce steam and electrical power usable by the plant.

The systems include a number of new features and thus differ from conventional systems in the following ways:

- Preconditioning of exhaust gases to process (or oxidize) combustible gases at controlled temperature and to remove a large percentage of particulates so that the gases can be used in a heat recovery system. This results in clean or combustibles-free gases for use in heat recovery systems.

- Extraction of off-gases from the furnace while keeping the off-gas pressure under the furnace roof nearly constant.

- Controlled temperature and gas composition during transfer of heat in a WHR system.

- Use of a WHR system, as opposed to use of a large volume of cooling air, to reduce the exhaust gas temperature.

- Use of a heat transfer system that provides heat accumulator capability to reduce the effects of variations in the sensible and chemical heat content of EAF exhaust gases during a heat or the cycle.

- Scrap preheating using hot gases that contain no combustible material and are at a controlled temperature to enable convective heating of scrap or charge for heating the entire mass of scrap before charging in an EAF.

- Use of clean exhaust gases in a steam generator that includes auxiliary fuel firing to deliver a fairly constant amount of steam for use in the plant.

- Use of steam to generate electrical power to offset some power costs, if economically justified.

4.2.5 Detailed Technical Description of the Proposed System

The proposed systems for recovering sensible and chemical heat from EAF exhaust gases consist of several modules. They are shown in Figures 4.8 and 4.9 and described as follows.

1. A heat recovery subsystem is used to condition exhaust gases. This is designed to complete the combustion of gases containing chemical heat under controlled temperature using the minimum amount of combustion and cooling air. It consists of a heat source module from which heat from hot gases is transferred to a heat transfer medium that can withstand high temperatures and can store heat.

2. A heat transfer module (heat sink) transfers heat stored in the medium from the heat source module to air or other fluid. The heat transfer module is used to cool the heat transfer medium that is then recycled to the heat source module.

3. A particulate removal or dropping arrangement is in or outside the heat transfer modules. Particulate removal is accomplished using a proper geometrical configuration and/or the use of a cleaning medium such as compressed air, mechanical scrubbing, or other methods to remove particulates attached to or mixed with the heat transfer medium.

4. A mixture of hot air from the heat sink module and hot and relatively clean gases, free of combustibles and vapors but including small amount of particulates, is used at a controlled temperature in the secondary heat recovery subsystem.

5. The secondary heat recovery system may include a scrap or charge preheater and/or a steam generator.

6. The gases are distributed to the scrap preheater and/or to a steam generator based on heat demand in the scrap preheater, with excess gases going to the steam generator. The exact use, distribution, and control of the heat depends on specific plant requirements.

7. Scrap preheater exhaust gases are recirculated to the heat source module, in which the temperature is well above 982°C (or 1,800 ºF) to combust any combustible gases or volatile organic compounds mixed with heating gases in the scrap or charge preheater.

8. A steam generator uses clean, hot gases and air from the heat sink to produce steam. The steam generator may fire an auxiliary fuel, such as natural gas, to maintain constant steam production when the heat content of hot gas and air is not adequate to deliver the desired steam production.

9. The steam produced is used in the plant or for other applications, if required (e.g., the vacuum degassing system, vacuum pumps). Or the steam can be used for power generation using a conventional steam turbine–generator system.

10. Clean, lower-temperature exhaust gases from the steam generator are directed to the baghouse or another type of pollution control equipment at a controlled temperature by using dilution air if necessary.

11. If necessary, a gas treatment device, such as injection of activated carbon, can be used to reduce the concentration of pollutants such as dioxin and furan to meet environmental control regulations.

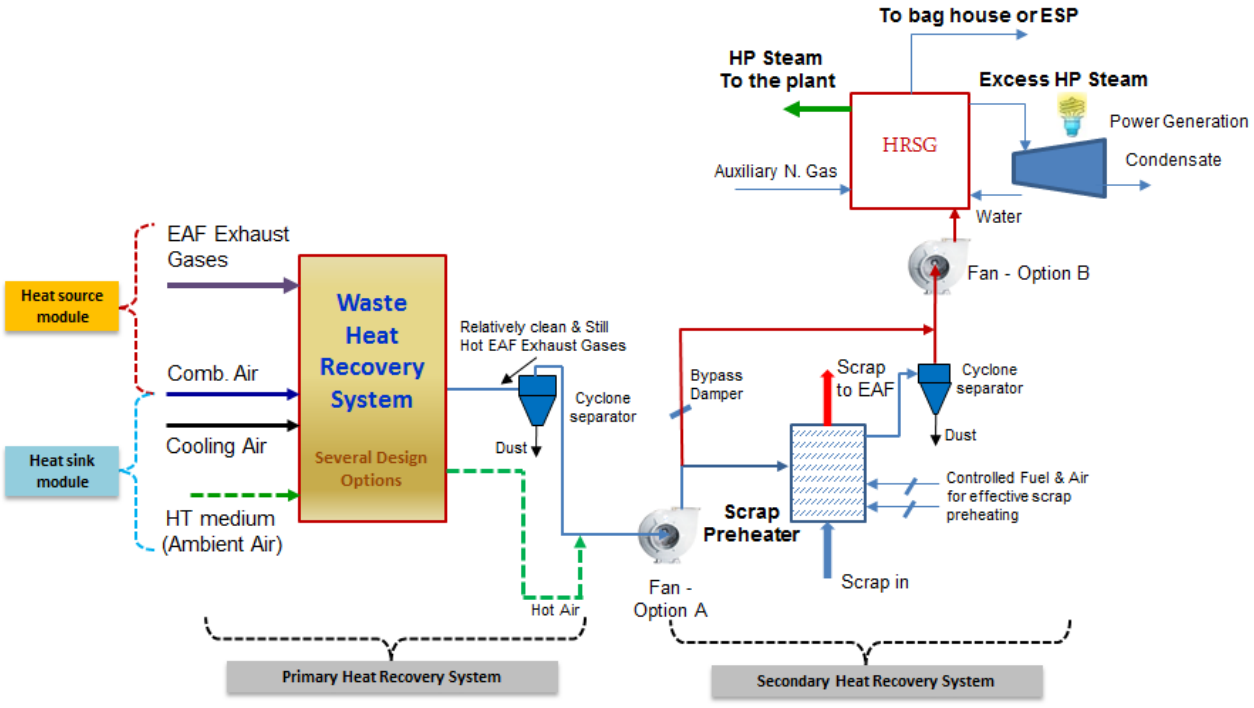

Figure 4-8. A system for recovery of sensible and chemical heat from EAF exhaust gases with integrated clean charge preheating.

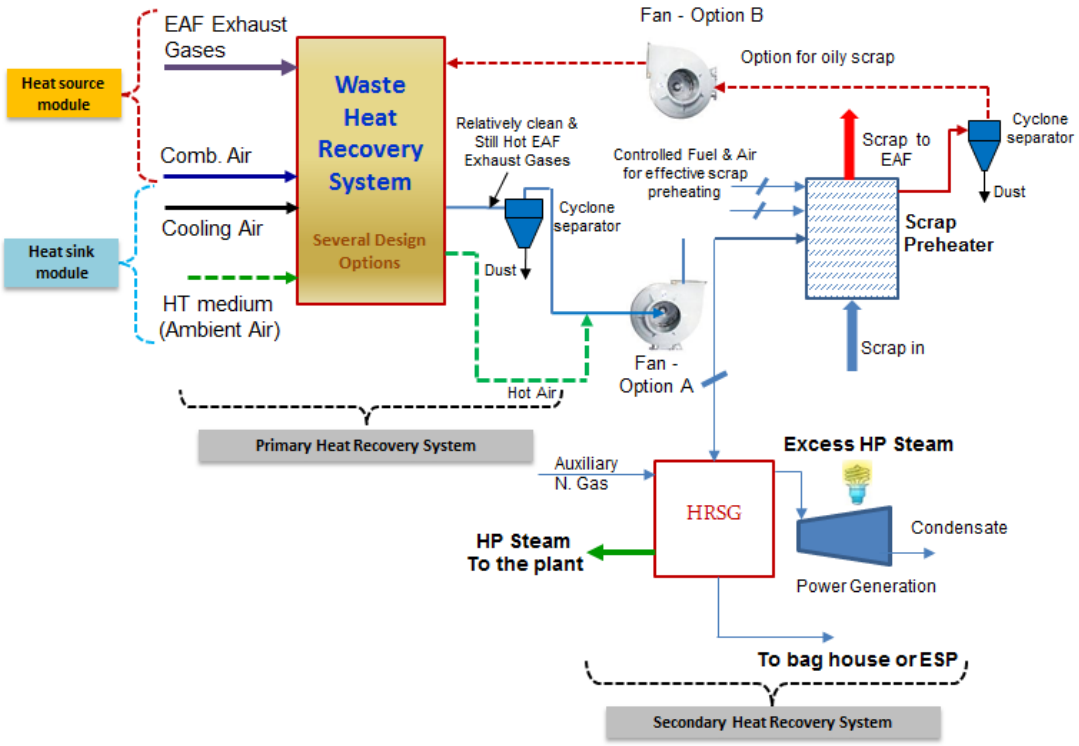

Figure 4-9. A system for recovery of sensible and chemical heat from EAF exhaust gases with integrated clean charge preheating (scrap with oil and combustibles).

4.2.6 Conclusions

Use of EAF off-gas heat to preheat scrap in EAFs offers several benefits, including continuous charging, lower use of energy (power level, megawatts) in the EAF, and increased productivity (t/h/MW). At this time, use of scrap preheating with heat from EAF off-gases is practiced by a very small number (<15%) of EAF operators in the US. In these cases, only a part of the off-gas heat is transferred to the charge material, and a relatively large amount of heat is left in the exhaust gases that leave the scrap preheater. Commonly used scrap preheating systems require frequent maintenance and may result in uneven heating of scrap and localized melting of steel, resulting in operational problems. Many of these problems are due to varying gas temperatures and the presence of combustibles, together with unpredictable air flow patterns that may result in uncontrolled burning of combustible gases. Hence there is a need for the development of systems that overcome the issues and problems associated with the use of currently available designs and recover the maximum possible waste heat.

ORNL has developed innovative WHR concepts that can be used to recover a large percentage (>70%) of off-gas heat to preheat scrap; generate steam; and, if it can be done economically, produce electrical power. The proposed WHR systems aim to eliminate many problems associated with currently used practices and provide an opportunity to recover sensible and chemical heat through controlled burning of combustibles in the gases via the use of integral heat recovery. These proposed WHR systems also include removal of a large percentage of particulates, which will result in hot and relatively clean gases. These gases can be used for charge preheating and to produce steam and electrical power that are usable by the plant. The ORNL team expects to test one or more systems in collaboration with industrial partners and end users.

4.2.7 Acknowledgement

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5. ALUMINUM INDUSTRY

5.1 ALUMINUM MELTING FURNACES

5.1.1 Background and Potential Opportunity

There are currently more than 300 aluminum production plants in the US [1], which consume about 770 TBtu ($2.26 \cdot 10^{11}$ kWh of energy per year. [1] Aluminum production relies on two different technologies. The primary production method, refining aluminum from bauxite, relies on electrolytic cells that are very energy-intensive. Secondary aluminum production involves recycling aluminum scrap and aluminum metal received from primary production plants. This method requires only about one-sixth of the energy that the primary method requires. The scrap consists of both new scrap (created in aluminum processing steps) and old scrap (disposed at the end of life). In 2013, aluminum recovered from purchased scrap in the US totaled about 3.27 million tons, of which about 56% was new scrap and 44% old scrap. [2] This scrap is first preheated to remove any contaminants and then sent to an aluminum melting furnace, in which it is melted and impurities are removed through fluxing. [1] The heat is produced by burning fossil fuels, typically natural gas. [3] NaCl and KCl are mixed with the molten scrap in the furnace to separate impurities and prevent oxidation of the aluminum in the furnace. [1]

Commonly used aluminum alloys melt at about 1,254°F (678°C) and are usually poured at 84.2 to 122°F (29 to 50°C) above the melting point. The temperature of flue gases from an aluminum melting furnace ranges from 1900 to 2200°F (1,038–1,204°C), with a very large amount of energy content. [3] The temperature range for flue gases can result in as much as 60% of the energy input being lost (sensible heat) to flue gas waste heat, depending on the furnace. [1] On average, flue gases contain 50 to 70% of the total furnace heat input. [3] Thermal conduction heat losses through furnace walls account for 2–12% of the total furnace heat input. The heat loss due to dross production is around 1–2% of the total furnace heat input. Heat used for actual aluminum melting ranges from 11 to 40% of the total furnace heat input, depending on the furnace. [4] There are additional heat losses through insulated walls, radiation, and other losses. The latter may account for 5 to 10% of the total heat input. [3] Figure 5.1 shows an example of a heat balance carried out in an aluminum melting furnace. Most of the heat loss numbers from this figure are close to the percentage ranges stated. The flue gas heat loss increases linearly as the flue gas temperature increases. Flue gas heat loss also depends on the molar fraction of combustion products and the total moles of flue gas. [4] The flue gas heat losses will therefore vary from furnace to furnace. From Figure 5.1, it can be seen that a large amount of heat is escaping as waste off-gas. Recovery of this heat can open up opportunities to reduce emissions, save money, and save energy. Several heat recovery technologies are available that can help capture these savings.

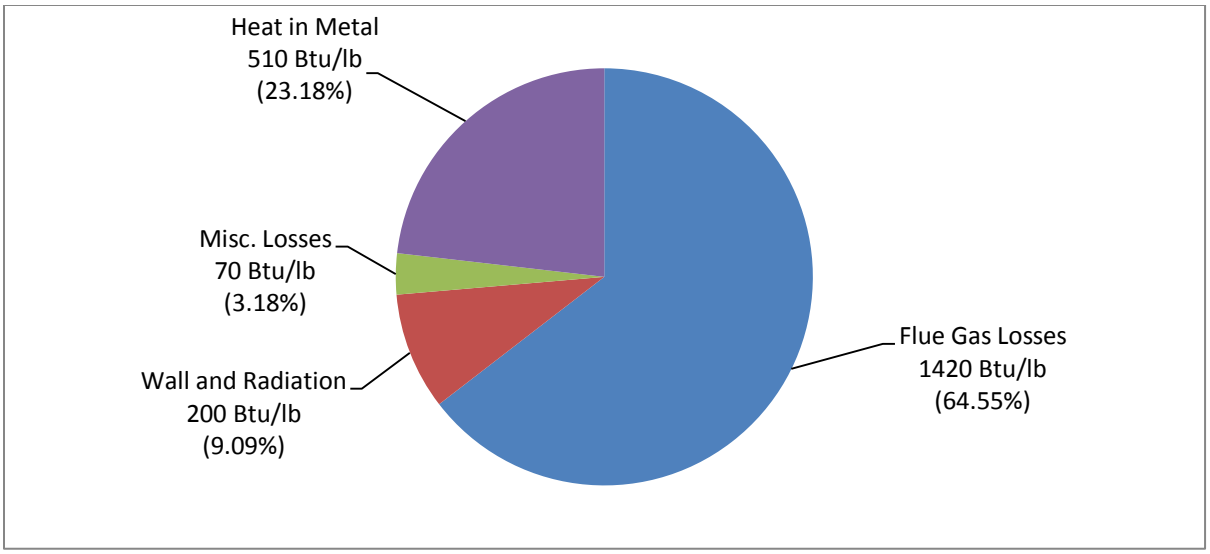

Figure 5-1. Heat analysis of aluminum melting furnace. [3]

5.1.2 Current Methods of Waste Heat Recovery from Aluminum Melting Furnaces

WHR in aluminum melting furnaces has the potential to impact the aluminum industry dramatically. There are about 400 aluminum melting furnaces in operation, of which only about a third actually employ WHR technologies. The reason is that there are several barriers associated with these methods that can complicate the recovery process. This section reviews and analyzes several existing and emerging WHR methods (see Table 5.1). [1]

5.1.2.1 Recuperator systems

One WHR method for aluminum melting furnaces is preheating combustion air by means of a conventional recuperator. Recuperators are a method of transferring heat from the flue gas to the air used for combustion in the gas burners. [3] The exhaust gases flow through the burner that preheats the combustion air and transfer their heat to the inlet air before leaving the system. The burner has a recuperator installed inside it. [5] Preheating the combustion air reduces the amount of fuel needed to raise the temperature of the gas to the appropriate level and saves fuel and energy. Furnaces that incorporate recuperators are 20–30% more efficient than furnaces without them. Currently, the economics of flue gas heat recovery for combustion air preheating and the limitations of the technology allow 40 to 60% heat recovery. Recuperators can reduce fuel consumption by 30%. [3] They have the potential to save 3–5 trillion Btu annually (879–1,465 million kWh). [5] Recuperator technology is available and frequently used in the US. There are several different heat exchanger designs that can be used for preheating combustion air, depending on the furnace in which it is being used. [3] Each design has its own set of advantages and disadvantages.

Recuperators are classified by the material of which they are made (typically metal or ceramic). The convection recuperator is one type that can be used in aluminum melting furnaces. Air-tube type recuperators consist of a bundle of several hundred tubes outside which flue gases pass, guided by baffle plates. These recuperators are typically used when flue gas temperatures are 1,292-2,012°F (700–1,100°C). Gas-tube type recuperators have much larger-diameter heating tubes and are more compact. Air-type recuperators are more leak proof, but they are easily affected by dust and their tubes are more sensitive to abrasive wear by solid suspended particles. A diagram of a convection type recuperator is shown in Figure 5.2.

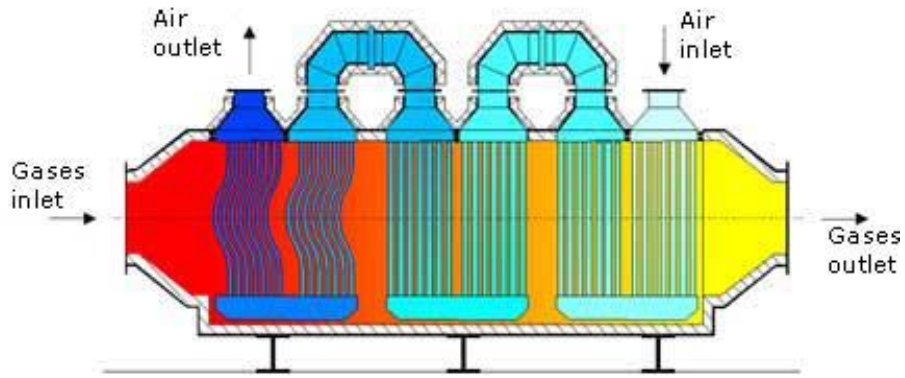

Figure 5-2. Convection recuperator (six bundles). [6]

Another recuperator type, the radiation recuperator, is based on thermal radiation of nonluminous gases that are present in combustion products. Radiation recuperators are commonly used for metal melting, as in an aluminum melting furnace. A double-shell radiation recuperator (Figure 5.3) contains two metallic shells connected at each end by air inlet and outlet headers. Flue gases pass through the inner shell and transfer their heat as they do so, primarily by radiation but also by convection. The air passes through a space between the inner and outer shells, an arrangement that provides very high surface conductance compared with the flue gas side. Another type of radiation recuperator, the tubular or cage type, is used for higher pressures and larger capacities. The heating surfaces in tubular recuperators are made up of many tubes arranged on a large-diameter outer circle. The entire tube bundle is placed inside an insulated smaller-diameter inner shell. A diagram of a tubular radiation recuperator is shown in Figure 5.4. Radiation recuperators are typically used when flue gases are around 1,650 – 2,550°F (900–1,400°C).

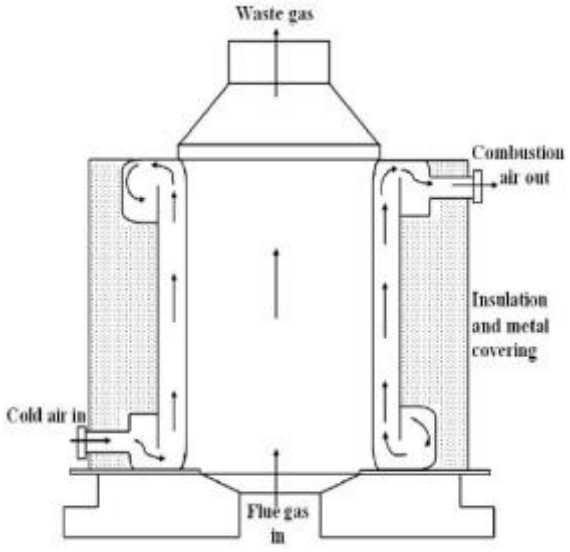

Figure 5-3. Double shell radiation recuperator. [3]

A third recuperator type, the ceramic recuperator, is designed for higher-temperature flue gases (above 2,000°F or 1,100°C). Although these recuperators can withstand higher temperatures, they are more prone to fouling and air leakage caused by high thermal stresses. [7]

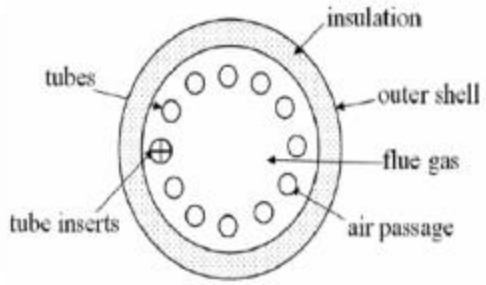

Figure 5-4. Cross section of tubular radiation recuperator [3]

5.1.2.2 Regenerative burner systems

Another means of WHR for aluminum melting furnaces is preheating combustion air by means of a pair of regenerative burners. Like the other methods, it uses exhaust gases from the furnace to preheat the combustion air. In regenerative burner systems, a pair of burners connected to an integral heat storage medium is used to recover heat and transfer it to the combustion air. The two burners are installed on the melting furnace. Each of them has a heat storage device, such as packed ceramic spheres. The burners take turns firing. While burner one is firing, the other burner exhausts the flue gases from it. The hot gases pass over the heat storage device and transfer the heat to the heat storage medium, which cools the flue gases as it heats. After a short period, usually around 15–20 seconds, the flow is reversed. The burner that previously was exhausting begins to fire, and the burner that was firing begins exhausting. The burner that is firing receives combustion air that has been preheated by passing over the hot heat storage medium. This continuous cycling recovers heat from the flue gases. [3] The heat storage medium in a burner cools as its burner fires.

Regenerative burner systems are reasonably practical and reliable. [8] A system can recover 72–75% of the heat in exhaust gases and can reduce fuel consumption by approximately 40%. [3] Regenerators have the ability to heat the combustion air to a higher temperature. [7] The entire regenerative system (regenerative bed, burners, associated valves, linkages, and furnace temperature controls) is estimated to be about 1.5 times more expensive than a simple recuperator system; however, the life cycle cost analysis and payback period with current energy prices justifies the higher initial costs. According to one source [3] and assuming current energy prices are $7 to $10 per MM Btu, the estimated payback period is usually less than one year. It could be even shorter if the economics of increased production is considered. [3] Use of regenerative burners is becoming common in many parts of the world for new installations. Rotary regenerators have been developed and commercialized in Europe, but they have not been commercialized in the US because of their high capital costs. [1] Only a few companies are installing regenerative recovery systems on existing furnaces that represent 65 to 75% of the operating capacity in the US.

Several issues associated with regenerators can cause problems within an aluminum melting furnace. One problem is plugging of the bed. This occurs when the furnace is operated with dirty scrap, which causes it to generate high amounts of dross and soot particles. It is necessary to clean the bed to avoid performance issues. The equipment and installation costs for retrofit applications are high. Floor space requirements can also be an issue. More maintenance must be done on systems with regenerators, which can lead to more work and expenses. There is also very little flexibility in the furnace heating system designs to accommodate regenerators. For example, the location of the burners and flue gas discharge cannot vary much from furnace to furnace. [3]

5.1.2.3 Load or charge preheating systems

Aluminum melting furnaces also use load or charge preheating to recover heat from flue gases. A typical charge preheating system uses flue gases from the furnace to preheat the charge material in a separate preheater device or in an extension of the furnace charge system. The charge material is typically heated from 500 to 800°F (260 to 427°C) before being charged manually or by a conveyor system. The preheating process removes moisture and volatile organic compounds in the charge material. This method can offer energy savings of 20 to 35% if the heat used for preheating comes from flue gases. [3] It is possible to increase the production level of the furnace by 25.5% using charge preheating. [9]

The idea behind charge preheating is that if the exhaust gases leaving a furnace can be brought into contact with the cooler incoming air, the heat can be transferred straight to the load. Preheating the load reduces the amount of energy consumed. There are different ways of accomplishing load preheating. One

technique uses an unfired load preheat section, bringing furnace flue gases into contact with the incoming load in an extended part of the furnace. Another approach uses an external preheater box in which high-temperature flue gases are used to dry and/or preheat the charge before it is loaded into the furnace. A third approach uses a counter-current flow design in the furnace: the burner gases flow in the opposite direction from the load being heated.

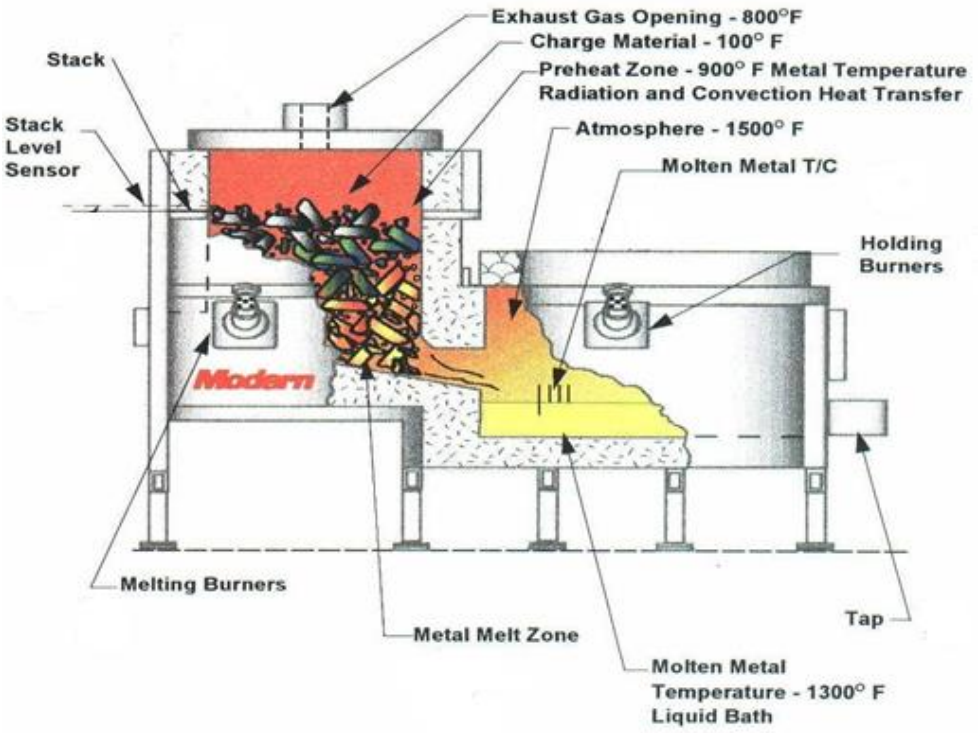

Figure 5-5. Aluminum shaft, or stack furnace [10]

The stack melter efficiency is improved by better sealing of the furnace and the use of the flue gases to preheat the charge materials. The charge materials slide down the shaft and reach the melting zone where they are melted by the burners, and the molten metal flows down to the holding area. The hot exhaust gases from the melting zone flow through the shaft to preheat the incoming charge, improving the energy efficiency of the stack furnace by 40 to 50%. Melt loss is also dramatically reduced from 4-8% in a reverberatory furnace, down to 1% or less in a well operated stack melter.

The amount of energy savings from charge preheating is higher than the amount of actual heat transferred to the load. The net heat delivered to the load accounts for the efficiency of the furnace. Furnace efficiency never exceeds 100%; therefore, the energy savings always exceeds the energy picked up by the load. Charge preheating increases the furnace production. [9] It has the highest potential efficiency of any waste gas recovery system.

Load preheating does present problems that should be considered. Some charge preheating systems and methods are difficult to install as retrofits, particularly if an external box or system is not used. This method is bested suited for continuous furnaces, rather than batch furnaces such as aluminum melting furnaces. [11] Capital costs for these systems may be high, and there can be difficulties in controlling product quality when they are used. [1]

Charge preheaters are not common in the US but are widely used in other countries, including Japan, Europe, India, and China. Most of the charge preheating done in the US involves heating in a separate charge dryer to remove moisture from the charge. [3]

5.1.2.4 Steam generation from waste heat

Recovered heat from a furnace can be used to generate steam in a waste heat boiler. Waste heat boilers can be used on most furnace designs. This method is especially helpful for plants that need a source of hot water or steam. [10] Waste heat boilers are water boilers that use medium- to high-temperature exhaust gases to create steam. They are available in a variety of capacities. These boilers can allow for gas intake levels ranging from 1,000 to 1 million ft^3 min (28.3 to 28,317 m^3 min). The steam generated by the boiler can be used for process heating or for power generation. [1] The process of converting waste heat into electricity is a multistep process. First, the dirty hot gases are converted to clean hot gases using a heat exchanger. Next, the clean hot air is converted to steam using the waste heat boiler. Finally, the steam is used to generate electricity using a turbine or a generator. The electricity then can be passed to the grid if desired.

An example shows the effects of steam generation from waste heat. Assume that an aluminum melting system wastes 12 million Btu of heat per hour (3,500 kW). If the overall efficiency of the entire system is assumed to be about 41%, then 5 million Btu (1,400 kW) of the 12 million Btu could be used to be converted into electricity. Assume that this level of energy is produced 24 hours per day, 7 days per week, and that the utility grid will pay 10 cents per kilowatt-hour for the electricity. The results of the calculations show that 12 million kWh (41 TBtu) can be generated in one year. This amounts to $1.2 million in energy costs savings per year, or $2.4 million in savings over a 2 year payback period. [12] This method of heat recovery is now a commercialized process. [13]

Although this method of heat recovery has many advantages, there are also several barriers associated with it. One barrier is that steam can be generated only while the aluminum melting furnace is in operation. [11] Installing such a system could be costly because of the capital costs of heat exchangers, boilers, and turbines/generators and the installation costs. The amount of maintenance needed for the furnace would increase. Further, designing the process would take company time and management attention. [12]

5.1.2.5 Oxygen-enriched combustion

Oxygen-enriched combustion is a way of reducing waste heat, rather than recovering it. Oxygen-enriched combustion is used within the aluminum melting furnace. When fuel is burned in the furnace, oxygen combines with hydrogen and carbon in the fuel to form water and CO_2. This process releases heat. During combustion, nitrogen in the air dilutes the reactive oxygen and carries away some of the energy from the combustion exhaust gas. If the amount of oxygen in the air is increased during combustion, less energy is lost in the exhaust gases. The basic idea is to increase oxygen to increase the heating system efficiency. Although this method does not actually recover waste heat, it does reduce flue gas losses and waste heat that escapes the furnace. Most furnaces use either liquid oxygen to increase the oxygen content or vacuum pressure swing absorption (VSA) units to remove some of the nitrogen and increase the amount of oxygen. [14] VSA oxygen systems use an air oxy-natural gas burner. [15] Some systems use oxy-fuel burners in which oxygen is added to the air entering the burner just before the air meets the fuel for combustion. Oxygen-enriched combustion has the ability to increase efficiency because there is less nitrogen to carry heat away from the furnace, resulting in less heat in exhaust gases. This method also can lower emissions (nitrogen oxides, CO, and hydrocarbons), improve heat transfer, and increase

productivity. Efficiency improvement depends on the exhaust gas temperature and percentage of oxygen in the combustion air. [14]

In 1999, a VSA system used to enrich oxygen combustion was able to achieve a 30% increase in furnace productivity and a 40% reduction in specific fuel consumption relative to air-fuel operation. Potential savings in 2015 could reach 1.76 billion to 2.34 billion kWh (6–8 Tbtu). The enrichment range was 35–50% oxygen, which optimized the burner thermal performance. Field tests showed that this technology has the ability to meet a target of 0.323 lb NO_2/ton of aluminum (146.5 g NO_2/ton of aluminum). The VSA oxygen supply lowers oxygen production costs by using a sieve-filled vessel that stores oxygen during periods of low demand from the furnace. The oxygen is used when demands are high. This technology can be easily retrofitted to existing aluminum melting furnaces. The technology is adaptable to different configurations. [15] One of the most important issues for oxygen-enriched combustion is cost. High costs have resulted in very few oxygen-enriching systems being used in the US today.

Table 5.1. Existing waste heat recovery techniques/methods from aluminum melting furnaces

Existing method of waste heat recovery	Brief description	WHR technology/system status	Advantage	Barrier/disadvantage	Waste heat recovery potential
Combustion air preheating using conventional recuperator	Use of conventional metallic tube type of heat exchanger to preheat combustion air using heat from furnace exhaust gases [5]	Available and frequently used in the US [3]	Heat is recycled and there is synchronization—matching between the heat demand and supply. Furnaces with recuperators typically show 20–30% energy savings [3]. Method has the potential to save 3–5 trillion Btu annually [5]	High maintenance because of tube failure. Very high maintenance costs. Corrosion occurs from chlorides and fluorides released during fluxing operations. Overheating may occur [1]. Some metallic tubes have a lifetime of only 6–9 months [3]	Furnaces with recuperators are typically 20–30% more energy efficient than those without them. Fuel consumption can be reduced by ~ 25 to 30% using recuperators [5]. Preheating allows 40–60% heat recovery from flue gases [3]
Combustion air preheating using regenerative burners	Use of a pair of regenerative burners. While one burner is firing, the other is exhausting the furnace gases. The heat from the exhaust gas is transferred to the inlet air [5]	Available. Rotary regenerators were developed and commercialized in Europe. Efforts to commercialize in the US have been unsuccessful owing to high capital costs. Fixed regenerators are becoming more common in the US [1]	High degree of heat recovery. Fuel is saved. Higher combustion efficiency is obtained [3]	High capital cost; difficult to retrofit; bed plugging occurs where the charge material contains particles; maintenance cost for cleaning the heat transfer media can add up; This process may not be as efficient as it seems initially because of the bed plugging. Economic feasibility is application-specific [3]	Burners have an efficiency of 72–75% and have the ability to reduce fuel consumption by about 40% [3]

Table 5.1. Existing waste heat recovery techniques/methods from aluminum melting furnaces (continued)

Existing method of waste heat recovery	Brief description	WHR technology/system status	Advantage	Barrier/disadvantage	Waste heat recovery potential
Charge preheating	Flue gases from the furnace are used to preheat the charge material in a separate preheater or extension of the furnace charge system [3]	Not common in the US but extensively used in other parts of the world, including Japan, Europe, and China [3]	Reduces energy use, increases productivity through reduction in melt time. Ideally suited for virgin aluminum such as sows [3]	There are high capital costs. Method may not be feasible for installations where the scrap quality, size and composition (e.g., presence of oils) varies considerably. There are difficulties associated with controlling product quality [1]	Recovery potentials vary depending on the plant and the system used to preheat the exhaust gas [1]. Potential savings also depend on flue gas temperature and rise in combustion air temperature or effectiveness of the air preheater used. At this time, flue gas heat recovery for combustion air preheating allows 40–60% heat recovery. Energy savings can be from 20–35% if heat comes from flue gases [3]. It is possible to increase productions by 25.5% [9]
Use of oxy-fuel burner for aluminum melting	The use of enriched oxygen in furnace combustion is expected to improve heat transfer to the melt as well as reduce emissions [15]	The system is currently in the demonstration phase and is expected to reach commercial viability in the near future (1999) [14]. Not common in the US but used some in other parts of the world [3]	The use of enriched air in furnace combustion is expected to improve heat transfer to the melt as well as reduce emissions. The goal is to increase melting productivity by 30%. [15] This is a process heating best practice that can improve furnace efficiency by 10% to 12% [16]	Major barrier is cost. <2% furnaces using oxygen enriched combustion today	Potential savings in 2015 could reach 1.76 billion to 2.34 billion kWh (6–8 Tbtu) [15] Furnace efficiency can be improved by 10–12% [16] Melting productivity can be increased by 30% [15]

Table 5.1. Existing waste heat recovery techniques/methods from aluminum melting furnaces (continued)

Existing method of waste heat recovery	Brief description	WHR technology/system status	Advantage	Barrier/disadvantage	Waste heat recovery potential
Use of waste heat boiler to generate steam	Waste heat boilers are water boilers that use medium- to high-temperature exhaust gases to create steam. The steam generated by the boiler can be used for process heating or for power generation [1]	Commercial status [13]	The steam generated by the boiler can be used for process heating or for power generation. Waste heat can be converted to useful energy [1]. Boilers can be used on most furnace applications [11]	Steam can only be generated while the furnace is in operation [11]. There are high capital costs owing to the expense of the boiler, heat exchangers, and turbine/generators that may be associated with the boiler. The amount of furnace maintenance needed would increase [12]	Information not found

5.1.3 Barriers and Limitations of Existing Waste Heat Recovery Technologies for Aluminum Melting Furnaces

Despite the advantages attributed to the aluminum melting furnace WHR methods, use of some of these technologies is quite limited in the US as well as the rest of the world. This can be explained by the following barriers.

- Cost is a huge issue with every WHR method currently being used in aluminum melting furnaces. Capital and maintenance costs can be very high. Cleaning costs may also become significant because of particle remnants from dirty gases. [1, 3]

- In most WHR methods, only a portion of the waste heat is recovered and put to use. In many cases, such as preheating combustion air, <50% of the sensible heat is recovered. [1, 3]

- It is difficult to retrofit heat recovery systems onto existing installations. It may not be possible to use reliable and long-life (>2 year) systems in situations where the scrap quality, size, and composition vary considerably. [1]

- Maintenance and upkeep of recovery systems can be very problematic and costly. When conventional metallic tube type heat exchangers are used, corrosion often occurs from the chemicals released during fluxing. Overheating due to occasional combustion of products of incomplete combustion can become an issue. Plugging of heat exchangers or media beds occurs in regenerative systems in which regenerators are used when the charge material contains particles. These issues can lead to many problems and extra expenses. [1, 3]

- Economic feasibility is application-specific. Some recovery methods work well with some furnaces but not with others. [3]

Many of the problems involved in aluminum melting furnace WHR are a direct result of the dirty gases and very high temperatures associated with the furnaces. The most widely used WHR devices are recuperators and regenerators, which are particularly affected by high temperatures and dirty gases. The performance of recuperators in the melting furnaces depends greatly on flue gas temperature, requirements for duty cycle, composition of furnace flue gases (O_2 and/or the presence of combustibles such as CO, H_2, and hydrocarbons), presence of particulates, and furnace operating practices. [3] Recuperator tubes and plates become fouled and damaged by the high-temperature gases over time. Fouling requires periodic cleaning of the heat transfer surfaces to prevent damage as well as improve heat transfer efficiency. [17] Studies have shown that the lifetimes of metallic recuperator tubes in the highest-temperature furnaces are often about 6–9 months. The short life is primarily due to the exposure of the recuperator heat transfer surfaces to high-temperature air and corrosive fluxing agents such as fluorine and chlorine. Replacing recuperators creates additional cost and work. In response to the short lifetimes, many companies and laboratories are conducting studies to find alternate materials or operating procedures that could extend the lifetimes of these tubes. [3] The different types of recuperators and their respective barriers were discussed in a previous section.

Regenerators, on the other hand, operate intermittently and must use a high-temperature heat storage material (such as ceramic balls). The difficulty is that this operation requires maintenance, and the ceramic balls need periodic cleaning to reduce the pressure drop across the regenerator. [17] This process also may not be as efficient as it seems initially, because of bed plugging when the charge material contains particles. [3] The use of both recuperators and regenerators increases the combustion temperature and hence the production of NOx and other pollutants. [17] These problems can greatly complicate the process of melting aluminum.

5.1.4 Conclusions

Secondary aluminum production using an aluminum melting furnace (fuel-fired furnace) is a very important process that produces large amounts of aluminum. Use of the furnace off-gas heat to preheat combustion air, charge preheating, and other options such as generation of electricity using waste heat offers potential benefits such as increased thermal efficiency, lower greenhouse gas emissions, and increased furnace productivity. The methods discussed in this section have the ability to save energy and save money. Although there are many positive effects of heat recovery, there are also many barriers that can cause problems and complicate the aluminum production process. It is important to understand and study these barriers so that improvements can be made to eliminate them. The purpose of this report is to provide information regarding the many waste heat recovery methods that are available and point out the shortcomings of each method. Future work can focus on improving these technologies. Currently, many companies and laboratories are researching alternate materials or operating procedures to improve heat recovery and reduce or eliminate the barriers. New developments and technologies for WHR have the potential to change industrial processes.

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6. GLASS INDUSTRY

6.1 GLASS MELTING REGENERATIVE SYSTEM

6.1.1 Background and Potential Opportunity

The US glass industry can be classified in four major subsectors: flat glass (25% of total annual production), container glass (50%), specialty glass (10%), and glass fiber products (e.g., insulation) (15%) [1]. Furnaces used by each of these subsectors can be grouped into four categories: regenerative and recuperative, oxy-fuel, non-regenerative, and other. Table 6.1 shows this distribution in both percentages and total production statistics. A different array of furnace types is deployed by each subsector; however, of primary interest here are regenerative and recuperative (R/R) furnaces. These furnaces account for about 59.1% of the total glass production capacity throughout the US, across the subsectors [1]. Primary contributors to this total are flat glass and container glass furnaces, which employ 80 and 70% R/R type furnaces, respectively. Specialty and glass fiber furnaces produce only 26% and 10% of their respective output with R/R furnaces. Total production by R/R furnaces in the US is 11.82 MM tons/year. [1].

A significant amount of energy is expended to produce this glass. The specific energy consumption across segments using R/R furnaces averages 2,088 kWh/ton (or about 7.125 MMBtu/ton). From this, the total energy use is determined to be about 13.45 billion kWh $year^{-1}$ (or 45.91 trillion Btu/year). [1] In an average furnace, about 45% of the total overall energy input is used to melt the charge material consisting of fresh batch and cullet, and 34% is lost in exhaust gases. [1, 2]This is illustrated by Figure 6.1, a diagram demonstrating an energy distribution for an example R/R furnace. The three primary contributors to waste heat losses are convective and radiative losses from the furnace walls, radiative losses from open ports and gaps, and flue/exhaust gas losses. [3, 4, 5] Figure 6.1 shows that for this furnace, 27.2% of the energy input is expended in the exhaust gases. The specifics of these numbers depend upon the furnace, whether a recuperator (less efficient) or a regenerator (more efficient) is used, the batch/cullet ratio, moisture in the batch, the fuel, and other parameters. [6] From production data, it was estimated that a little less than 9 billion kWh/year, or 31 trillion Btu/year, of waste heat in exhaust gases is lost from R/R furnaces, assuming a 25°C reference temperature. [1] (Note that these production data are from 1988–1997. No newer data could be found.)

Although they are mechanically different, the goal of regenerative and recuperative furnaces is the same: both strive to capture or recover a part of the heat of exhaust gases to preheat combustion air used in the furnaces. Even after recovery of heat from the exhaust gases, the exhaust gas stream from an R/R system is typically still at a moderate temperature, between 400 and 600°C. [1] The temperature and composition of exhaust gas are defining factors in the material and design considerations in all WHR systems. Exhaust gases from R/R furnaces typically contain a variety of chemical compounds and a large amount of particulates and contaminants that affect the lives of the materials used. The specifics of exhaust gas composition depend upon the type of fuel used, composition of the charge material, and operation of the furnace. For example, a glass melting furnace burning coal, oil, or gas could produce exhaust gas containing combustion products such as CO_2, H_2O, SO_x, NO_x, O_2, and N_2, combined with other products such as HCl, hydrogen fluoride, and boron vapors. [7, 8] The combustion product composition of the exhaust gases depends upon the type of fuel used. For example, melters using coal or petroleum coke have high concentrations of SO_2, whereas melters using natural gas have negligible amounts of SO_2. [6.1:7] Compounds from the glass melt are present as well: NaOH, vanadium, and SiO_2 carryover can all be expected, along with ash and other nonflammable substances. [7, 8] Two example exhaust gas compositions may be illustrative. Table 6.2 presents the chemical compositions of exhaust from two 1,200 tonne/day furnaces, one burning natural gas and the other burning petroleum coke.

Table 6.1. US glass industry production by furnace type and glass segment (2007 data). [1]

Furnace type / Industry segment	Regen/recup MM t/year (%)	Oxy-fuel MM t/year (%)	Nonregenerative MM t/year (%)	Other MM t/year (%)
Flat glass	4 (20%)	1 (5%)	—	—
Container glass	7 (35%)	3 (15%)	—	—
Specialty glass	0.52 (2.6%)	0.7 (3.5%)	0.68 (3.4%)	0.1 (0.5%)
Glass fiber	0.3 (1.5%)	1.05 (5.25%)	—	1.65 (8.25)
Totals	11.82 (59.1%)	5.75 (28.8%)	0.68 (3.4%)	1.75 (8.75%)
Grand total				**20 (100%)**

Table 6.2. Example exhaust gas compositions from a petroleum coke (PC) and natural gas (NG) burning glass furnace [7]

Compound	Volume fraction PC (%)	Volume fraction NG (%)
O_2	10.00	10.00
CO_2	10.91	7.15
H_2O	4.00	9.49
N_2	75.58	73.36
SO_2	0.27	—

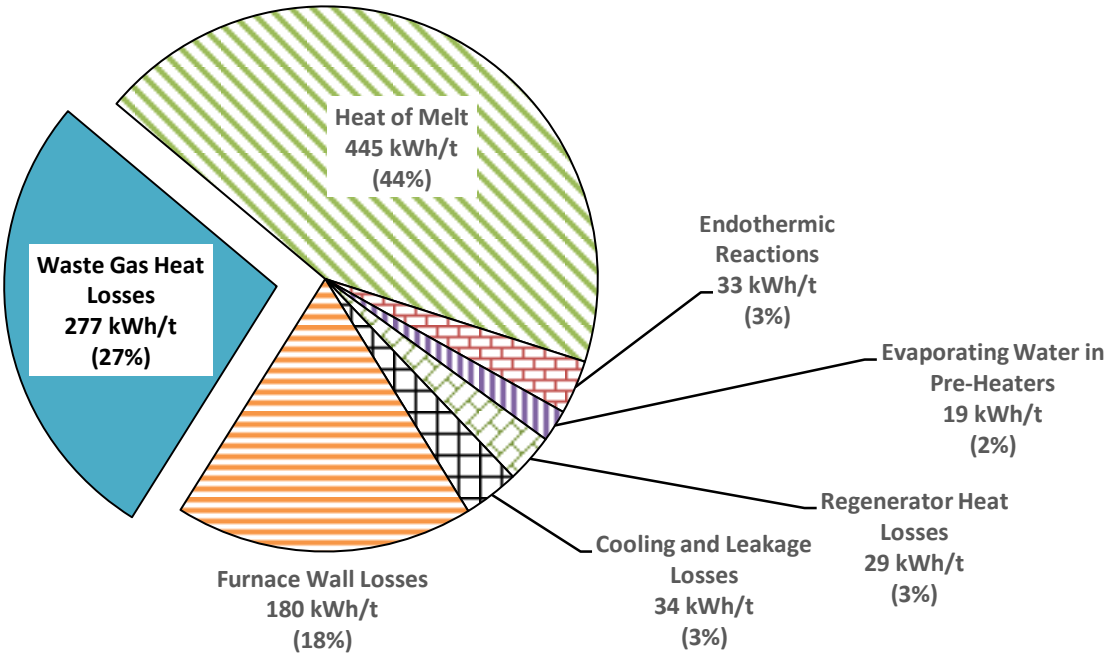

Figure 6-1. An example energy or heat distribution for an R/R glass furnace. [6]

6.1.2 Current Methods

R/R furnaces are classified as such because they use either a regenerator or a recuperator to capture waste heat. However, as has been shown, they capture only a portion of the medium- to high-grade waste heat from the glass melting operation. Thus the potential exists to capture substantially more energy. A number of these systems to recover waste heat have been developed, of which the three most prominent are discussed in this section. Table 6.3 shows a comprehensive accounting of existing and emerging WHR technologies for R/R glass furnaces identified in this study. The three primary methods are

1. More efficient regenerators and recuperators
2. Batch and cullet preheating
3. Steam and/or electricity generation

6.1.2.1 Regenerators and Recuperators

The most notable WHR technology is increasingly more efficient regenerators and recuperators. Regenerators have been studied for many years, and the research has resulted in continuous and incremental performance increases. [9] The use of more modern and efficient R/R systems would result in potential WHR of between 60 and 80% for regenerative systems and slightly less for recuperative systems. [9]

Regenerators alternate passing hot exhaust gases and cold combustion air through a matrix of high-heat-capacity material (usually ceramic blocks termed “checkers”). Cycles usually last between 20 and 30 minutes (see Figure 6.2). [10] This direct impingement method of preheating the combustion gases usually decreases the exhaust gas temperature to 400 to 600°C and heats the incoming gases to at most 1450°C. [10, 11] In a regenerator with a specific energy consumption of about 1.11 kWh/kg of glass, about 0.42 kWh/kg of glass is recovered via combustion air heating, or about 37.8%. [9] A target recovery rate of 54% was set by Sardeshpande et al. [9]. It was not reached because of a number of constraints, including blocking of the regenerator, which reduced the heat transfer area, and temperature limits due to material concerns. [9, 12] Materials used in regenerators must be able to resist chemical attack and bonding from alkali, V_2O_5, and SiO_2 while resisting creep deformation and experiencing low thermal expansion. [2] Wall materials must have low thermal conductivity to reduce wall heat losses, whereas checkers must have high thermal conductivity to efficiently transfer heat to and from the surrounding gases. [12] Continuing research to optimize regenerator materials has resulted in incremental improvement in efficiency and effectiveness; however, materials that can better cope with the oxidizing condensates present in cooled exhaust gases are not yet widely accepted. [12]

In recuperators, heat exchangers are employed to transfer heat from the exhaust gases to the cold combustion air. Incoming combustion air can be heated to between 600 and 980°C; the exhaust gas temperature is lowered to about 800°C, depending upon the system. [13, 14] Metallic radiation recuperators are most often used in glass furnaces. These systems are usually of a double-shell design, in which hot exhaust gases pass through the inner shell at low velocity and cold combustion gases pass between the outer and inner shells at relatively high velocity, as shown in Figure 6-3. [13, 14] Designs of heat exchangers for recuperators include heat pipe and shell-and-tube configurations. Recuperators are typically 1.3 m in diameter and 10 m tall. [13] Along with designs, materials for high-temperature applications must be carefully selected. Metals such as alloys 625, HR120, and AL20-25+Nb have been considered for metallic recuperators. [15] Thin films for high-temperature corrosion resistance, such as Cr_3C_2-NiCr, cited by Sharma et al., are currently of primary interest. [13] Earlier recuperators are cited at between 35 and 40% thermal efficiency. For example, two 1991 articles claim 30 and 38% fuel savings, as reported by Sharma et al. [13]. More recent papers, also covered in Sharma et al., indicate efficiencies of 34 to 40%. [13]

Table 6.1. Existing and emerging waste heat recovery technologies for R/R glass furnaces

Methods of waste heat recovery	Brief description	WHR technology/ system status	Advantages	Barriers/disadvantages	Waste heat recovery potential
Regenerators for primary heat recovery	Stationary regenerators (one pair of two) are used to recover ~60 to 70% of the waste heat from exhaust gases from a glass melting furnace	Available and used commonly	Relatively high recovery percentage of waste heat; can handle particulates; long life (>10 years); and relatively low maintenance	Unrecovered heat still represents a large amount of heat (outlet gases can still be 300– 600°C) [18]. Large size. Requires rebuild of furnace. High cost. Blockages, air leaks, and heat loss from the walls hinder the efficiency of regenerators [9]	Typically 60– 70% heat recovery is expected for a well-designed system. 46% recovery was actually achieved [9] in a 130 tonne/day furnace
Radiation type recuperators for combustion air preheating	Radiation recuperator consists of unobstructed flue gas passages. Uses gas radiation (from CO_2 and H_2O) with some convection from flue gases to the heat exchanger walls	Available and widely used. Most often used for glass and glass fiber, though often smaller	Relatively low cost compared with regenerators. Does not require use of ceramic refractory materials	Lower heat recovery (usually less than 40%). Some maintenance related to cleaning of inner surface of the heat exchanger [13]	Sharma [13] gives an example of 34 and 40% fuel reduction and cites a fuel reduction of 10–30%, depending on the system
Batch/cullet preheating	Use of exhaust gases to preheat and dry the glass furnace batch/cullet before they enter the furnace. This can be done via direct contact between the gases or via a heat exchanger	Available but not used extensively in the US. Used in more than 10 container furnaces [18]. Used only in container furnaces	Reduces energy required and increases productivity. Can be secondary WHR system to increase overall efficiency. Reduces NO_x emissions [9]	Not proven for all types of glass batch compositions. Several operating problems for fresh batch vs recycled glass (cullet). Difficult to justify the overall economics. Good/clean sources of cullet are sometimes scarce (for example, see [12]). Worrell et al., [17] cites overall costs and dry batch carryover as concerns.	60–80% of waste heat could be recovered. [1] Energy savings of 12–25% overall [18]. Potential for 30% energy savings over state-of-the-art regenerative systems [16]
Electric power generation using melting furnace exhaust gases	Use of conventional steam generator to produce high-pressure steam and use of steam to generate electrical power (can be synonymous with cogeneration) [23]	Available but not used extensively in the US. All float glass furnaces in Germany have such systems	Electrical power generation	High maintenance for boilers. Not yet well proven. Large capital expense. Installation costs of 1,100–4,000 $/kW and operating and maintenance costs 0.060–0.125 $/kWh [1, 19]	Some systems report 31 million kWh per annum [7] production with the attached boiler (1,200 t/day Chinese facility)
Electric power generation using exhaust gases from primary heat recovery unit	Use of exhaust gases from regenerators at ~430–540°C to generate electricity using steam generators or organic Rankine cycle	Available but seldom used	Relatively high heat recovery potential and availability of electric power	Cost; unproven technology for gases containing particulates	Thermal recovery efficiency between 30 and 60%. This could account for about 10% fuel saving over regenerative systems [7, 23]

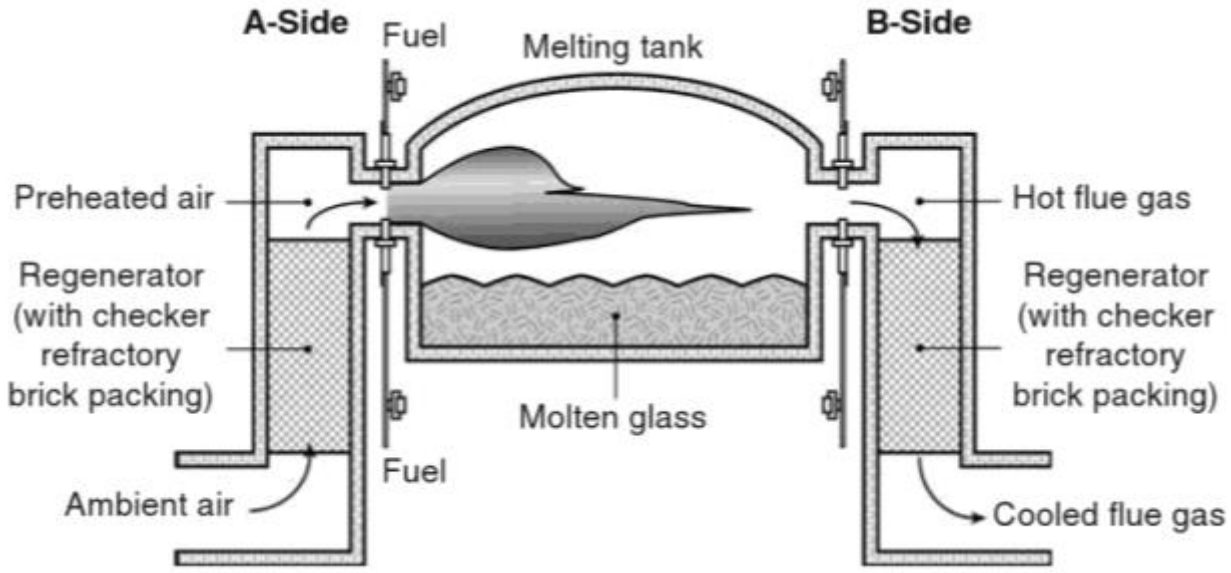

Figure 6-2. Diagram of a classic regenerator for glass furnaces. [10]

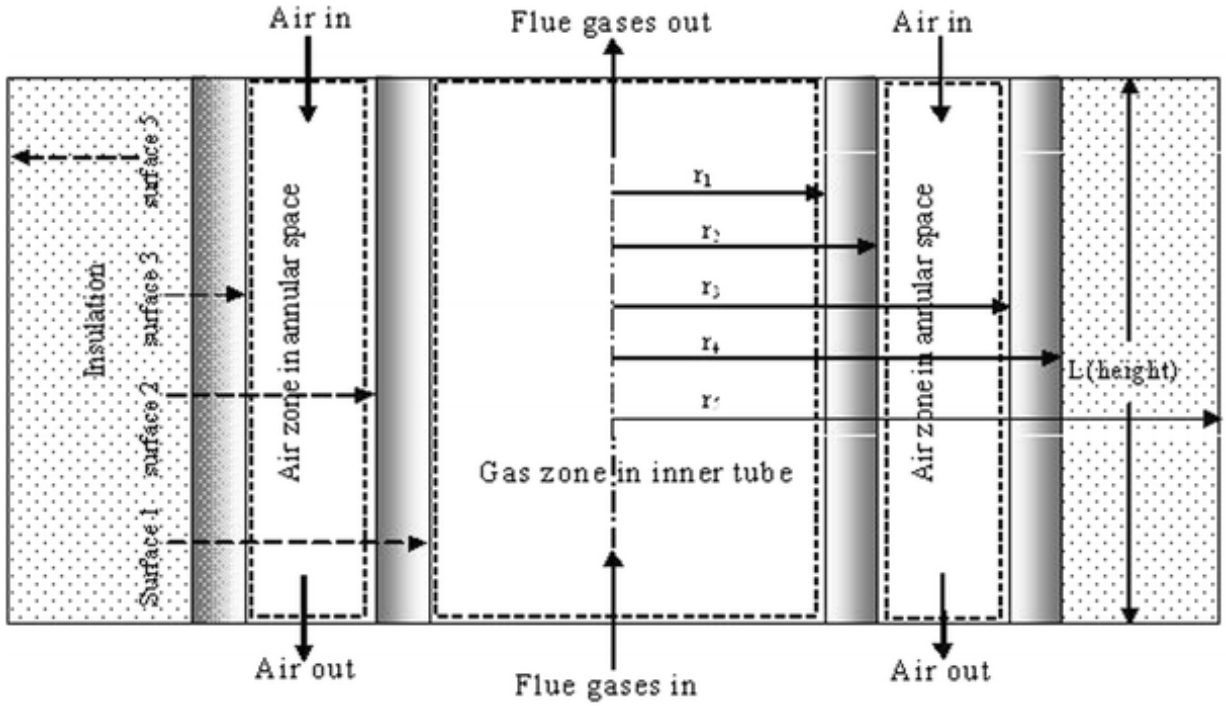

Figure 6-3. Diagram of metallic radiator type recuperator, using a counter flow heat exchanger. [13]

A thermochemical recuperator design was proposed by Rongen et al., with the CelSian and Hygear corporations [16]. This recuperator design uses waste heat to reform the combustion gases to produce H_2, with the goal of producing more efficient firing. The group reports 25–35% energy savings potential, with a commensurate decrease in CO_2 emissions. [16]

For both regenerators and recuperators, difficulties include frequent maintenance because particulate buildup on heat transfer surfaces results in poor system efficiency. Sardeshpande et al., indicate that a 50% blockage of the recuperators could result in a 7% reduction in regenerator efficiency [9]. Both types of systems are large and expensive; however, recuperators are less expensive and require less extensive furnace rebuilds to install than regenerators. In each case, the capital expense may be prohibitive. [11]

6.1.2.2 Batch and Cullet Preheating

Charge material preheating is a WHR technique used primarily in container glass furnaces. It is used more extensively in Europe and Asia than in the US. [1] A number of manufacturers produce preheaters, including Interprojekt, Zippe, Sorg, and Praxair; each product differs slightly. The method primarily involves radiation heat exchange between a counter-flow of exhaust gas from the furnace that directly impinges upon incoming (moving bed) charge material. Indirect heating is also used; in an indirect system, a parallel plate heat exchanger radiates heat between the charge material and the exhaust gases. [1, 11, 13, and 17] Another design drops the batch or cullet through a heat exchanger, allowing the material to heat as it falls through the exhaust gases. Some designs combine electrified filtering units with such preheaters. More than 10 preheater systems are in use in container glass furnaces in the US; these systems can be used for oxy-fuel glass furnaces as well, although they are more common among air-fuel furnaces at this time. [18] Kobayashi et al., cites 13 specific cases of preheaters installed since 1988 on container glass furnaces worldwide, eight of which are in Germany. [18]

Batch or cullet preheating offers moderate to high potential for waste heat recovery from exhaust gas. Charge materials are preheated to between 300 and 500°C, depending upon the technology employed. Cullet can be preheated to a higher temperature than can batch, as it suffers less from sticking/melting problems. Worrell et al., reports that overall plant energy efficiency increases of up to 25% could be realized using batch or cullet preheating [6.19]. Beerkens indicates that 12–20% energy savings have been achieved for regenerative air-fired furnaces. [6]. For one example project, the payback period for a packaging glass plant in the Netherlands was 2.6 years on a $1.4 million project (assuming a natural gas price of $3.8/MMBtu and electricity price of 0.05 $/kWh). [19] Such systems could also be used as secondary heat recovery systems, i.e., in combination with some other form of WHR like electric power generation or recuperators.

One important characteristic for batch and cullet preheating systems is the batch to cullet ratio. The systems must operate at above 35% cullet. A high batch-to-cullet ratio can result in clumping, which can cause poor product quality; likewise, very fine cullet can result in clumping. [9] Thus relatively high cullet percentage (usually greater than 50%) is used. This causes concerns over the availability of high-quality, cullet of the correct composition. Note that the use of cullet reduces furnace energy requirements by 337 kWh/tonne of cullet. [20] A concern that dry batch could be trapped in the system and contaminate later melts has also been expressed. [17]

6.1.2.3 Electricity Generation

Electricity generation provides a third WHR opportunity. Waste heat–to-power technologies, including those used in exhaust gas heat capture, can largely be divided into three categories: steam cycle generator, ORC, and Kalina cycle generator systems. Each use exhaust gases to heat a working fluid via a heat exchanger; the working fluid is then used to mechanically generate electricity. In such systems, high-temperature exhaust gas is used in a WHR boiler or steam generator to produce high-pressure steam or drive an ORC or Kalina cycle. Steam cycle generators are used with high-grade waste heat sources (>600°C), whereas ORCs use a cycle well adapted for low- to medium-grade waste heats (between 100 and 600°C). The Kalina cycle uses a mix of steam and ammonia suited for a larger range of moderate temperatures (about 100–800°C) and has the highest theoretical efficiency; however, Kalina systems are

not well suited to small installations. [1, 21, 22] ORC systems operate at lower temperatures than steam cycles and are more expensive. Steam cycles are the most familiar and well proven, but they require more physical space and greater operational supervision. [22] In any case, the infrastructure required to implement any such scheme is extensive.

Installation and operating/maintenance costs vary between technologies and generator size. Installation costs between 1,100 and 4,000 $/kW are common for waste heat electrical generation systems. Typical operating/maintenance costs are between 0.005 $/kWh and 0.020 $/kWh (for a 400 kW to 5MW capacity range and accounting for different technologies). [1, 21] Installation costs depend upon the technology and the capacity (large systems are generally less expensive when normalized for production capacity). [19] Accounting for the amortized installation costs, the total normalized price could total as much as 0.060 to 0.125 $/kWh. [23] Moreover, such a system must compete with the utility grid electricity price to be cost-effective: if the electricity production cost, including amortized installation expense, is greater than the price to purchase electricity from the grid, such systems could be economically unjustifiable. Steam and ORC generators have been deployed mostly outside the US. Relatively high energy prices drive development in Europe, and energy prices and environmental regulations drive development in China for these types of systems, [7, 21] The energy capture potential is reasonable, with Li et al., reporting 31 million kWh of electrical production from a 1200 ton/day flat glass furnace; this system was designed to operate with an exhaust gas heat of 450°C, an expected temperature for regenerative furnace exhaust gases. [7] Thermal efficiencies for OCR systems are usually between 15 and 25% and are often over 30% for steam systems. [22, 30]

6.1.3 Barriers and Limitations of Existing Technologies

As indicated in Table 6.3, WHR techniques have both advantages and disadvantages. Mediation of the disadvantages or barriers to implementation of these systems has been the primary goal of extensive and ongoing research surrounding WHR systems. Broadly, the disadvantages and barriers can be classified as related to either structure/design or materials. Often construction materials and designs must accommodate the components that are exposed to the chemical compositions present in exhaust gases. The specifics of exhaust gas composition depend upon the fuel being burned and the composition of the charge material. It is likely that boric acid and SO_2 are both present. [7] Li et al., emphasizes the importance of the furnace fuel in exhaust gas WHR device design. [7] For example, most recuperators are limited by materials: the inflow and outflow gas temperature must be maintained between defined threshold values to avoid damage to the device either from the caustic/corrosive agents in the exhaust gas or property degradation from the temperature.

Costs

An overarching challenge with WHR technologies is capital investment and operating expenses. These systems require a large capital expense. For example, Worrell et al. cites an expense of $1 million for a steam-based electrical generation system. [17] As another example, expenses measured in US dollars per kilowatt range between $1,100/kW and $3,500/kW, depending upon the technology employed for electrical power generators (steam generators usually are the least expensive and OCR generators are usually the most expensive). [1] Another source cites $1,200/kWh to $4,950/kWh for ORC generators capable of 0.2 to 2 MW_e output; however, these figures are not specifically for the glass industry. [24] For smaller operations, these costs may not be justifiable; and for larger operations, the system must represent a justifiable investment. [24] Payback times vary between technologies but are most often measured in years. For example, in the system analyzed by Li et al., the payback period was between 1.3 and 1.5 years, although this is an optimistic estimate. [7] Initial capital expense is governed by factors such as the system design, materials required, and other fixed costs; however, payback time is also influenced by the system efficiency, productivity and yield improvements, product quality–related returns, and life of the

system. Thus design and materials also determine, to a large extent, the economic viability of WHR technologies.

Regenerators and Recuperators

Regenerative systems are limited by availability and by the ability of the designer to make changes in the system design parameters, such as system size, cost, life, and maintenance.[6, 9, 11, 17, 23] Installation of these systems requires a furnace rebuild. [18]. Sardeshpande et al., enumerates many of the difficulties with regenerative systems. [9] Current regenerator designs suffer from potential blockages: the exiting flue gas contains a substantial amount of dust, which is deposited along the exhaust gas path. Accumulations of dust can develop within regenerator checkers, limiting fluid flow and heat transfer into and out of the matrix material. Material degradation concerns limit material choices for checker blocks. [24] Blockage development also affects the pressure drop and chemical composition within the regenerator, resulting in frequent maintenance requirements. Regenerator efficiency is further limited by air leaks, reducing the exhaust gas temperature and again altering the chemical composition. During the exhaust cycle, regenerators have reduced pressure due to flue draft; therefore, air infiltration occurs through cracks in the regenerator body, cooling the system and reducing efficiency [9]. Convective and radiative losses through the walls limit the efficiency potential of regenerative systems. The heat capacity and the heat transfer coefficient of the checker bricks under transient heating absorption and rejection governs the absolute efficiency of a regenerative system. [9] The material used in this component is of fundamental importance. The material must have a high heat capacity and high heat transfer coefficients. Moreover, it must be resistant to extreme temperatures (exhaust temperatures are typically about 1,500°C before entering the regenerator) and to abrasion, inhibit dust accumulation, and resist the actions of alkaline gases and volatiles within the exhaust gas.

Recuperators are primarily limited by material concerns that largely influence the system designs. Recuperators, much like regenerative systems, cannot be installed ex post facto. They have many of the same limitation as regenerators for similar reasons. Fouling from dust in exhaust gases reduces the effectiveness of heat transfer in both radiative and convective recuperators. [27] Recuperators are limited by the convective and radiative heat transfer properties of their components: the solid and the fluid properties of the exchanger determine the effectiveness of the recuperator. The systems may experience air leaks that reduce the temperature of the heated combustion air and the exhaust gases. Thermal stress is a primary concern in the design of recuperator heat exchangers; however, pressure drop through a recuperator must also be considered: the development of air leaks necessitates pressure control to maintain operational effectiveness. [28] Exhaust gas temperatures above 1,100°C are difficult to use effectively use. [13] Advanced materials are required for recuperators to operate effectively at such high temperatures. These require extensive research and, once commercially available, often have high production and machining costs. [13, 15, 16]

The thermochemical system presented by Rongen et al., is not suited well to installations requiring large combustion air throughput. It is currently undergoing proof of concept and pilot-scale testing. In furnaces using this system, an altered combustion reaction would cause higher water vapor concentrations than in a conventional furnace. This may impact NaOH and NOx emissions as well as sulfate fining. Additionally, modified flame properties may cause difficulties for some furnace configurations. [16]

Batch and Cullet Preheating

Batch/cullet preheating has the potential to recapture a large amount of waste heat. However, there are difficulties and limitations with implementing such a scheme. In this case, the difficulties are mostly design related, with the primary concern being operational. Batch melts more easily than cullet. Typically, >50% of cullet is used to avoid sticking and localized melting. A range of batch/cullet ratios are used.

However, use of less than 35% cullet or more than 90% cullet is not feasible. [18, 23] This fundamentally limits the temperature to which charge materials can be heated. Transportation of the hot charge material requires careful design. Fluidized bed designs have been suggested for such applications. It may be difficult to operate at high cullet ratios, as high-quality sources of pure cullet can be difficult and/or uneconomical to obtain. Thus preheaters are used primarily in container glass furnaces, where higher degrees of impurities and higher ratios of discolored glass can be tolerated than in flat glass, specialty glass, or glass fiber furnaces. Colored glass, often used in container furnaces, is more resilient against foreign matter that may be present in cullet. Additionally, concerns about dry batch carryover (fine-grain batch material trapped within the preheater and deposited in later melts) and volatilization of batch materials (conversion of batch into vapor, contaminating the preheater and reducing operational efficiency of the furnace) limit the application of preheaters in some cases. [18, 23] Cullet preheaters have been assessed; however, they offer limited potential for efficiency gains, as a mix of batch/cullet must be used in a melt. The primary factor prohibiting widespread adoption of batch/cullet preheating is operational and installation expense. These systems are large and expensive to install, as is typical of WHR systems. Moreover, preheaters are complex and require frequent maintenance, making them largely undesirable because of the downtime they impose. [23]

Electricity Generation

The primary difficulty with waste heat–to-power systems is cost. Techniques that produce electricity must compete with conventional electricity purchase prices. In addition, these systems are large and difficult to site: optimally, they will be as close to the exhaust gas source as possible. [1, 7, 11, 17, 21, 26, 27, 28, 29] Most of the materials and design problems are encountered at the waste heat collection stage of generation, as the technologies and techniques for producing useful energy from heat are have been well developed for generators served by more conventional heat sources. [21] Therefore, steam, ORC, and Kalina cycles share many difficulties. [22] They require constant sources of heat: noncontinuous operation substantially reduces their effectiveness. As with all systems requiring heat exchangers, high levels of maintenance are required. [23] Each system is limited by the fundamental efficiency of the cycle it employs. [21, 30]

The primary barriers to deployment of WHR technologies and systems with R/R glass furnaces are material and structural. Material concerns are often due to the high-temperature and particulate-laden environment in which these systems must operate. These factors are compounded by the reactivity of the chemicals in the waste heat stream. Structural limitations include size requirements, siting concerns, and a requirement for easily maintained devices with few points of failure. Further material handling requirements constrain these systems. Finally, high capital costs provide a disincentive to investment in WHR system installation.

6.1.4 Conclusions

Regenerative and recuperative systems make up a significant portion of glass furnaces, yet their efficiency remains limited, with only about 45% of the fuel energy being used to melt the incoming batch and cullet. Of the wasted heat, about a third is embodied in exhaust gases. The current state of technology for recapturing exhaust gas waste heat in R/R furnaces was examined. A number of technologies have been identified from the literature, with an emphasis on identifying weakness and limitations of current technologies. The foremost technologies include improved-efficiency regenerators and recuperators, batch/cullet preheating, and electricity/steam generation. Further, structural/design and materials issues with these WHR techniques are identified and enumerated. A need for further development of materials and designs suited to the needs of such applications has been identified. For example, further development of ceramic materials for use in regenerator checkers and walls could increase regenerator efficiencies, reduce problems with blockages, reduce maintenance requirements, and increase life

expectancy. For recuperators, development of more temperature- and corrosion-resistant metallic material would allow for high-efficiency devices by permitting a larger temperature drop in the exhaust gases so that more of the sensible energy could be extracted.

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7. CEMENT-LIME INDUSTRY

7.1 CEMENT AND LIME KILNS

7.1.1 Background and Potential Opportunity

The US produced about 77.8 million tonne (metric ton) of cement and about 19.0 million tonne of lime in 2013. [1, 2] Worldwide, production was 4.0 billion tonne of cement and 350 million tonne of lime. [1, 2] The cement and lime production processes are similar: both use fuel-fired kilns to process raw materials at high temperatures, and both are energy-intensive, continuous-production industrial processes. The specific energy use of cement and lime kilns varies depending upon the type of kiln, the reactants, and the fuel; energy use for cement kilns is between 798 kWh/tonne of clinker (2.5 MMBtu/ton of clinker) for a dry kiln with preheater and precalciner and 2,843 kWh/tonne of clinker (8.8 MMBtu/ton of clinker) for a wet kiln without preheater. [3] With such substantial energy expenditures, reduction and recovery of the energy lost within such processes is an appealing prospect. This section outlines the emerging and existing WHR techniques for exhaust gases from cement and lime kilns, with a focus on identifying material and structural/design barriers to these technologies.

In both cement and lime production facilities, there are many energy-intensive processes; however, this report focuses on the kiln, and specifically on the exhaust gas waste heat from the kiln. This is because kilns use a substantial amount of the heat energy required for these processes; e.g. for cement production, kilns consume about 74% of the total energy required. [4, 5] Raw material preparation of cement takes between 25 and 35 kWh/tonne of electrical energy, compared with 798 kWh/tonne for kilning. [3] Two primary types of kilns are used: rotary and shaft. Rotary kiln technologies can be further defined by material moisture content and existence of a preheater on the kiln. Rotary kilns of both the wet and dry types, with and without preheaters are examined. Shaft kilns also are discussed, as they are often used in the quicklime production process. [6]

A rotary kiln consists of an annulus oriented at about 3° to 4° from the horizontal and rotating at between 1 and 3 rpm. [7] Production rate is determined by size (length and diameter), slope, and rotation rate. In such kilns, the raw materials migrate from the high end to the low end of the annulus. The burner is located at the low end, and combustion gas is released from the high end. Thus as the raw material falls, it is heated by the escaping burner gases. Rotary kilns are used when high-quality, smaller-size feed materials in large quantities are used. [6] Often rotary kilns complement shaft kilns. [6] Shaft kilns are also used in the cement industry, although rotary kilns are the dominant technology, as they produce more chemically uniform materials. [3] Shaft kilns, and their variants, are often used for lime, as they tend to be more energy-efficient and simpler than rotary kilns. Conventional shaft kilns have raw material charged into the top of the kiln, in a preheating zone, where combustion products heat the raw materials. In the calcining zone, fuel and combustion air are ignited to heat the raw material to the temperatures required to affect a dissociation of the reactants. The final zone cools the reactants; the cooling air used to do so is drawn through the shaft to supplement the combustion air and provide additional heat to the reaction. A vertical shaft kiln is outlined in Figure 7-1. [6]

For cement, three primary phases are encountered in this heating process: drying, calcining, and sintering. [3, 6] Each of these phases requires heat energy input. Calcining is an endothermic chemical process in which carbonate is decomposed into oxide and CO_2. Flame temperatures are 1,800–2,000°C, and sintering takes place at 1,480°C in the production of clinker. The hot clinker exits at the lowest end of the kiln and enters an air quenching phase. [7] Two processes are primarily used: wet and dry. The wet process starts with a slurry input material with a moisture content of about 35%, requiring significantly more energy to dry. The more modern dry process has been enabled by developments in process control techniques in grinding and processing phases and results in feed material with about 0.5% moisture content. [8]

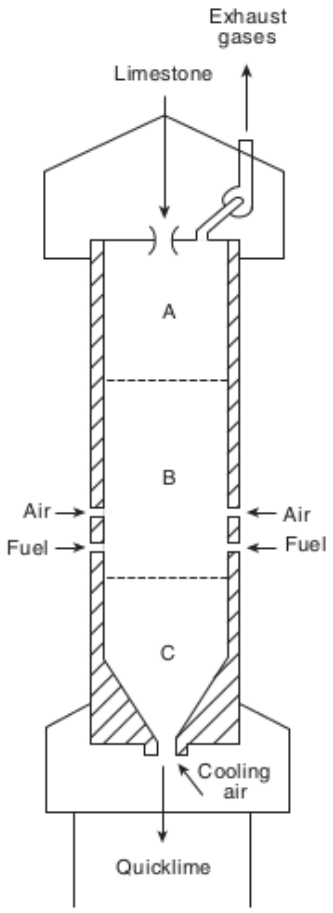

Figure 7-1. Simple diagram of a lime shaft kiln. Section A is the preheating area, B the calcining area, and C the cooling area. [6]

Lime kilns operate with similar principles to cement kilns but with different reactants and reaction temperatures. Lime calcination, the decomposition of $CaCO_3$ to CaO, requires temperatures of at least 900°C but no more than 1,100°C. [9, 10] Lime kilns can be divided into two general groups: shaft type and rotary type. Lime rotary kilns operate in the same way as cement rotary kilns. Shaft kilns can be described as having three primary zones: at the top of the process stack is the preheating zone, where limestone in 50–100 mm particle sizes is injected and exhaust gases exit; these particles then enter the calcination zone, where temperatures are sufficient to drive the decomposition reaction required; after the reaction concludes, the material is deposited below the burners in the cooling zone, where secondary cooling air is injected. [8, 9, 5] Quicklime is collected at the bottom of the kiln shaft. [10] Most lime kilns are of the shaft type, and the largest share of these are parallel flow regenerative kilns (described in the following section with regenerative systems). [11] In the EU-27 (all European Union member states in 2013), 46% of lime production uses parallel flow regenerative kilns, although in the US most lime production is in rotary kilns. [12, 13]

A significant portion of the fuel input energy is wasted in kilns. Figure 7.2 shows an example energy distribution (rounded to whole numbers) for a 6,364 tonne/year (7,128 ton/day) capacity, 5.5 m diameter, 66 m long rotary cement kiln. [12] This kiln has a total estimated specific energy consumption of about 1,040 kWh/tonne of clinker. Engin and Ari report 19.15% energy rejection from exhaust gases (after a preheating system) in a 600 tonne/day dry-type rotary kiln in Turkey. [14] A similar, but less discretized, distribution of heat from a lime kiln is shown in Figure 7.3 (rounded to whole numbers). This is for a 24 tonne/day shaft lime kiln. [10] A second shaft kiln is also presented by Gutierrez et al. [10]. This one, with a production rate of 100 tonne/day, indicates higher efficiency (enthalpy of reaction is 71.6% of energy use); however, the exhaust gas losses are 23.2% of the input energy. Another source cites that, for a rotary type lime kiln, between 20 and 25% of the input energy is lost in exhaust gases. [9] Atmaca and Yumrutas [15] cite 32.6% energy losses from exhaust gas from a 4.2 m diameter, 59 m long rotary kiln. Rotary kilns are commonly fitted with preheaters (most often of the cyclone type, described below) to help reduce energy requirements. [15]

A range of fuels are used to provide for the energy requirements of cement and lime kilns, including petroleum coke, coal, natural gas, fuel oil, diesel fuel, and others. [8] The exhaust gas from cement kilns typically consists of CO_2, NO_2, H_2O, Ar, NO_x, SO_2, O_2, and dust. [15, 16] Engin and Ari cite 1.8% O_2, 27.4% CO_2, and 70.8% N_2 post-preheater exhaust gas composition by weight for a kiln burning dried coal. [14] A significant amount of dust is also produced; for example, in a 2.7 m diameter, 55 m long, 500 tonne of clinker per day kiln analyzed by Sen et al., [17], the preheaters exhausted 2.559 kg/kg of clinker of gas and 0.035 kg/kg of clinker of dust, or about 1.4% of the exhaust gas. [17] This represents 17.5 tonne of dust per day. In a kiln assessed by Ari, 0.165 kg/kg of clinker of dust was produced. [12] A broad study of rotary cement and lime kilns in the European Union reported dust emissions between 0.27 and 30 mg/Nm^3 after filtering. [11] Systems with preheaters typically have lower dust emissions. Dust typically consists of CaO, Al_2O_3, Fe_2O_3, SiO_2, and ash; this is largely contaminated clinker, much of which is recycled using dust collectors. [15] However, volatile compounds are released as the raw meal is heated; this results in volatile organic compounds, volatile metals, and other chemical species in the kiln. These either are decomposed in higher-temperature zones or recondense, most often within the preheaters. [11] This process results in negligible emissions, although the environment within the kiln contains substantial amounts of particulates and combustibles. [11] For lime kilns, exhaust components are similar—generally CO, CO_2, H_2O, SO_2, NO_x O_2, HCl, and N_2 are expected. [10, 11] A large amount of dust is also produced, which must be filtered from the exhaust gas. SO_2 and NO_x emissions are typically low, with less than 500 mg/Nm^3 produced from lime kilns. Depending upon the type of lime produced, NO_2 emissions could be greater than 800 mg/Nm^3. [6] Emission of significant quantities of other dangerous or hazardous particulates is negligible. [6]

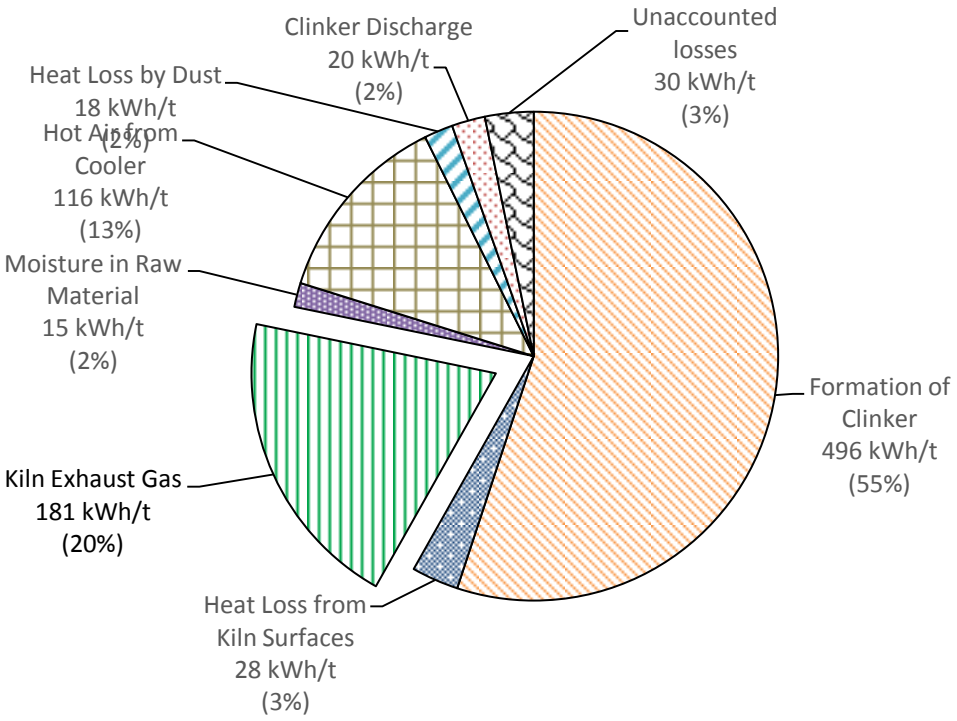

Figure 7-2. Example heat distribution from a rotary cement kiln. [12]

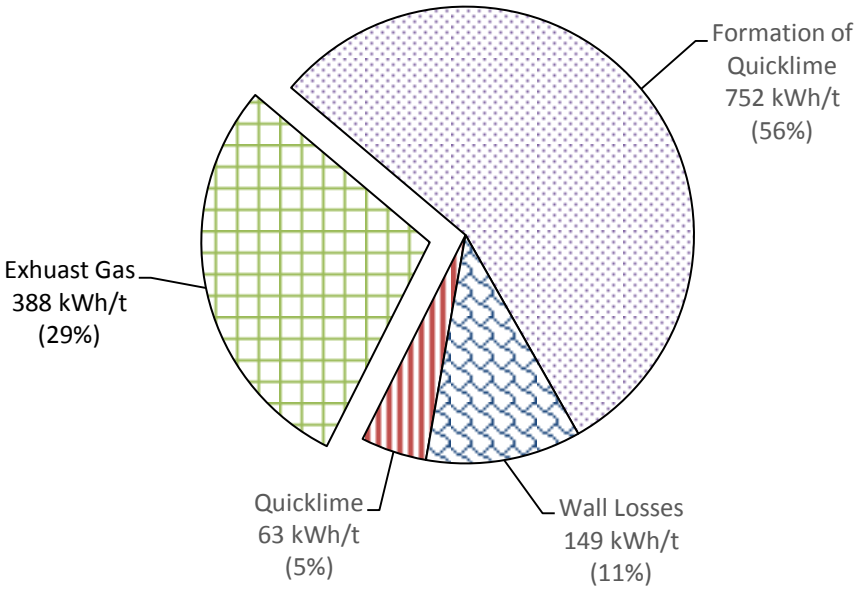

Figure 7-3. An example heat or energy distribution in a rotary lime kiln. [10]

7.1.2 Current Methods of Waste Heat Recovery

A variety of exhaust gas WHR techniques exist or are being developed for kilns in the cement and lime industries. The most extensively employed WHR technique for kilns is stack preheaters, often of the cyclone configuration. Also frequently used are precalciners. Kiln exhaust gases have also been used for steam/electrical generation. A complete listing of existing and emerging technologies for WHR in cement kilns is presented in Table 7.1; Table 7.2 presents these technologies for the lime industry. Although many of the technologies presented are the same, application to the slightly different processes of lime kilns necessitates slightly different approaches. Further, some technologies have been proposed only for lime kilns or for cement kilns, though transfer is often possible. [6]

Raw material preheating

The most prominent WHR technique, currently employed in nearly all modern dry process rotary cement kilns and lime kilns, is preheating the charge material with exhaust gas. This takes the form of a series of suspension preheaters, called cyclones, that drop the incoming solids through the exhaust gases before they enter the kiln. [18] Preheating is performed in stages, with each cyclone unit progressively increasing the temperature of the charge material. Up to six such units have been used. [3, 4, 7, 19, 20] Shaft type preheaters are also used. In wet process cement kilns, slurry driers can be used. These use waste heat from the exhaust gases, via a traveling gate design. [3] A fuel consumption reduction of 452 kWh/tonne of clinker was achieved for a cement kiln. [3] A kiln using a four-stage cyclone preheater consumed only 77% of the energy used by an equivalent long dry process kiln without preheaters. In cement kilns with four or more preheaters, precalciners are often employed. The devices contain relatively small secondary burners to heat the charge material to calcining temperatures before their entry into the kiln proper. The addition of precalciners requires a significant plant rebuild; however, the technologies enable energy savings of 11–14% and a capacity increase of 80–100%. [21] A kiln with a six-stage preheater, a precalciner, and a high-efficiency clinker cooler used 64% of the energy used in a long dry process kiln. [4] However, the addition of preheaters to a plant increases maintenance requirements. Preheaters are expensive to install, which may prohibit their use in small production facilities.

Table 7.1. Existing and emerging waste heat recovery technologies for cement kilns

WHR method	Brief description	WHR technology/system status	Advantages	Barriers/Disadvantages	Waste heat recovery potential
Steam generation from heat	Exhaust gases generate steam in a waste heat recovery boiler. Flash steam, duel-pressure steam, Kalina, and ORC cycles have all been proposed [22, among others]	Available and used at a very few locations in the US. Widely used elsewhere (especially China). Used with long dry kilns. Efficiencies are better in kilns without preheaters and precalciners	Large percentage heat recovery from exhaust gases	High capital cost, added operating cost. Can be applied only in cases where low-pressure steam is required. May require maintenance of boiler because of particulates. Typical costs for steam are $1,100–1,400/kW; for Kalina $1,100–1,500/kW; for ORC $1,500–3,500/kW [5]	Recovery potential is medium to high. [5] Limited to 20–25% efficiency without modifying the kiln: 8–22 kWh/t clinker electrical production. If kiln is modified, up to 45 kWh/t [19] According to Engin, cost savings of $540,000 /year is possible (1.38 year simple payback period) [14]
Organic Rankine Cycle (ORC) for electricity	ORC uses waste heat to vaporize a refrigerant, which drives a turbine generator [33]	Available, not frequently used outside of China [4]	Captures low- to medium-grade waste heat. Relatively high efficiency	Expensive. ORC can be twice the cost per kilowatt of a steam cycle generator	ORC efficiency is limited to about 20–25% electrical generation (maximum). However, 70% of the exhaust gas energy can be captured [23]
Preheating/ precalcining and drying of charge material	Use of shaft type or cyclone type charge preheater at the gas exit (charging) end of the kiln	Available and used widely in modern plants. Sometimes retrofitted to older plants	Large percentage of heat recovered	Economics, use of selective feed material. Limited use with wet process. Increased maintenance	1–1.3 MMBtu/ton of clinker is recovered [5]
Fuel moisture removal or drying	Use of hot gases to dry fuel and reduce moisture content before fuel combustion.	Available and used widely where applicable	Improves heating value and increases available heat with higher overall efficiency [21]	Overall economics. Difficult to design, and operational issues with process equipment	Such a scheme can increase efficiency up to 10%. [38] However, this is for furnaces in general, not specifically for a cement kiln
Thermo-electric regenerator	Uses materials to produce electricity directly from a thermal gradient	Not demonstrated. Still under development	Avoids steam/ORC/ Rankin boiler and moving parts	Very high cost; cannot be used with gases. Short lifetime. Costs can be as high as 10 M$/kW. Contamination concerns [5]	Inefficient—typically < 10% efficiency [25]

Table 7.1. Existing and emerging waste heat recovery technologies for cement kilns (continued)

WHR method	Brief description	WHR technology/system status	Advantage	Barrier/Disadvantage	Waste heat recovery potential
District heating (steam or hot water)	Waste heat is used to supply residential heat through the production of steam or high-temperature water	Deployed in some places (Europe and China mostly). Still under study [26]	Good heat recovery from low-grade heat; displaces other heaters	District heating is not prevalent; without district heating initially, system is not feasible to implement. Low percentage of available heat used	Only about 5% of waste heat used. Sogut et al. cites coal and natural gas consumption overall were reduced by 52% and 63% respectively [26]
Clinker cooling air heat recovery	Clinker material is cooled via cross-flow of air. The air is then used to heat combustion air; several designs exist	Commonly used, though more efficient and modern techniques are being developed [3]	Good heat recovery; need to cool clinker anyway	Improved heat recovery may alter product quality and kiln emissions. Cost depends on plant size; more efficient designs may not be available to smaller kilns	As high as 70–75% heat recuperation potential. Lower potentials are above 50% [4]

Table 7.2. Existing and emerging waste heat recovery technologies under consideration for lime kilns

Waste heat recovery method	Brief description	WHR technology/ system status	Advantage	Barrier/Disadvantage	Waste heat recovery potential
Steam generation from exhaust gases	Exhaust gases are used to generate steam in a waste heat recovery boiler. Steam has been used for district heating in Sweden	Available and used at only a few locations	Large percentage heat recovery from exhaust gases	High initial deployment cost, added operating cost. Produces only low-pressure steam. Heat exchangers foul quickly	Recovery potential is medium to high where an innovative heat recovery system can be used to generate steam using ORC or other similar power generation system
District heating (hot water or steam)	Warm water heater installed directly in the flue gas channel. Hot water or steam used for district heating	Used selectively in Europe and China	Displaces other sources of home heating. Can be used with low-grade heat	Low amount of heat recovered. Feasible only in limited locations/situations	Relatively low. About 5% of heat energy is used. Also see district heating entry for cement [26]
Organic Rankine cycle generators	ORC uses waste heat to vaporize a refrigerant, which drives a turbine generator [10, 16]	Available and in use in a few places; development is to reduce costs and increase efficiency	Can be used with lower-temperature waste heat. Relatively large amount of heat recovered	More expensive than comparable steam generator. Best for low- to medium-grade waste heat	ORC efficiency is limited to ~20–25% efficiency for electrical generation. 70% of the exhaust gas energy captured [23]
Preheating charge material	Use of shaft type charge preheater at the gas exit (charging) end of a rotary kiln. Cyclone preheaters are usually used. Up to 6 preheater stages can be applied	Available and used in modern plants	As in Table 7.1 for cement	Installation expense. Use for selective feed material. Cannot be used with wet process	1–1.3 MMBtu per ton of clinker is recovered [5]
Preheat combustion air (recuperators)	High-temperature exhaust gases are recirculated to heat the combustion air	In use	More efficient combustion	Cost. Smaller facilities cannot justify the initial expense. Can result in excess dust creation	About 5% reduction in fuel use possible [27]
Regenerators	In parallel flow regenerative system, one shaft is burning while the other is non-burning. Airflow is alternated between them to preheat the air. [5]	Available and in use [11]	Highly efficient. Good conditions for low-burn-temperature limes. Operates with a variety of fuels	Limited producers of such kilns. Difficulty handling small or large stone sizes. Some difficulties with fouling with poor-quality feed material	Regenerative heat recovery increases efficiency by 15–25% [6]. Off-gas temperature is 100°C, and 3.02 MMBtu/ton-lime is required [9]

Table 7.2. Existing and emerging waste heat recovery technologies under consideration for lime kilns (continued)

Waste heat recovery method	Brief description	WHR technology/ system status	Advantage	Barrier/Disadvantage	Waste heat recovery potential
Waste heat as process driver (carbon capture)	Waste heat (flue gases) is used to drive a carbonization process to convert Mg to $Mg(OH)_2$. [28] $Mg(OH)_2$ then reacts exothermically with CO_2 to make $MgCO_3$. This captures CO_2	Lab-scale test; ref. [28] discusses scale-up to pilot	Currently (theoretically) capable of 178 kg CO_2/hour conversion [28]	Economics; technical development required. Materials to cope with the harsh reactor environment (very basic, high pressure [up to 8000 kPa]) are needed. Condensate forms ammonium sulfate salts [28]	Much of the waste heat used [28]. In a plant with capacity of 2740 t/day, 4.9 MW of electricity generated from waste heat with 78.5% of CO_2 captured [16]

Fuel drying and preheating

A similar technique to raw material preheating is fuel drying/preheating. It is used with coal, the most commonly used fuel for cement kilns. [20] Coal is transported with a high moisture content (5–10%) to avoid dangerous dust formation. Drying of coal with waste heat from off-gases is usually done by passing relatively low-temperature gases through the coal mill. Using one technique, the theoretical coal requirements of a cement plant were reduced from 1,650 to 1,230 tonne/day in a 6,850 tonne/day cement kiln. [21]

Power generation

An often discussed WHR technology is power generation. The technique uses heat exchangers to collect the mid-grade exhaust gas waste heat and use that energy to power a steam, ORC, or Kalina cycle turbine. [22] A conventional steam Rankine cycle is optimized for higher-temperature sources than unmodified kilns. Steam turbines have undergone extensive development for other applications and are a proven technology. Steam systems are the most common WHR power generation technology. [7] Although steam systems require a waste heat source with a temperature above 260°C, they have the lowest price for the electrical generation potential. [5, 7] ORC and Kalina turbines are designed to operate efficiently with less available heat: they are more efficient than conventional steam turbines when both are operated with exhaust gases at temperatures of 310°C or less. [7, 29] ORC turbines cannot operate at temperatures below 150°C. [7, 29] Kalina cycles operate in a moderate temperature regime, at 95–535°C. [7] However, the Kalina system has not yet achieved widespread use, even though at the same temperatures it can be 15–25% more efficient than ORCs. [30] This is potentially due to price and state of development.

Waste heat–to-power systems have yet to be used widely outside China. A total of 865 WHR systems have been installed in cement kilns worldwide, and 739 of those are in China. [7] WHR systems are installed in 48.8% of production facilities worldwide and assist more than 50% of cement production capability. [7] Of all power generation installations, 99% are steam, with nine ORC and only two Kalina systems in use. [7] Gaozuo et al., report optimal thermal cycling efficiency of 24.6% for a steam cycle producing 5,700 kW, from a cement kiln with preheaters that produces 2,790 tonne/day. [30] However, efficiencies of between 10 and 20% are more common. [19] This would result in an electrical production potential of between 8 and 22 kWh/tonne of clinker. [19] Payback periods for these projects depend upon a number of factors but are typically between 3 and 4 years. [7] They are more economically feasible in larger facilities. [11] High costs are prohibitive to the installation of power generation systems. Further, the heat exchangers require maintenance, and steam turbines require a full-time operator. The moisture content of the feed material must also be considered, as it affects the waste heat temperature. [6, 19] More efficient processes and working fluids for the generators are being developed. [19]

Regenerative shaft kilns

Another technology unique to shaft kilns is the regenerator. The device is typically a double shaft with combustion alternating between the two shafts. In parallel flow regenerative kilns (see Figure 7-4), combustion air and fuel are added to one stack, and the exhaust gases (at about 1,050°C) are ejected through the second stack, where much of the heat is absorbed. [6] Each burn typically lasts between 8 and 15 minutes, and then the process is reversed. This process increases thermal efficiency by 15–25%. [6] The Maerz system operates with an exhaust gas temperature of about 100°C and heat content of approximately 290 kJ/kg. [9] Energy efficiencies of 85% are possible. [9] These kilns work best with relatively small stone sizes. Typical load capacities are between 50 and 100 tons per day. These systems are optimized for kilning highly reactive lime products, which require lower burn temperatures. [6] Regenerative systems are more costly to deploy than are more conventional lime kilns. Further, these systems are not capable of producing some types of lime (i.e., hard burnt). [9]

Thermoelectric generation

A WHR technique currently under development is the use of thermoelectric generation (TEG) devices to directly convert heat into electricity. With equal applicability to either cement or lime kilns, these devices use the Seebeck effect to produce electricity. Efficiencies of these systems are low, between 2 and 5%. [6] Durability, cost, and scalability are a few examples of the limitations on TEG implementation in industry. [25, 31, 32] Current research has been focused on producing more efficient devices. [6] WHR from exhaust gases requires the use of a heat exchanger, further reducing efficiency, increasing complexity, and adding to maintenance requirements. One study of TEGs examined the recovery potential of a system of generators recovering energy from the wall of a kiln using a heat exchanger and heating rods to apply a high temperature to one side of the device and a water cooling loop to keep the other side cool. The maximum operating temperature was 250°C, and the devices were operated at an optimal temperature difference of 179°C. [31] The maximum thermoelectric efficiency was about 3.5%, and the maximum output of the system was 48 W. [31]

District heating

A less well developed WHR scheme is district heating. In this application, waste heat is converted to steam or hot water, which is used to heat local buildings. Such systems require sufficient density of heat users to be feasible; they are often supplemental to or supplemented by other heat sources. [33] District heating has been evaluated for a Turkish community, and the conclusion was that about 678 residences could be heated from a cement kiln with average clinker production of 948 tonne/day. [26] This study considered waste heat captured from the surface of the kiln, primarily, rather than exhaust gases. Kilkovsky et al., studied flue gas heat recovery from a waste/biomass incinerator for combined heat and power with applications in district heating. [34] This burner has a similar exhaust gas temperature to cement and lime kilns (low temperature of 250°C). In this example, heat exchangers are used to capture waste heat, which provides steam to a district heating distribution network. The primary difficulty with district heating is distribution, although challenges with contamination of heat exchangers exist as well. [11]

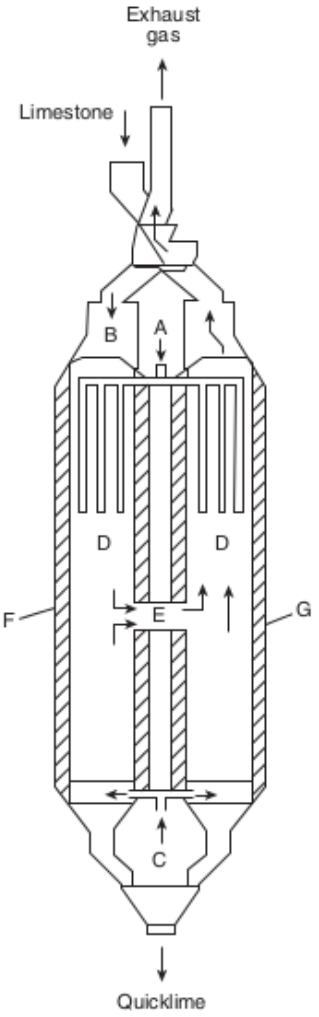

Figure 7-4. Schematic of a parallel flow regenerative kiln. (A) Fuel ports. (B) Combustion air ports. (C) Cooling air inlet. (D) Stacks. (E) Cross-flow duct. (F) Shaft wall one. (G) Shaft wall two. [6]

Recuperators

In lime kilns, shaft burners with recuperators are in use. In an annular shaft kiln presented by Senegacnik et al., exhaust gas excess air was recirculated in a recuperator to preheat combustion air. This system resulted in an overall fuel use reduction of 4.6% for a 150 tonne/day lime kiln. [27] However, this system decreases the overall burn temperature and can result in increased dust accumulation within the kiln. [27]

Clinker cooler heat recovery

Cement clinkers exit rotary kilns at about 1,200°C and are rapidly cooled to about 100°C (82°C in the most efficient systems). [3] To achieve this, cement kilns employ several clinker cooler designs. In each design, large quantities of air are forced past the clinker. The most common cooler designs are reciprocating grate, planetary, and traveling gate (less used). Grate coolers are the most efficient and are the preferred equipment for large-capacity kilns. [3] The air exiting these coolers is at elevated temperature and has been used to heat combustion air or air used for precalciners. Energy savings are between 13.9 and 44.4 kWh/tonne of clinker, depending upon the system and its parameters. [4] Modern reciprocating grate coolers, the most efficient cooler option currently installed, have 70–75% heat recuperation efficiency, with up to 8% fuel consumption reduction possible. [4] The cost of installation of a cooler, according to a 2009 estimate, is between $11 and $13.9/tonne of clinker, with annual plant operation costs increasing by $0.22–0.55/tonne of clinker. [4] However, this is accompanied by a 20% increase in throughput. [4]

Process modification

Another WHR technique used is process modification using waste heat for reduction of CO_2 emissions. One example, the heat contained within exhaust gases from a 6.6 tonne/day lime kiln was used to drive a process that captures CO_2. [28] This technique has only been presented in one case and is undergoing scale-up to a pilot plant. Other sources cite using waste heat for CO_2 capture; however, the cases discussed in these other sources (e.g. [16]) power a capture process using an ORC electrical generator, which was discussed earlier. The process proposed by Slotte et al., [28] uses the exhaust gas waste heat, via a heat exchanger, to drive several endothermic carbonation reactions. A complete description of the process is available in Slotte et al., [28] but is outside the scope of this paper. The system is able to sequester 187 kg of CO_2/h. [28] Although Slotte et al., used a lime kiln, the process could be adapted to other exhaust gas waste heat sources without much ado. Carbon capture potential is limited by available heat, and the efficiency of the system is limited by compressor limitations, heat exchanger limitations, and heat transportation losses.

7.1.3 Barriers and Limitations of Existing Technologies

Many common barriers exist among WHR technologies, as several problematic technologies are shared among the various WHR techniques outlined. The foremost of these is the heat exchanger, which is used in many WHR technologies. Fundamental materials and design challenges limit the effectiveness of these devices in such harsh environments. In the following paragraphs, limitations, barriers, and weaknesses of each of the technologies will be discussed, with a focus upon materials and structural/design concerns.

Raw material preheaters

Although preheaters are ubiquitous among modern rotary cement and lime kilns, the technologies nevertheless have limitations and barriers. The primary barrier is capital expense; while in the long term, charge material preheating reduces the operating cost of a kiln, the capital cost associated with the installation of preheaters is high. The initial cost for installing a preheater was estimated at $25–155/ton of clinker annually, depending upon the kiln setup before installation. [3] In the calculation, adding preheater stages is represented by the low price, and complete retrofitting is represented by the high price. The amount of preheating is limited by the moisture content of the raw material. With moderately wet material (above 8%), fewer preheater stages can be employed; and in the wet production process, options for preheating are further reduced. [3, 20] Preheaters are associated with a pressure drop, as they inhibit flow; so the efficiency of the kiln can be improved with preheater upgrades to be a more modern system with less pressure drop. Decreasing pressure drop increases the efficiency of the system and abates other

difficulties commonly associated with large pressure differentials. Energy is lost from the preheater in the form of radiation and convection; a reduction of these losses with the development of better insulating materials would improve the efficiency of these systems. [3] The environment in which preheaters operate is abrasive, and the exhaust gases contain potentially corrosive species (primarily sulfur). Thus the temperature drop must avoid condensation of these chemicals, limiting the potential heat recovery. An increase in dust due to the installation of preheaters has also been a concern. [3] Similar issues exist with a precalciner; however, the installed cost of a precalciner is typically less than the cost of preheaters, at $8.5 to $26/ton of clinker-annually. [3]

Fuel drying

Fuel drying applies only to coal-fired kilns. Barriers primarily include the efficiency of the dryer and the efficiency of the waste heat capture technique. As the technology is not widely discussed, limited information is available with which to determine barriers and limitations.

Power generation

Power generation using waste heat is primarily limited by the fundamental efficiency of the thermodynamic cycle used. This is governed primarily by the working fluid. Research continues to identify increasing more efficient working fluids for Rankine cycles operating in the temperature ranges required for cement and lime kilns. [35, 36] Barriers to adoption are primarily expense considerations: the capital required is a disincentive to installation of the devices. [36] ORC systems are typically more expensive than steam cycles; the total cost of ORC systems varies between about $2,800 and $5,500/kW, with the specific price inversely dependent upon designed output. [37] For a general waste heat–to-power generating facility (not specifically for cement and lime kilns), power costs (including operating/maintenance and amortized capital costs) are between $0.060 and $0.125 per kWh. [30] Working fluids that are flammable or toxic, relatively lower efficiencies (compared with steam cycles), and a relatively high “back work ratio” (the ratio between pump consumption and turbine output power) inhibit ORC turbines. Steam turbines are a more fully developed technology; however, such systems still are limited by the working fluid boiling temperature (thus the requirement for high-grade waste heat sources for steam cycles). Low working fluid density requires a large installation (due to higher volumetric flow rate) and complex system design, and results in the corrosion of metallic parts. [37] Further limiting the efficiency of these systems is the heat exchanger required to supply energy from exhaust gases.

Heat exchangers

Efficiency-limiting factors in heat exchangers are both structural and material. In moderate- to high-temperature environments (800–1,500°C), materials in heat exchangers are challenged. The large amounts of particulates in cement and lime kiln exhaust gases tend to inhibit heat exchangers. Particulate buildup and fouling on heat exchange surfaces, such as those required for TEG systems, significantly reduce the amount of heat transfer that can occur. [39] At high temperatures, the chemical species present in the exhaust gases react with the material used in the heat exchanger, resulting in corrosion. Operating cycles can accelerate age-hardening and embrittlement of the material. Creep deformation is also a concern, as it can deleteriously affect the structure of the device. [40] Recent development and current research yield high-temperature materials designed for such applications: the effectiveness of both metallic alloys and ceramics in heat exchanger applications has improved. [34, 36, 40, 41] With these advanced materials, care must be taken to select the correct material, coating, and geometric design, although material concerns have been mitigated. [34] Nevertheless, elevated levels of maintenance are required if heat exchangers are employed (Refer to Chapter 3 for material considerations).

Shaft kiln regenerators

Regenerators are only used with shaft kilns. These systems are more expensive than a conventional single-shaft lime kiln. Because the exhaust gases must pass through a crossover channel, poor-quality feed material can cause excessive fouling, resulting in a need for increased maintenance. The systems produced by Maerz operate under pressure and so must be closed during operation, adding complexity and decreasing the effective efficiency. Alternate flow between two stacks and control of a number of parameters require a high degree of active control of the kiln. [9] The kilns operate best with a small stone size range. However, many of these potential barriers are shared among all shaft kilns. Although in some cases it is possible to install a regenerative system with a furnace rebuild, in many cases the only way to install such a system is the development of a new kiln. [9]

Thermoelectric generation

TEGs are hindered by many factors, including efficiency, expense, inability to operate in harsh environment, longevity, and lack of compactness. Contemporary TEG devices have low operating efficiency, less than a 10% heat-to–electrical energy ratio for the most advanced systems, limiting the potential for heat recovery. [5, 25] TEGs also are expensive, primarily owing to the use of exotic and expensive materials and heat exchangers. TEGs operate best when applied to a hot solid; thus a heat exchanger is required, which introduces the limitations of heat exchangers detailed earlier. The particulars of system costs vary depending upon material costs, but the least expensive TEG systems cost about $6,000/kW and the most expensive can be more than $600,000/kW. [32] Further concerns about TEGs include their performance in the harsh environments presented by industrial heat recovery applications. Mechanical concerns (e.g., brittleness, hardness, and compressive and shear strength) are being addressed in ongoing research. [25] Oxidization can significantly affect the operability of TEG devices. The systems must also resist high levels of atmospheric dust and other particulate contaminants. Concerns regarding the ability of TEGs to maintain electrical productivity over a long time period (a prerequisite for investment in the devices) exist as well. The energy generation capacity density of TEG devices is also limited, making them difficult to deploy in significant quantity in industrial applications. [32]

District heating

The primary limiting factor for district heating is infrastructural: waste heat sources must be located proximally to consumer locations. Efficiencies of heat transport vary between 25 and 75%, depending upon travel distance, among other things. [33] Maximum travel distance is often quite limited (e.g., 10 km, perhaps up to 40 km). [33] Further, without preexisting district heating, such a system is often impractical. This combination of factors severely restricts the implementation of these systems. They incorporate heat exchangers and thus experience the difficulties outlined for those devices. A relatively low percentage of the available heat is used in these systems, which have an ~5% capture rate. [9]

Recuperators

Recuperators are typically not employed in rotary kilns, as the exhaust gas port location is substantially removed from the burner, making recuperator implementation impractical. In the shaft kilns used for lime burning, exhaust gas recuperators are employed. Shaft-type kilns in general have lower yield and produce lower-quality lime; this is offset by higher thermal efficiency and larger stone size acceptance. One difficulty with adding a recuperator—in this case, directly employing exhaust gases for preheating—is an increase in dust buildup within the kiln, requiring more maintenance. [27] A mechanical dust separator is required for such a system.

Clinker coolers

Although upgrading clinker coolers for higher heat recovery efficiency is relatively less expensive than, for example, installing a steam generator, the change may be inefficient economically for a plant operating at less than 500 tons/day. [4] Additionally, improving the cooling efficiency may deleteriously affect the emissions and quality of product of the kiln; no specific data for these changes have been identified.

In general, the barriers and limitations associated with WHR for cement and lime kilns are material, structural, and economic. Material limitations include mechanical issues; surface degradation from chemical wear and ablation, high temperatures, and fouling concerns. Structural and infrastructural challenges such as siting, size, feed material, kiln type, and fuel type must be considered. Finally, the payback of any project must justify its expense; this can be a challenge for many novel projects. For example, electrical generating techniques must be able to produce electricity at a net operating cost competitive with grid prices.

7.1.4 Conclusions

Exhaust gas WHR technologies for cement and lime kilns, with a focus on rotary kilns, have been assessed, with a detailed evaluation of the barriers and limitations of these technologies. In each of these industries, waste heat from exhaust gases represents a significant portion (20–30%) of the energy input to the burner. Thus substantial amounts of energy are available for capture. WHR techniques from the extant literature have been identified and enumerated, including electrical generation and raw material preheating/precalcining. Barriers to each technology and its implementation have been outlined, with a focus on material and structural limitations.

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APPENDIX A. WASTE HEAT SOURCES FROM MAJOR INDUSTRIAL SECTORS

APPENDIX A. WASTE HEAT SOURCES FROM MAJOR INDUSTRIAL SECTORS

Table A.1. Exhaust gas temperature and characteristic of exhaust gases from GLASS industry heating processes—equipment

Waste heat source[a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Glass melting and refining furnace exhaust gases			
Regenerative system	400 to 600	750 to 1100	5
Oxy-fuel system	1500 to 1550	2730 to 2820	5
Non regen + other (approximate values)	1500 to 1550	2730 to 2820	5
Conditioning	740 to 1400	1370 to 2550	1
Annealing furnace[a]	500 to 900	930 to 1650	1
Tempering furnace[a]	550 to 700	1020 to 1290	1

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

Table A.1. Exhaust gas temperature and characteristic of exhaust gases from STEEL industry heating processes—equipment

Waste heat source [a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Blast furnace stove exhaust gases	200 to 320	400 to 600	6
EAF exhaust gases	1,500 to 1,700	2,700 to 3,000	5
Ladle preheater exhaust gases [a]	900 to 1,250	1,650 to 2,300	1
Tundish heaters [a]	909 to 1,250	1,650 to 2,300	1
Basic oxygen process	1,250 to 1,700	2,300 to 3,000	5
Reheat furnace (with recuperator) [a]	450 to 550	850 to 1,000	1
Reheat furnace (with regenerative burners) [a]	200 to 400	400 to 750	1
Annealing furnace [a]	600 to 750	1,100 to 1,300	1
Galvanizing—galangal furnace [a]	400 to 600	750 to 1,100	1
Other heat treating [a]	300 to 800	575 to 1,475	1
Gas (combustion) turbine exhaust gases [a]	900 to 1,100	1,650 to 1,830	1
Boiler flue gases	175 to 300	350 to 575	1

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

Table A.2. Exhaust gas temperature and characteristic of exhaust gases from aluminum industry heating processes—equipment

Waste heat source [a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Aluminum industry waste heat sources			
Calcining	300 to 500	575 to 925	5
Anode baking	300 to 500	575 to 925	5
Alumina reduction	<300	<575	5
Melting furnaces (fuel fired)	750 to 950	1389 to 1750	5
Homogenizing furnaces	500 to 600	950 to 1100	1
Annealing furnaces [a]	400 to 500	750 to 900	1
Reheat furnace [a]	400 to 500	750 to 900	1
Aging ovens	150 to 250	300 to 500	1
Drying system with thermal oxidizer (coated products)	150 to 300	300 to 600	1
Gas (combustion) turbine exhaust gases [a]	900 to 1,100	1650 to 1830	1
Boiler flue gases	175 to 300	350 to 575	1

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

Table A.3. Exhaust gas temperature and characteristic of exhaust gases from cement and lime industry heating processes—equipment

Waste heat source [a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Cement and lime industry waste heat sources			
Cement kiln exhaust gases from modern clinker making operations	200 to 500	400 to 950	5
Hot clinker	300 to 600	575 to 1100	6
Lime kiln exhaust gases	200 to 500	400 to 950	5

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

Table A.4. Exhaust gas temperature and characteristic of exhaust gases from petroleum refining industry heating processes—equipment

Waste heat source [a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Petroleum refining industry waste heat sources			
Process heaters	200 to 300	400 to 900	1
Calciners (coke)	300 to 500	575 to 930	2
Flared gases	200 to 400	400 to 750	2
Reactors—crackers	200 to 400	400 to 750	1
Gas (combustion) turbine exhaust gases [a]	900 to 1100	1650 to 1830	1
Waste heat and fuel fired boilers—flue gases	175 to 300	350 to 575	1

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

Table A.5. Exhaust gas temperature and characteristic of exhaust gases from chemical industry heating processes—equipment

Waste heat source [a]	Temperature (°C)	Temperature (°F)	Exhaust gas characteristics (as defined in Table 1.1)
Chemical industry waste heat sources			
Pyrolysis furnaces	200 to 300	400 to 575	1
Process (fired) heaters	200 to 480	400 to 900	2
Reactors (incl. fluidized beds)	200 to 400	400 to 750	2
Thermal oxidizers	300 to 400	575 to 750	1
Gas (combustion) turbine exhaust gases [a]	900 to 1100	1650 to 1830	1
Waste heat and fuel fired boilers—flue gases	175 to 300	350 to 575	1

[a] **Assumes that natural gas or other gaseous fuel or light oil is used as fuel for the burners.**

APPENDIX B. CALCULATIONS FOR RECOVERABLE HEAT FROM SELECTED PROCESSES

APPENDIX B. CALCULATIONS FOR RECOVERABLE HEAT FROM SELECTED PROCESSES

B.1 BLAST FURNACE

The following information is derived from the Institute for Industrial Productivity (IIP) website (www.iipnet.org) [1], which is used for further calculations.

- Typically, blast furnaces (BFs) produce exhaust gases with a low calorific value (~ 3 MJ/Nm3) at a rate of 1,300–2,200 Nm3/t of pig iron. These gases are generally at a pressure of 2–3 bar. After cleaning, BF gas can be used as fuel [2]. The BF exhaust gas temperature leaving the furnace is approximately 392°F (200°C) [3].
- Pig iron production in the US in 2013 was 30.381 million tonne per year [4].
- Average BF gas value used = (1300 + 2200)/2 = 1750 Nm^3/ton of pig iron
- Heating value of BF gas = 92 Btu/scf [5].
- Chemical heat in BF waste gas = 92 × 1750 × 35.31 (cf/Nm^3) = 5.684 MM Btu/ton of pig iron
- Top gas temperature = 392°F or 200°C
- Sensible heat in BF waste gas = specific heat in Btu/(scf. °F) × volume flow rate × (gas temperature— reference temperature)
- BF gas is mostly N_2 and CO. Its volumetric specific heat is approximately 0.025 Btu/scf [6].
- Sensible heat in BF waste gas = 0.025 × 1750 × 35.31 × (392 – 60) = 512,877 Btu/ton of pig iron or 0.51 MMBtu/ ton of pig iron.
- Total recoverable heat = (chemical heat + sensible heat) per ton of pig iron × tons of pig iron produced per year = (0.51 + 5.684) MM Btu/ton × 30.381 MM tons/year = 188.2 MMBtu/year.

Table B.1. Summary of sensible, chemical and total recoverable heat from BFs in USA

Waste heat source	Temperature range (°F)	Characteristics	Production (MM tons/year)	Unit energy use (MM Btu/ton)	% in waste gas (sensible + chemical)	Heat in waste gas /ton of product (MM Btu/ton) —sensible	Heat in waste gas /ton of product (MM Btu/ton) —chemical	Energy in waste gases (TBtu/year)
Blast furnace gases	400 to 600	Contain combustibles, particulates, etc.	30.381	NA	NA	0.51	5.684	188.2

B.2 BASIC OXYGEN FURNACE (BOF)

The BOF steel production value is derived by subtracting the electric arc furnace (EAF) steel production value from the total US steel production. The following method gives the total EAF steel production

value of 31,680 tons/year, equal to about 33% of the total steel production. This value is derived from production figures for EAF steel.

- US steel production (March 2013 to March 2014) — 8,000 tons/month (average of 96,000 tons/year [7].
- EAF production as percentage of total US steel production — 67% [8].
- Based on this, BOF steel production is 33% of the total 96,000 ton/year production in the US for the year 2013.
- According to ref. [1], the gas produced in the BOF has a temperature of approximately 1,200°C and a flow rate of approximately 50–100 Nm^3/t-steel. The gas contains approximately 70–80% CO when leaving the BOF and has a heating value of approximately 8.8 MJ/Nm^3 [3] or 0.84GJ/t of steel [9].
- Chemical heat content = 0.84 GJ/ton or 0.80 MMBtu/ton.
- BOF exhaust gas volume = 75 Nm^3/t of steel or 2,648 scf per ton of steel. This is an average of the range of 50 to 100 Nm^3/t of steel as given above.
- BOF exhaust gas temperature = 1,200 °C or 2,192 °F.
- Specific heat of BOF exhaust gases = 0.025 Btu/sensible heat as stated in BF section above.
- Sensible heat = 0.025 × 2,648 × (2,192 – 60) = 141,138 Btu/ton = 0.14 MMBtu/ton of steel.
- Total heat available for recovery = 0.14 + 0.80 = 0.94 MMBtu/ton of steel
- For total annual production of 31,680 tons/year, total heat available for recovery = 31,680 × 0.94 MM Btu/year or 29,779 MMBtu/year or 29.8 TBtu/year.
- The following calculations give 29.7 TBtu/year, which may be rounding of numbers in one of these calculations.

Table B.2. Summary of sensible, chemical and total recoverable heat from BOFs in USA

Waste heat source	Temperature range (°C)	Characteristics	Production (MM tons/year)	Unit energy use (MM Btu/ton)	% in waste gas (sensible + chemical)	Heat in waste gas /ton of product (MM Btu/ton) –Sensible	Heat in waste gas /ton of product (MM Btu/ton) –Chemical	Energy in waste gases (TBtu/year)
Basic Oxygen Process	1200	Contain combustibles, particulates etc.	31.68	NA	NA	0.141	0.796	29.7

B.3 ELECTRIC ARC FURNACE

During the last three decades, the role of the EAF in steel production in the US has been increasing steadily. During this period, the energy supply for EAFs has changed to increased use of fuels such as natural gas, coal or coke injection, or oxygen injection to reduce use of electricity and energy cost. However, this trend has also resulted in increased off-gas volume and the presence of chemical heat in

off-gases. This has increased waste heat discharge from EAFs. In some cases (for <10% of the total EAFs in the US), the waste heat from EAF off-gases is recovered and used for either scrap preheating or steam generation. In the vast majority (>90% in US) of installations [10], it is common practice to collect EAF exhaust gases, mix them with ambient air to oxidize the combustible materials, and then drop the temperature of the gases to less than 400°F (or 200°C). These relatively low-temperature gases are then passed through a pollution control device such as a baghouse before being discharged into the atmosphere.

The following section describes the methodology used for calculating recoverable waste heat from EAF installations in the US. The data used for these calculations has been derived from various sources.

- Typical temperature range of EAF off-gases — 1,500 to 1,600°C [9, 50].
- US steel production (March 2013 to March 2014) — 8 million tonnes/month (average or 96 million tonnes/year [10].
- EAF production as percentage of total US steel production — 67% [8].
- Energy input = 742 kWh/tonne or 2.535 MMBtu/tonne molten steel.
- Sensible heat in EAF exhaust gases = 16.7% or 0.423 MMBtu/tonne
- Chemical heat in EAF exhaust gases = 21.4% or 0.542 MMBtu/tonne
- Total waste heat in EAF exhaust gases = 0.423 + 0.542 = 0.965 MMBtu/tonne.
- Total waste heat for the EAF industry in USA = 0.965 × 96,000,000 × 0.67 = 62,068,800 MMBtu/year or 62.1 TBtu/year. Details of heat used or wasted and off-gas temperature during a heat are shown in Figure B.1.
- In few cases (for <10% of the total EAFs in the US) the waste heat from EAF off-gases is recovered and used for either scrap preheating or steam generation. As per the electric arc furnace roundup [10], there are total 9 EAFs (7 operational, 1 idled, and 1 under construction) with Consteel scrap preheating system. Also, there are total 9 EAFs (1 EAF is not melting) with shaft, twin shaft, and twin shell type of scrap preheating systems. These EAFs produce 19% of the total steel produced using all EAFs.
- A summary of sensible, chemical and total recoverable heat is given in the following Table B.3.

Table B.3. Summary of sensible, chemical and total recoverable heat from EAFs in US

Waste heat source	Temperature range (°C)	Characteristics	Production (MM tons/year)	Unit energy use (MM Btu/ton)	% in waste gas (sensible + chemical)	Heat in waste gas /ton of product (MM Btu/ton) —sensible	Heat in waste gas /ton of product (MM Btu/ton) —chemical	Energy in waste gases (TBtu/year)
EAF exhaust gases	1,500 to 1,600	Contain combustibles, particulates, etc.	64.32	2.535	38.1%	0.423	0.542	62.1

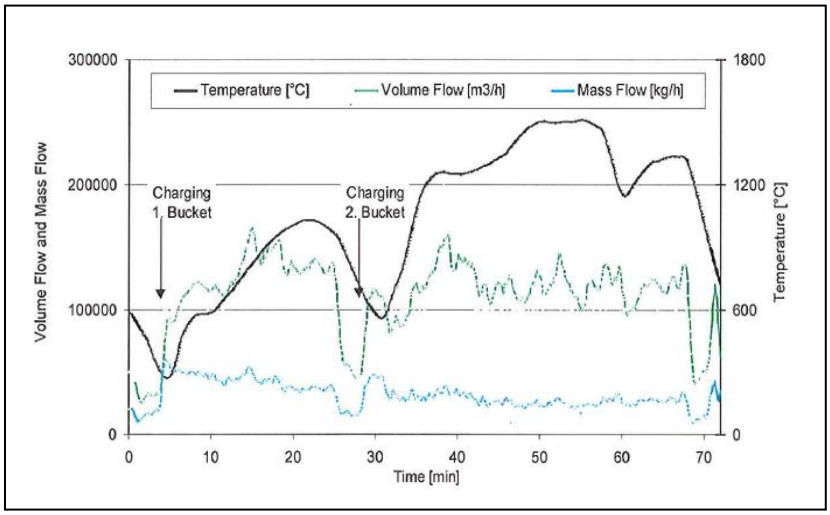

Figure B.1. Details of heat used or wasted and off-gas temperature during an EAF heat. *Source:* [11]*

*Note that there is an error in the summation and this is a corrected figure.

B.4 GLASS MELTING AND REFINING

Glass melting is the largest energy user in various glass manufacturing processes for the glass industry. The glass industry is classified according to main products supplied by a plant. They are flat glass, container glass, glass fiber, and specialty glass. Each of these sectors uses a variety of fuel-fired furnaces. They include regenerative, oxy-fuel, direct-fired (without use of preheated air or oxygen), electrical, or furnaces with electric boost. Each of these furnaces discharges a large amount (from 25 to 70%) of the total heat input as waste heat in the form of hot exhaust gases. These gases contain large amounts of particulates, volatiles and, in some cases, condensable vapors.

The following methodology is used to calculate total recoverable waste heat in the form of harsh environments, mainly from glass melting furnaces.

1. Obtain total energy used by the US glass industry.

2. Calculate how much of this energy is used for glass melting furnaces that produce waste heat in the form of harsh environments.

3. Find distribution of total energy used for glass melting for each of the four glass sectors: flat glass, container glass, glass fiber, and specialty glass.

4. Use the type of furnace or firing used for each of these sectors. The main types of furnaces are regenerative, oxy-fuel, electric (total or boost), recuperative, and direct-fired with no heat recovery.

5. Identify energy intensity for each type of firing or furnace system.

6. Calculate available heat for each furnace type, based on exhaust gas temperature and firing method and use this information to calculate heat losses, which are equal to [energy intensity × (1 – available heat)].

7. Calculate waste heat content in exhaust gases. Note that the glass furnace waste heat stream does not contain any chemical heat. The entire amount of heat is sensible heat.

Total energy used by the glass industry in the US and various process steps, as collected and published by the Energy Information Agency (EIA) of the US Department of Energy (DOE) [12] is given in Figure B.2. The main data point used for the further calculations is the glass industry's total energy consumption—200 TBtu/year (2010 data).

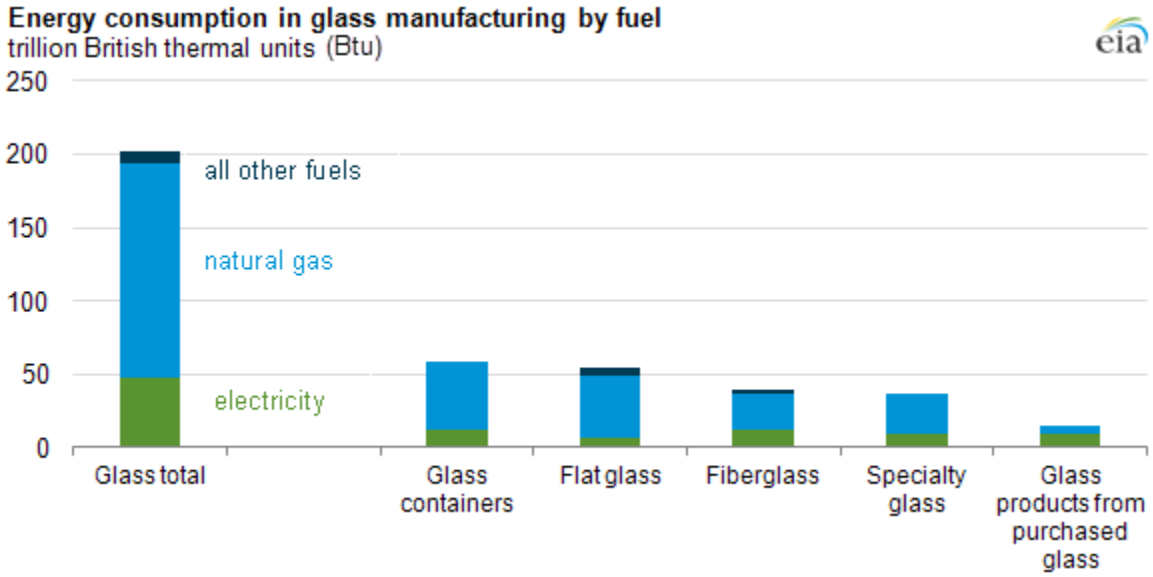

Figure B.2. Energy consumption in glass manufacturing by fuel (2010 data). [12]

The share of melting furnaces is derived by using information developed by Energetics, Inc. [13]; it is given in Table B.4. This information is for the year 2002, so it is used to derive the energy used for melting furnaces as a percentage of the total energy used by the glass industry. The glass melting and refining area in a plant uses almost 49.4% of the total plant energy used. Note that the other plant areas use fuel energy that discharges waste heat at a relatively lower temperature; and that exhaust does not contain significant amounts of constituents that require specially designed heat recovery equipment, as opposed to the gases classified as harsh environments.

Glass production data in million ton/year (MM ton/year) were obtained from an EPA document prepared by Lawrence Berkeley National Laboratory [14] and a DOE report prepared by the Gas Technology Institute [15]. These date are provided in Table B.5. This table also gives the distribution of glass production by the type of furnace or firing system used. This information is used to obtain production

(MM tons/year) data for each type of furnace heating system. The table shows that a large percentage, almost 60%, of glass is melted in regenerative furnaces. The "other" category includes furnaces with straight electric heating and without the use of any type of heat recovery equipment. Nonregenerative systems include furnaces with recuperative heat recovery systems.

Table B.4. Share of energy use by different sectors of the US glass industry [13]

Process step		Annual energy use 10^12 Btu/year		Percentage
Batch preparation		13.7		
	Sub Total		13.7	4.8%
Melting–flat glass		42.9		
Melting–container		53.1		
Melting–pressed-blown		18.1		
Melting–fiber		25.6		
	Sub Total		139.7	49.4%
Forming–flat glass		7.5		
Forming–container		38.4		
Forming–pressed-blown		13.2		
Forming–fiber		21.9		
	Sub Total		81	28.6%
Post forming–flat glass		11.1		
Post forming–container		17.8		
Post forming–pressed-blown		7.5		
Post forming–fiber		12		
Subtotal			48.4	17.1%
Grand total			**282.8**	**100.0%**

Table B.5. Glass production data by various sectors and type of heating system used [14, 15]

	Production [a]		Regen/recup	Oxy-fuel	Nonregen	Other	
Glass industry	MM tons/year	%	% distribution–firing method [a]				Total
Flat glass	5	25%	80%	20%	0%	0%	
Container glass	10	50%	70%	30%	0%	0%	
Specialty glass	2	10%	26%	35%	34%	5%	
Fiber glass	3	15%	10%	35%	0%	55%	
	20	100%					
Production MM ton/year			**11.82**	**5.75**	**0.68**	**1.75**	**20**
% production by each system			**59.1%**	**28.8%**	**3.4%**	**8.8%**	**100%**

[a] Ernst Warrell, Christina Galitsky, Eric Masanet, and Wina Graus, *Energy Efficiency Improvement and Cost Saving Opportunities for Glass Industry*, US Environmental Protection Agency, August 2008

[b] David M. Rue, James Servaites, and Warren Wolf, *Final Report, Industrial Glass Bandwidth Analysis*, Gas Technology Institute, Energy Utilization Center, August 2007.

Total heat in the waste heat stream for each sector of the glass industry and each type of furnace used is calculated using the following steps. Each of these steps, with the source of information used, is given in Table B.6.

- Use share of production in terms of tons/year (expressed as %) and average energy used in terms of MMBtu/ton of glass produced. Note that the table gives a range of energy intensities and an average value.

- Use the exhaust gas temperature from each type of furnace to calculate available heat for the furnace. This represents energy used in the melting furnace as percentage of total energy supply.

- The energy content of the waste heat stream is the difference between heat input and the heat used in the melter. Note that the heat used in the melter includes heat supplied to glass for melting plus all other heat loss, such as wall losses, opening loss, and water cooling loss.

- Based on production, energy intensity, available heat, and heat loss values, we arrive at the total amount of heat in the waste heat stream for each sector of the glass industry and total heat recoverable heat loss for the US glass industry.

Note that these values are based on average values; so they are representative, and the exact amount of waste heat could be somewhat different.

As shown in Table B.6, based on these calculations, the total amount of recoverable heat from glass smelting furnaces is 42.9 TBtu/year.

Table B.6. Waste heat loss from various sectors of the US glass industry

Calculations for waste heat loss from glass melting—refining furnaces (US glass industry)

Industry segment/furnace type	Current estimated share	Average specific energy (MMBtu/ton)	Average	Exhaust gas temperature	Available heat	Ex. gas heat loss	Production	Total waste heat
			MM Btu/ton *	Deg. F. **	***	MM Btu/ton	MM ton/year	TBtu/year
		Flat glass					5	**12.38**
Regenerative	80%	8.5 (6.2-11.8)	8.50	900	68%	2.72		
Oxy-fuel	20%	4.7	4.70	2600	68%	1.504		
Electric boost	0	5.7 (5.1–6.3)	5.70	800	72%	1.596		
Container glass							10	**19.30**
Regenerative	55%	7.5 (4.8–10.2)	7.50	900	68%	2.4		
Electric boost	15%	4.7 (3.3–6.0)	4.70	800	68%	1.504		
Oxy-fuel	30%	4.0 (3.7–4.3)	4.00	2600	68%	1.28		
Electric melter	n.a.							
Specialty glass							2	**7.60**
Regenerative	26%	5.5 (3.8–7.1)	5.50	900	68%	1.76		
Direct melter	34%	12.0 (8.0–16.0)	12.00	2400	28%	8.64		
Oxy-fuel	35%	3.6 (3.0–4.2)	3.60	2600	68%	1.152		
Electric melter	5%	–						

Table B.7. Waste heat loss from various sectors of the U S glass industry (continued)

Calculations for waste heat loss from glass melting - refining furnaces (US glass industry)

Industry segment/ furnace type	Current estimated share	Average specific energy (MMBtu/ton)	Average	Exhaust gas temperature	Available heat	Ex. gas heat loss	Production	Total waste heat
			MM Btu/ton [a]	°F [b]	[c]	MM Btu/ton	MM ton/year	TBtu/year
Glass fiber insulation [d]							1.5	**1.53**
Electric melter	55%	–	–					
Recuperative	10%	7.0 (6.0–8.0)	7.00	1800	44%	3.92		
Oxy-fuel	35%	5.6 (3.4–7.8)	5.60	2600	68%	1.792		
Textile/reinforcement fibers [d]							1.5	**2.12**
Recuperative	25%	10.5 (6.0–15.0)	0.50	1800	44%	0.28		
Oxy-fuel	75%	5.6 (3.4–7.8)	5.60	2600	68%	1.792		
						Total waste heat loss (TBtu/year)		**42.93**

Source: US Department of Energy (2002) [13]; Rue et al., (2006) [15]
[a] Ernst Warrell, Christina Galitsky, Eric Masanet, and Wina Graus, *Energy Efficiency Improvement and Cost Saving Opportunities for Glass Industry*, US Environmental Protection Agency, August 2008.
[b] Average of BCS data [16] and actual measurements at two glass furnaces at container glass manufacturing plant.
[c] Richard J. Reed, North American Combustion Handbook, Vol 1 and vol 2, North American Manufacturing Company 1952 [17].
[d] Assumes 50% each of the total for fiber glass production of 3 MM ton/year.

B.5 ALUMINUM MELTING

There are more than 300 aluminum production plants in the US [16]. These plants consume about 770 TBtu (2.26×10^{11} kWh) of energy per year. Aluminum production is carried out in primary and secondary plants. In each case, aluminum is used in the molten state and involves holding and/or reheating liquid metal from the primary melting site, melting "solid" aluminum in the form of sows or other shapes obtained from the primary plant, melting of in-plant aluminum scrap, or melting of purchased scrap such as used beverage cans and other scrap collected from various sources. Production and use of aluminum in the US has varied significantly during the past 10 years, depending on economic conditions. Currently available data (year 2012) from the Aluminum Association [18] are given in Table B.7. However, the table does not supply data for the value of aluminum metal melted in the US.

Table B.8 Aluminum supply data from Aluminum Association (2012)

Aluminum Supply		
figures in millions of pounds	2012	% of total
Primary Production	10,695	43.5
Secondary Recovery	9,554	38.8
Imports of Ingot & Mill Products	4,361	17.7
Total Supply	24,609	100.0

Source: The Aluminum Association, Aluminium Association of Canada, U.S. Geological Survey, U.S. Bureau of the Census, Natural Resources Canada

It is difficult to obtain exact values for the total weight of aluminum melted, since in some cases aluminum metal is melted or heated several times during the production process. Figure B.3 shows

several steps and processes used by the aluminum and other related industries such as foundries and forging. A telephone conversation with a representative of the Aluminum Association confirmed that data for the exact amount of aluminum metal melting are not available. However, rough estimates were used for many manufacturing operations in which aluminum is melted from primary and secondary sources such as plant scrap and other scrap (e.g., used beverage cans, transportation equipment scrap, appliance scrap). Figure B.3 shows several inputs to the melting operation for which exact data are unavailable at this time.

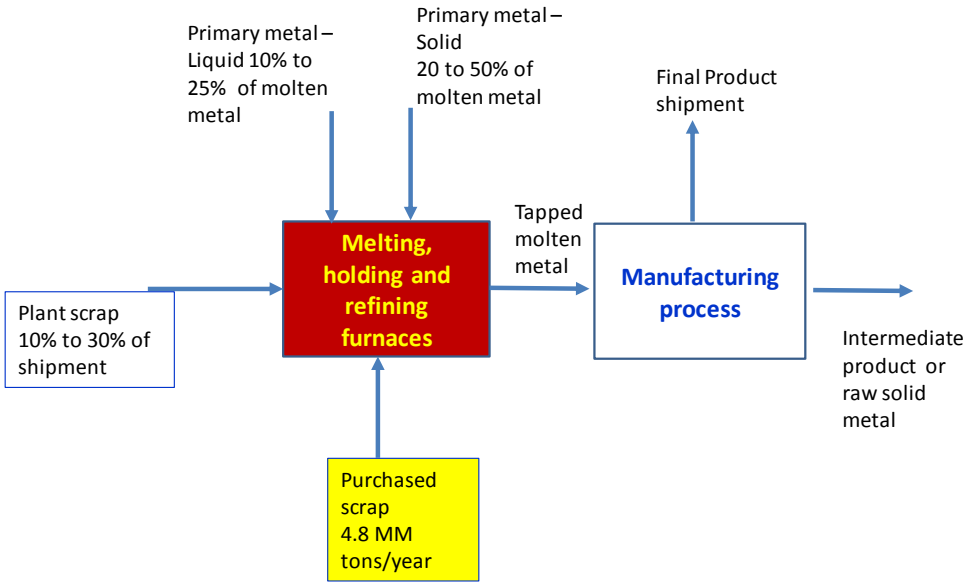

Figure B.3. Aluminum melting furnace—charge material sources.

An additional data source that can be used to estimate the amount of aluminum melted by secondary aluminum plants in the US is information on the capacity of various plants. *Light Metal* magazine publishes a list of all known secondary aluminum plants in the US [19]. It lists 500 secondary aluminum plants and the metal melting capacity for about 170 plants. No data are available for the remaining 330 plants. The total capacity listed in this database is 10.9 million tons/year. In addition to this figure, many foundries melt metal for cast products, and their capacity is not accounted in the database.

Based on this background information, it is estimated that the actual amount of metal melting is between a minimum of 4.8 MM ton/year and 10.9 MM ton/year. The following calculations are based on a figure of 10 MM ton/year of molten metal for the US. The waste heat values could change as more accurate data become available.

Commonly used aluminum alloys melt at about 678°C (1,254°F) and are usually poured at 29 to 50°C (84.2 to 122°F) above the melting point. The temperature of flue gases from aluminum melting furnaces range from 1,038 to 1,204°C (1,900 to 2,200°F). This results in a very large amount of energy content (sensible heat) for the flue gases. During melting of charge material, several flux materials such as NaCl and KCl are mixed with the molten scrap in the furnace to separate impurities and prevent oxidation of the aluminum in the furnace [16]. The temperature range for flue gases can result in as much as 60% of the energy input being lost to flue gas waste heat, depending on the furnace design and operation. This is evident from data presented for two typical heat balances carried out for aluminum melting furnaces during DOE energy assessments (Figure B.4) [20].

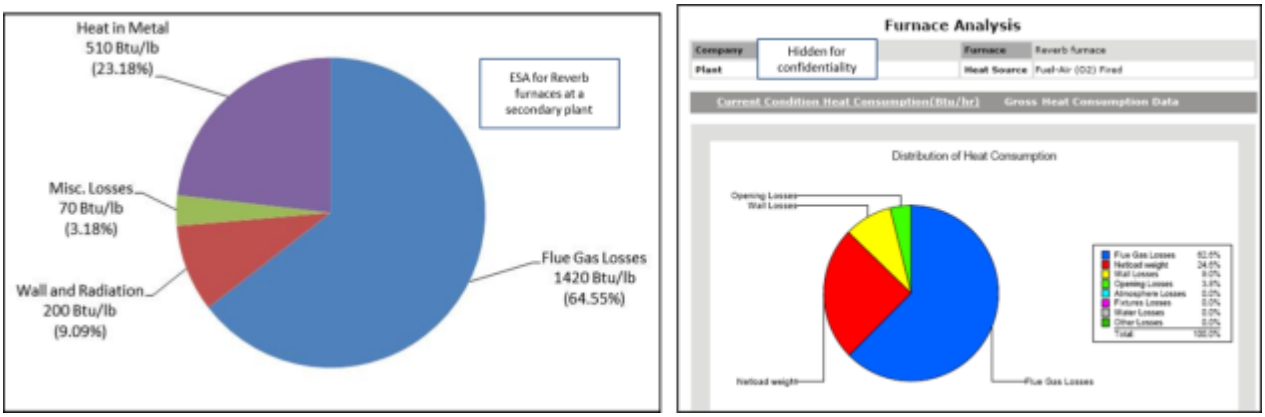

Figure B.4. Typical heat balances carried out on aluminum melting furnaces during US DOE energy saving assessments. [20]

- On average, flue gases contain 50 to 70% of the total furnace heat input [16].
- Energy use for aluminum melting varies from 1,200 to 3,000 Btu/lb [20].
- One of the heat balances shows an energy use of 2,200 Btu/lb of molten metal. For calculations of waste heat, this report used an average value of 2,100 Btu/lb energy required for a melter not using any heat recovery.
- Reference [21] shows a melting energy use between 1,800 Btu/lb at full production and 2,800 Btu/lb at low production conditions.
- Reference [21] shows 1,800 to 1,900 Btu/lb.
- Based on these values, 1,800 Btu/lb was used as an average value.

The heat loss in exhaust gases is calculated by using exhaust gas temperatures from aluminum melting furnaces that do not use any heat recovery equipment and from those using recuperators and regenerative burners.

The population of furnaces using each of the three different types of heating systems was derived based on one-on-one discussions with a combustion equipment supplier (Bloom Engineering) [22]. The discussions included typical exhaust gas temperatures, as listed in Table B.6, and average values of excess air. Note that almost all aluminum melting furnaces are semi-continuous since the liquid metal is tapped at a certain frequency and continuously. This results in changes in the firing rate (burner input) and air-fuel ratio. This factor and changes in air leakage in the furnace due to negative pressure at the low firing rate result in a high oxygen percentage or high "apparent" excess air. A value of 30% was used for these calculations. Heat in exhaust gases was calculated based on the calculation of available heat from the heating system (furnace) and the amount of heat left in the exhaust gases. The available heat and corresponding heat in exhaust gases depend on the exhaust gas temperature, excess air, and combustion air temperature used for each type of heating system. Note that the control volume includes the furnace and heat recovery equipment. Total aluminum liquid metal production is based on the population of furnaces using each of the three types of heating systems.

Exhaust gas heat loss calculations include the following steps:

- Heat input used per lb of liquid metal.
- Calculation of available heat using the information discussed above.
- Calculation of heat in exhaust gas per lb of liquid metal using the following equation:
    - Heat in exhaust gas per lb = (heat input per lb) × (1– available heat %)
- Total heat in exhaust gases = Heat in exhaust gas per lb × total metal produced per year based on furnace population.

Note that the exhaust gases from aluminum melting furnaces do not contain significant amounts of chemical heat. Only in rare cases, while the furnace is not operating properly, it is possible to detect high values for combustibles and hence the presence of chemical heat in exhausts gases. These are unaccounted for in these calculations.

Table B.8 summarizes the results of these calculations. It shows that the estimated waste heat content in exhaust gases from aluminum melting furnaces in the US is 15.88 TBtu/year.

Table B.9. Estimate of exhaust gas heat from aluminum melting furnaces in the US (2012 data)

Aluminum metal melted—secondary melting	**Million tonne/year**	**10.00**	**[18] See text for source and explanation**		
Item		**Non recup.**	**Recup.**	**Regen.**	**Comment**
Flue gas temp at the stack after heat recovery equipment		1700	1000	700	Avg. for regen
Comb air temp ()F)		80	80	80	
% excess air average		30%	30%	30%	
Average heat		45%	65%	70%	From avg. heat graphs
Flue gas losses		55%	35%	30%	
% of total population		65%	25%	10%	
Production from each category of furnace MM tons/year		6.50	2.50	1.00	
Heat in flue gases based on energy use, production and heat loss TBtu/year		12.87	2.36	0.65	
Total flue gas loss	**For the furnace population**		**15.88**		**TBtu/year**
Average value—flue gas loss %	**For the furnace population**		**48%**		%
Energy use per lb of molten aluminum metal tapped					
Item	Type of furnace	Btu/lb.	Notes		
Average energy use for melting	Non-recuperative furnaces	1,800	Baseline—see text for explanation		
	Furnaces with recuperators	1,350	Fuel saving—25% based on exhaust gas temperature		
	Furnaces with regen. burners	1,080	Fuel saving—40% based on exhaust gas temperature		

B.6 ANODE MAKING

Carbon anodes are used in the electrolysis of alumina to carry the electrical current used in the process. Anodes are made using petroleum coke and tar-pitch. The manufacturing process requires baking of the anodes between 1,250 and 1450°C (2,280 and 2,640°F). The heating system is a ring furnace (Figure B.5), which itself can be considered as a counter-flow heating system to maximize the use of the heating value of tar and pitch and minimize fuel use. The process results in exhaust gases that are at high temperatures and contain large amounts of particles and combustible gases with a fairly high heating value. Currently, the heat content of these gases is not used.

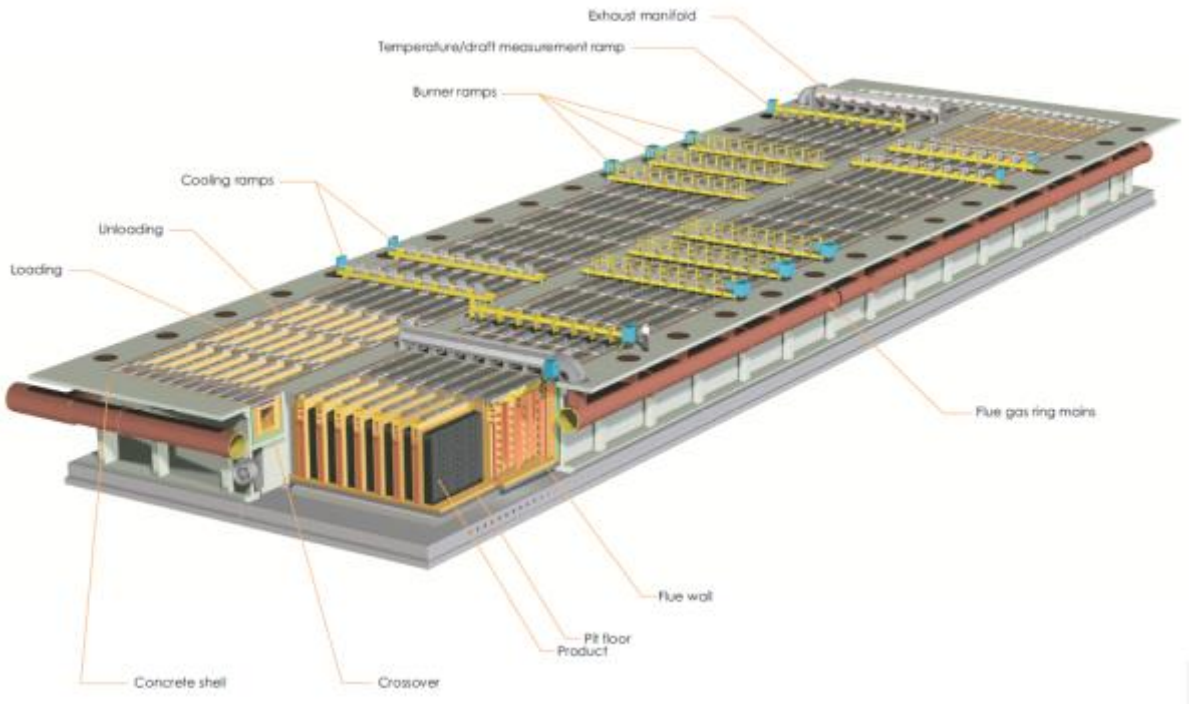

Figure B.5. Design of an open top anode baking furnace. [23]

The following calculations were used to estimate the total recoverable heat from anode baking facilities.

The calculations are based on available information for anode use per kg of aluminum metal produced (0.415 lb of anode per lb of aluminum produced) as given in ref. [24]. The energy required (external, not accounting for volatiles from the "green" or unbaked anode, is 2.57 GJ/metric ton of anode or 2.18 MMBtu/ton of anode [25]. The other required information in the following list also was obtained from ref. [25].

- Exhaust gas temperature: 300°C (572°F).
- Heat in exhaust gas (average of three readings): 1 GJ/metric ton or 0.85 MMBtu/metric ton of anode.
- This represents 39% (= 0.85 MM Btu in exhaust gas /2.18 MMBtu input per metric ton of anode) of the heat input in the kiln.

- Primary aluminum production in US (year 2012) = 5.35 MM ton/year (from Aluminum Association) [18].

- Anodes required for production = 5.35 × 0.415 = 2.22 tons/year.

- Heat in exhaust gases = 1.88 TBtu/year (2.22 MM tons anode/year × 0.85 MMBtu of heat in exhaust gases per metric ton of anodes). A summary of these calculations is given in Table B.9.

Table B.10. Waste heat in exhaust gases from anode baking furnaces

Anode production energy requirement and waste heat in exhaust gases		
1 kg aluminum requires . . .		
($2Al_2O_3 + 3\ C = 4\ Al + 3CO_2$)	0.415	kg of carbon
Energy required for anode baking	2.57	GJ/tonne of anode
	2.18	MM Btu/US ton
Exhaust gas temperature	300.00	°C
Heat in exhaust gases—metric units	1.00	GJ/metric ton of anode—average of 3 readings
Heat in exhaust gases —US units	0.85	MMBtu/US ton of anode
Heat in exhaust gases	39%	As percentage of fuel input (not including heat of volatiles)
Primary Al production	5.35	MM ton/year, according to Aluminum Association
Anodes required–produced	2.22	MM tons/year
Heat in exhaust gases	1.88	TBtu/year

B.7 CEMENT INDUSTRY

Cement production involves production of clinker in a rotary kiln. The clinker making process uses almost all of the fossil fuel used in a cement plant [25].

Until ~20 years ago, cement production in the US primarily used the wet process. However, during the last two decades, almost all production has been by the dry process using rotary kilns with precalciners and several stages of preheaters. According to data from the US Geological Survey (USGS) ([26]), US cement production has been declining; for the year 2013, total cement production was 77.2 MM tons/year. The corresponding clinker production was 69.3 MM ton/year. Based on data from DOE's 2010 Manufacturing Energy Consumption Survey (MECS) [27], the energy intensity of the cement (and clinker) production process was 235 TBtu/year for clinker production of 59.8 MM ton/year. The survey sets the energy intensity for clinker production in the US at 3.92 MMBtu/ton of clinker. Warrell et al., [28] give an energy consumption of 2.7 to 3.0 MM Btu/ton for "the most efficient" kilns using four to five preheater stages. Very few plants in the US, because of their age, use four to five preheater stages. Using these two sets of values, this report arrives at an average value of 3.5 MMBtu/ton as the energy intensity of US plants.

The kiln exhaust gases contain large amounts of CO_2 and water vapor (~30% of the exhaust gases) from moisture in the raw material. Both of these gases have a high specific heat, resulting in much higher heat content than combustion products from coal or natural gas combustion.

Flue gas from the kiln contains dust, commonly known as cement kiln dust, and several gaseous components such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), hydrogen chloride (HCl), and volatile organic compounds, all of which are subject to regulation by the Environmental Protection Agency (EPA). The SO_2 content of the flue gas is a function of the sulfur content in the fuel and the mineral raw materials, as well as the design and operating conditions of the cement kiln. When medium- or high-sulfur coal is used as the fuel, the SO_2 content of the flue gas is likely to exceed air-quality-emission limitations. The active ingredients of cement kiln dust are primarily the oxides of calcium, magnesium, and potassium. In addition, there are considerable amounts of inert compounds, such as silica, as well as traces of carbon resulting from incomplete fuel combustion.

All of these factors make it extremely difficult to use conventional WHR equipment in these plants without encountering major operating and maintenance issues. It is necessary to develop equipment that uses proper design and materials to reduce the operating and maintenance problems.

Waste heat from clinker production comes from two major sources: kiln exhaust gases and clinker cooler air. In modern plants in countries such as China and India, this waste heat is recovered by using various heat recovery methods, including power generation. However, very few plants in the US can justify capital investments for power generation from waste heat.

The average waste gas temperature given in a BCS, Inc., report [16] is from 640 to 840°F. Typically, the clinker coolers release large amounts of heated air at 250 to 340°C (480 to 645°F) directly into the atmosphere [28]. At the kiln charging side, the 300 to 400°C (570 to 750°F) kiln gas coming off the preheaters is typically used to dry material in the raw mill and/or the coal mill and is then sent to electrostatic precipitators or bag filter houses to remove dust before it is finally vented to the atmosphere. The amount of waste heat available for recovery depends on kiln system design and production, the moisture content of the raw materials, and the amount of heat required for drying in the raw mill system, solid fuel system, and cement mill.

For commonly used preheater kilns, according to a report from the International Finance Corporation [29], the waste heat is 0.904 GJ/tonne of clinker produced. Table B.10 shows the calculation method used to estimate the total waste heat from cement kilns.

Table B.11. Parameters used for calculation of waste heat from kilns in cement industry

Clinker production (MM TPY)	69.3	From 2014 USGS data [26]
Waste heat GJ/tonne of clinker	0.904	From IFC June 2014 report [29]
Waste heat MMBtu/tonne of clinker	0.77	Calculated
Heat in waste gases (TBtu/year)	53.02	Calculated

Note that this value is substantially lower than the value given in a BCS report [16], which uses a cement production value of 99 MM ton/year for 2005. Cement production in the US has declined significantly and is at 77 MM tons/year with clinker production of 69.2 MM ton/year. In addition, because of energy saving measures taken during the past 9 years, the amount of waste heat value has declined considerably.

B.8 LIME INDUSTRY

Quicklime is produced by the thermal decomposition of limestone. It consists mainly of calcium oxide, with magnesium oxide as a secondary component. Limestone is a high-purity, high-calcium or dolomitic limestone containing of at least 95% mass of total carbonate (CaCO3+MgCO3). Normally used quicklime is produced by providing heat at temperatures >900°C (1,650°F) to dissociate calcium and magnesium carbonates into their respective oxides and CO_2. Calcination of calcium carbonate is a highly endothermic reaction, requiring 3.16 GJ of heat input to produce a tonne of lime (CaO). The reaction begins only when the temperature is above the dissociation temperature, typically between 1,440 and 2,450°F (780 and 1,340°C), of the carbonates in the limestone or lime mud.

According to the USGS [30], lime production in the US has been steadily increasing, with a total production of 19 MM tonne or 20.9 MM ton per year by the year 2013.

Based on the 2010 MECS survey data [12], energy use in 2010 for the lime industry was approximately 96 TBtu/year. Production of lime in 2010, according to USGS, was 18.3 million tonne/year. Note that the data used are for the year 2010 for consistency of energy intensity calculations. Based on these data, energy intensity or use for lime production is 5.24 MMBtu/tonne. As shown in Table B.11, energy use is 5.5 to 13.0 GJ/tonne lime for commonly used lime kilns (short rotary kilns and long rotary kilns) and 7.2 GJ/t in Canada [31] and in lime kilns in US pulp mills [32]. (A tonne is a metric ton, 2,240 lb, rather than a US ton, 2,000 lb.)

Table B.12. Energy intensities of commonly used lime kilns [33]

Design of kiln	Energy use range (GJ/tonne)
Long rotary kilns (typically with no preheat)	7.0 – 13.0
Rotary hearth kilns (calcimatic)	6.0 – 9.0
Short rotary kilns (typically with preheaters)	5.5 – 8.0
Shaft or vertical kilns	5.0 – 7.0
Double shaft or annular shaft kilns	4.0 – 4.5

Source: Canadian Lime Institute, Energy Efficiency Opportunity Guide in the Lime Industry, 2001.

Based on these data, for the US and Canada, energy use can be approximated as 6.09 MMBtu/US ton.

Waste heat loss from kilns depends on many variables, including type of fuel used, combustion practices, kiln design, and operating condition. The best available information is provided by Moffat and Walmsley [34], which indicates flue gas losses as 32% of the total heat input (Figure B.6).

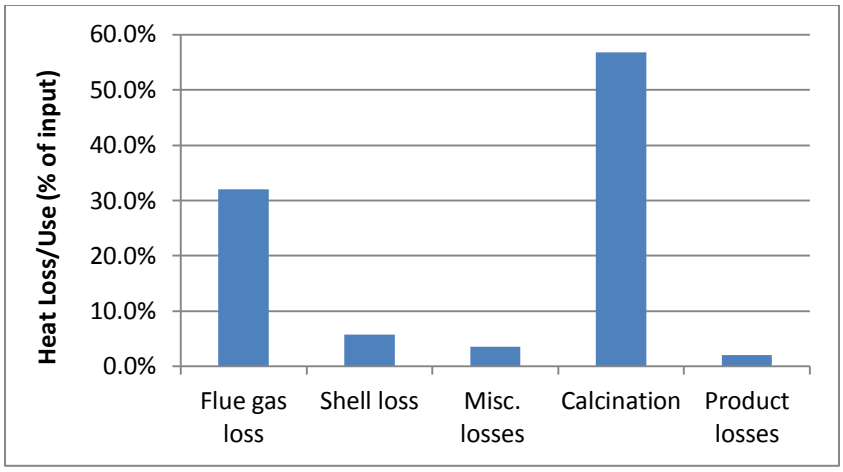

Figure B.6. Heat balance on a typical lime kiln [34].

The following calculations, based on the data presented above, are used to calculate the total recoverable heat content of the waste heat in exhaust gases from lime kilns.

Total lime production in the US (2013) = 20.9 MM ton/year
Energy intensity used = 6.09 MMBtu/ton
Total energy used = 20.9 × 6.09 = 127.28 TBtu/year
Exhaust gas loss = 32% of the heat input
Exhaust gas heat loss for the US lime industry = (32/100) × 127.28 = 40.73 TBtu/year

The calculations are summarized in Table B.12.

Table B.13. Calculations for waste heat loss for the US lime industry (2013)

Item and units	Value	Year 2013 data
Lime production (MM ton/year)	20.90	From 2014 USGS data [26]
Energy intensity (MMBtu/ton)	6.09	Average (5.5 to 8.0 GJ/tonne) from various sources—see Chapter 7 of this report for details
Total energy used (TBtu/year)	127.28	Calculated from data in Appendix B8 of this report
Exhaust gas losses (% of total input energy)	32%	Data from a reference—see Chapter 7 of this report
Waste heat loss (TBtu/year)	40.7	Calculated from data in Appendix B8 of this report

Depending on the type of kiln used, the exhaust gas temperature is in the range of 150 to 350°C (300 to 660°F) [35].

The kiln exhaust gases contain large amounts of CO_2 and water vapor (almost 50% of the exhaust gases) from moisture in the raw materials. Both of these gases have a high specific heat, resulting in much higher heat content than in combustion products from coal or natural gas combustion.

Flue gas from the kiln contains dust and several gaseous components such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), hydrogen chloride (HCl), and volatile organic compounds, all of which are subject

to EPA regulation. The SO_2 content of the flue gas is a function of the sulfur content in the fuel and the mineral raw materials, as well as the design and operating conditions of the cement kiln. When medium- or high-sulfur coal is used as the fuel, the SO_2 content of the flue gas is likely to exceed air-quality-emission limitations. The active ingredients of the kiln dust are primarily oxides of calcium, magnesium, and potassium. In addition, there are considerable amounts of inert compounds, such as silica, as well as traces of carbon resulting from incomplete fuel combustion.

All of these factors make it extremely difficult to use conventional WHR equipment in these plants without encountering major operating and maintenance issues. It is necessary to develop equipment that uses proper design and materials to reduce the operating and maintenance problems.

Table B.13 provides a summary of waste heat sources.

Table B.14. Waste heat recovery potential from selected harsh environment waste gas streams

Criteria: Exhaust gases considered either >1200°F (650°C) and/or containing combustibles and contaminants

Industry	Waste heat source	Temp. range (°F)	Characteristics	WHR technology/system status	Production** (MM tons/year)	Waste Heat Recovery Potential TBtu/year*			Ex. gas flow
						Sensible	Chemical	Total	
Steel	Blast furnace gases	400 to 600	Contain combustibles, particulates, etc.	Available and widely used, partial WHR	30	15.49	172.69	188.2	Constant
	EAF exhaust gases	2,700 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used, partial WHR	64.32	27.21	34.86	62.1	Varying
	Basic oxygen process	2,250 to 3,000	Contain combustibles, particulates, etc.	Available, not widely used, partial WHR	31.68	4.47	25.22	29.7	Varying
Glass	Flat glass	800 to 2,600	Contain particulates, etc.	Available for air-fuel combustion only and widely used, partial WH***	5.00	12.38	Negligible	12.4	Constant
	Container glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and widely used, partial WHR***	10.00	19.30	Negligible	19.3	Constant
	Fiber glass (all types)	1,800 to 2,600	Contain particulates, condensable vapors, etc.	Available for air-fuel combustion only and partially used, partial WHR***	3.00	3.65	Negligible	3.7	Constant
	Specialty glass	800 to 2,600	Contain particulates, condensable vapors, etc.	Available for partial heat recovery but rarely used.	2.00	7.60	Negligible	7.6	Constant
Aluminum	Al melting furnaces (fuel fired)	1,400 to 1,700	Contain combustibles, particulates, etc.	Available, not widely used, partial WHR	10.00	15.88	Small/site specific	15.9	Constant
	Anode baking	570 to 930	Contain combustibles, particulates, polycyclic organic matter, etc.	Available but NOT demonstrated	2.22	1.88	Small/site specific (unknown)	1.9	Constant
	Calcining	570 to 930	Particulates, fuel combustion products, etc.	Available but NOT demonstrated			Data not available at this time		
Cement (Clinker)	Cement kiln exhaust gases from modern clinker making operations	390 to 750	Exhaust gases contain particulates, etc. Relatively easy to handle	Available, not widely used, partial WHR	69.3	53.02	Negligible	53.0	Constant
Lime	Lime kiln exhaust gases based on commonly used rotary kiln type operations	390 to 1,100	Exhaust gases contain particulates, etc. Relatively easy to handle	Available, not widely used, partial WHR	20.9	40.7	Negligible	40.7	Constant
							Grand total	**434.4**	

* For few waste heat sources (particularly in steel, aluminum, and glass industry), a small quantity of waste heat is already being recovered using the existing WHR technologies.
** Production data for steel industry is from 2013, glass industry 2002, aluminum industry 2012, and for cement and lime industry production data is from 2013.
*** WHR technologies currently not available/used for oxy-fuel fired systems.

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