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Improving Process Heating Systems Performance

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SECTION 1: PROCESS HEATING SYSTEM BASICS

Overview

Process heating is essential in the manufacture of most consumer and industrial products, including those made out of metal, plastic, rubber, carbon fiber, concrete, glass, and ceramics. Process heating systems can be broken into three basic categories:

Fuel-Based Process Heating

With fuel-based systems, heat is generated by the combustion of solid, liquid, or gaseous fuel, and transferred either directly or indirectly to the material. The combustion gases can be either in contact with the material (direct heating), or be confined and thus be separated from the material (indirect heating, e.g., radiant burner tube, retort, muffle). Examples of fuel-based process heating equipment include furnaces, ovens, kilns, lehrs, and melters. Within the United States, fuel-based process heating (excluding electricity and steam generation) consumes 5.2 quads of energy annually[1], which equals roughly 17% of total industrial energy use. Typically, the energy used for process heating accounts for 2% to 15% of the total production cost.[2]

Electric-Based Process Heating

Electric-based process heating systems (often called electrotechnologies) use electric currents or electromagnetic waves to heat materials. Direct heating methods generate heat within the work piece itself, by either (1) passing an electrical current through the material, (2) inducing an electrical current (eddy current) into the material, or (3) exciting atoms and/or molecules within the material with electromagnetic fields (e.g., Radio frequency (RF), Microwave (MW).

Indirect heating methods use one of these three methods to apply heat to the work piece surface or to a susceptor material which transfers the heat to the work piece by either conduction, convection, radiation, or a combination of these.

Steam-Based Process Heating

Steam systems, covered in a separate sourcebook, account for about 30% of the total energy used in industrial applications for product output. These systems can be indispensable in delivering the energy needed for process heating, pressure control, mechanical drives, separation of components, and production of hot water for process reactions. Steam has several favorable properties for process heating applications. Steam holds a significant amount of energy on a unit mass basis (between 1,000 and 1,250 British thermal units per pound [Btu/lb]). Since most of the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature, which is a useful attribute in many process heating applications. Steam-based process heating has low toxicity, ease of transportability, and high heat capacity. For more information on steam process heating systems, see the DOE sourcebook *Improving Steam System Performance: A Sourcebook for Industry*.

Hybrid systems use a combination of process heating systems by using different energy sources or different heating methods of the same energy source. Infrared, in combination with a convection oven is a hybrid system. A paper- drying process that combines infrared technology with a steam-based drum dryer is also a hybrid system.

Efficiency and Energy Intensity Opportunities

Energy efficiency refers to the activity or product that can be produced with a given amount of energy; for example, the number of tons of steel that can be melted with a megawatt hour of electricity. Energy

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[1] A quad is a unit of energy equal to 1 quadrillion British thermal units.

[2] *Roadmap for Process Heating Technology: Priority Research & Development Goals and Near-Term Non-Research Goals To Improve Industrial Process Heating*, Industrial Heating Equipment Association, U.S. Department of Energy, Capital Surini Group International, Inc., Energetics, Inc., 2001.

Intensity is measured by the quantity of energy required per unit output or activity, so that using less energy to produce a product reduces the intensity. In this example, energy intensity is the number of megawatt hours used to melt one ton of steel. The difference between efficiency and energy intensity is insignificant, as one is simply the inverse of the other. Having a goal to improve efficiency or reduce energy intensity puts you on the correct path for process improvements.

Approaches to improve a certain heating operation might be applicable to multiple processes To identify synergies and encourage improvements by technology and knowledge transfer, opportunities common to industry segments, applications, and, where possible, equipment type, are identified in this sourcebook. References to further reading and other information sources are given where appropriate.

In some cases, a process heating requirement can be eliminated altogether. For example, there is a current trend to use chemicals that do not require heating to be effective in washing systems used to clean metals parts prior to painting operations.

Many companies focus on productivity related issues. While productivity and output are clearly important, significant energy cost savings are also achievable in industrial process heating systems, and these opportunities are often overlooked. One of the goals of the sourcebook is to build awareness of the economic benefits resulting from the improvement of the energy efficiency of these systems.

Since process heating system performance is fundamental to the quality of a wide range of finished products, efficiency and performance must be considered together. In order to identify system improvement opportunities, it is helpful to understand some common losses and avoidable costs. Performance improvement opportunities are described in Sections 2 through 4, in the tip sheets in Appendix B, and in the technical briefs in Appendix C. The reader is also encouraged to seek greater technical detail in other resources, such as those listed in the "*Where to Find Help*" section. Due to a wide range of operating characteristics and conditions, the guidelines and recommendations given in the sourcebook tend to be fairly general. The intent is to help industry identify and prioritize potential improvement opportunities, and implement projects that are technically and economically feasible.

Systems Approach

Depending on the process heating application, system sizes, configurations, and operating practices differ widely throughout industry. For a given system, there are usually a variety of improvement opportunities. In order to achieve maximum improvement at the lowest cost both, a systems approach and individual component analyses should be used.

A systems approach provides a tops-down review of the entire process and how the individual components perform and interact with each other. An important part of this approach is to create process flow diagrams which show the movement of materials and energy throughout the system. This not only gives a birds-eye view of the entire process but also allows the ranking of components according to their importance for efficiency opportunities, and how changing one component may affect the others. Most importantly, the exercise highlights the confidence in the data and therefore what additional measurements are needed.

Next, the individual components, determined to be the most important from the system's approach, are carefully analyzed to determine their detailed performance and ways to improve their efficiency.

Finally, an iterative step is taken in which the component's new performance is fed back to the system's approach analysis to determine the true improvements when interactions among all the components are evaluated.

The benefits of a systems approach can be illustrated through the following example. Operators often focus on the immediate demands of a particular process step, but underestimate the effects of a particular setting on the long-term performance of the equipment, or other processes downstream. A systems approach would take those effects into account, and weigh them against each other to achieve optimum overall performance. The operator might notice a product problem related to temperature and might make an adjustment as a quick fix instead of finding the root cause in the system, such as poor insulation.

Poor insulation might reduce a process heating system's efficiency, thereby increasing the amount of energy needed to perform a given process heating task. In addition to an increased cost for energy, the system is exposed to higher stress, which can accelerate wear and subsequently lead to more frequent breakdowns. Other side effects can be reduced product quality and increased maintenance.

Other examples are short-term fixes, including replacements and routine maintenance, which might require multiple partial upgrades of an aging infrastructure. Short-term fixes can increase the complexity of a system, lower its reliability, and effectively block improvements that have the potential to lead to substantial long-term gains.

Basic Process Heating Operations

Process heating is used in many industries for a wide range of applications, which often comprise multiple heating operations. The manufacture of steel often involves a combination of smelting, metal melting, and various heat treatment steps. The fabrication of polymers typically employs fluid heating to distill a petroleum feedstock and to provide heat for a curing process to create a final polymer product.

Common to all process heating applications is the generation and transfer of heat. In general, they can be grouped into 14 major categories:

Agglomeration and Sintering

Agglomeration and sintering refers to the heating of a mass of fine particles (e.g., lead concentrates) below the melting point to form larger particles or solid parts. Sintering is commonly used in the manufacturing of advanced ceramics and the production of specialty metals.

Calcining

Calcining is the removal of chemically bound water and/or gases, such as carbon dioxide, through direct or indirect heating. Common applications include construction materials, such as cement and wallboard, the recovery of lime in the kraft process of the pulp and paper industry, the production of anodes from petroleum coke for aluminum smelting, and the removal of excess water from raw materials for the manufacture of specialty optical materials and glasses.

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Curing

Curing is the controlled heating of a substance to promote or control a chemical reaction; in the manufacture of plastics, curing is the cross-linking reaction of a polymer. Curing is a common process step in the application of coatings to metallic and nonmetallic materials, including ceramics and glass.

Drying

Drying is the removal of free water (water that is not chemically bound) through direct or indirect heating. Drying is common in the stone, clay, and glass industries, where the moisture content of raw materials, such as sand, must be reduced; and in the food processing, textile manufacture, and chemical industry, in general. There are several types of industrial dryers, including conveyor, fluidized bed, rotary, and cabinet dryers.

A rotary dryer for the removal of free water

Fluid Heating

Fluid heating is used to increase the temperature of a liquid or gas, including the complete or partial vaporization of the fluid, and is performed for a wide range of purposes in many industries, including chemicals, food processing, and petroleum refining. In chemical manufacturing, fluids are heated in both batch and continuous processes to induce or moderate a chemical reaction. Food processing applications include cooking, fermentation, and sterilization. In petroleum refining, fluid heating is used to distill crude oil into several component products.

Fluid heating in a petroleum process heater

Forming

Forming operations, such as extrusion and molding, use process heating to improve or sustain the workability of materials. Examples include the extrusion of rubber and plastics, the hot-shaping of glass, and plastic thermoforming.

Heating and Melting: High-Temperature

High-temperature heating and melting is conducted at temperatures higher than most steam-based systems can support (above 400˚F, although very high-pressure steam systems support higher temperatures and are used in applications like petroleum processing). High-temperature heating is typically performed on metals, but this category does not include metals reheating or heat treating (see below).

High-temperature melting is the conversion of solids to a liquid by applying heat, and is common in the metals and glass industries. Melting can be combined with refining processes, which demand the increase of temperature to remove impurities and/or gases from the melt. Metal melting processes comprise both the making of the metals, such as in the conversion of iron into steel, and the production castings. Energy-intensive nonmetal melting applications include container and flat glass production.

Heating and Melting: Low-Temperature

Low-temperature heating and melting is done at temperatures that steam-based systems can support (less than 400˚F), although not all applications are steam-based. Nonmetallic liquids and solids are typically heated or melted.

Heat Treating

Heat treating is the controlled heating and cooling of a material to achieve certain mechanical properties, such as hardness, strength, flexibility, and the reduction of residual stresses. Many heat treating processes require the precise control of temperature over the heating cycle. Heat treating is used extensively in metals production, and in the tempering and annealing of glass and ceramics products.

A quench furnace line for heat treating

Incineration/Thermal Oxidation

Incineration refers to the process of reducing the weight and volume of solids through heating, whereas thermal oxidation refers to heating waste (particularly organic vapors) in excess oxygen at high temperatures. The main application is the treatment of waste to render it disposable via landfill.

Metals Reheating

Metals are reheated to establish favorable metalworking properties for rolling, extrusion, and forging. Metal reheating is an important step in many metal fabrication tasks.

A walking beam furnace for metal reheating

Smelting

Smelting is the chemical reduction of a metal from its ore, typically by fusion. Smelting separates impurities, thereby allowing their removal from the reduced metal. A common example is the reduction of iron ore in a blast furnace to produce pig iron. Other applications include the extraction of aluminum from bauxite using electrolytic reduction, Hall-Heroult or Bayer process, referred to as aluminum smelting.

Other Heating Processes

Many process heating applications do not fall in the preceding categories; however, collectively, they can account for a significant amount of industrial energy use. Common applications that use process heating include controlling a chemical reaction, cooking foods, and establishing favorable physical or mechanical properties, such as in plastics production. In the food products industry, process heating is used in preparation tasks, particularly baking, roasting, and frying. In the textile industry, process heating is used to set floor coverings and to prepare fabrics for various types of subsequent treatments. This category includes fuel, electric, and steam-based applications.

Table 1 on page 8 summarizes the processes and identifies the applications, equipment, and industries where these processes are commonly used.

Common Types of Process Heating Systems and Equipment

In all process heating systems, energy is transferred to the material to be treated. Direct heating methods generate heat within the material (e.g., microwave, induction, or controlled exothermic reaction), whereas indirect methods transfer energy from a heat source to the material by conduction, convection, radiation, or a combination of these functions. In most processes, an enclosure is needed to isolate the heating process and the environment from each other. Functions of the enclosure include, but are not restricted to, the containment of radiation (e.g., microwave or infrared), the confinement of combustion gases and volatiles, the containment of the material itself, the control of the atmosphere surrounding the material, and combinations thereof.

Common industrial process heating systems fall in one of the following categories:

- Fuel-based
- Electric-based
- Steam-based
- Other, such as heat recovery, heat exchange systems, and fluid heating systems.

The choice of the energy source depends on the availability, cost, and efficiency; and, in direct heating systems, the compatibility of the exhaust gases with the material to be heated. Hybrid systems use a combination of process heat systems by using different energy sources, or different heating methods with the same energy source.

Steam is most commonly generated by using fuel or electricity in a boiler. Focused Solar generation of steam is a reality with several installations being built throughout the world. No matter how the steam is generated, it is a major source of energy for many industrial processes, from fluid heating to drying. In addition to steam, several other secondary energy sources are used by industry. They include hot air, heat transfer by liquids, and water. These secondary sources are generated by a heating system of its own that can fall under the general category of “other process heating systems.”

The cost of energy can vary greatly depending on the area of the country your operation resides. You will need to consult your Utility provider to get an accurate assessment of your current energy cost and an evaluation as to price changes that may result from your adding or reducing energy consumption. Some sources are more expensive than others, and equipment efficiency needs to be considered. Comparatively expensive energy types tend to promote shorter payback periods for projects that improve system efficiency. In contrast, byproduct fuel sources, such as wood chips, bagasse (the residue remaining after a plant has been processed, for instance, after the juice has been removed from sugar cane), and black liquor (a byproduct of the paper production process) may be much less costly than conventional fuels, possibly making their paybacks comparatively longer.

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Table 1. Examples of process heating operations

Process	Application	Equipment	Industry
Agglomeration - Sintering	Metals Production	Various Furnace Types, Kilns Microwave	Primary Metals
Calcining	Lime Calcining	Various Furnace Types	Cement, Wallboard, Pulp and Paper Manufacturing, Primary Metals
Curing and Forming	Coating, Polymer Production, Enameling	Various Furnace Types, Ovens, Kilns, Lehrs, Infrared, UV, Electron Beam, Induction	Ceramics, Stone, Glass, Primary Metals, Chemicals, Plastics, Rubber
Drying	Water and Organic Compound Removal	Fuel-Based Dryers, Infrared, Resistance, Microwave, Radio-Frequency	Stone, Clay, Petroleum Refining, Agricultural and Food, Pulp and Paper, Textiles
Forming	Extrusion, Molding	Various Ovens and Furnaces	Rubber, Plastics, Glass
Fluid Heating	Food Preparation, Chemical Production, Reforming, Distillation, Cracking, Hydrotreating, Visbreaking	Various Furnace Types, Reactors, Resistance Heaters, Microwave, Infrared, Fuel-based Fluid Heaters, Immersion Heaters	Agricultural and Food, Chemical Manufacturing, Petroleum Refining
Heating and Melting – High-Temperature	Casting, Steelmaking, Glass Production	Fuel-Based Furnaces, Kilns, Reactors, Direct Arc, Induction, Plasma, Resistance	Primary Metals, Glass
Heating and Melting – Low-Temperature	Softening, Liquefying, Warming	Ovens, Infrared, Microwave, Resistance	Plastics, Rubber, Food, Chemicals
Heat Treating	Hardening, Annealing, Tempering	Various Fuel-Based Furnace Types, Ovens, Kilns, Lehrs, Laser, Resistance, Induction, Electron Beam	Primary Metals, Fabricated Metal Products, Transportation Equipment, Glass, Ceramics
Incineration/Thermal Oxidation	Waste Handling/Disposal	Incinerators, Thermal Oxidizers, Resistance, Plasma	Fabricated Metals, Food, Plastics and Rubber, Chemicals
Metals Reheating	Forging, Rolling, Extruding, Annealing, Galvanizing, Coating, Joining	Various Furnace Types, Ovens, Kilns, Heaters, Reactors, Induction, Infrared	Primary Metals, Fabricated Metal Products, Transportation Equipment
Separating	Air Separation, Refining, Chemical Cracking	Distillation, Membranes, Filter Presses	Chemicals
Smelting	Steelmaking and Other Metals (e.g., Silver)	Various Furnace Types	Primary Metals
Other Heating Processes	Food Production (including Baking, Roasting, and Frying), Sterilization, Chemical Production	Various Furnace Types, Ovens, Reactors, Resistance Heaters, Microwave, Steam, Induction, Infrared	Agricultural and Food, Glass, Ceramics, Plastics, Rubber, Chemicals

Most process heating applications are fueled by gas or electricity, with some fueled by coal or fuel oil. In many industries, other waste product fuels account for a large portion of the energy use. These fuels include sawdust, wood waste, black liquor, refinery gas, blast furnace gas, and petroleum coke. In many of these systems especially, justifying energy efficiency projects must emphasize performance and reliability benefits that usually accompany improvements in efficiency.

Fuel-Based Process Heating

Heat is generated by the combustion of solid, liquid, or gaseous fuels, and transferred either directly or indirectly to the material. Common fuel types are fossil fuels (e.g., oil, natural gas, coal, and biomass such as vegetable oil, wood chips, cellulose, charcoal, and ethanol). For combustion, gaseous or liquid fuels are mixed with oxidants (e.g., oxygen and air). The combustion gases can be either in contact with the material (direct heating), or be confined and thus be separated from the material (indirect heating, e.g., radiant burner tube, radiant panel, and muffle). Solid fuels are utilized in a wide variety of combustion systems, including fluidized bed, grate, and stokers.

Fuel-based process heating systems are common in nearly every industry segment. They include enclosed heating, like furnaces, ovens, heaters, kilns, and melters, as well as surface treatment applications in ambient air. Typical fuel-based furnaces include the following:

Atmosphere generators. Used to prepare and/or condition protective atmospheres. Processes include the manufacture of endothermic gas used primarily to protect steel and iron during processing, and exothermic gas used to protect metals, but also to purge oxygen or volatile gases from confined areas.

Blast furnaces. Furnaces that burn solid fuel with a blast of air, often used to smelt ore.

Crucible furnaces. A furnace in which the heated materials are held in a refractory vessel for processes such as melting or calcining.

Dryer. A device that removes free water, or other volatile components, from materials through direct or indirect heating. Dryers can be grouped into several categories based on factors such as continuous versus batch operation, type of material handling system, or source of heat generation.

Flares. Used to protect the environment by burning combustible waste products in the petrochemical industry.

Indirect process heaters. Used to indirectly heat a variety of materials by remotely heating and circulating a heat transfer fluid.

Kilns. A furnace used to bake, dry, and fire ceramic ware or wood. Kilns are also used for calcining ores.

Lehrs. An enclosed oven or furnace used for annealing, or other forms of heat treatment, particularly in glass manufacturing. Lehrs may be the open type (in which the flame comes in contact with the ware), or the muffle type.

Muffle furnaces. A furnace in which heat is applied to the outside of a refractory chamber or another enclosure containing the heated material that is enveloped by the hot gases. The heat must reach the charge by flowing through the walls of the container.

Ovens. A furnace-like chamber in which substances are heated for purposes, such as baking, annealing, curing, and drying. Heated systems can use forced convection or infrared.

Radiant-tube heat-treating furnaces. Used for processing iron, steel, and aluminum under a controlled atmosphere. The flame is contained within tubes that radiate heat to the work. Processes include carburizing, hardening, carbo-nitriding, and austempering. The atmosphere may be inert, reducing, or oxidizing.

Reverberatory furnaces. Furnaces in which open flames heat the upper portion of a chamber (crown). Heat is transferred to the material mainly by radiation (flame, reflection of the flame by the crown) and convection (combustion gases).

Salt bath furnaces. Metal pot furnaces filled with molten salt where heat is applied to the outside of the pot or inside of the pot by radiant tube. Salt bath furnaces are used for processes such as heat treating metals and curing plastics and rubber.

Solid waste incinerators. Used to dispose of solid waste material through burning.

Thermal oxidizers. Used to oxidize volatile organic compounds (VOC) in various industrial waste streams. Thermal oxidizing processes include paint and polymer curing and/or drying.

Furnaces in any configuration can be considered heating systems that consist of many components. Examples of improving process heating efficiency include optimizing the combustion process, recovering energy from the exhaust gases, reducing the amount of energy lost to the environment, recycling rejected product, using recycled materials in place of virgin feedstocks, and improving furnace scheduling.

Electric-Based Process Heating (Electrotechnologies)

Electric currents or electromagnetic fields are used to heat the material. Direct heating methods generate heat within the work piece by passing an electrical current through the material; by inducing an electrical current into the material; or by exciting atoms or molecules within the material with electromagnetic radiation. Indirect heating methods use one of these three methods to heat an element or susceptor, and transfer the heat either by conduction, convection, radiation, or a combination of these to the work piece.

Examples of electric-based process heating systems include:

Arc furnaces. Electric arc furnaces are process heating systems that heat materials by means of an electric arc from the electrode(s) to the conductive material. The furnace can be either an AC or DC depending on the application. Arc furnaces range in size from foundry applications as small as 1-ton capacity for producing cast iron products, to units of more than 400 tons used for making steel from scrap iron.

Electric infrared processing. An electrical current is passed through a solid resistor, which heats up to a desired source temperature to emit infrared radiant energy. Electric infrared heating systems are generally used where precise temperature control is required to heat treat surfaces, cure coatings, and dry materials, but infrared can also be used in bulk heating applications such as booster ovens. The work piece to be heated must have a reasonable absorption to infrared. This is determined and measured by the emissivity of the material and is helpful to determine which infrared spectrum is best suited; short-, medium-, or long-wave.

Electron beam processing. In electron beam heating, metals are heated by a directed, focused beam of electrons. In electron beam curing, materials can be chemically transformed by cross linking of molecules from exposure to electrons. Electron beam heating is used extensively in many high-volume applications for welding, especially in the automotive industry. Heat treatment with electron beams is relatively new; the primary application is the local surface hardening of high-wear components for automotive applications. It is also used in processing scrap titanium and superalloys.

Gas infrared heating. A flame is contained within a porous surface or impinges onto a surface which then emits radiation with a broad range of wavelengths at high power density. The work piece absorbs energy at high rates due to total summation over the broad spectral range. Gas infrared heating systems are used for food processing, annealing, forming, melting snow, setting (gel) powder coatings before their curing cycle, and for other high power and quick heat time applications.

Induction heating and melting. Induction heating occurs when passing alternating magnetic fields through conductive materials. This is accomplished by placing an alternating current carrying coil around or in close proximity to the materials. The alternating fields generate eddy currents in the materials. These currents interact with the resistance of the material to produce heat. There is a secondary heating process called hysteresis; heating that is only produced within magnetic materials as a result of the rapidly changing magnetic fields by the inductor generating internal friction. This secondary heating disappears at the temperature at which the material loses its magnetic properties

- *Direct induction.* Direct induction heating occurs when the material to be heated is in the direct alternating magnetic field. The frequency of the electromagnetic field and the electric properties of the material determine the penetration depth of the field, thus enabling the localized, near-surface heating of the material. Comparably high power densities and high heating rates can be achieved. Direct induction heating is primarily used in the metals industry for melting, heating, and heat treatment (hardening, tempering, and annealing).
- *Indirect induction.* With indirect induction heating, a strong electromagnetic field generated by a water- cooled coil induces an eddy current into an electrically conducting material (susceptor), which is in contact with the material to be treated. Indirect induction heating is often used to melt optical glasses in platinum crucibles, to sinter ceramic powders in graphite crucibles, and to melt materials in crucibles prior to drawing crystals. Indirect induction is also used to heat susceptors used for joining operations.

Laser processing. A laser beam rapidly heats the surface of a material to create a hardened layer, either by subsequent quenching or self-quenching. The beam shape, beam direction and power output of lasers can be precisely controlled. A common application is the localized hardening of metal parts.

Microwave processing. Microwave heating systems use electromagnetic radiation in the microwave band to excite water molecules in the material, or to generate heat in a susceptor (for example, graphite). Common applications include the drying of textiles and polymers, food processing, and drying and sintering of ceramics. Microwave process applications typically have high efficiency, high energy densities, reasonably good control, and a small footprint for the equipment.

Plasma processing (arc and nontransferred arc). An electric arc is drawn between two electrodes, thereby heating and partially ionizing a continuous stream of gas; the partly ionized gas is known as plasma. There are two basic configurations, namely, transferred arc and nontransferred arc.

In the transferred arc configuration, the arc is transferred from an electrode to the work piece, which is connected to a return electrode; heating of the material occurs through radiation, convection, and direct resistance heating. In some cases, the work piece is the electrode and its plasma or glow discharge provides surface treatment.

In nontransferred arc configurations, the arc is drawn between two electrodes not connected to the work piece; heating of the work piece occurs via radiation, and to a certain extent, through convection. In both configurations, either AC (single-phase, three-phase) or DC current can be used.

Radio frequency processing. Radio frequency heating is similar to microwave heating (high-frequency electromagnetic radiation generates heat to dry moisture in nonmetallic materials), but radio frequency waves are longer than microwaves, enabling them to more efficiently heat larger volume objects better than microwave energy.

Resistance heating and melting (direct and indirect).

- *Direct resistance heating.* This refers to systems that generate heat by passing an electric current (AC or DC) through a conductor, causing an increase in temperature; the material to be treated must have a reasonable electrical conductivity. Contact to the work piece is made by fixed connectors, or in the case of melts, by submerged electrodes. The connector and/or electrode material has to be compatible with the material to be heat-treated or melted. In industrial applications, consumable and nonconsumable electrodes are common. Applications of direct resistance heating include the melting of glass and metal.
- *Indirect resistance heating and melting.* This refers to systems in which an electrical current is passed through a resistor, and energy is transmitted to the work piece through convection and/or radiation.

Ultraviolet curing. Ultraviolet (UV) radiation is applied to initiate a photochemical process to transform liquid polymers into a hard, solid film. Applications include decorative and protective coatings, laminations (glass-to-glass, glass-to-polymer, glass-to-metal, polymer-to-polymer), electronics, and printing. Due to the absence of solvents, processes using UV-cured polymers can be faster, and in some cases, less toxic than those using conventional, solvent-based adhesives or coatings.

Steam-Based Process Heating

Boilers account for a significant amount of the energy used in industrial process heating. In fact, the fuel used to generate steam accounts for 84% of the total energy used in the pulp and paper industry, 47% of the energy used in the chemical manufacturing industry, and 51% of the energy used in the petroleum refining industry.[3] Hybrid boiler systems combining a fuel-based boiler with an electric- based boiler are used to fuel switch based on pricing incentives, off-peak pricing, offered by your utility provider.

Steam holds a significant amount of energy on a unit mass basis (between 1,000 and 1,250 Btu/lb).

Since most of the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature. Among the advantages of steam as a source of process heat are low

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[3] *Steam System Opportunity Assessment for the Pulp and Paper, Chemical Manufacturing, and Petroleum Refining Industries*, U.S. Department of Energy, October 2002.

toxicity, ease of transportability, high heat capacity, and low cost. About 30% to 35% of the total energy used in industrial applications is for steam generation.

Steam systems can be relatively complex. As a result, there are many sources of inefficiencies and many opportunities to improve their performance. An excellent resource and companion sourcebook titled *Improving Steam System Performance, A Sourcebook for Industry*, presents efficiency opportunities for boilers and steam systems, so they are not described in detail in this sourcebook. This resource is available from the Steam Systems section of the AMO website at www.energy.gov/eere/amo/steam-systems

Other Process Heating Systems

Many industrial facilities have process heating applications that are end-use specific. These applications often use heat exchangers to transfer energy from one process to another. Other examples are chemical reaction vessels that rely on energy released by exothermic reactions to heat another process, and hot-water-based systems.

A common type of heat exchange system is called thermal fluid systems. Thermal fluid systems use an oil- or salt-based heat transfer medium to carry heat from the generation source to the heated product, similar to the way steam is used in process heating applications. Thermal fluid systems have much lower vapor pressure-to-temperature characteristics, which means that thermal fluids can provide high-temperature service (up to 750˚F) without the high pressures that would be required with steam.

This catchall group of process heating applications represents a significant amount of energy, and also includes various types of fuel-, steam-, and electric-based systems. In many cases, the opportunities available to improve these systems depend on many different characteristics, including equipment, type of heating operation (e.g., melting, heating, or calcining) and material handling type. As a result, characterizing efficiency and performance opportunities is difficult; however, taking a systems approach provides the best way of finding the "low-hanging fruit" or the options that usually provide the shortest payback period.

SECTION 2: PERFORMANCE IMPROVEMENT OPPORTUNITIES – FUEL-BASED SYSTEMS

Figure 1 shows a schematic of a typical fuel-based process heating system, as well as potential opportunities to improve the performance and the efficiency of the system. Most of the opportunities are not independent, as reducing the energy use of one component may reduce the impact of a second reduction. For example, tuning the burners will reduce energy use, but will also make the gains from flue gas heat recovery less than before the burners were tuned.

Fuel-Based Process Heating Equipment Classification

Fuel-based process heating equipment is used by industry to heat materials under controlled conditions. The process of recognizing opportunities and implementing improvements is most cost effective when accomplished by combining a systems approach with an awareness of efficiency and performance improvement opportunities that are common to systems with similar operations and equipment.

It is important to recognize that a particular type of process heating equipment can serve different applications and that a particular application can be served by a variety of equipment types. For example, the same type of direct- fired batch furnace can be used to cure coatings on metal parts at a foundry and to heat treat glass products at a glassware facility. Similarly, coatings can be cured either in a batch-type furnace or a continuous-type furnace. Many performance improvement opportunities are applicable to a wide range of process heating systems, applications, and equipment. This section provides an overview of basic characteristics to identify common components and classify process heating systems.

Equipment characteristics affect the opportunities for which system performance and efficiency improvements are likely to be applicable. This section describes several functional characteristics that can be used in classifying equipment.

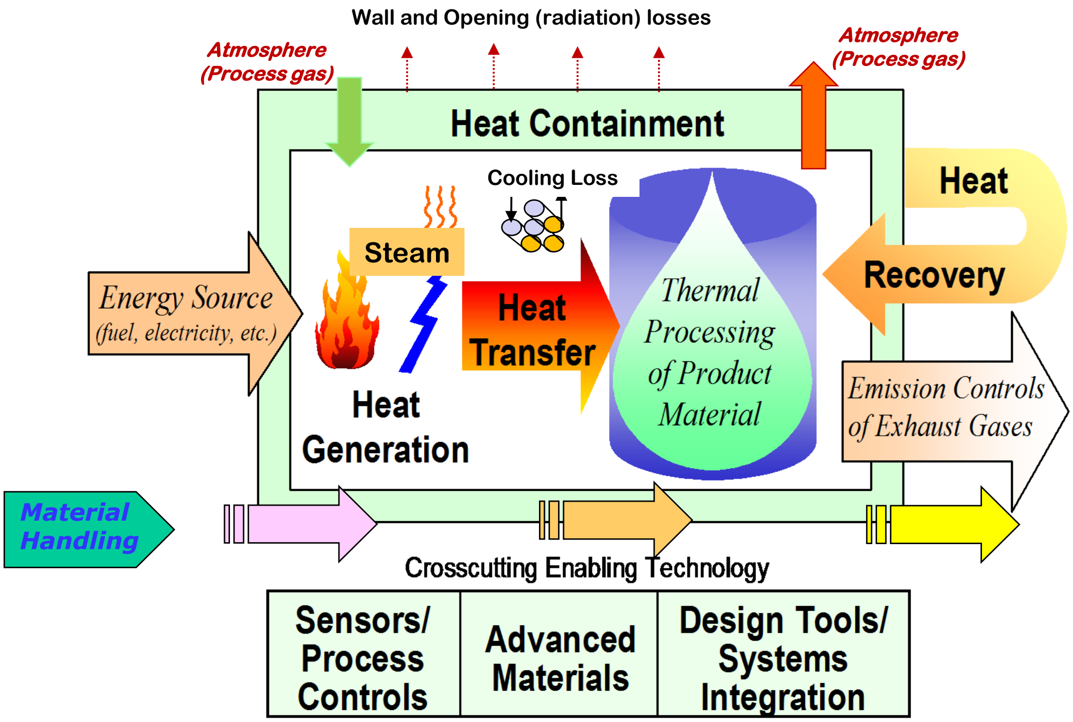

Figure 1. A fuel-based process heating system and opportunities for improvement

Fuel-based process heating equipment can be classified in many different ways, including:

- Mode of operation (batch versus continuous)
- Type of heating method and heating device
- Material handling system.

Table 2 lists these classification characteristics by equipment/application and industry.

Table 2. Process heating system equipment classification

Furnace Classification Method	Equipment/Application Comments	Primary Industries
Batch versus Continuous		
Batch	Furnaces used in almost all industries for a variety of heating and cooling processes	Steel, Aluminum, Chemicals, Food
Continuous	Furnaces used in almost all industries for a variety of heating and cooling processes	Most manufacturing sectors
Type of Heating Method		
Direct-fired	Direct-fired furnaces using gas, liquid or solid fuels, or electrical furnaces	Most manufacturing sectors
Indirectly heated	Heat treating furnaces, chemical reactors, distillation columns, salt bath furnaces, etc.	Metals, Chemicals
Material Handling System		
Fluid heating (flow-through) systems	Gaseous and liquid heating systems including fluid heaters, boilers	Petroleum Refining, Chemicals, Food, Mining
Conveyor, belts, buckets, rollers, etc.	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Metals, Chemicals, Pulp and Paper, Mining
Rotary kilns or heaters	Cement and lime kilns, heat treating, applications in the chemical and food industries	Mining, Metals, Chemicals, Food
Vertical shaft furnaces	Blast furnaces, cupolas, vertical shaft calciners, exfoliators, coal gasifiers	Metals, Minerals Processing, Petroleum Refining
Rotary hearth furnaces	Furnaces used for metal or ceramics heating or heat treating of steel and other metals, iron ore palletizing, etc.	Metals
Walking beam furnaces	Primarily used for large loads, such as reheating of steel slabs, billets, ingots, etc.	Metals (steel)
Car bottom furnaces	Used for heating, heat treating of material in metals, ceramics and other industries	Metals, Chemicals, Ceramics
Continuous strip furnaces	Continuous furnaces used for metal heating, heat treating, drying, curing, etc.	Pulp and Paper, Metals, Chemicals
Vertical handling systems	Primarily for metal heating and heat treating for long parts and in pit, vertical batch, and salt bath furnaces	Metals, Chemicals, Mining
Other	Pick and place furnaces, etc.	Most manufacturing sectors

Mode of Operation

During heat treatment, a load can be either continuously moved through the process heating equipment (continuous mode), or kept in place, with a single load heated at a time (batch mode). In continuous mode, various process heating steps can be carried out in succession in designated zones or locations, which are held at a specific temperature or kept under specific conditions. A continuous furnace generally has the ability to operate on an uninterrupted basis as long as the load is fed into and removed from the furnace. In batch mode, all process heating steps (i.e., heating, holding, cooling) are carried out with a single load in place by adjusting the conditions over time.

Type of heating method. In principle, one can distinguish between direct and indirect heating methods. Systems using direct heating methods expose the material to be treated directly to the heat source or combustion products. Indirect heating methods separate the heat source from the load, and might use air, gases or fluids as a medium to transfer heat from the heating device to the load (for example, convection furnaces).

Type of heating device. There are many types of basic heating devices that can be used in process heating systems. These include burners, radiant burner tubes, gas infrared emitters, heating panels, bands, and drums.

Material Handling Systems

The selection of the material handling system depends on the properties of the material, the heating method employed, the preferred mode of operation (continuous, batch) and the type of energy used. An important characteristic of process heating equipment is how the load is moved in, handled, and moved out of the system. Important types of material handling systems are described below.

Fluid heating (flow-through) systems. Systems in which a process liquid, vapor, or slurry is pumped through tubes, pipes, or ducts located within the heating system by using pumps or blowers.

Conveyor, belt, bucket, or roller systems. Systems in which a material or its container travels through the heating system during heating and/or cooling. The work piece is moved through the furnace on driven belts or rolls. The work piece can be in direct contact with the transporting mechanism (belt, roller, etc.), or supported by a tray or contained in a bucket that is either in contact with or attached to the transporting mechanism.

Rotary kilns or heaters. Systems in which the material travels through a rotating drum or barrel while being heated or dried by direct-fired burners or by indirect heating from a kiln shell.

Vertical shaft furnace systems. Systems in which the material travels from top to bottom (usually by gravity) while it is heated (or cooled) by direct contact of the hot (or cooling) gases or indirectly from the shell of the fluidizing chamber.

Rotary hearth furnaces. Systems in which the load is placed on a turntable while being heated and cooled.

Walking beam furnaces. The load is “walked” through the furnace by using special beams. The furnaces are usually direct-fired with several top- and bottom-fired zones.

Car bottom furnaces. The material is placed on a movable support that travels through the furnace or is placed in a furnace for heating and cooling of the load.

Continuous strip furnace systems. Systems in which the material in the form of a sheet or strip travels through a furnace in horizontal or vertical direction while being heated and cooled. The material heating could be by direct contact with hot gases or by radiation from the heated “walls” of the furnace.

Vertical material handling systems (often used in pit or vertical batch furnaces). The material is supported by a vertical material handling system and heated while it is “loaded” in an in-ground pit or an overhead furnace.

Other types. Various types of manual or automatic pick and place systems that move loads of material into salt, oil, air, polymers, and other materials for heating and cooling. Other systems also include cyclone, shaker hearth, pusher, and bell top.

Many furnace types, such as pit and rotary, can be designed and configured to operate in batch or continuous mode, depending on how material is fed into the furnace. A pit furnace used for tempering manually fed material with a pick-and-place system is a type of batch furnace. In contrast, a pit furnace used for heat treatment of automatically fed material with a vertical material handling system is a continuous furnace.

Efficiency Opportunities for Fuel-Based Process Heating Systems

The remainder of this section gives an overview of the most common performance improvement opportunities for fuel-based process heating systems. The performance and efficiency of a process heating system can be described with an energy loss diagram, also known as a Sanke Diagram, as shown in Figure 2. The main goals of the performance optimization are reduction of energy losses and increase of energy transferred to the load. It is therefore important to know which aspects of the heating process have the highest impact. Some of the principles discussed also apply to electric- or steam-based process heating systems.

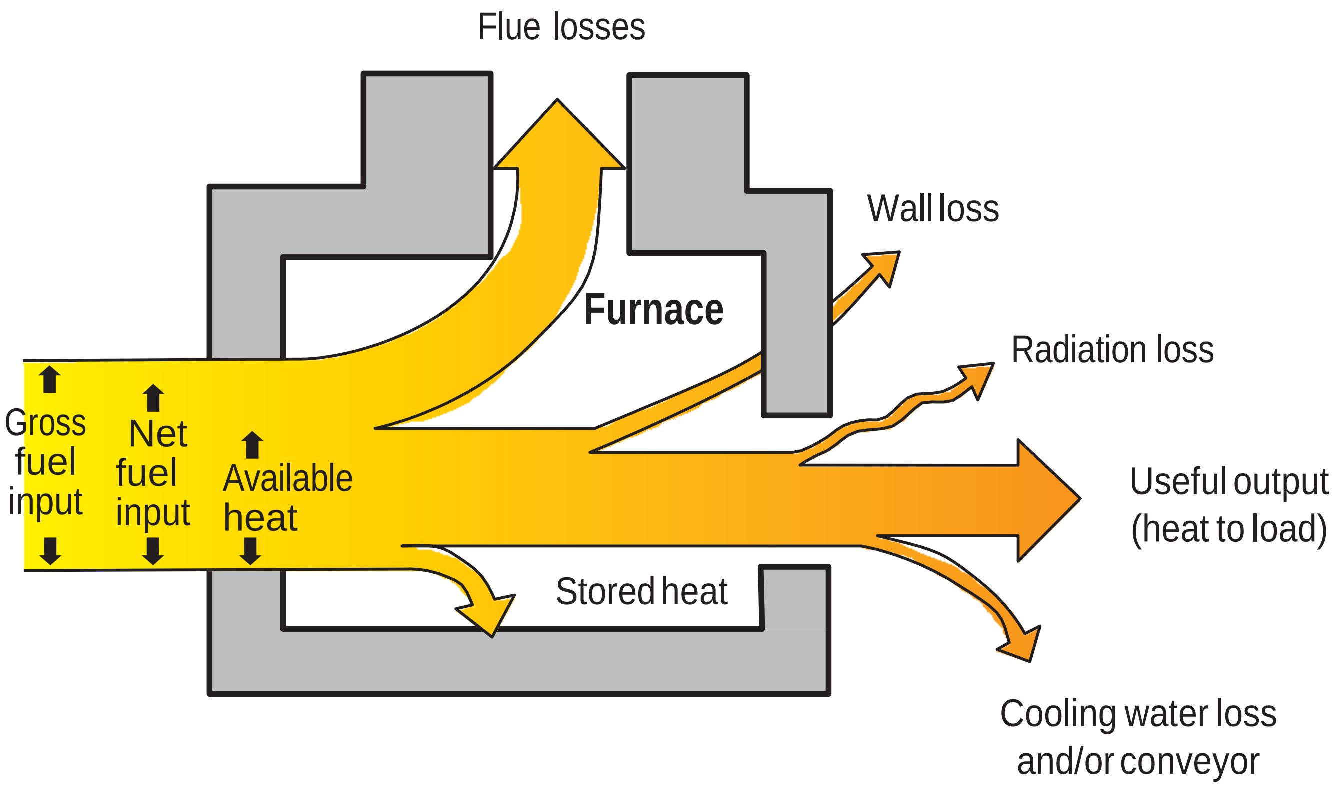

Figure 2. Energy loss diagram in a fuel-based process heating system.

Performance and efficiency improvement opportunities can be grouped into five categories:

- Heat generation: discusses the equipment and the fuels used to heat a product
- Heat containment: describes methods and materials that can reduce energy loss to the surroundings
- Heat transfer: discusses methods of improving heat transferred to the load or charge to reduce energy consumption, increase productivity, and improve quality
- Waste heat recovery: identifies sources of energy loss that can be recovered for more useful purposes, and addresses ways to capture additional energy
- Enabling technologies: addresses common opportunities to reduce energy losses by improving material handling practices, effectively sequencing and scheduling heating tasks, seeking more efficient process control, and improving the performance of auxiliary systems. Enabling technologies include:
  - *Advanced sensors and controls*
  - *Advanced materials*—identifying performance and efficiency benefits available from using advanced materials
  - *Auxiliary systems*—addressing opportunities in process heating support systems.

2 – PERFORMANCE IMPROVEMENT OPPORTUNITIES – FUEL-BASED SYSTEMS

Figure 3 shows several key areas where the performance and efficiency of a system can be improved. Some opportunities may affect multiple areas. For instance, reducing radiation losses by sealing the furnace will also reduce flue losses since less fuel will need to be consumed.

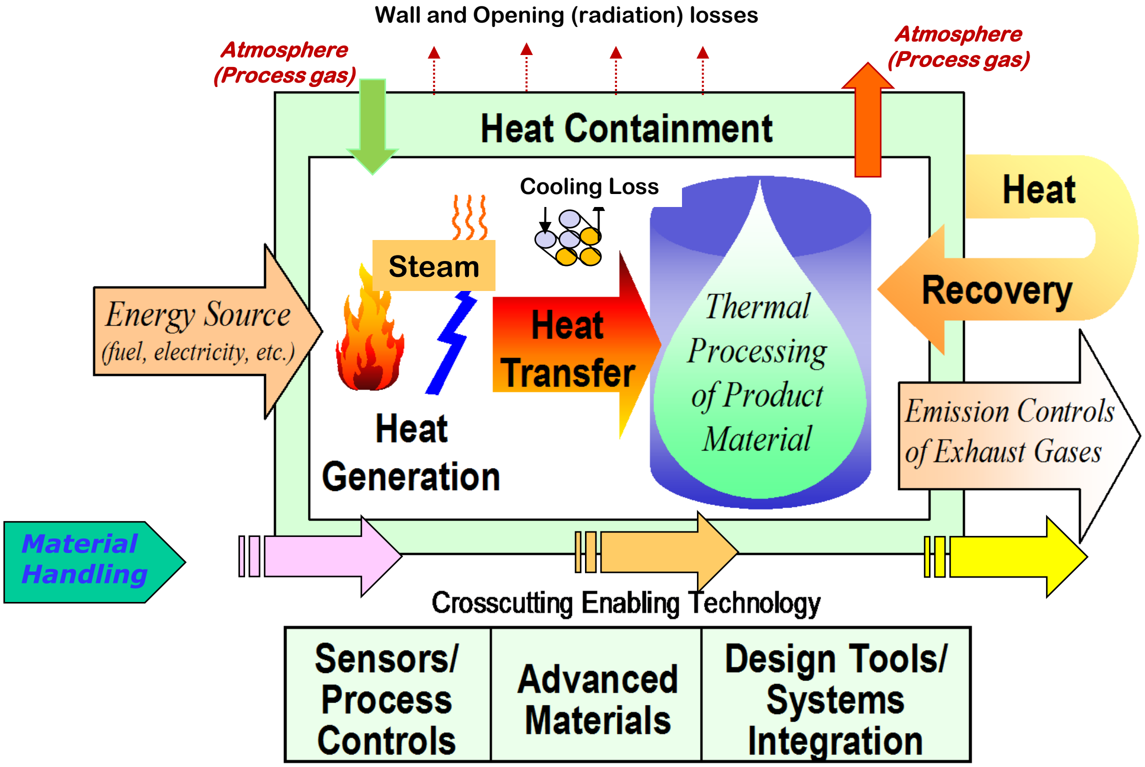

Figure 3. Key opportunities in a fuel-based system

Despite overlaps among the five categories, these groupings provide a basis for discussing how process heating systems can be improved and where end users can seek further information for opportunities that seem to be applicable to their system.

Many improvement opportunities are addressed in a series of tip sheets developed by the U.S. Department of Energy's (DOE) Advanced Manufacturing Office (AMO), which are included in Appendix B. These tip sheets provide low- and no-cost practical suggestions for improving process heating system efficiency. When implemented, these suggestions often lead to immediate energy-saving results.

In addition to tip sheets, the AMO has developed technical briefs that cover key issues in greater detail. The first technical brief, *Materials Selection Considerations for Thermal Process Equipment*, discusses how material selection can provide performance and efficiency improvements. The second technical brief, *Waste Heat Reduction and Recovery*, discusses the advantages of reducing energy losses to the environment and heat recovery. These technical briefs are included in Appendix C.

The following sections discuss the principal components of a process heating system and the associated opportunities, how to identify said opportunities, and where to seek additional information.

Heat Generation

In basic terms, heat generation converts chemical or electric energy into thermal energy, and transfers the heat to the materials being treated. The improvement opportunities related to heat generation address the losses that are associated with the combustion of fuel and the transfer of the energy from the fuel to the material. Key improvement areas include:

- Controlling air-to-fuel ratio and reducing excess air
- Preheating of combustion air or feedstock
- Using oxygen enriched air
- Improving mixing

Controlling air-to-fuel ratio and reducing excess air. For most process heating applications, combustion burns a hydrocarbon fuel in the presence of air, thereby forming carbon dioxide and water, and releasing heat. One common way to improve combustion efficiency is to ensure that the proper air-to-fuel ratio is used. This generally requires establishing the proper amount of excess air, typically around 3%.

When the components are in the theoretical balance described by the combustion reaction, the reaction is called stoichiometric (all of the fuel is consumed and there is no excess air). Stoichiometric combustion is not practical in nozzle-mix burners, because a perfect mixing of the fuel with the oxidant (oxygen in air) would be required to achieve complete combustion. Without excess oxidant, unburned hydrocarbons can enter the exhaust gas stream, which can be both dangerous and environmentally harmful.

On the other hand, too much excess air is also not desirable because it carries away large amounts of heat. With pre-mix burners, it is easier to approach the stoichiometric ratio since the air and fuel are combined before the nozzle and continue mixing for the length of the mixture piping. Pre-mix equipment can be supplied with automatic adjustment that compensates for variations in air density and fuel content.

Caution should be used when reducing excess air. Although this approach is often worth considering, it is important to maintain a certain amount of excess air. Excess air is essential to maintain safe combustion; it is also used to carry heat to the material.

Heat Generation Opportunities

Performance Improvement	**Savings**
Control air-to-fuel ratio	**5% to 25%**
Preheat combustion air	**15% to 30%**
Use oxygen-enriched combustion air	**5% to 25%**
Fuel conditioning	**5% to 10%**

What to Watch

- Combustion air leaks downstream of control valve.
- Linkage condition can lead to poor control of the fuel/air mixture over the range of operating conditions.
- Excess oxygen in the furnace exhaust (flue) gases indicates too much excess air.
- Flame stability indicates improper fuel/air control.

Find Additional Information

The AMO offers these resources to help you implement energy efficiency measures in process heating generation:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Technical Brief: *Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emission Performance* (see Appendix C)

Also visit the AMO Web site to download these and other process heating related resources: ***www.energy.gov/eere/amo.***

As a result, operators should be careful to establish the proper amount of excess air according to the requirements of the burner and the furnace. Important factors for setting the proper excess air include:

- Type of fuel used
- Type of burner used
- Process conditions
- Process temperature.

Preheating combustion air. Another common improvement opportunity is combustion air preheating. Since a common source of heat for this combustion air is the stream of hot exhaust gases, preheating combustion air is also a form of heat recovery. Transferring heat from the exhaust gases to the incoming combustion air or incoming cold process fluid reduces the amount of energy lost from the system and also allows more thermal energy to be delivered to the heated material from a certain amount of fuel. However, the higher combustion air may increase formation of nitrogen oxide (NOx), a precursor to ground level ozone, if flue gas recirculation or other burner mitigating strategies aren't used. Also, higher flame temperatures resulting from the higher combustion air temperature may reduce refractory life.

Enriching oxygen. Oxygen enrichment is another opportunity that is available to certain process heating applications, particularly in the primary metals industries. Oxygen enrichment is the process of supplementing combustion air with oxygen. Recall that standard atmospheric air has oxygen content of about 21% (by volume), so oxygen enrichment increases this percentage for combustion. Oxygen-enhanced combustion is a technology that was tried decades ago, but did not become widely used. However, because of technological improvements in several areas, oxygen enrichment is again being viewed as a potential means of increasing productivity.

Improving mixing. The mixing of the fuel and oxidant for combustion can be modified to produce the desired heat generating characteristics that are best for the process and type of equipment. A burner's flame can have various shapes and distribution of temperature across its shape by varying the mixing and changing the burner nozzle. New technology has been introduced that changes the mixing and flame temperature of existing burner systems by installing a fuel conditioner in close proximity to the burner.

Heat Transfer

Improved heat transfer within a furnace, oven, or boiler can result in energy savings, productivity gains, and improved product quality. The following guidelines can be used to improve heat transfer:

- Maintain clean heat transfer surfaces by:
  - Using soot blowers, where applicable, in boilers
  - Burning off carbon and other deposits from radiant tubes
  - Cleaning heat exchanger surfaces.
- Achieve higher convection heat transfer through use of proper burners, recirculating fans or jets in the furnaces and ovens.
- Use proper burner equipment for the location within the furnace or ovens. Consider increasing or changing to radiant heat transfer.
- On radiant tube systems, add devices to increase turbulence and radiation in the exhaust leg.
- Establish proper furnace zone temperature for increased heat transfer. Often, furnace zone temperature can be increased in the initial part of the heating cycle or in the initial zones of a continuous furnace to increase heat transfer without affecting the product quality.

Heat Containment and Recovery

In addition to improving heat generation and heat transfer, waste heat from process heating systems can be contained, recovered, and utilized. These practices are covered in Section 4, *Waste Heat Management*.

Heat Transfer Opportunities

Performance Improvement	Savings
Improve heat transfer with advanced burners and controls	5% to 10%
Improve heat transfer with a furnace	5% to 10%
Radiant tube inserts	5% to 20%

What to Watch

- Higher than necessary operating temperature.
- Exhaust gas temperatures from heat recovery device.

Find Additional Information

The Advanced Manufacturing Office offers these resources to help you implement energy efficiency measures in heat transfer:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Visit the AMO web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

Enabling Technologies

Enabling technologies include a wide range of improvement opportunities, including process control, advanced materials, and auxiliary systems.

Sensors and process controls. Process control refers to opportunities that reduce energy losses by improving control systems that govern aspects such as material handling, heat storage, and turndown. In addition, emerging technologies can now be used to measure feedstock and melts in real-time, along with feedback controls, can result in substantial energy reductions and productivity increases. Advanced Process controls techniques do also allow for the system to be predictive instead of reactive, with the result of improving process efficiencies.

Process heating systems have both fixed and variable losses. Variable losses depend on the amount of material being heated, while fixed losses do not. Fixed losses are incurred as long as the unit is being used, regardless of the capacity at which it is operating.

Advanced materials. The use of advanced materials can improve the performance and efficiency of a process heating system. To avoid thermal damage, many high-temperature processes require the cooling of components. In some cases, advanced materials that can safely withstand higher temperatures may replace conventional materials. This can avoid or reduce energy losses associated with cooling. Use of advanced materials can reduce the mass of fixtures, trays, and other material handling parts, with significant reduction in process heat demand per unit of production.

Furnace heat transfer can also be improved by using lighter, high-temperature convection devices such as fans for dense, tightly packed loads. Also, high temperature ceramics and silicon carbides are being used in heat recovery and preheating systems for improved efficiency. Also, complex shapes of these materials are formed through 3D printing which allows higher surface area density and improved effectiveness.

Auxiliary systems. Most process heating applications have auxiliary systems that support the process heating system. For example, large furnaces require forced draft fans to supply combustion air to the burners. Inefficient operation of these fans can be costly, especially in large process heating systems with high run times.

- Material handling. Another important auxiliary system is the material handling system, which controls the delivery of material to the furnace and removes the material after the process heating task is completed. The type of process heating application has a significant effect on potential losses and the opportunities to reduce these losses. In continuous systems, the material is fed to the furnace without distinctive interruption. Batch systems, in contrast, are characterized by discrete deliveries of material to be treated into and out of the system.

Opportunities to improve the overall process heating system efficiency by modifying the material handling system are generally associated with reducing the amount of time that the furnace is idle or that it operates at low capacity. For example, a slow mechanical action into and out of an oven can result in unnecessary heat loss between batches. Similarly, imprecise mechanical controls can result in uneven heating and the need for rework. A systems approach is particularly effective in evaluating potential improvement opportunities in material handling systems.

- Motor systems. Motor systems are found throughout industry, accounting for approximately 59% of manufacturing industrial electricity use. Within process heating systems, motors are used to power fans, and run pumps and material handling systems. Motors, in general, can be very efficient devices when properly selected for an application and properly maintained. In contrast, when motors operate far below their rated capacity or are not properly maintained, their corresponding efficiency and reliability can drop significantly. One common opportunity to improve the efficiency of auxiliary motor systems is to use motors controlled by variable frequency drives instead of controlling motors with dampers or throttle valves.

The AMO has several resources that address the opportunities available from improving motor system performance and efficiency. Motor Master+ is one of the software programs that helps end users make informed motor selection decisions. This tool can be downloaded along with many other useful motor-related resources through the Motor Systems section of AMO's web site, www.energy.gov/eere/amo/motor-systems.

- Fans. Fans are used to supply combustion air to furnaces and boilers. In many process heating applications, fans are used to move hot gases to heat or dry material, and, frequently, fans are used in material handling applications to move heated materials. The performance, efficiency, and reliability of fans, as with motors, are significantly affected by sizing and selection decisions and the fan maintenance effort. Common fan problems and opportunities to improve fan performance are discussed in a companion sourcebook, *Improving Fan System Performance: A Sourcebook for Industry*. This resource is also available from the Fan Systems section of the AMO web site at www.energy.gov/eere/amo/fan-systems.
- Pumps. Some process heating applications require cooling to prevent thermal damage to certain system parts, such as conveyor systems. Pumps are particularly essential in thermal fluid applications to move hot oil to the end use. In general, pumps do not account for a significant amount of energy used by the system; however, pump performance can be critical to keeping the system up and running. Further information on pumps and pumping systems is available in a companion sourcebook, *Improving Pumping System Performance, A Sourcebook for Industry*. This resource is available from the Pump Systems section of the AMO website, www.energy.gov/eere/amo/pump-systems.

Another key enabling technology is numerical simulation. The development of modeling techniques and ever-increasing computing power has made numerical modeling a useful tool for improving system performance. Computational Fluid Dynamics (CFD) of fuel based systems gives insight in fields like velocities, temperatures, pressures and stresses at any point of the system. These can generate new ideas on how to improve system efficiencies and help further decision making. These tools also have the ability to run virtual experiments – i.e. various design or operating parameters can be investigated on computer without actually building lab set-ups. Also, it may be too risky and costly to run experiments on live equipment such as furnaces.

Enabling Technology Opportunities

Performance Improvement	**Savings**
• Install high-turndown combustion systems	**5% to 10%**
• Use programmed heating temperature setting for part-load operation	**5% to 10%**
• Monitor and control exhaust gas oxygen, unburned hydrocarbon, and carbon monoxide emissions	**2% to 15%**
• Maintain furnace pressure control	**5% to 10%**
• Ensure correct sensor locations	**5% to 10%**

What to Watch

- Frequent and avoidable furnace starts and stops.
- Long periods of idle time between batches.
- Extended periods of low-capacity furnace operation.
- Piping insulation sagging and distortion.
- Higher than necessary operating temperature.

Find Additional Information

The Advanced Manufacturing Office offers these resources to help you learn more about enabling technology opportunities for process heating:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Technical Brief: *Material Selection Considerations for Thermal Process Equipment* (see Appendix C)

Also visit the AMO Web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

2 – PERFORMANCE IMPROVEMENT OPPORTUNITIES – FUEL-BASED SYSTEMS

With techniques such as CFD, the geometry of furnaces, along with the load and all individual burners, can be analyzed in detail. Similarly, Finite Element Analysis (FEA) can give insights to the structural integrity of the system by calculating stresses and displacements. Over the last decade, these numerical tools have become widely used across all industries, as they provide fundamental technical understanding, reduce cost, and increase speed to execution and commercialization. Such tools can also be applied to the electric based systems described in the next section.

SECTION 3: PERFORMANCE IMPROVEMENT OPPORTUNITIES – ELECTRIC-BASED SYSTEMS

The term *electrotechnologies* describes a wide range of electric-based industrial operations. An important class of electrotechnologies incorporates thermal processes like heating, drying, curing, melting, and forming to manufacture or transform products. These technologies utilize equipment and systems that convert incoming electricity at line voltage to a form of applied energy that can efficiently achieve the necessary thermal effect. Some examples of industrial electrotechnology applications include infrared curing of coatings; induction melting and heat treating of metals; radio frequency drying of textiles; laser sintering, microwave curing of rubber, resistive heating by electric boosting of glass furnaces, and electric arc furnaces.

Also included in this section are some non-thermal based technologies such as ultraviolet (UV) and electron beam (EB). Their inclusion is warranted because they compete with other thermal-based technologies. For UV, the process is a photo-initiated reaction chemical conversion process. EB can direct drive cross-linking reactions that achieve curing without the need for high temperatures used in conventional curing processes. Both of these technologies are alternatives to thermal-based curing technologies such as infrared and induction curing.

Types of Electric-Based Process Heating Systems – Direct and Indirect

Electric-based process heating technologies can heat materials in two ways:

1. Direct Heating, heat generated within the material by:
    - Passing an electrical current through the material, making the material a resistive heater
    - Inducing an electrical current called an eddy current into the material
    - Exciting atoms and/or molecules within the material with electromagnetic energy (e.g., microwave and radio frequency)
2. Indirect heating is where the heat is generated external to the material and transferred to the material to be heated by Convection, Conduction, Radiation, or any combination of the three.

Hybrid Systems

Hybrid systems are becoming more common as a best practice to optimize energy use and increase overall process thermal efficiency. Hybrid process heating systems utilize a combination of process heating technologies based on different energy sources and/or different heating methods of the same energy source. Hybrid process heating systems that combine multiple forms of heat transfer through radiant, conductive, and/or convective methods can reduce heating time, increase energy efficiency, and improve product quality. As you read and learn about the different electric heating technologies in this section, do not overlook hybrid systems. Examples include electric infrared in combination with either an electric convection oven or a gas convection oven; and a paper-drying process that combines a natural gas or electric-based infrared technology with a steam-based drum dryer.

The remainder of this section covers these process heating electrotechnologies:

- Arc furnaces
- Electric Infrared processing
- Electron beam processing
- Induction heating and melting
- Laser heating
- Microwave processing
- Plasma processing (arc and non-transferred arc)
- Radio-frequency processing
- Resistance heating and melting (direct and indirect)
- Ultraviolet curing (while this is a chemical conversion process, it competes with thermal processes)

Arc Furnaces

History and Status

The first electric arc furnace was installed at the Sanderson Brothers Steel Company in Syracuse New York in 1907. Initially, arc furnaces were used to produce specialty metals such as spring steel. Today, they are used for the production of more common carbon and low-alloy steels, and in foundries to melt iron and steel for casting operations.

How the Technology Works

Arc furnaces melt steel and/or iron scrap by direct contact with an electric arc struck from an electrode to the metal charge. There is also melting occurring from the radiant energy generated by the arc. To begin the direct arc melting process, a charge of scrap metal, often with Direct Reduced Iron (DRI) pellets, is fed into the furnace. The furnace top is sealed and the arc is struck.

There are two ways to power the electrode(s) used in the arc furnace; using Direct Current (DC) or Alternating Current (AC). Generally, the DC arc furnace is identified by the use of one or two electrodes while the AC furnace will have 3 electrodes. Which is used depends on the application.

Arc furnaces consist of a water-cooled refractory-lined vessel, which is covered by a retractable roof through which graphite or carbon electrodes protrude into the furnace. The distance between the electrode tips and the melt surface can be adjusted, and during operation the electrodes are lowered into the furnace to compensate for wear. The cylindrical electrodes consist of multiple segments with threaded joints; new segments can be added to the cold end of the electrode as the wear progresses. The arc forms between the charged material and the electrodes, and the charge is heated both by current passing through the charge and by the radiant energy from the arc.

The electrodes are raised and lowered by a positioning system. A control system maintains the proper current and power input during charge melting – control is important because the amount of scrap may change under the electrodes while it melts. The arms holding the electrodes carry bus bars, which are usually hollow, water-cooled copper pipes, and convey current (electricity) to the electrode holders. The electrodes move up and down automatically to regulate the arc, and are raised to allow removal of the furnace roof. Heavy water-cooled cables connect the bus tubes with a vault-protected transformer, located adjacent to the furnace. The hearth, the bowl- shaped bottom of the furnace, is lined with refractory bricks and granular refractory material. The furnace can tilt (be tapped) so liquid steel can be poured into another vessel for transport.

Producing a ton of steel in an electric arc furnace requires around 400 to 500 kilowatt-hours. This is about one-third to one-tenth the energy required by basic oxygen furnaces or integrated blast furnaces

The systems described above are direct arc melting applications. Another type of furnace, using indirect arc melting, is also available. These furnaces have a horizontal barrel-shaped steel shell, lined with refractory. An arc is drawn between two carbon electrodes positioned above the load, and heat is transferred by radiation from the arc to the metal being melted. The shell rotates and reverses to avoid excessive heating of the refractory above the melt level, and to increase the efficiency. Indirect arc furnaces are common in the production of copper alloys. These units are generally much smaller than direct arc furnaces.

Submerged arc furnaces are another type of arc furnace. The term “submerged” is used because the electrodes are deep in the furnace and the reaction takes place at the tip of the electrodes. These furnaces are used to produce various metals by smelting minerals, and are also used to produce foundry iron from scrap iron. Ore materials are mixed with a reducing agent (usually carbon) outside the furnace, and this charge mix is added periodically to the furnace. The reduction reaction inside the furnace proceeds continuously and the metal accumulates until the furnace is tapped at intervals.

Process, Applications, and Industries

The primary application of large arc furnaces is in processes for melting of metals, primarily iron and steel from scrap steel and iron as raw materials; applications for smaller arc furnaces include the melting of iron and steel, and refractory metals. Refractory metals are generally categorized as metals having a high melting point such as Tungsten.

Direct arc furnaces used for steelmaking are typically smaller than integrated basic oxygen furnaces. These direct arc furnaces (sometimes known as mini-mills) use scrap iron and steel, instead of iron ore, to make steel. Arc furnaces use electricity, while basic oxygen furnaces typically use coal. In terms of capital cost, direct arc furnaces are less expensive (in terms of dollars per ton of steel capacity) than basic oxygen furnaces.

Direct arc furnaces used in foundries are usually for producing iron for casting operations. These units are typically less than 25 tons, and also use scrap steel and scrap iron. These furnaces are often used for the continuous casting for flat products like steel plates.

Submerged arc furnaces are used in smelting processes to produce materials such as silicon alloys, ferromanganese, calcium carbide, and ferronickel.

Improve the Efficiency of Existing Arc Furnace Systems

- Use bottom stirring/stirring gas injection. An inert gas (e.g., argon) is injected in the bottom of the arc furnace, increasing heat transfer in the melt and the interaction between slag and metal (increasing liquid metal).
- Install ultra-high-power transformers. Transformer losses depend on the sizing and age of the transformer. When replacing a transformer, the furnace operation can be converted to ultra-high-power, increasing productivity and reducing energy losses.
- Preheat scrap. The waste heat of the furnace is used to preheat the scrap charge.
- Insulate furnaces. Insulation using ceramic low-thermal mass materials reduces the heat losses through the walls better than conventional ceramic fiber linings.
- Use oxy-fuel burners in hybrid systems in first part of melt cycle. Using a fuel-based system in the first part of the heat cycle saves energy by increasing heat transfer and reducing heat losses.
- Post-combustion of flue gases. Burning flue gases optimizes the benefits of oxygen and fuel injection. The carbon monoxide in the flue gas is oxidized to carbon dioxide, while the combustion heat of the gases helps heat the steel in the arc furnace ladle.
- Use variable speed drives on flue gas fans. Monitoring flue gas and controlling flue gas fans with variable speed drives reduces heat loss.

Electric Infrared Processing

Infrared processing systems are used for heating, drying, curing, thermal-bonding, sintering, and sterilizing applications. Infrared applications, when designed and sized correctly, can rapidly heat an object quicker than hot air ovens. This is successfully accomplished if the absorption characteristics of the material are correctly matched to the wavelength emitted from the infrared system. Infrared systems do most of their heating using radiant energy. However, convection and conductivity can have a role in delivering and moving heat throughout the material being heated.

When discussing infrared applications, wavelength of the applied energy is one of many terms used to describe the heating process. Infrared emitters generate wavelengths generally classified as short, medium, and long, and are based on the temperature of the infrared emitter called the source temperature. Other infrared terms such as emissivity, energy density, and source temperature are important terms to know. These terms and more information on both electric and gas infrared technologies can be referenced in IHEA *Infrared Process Heating Handbook for Industrial Applications*.

History and Status

Industrial electric infrared systems were first used in the mid-1930s by Ford Motor Company to cure paint on auto bodies. With the advent of new infrared-absorbing coatings, and improved emitter designs and controls, infrared is replacing many of the traditional hot air heating systems used to cure coatings. Improved quality, faster cycle time, and a smaller footprint are just a few of the advantages.

Operation

Infrared is the name given to the part of the electromagnetic spectrum between visible light and radio waves. Infrared wavelengths range from 0.8 to 10 microns. Infrared energy, like light energy, can be transmitted, absorbed, and reflected. The absorbed energy is what heats the material. Objects being heated generally need to be in line-of-sight of the emitters (and/or reflectors which are used to direct the infrared energy to the part). However, heating and thus curing can still occur in areas not directly seen by the infrared by the heat transfer method of conductivity.

Electric infrared heating systems are typically comprised of an emitter (temperature source), a reflector system that directs the radiant energy toward the part, and a control system designed for the application. There is a wide selection of infrared emitters, reflector designs, and control systems to choose from. Therefore, the best approach for evaluating infrared is to test the application, and work with the many infrared distributors and manufacturers of infrared equipment to determine which option fits best for your application.

Some infrared emitters are designed with a ceramic board as both a reflector and absorber of infrared. The advantage of this design is to re- radiate energy from the board at a different wavelength, because of a different source temperature of the board, in combination with the primary wavelength from the source emitter. For some applications, an exhaust system may not be required. An infrared system designed to rapidly heat a material not releasing VOCs may not require ventilation; an example is water dry-off after a product wash. Because infrared systems can heat a product in as little as seconds, accurate control is critical. Using infrared without giving thought to the controls can lead to quality issues. Figure 1 shows a schematic of a typical electric infrared system with a simple feedback control system where temperature is the control point. More information about control systems can be referenced in the IHEA Infrared Process Heating Handbook for Industrial Applications.

Infrared heaters can be designed and built in a variety of shapes, sizes, and configurations. Ovens can take the form of flat lines, clam shell, tunnel u-shape, square, and round. Emitters can be selected to operate in any xyz axis orientation. There are many emitter designs, including: ceramic body types with embedded coils, exposed metal coils, ribbons, and foils mounted on ceramic boards, carbon fiber heaters, and quartz lamp and tube. These design variations give the end user the flexibility to use electric infrared technology replicate existing process applications as well as to explore new applications. Working with a knowledgeable infrared designer and applications expert, to include product testing, will ensure that the process is efficient and meets the performance required.

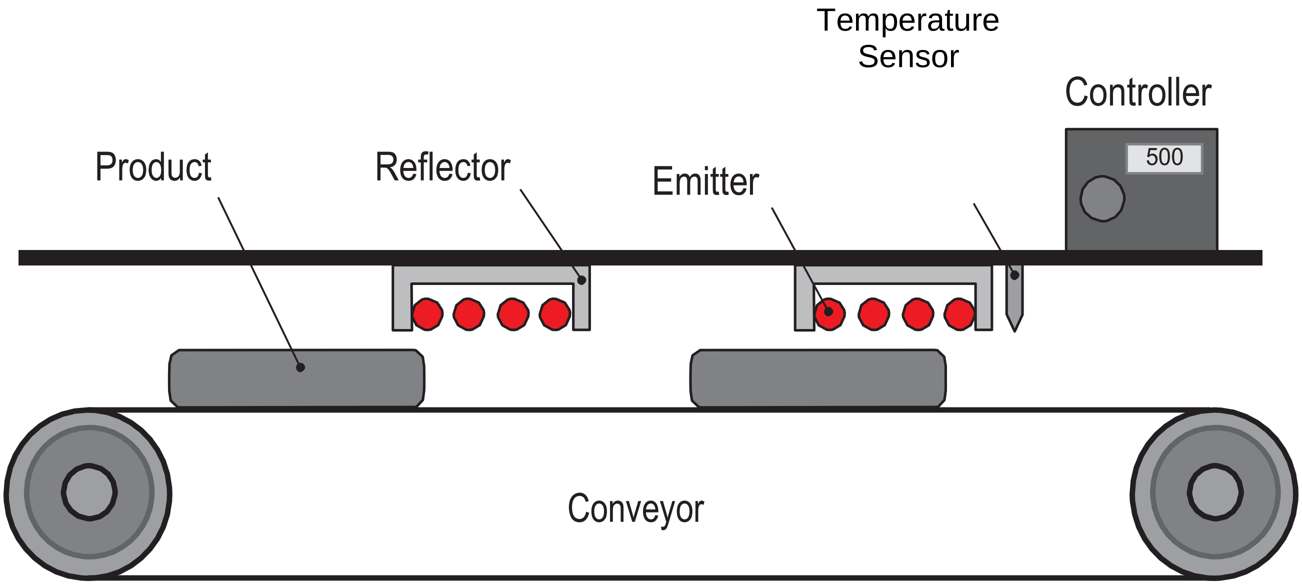

Figure 4. Simple schematic of an electric infrared heating system

Processes, Applications, and Industries

Electric infrared is ideal for situations where a fairly flat product is being heated, dried, or cured. In heating applications where infrared is used to heat heavier objects, the time to temperature is often much faster than hot air systems. However, an uneven heating situation may occur if the system is not properly designed and controlled. An example is an excavator arm that has been painted and is rapidly heated to temperature in the first zone of an infrared oven, then enters the second zone with less radiant energy applied to let temperature differences equilibrate, and finally enters a hold zone to meet curing specifications for the coating being used.

For products with complex hidden surfaces, there are solutions that can work around the line-of-sight issues. It could require a hybrid system with a convection oven where the infrared emitter panels are located in the vestibule or in the hot zone of the oven. Another solution is to use a material handling system to rotate the part to expose as much of the surface to direct infrared energy as possible. This will also assist with a more even heating of the part.

Common industrial applications for infrared are heating, curing, and drying in areas such as:

- Adhesive drying
- Annealing and curing of rubber
- Drying of parts (coated with paints or varnishes)
- Profile drying textiles and paper
- Drying coatings on steel and aluminum coil
- Ink curing
- Thermo forming of plastics
- Powder coating curing
- Shrink wrapping
- Silk screening.

Types of Electric-based Infrared Emitters

Electric infrared heating systems typically comprise an emitter, a reflector system, and controls. The emitter,(heat source), is a key part of the system – the energy emission characteristics must be well matched to the absorption characteristics, called emissivity, of the materials being heated to ensure efficient operation. There are many varieties of emitters that can be incorporated into IR systems, including panel heaters, ceramic bodies with embedded coils, metal coils, ribbons, foils, fiber heaters, and other designs. Manufacturers typically classify emitters based on the wavelength of emitted energy. These classifications are described in Table 3.

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Table 3. Infrared emitters by wavelength category

Infrared wavelength category	Source temperature* range (typical)	Peak wavelength/ radiant output	General category of IR emitters (typical)
Short (near)	Up to 4,000 ° F	1.15 µm / 90%	Quartz lamps having an inert gas to sustain the high source temperature. Often called T-3 for its 3/8 inch diameter lamp envelope. Considered very fast response
Medium (middle)	Up to 1,800 ° F	2.3 µm / 60%	Embedded coils in ceramic, surface mounted coils/ribbons, carbon fiber, coils in quartz tubes. Depending on emitter; medium to fast response
Long (far)	Up to 1,000 ° F	3 – 5 µm/ 50%	Embedded coils in ceramics and metal sheath Typically slow heat up time to temp; often because the heating element is of a heavier gauge metal

*Source temperature is the actual operating temperature of the infrared emitter. This is a determining factor as to the primary wavelength and radiant efficiency of the emitter. With controls, this source temperature can changed, within limits of the material, thereby changing both the radiant efficiency and wavelength.

Improve the Efficiency of Existing Electric Infrared Systems

Incorporating one or more of these recommendations can result in significant energy savings. Efficiency improvements from 10% to 30% in existing ovens have been demonstrated with the employment of these recommendations:

- Add baffles or additional reflectors to sides/top/bottom of the oven to re-radiate stray infrared energy back to the product.
- Keep a regular maintenance schedule that includes the cleaning of reflectors, end caps and emitters; and replacement of all failed emitters. Clean reflectors and emitters will more efficiently radiate the heat to the intended target.
- Perform periodic testing* to ensure performance. Data pack the product to review temperature profile is correct. A different emitter type or wavelength change through controls maybe necessary if a coating or process change has been made. Consider zoning that can direct the radiant energy most appropriately to the product. Zoning can be configured horizontally or vertically, and can be specifically profiled for the product, due to the controllability of electric infrared energy. A more sophisticated control system will be required.
- Consider the addition (retrofit) of moveable infrared banks. The electric emitters can be moved closer to smaller products and moved farther out for larger products. Proper emitter positioning with respect to the product can improve efficiency.
- Install a more efficient control system. In addition to providing for zoning, an effective control system can also provide for a variable control system instead of simple on/ off control. Some systems employ “closed-loop” control that can precisely deliver the required amount of radiant energy to the product, even if product size, shape, or color, etc. might vary. These systems generally employ non- contact radiometers and a PLC-based control panel.
- The Infrared Equipment Division (IRED) of the Industrial Heating Equipment Association (www.ihea.org) can provide a list of companies with infrared testing facilities. These companies generally provide free testing in their infrared labs.

Electron Beam Processing

History and Status

The principle of electron beam (EB) heating, in which the kinetic energy of an accelerated stream of electrons is converted to heat when impinged on a metal surface, was first developed as early as 1905. Today, EB systems have become a widely used method of manufacture. They are recognized for their ease of handling, operation, and focus on safety. EB heating is used extensively in many high-production applications for welding, particularly in the automotive industry

Using electron beam technology for heat-treating applications is relatively new. The primary application is local surface hardening of high-wear components for the automotive industry. Electron beams are also used for curing and can cure multiple layers of web material simultaneously, as well as curing surface coatings.

Electron beams can also be used for low temperature processing of some materials. Similar to ultraviolet energy, electron beams are an ionizing form of radiation that can induce chemical reactions such as polymerization for curing of coatings and composites. Sometimes referred to as “cold curing,” the process can accelerate curing times and utilize low-temperature tooling. Other non-thermal applications of electron beam processing are food irradiation and sterilization.

How the Technology Works

The basic components needed to produce a typical electron beam are an electron gun and a magnetic optic for controlling the beam to the target. The electron gun is comprised of a cathode, grid, and anode. When energized, the cathode, which directs a stream of electrons in a vacuum, and an anode, which collects the electrons, are accelerated and shaped into a controlled beam, either focused or defocused, onto the work piece. In EB heating, metals are heated to intense temperatures when a directed beam of electrons is focused against the work surface. In EB curing, a liquid is chemically transformed to a solid on the work surface by a stream of directed electrons. EB processing can be done under vacuum, partial vacuum, and nonvacuum conditions. High-vacuum conditions result in fewer gaseous molecules between the electron gun and the work piece, which results in less scattering and a tighter beam. Creating vacuum conditions, however, can slow production because of idle time between treating work pieces.

Process, Applications, and Industries

EB processing is used in many thermal process applications; welding metals, machining holes and slots, surface hardening of metals, and melting. In addition to thermal heating, EB competes with conventional drying methods to cure coatings, inks, and adhesives.

High Energy EB Applications

Electron beam processing of materials in a high-energy vacuum is used in many industries as a melting technique that does not introduce contamination. High energy EB systems are easily controlled by computer and operate with precise line of sight control of the beam producing energy in a very defined area.
They are used to produce materials ranging from refractory metal alloys to metallic coatings on plastic components. EB processing allows for super-pure materials and can impart unique properties to existing products. Another competitive benefit is minimal thermal distortions, because the power density and energy input can be precisely controlled. In addition, setup and cleaning time are substantially reduced, labor costs are low, and it can achieve complex and precise heating patterns.

Low-energy EB applications

Many of the traditional applications of EB technology are based on the use of low energy EB equipment, which is defined as operating with an accelerating voltage of less than 300 kV. The main processes enabled by low energy electron beam can be classified as: (A) curing, (B) crosslinking, (C) scission, and (D) grafting.

EB Curing

EB curing occurs when an electron beam creates radicals that initiate the polymerization of monomers and oligomers. Acrylate functional materials are most commonly used because of their high reactivity. In most cases, multifunctional monomers and oligomers are used to produce a cross-linked polymer network in the cured state. A well-established application for EB curing is the “drying” of inks on web-offset printed cartons, labels, and flexible packaging. There are also many other well established and emerging applications for EB curing which include applications in wood and metal coil coating and in the converting of release materials used for tape, label, electronics, and casting applications. The usage of EB curing in additive manufacturing is another emerging application area. Electron beam curing provides the ability to cure highly filled and opaque substrates at room temperature where ultraviolet (UV) curing struggles in performance in these areas.

Compared with conventional hot air drying methods, EB curing requires a much smaller footprint and lower operating labor. EB curing also drastically reduces the full cure time for coatings, inks and adhesives to less than a second. EB systems provide environmental benefits because they eliminate most volatile organic compounds, use little energy, and operate at near room temperature. Contrary to free-radical UV curing which requires a photoinitiator (or at least some photo-reactive moiety incorporated into the oligomer), free-radical EB curing occurs without adding a photoinitiator. The accelerated electrons produced by EB systems have sufficient energy to break chemical bonds within the materials themselves.

EB Crosslinking

Electron beam crosslinking occurs when free radicals recombine with each other. Crosslinking usually starts with a linear polymer material and results in the joining of adjacent polymer chains to form a three dimensional network. A relatively small number of crosslinks can often have a large impact on the thermal and mechanical properties of a polymer. Most polymers undergo both crosslinking and scissioning and the process that predominates depends on chemical structure and morphology of the polymer. Other well-established applications for EB crosslinking include high performance pressure sensitive adhesives and the nylon cord layer in automotive tires where electron beam irradiation maintains dimensional stability during the vulcanization process.

EB Scission

Electron beam scission occurs when polymer chains are broken and fail to recombine. The net result of polymer scission is a reduction in molecular weight. Industrial processes for EB scission are less common than curing or crosslinking. An example of scission is the processing of polytetrafluoroethylene (PTFE) to make low molecular weight fragments for use in waxes and lubricants. Electron beam scission can also be applied to biopolymers and cellulose. The irradiation of pulp where the modification of cellulose is needed (such as with cellulose acetate) is another emerging area of electron beam technology that could provide cost saving advantages and reduction in environmental pollutants.

EB Grafting

Electron beam induced graft copolymerization (EIGC) occurs when radicals formed in and on a polymer substrate become a site for initiation of monomer polymerization. The net result is that two dissimilar polymers are covalently joined to form a new copolymer material. Electron beam grafting is less well known than curing or crosslinking but is an important process for creation of new functional materials. It can be used to modify the properties of polymer films, gels, fibers, beads, or membranes. Applications for EB grafting include the production of polymer membranes tailored for specific separation or purification processes.

Improve the Efficiency of Existing Electron-beam Systems

- Operate under vacuum conditions. When electron-beam processing is performed under vacuum conditions, there is less scattering of the beam, resulting in higher energy efficiency because more of the energy is transferred to the product.
- Improve control systems. Better process control systems, including those with feedback loops, allow systems to use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Electron beam systems require consumable part replacement and a consistent maintenance program for “wearable” components such as filaments and foils.
- Any changes in any of the original design parameters will require analysis of the original design to assure an efficient application of the technology.

Induction Heating and Melting

History and Status

The principles of induction heating have been applied to manufacturing operations since the 1930s, when the first channel-type induction furnaces were introduced for metals melting operations. Soon afterward, coreless induction furnaces were developed for melting, superheating, and holding. In the 1940s, the technology was also used to harden metal engine parts. More recently, an emphasis on improved quality control has led to increased use of induction technology in the ferrous and nonferrous metals industries.

How the Technology Works

In a basic induction heating setup, a solid-state power supply sends an alternating current (AC) through a copper coil creating an electromagnetic field. The material to be heated is placed inside the magnetic field where circulating eddy currents are induced within the part. These currents flow against the electrical resistivity of the metal generating heat.

The efficiency of an induction heating system for a specific application depends on several factors: the characteristics of the part itself, the design of the induction coil, the capacity of the power supply, and the degree of temperature change required for the application. Induction heating only works with electrically conductive materials, and metals are the usual application. However, carbon fiber is a conductive material and some carbon fiber composites can also be heated using induction. It is possible to introduce heat indirectly into non-conductive materials such as plastics by first heating a conductive metal called a susceptor, which is designed to transfer heat into the nonconductive material.

Heating and Heat Treating. For rapid heating and heat treating processes, the heating depth is easily controlled by the frequency of the electric current applied to the coil. No direct contact between the part and the coil is required, but the coil must be in close proximity to the work piece. Because there is no contract, this technology is ideal for automating industrial processes. Induction heating is often used where repetitive, high volume operations are performed. Once an induction system is calibrated for a part, work pieces can be loaded and unloaded automatically.

Melting. An induction furnace induces an electric current in the material to be melted, creating eddy currents which dissipate energy and produce heat. The current is induced by surrounding the material with a wire coil carrying an electric current. When the material begins to melt, electromagnetic forces agitate and mix the liquid. Mixing and melting rates can be controlled by varying the frequency and power of the current in the coil. For melting operations, induction processing is used primarily in the refining and remelting of metals. Metals that are melted include aluminum, copper, brass, bronze, iron, steel, and zinc.

Coreless furnaces have a refractory crucible surrounded by a water-cooled AC current coil. Coreless induction furnaces are used primarily for remelting in foundry operations and for vacuum refining of specialty metals.

Channel furnaces consist of a primary coil wound around a core. The secondary side of the core is in the furnace interior, surrounded by a molten metal loop. Channel furnaces are usually holding furnaces for nonferrous metal melting, combined with a fuel-fired cupola, arc, or coreless induction furnace.

Process, Applications, and Industries

Common applications for induction heating include the rapid heating of metal based parts, metal joining, welding, soldering and brazing, and selective heating and heat treating processes on metal components. Induction heat treating systems used for hardening, tempering and annealing are common, particularly in the transportation industry. Induction heat treating is used on a range of metal parts, including bar and tubing, bearings, axel shafts, camshafts, gears and sprockets.

Induction heating can produce high power densities resulting in very fast heating times to reach a target temperature. For common hardening processes, induction heating is used for localized surface hardening of an area that needs wear-resistance, while retaining the toughness for the rest of the part. These processes are easily accomplished with induction heating, and they are repeatable from part to part with a precision unmatched by most competing technologies. The depth of induction hardened patterns can be controlled by changing the induction-frequency, power-density and dwell time. With precise control of the heating zone pattern, minimal thermal distortion is seen in the part.

With conductive materials, about 80% of the heating effect occurs on the surface or “skin” of the part. The heating intensity diminishes as the distance from the surface increases, so small or thin parts generally heat more quickly than large thick parts, especially if the larger parts need to be heated all the way through. It is easiest to heat magnetic materials with induction technology. In addition to the heat induced by eddy currents, magnetic materials also produce heat through the hysteresis effect. During the induction heating process, magnetics naturally offer resistance to the rapidly alternating electrical fields, and this causes enough friction to provide a secondary source of heat. This effect ceases to occur at temperatures above the “Curie” point, which is the temperature at which a magnetic material loses its magnetic properties. The relative resistance of magnetic materials is rated on a “permeability” scale of 100 to 500: nonmagnetics have a permeability of 1, while magnetic materials can have a permeability as high as 500.

Induction heating can also be used to heat liquids in vessels and pipelines, primarily in the petrochemical industry. Induction heating involves no contact between the material being heating and the heat source, which is important for some operations. This lack of contact facilitates automation of the manufacturing processes.

Induction systems are often used in applications where only a small targeted area of a work piece needs to be heated. Hand tools are an example. Because induction systems are clean and release no emissions, sometimes a part can be hardened on an assembly line without having to go to a remote heat treating operation. Other applications for induction heating include the curing of protective coatings on cast and welded pipes

Improve the Efficiency of Existing Induction Systems

Melting

- Use high-efficiency solid-state power supplies. High-efficiency units have less heat loss in the power supply itself.
- Improve the refractory. Improving refractory provides better insulation and reduces heat loss. Savings up to 20%.
- Apply short bus bars. Shorter bus bars reduce resistive losses.
- For highly conductive metals such as aluminum, copper alloys, and magnesium, increase the load resistance by coupling the electromagnetic field to the crucible instead of the metal itself.
- Shared power supply. Two melters can share the same power supply by taking advantage of an optimized melting schedule.
- Melting without a cover on the crucible can account for approximately a 30% energy loss.

Heating and Heat Treating

- Use high-efficiency solid-state power supplies. High- efficiency units have less heat loss in the power supply itself.
- Adopt a dual-frequency design. A low-frequency design is used during the initial stage of the heating when the bar retains its magnetic properties, and a higher frequency is used in the next stage when the bar becomes nonmagnetic.
- Use flux concentrators. These passive devices channel the induction field to provide a contained pathway for the magnetic fields. Stray magnetic fields are reduced and less power is required to complete the tasks.
- For multi-stage coil designs, any existing open inspection or work access gaps needs to be shielded to reduce heat loss. If an inspection port is needed, a quartz window can be installed.
- Tailor the coil design to the product to increase the efficiency of heating. In many cases, the same coil is used to produce a number of different products. Using coils designed specifically for a product will improve efficiency by up to 50%.

Laser Processing

History and Status

Laser processing systems started with small laboratory lasers developed in the 1960s. Today, thousands of commercial-scale units are in use by industry for surface hardening, material removal, and welding operations.

How the Technology Works

The word "laser" is an acronym for Light Amplification by the Stimulated Emission of Radiation. Lasers are a source of high-intensity light produced by passing electricity through a lasing medium. Lasing mediums can be gases or solid-state. All of a laser's light is of the same wavelength and is in phase, creating a high-energy density. With laser processing, a laser beam is focused with high intensity, which causes a surface to be heated rapidly.

Laser heat treating transmits energy to a material's surface to create a hardened layer, caused by metallurgical transformation. After being heated, the material is quenched, or heat sinking from the surrounding area provides rapid self-quenching. Lasers can be precisely controlled dimensionally and directionally, and can be varied in output and by timeframe. They are best used to harden a specific area instead of an entire part. Because of their controllability, laser hardening is generally an energy-efficient technology. These attributes also make laser processing useful for precise material removal.

Processes, Applications, and Industries

Except for single-phase stainless steels and certain types of cast iron, most common steels, stainless steels, and cast irons can be surface heat treated (hardened) by laser processing. Each kind of steel has special characteristics that need to be considered. A laser is typically used to harden localized areas subject to high stress, such as crankshafts, gears, and high-wear areas in engine components. Laser processing can also be used for a variety of other applications, including trimming electronic components; cutting fabrics, metal, and composites; and material removal.

For cutting and material removal operations, lasers have capabilities beyond conventional numerically controlled machine tools. In the past, laser processing was generally used for prototypes or small production runs, but now it is increasingly used for metal working applications, such as a new way of stamping. Laser processing can rapidly and accurately cut most materials with little heat-induced distortion.

For welding operations, conventional welders can perform the same operations as laser welding. Laser processing is usually used for applications requiring a narrow weld, such as welding turbine blades onto rotor shafts. Laser processing tends to be faster and has less product distortion compared to conventional welding techniques.

For surface hardening applications, laser processing performs the same process as induction heating and fuel- based furnaces. Laser processes are generally use for applications where selective areas within a given work piece need to be hardened.

Improve the Efficiency of Existing Laser-Processing Systems

- Understand the type of laser used in the process. There are many types of lasers used which have different efficiencies and performance parameters. Each type has its own set of steps to improve efficiency.
- Many lasers cannot be turned off/on quickly enough for a process and therefore must dump the beam into a closed shutter. In this position, heat is generated and must be removed by the cooling system. Improving your laser path layout can reduce closed shutter time.
- Chiller operational efficiency. This is the system component that uses the most energy in a laser process. Better laser efficiency uses less chiller process energy. Maintenance on the chiller can mean energy savings of up to 35%.
- Beam delivery optical losses. Maintain beam optics by assuring cleanliness. Dirty optics reduce power at delivery, generating heat and reducing efficiency by up to 10%
- Laser cavity optical losses. Check mirrors for alignment; misalignment can cause thermal distortion and will degrade performance by up to 20%.

Microwave Processing

History and Status

Microwave processing technology development was a result of research on radar systems during World War II. The first industrial use of microwave processing was in the food industry. Although considerable research and development was spent in the 1950s and 1960s to develop other industrial applications, few emerged. Interest in microwaves increased in the 1980s as a way to raise productivity and reduce costs. There are currently many successful applications of microwave processing in a variety of industries, including food, rubber, ceramic, pharmaceutical, polymers, plastics, and textiles.

How the Technology Works

Microwave refers to the radio-frequency portion of the electromagnetic spectrum between 300 and 300,000 megahertz (MHz). Industrial sources of microwaves are generally limited to FCC-allocated frequencies of 915 MHz, 2,450 MHz and 5,800 MHz.[4] Microwaves are used to heat materials that are electrically non-conducting (dielectrics) and composed of polar molecules. Polar molecules have an asymmetric structure and align themselves to an imposed electric field. When the direction of the field is rapidly alternated, the molecules move in synchronization, creating friction and producing heat.

Industrial microwaves are produced by magnetron tubes, which are composed of a rod-shaped cathode surrounded by a cylindrical anode. Electrons flow from the cathode to the anode, creating an electric and magnetic field. The field frequency is a function of the dimension of the slots and cavities in the magnetron. Oscillations in the slots and cavities form microwaves.

A microwave processing system is usually comprised of four components:

1. **Generator** - The power supply and the magnetron. A magnetron is typically water or air-cooled and is a replacement component.

2. **Applicator** - Waveguides, usually constructed of aluminum in duct form, direct microwaves to the product being heated.
3. **Materials Handling System** - System that positions the product under the applicator or exposure area.
4. **Control System** - System that monitors heating and regulates exposure time.

Process, Applications, and Industries

The most widespread use of industrial microwave processing is in the food industry for applications such as heating, tempering (bringing from deep-freeze to just below freezing), drying, and precooking. Other applications include the following:

- Vulcanizing rubber
- Polymerizing resins
- Welding plastics
- Dewaxing molds
- Drying products.

Microwave operations can perform many of the functions of convection ovens, but are typically used where speed and unique heating requirements are dictated. Hybrid systems, in which microwave processing is combined with other process heating systems, are common. Microwaves have a higher power density than radio frequency (RF) energy and usually heat materials faster, although RF's longer wavelengths can penetrate thicker material. For a given application, one technology is usually better than the other, and testing is recommended to determine suitability.

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[4] Note – these frequencies and those used in radio frequency (RF) applications are designated as ISM bands (Industrial, Scientific and Medical)

Improve the Efficiency in Existing Microwave Systems

- Frequent visual inspection of the overall system process to include cleanliness of the wave guides and the operating condition of all motors and drives associated with process will reduce system down time.
- Re-evaluate the system. Once a system is installed for a designed application, the efficiency will remain the same until product parameters change. Any change in the material (e.g. width, depth, or weight) will require a re-evaluation of the system in order to maintain the efficiency.
- Replace aging generators. Magnetrons have a serviceable life measured in hours. Replacing them per the vendor’s recommendations will keep the system operating at designed efficiency.

Plasma Processing (Arc and Nontransferred Arc)

History and Status

Industrial plasma processing systems have been in use for more than 30 years. In the early stages, plasma processing was used for welding, cutting, and surface hardening. Metals heating and melting applications were first commercialized about 20 years ago.

How the Technology Works

Plasma is a state of matter formed when a gas is ionized. Plasma is created when gas is exposed to a high-intensity electric arc, which brings it up to temperatures as high as 20,000˚F, freeing electrons from their atoms. Plasmas are good conductors of both heat and electricity.

Plasmas can be generated by exposing certain gases to a high-intensity arc maintained by two electrodes, or by rapidly changing electromagnetic fields generated by induction, capacitive, or microwave generators. Power is regulated by levels of arc current and arc voltage.

There are two types of plasma processing: transferred arc and nontransferred arc. In transferred arc processing, an arc forms between the plasma torch and the material to be heated. The torch acts as the cathode, the material as the anode, and an inert gas passing through the arc is the plasma. These systems are used for metals heating and melting. In nontransferred arc processing, both the anode and the cathode are in the torch itself and compressed air is used to extend the arc to the process. The torch heats plasma gas composed of gases like argon or hydrogen, creating extremely high temperatures for chemical reactions or other processes.

Process, Applications, and Industries

Applications for plasma processing include bulk melting of scrap and remelting in refining processes. Plasma processing is common in the titanium industry, as well as in melting high-alloy steels, tungsten, and zirconium. It can also be used in the reduction process for sponge iron and smelting reduction of iron ore and scrap.

Other plasma heating applications include disposal of toxic ash, asbestos, and sludge; diamond film production; hydrocarbon cracking; boiler ignition; and surface hardening. Plasma processing is also used for metals fabrications processes, welding, cutting, and spray metal and ceramics coatings. It is also used in the semiconductor industry for water production. For melting metal applications, electric arc furnaces and various types of fuel-based furnaces can perform the same function as plasma processing. Unlike the electric arc, the nontransfer arc plasmas can be used to heat nonconductive materials.

Improve the Efficiency of Existing Plasma Processing Systems

- Replace aging torch electrode. As torches age, they become less efficient.
- Improve control systems. Better process control systems, including those with feedback loops, allow systems to use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Perform preventative maintenance on the process gas and cooling systems to maximize electrode life.

Radio-Frequency Processing

History and Status

The concept of using radio waves to heat material was known in the late 19th century, but industrial applications did not arrive until the 1930s, when techniques for generating high-power radio waves were developed.

How the Technology Works

The radio frequency (RF) portion of the electromagnetic spectrum is between 2 and 100 MHz. RF waves can be used to heat materials that are electrically nonconducting (dielectrics) and composed of polar molecules. Polar molecules have an asymmetric structure and align themselves to an imposed electric field. When the direction of the field is rapidly alternated, the molecules move in synchronization, producing heat by creating friction.

RF waves are produced by generators that use either a controlled frequency oscillator with a power amplifier (also called “50-ohm” or “fixed impedance”), or a power oscillator in which the load to be heated is part of the resonant circuit (also known as “free-running” oscillators). The 50-ohm generators are used most prevalently in industrial processes, and typical frequencies for industrial applications are 13.56 MHz and 27.12 MHz.

RF processing systems usually has five components:

1. **Generator.** The oscillator and an amplifier.
2. **Impedance matching network.** Used only in 50-ohm generators.
3. **Applicator.** Electrodes that expose the radio-frequency electric field to the product being heated.
4. **Material handling system.** The part of the system that positions the product under the applicator or exposure area.
5. **Control system.** This monitors heating and regulates exposure time.

Process, Applications, and Industries

The most widespread use of industrial RF processing is in the production of plasmas for semiconductor manufacture and in drying products in the food, lumber, and paper industries. Other applications include drying textiles and films, curing adhesives, heating plastics, baking, drying ceramic products, and sterilizing medical waste.

Convection ovens can perform the same heating processes as RF ovens. RF processing is generally used because of increased production needs, increased energy efficiency, labor savings, or space savings. In some cases, hybrid systems utilize both RF energy and a convection heating/drying.

For new applications that involve the heating/drying of dielectric materials, RF and MW should both be considered; testing can provide a good indication of the relative strengths/weaknesses of each technology for a given application.

Improve the Efficiency of Existing Radio Frequency (RF) Systems

- Verify that the correct frequency is being used. The amount of heat generated is a function not only of the output of the power supply, but also the frequency of the field.
- Use programmable logic controller to optimize your process. Good control systems allow for precise application of heat at the proper temperature for the correct amount of time.
- Consider a hybrid radio-frequency/convection heating system. The efficiency of a convection dryer drops significantly as the moisture level in the material decreases, and RF energy couples directly with the water. At this point, RF energy is more efficient at removing the moisture. This technology is particularly useful for drying of heat sensitive materials, since efficient drying can occur without exceeding the boiling point of water.

Resistance Heating and Melting

History and Status

Resistance heating is the simplest and oldest electric-based method of heating and melting metals and nonmetals. Efficiency can reach close to 100% and temperatures can exceed 3,600ºF. With its controllability, and rapid heat-up qualities, resistance heating is used in many applications from melting metals to heating food products. Resistance heating can be used for both high-temperature and low-temperature applications.

How the Technology Works

There are two basic types of this technology: direct and indirect resistance heating.

Direct resistance. With direct resistance (also known as conduction heating), an electric current actually flows through a material and heats it directly. This is an example of the Joule Law or effect5 at work. Typically, metal is clamped to electrodes in the walls of the furnace and charged with electric current. Electric resistance within the load generates heat, which heats or melts the metal. The temperature is controlled by adjusting the current, which can be either alternating current (AC) or direct current (DC).

The material to be heated must conduct at least a portion of the electric current for direct resistance to work. Metals with low conductivity, such as steel, create more resistance and more heat, which makes the process more efficient. Direct resistance heating is used primarily for heat treating, forging, extruding, wire making, seam welding, glass heating, and other applications. Direct resistance heating is often used to raise the temperature of steel pieces prior to forging, rolling, or drawing applications. Direct resistance heating is also commonly used for heating and melting applications in the glass industry.

Indirect resistance. With indirect resistance heating, a heating element transfers heat to the material by radiation, convection, or conduction. The element is made of a high- resistance material such as graphite, silicon carbide, or nickel chrome. Heating is usually done in a furnace, with a lining and interior that varies depending on the target material. Typical furnace linings are ceramic, brick, and fiber batting, while furnace interiors can be air, inert gas, or a vacuum.

Indirect resistance heating can also be done with an encased heater, in which the resistive element is encased in an insulator. Called metal sheath heaters this type of heater can be placed directly in liquid to be heated or close to a solid that requires heating. Numerous other types of resistance heating equipment are used throughout industry, including strip heaters, cartridge heaters, and tubular heaters.

Resistance heaters that rely on convection as the primary heat transfer method are primarily used for temperatures below 1,250˚F. Those that employ radiation are used for higher temperatures, sometimes in vacuum furnaces.

Indirect resistance furnaces are made in a variety of materials and configurations. Some are small enough to fit on a counter top, and others are as large as a freight car. This method of heating can be used in a wide range of applications. Resistance heating applications are precisely controlled, easily automated, and have low maintenance. Because resistance heating is used for so many different types of applications, there are a wide variety of fuel-based process heating systems, as well as steam-based systems, that perform the same operations. In many cases, resistance heating is chosen because of its simplicity and efficiency.

Process, Applications, and Industries

Direct resistance heating is used extensively in the glass industry. Resistance furnaces are also used for holding molten iron and aluminum. Direct resistance processing is also used for welding steel tubes and pipes.

Indirect resistance heaters are used for a variety of applications, including heating water, sintering ceramics, heat pressing fabrics, brazing and preheating metal for forging, stress relieving, and sintering. This method is also used to heat liquids, including water, paraffin, acids, and caustic solutions. Applications in the food industry are also common, including keeping oils, fats, and other food products at the proper temperature. Heating is typically done with immersion heaters, circulation heaters, or band heaters. In the glassmaking industry, indirect resistance provides a means of temperature control. Many hybrid applications also exist, including “boosting” in fuel-fired furnaces to increase production capacity.

Resistance heating applications are precisely controlled, easily automated, and have low maintenance. Because resistance heating is used for so many different types of applications, there are a wide variety of fuel-based process heating systems, as well as steam-based systems, that perform the same operations. In many cases, resistance heating is chosen because of its simplicity and efficiency.

Improve the Efficiency of Existing Resistance Heating Systems

- Improve control systems. Better process control systems, including those with feedback loops, use less energy per product produced. Good control systems allow precise application of heat at the proper temperature for the correct amount of time.
- Clean heating elements. Clean resistive heating elements can improve heat transfer and process efficiency.
- Improve insulation. For systems with insulation, improvements in the heat containment system can reduce energy losses to the surroundings.
- Match the heating element more closely to the geometry of the part being heated.

Ultraviolet Processing

History and Status

Ultraviolet (UV) processing has been used for many years to cure various types of industrial coatings and adhesives, as well as for curing operations in printing and electronic parts applications.

How the Technology Works

UV radiation is the part of the electromagnetic spectrum with a wavelength from 4 to 400 nanometers. Applying UV radiation to certain liquid polymeric substances transforms (cures) them into a solid coating. Curing is the process of bonding or fusing a coating to a substrate and developing specified properties in the coating. Curing involves a change in the molecular structure of the coating to form a solid.

Curing is different than drying in which coating materials are suspended in a solvent and remain on a surface when the solvent evaporates.

- UV curing systems are based upon either acrylate chemistry or cationically cured coatings
- Acrylate chemistry is much more common and cures free radical polymerization
- A major benefit of the acrylate method is that one can create a cured film with diverse properties because there are a wide variety of oligomers to choose from

UV radiation is created using a UV lamp, typically a mercury vapor lamp or xenon gas arc. The most common UV system is a medium-pressure mercury lamp. A high- voltage discharge ionizes a mercury gas-filled tube, creating UV radiation. The discharge can be created by an arc between two electrodes by microwave radiation, or by solid state light emitting diode devices. The lamp is housed in an enclosure with a reflector, with air or water cooling to prolong lamp life.

A relatively new UV LED (Light Emitting Diode) technology is encroaching on the applications that were previously served by conventional medium pressure mercury lamps. In many UV curing applications, UV LED offers reduced energy and operations costs compared to the incumbent technology. LED UV emitters are becoming more common and they are likely to eclipse the older mercury vapor lamp and xenon gas arc technologies in the coming years.

Process, Applications, and Industries

With the UV light generated, the process of curing can begin. Photoinitiators in the coating or adhesive are excited and activates the polymerization process. Photoinitiators typically absorbs light in two wavelength regions, either 260nm or 365nm. UV curing occurs via a photochemical reaction. UV coatings contain monomers, oligomers, and pigments as well as the photoinitiators. The coatings polymerize almost instantaneously into a hard plastic-like substance.

Wavelength of intense absorption tends to favor coating surface cure while wavelength of lower absorption tends to favor coating through cure, which is why some coatings require a mixture of multiple photoinitiators. There are four ranges of UV wavelengths:

UV Type	Range (nm)	Uses
UVA	315-400	For curing of thick layers i.e. floor coverings w/wear layers
UVB	280-315	In-depth drying for heavier inks coats i.e. silk screen
UVC	200-280	Maintain reaction for through curing i.e. general ink surface hardening
UVV	100-200	For surface cure/touch care; activates photoinitiators; germicidal UV

The four main applications for UV curing are coatings, printing, adhesives, and electronic parts.

Coatings. Common industrial coatings cured with UV radiation include those applied to wood, metals, paper, plastics, vinyl flooring, and wires. The coating can be a liquid or a powder, with both having similar characteristics.

Printing. Lithographic, silk screen, and flexographic printing operations can use UV curable inks instead of solvent-based, thermally cured inks.

Adhesives. Adhesive materials processed with UV radiation are common in the structural and packaging markets.

3 – PERFORMANCE IMPROVEMENT OPPORTUNITIES – ELECTRIC-BASED SYSTEMS

Electronic parts. UV processing is used throughout the electronics and communications parts manufacturing industry to cure polymeric materials, especially with printed circuit board lithography

UV processing is also used in the wastewater industry to treat water and to purify indoor air. Convection and radiant systems can perform the same curing processes as UV-based systems. However, UV-based systems typically have more rapid curing speeds, produce fewer emissions, and can cure heat-sensitive substrates. The cross linking of molecules requires minimal or no solvents as part of the coating. These systems require special UV-curable coatings and generally a custom-made lamp system for a particular application. UV curing takes about 25% of the energy required by a thermal-based system using a fuel-fired oven. They can increase output because of the nearly instantaneous curing time. Although UV coatings are more expensive on a cost- per-gallon basis, they do not require costly thermal oxidizers to destroy VOCs emitted by solvent-based coatings. In addition, there is no reduction in the cured coating thickness versus applied coating thickness.

Improve the Efficiency of Existing UV Systems

- Keep lamps clean. Lamps should be cleaned on a regular schedule. A clean lamp surface not only provides unrestricted output of the UV wavelength but more importantly prevents devitrification, or breakdown of the quartz envelope, which would cause premature lamp failure.
- Keep reflectors clean. Dull and corroded reflectors can reduce UV output by up to 50%. Also check for dented or distorted reflectors which can change the focus point and the performance of the UV emitter.
- Visually inspect all components of the system. The cooling and exhaust systems must be properly maintained to prevent overheating and premature failure of the lamps and other system components. Actions such as cleaning cooling fan filters per manufacturer's recommendations should be performed.
- Monitor the hours of operation. Under normal operating conditions, UV lamps have an expected serviceable life measured in hours. Going beyond the recommended hours will result in a drop-off of UV output.

Summary of Electrotechnologies for Process Heating

Table 4 summarizes the electrotechnologies that were covered in this section, with their applications, the primary industries that utilize them, and competing technologies.

Table 4. Summary of electrotechnologies for process heating

Electrotechnology	Applications	Primary Industries	Competing Technologies
Arc Furnaces	Steel production, melting steel, iron and refractory metals, smelting	Primary metal production, especially steelmaking	Oxygen furnaces (coal), plasma processing
Electric Infrared Processing	Heating, drying, curing, thermal-bonding, sintering, sterilizing	Fabricated metal products, transportation equipment, plastics and rubber	Electron beam processing, ultraviolet curing, resistance heating, induction heating
Electron Beam Processing	Melting, drying, welding, machining, curing, crosslinking, grafting	Fabricated metal products, machinery, transportation equipment, plastics	Infrared processing, laser processing, ultraviolet curing, induction melting, arc welding
Induction Heating and Melting	Heating, heat treating, melting	Fabricated metal products, primary metals, transportation equipment, machinery	Resistance heating, infrared processing, electron beam processing, gas furnaces
Laser Processing	Heat treating, hardening, trimming and cutting, welding	Transportation equipment, fabricated metal products, electronics	Electron beam processing, plasma processing, induction heating, arc welding
Microwave and RF Processing	Heating, tempering, drying, cooking, plasma production	Food/beverage, plastics and rubber, wood products, chemicals	Resistance heating, induction heating, ovens
Plasma Processing	Melting scrap, remelting for refining, reduction, surface hardening, welding, cutting	Primary metals (titanium, high-alloy steels, tungsten)	Arc furnaces, oxygen furnaces, electron beam processing, laser processing
Resistance heating and melting	Heating, brazing, sintering, melting	Glass production, metal products, plastics, chemicals, food	Induction heating and melting, infrared processing, microwave/RF processing, gas furnaces
Ultraviolet Curing	Curing, coatings, printing, adhesives, purifying	Computers, electronics, printing, fabricated metal products, transportation equipment, machinery	Electron beam processing, infrared processing

SECTION 4: WASTE HEAT MANAGEMENT – REDUCTION, RECYCLING AND RECOVERY

The Department of Energy's Advanced Manufacturing Office (AMO) has previously conducted several studies to identify heat losses from industrial energy systems. This section explores major sources and characteristics of industrial waste heat and its generation for industrial sectors, focusing on fuel-based process heating technologies. For tip sheets on specific waste heat management strategies for process heating systems, see Appendix B. A technical brief for waste heat reduction and recovery is also provided in Appendix C.

Waste heat is generated from a number of industrial systems distributed throughout a manufacturing plant. The largest sources of waste heat for most industries are exhaust or flue gases and heated air from heating systems from heat treating furnaces, dryers, and heaters; and heat from heat exchangers, cooling liquids, and gases. While waste heat in the form of exhaust gases is readily recognized, waste heat can also be found in liquids and solids. Liquids containing waste heat include cooling water, heated wash water, and blow-down water. Solids containing waste heat can be hot products that are discharged after processing or after reactions are complete, or they can be hot by-products from processes or combustion of solid materials. Other waste heat sources that are not as apparent include hot surfaces, steam leaks, and boiler blow-down water etc. Table 5 shows major sources of industrial waste heat along with the temperature range and characteristics of the source

Table 5. Temperature range and characteristics for industrial waste heat sources[5]

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

Typical Waste Heat Streams in Plant Operations

The waste streams from almost all industries vary in temperature, composition, and content, which may include particulates, vapors, or condensable materials. Following are the types of waste heat streams:

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[5] Oak Ridge National Laboratory (ORNL), *Industrial Waste Heat Recovery: Potential Applications, Available Technologies and Crosscutting R&D Opportunities*, Arvind Thekdi (E3M Inc.) and Sachin Nimbalkar (ORNL), ORNL/TM-2014/622, January 2014.

Exhaust Gases or Vapors

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

- High-temperature combustion products or hot flue gases that are relatively clean and can be recovered using commercially viable heat recovery equipment to produce high-temperature air, steam, or water for use in processing equipment or other uses such as direct discharge for building heating. Examples include a large number of directly fired and indirectly fired heating processes that are widely used by all major industries.
- High-temperature flue gases or combustion products with contaminants such as particulates and condensable vapors. In many cases, these contaminants would present problems due to condensation of vapors in liquids or on solids, which can foul the surfaces of the heat transfer equipment. Examples include exhaust gases from melting furnaces, dryers, kilns, and coal-fired boilers.
- Heated air or flue gases containing high (>14%) O2 without a large amount of moisture and particulates. This stream does not have as many restrictions on condensation temperature as the combustion products due to the low concentration or absence of acid-forming gases (e.g., CO2) and can be cooled to a lower temperature without having major detrimental effect of corrosion. Examples include indirectly used cooling air from processes, gas turbine exhaust gases, some product cooling systems, and air coolers used in refrigeration or chiller systems.
- Process gases or by-product gases and vapors that contain combustibles in gaseous or vapor form requiring further treatment before their release into the atmosphere. Examples are exhaust from coating ovens and process reactors.
- Process or make-up air mixed with combustion products, large amounts of water vapor, or moisture mixed with small amounts of particulates but no condensable organic vapors. Examples include exhaust air from paper machines, ceramic dryers, and food dryers.
- Steam discharged as vented steam or steam leaks.
- Other gaseous streams.

Heated Water or Liquid

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

- Clean heated water discharged from indirect cooling systems such as process or product cooling or steam condensers. This stream does not contain any solids or gaseous contaminants.
- Hot water that contains large amounts of contaminants, such as solids from the process or other sources, but does not contain organic liquids or vapors. The solids can be filtered out without further treatment of water. Examples include quenching or cooling water used to cool hot parts in the metals industry, paper industry, or cement industry.
- Hot water or liquids containing dissolved solids, dissolved gases (e.g., CO2, SO2), or liquids. These liquids (water) require further treatment before their use or discharge in the streams. Examples include scrubber water; wash water from chemical processes or from the food, paper, or textile industries.

Heated Products or By-Products

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

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

aluminum melters, and bottom waste from reactors or sludge.

High-Temperature Surfaces

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

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

Waste Heat Management

Waste heat management includes waste heat reduction, recycling, and recovery.

1) Waste heat reduction (heat containment):

Waste heat reduction refers to the reduction of energy losses to the surroundings. Most process heating equipment including boilers loose heat in many different ways. Major areas of heat loss, which can be reduced through use of good system design, operating practices and maintenance of heating systems, are discussed below.

A large amount of literature and a number of tools such as the Process Heating Assessment Tool (PHAST) are available that can be used to reduce heat losses.
Major areas of heat loss from process heating systems include:

- Exhaust or flue gas. All fuel fired equipment and some electrically heated equipment require discharge of large amount of hot gases at temperature that is dependent on the process temperature and other factors such as use of heat recovery systems. These gases may contain combustion products such as CO_2, H_2O, O_2, N_2 and, in some cases gaseous or solid contaminants.
- Walls. The hot surfaces of the furnace, dryer, and heat exchanger lose energy to the ambient spaces through both radiation and convection.
- Air infiltration. Many furnaces operate at slightly negative pressure. Under these conditions, air can be drawn into the furnace, especially if integrity of the furnace is not inspected often.
- Radiation heat loss from openings in furnace walls or doors. This is the result of not having proper seals at the doors used for material handling.
- Water- or air-cooled parts located within the furnace. These parts should be avoided where possible or insulated to avoid direct exposure to the hot furnace surroundings.
- Extended parts or surfaces from the furnace. Parts such as roller shafts get hot and result in heat losses.
- Poor insulation condition. Like furnace walls, surfaces such as piping and ductwork that have poor insulation are sources of energy loss. In many cases, the loss of energy to work spaces that are HVAC conditioned results in additional burdens on cooling systems. This added demand on the cooling system should be accounted for when considering the restoration or installation of the insulation.

Heat Containment Opportunities

Performance Improvement	Savings
• Reduce wall heat losses	2 to 5%
• Furnace pressure control	5 to 10%
• Maintain door and tubes seals	up to 5%
• Reduce cooling of internal parts	up to 5%
• Reduce radiation heat losses	up to 5%

What to Watch

- Air leaks into the furnace.
- Localized cold spots.
- Furnace shell and casing conditions such as hot spots, cracks, or insulation detachment.
- Piping insulation sagging and distortion.
- Damper positioning and operation.

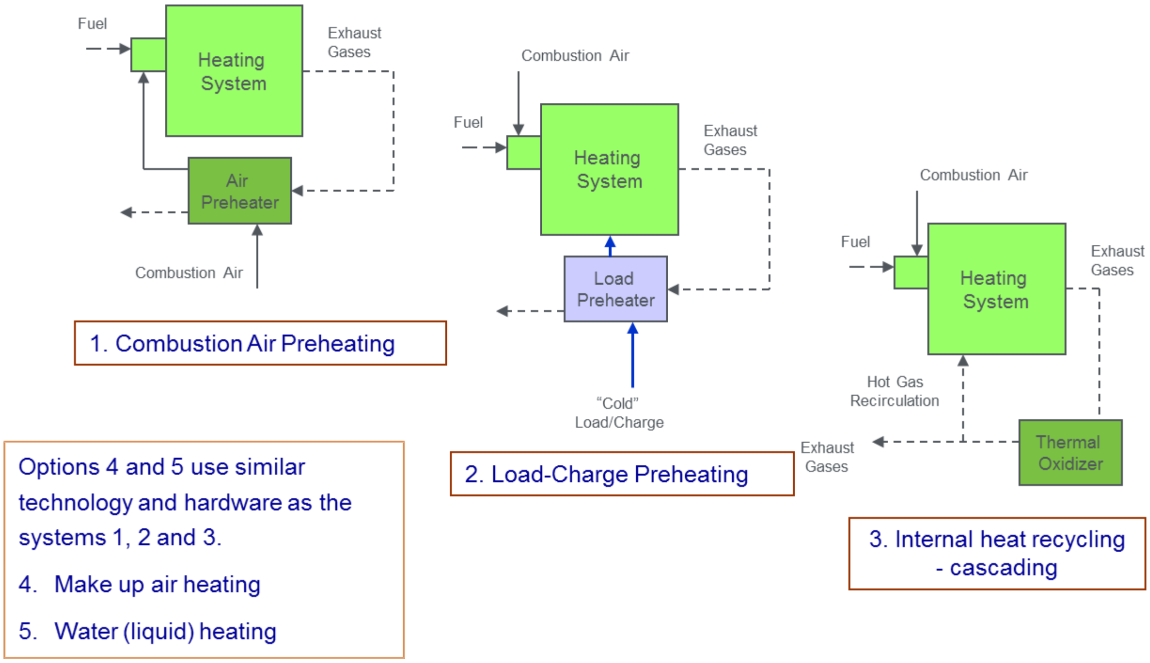
2) Waste heat recycling:

Waste heat recycling is the use of waste heat from a process heating system for its use within the same system (see Figure 5). Important characteristic of waste heat recycling is complete synchronization of heat supply and heat demand or use for a given heating system. Heat recycling opportunities depend largely on the design of the system and the requirements of the process.

A commonly used method of waste heat recycling is use of exhaust gas heat from a fuel fired system to preheat the burner combustion air or make up air in ovens or dryers. In this case heat from the exhaust gases or combustion products is transferred to combustion air for the burners using a recuperator, regenerator, heat pipes etc. This type of preheating reduces the amount of fuel required to establish and maintain the necessary temperature of the process.

Another example of heat recycling is the transferring exhaust gas heat back to the material being heated or processed, which also reduces energy use in the heating system since the product does not have to be heated from ambient or lower temperature. Use of an economizer used to heat feed water is another example of waste heat recycling. Recycling of waste heat can reduce energy use or energy intensity by as much as 25%.

The heat lost from exhaust gases depends on mass flow and temperature of gases. The exact amount of energy reduction, commonly expressed in terms of energy intensity or energy used per unit of production depends on various factors such as exhaust gas temperature, method of heat recycling, percentage heat recycled, heat recycling equipment design etc. Depending on the factors mentioned earlier, it is possible to reduce energy intensity by 5% to 25% for heating systems.



Options 4 and 5 use similar technology and hardware as the systems 1, 2 and 3.

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

Figure 5. Waste heat recycling options (Courtesy – Arvind Thekdi, E3M Inc.)

4 – WASTE HEAT MANAGEMENT – REDUCTION, RECYCLING AND RECOVERY

Waste heat recycling should be the first consideration before other method of waste heat recovery is considered.

Transferring excess energy from exhaust gas back into the same system can be an excellent efficiency improvement. Two common targets for receiving this energy are the combustion air and the product being heated. Combustion air accounts for a significant amount of mass entering a furnace. Increasing the temperature of this mass reduces the fuel needed to heat the combustion products to the exhaust temperature. In many systems, particularly in solid-fuel burning applications or when using low heating-value fuels such as blast furnace gas, combustion air preheating is necessary for proper combustion and efficiency.

However, even in applications that do not require this type of preheating for proper performance, combustion air preheating can be an attractive method of efficiency improvement.

Where permitted by system configuration, preheating the product charge can also be a feasible efficiency improvement. Much like combustion air preheating, this form of energy transfer to an upstream mass can reduce fuel use.

Advantages of waste heat recycling are:

- Compatible with process demand and variations in operating conditions
- Can be used as retrofit for existing equipment
- Relatively easy and inexpensive to implement
- Heat recovery – 30% to 90% of the waste heat
- Typical payback periods – one year to three years
- Application temperature range – Typically it ranges from 225°C and higher. Depends on specific process conditions.

3) Waste heat recovery:

Waste heat recovery is the extraction of waste heat from one process heating system and using it in another system. Using waste heat from waste or flue gases from high-temperature processes to supply heat to lower temperature processes can improve the efficiency of the overall process. For example, using flue gases from process heaters to generate steam, electrical power or to heat feed water for other boilers can increase the system efficiency significantly. The most important consideration while selecting waste heat recovery system is matching of heat supply to the heat demand for the selected utility within a plant or a neighboring plant.

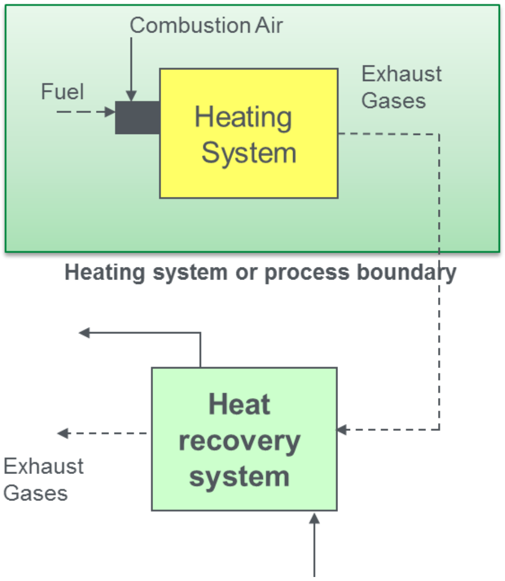


Figure 6. Waste heat recovery concept (Courtesy – Arvind Thekdi, E3M Inc.)

4 – WASTE HEAT MANAGEMENT – REDUCTION, RECYCLING AND RECOVERY

At 2 page tip sheet on waste heat recovery was developed by DOE in 2011[6]. Commonly used waste heat recovery options and equipment are:

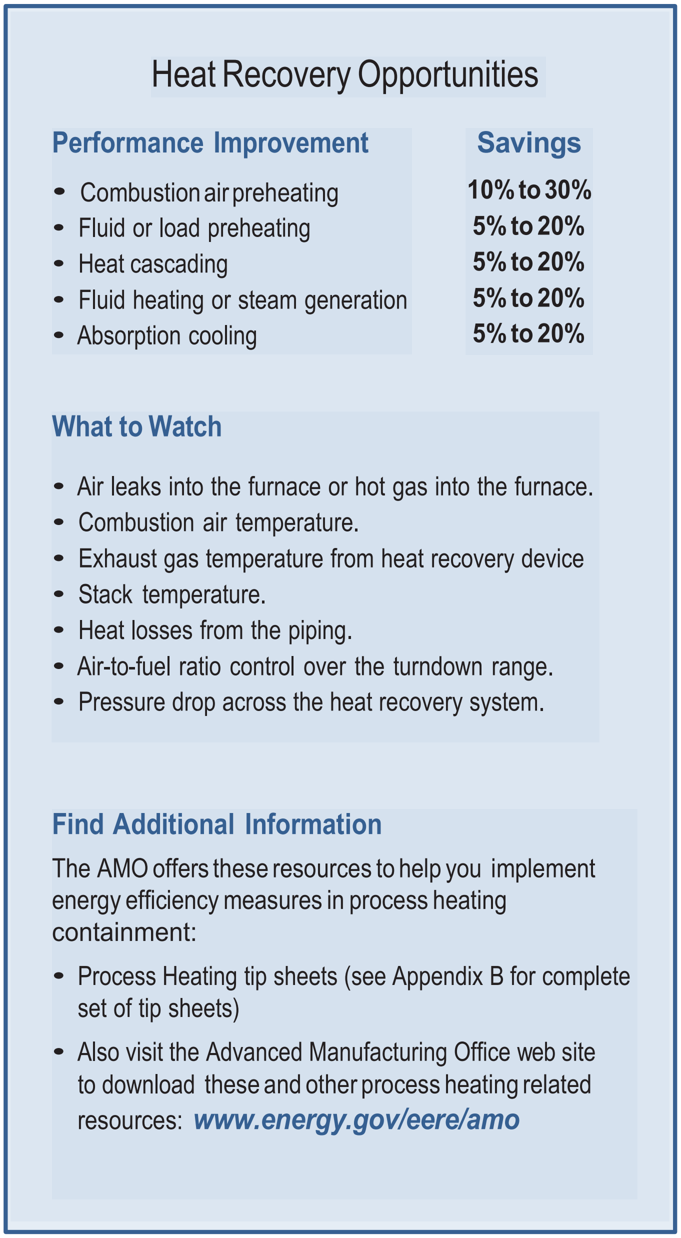
- Water (i.e. process, boiler feed water) or other fluid (i.e. heat transfer liquids) heating - use water to gas heat exchangers
- Air heating for process or HVAC application – use gas to gas heat exchanger or regenerative systems
- Steam generation – use waste heat recovery boilers
- Heat cascading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

Advantages of waste heat recovery are:

- Use of waste heat to supplement the plant utility or auxiliary systems reduces the plant energy use.
- Can be used as retrofit for existing equipment or for new processes
- Heat recovery – 10% to 75% of the waste heat
- Typical payback periods – one-half year to five years. Installed cost varies with the type of system selected.
- Application temperature range – as low as 225°C exhaust gas temperature. Higher temperature limit is usually 900°C exhaust gas temperature.

Commonly Used Waste Heat Management Systems

Industry uses a wide variety of waste heat management equipment offered by a number of suppliers in United States and from other countries. Much of this equipment is designed for specific crosscutting industrial applications. There is no standard method for classifying this equipment; in many cases the manufacturers offer application-specific designs. A summary of conventional or commonly used waste heat management technologies for various temperature ranges is found in Table 6.



Heat Recovery Opportunities

Performance Improvement	Savings
Combustion air preheating	10% to 30%
Fluid or load preheating	5% to 20%
Heat cascading	5% to 20%
Fluid heating or steam generation	5% to 20%
Absorption cooling	5% to 20%

What to Watch

- Air leaks into the furnace or hot gas into the furnace.
- Combustion air temperature.
- Exhaust gas temperature from heat recovery device
- Stack temperature.
- Heat losses from the piping.
- Air-to-fuel ratio control over the turndown range.
- Pressure drop across the heat recovery system.

Find Additional Information

The AMO offers these resources to help you implement energy efficiency measures in process heating containment:

- Process Heating tip sheets (see Appendix B for complete set of tip sheets)
- Also visit the Advanced Manufacturing Office web site to download these and other process heating related resources: ***www.energy.gov/eere/amo***

Table 6. Commonly used waste heat management systems, by temperature range

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[6] Unlock Energy Savings with Waste Heat Recovery, US Department of Energy, DOE/EE-0577, July 2011

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

Table 7 lists emerging technologies that may be used in a few cases, or are in some stage of development and demonstration

Table 7. Emerging or developing waste heat management technologies, by temperature range

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

Waste Heat to Power Technologies

Waste heat to power (WHP) is the process of capturing heat discarded by an existing process and using that heat to generate electricity. WHP technologies fall under the waste heat recovery category. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. If it is not feasible to recover energy from a waste heat stream for another thermal process, then a WHP system may be an economically attractive option.

Commonly used WHP technologies are:

- Rankine Cycle (RC) - The most common example of the Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In a SRC system, the working fluid is water, and steam is created to drive a turbine.
- Organic Rankine Cycle (ORC) - Organic Rankine cycle (ORC) systems are similar to SRC systems, but instead of water the working fluid is a hydrocarbon, hydrofluorocarbon, or ammonia.
- Kalina Cycle (KC) - The Kalina cycle is a variation of the Rankine cycle, using a binary fluid pair as the working fluid (typically water and ammonia).
- Supercritical CO2 Cycle - Another variation of the Rankine Cycle is the supercritical CO2 (sCO2) cycle, which utilizes carbon dioxide in place of water/steam for a heat-driven power cycle.

Waste Heat to Power Considerations

While conducting the feasibility analysis of WHP technologies for specific industrial applications, the following factors should be taken into consideration:

- Need relatively clean and contamination free source of waste heat (gas or liquid source). Avoid heavy particulate loading and/or presence of condensable vapors in waste heat stream.
- Continuous or predictable flow for the waste heat source
- Relatively moderate waste heat stream temperature (at least 150°C, but >325°C is preferred) at constant or predictable value
- Cannot find or justify use of heat within the process or heating equipment itself
- Cannot find or justify alternate heat recovery methods (steam, hot water, cascading etc.) that can be used in the plant
- Try to avoid or reduce use of supplementary fuel for power generation. It can have a negative effect on overall economics unless the power cost can justify it.

An extensive market assessment for WHP applications was published by Oak Ridge National Laboratory in March 2015.[7] This report should be consulted for detailed analyses and recommendations for WHP applications and technologies.

Barriers to Waste Heat Management

Commonly observed barriers to waste heat management are listed below. A few of these barriers may be interrelated. Some of the technical barriers lead to cost barriers.

Temperature of waste streams:

- High – costly high temperature resistant materials needed for the heat recycling or recovery equipment
- Low – Condensation of water vapor or other condensable may result in corrosion of metals used in heat recycling or recovery equipment. It is also necessary to use large surface areas. Few viable uses for recovered heat at lower temperature.
- Temperature variations in streams

Chemical composition of waste streams:

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

Mass flow rate of waste streams:

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

Cost effectiveness:

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

Implementation constraints:

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

General Guidelines and Considerations for Waste Heat Management

The first step is to identify waste heat sources and reduce generation of waste heat. Use all possible methods given in resources available in the form of tip sheets and training programs developed by the US DOE – AMO and other organizations. This is the most cost effective and quickest way to reduce energy use and improve overall thermal efficiency of a heating system.

The next step is to select an appropriate method of heat recycling where the waste heat is used within the heating system itself. This would eliminate issues

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[7] *Waste Heat to Power Market Assessment*, Prepared by ICF International, Prepared for Oak Ridge National Laboratory, U.S. Department of Energy, March 2015.

related to matching of supply and demand of heat. The most commonly used method of waste heat recycling for fuel fired systems is preheating combustion air where the flue gas temperature is relatively high – usually higher than 1000 deg. F. However, preheating of makeup air or dilution air should be considered at all temperatures for processes using high volumes of air as in case of drying ovens.

The possibility of load or charge preheating should be considered for new equipment and in cases where available space and system configuration allows its use. A few examples of charge preheating include feed water heating for boilers, drying and preheating of materials in metals and non-metal industries.

If heat recycling is not possible, or there is a considerable amount of waste heat remaining after recycling avenues have been explored, then consider using recovered waste heat within the plant. Commonly used examples are:

- Use of hot gases in lower temperature processes, to preheat water or cleaning liquids used in the plant
- Use of heat for space heating in plants located in colder climate
- Steam generation where waste heat streams contain large (>10 MMBtu/hr) amounts of recoverable heat.

Consider use of electric power generation using steam turbine-generator system or other systems such as organic Rankin Cycle (ORC) systems when it is not possible to use heat within the plant or when there is a strong case based on economics to use on site power generation.

It is necessary to evaluate waste heat characteristics such as temperature, flow rates, waste gas, and presence of contaminations (solids or liquid vapors and other condensable materials). These factors, along with variations in temperature and flow rates will affect the overall economics of the waste heat recycling or recovery system.

Finally, consider the use of professional help to investigate and analyze waste heat reduction, recycling and recovery projects so all aspects of the project are considered and a proper economic analysis is carried out before moving forward with a plan.

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SECTION 5: PROCESS HEATING SYSTEM ECONOMICS

Usually, industrial facility managers must convince upper management that an investment in efficiency is worthwhile. Communicating this message to decision-makers can be more difficult than the actual engineering behind the concept. The corporate audience will respond more readily to a dollars-and-cents impact than to a discussion of energy use and efficiency ratios. By adopting a financial approach, the facility manager relates efficiency to corporate goals.

Collaboration with financial staff can yield the kind of proposal that is needed to win over corporate officers who have the final say over capital investments such as system upgrades.

Before presenting some recommendations for how to justify improvement projects, it is useful to understand the world as the corporate office usually sees it.

Understanding Corporate Priorities

Corporate officers are held accountable to a chief executive, a board of directors, and an owner (or shareholders). It is the responsibility of these officers to create and grow the capital value of the firm. The corporation's industrial facilities do so by generating revenue that exceeds the cost of owning and operating the facility itself. Plant equipment— including system components—is considered an asset that must generate an economic return. The annual earnings attributable to the sale of goods produced by these assets, divided by the value of the plant assets themselves, describe the rate of return on assets. This is a key measure by which corporate decision-makers are held accountable.

Financial officers seek investments that are most certain to demonstrate a favorable return on assets. When faced with multiple investment opportunities, the officers will favor those options that lead to both the highest return on capital employed and the fastest payback.

This corporate attitude may impose the following (sometimes unpleasant) priorities on the facility manager: ensuring reliability in production, avoiding unwanted surprises by sticking with familiar technology and practices, and helping control costs by cutting a few corners in maintenance and upkeep. This mindset may cause industrial decision-makers to conclude that efficiency is a luxury that cannot be afforded.

However, industrial efficiency can save money and contribute to corporate goals while effectively reducing energy consumption and cutting noxious combustion emissions.

Measuring the Dollar Impact of Efficiency

Process heating efficiency improvements can move to the top of the list of corporate priorities if the proposals respond to distinct corporate needs. Corporate challenges are many and varied, which opens up opportunities to sell efficiency as a solution. Process heating systems offer many opportunities for improvement; the particulars are shared elsewhere in this sourcebook. Once the selections are made, the task is one of communicating the proposals in corporate (i.e., "dollars-and-cents") language.

The first step is to identify and enumerate the total dollar impact of an efficiency measure. One framework for this is known as life-cycle cost analysis. This analysis captures the sum total of expenses and benefits associated with an investment. The result—a net gain or loss on balance—can be compared to other investment options or to the anticipated outcome if no investment is made. As a comprehensive accounting of an investment option, the life- cycle-cost analysis for an efficiency measure would include projections of:

- Search and selection costs for seeking an engineering implementation firm
- Initial capital costs, including asset purchase, installation, and costs of borrowing
- Maintenance costs
- Supply and consumable costs
- Energy costs over the economic life of the implementation
- Depreciation and tax impacts
- Scrap value or cost of disposal at the end of the equipment's economic life
- Impacts on production, such as product quality and equipment efficiency.

One revelation that typically emerges from this exercise, is that in some cases fuel costs may represent as much as 90% or more of life-cycle costs, while the initial capital outlay is only 3%, and maintenance a mere 1%. Clearly, any measure that reduces fuel consumption (while not reducing reliability and productivity) will certainly yield positive financial results for the company.

Presenting the Financial Benefits of Efficiency

As with any corporate investment, there are many ways to measure the financial impact of efficiency investments. Some methods are more complex, and proposals may use several analytical methods side-by-side. The choice of analyses used will depend on the sophistication of the presenter and the audience.

A simple (and widely used) measure of project economics is the payback period. This is defined as the period of time required for a project to break even. It is the time needed for the net benefits of an investment to accrue to the point where they equal the cost of the initial outlay.

For a project that returns benefits in consistent, annual increments, the simple payback equals the initial investment divided by the annual benefit. Simple payback does not take into account the time value of money. In other words, it makes no distinction between a dollar earned today versus a dollar of future (and therefore uncertain) earnings. Still, the measure is easy to use and understand and many companies use simple payback for a quick go/no-go decision on a project. There are several important factors to remember when calculating a simple payback:

- Payback is an approximation, not an exact economic analysis.
- All benefits are measured without considering their timing.
- All economic consequences beyond the payback are ignored.
- Payback calculations will not always indicate the best solution for choosing among several project options (because of the two reasons cited immediately above).
- Payback does not consider the time value of money or tax consequences.

More sophisticated analyses take into account factors such as discount rates, tax impacts, the cost of capital, etc. One approach involves calculating the net present value of a project, which is defined in the equation below:

Net Present Value (NPV) = Present worth of benefits – Present worth of costs

Another commonly used calculation for determining economic feasibility of a project is internal rate of return (IRR), which is defined as the discount rate that equates future net benefits (cash) to an initial investment outlay. This discount rate can be compared to the interest rate at which a corporation borrows capital.

Many companies set a threshold (or hurdle) rate for projects, which is the minimum required IRR for a project to be considered viable. Future benefits are discounted at the threshold rate, and the net present worth of the project must be positive in order for the project to move ahead.

Relating Efficiency to Corporate Priorities

Operational cost savings alone should be a strong incentive for improving process heating system efficiency. Still, that may not be enough for some corporate observers. The facility manager’s case can be strengthened by relating a positive life-cycle cost outcome to specific corporate needs. Some suggestions for interpreting the benefits of fuel cost savings include the following. (Finance staff can suggest which of these approaches are best for the current corporate climate.)

New Source of Permanent Capital

Reduced fuel expenditures—the direct benefit of efficiency—can be thought of as a new source of capital to the corporation. The investment that makes this efficiency possible will yield annual savings each year over the economic life of the improved system. Regardless of how the efficiency investment is financed, whether borrowing, retained earnings, or third party financing, the annual savings will be a permanent source of funds as long as efficiency savings are maintained on a continuous basis.

Added Shareholder Value

Publicly held corporations usually embrace opportunities to enhance shareholder value. Process heating efficiency can be an effective way to capture new value. Shareholder value is the product of two variables: annual earnings and the price-to-earnings (or P/E) ratio. The P/E ratio describes the corporation's stock value as the current stock price divided by the most recent annual earnings per share. To take advantage of this measure, the efficiency proposal should first identify annual savings (or rather, addition to earnings) that the proposal will generate. Multiplying that earnings increment by the P/E ratio yields the total new shareholder value attributable to the efficiency implementation.

Reduced Cost of Environmental Compliance

Facility managers can proactively seek to limit the corporation's exposure to penalties related to environmental emissions compliance. Efficiency, as total-system discipline, leads to better monitoring and control of fuel use. Combustion emissions are directly related to fuel consumption. They rise and fall in tandem.

By improving efficiency, the corporation enjoys two benefits: decreased fuel expenditures per unit of production, and fewer incidences of emission-related penalties.

Worker Comfort and Safety

Process heating system optimization requires ongoing monitoring and maintenance that yields safety and comfort benefits, in addition to fuel savings. The routine involved in system monitoring will usually identify operational abnormalities before they present a danger to plant personnel. Containing these dangers precludes threats to life, health, and property.

Reliability and Capacity Use

Another benefit to be derived from efficiency is more productive use of assets. The efforts required to achieve and maintain energy efficiency will largely contribute to operating efficiency. By ensuring the integrity of system assets, the facility manager can promise more reliable plant operations. The flip side, from the corporate perspective, is a greater rate of return on assets employed in the plant.

Call to Action

A proposal for implementing an efficiency improvement can be made attractive to corporate decision-makers if the facility manager takes the following steps:

- Identifies opportunities for improving efficiency
- Determines the life-cycle cost of attaining each option
- Identifies the option(s) with the greatest net benefits
- Collaborates with financial staff to identify current corporate priorities (for example, added shareholder value, reduction of environmental compliance costs, and improved capacity utilization)
- Generates a proposal that demonstrates how project benefits will directly respond to current corporate needs.

Appendix A: Glossary of Terms

Adjustable speed drive (ASD)—An electric drive designed to provide easily operable means for speed adjustment of the motor, within a specified speed range.

Air/fuel ratio (a/f ratio)—The ratio of the air supply flow rate to the fuel supply flow rate when measured under the same conditions. For gaseous fuels, usually the ratio of volumes in the same units. For liquid and solid fuels, it may be expressed as a ratio of weights in the same units, but it is often given in mixed units such as cubic feet of air per pound of fuel.

Agglomeration—The combining of smaller particles to form larger ones for separation purposes. Sintering, for example.

Alternating Current (AC)—The characteristic of electricity in which the current flow in a circuit changes direction (180 degrees). Each change is called a cycle. The number of cycles during a given time period is called frequency. The standard frequency in the United States is 60 cycles per second.

Ambient—Immediate surroundings or vicinity.

Amps—A unit of electric current flow equivalent to the motion of one coulomb of charge or 6.24 X 1018 electrons past any cross section in one second.

Ash—Noncombustible mineral matter in residual fuel oils. Ash consists mainly of inorganic oxides and chlorides. ASTM specifications limit ash weight in #4 and #5 oils to 0.1% (no limit in #6 oil). Ash can cause difficulties with heat transfer surfaces, refractories, and burner ports.

Atmosphere (atm)—A mixture of gases (usually within a furnace). Also a unit of pressure equal to 14.7 lb/square inches or 760 millimeters (mm) of mercury.

Atmospheric pressure—The pressure exerted upon the earth's surface by the weight of the air and water vapor above it. Equal to 14.7 lb/square inch or 760 mm of mercury at sea level and 45° latitude.

Available heat—The gross quantity of heat released within a combustion chamber minus both the dry flue gas loss and the moisture loss. It represents the quantity of heat remaining for useful purposes (and to balance losses to walls, openings, and conveyors).

Basic refractories—Refractories consisting essentially of magnesia, lime, chrome ore, or forsterite, or mixtures of these (by contrast, acid refractories contain a substantial proportion of free silica).

Batch-type furnace—A furnace shut down periodically to remove one load and add a new charge, as opposed to a continuous-type furnace. Also referred to as an in-and-out furnace or a periodic kiln.

Blast furnace gas—A gas of low Btu content recovered from a blast furnace as a by-product and used as a fuel.

British thermal unit (Btu)—The quantity of energy required to heat one pound of water from 59°F to 60°F at standard barometric pressure (0.252 kilocalories or 0.000293 kilowatt-hours).

Bunker oil—A heavy fuel oil formed by stabilization of the residual oil remaining after the cracking of crude petroleum.

Calcining—The removal of chemically bound water and/or gases through heating.

Coke—The solid product, principally carbon, resulting from the destructive distillation of coal or other carbonaceous materials in an oven or closed chamber. In gas and oil combustion, the carbonaceous material formed due to abnormal circumstances.

Coke oven gas—A gas composed primarily of hydrogen and methane, saved for use as a fuel when coke is made from coal in byproduct ovens.

Combustion air—Main air. All of the air supplied through a burner other than that used for atomization.

Combustion products—Matter resulting from combustion such as flue gases, water vapor, and ash. See products of combustion.

Compressor—A device that increases the pressure of a gas through mechanical action. Compressors are used to provide compressed air to facilities and in mechanical vapor compression systems to provide cooling and refrigeration.

Conduction—The transfer of heat through a material by passing it from molecule to molecule.

Conductance—See thermal conductance.

Conductivity—See thermal conductivity.

Convection—Transfer of heat by moving masses of matter. Convection currents are set up in a fluid by mechanical agitation (forced convection) or because of differences in density at different temperatures (natural convection).

Curing—The controlled heating of a substance to promote or control a chemical reaction.

Demand—The load integrated over a specific interval of time.

Demand charge—That portion of the charge for electric service based upon a customer's demand.

Diesel fuel—A distillate fuel oil similar to #2 fuel oil.

Direct current (DC)—A unidirectional current in which the changes in value are either zero or so small that they may be neglected. (As ordinarily used, the term designates a practically non-pulsing current)

Drying—The removal of free water (water that is not chemically bound) through heating. The process of removing chemically bound water from a material is called calcining.

Effective area of furnace openings—The area of an opening in an infinitely thin furnace wall that would permit a radiation loss equal to that occurring through an actual opening in a wall of finite thickness. The effective area is always less than the actual area because some radiation always strikes the sides of the opening and is reflected back into the furnace.

Efficiency—The percentage of gross Btu input that is realized as useful Btu output of a furnace.

Emissivity—A measure of the ability of a material to radiate energy. The ratio (expressed as a decimal fraction) of the radiating ability of a given material to that of a black body (a black body always emits radiation at the maximum possible rate and has an emissivity of 1.0). See emittance.

Emittance—The ability of a surface to emit or radiate energy, as compared with that of a black body, whose emittance is 1.0. Geometry and surface conditions are considered when calculating a surface's emittance, while emissivity denotes a property of the bulk material and is independent of geometry or surface conditions. See emissivity.

Emittance factor, Fe—The combined effect of the emittances of two surfaces, their areas, and relative positions.

Equivalent thickness—For refractory walls, this term refers to the thickness of firebrick wall that has the same insulating capability as a wall of another refractory material.

Excess air—The air remaining after a fuel has been completely burned, or that air supplied in addition to the quantity required for complete stoichiometric combustion. A lean fuel/air ratio contains excess air.

f/a ratio or fuel/air ratio—The reciprocal of the a/f (air/fuel) ratio. See a/f ratio.

Fireclay brick—A refractory brick manufactured substantially or entirely from fireclay.

Flue gas—All gases, combustion gas, products of combustion that leave a furnace, recuperator or regenerator, by way of the flue, including gaseous products of combustion, water vapor, excess oxygen, and nitrogen. See products of combustion.

Fluid heating—Fluids are heated in batch or continuous processes to induce or moderate a chemical reaction in the product material.

Forced convection—Convection heat transfer by artificial fluid agitation.

Fuel oil—A petroleum product used as a fuel. Common fuel oils are classified as:

#1 – distillate oil for vaporizing type burners.
#2 – distillate oil for general purpose use, and for burners not requiring #1.
#4 – blended oil intended for use without preheating.
#5 – blended residual oil for use with preheating facilities. Usual preheat temperatures are 120°F to 220°F.
#6 – residual oil, for use in burners with preheaters permitting a high viscosity fuel. Common preheat temperatures are 180°F to 260°F.

Furnace—An enclosed space in which heat is intentionally released by combustion, electrical devices, or nuclear reaction.

Furnace pressure—The gauge pressure that exists within a furnace combustion chamber. The furnace pressure is said to be positive if greater than atmospheric pressure, negative if less than atmospheric pressure, and neutral if equal to atmospheric pressure.

Gross heating value—See higher heating value.

Heat content—The sum total of latent and sensible heat stored in a substance minus that contained at an arbitrary set of conditions chosen as the base or zero point. It is usually designated h, in Btu per pound, but may also be expressed in such units as Btu per gallon and Btu per cubic foot if the pressure and temperature are specified.

Heat transfer—Flow of heat by conduction, convection, or radiation.

Heat treating—The controlled heating and cooling of a material to achieve favorable mechanical properties such as hardness, strength, and flexibility.

Higher heating value (HHV)—Gross heating value—equal to the total heat obtained from combustion of a specified amount of fuel and its stoichiometrically correct amount of air, both being at 60°F when combustion starts, and after the combustion products are cooled. See net or lower heating value.

Insulation—A material that is a relatively poor transmitter of heat. It is usually used to reduce heat loss from a given space.

Kilowatt —A measure of power equal to 1.34 horsepower.

Latent heat—Heat absorbed or given off by a substance without changing its temperature, as when melting, solidifying, evaporating, condensing, or changing crystalline structure.

Lower heating value (LHV)—Net heating value. The gross heating value minus the latent heat of vaporization of the water vapor formed by the combustion of hydrogen in the fuel. For a fuel with no hydrogen, net and gross heating values are the same.

Mineral—A natural, inorganic substance sometimes of variable chemical composition and physical characteristics. Most minerals have definite crystalline structure; a few are amorphous.

Natural convection—Free convection. Transfer of heat due to currents created by the differences in gas density caused by temperature gradients.

Net heating value—See lower heating value.

Nine-inch equivalent—A brick volume equal to that of a standard 9 x 4.5 x 2.5 inch straight brick; the unit of measurement of brick quantities in the refractories industry.

Percent air—The actual amount of air supplied to a combustion process, expressed as a percentage of the amount theoretically required for complete combustion.

Percent excess air—The percentage of air supplied in excess of that required for complete combustion. For example, 120% air equals 20% excess air.

Perfect combustion—The combining of the chemically correct proportions of fuel and air in combustion so that both the fuel and the oxygen are totally consumed. See stoichiometric ratio.

Plastic refractory—A blend of ground refractory materials in plastic form, suitable for ramming into place to form monolithic linings.

Power—The rate of energy transfer, usually measured in watts or Btu/hr.

Preheated air—Air heated prior to combustion, generally transferring energy from the hot flue gases with a recuperator or regenerator.

Products of combustion—Products of combustion gases in a combustion chamber or on their way through a flue, heat recovery device, pollution reduction equipment, or stack. Usually consists of carbon dioxide, water, and nitrogen, but may also include oxygen, carbon monoxide, and H2, complex hydrocarbons, sulfur and nitrogen compounds, and particulates. May be termed flue gas, stack gas, or exit gas.

Radiation—Emission and propagation of wave form energy. A mode of heat transfer in which the energy travels very rapidly in straight lines without leaving the intervening space. Heat can be radiated through a vacuum, through many gases, and through some liquids and solids.

Recuperator—Equipment that uses hot flue gases to preheat air for combustion. The flue gases and airflow are in adjacent passageways so that heat is transferred from the hot gases, through the separating wall, to the cold air.

Refractories—Highly heat-resistant materials used to line furnaces, kilns, incinerators, and boilers.

Regenerator—A cyclic heat interchanger, which alternately receives heat from gaseous combustion products and transfers heat to air before combustion.

Saturated air—Air containing all the water vapor it can normally hold under existing conditions.

Saturated steam—Steam at the boiling point for water at the existing pressure.

Sensible heat—Heat, for which the addition to or removal of will result in a temperature change, as opposed to latent heat.

Smelting—The chemical reduction of a metal from its ore, usually by fusion. Smelting separates impurities, allowing for their removal from the metal.

Specific heat—The amount of heat required to raise a unit weight of a substance under a specified temperature and pressure.

Standard air—Air at standard temperature and pressure, namely 60°F (15.56°C) and 29.2 inches of mercury (14.7 pounds per square inch [psi], 760 mm specific gravity [Hg]).

Standard pressure—Standard atmosphere, equal to a pressure of 29.92 inches of mercury (14.7 psi, 760 mm Hg)

Standard temperature—60°F (15.56°C) in this book and for most engineering purposes. In the fan industry, it is 70°F (21.1°C) and in scientific work it is 32°F (0°C) or 39.2°F (4°C).

Stoichiometric ratio—The chemically correct ratio of fuel to air, i.e., a mixture capable of perfect combustion, with no unused fuel or air.

Sustainable Manufacturing — The ability to continuously utilize resources to manufacture products and maintain the environment and our lifestyles indefinitely.

Thermal conductance, C—The amount of heat transmitted by a material divided by the difference in temperature of the material's surfaces. Also known as conductance.

Thermal conductivity, k—The ability of a material to conduct heat, measured as the heat flow through a square foot of cross sectional area and a one foot (or inch) thickness with 1°F of temperature difference across the thickness. The refractory and insulation industries use the "inch thickness," while most other industries use "foot thickness" to measure this material property.

Three-phase—Commonplace AC electrical service involving three conductors offset in phase from each other. The concept eliminates torque pulsation and accommodates creation of rotating magnetic fields, within motors, to facilitate starting and running torque.

Wall loss—The heat loss from a furnace or tank through its walls.

Warm-up time—The time required to bring a process heating system up to operating temperature.

Watt—The unit of power in the International System of Units (SI). The watt is the power required to do work at the rate of 1 joule per second.