# Improving Process Heating System Performance

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Industrial Technologies Program

# Improving Process Heating System Performance:

## A Sourcebook for Industry

Second Edition

U.S. Department of Energy
**Energy Efficiency and Renewable Energy**
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INDUSTRIAL HEATING
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# Acknowledgements

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The mission of BestPractices is to help U.S. manufacturers maintain global competitiveness through strategic energy management, including the use of energy-efficient technologies. BestPractices helps industrial manufacturers cut costs and emissions—and this helps our nation achieve its economic and environmental goals.

The mission of IHEA is to provide services that will enhance member company capabilities to serve end users in the industrial heat processing industry and improve the business performance of member companies. Consistent with that mission, IHEA supports energy efficiency improvement efforts that provide cost savings, performance benefits, and other competitive advantages that enable success in the global marketplace.

For more information about ITP's BestPractices and IHEA, see Section 7, "Where to Find Help."

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# Quick Start Guide

This sourcebook describes basic process heating applications and equipment, and outlines opportunities for energy and performance improvements. It also discusses the merits of using a systems approach in identifying and implementing these improvement opportunities. It is not intended to be a comprehensive technical text on improving process heating systems, but serves to raise awareness of potential performance improvement opportunities, provides practical guidelines, and offers suggestions on where to find additional help. The sourcebook contains information in the following sections:

- **Section 1: Process Heating Basics**
  For users unfamiliar with the basics of process heating systems, or for users seeking a refresher, a brief discussion of the equipment, processes, and applications is provided.

- **Section 2: Performance Improvement Opportunities—Fuel-Based Systems**
  This section discusses key factors for improving the performance of fuel-based process heating systems. This section is categorized by opportunity type: 1) heat generation; 2) heat containment; 3) heat transfer; 4) waste heat recovery; and 5) enabling technologies.

- **Section 3: Performance Improvement Opportunities—Electric-Based Systems**
  This section discusses key factors for improving the performance of electric-based process heating systems. Electric-based solutions and opportunities are described by technology type.

- **Section 4: BestPractices Process Heating Performance Improvement Tools**
  This section describes several resources and tools developed through the BestPractices initiative within DOE's Industrial Technologies Program.

- **Section 5: Process Heating System Economics**
  To support the improvement opportunities presented in Sections 2 through 4, this section provides recommendations to financially justify process heating improvement projects.

- **Section 6: Where to Find Help**
  In addition to a comprehensive listing of resources and tools, this section contains a directory of associations and other organizations engaged in enhancing process heating system efficiency.

- **Appendices**
  Appendix A is a glossary defining terms used in process heating systems. Appendix B contains a series of process heating system tip sheets. Developed by DOE, these tip sheets discuss additional opportunities for improving the efficiency and performance of process heating systems. Appendix C contains technical briefs developed by DOE. These technical briefs discuss specific performance improvement topics in more detail than the tip sheets. Appendix D is a compendium of references used in the development of this sourcebook. Appendix E provides guidelines for submitting suggested changes and improvements to the sourcebook.

# 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, 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 (sometimes called electrotechnologies) use electric currents or electromagnetic fields to heat materials. Direct heating methods generate heat within the work piece, 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 radiation (e.g., microwave). Indirect heating methods use one of these three methods to heat an element or susceptor, which transfers the heat to the work piece by either conduction, convection, radiation, or a combination of these.

- **Steam-Based Process Heating**
  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.

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

## Efficiency Opportunities

The performance of a process heating system is determined by its ability to achieve a certain product quality under constraints (for example, high throughput, and low response time). The energy efficiency of a process heating system is determined by the costs attributable to the heating system per unit produced. Efficient systems manufacture a product at the required quality level and at the lowest cost. Energy-efficient systems create a product with less input energy to the process heating systems per unit produced.

Approaches to improve a certain heating operation might be applicable to multiple processes, but may be unknown within and/or outside a given industry segment. 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 utility systems, including 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.

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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 Industrial Technologies Program, Capital Surini Group International, Inc., Energetics, Inc., March 16, 2001.

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 5, 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. Consequently, there are many different ways to improve the system performance. In order to achieve maximum improvement at the lowest cost, a systems approach should be used.

A systems approach analyzes both the supply and demand sides of process heating systems and how they interact, essentially shifting the focus from individual components to total system performance. In engineering, a common approach is to break down a system or process into basic functional units (components, modules, process steps), optimize and/or replace them, and then reassemble the system. Since the basic functional units have a lower complexity, their optimization might be easier. The approach is well suited if the functional units are independent, and do not interact. In contrast, a systems approach evaluates the entire system to determine how the end-use requirements can be most effectively and efficiently served.

Simplistic approaches, which focus solely on the optimization of individual components of a process heating system, fail to recognize that system efficiency, reliability, and operating stability are closely connected and depend on the performance of multiple components. By considering dependencies between components, adverse effects can be avoided and maximum performance and efficiency can be achieved at the lowest cost.

In practice, process heating systems evolve over time; components are added, removed, or replaced by newer or alternate versions. Individual components might age in unpredicted ways, steadily changing the performance of the system. Adding new components to a process heating system may require substantial changes to operating conditions and practices. Regular process design reviews can help to reduce the complexity of process heating systems, and increase their reliability and overall performance.

The benefits of a systems approach can be illustrated through examples. 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.

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**

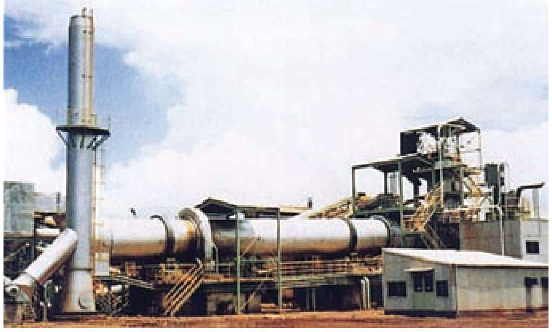
Calcining is the removal of chemically bound water and/or gases, such as carbon dioxide, through direct or indirect heating. Common applications include construction materials, such as cement and wallboard, the recovery of lime in the kraft process of the pulp and paper industry, the production of anodes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

- **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 dryers, including conveyor, fluidized bed, rotary, and cabinet dryers.



*A rotary dryer for 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.

### Separating

Separation involves dividing gaseous or liquid streams into various components. Separation can be accomplished through distillation, membranes, or by other means.

*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 in arc furnaces, and the production of copper.

### 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 7 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 process heating systems
- Electric-based process heating systems
- Steam-based process heating systems
- Other process heating systems, including 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.

*Table 1. Summary 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 and 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, Textile |
| **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, 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 |
| **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, and Resistance Heaters. Microwave, Steam, Induction, Infrared | Agricultural and Food, Glass, Ceramics, Plastics and Rubber, Chemicals |

Although steam is generated by using fuel or electricity in a boiler, it is a major source of energy for many industrial processes, such as fluid heating and drying. In addition to steam, several other secondary energy sources are used by industry. They include hot air, heat transfer by liquids, and water. The secondary sources are generated by a heating system of its own that can fall under the general category of "other process heating systems."

Some energy 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) tend to be much less costly than conventional fuels, making the payback periods for efficiency improvement projects comparatively longer.

Figure 1 illustrates how fuels are used in several process heating applications. In many industries, "other" fuels account for a large portion of the energy use. A significant portion of other fuels usually refers to opportunity fuels, which are often waste products, such as sawdust, refinery gas, or petroleum coke. In many of these systems especially, justifying energy efficiency projects must emphasize performance and reliability benefits that usually accompany improvements in efficiency.

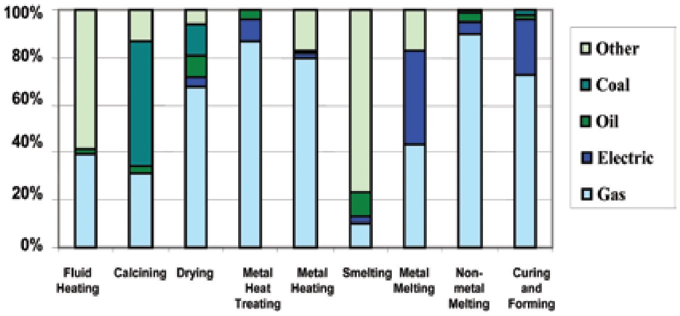


*Figure 1. Energy sources for key industrial process heating operations.*

### ■ 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, and coal), and biomass (e.g., vegetable oil, wood chips, cellulose, charcoal, and ethanol). To enhance 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.

Examples of fuel-based process heating equipment include ovens, heaters, kilns, and melters. Throughout the sourcebook, the term "fuel-based furnace" describes this broad range of equipment. In many cases, similar electronic-based equipment is also available. Fuel-based process heating systems are common in nearly every industry segment, and include furnaces like ovens, heaters, kilns, and melters, but also the surface treatment 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, carbonitriding, 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. Processes include paint and polymer curing and/or drying.

Furnaces in any configuration can be considered heating systems that consist of many functional components. Most opportunities to improve process heating efficiency are related to optimizing the combustion process, extracting and/or recovering energy from the exhaust gases, and reducing the amount of energy lost to the environment.

### ■ 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. 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 in turn emits infrared radiation. 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.

**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. This 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. However, uniform heating of materials in microwave systems operating on a single frequency is difficult due to standing waves in the cavity, which generate local hot spots. To avoid harm to living organisms and interference with other equipment, proper shielding of the equipment is required.

**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 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 using off-peak electricity are sometimes used in areas with inexpensive electricity.

Boilers generate steam, generally using heat from fuel combustion, although electric-based boilers have a niche market. Steam has several favorable properties for process heating applications. For example, steam holds a significant amount of energy on a unit mass basis (between 1,000

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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.

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, which is a useful attribute in many process heating applications. Among the advantages of steam as a source of process heat are low 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. However, since they are discussed more thoroughly in a companion sourcebook titled *Improving Steam System Performance, A Sourcebook for Industry*, boilers and steam systems are not described in detail in this sourcebook. This resource is available from the BestPractices Web Site at www.eere.energy.gov/industry/bestpractices. Efficiency opportunities involving end-uses of steam-based process heating systems (e.g., heat exchangers) will be addressed in Section 4.

### ■ 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.

# Section 2: Performance Improvement Opportunities—Fuel-Based Systems

Figure 2 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, for example, in the case for heat recovery and heat generation. Transferring heat from the exhaust gases to the incoming combustion air reduces the amount of energy lost from the system, but also allows the more efficient combustion of a given amount of fuel, thereby delivering more thermal energy to the material to be heated.

## 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. 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 element
- Material handling system.

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

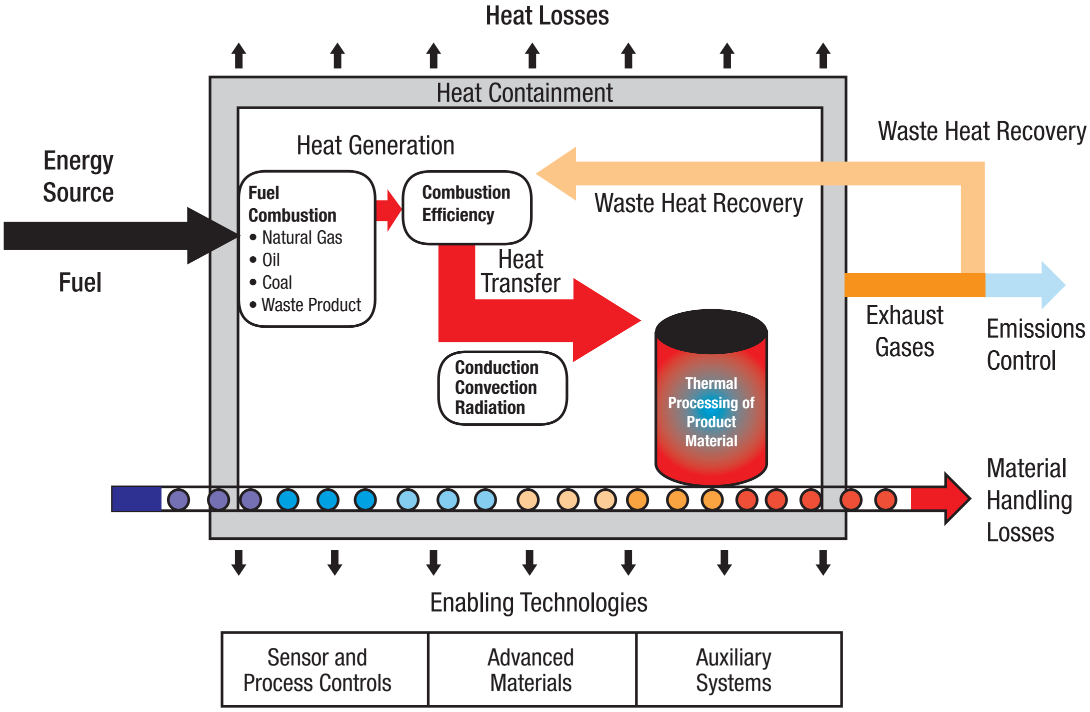

*Figure 2. A fuel-based process heating system and opportunities for improvement.*

*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, Chemical, 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 heated furnaces. | Most manufacturing sectors |
| **Indirectly heated** | Heat treating furnaces, chemical reactors, distillation columns, salt bath furnaces, etc. | Metals, Chemical |
| **Material Handling System** | | |
| **Fluid heating (flow-through) systems** | Gaseous and liquid heating systems including fluid heaters, boilers. | Petroleum Refining, Chemical, Food, Mining |
| **Conveyor, belts, buckets, rollers, etc.** | Continuous furnaces used for metal heating, heat treating, drying, curing, etc. | Metals, Chemical, Pulp and Paper, Mining |
| **Rotary kilns or heaters** | Rotary kilns used in cement, lime, heat treating, chemical and food industry. | Mining, Metals, Chemical |
| **Vertical shaft furnaces** | Blast furnaces, cupolas, vertical shaft calciners, exfoliators, and 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, Chemical, Ceramics |
| **Continuous strip furnaces** | Continuous furnaces used for metal heating, heat treating, drying, curing, etc. | Pulp and Paper, Metals, Chemical |
| **Vertical handing systems** | Primarily for metal heating and heat treating for long parts and in pit, vertical batch, and salt bath furnaces. | Metals, Chemical, 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 element to the load (for example, convection furnaces).

**Type of heating element.** There are many types of basic heating elements that can be used in process heating systems. These include burners, radiant burner tubes, 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, as shown in Figure 3. 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.

Performance and efficiency improvement opportunities can be grouped into five categories (shown in italics in Figure 4):

- 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.

Figure 4 shows several key areas where the performance and efficiency of a system can be improved. It is important to note that many opportunities affect multiple areas.

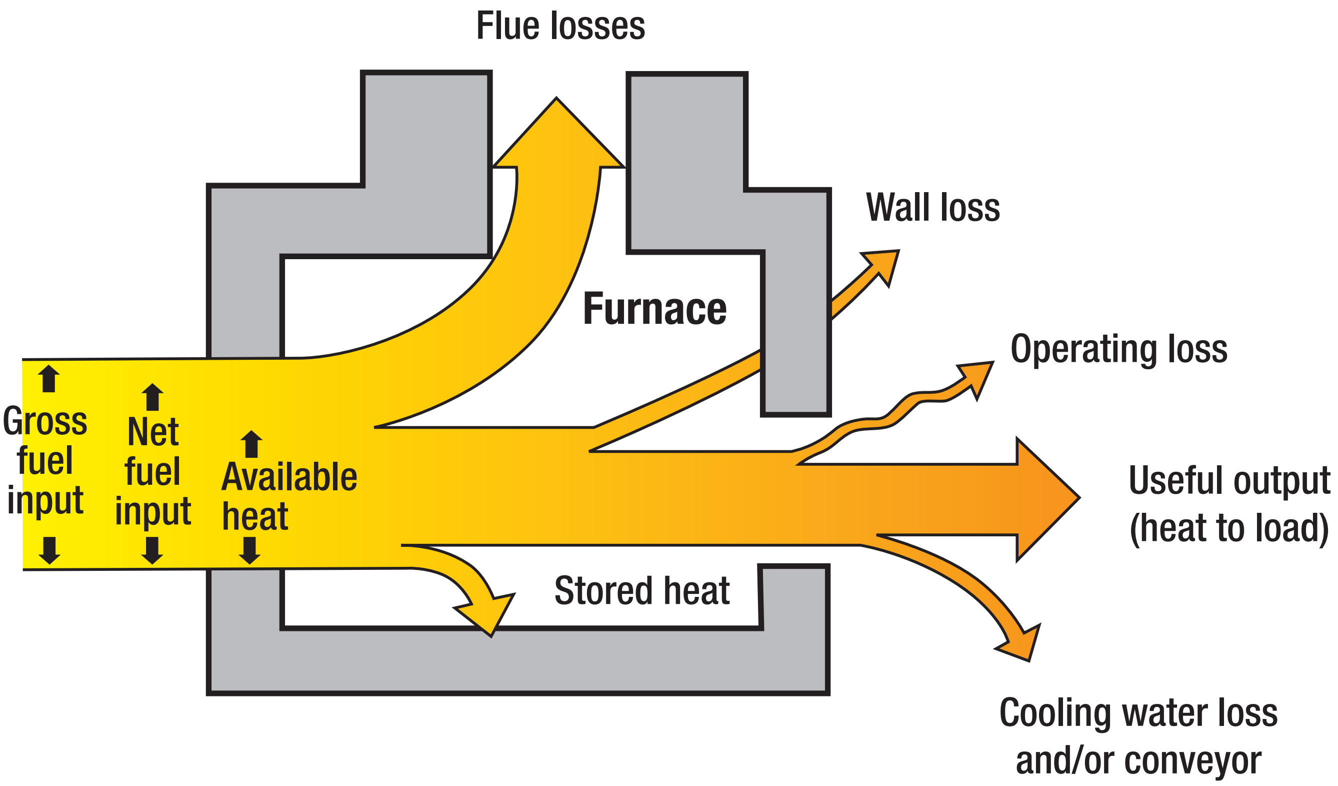

*Figure 3. Energy loss diagram in a fuel-based process heating system.*

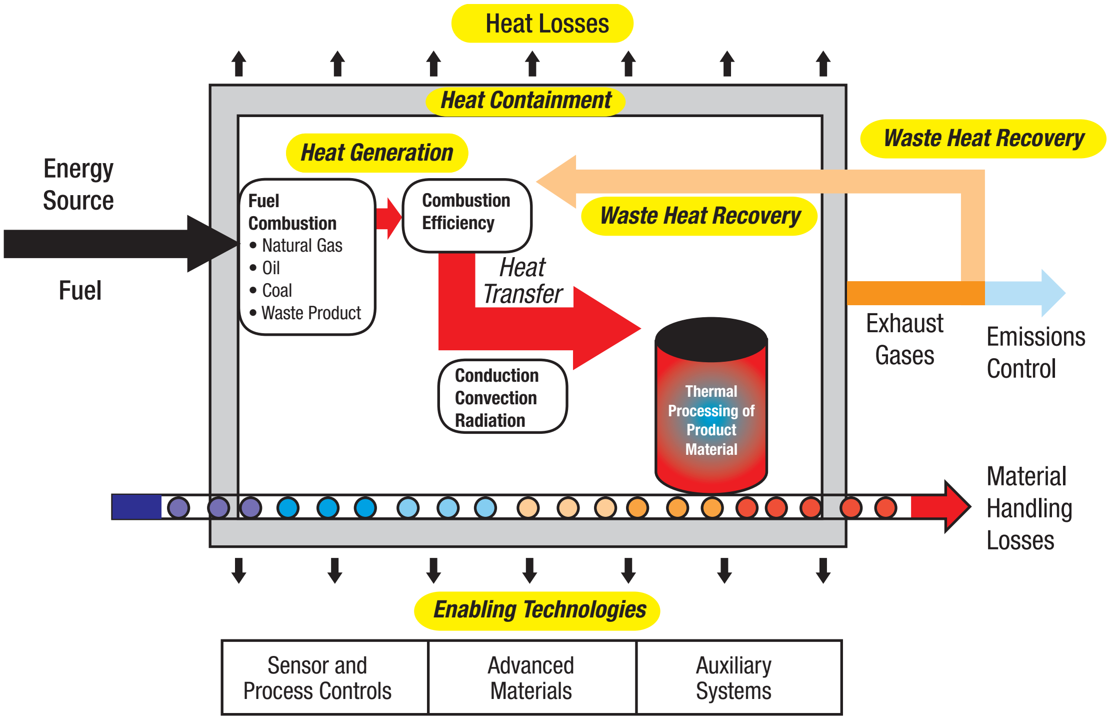

*Figure 4. Key opportunities in a fuel-based system.*

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.

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) Industrial Technologies Program (ITP), 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. For the latest updates, visit the BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

In addition to tip sheets, ITP 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
- Reducing excess air
- Preheating of combustion air or oxidant
- Enriching oxygen.

**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.

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, 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.

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. 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. However, the higher combustion air temperature does increase formation of nitrogen oxide ($NO_x$), a precursor to ground level ozone.

**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.

## 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%** |

### 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

ITP's BestPractices 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 ITP BestPractices Web site to download these and other process heating related resources: **www.eere.energy.gov/industry/bestpractices.**

## ■ 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.
- 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 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%** |

### What to Watch

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

### Find Additional Information

ITP's BestPractices 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 ITP BestPractices Web site to download these and other process heating related resources: **www.eere.energy.gov/industry/bestpractices.**

## Heat Containment

Heat containment refers to the reduction of energy losses to the surroundings. In most heat generation equipment, convection and radiation losses at the outer surface and through openings are major contributors to heat loss. Insulating materials, such as brick, heat-shields, and fiber mats, as well as the proper sealing of openings, are essential in minimizing heat that can be lost to the surroundings.

Another important cause for heat loss is air infiltration. Often, furnaces are operated at slightly negative pressure because of nonexistent or improper pressure control operation to prevent the loss of furnace gases to the surroundings. The slightly negative pressure can cause air to infiltrate the furnace. Air infiltration can cause significant energy loss as the cool air carries heat away from the product and up the stack. However, fixing leaks around the furnace chamber and properly operating a pressure control system can be a cost-effective way to improve furnace efficiency.

Major loss sources from process heating system containment include:

**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.

**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 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 also sources of energy loss. In many cases, the loss of energy to work spaces that are HVAC conditioned often creates 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%** |
| Maintain furnace pressure control | **5% to 10%** |
| Maintain door and tube 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.

### Find Additional Information

ITP's BestPractices 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)
- Technical Brief: *Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emission Performance* (see Appendix C)

Also visit the ITP BestPractices Web site to download these and other process heating related resources: **www.eere.energy.gov/industry/bestpractices.**

### ■ Heat Recovery

Heat recovery is the extraction of energy, generally from exhaust gases, and subsequent reintroduction of that heat energy to the process heating system. Heat recovery opportunities depend largely on the design of the system and the requirements of the process. In most cases, thermal energy from the exhaust gases is transferred back to the combustion air. This type of preheating reduces the amount of fuel required to establish and maintain the necessary temperature of the process. In some cases, heat can be "cascaded," a process in which waste heat is used several times on subsequent lower levels. Another example of heat recovery is the transferring exhaust gas energy back to the material being heated, which also reduces fuel use. The heat lost from exhaust gases depends on mass flow and temperature of gases.

In many process heating systems, the exhaust gases contain a significant amount of energy, particularly in high-temperature applications. Products that must be heated to high temperatures are limited in the amount of energy that they can extract from combustion gases by this temperature requirement. For example, a forging that must be heated to 1,200°F will have exhaust gases close to this temperature. Unless there is some form of waste heat recovery, the exhaust gases in this application will leave the system with a significant amount of thermal energy.

Transferring excess energy from exhaust gas back to some other part of the 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 gases to the operating 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 flame stability. However, even in applications that do not require this type of preheating for proper performance, combustion air preheating can be an attractive 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.

Preheating air reduces the exhaust gas temperature and mass flow through the heating 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 or to heat feedwater for other boilers can increase the system efficiency significantly.

### 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

ITP's BestPractices 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 ITP BestPractices Web site to download these and other process heating related resources: **www.eere.energy.gov/industry/bestpractices.**

## ■ 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. This opportunity addresses energy losses that are generally attributed to system operation during periods of low throughput. 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.

In many cases, fixed losses can be minimized by improving process scheduling, such as reducing the amount of time that systems operate far below rated capacity, and minimizing idle time between batches.

Similarly, energy loss from heat storage can often be minimized with more effective process control. Heat storage refers to the energy required to bring a system up to operating temperature. In many process heating applications, the system has a considerable mass that must be heated until it reaches a sufficient temperature to begin the heating operation. Though a certain amount of heat storage loss is unavoidable, reducing the number of times that a process heating system is cycled from a de-energized to an energized state can reduce the size of heat storage losses.

Increasing the turndown capacity of a process heating system can also reduce some energy losses. Turndown is the ratio of the highest capacity to lowest capacity that a system can operate. Heating equipment often cannot support operation at very low capacities because of combustion instabilities. Generally, when the load on a system drops below its lowest safe operating capacity, the system must be shut down. Frequently shutting down and restarting a system results in heat storage losses, and also causes purge losses that accompany clearing the remaining combustible gases from the burner area. However, increasing a system's turndown ratio allows the unit to remain operating until the load picks back up and can offer opportunities for savings.

In addition, improving production schedules to maintain a system's continuity of operations is often worth consideration.

**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.

**Auxiliary systems.** Most process heating applications have auxiliary systems that support the process heating system. For example, large furnaces require forced draft fans to

## 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

ITP's BestPractices 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 ITP BestPractices Web site to download these and other process heating related resources: **www.eere.energy.gov/industry/bestpractices.**

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.[4] 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.

ITP 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 at ITP's BestPractices Web site, www.eere.energy.gov/industry/bestpractices.

- *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.

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[4] *United States Industrial Electric Motor Systems Market Opportunities Assessment,* U. S. Department of Energy, 1998.

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 BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

- *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 ITP's BestPractices Web site, www.eere.energy.gov/industry/bestpractices.

# Section 3: Performance Improvement Opportunities—Electric-Based Systems

Electric-based process heating systems are manufacturing technologies that use electricity to make or transform a product through heat-related processes. Electric-based process heating systems (sometimes called electro-technologies) perform operations such as heating, drying, curing, melting, and forming.

Electric-based process heating systems are controllable, clean, and efficient. In some cases, electric-based technologies are chosen for unique technical capabilities, while in other cases the relative price of natural gas (or other fuel) and electricity is the deciding factor. Sometimes the application cannot be performed economically without an electric-based system. For some industrial applications, electric-based technologies are the most commonly used; in others these are only used in certain niche applications.

## Types of Electric-Based Process Heating Systems

Electric-based process heating systems use electric currents or electromagnetic fields to heat materials. Direct heating methods generate heat within the work piece, by either:

1. Passing an electrical current through the material
2. Inducing an electrical current (eddy current) into the material
3. Exciting atoms and/or molecules within the material with electromagnetic radiation (e.g., microwave) Indirect heating methods use one of these three methods to heat an element or susceptor that transfers the heat either by conduction, convection, radiation, or a combination of these to the work piece.

The remainder of this section covers these process heating electrotechnologies:

- Arc furnaces
- Electric infrared electric processing
- Electron beam processing
- Induction heating and melting
- Laser heating
- Microwave processing
- Plasma processing (arc and nontransferred arc)
- Radio-frequency processing
- Resistance heating and melting (direct and indirect)
- Ultraviolet curing.

## Arc Furnaces

### History and Status

The first commercial electric arc furnaces were established in the United States in 1907. Initially, arc furnaces were used to produce specialty metals such as spring steel. Today, they are increasingly 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 or iron scrap by direct contact with an electric arc struck from an electrode to the metal charge. At the beginning of the direct arc melting process, a charge of steel scrap is placed into the furnace. Then, the furnace is sealed and the arc is struck. Direct arc furnaces range from less than 10 tons (in foundries that melt iron and steel for castings) to more than 400 tons (in industrial-scale processes that make steel from scrap steel).

For steelmaking, electric 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-

## 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.

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.

To produce a ton of steel in an electric arc furnace requires around 400 to 500 kilowatt-hours per short ton. This is about one-third to one-tenth the energy required by basic oxygen furnaces or integrated blast furnaces. Electric arc furnaces used for steelmaking are usually employed where there is a plentiful and inexpensive supply of electric power.

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 air 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 also used for producing 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.

Direct arc furnaces used for steelmaking are typically smaller than integrated basic oxygen furnaces. These direct arc furnaces (sometime 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.

Induction arc furnaces are used for a variety of metal melting applications and perform the same processes as various types of fuel-based furnaces.

## Electric Infrared Processing

Electric infrared processing systems are used by many manufacturing sectors for heating, drying, curing, thermal-bonding, sintering, and sterilizing applications. Electric infrared is most often used on applications in which only the surface of an object needs to be heated. Natural gas infrared systems can also be used on many of these same 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-tolerant coatings, and improved emitter designs and controls, electric infrared is used in many successful applications throughout the manufacturing sector.

### ■ 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, and is usually used when the object being heated is in line-of-sight of the emitters and/or reflector. Some infrared systems can cure coatings that are not in line of sight. An example is curing a coating on the inside of pipe using infrared focused on the outside of the pipe. While the curing is being accomplished by conductivity, it is using infrared processing.

Electric infrared heating systems typically comprise an emitter, a reflector system, and controls. Most electric infrared applications also have a material handling system and a ventilation system. Because infrared systems can dry or cure a product in as little as seconds, accurate control is critical. Figure 5 shows a schematic of a typical electric infrared system.

The emitter shown in Figure 5 is a long tube-type (shown in profile), but there are many varieties of emitters and systems, including panel heaters, ceramic bodies with embedded coils, metal coils, ribbons, foils, fiber heaters, and other designs. These design variations give manufacturers the flexibility to use electric infrared technology in many applications.

Infrared radiation is emitted by conducting electric current through the emitter or filament, and systems are classified by wavelength: short, medium, and long. Each class of wavelength has its own heat transfer qualities.

Short-wave emitters are clear quartz tubes with tungsten filiments that are sealed at each end, creating a lamp that looks similar to a fluorescent tube. An inert gas, such as argon, is used to prevent oxidation of the filament. Operating temperatures are around 3,500°F and heat-up times are short—less than a few seconds. Shortwave systems are often used for spot heating or booster ovens.

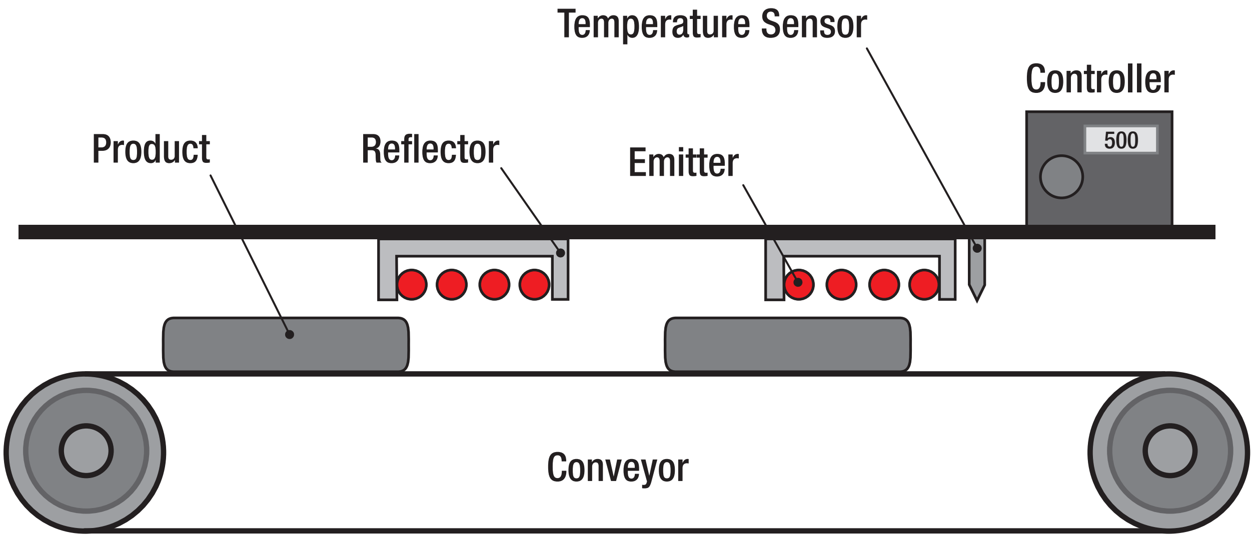

*Figure 5. An electric infrared heating system.*

Medium-wavelength emitters come in two main varieties. The first type has a helically wound coil encased in a long quartz glass tube that is unsealed. These systems use convection and radiant energy to heat. The second type uses metal radiant tubes that encase a resistance coil surrounded by magnesium oxide. Long-wave emitters normally are wires embedded in ceramic panels. Typical applications for medium-wave and long-wave systems are drying and heating.

### ■ Processes, Applications, and Industries

Electric infrared is ideal for situations where a fairly flat product is being heated, dried, or cured. Because infrared primarily heats the surface, it is usually not good for products that need to be heated deep beneath the product surface. Products with complex hidden surfaces require a hybrid system with a convection oven or a material handling system that can rotate parts. The work piece must also have a reasonable absorption in the infrared part of the spectrum.

Special paints, adhesives, and other coatings are made specifically for infrared drying.

Common industrial applications of infrared are:

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

Electric infrared is used in some of the same applications as direct-fired and fuel-fired process heating systems. Sometimes fuel-based equipment is used in conjunction with electric (or natural gas) infrared in hybrid systems (see below). Ultraviolet (UV) curing, another electric-based process heating system, is used for applications such as curing inks, coatings, adhesives, and liquid and powdered coatings. UV usually uses less energy and has lower volatile organic compound (VOC) emissions than infrared or convection ovens. However, UV can only be used with certain coatings for niche applications.

**Hybrid systems.** In many applications, electric infrared systems are used in conjunction with conventional direct-fired process heaters. In some cases, the infrared system pre-dries the product, and then the process is finished in a conventional oven. For example, auto body production lines use infrared to rapidly set the paint on the body, and then the car goes into a convection oven to complete the curing process. The rapid setting of the coating on the body eliminates dust damage. An additional benefit of a hybrid system is the potential to increase throughput by increasing line speed. A hybrid system can be used and configured to perform fuel switching based on energy signals sent by the energy provider. Such a configuration can result in energy cost savings.

**Natural gas-fired infrared.** Natural gas-fired emitters can be used in industrial infrared systems. Many factors are considered in the decision to use electric versus gas, including:

- The relative price of electricity and natural gas
- The cost of upgrading the electrical control panel or gas lines
- The required temperature control
- Equipment cost.

## Improve the Efficiency of Existing Electric Infrared Systems

- 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 the replacement of any failed emitters. Clean reflectors and emitters will more efficiently radiate the heat to the intended target.
- Perform testing* to ensure the best emitter type is employed for the process.
- 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.

Incorporating one or more of these recommendations can show significant savings. Efficiencies (lower cost/part) from 10% to 30% in existing ovens have been demonstrated with the employment of these recommendations.

## Electron-Beam Processing

### ■ History and Status

The principle of electron-beam 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. Electron-beam 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 can cure multiple layers of web material simultaneously, as well as curing surface coatings.

### ■ How the Technology Works

In electron-beam heating, metals are heated to intense temperatures when a directed beam of electrons is focused against the work surface. In electron-beam curing, a liquid is chemically transformed to a solid on the work surface by a stream of directed electrons. Electron-beam 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, and this 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

Electron-beam processing is used for welding metals, machining holes and slots, to harden the surface of metals, and for heat treating and melting. This technology can be more than ten times faster than conventional welding systems. Other competitive benefits include 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.

Electron-beam curing is generally used to cure thicker, heavily pigmented coatings in cases where UV curing is limited. It is used widely in web lamination, with applications also found in the wood finishing and automotive industries. Electron-beam curing systems can require much less floor space and operating labor, can improve productivity levels, and can reduce curing time from minutes to a second or less. Electron-beam systems provide environmental benefits because they eliminate solvents, use little energy, and produce less indoor heat.

Electron-beam processing of materials in a high vacuum is used in many industries as a melting technique that does not introduce contamination. It has been used to produce materials ranging from refractory metal alloys to metallic coatings on plastic jewelry. Electron-beam processing allows for super-pure materials, and can impart unique properties to existing products.

### Improve the Efficiency of Electron-beam Existing 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 highly engineered designs. The output of electron-beam devices does not diminish as a function of time as in some technologies that have "wearable" components. The operation of such systems is either designed output or zero output due to component failure. Any changes in any of the original design parameters requires analysis of the original design to assure an efficient application of the technology.

For welding, other technologies include arc welders or laser welders. For machining operations, other systems include numerically-controlled machine tools. For melting and heat treating operations, electron furnaces can perform the same operations as electron-beam systems. For curing coatings, ultraviolet systems and curing ovens can perform the same function as electron-beam systems.

Electron-beam systems are easily controlled by computer, and they have low inertia, so the systems can quickly and easily move from point to point. In addition, they can be easily pulsed on and off. They also produce energy in a very small area, and can be used for selective surface hardening.

## 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

**Heating and heat treating.** In a basic induction heating setup, a solid state power supply sends an alternating current (AC) through a copper coil, and the part to be heated is placed inside the coil. When a metal part is placed within the coil and enters the magnetic field, circulating eddy currents are induced within the part. These currents flow against the electrical resistivity of the metal, generating precise and localized heat without any direct contact between the part and the coil.

**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 it. Mixing and melting rates can be controlled by varying the frequency and power of the current in the wire coil. 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 have a primary coil wound on 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 metals melting, combined with a fuel-fired cupola, arc, or coreless induction furnace, although they are also used for melting as well.

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.

### ■ Process, Applications, and Industries

**Heating and heat treatings**. Induction heating works directly with conductive materials only, typically metals. Plastics and other nonconductive materials often can be heated indirectly by first heating a conductive metal susceptor that transfers heat to the nonconductive material.

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 easier to heat magnetic materials with induction

## 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.
- Vary coil by product. 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%.

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. Other examples include heat treating, curing of coatings, and drying.

Induction heating often is used where repetitive operations are performed. Once an induction system is calibrated for a part, work pieces can be loaded and unloaded automatically. Induction systems are often used in applications where only a small selected part of a work piece needs to be heated. 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.

For heat treating metals in selective areas, technologies such as laser processing can perform the same operation as induction heating.

**Melting.** For melting operations, induction processing is used primarily in the refining and remelting of metals. Other applications include foundry melting and casting of various metals. Metals that are melted include aluminum, copper, brass, bronze, iron, steel, and zinc. Fuel-based cupolas and other fuel-based metals melting furnaces can perform the same process heating applications as induction melting furnaces.

## 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 beam 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 good 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 used 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, 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). To avoid conflict with communications equipment, several frequency bands have been set aside for industrial microwave processing. Microwaves are 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, creating friction and producing heat.

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 usually comprises four components:

1. **Generator.** The power supply and the magnetron. A magnetron is typically water or air-cooled and is a wearable component.
2. **Applicator.** Wave guides 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.

### 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 of that system will remain the same until the product parameters change. Any change in the material, e.g. a change in width, depth, or weight will require a re-evaluation of the system in order to maintain system 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.

  The 50 ohm generators are most prevalent in industrial processes.

Microwaves have a higher power density than radio-frequency waves and usually heat material faster. Radio-frequency processing's lower frequency waves are better for thicker material. For a given application, one technology is usually better than the other.

## 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 formed 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 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. Plasma processing can also be used in the reduction process for sponge iron and smelting reduction of iron ore and scrap.

Other 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.

### 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.

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.

## 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 portion of the electromagnetic spectrum is between 2 and 100 MHz. Radio-frequency 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.

Radio-frequency waves are produced by radio frequency generators. These generators are 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.

A radio-frequency processing system 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 radio-frequency processing is in the production of plasmas for semiconductor processing and in drying products in the food, lumber, and paper industries. Other applications include drying yarn and film, curing glue, heating plastics, baking, drying ceramic products, and sterilizing medical waste.

Convection ovens can perform the same heating processes as radio-frequency ovens. Radio-frequency processing is generally used because of increased production needs, increased energy efficiency, labor savings, or space savings. In some cases, hybrid systems have both radio-frequency processing and a convection oven.

Microwave processing systems have higher power density than radio-frequency waves and usually heat material faster. Radio-frequency processing's lower frequency waves are better for thicker material. For a given application, one technology is usually better than the other.

### Improve the Efficiency of Existing Radio-Frequency 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. At this point, radio frequency is more efficient at removing the moisture.

## 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 flows through a material and heats it directly. This is an example of the Joule Law or effect[5] 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 or direct current.

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.

**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. The heater is placed in liquid that needs 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.

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[5] When electricity flows through a substance, the rate of evolution of heat in watts equals the resistance of the substance in ohms times the square of the current in amperes.

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.

### 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.

### ■ 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.

## 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 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.

### ■ Process, Applications, and Industries

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.

**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.

# Section 4: BestPractices Process Heating Performance Improvement Tools

The U.S. Department of Energy's (DOE) Industrial Technologies Program (ITP) has developed several resources and tools that can be used to identify and assess process heating system improvement opportunities. Additional resources are identified in the "Where to Find Help" section of the sourcebook.

## Process Heating Assessment and Survey Tool (PHAST)

In 2001, the Industrial Heating Equipment Association (IHEA) collaborated with ITP and other representatives from industry and equipment suppliers to develop the Process Heating Assessment and Survey Tool (PHAST). This user-friendly interactive tool helps users assess how much energy their furnaces, ovens, and heaters use. The tool also models different ways to improve individual unit performance, and manage bottom-line costs.

PHAST offers a way to help plant managers and process heating engineers survey their process heating equipment, identify equipment that uses the most energy, and specify improvements that may enhance productivity, reduce waste, and increase energy efficiency. PHAST is useful in almost all industries and is effective for almost any size furnace. Support for the software development is provided by the ITP BestPractices program, which works with industry to identify plant-wide opportunities for energy savings and process efficiency.

The first release of PHAST may prove most useful for process heating applications that rely on oil or natural gas to fire furnaces, ovens, heaters, kilns, or melters. The software may also be used for applications using electricity as a heating source, although it currently doesn't offer the same level of detail. A later version is expected to include applications to better evaluate electricity, as well as other fossil fuels.

PHAST helps industrial manufacturers in these ways:

- Introduces users to process heating energy conversion tools and includes easy-to-use calculators. These calculators assess the effects of a variety of combustion and heat recovery parameters.
- Allows users to compare furnace performance across a range of operating conditions.
- Calculates potential energy savings that may be achievable under different operating conditions.

### ■ Energy Calculators

The introductory section of the PHAST software includes three simple "calculators" and a link to sources of information that can be useful to the plant operators and users of the tool. The three calculators include these features.

**Energy equivalency.** This feature allows PHAST to calculate heat requirements when the heat source is changed from fuel firing (Btu per hour) to electricity (kilowatt-hours), or from electricity to fossil-fuel firing.

**Efficiency improvement.** This feature calculates available heat for fuel-based furnaces and expected energy savings when the burner operating conditions (exhaust fuel gas temperature, excess air, and preheated air) are changed for the burners.

**Oxygen enrichment.** This feature calculates available heat for fuel-based furnaces and expected energy savings when oxygen in combustion air is changed from standard (21%) to a higher value.

### ■ Equipment Surveys and Analyses

PHAST's plant information section assists users in surveying process heating equipment and identifying the most energy-consuming equipment. It does this by producing a report summarizing expected energy use for the surveyed equipment. The report also identifies which pieces of equipment consume the most process heating energy in the plant.

A plant equipment survey prompts users to supply a variety of information to create a comparative table of energy consumed by the furnaces and their cost of operation. These features create a list that helps users decide where to focus their efforts to better manage energy costs or improve performance.

The Furnace Analysis and Heat Balance section helps users analyze an energy balance for selected equipment with high energy use to identify energy usage and losses. This PHAST feature helps users identify locations within the furnace where energy is wasted or used less productively.

In this section, users can obtain an even more detailed assessment of individual pieces of equipment. PHAST provides users with a variety of parameters and tests to develop a diagnosis and recommend a course of action.

The report section provides a summary of results for the plant survey in the form of a table and pie chart. The table gives energy use and projected annual cost based on the energy cost data provided in the plant survey section. This allows the user to identify large energy–consuming equipment and perform an analysis to see the effects of changing operating conditions or retiring one or more furnaces.

A second part of the report section shows details of energy use in the selected furnace based on the data provided, and calculates the effects of selected changes under modified furnace operating or design conditions. The information is displayed in pie charts to illustrate different areas of energy use. A bar chart shows comparisons between current and modified operating conditions.

- **What-If Support**

For each step of this detailed analysis, PHAST offers an interactive guide to help users know which measurements to use and where to find appropriate data. Once all the relevant information is entered, the tool builds a summary table that shows how much energy is used in different parts of the furnace. It also shows how changes in one or more parameters may affect energy use.

The "what-if" decision support tool lets users easily compare existing conditions with modified conditions. This feature allows users to analyze how decisions affecting one part of a process heating operation will affect operations in another part.

## $NO_x$ Emission Assessment Tool ($N_x$EAT)

This tool is designed to analyze options for nitrogen oxide ($NO_x$) reduction and energy efficiency improvements. The tool was developed jointly by DOE and Texas Industries of the Future. An advisory committee from the chemical and petroleum refining industries provided input on the features and functions of the tool. Equipment suppliers and engineering consultants provided cost and performance data used in the tool database.

$N_x$EAT includes several features to help users identify $NO_x$ reduction and other energy efficiency opportunities.

- **$NO_x$ Inventory Method**

Users can inventory $NO_x$ sources, utility distribution systems, and equipment that use energy or the plant utility.

- **Information on Reducing $NO_x$**

The tool provides currently available combustion systems and other $NO_x$ reduction technologies.

- **Commonly Used Methods for $NO_x$ Reduction**

PHAST offers information on commonly used methods of energy efficiency improvements and $NO_x$ reduction using available technologies, hardware, or systems.

- **$NO_x$ Reduction Cost Data**

The tool provides cost guidelines for implementing technologies and equipment obtained from the vendors and engineering and construction firms. It also provides default data for $NO_x$ reduction potential and associated costs. The data can be changed by the user to allow for specific situations.

- **Resource Information**

The tool contains information on resources that will enable users to estimate energy reduction for plant equipment and processes.

- **Results Model**

This feature allows users to consolidate and summarize results.

**Summary report.** The tool generates a report that summarizes total $NO_x$ reduction, cost of $NO_x$ reduction per ton-year, energy savings,, and simple payback period.

*Note: This scoping tool is not a substitute for a detailed engineering study that may be required to meet regulatory requirements.*

## Combined Heat and Power (CHP) System Application Tool for the Process Heating Industry

This DOE-developed tool is designed to evaluate the feasibility of using combined heat and power (CHP) in industrial process heating systems. The heating systems include fuel-based furnaces, boilers, ovens, heaters, and heat exchangers used in the industry. The CHP systems use gas turbine exhaust gases to supply heat to the systems. The tool includes necessary performance data and cost information for commercially available gas turbines. The results include an estimate for a payback period that will help the industrial users decide whether it is worthwhile to carry out further engineering studies for the project. The tool can be used to estimate payback periods and perform what-if analyses for various utility costs.

The current version includes three commonly used CHP systems most suitable for use in process heating and steam generation applications.

- **Indirect Heating of Liquids and Gases**

In this application, gas turbine exhaust gases are used. The sensible heat of exhaust gases is transferred to the liquid or gas being heated.

- **Direct Heating**

Turbine exhaust gases are mixed or injected in a furnace, oven, dryer, or boiler in this type of application. The sensible heat of exhaust gases is transferred to heat material in an oven or to raise steam in a heat recovery boiler.

- **Turbine Exhaust Gases for Fuel Combustion**

Natural gas, light oil, or by-product gases are used in a furnace, heater, or boiler. The most commonly used system is a boiler using a duct-burner in which residual oxygen from the turbine exhaust gases is used for combustion of the fuel.

# 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.

# Section 6: Where to Find Help

This portion of the sourcebook lists resources that can help end users increase the cost-effective performance of process heating systems. Various programs involved in the process heating marketplace are described, including:

- DOE's Industrial Technologies Program (ITP), through its Technology Delivery strategy, helps industry improve the performance of industrial energy use, particularly in systems such as steam, compressed air, pumping, and process heating
- The Industrial Heating Equipment Association (IHEA), a trade association for process heating equipment manufacturers
- Associations and other organizations involved in the process heating system marketplace.

Information on books, reports, technical newsletters, government and commercial statistics and market forecasts, software, training courses, and other sources of information that can help end users make informed process heating system equipment purchase and system design decisions is also provided.

The information provided in this section was current as of the publication of this sourcebook. Please check the BestPractices Web site at www.eere.energy.gov/industry/bestpractices for the latest versions of DOE publications, software, and other materials referenced throughout. DOE cannot guarantee the currency of information produced by other organizations.

## ITP and Technology Delivery

**U. S. Department of Energy**
**Industrial Technologies Program (ITP)**
Room 5F-065, MS EE-2F
Washington, DC 20585
Phone: 1-877-EERE-INF (1-877-337-3463)
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### Overview

Industrial manufacturing consumes 36% of all energy used in the United States. ITP develops and delivers advanced energy efficiency, renewable energy, and pollution prevention technologies and practices for industrial applications. ITP works with the nation's most energy and resource intensive industries to develop a vision of their future and roadmaps on how to achieve these visions over a 20-year timeframe.

This collaborative process aligns industry goals with federal resources to accelerate research and development of advanced technologies identified as priorities by industry. The advancement of energy- and process-efficient technologies is complemented by ITP energy management best practices for immediate savings results. ITP assists industry to identify and realize their best energy efficiency and pollution prevention options from a system and life-cycle cost perspective.

In particular, through its Technology Delivery strategy, ITP offers several resources to assist in process heating system energy management. These include BestPractices software tools, technical resources, and training; energy assessments through ITP's Save Energy Now strategy; and assessments for small- to mid-sized plants through the university-based Industrial Assessment Centers (IAC). Collectively, these efforts assist industry in adopting near- and long-term energy-efficient practices and technologies.

Through activities such as energy assessments, implementation of emerging technologies, and technical resources for energy management of industrial systems, ITP delivers energy solutions for industry that result in significant energy and cost savings, waste reduction, pollution prevention, and enhanced environmental performance.

### Energy Assessments

Depending on the industry, energy can account for 10% or more of total operating costs. Save Energy Now energy assessments identify opportunities for implementing new technologies and system improvements to increase efficiency, reduce emissions, and boost productivity. Many recommendations from energy assessments have payback periods of less than 18 months and can result in significant energy savings.

Through its Save Energy Now strategy, ITP offers ongoing, targeted industrial system assessments. ITP encourages the nation's largest energy-consuming plants to apply for energy assessments as an important first step in identifying energy efficiency opportunities. Visit ITP's Save Energy Now Web site at www.eere.energy.gov/industry/saveneenergynow for more information.

Small- to medium-sized manufacturers can qualify for free assessments from IACs. Teams composed of engineering faculty and students from the centers, located at 26 universities around the country, conduct energy audits or industrial assessments and provide recommendations to manufacturers to help them improve productivity, reduce waste, and save energy. Learn more about IACs at www.eere.energy.gov/industry/bestpractices.

## ■ Emerging Technologies

Emerging technologies are those that result from research and development and are ready for full-scale demonstration in real-use applications. ITP recognizes that companies may be reluctant to invest capital in these new technologies, even though they can provide significant energy and process improvements. However, through technology implementation solicitations, ITP helps mitigate the risk associated with using new technologies that are supported by industry partnerships. By sharing implementation costs and providing third-party validation and verification of performance data, the energy, economic, and environmental benefits can be assessed to accelerate new technology to acceptance.

## ■ Energy Management

ITP encourages manufacturers to adopt a comprehensive approach to energy use that includes assessing industrial systems and evaluating potential improvement opportunities. Efficiency gains in compressed air, motor, process heating, pumping, and steam systems can be significant and usually result in immediate energy and cost savings. ITP offers software tools and training in a variety of system areas to help industry become more energy and process efficient, reduce waste, and improve environmental performance.

## ■ Qualified Specialists

A Qualified Specialist is an individual who has an extensive background in optimizing industrial systems. Individuals become qualified by taking DOE-sponsored training on BestPractices assessment and analysis software tools, and passing a rigorous exam. For more information on how to become a Qualified Specialist, or to locate Qualified Specialists in your area, go to www.eere.energy.doe.gov/industry/bestpractices.

## ■ Technical Resources

ITP offers a variety of resources to help industry achieve increased energy and process efficiency, improved productivity, and greater competitiveness.

**ITP and BestPractices Web sites**. The ITP Web site offers a large array of information, products, and resources to assist manufacturers who are interested in increasing the efficiency of their industrial operations. You can also learn about upcoming events, solicitations, and much more through the ITP Web site at www.eere.energy.gov/industry.

The BestPractices Web site offers case studies of companies that have successfully implemented energy efficient technologies and practices, software tools, technical publications, training events, and solicitations for plant assessments. You can see these and other resources at www.eere.energy.gov/industry/bestpractices.

**Software Tools.** In addition to the Process Heating System Assessment Tool (PHAST), ITP offers other software tools to help plant personnel identify and implement energy efficient practices in their manufacturing facilities.

- **AirMaster+** is a software tool developed by ITP and jointly sponsored by the Compressed Air Challenge™. This tool helps end users assess the potential for efficiency and productivity improvements in compressed air systems. The software features a number of what-if scenarios to determine which energy efficiency measures have the greatest savings potential for their facility.
- **Fan System Assessment Tool (FSAT)** helps determine the efficiency of fan system operations by identifying savings opportunities, rating system efficiency, and calculating energy savings.
- **MotorMaster+ 4.0** is an energy-efficient motor selection and management software tool, which includes a catalog of over 20,000 AC motors. The software also features motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.
- The **Pumping System and Assessment Tool (PSAT)** assesses pumping systems efficiency by using achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.
- **Steam System Tool Suite** helps users identify and implement the most effective solutions for a facility's steam systems. This includes:
  - The **Steam System Scoping Tool** helps steam system managers in large industrial plants. This program profiles and grades steam system operations and management, and evaluates steam system operations against identified best practices.
  - The **Steam System Assessment Tool** estimates the impact of key steam system improvements. The tool details the energy, cost, and emissions savings of different improvements.
  - **3E-Plus Insulation Appraisal Software** was developed by the North American Insulation

Manufacturers Association to increase awareness of the benefits of insulation and to assist plant personnel in assessing insulation opportunities.

- **Training**

ITP offers training sessions in industrial systems improvements using DOE software tools, including the Process Heating Assessment and Survey Tool (PHAST). See the discussion on the PHAST tool in *Section 4: BestPractices Process Heating Process Heating Improvement Tools*. More information on PHAST training and other system-specific training can be found on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

- **EERE Information Center**

The EERE Information Center fields questions on EERE products and services, including those focused on industrial energy efficiency. They can also answer questions about industrial systems such as compressed air, motors, pumps, fans, process heating, and steam. Contact the EERE Information Center at 877-337-3463 or www.eere.energy/gov/informationcenter.

- **Newsletters**

The ***E-Bulletin*** is ITP's monthly online newsletter that spotlights technologies; significant project developments, program activities; new ITP and BestPractices products; training and events; Web updates; and solicitations. Subscribe online at www.eere.energy.gov/industry/resources/ebulletin.

***Energy Matters*** is ITP's quarterly information source that informs industrial end users of energy efficiency opportunities, technical issues, new products, services, and events related to process heating systems and other industrial utilities such as motor, steam, and compressed air systems. Subscribe online at www.eere.energy.gov/industry/bestpractices.

## Directory of Contacts

**Industrial Heating Equipment Association (IHEA)**
P.O. Box 54172
Cincinnati, Ohio 45254
Phone: 513-231-5613
Fax: 513-624-0601
ihea@ihea.org
***www.ihea.org***

## Process Heating Specific Resources

### Software: Process Heating Assessment Tool (PHAST)

The Process Heating Assessment and Survey Tool (PHAST) provides an introduction to process heating methods and tools to improve thermal efficiency of heating equipment. Use the tool to survey process heating equipment that uses fuel, steam, or electricity, and identify the most energy-intensive equipment. Users can also perform an energy (heat) balance on selected equipment (furnaces) to identify and reduce non-productive energy use. Compare performance of the furnace under various operating conditions and test what-if scenarios. Further information on PHAST is provided in Section 3.

### Technical Publications

- **Tip Sheets:** To increase industry awareness of several fundamental improvement opportunities, ITP has developed several Process Heating tip sheets through its BestPractices program. These tip sheets provide concise descriptions of common improvement opportunities. Since BestPractices continues to develop and identify energy improvement programs, additional tip sheets are expected. Tip sheets can be found on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices, and Appendix B of this sourcebook.
- **Technical Briefs:** ITP has also developed technical briefs that provide an increased level of detail and guidance in identifying and implementing performance improvement opportunities. Technical briefs can be found on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices and Appendix C of this sourcebook

### Training

ITP offers both introductory and Qualified Specialist training in the use of PHAST. The introductory session provides an overview of process heating and process heating equipment, and highlights the use of PHAST to assess methods to improve thermal efficiency in industrial plants. The Qualified Specialist training is open to individuals with substantial knowledge of process heating systems and who are interested in taking a rigorous qualifying exam. Qualified PHAST Specialists apply the PHAST tool to accurately gather pertinent system information and provide realistic "what if" scenarios for process heating system operation.

IHEA's mission is to provide services that assist member companies to serve end users in the process heating industry. To achieve this mission, IHEA has determined the following objectives:

- Promote the interest of the industrial heat processing industry to the federal government, plus the many standard-setting groups relevant to this industry
- Educate member companies with regard to government regulations, industry standards, codes, and other matters that impact the heat processing industry
- Enhance the end user's image of member companies by stressing quality as viewed from the end user's perspective
- Raise the level of professionalism within the industrial heat processing industry and member companies
- Provide a forum for optimizing end-user operation of heat processing equipment through technical seminars and training sessions
- Develop and maintain relationships with related trade associations (domestic and foreign) in order to assimilate global information about our industry
- Engage in activities that will promote the common good of member companies such as gathering and disseminating non-competitive employment and statistical information, and providing educational programs for member company employee improvement.

## Other Process Heating System Contacts

Information on improving the performance of industrial process heating systems is available from several resources.

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**Electric Power Research Institute**
3420 Hillview Avenue
Palo Alto, CA 94304
Phone: 650-855-2000
Fax: 614-846-7306
***www.epri.com***

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California, and Charlotte, North Carolina, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States.

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**Electrotechnology Applications Center**
3835 Green Pond Road
Bethlehem, PA 18020-7599
Phone: 610-861-5081
Fax: 610-861-4101
***www.etctr.com***

The Electrotechnology Applications Center (ETAC) provides confidential assistance to industrial manufacturers to help them increase productivity, improve energy efficiency, and achieve and maintain environmental compliance. This is accomplished through ETAC's Coatings and Ink Research, Energy Management, Process Heating, and Sustainable Manufacturing Institutes. ETAC helps businesses gain a competitive advantage by applying technologies such as high efficiency natural gas systems, infrared, ultraviolet, induction, radio frequency, microwave, resistance, and electron beam to improve their heating, drying, coating and curing processes. ETAC engineers also use their extensive experience and knowledge of industrial processes and equipment to help manufacturers manage their energy usage and costs. Distance learning and classroom training for industry professionals is also developed and conducted by ETAC staff.

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**Gas Technology Institute (GTI)**
1700 S. Mount Prospect Road
Des Plaines, IL 60018
Phone: 847-768-0500
Fax: 847-768-0501
***www.gastechnology.org***

GTI is the leading research, development, and training organization serving the natural gas industry and energy markets. GTI is dedicated to meeting the nation's energy and environmental challenges by developing technology-based solutions for consumers, industry, and government.

GTI provides products, services, and information that help customers solve problems or capitalize on opportunities related to finding, producing, delivering, and using natural gas. More specifically, GTI:

- Performs contract research, development and demonstration projects (field and laboratory)
- Provides technical services in areas related to energy and the environment
- Commercializes new energy-related technology, directly and through subsidiaries
- Plans and manages technology development programs for the gas industry and other clients
- Aggregates funding for collaborative R&D programs of interest to individual companies, consortia, and government agencies

- Provides education and training on technical and business topics related to energy and natural gas.

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**National Insulation Association**
99 Canal Center Plaza, Suite 222
Alexandria, VA 22314
Phone: 703-683-6422
Fax: 703-549-4838
*www.insulation.org*

The National Insulation Association is a service organization that promotes the general welfare of the commercial and industrial insulation and asbestos abatement industries, and works to improve the service to the general public performed by the commercial and industrial insulation and asbestos abatement industries.

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**North American Insulation Manufacturers Association**
44 Canal Center Plaza, Suite 310
Alexandria, VA 22314
Phone: 703-684-0084
Fax: 703-684-0427
*www.naima.org*

North American Insulation Manufacturers Association (NAIMA) is a trade association of North American manufacturers of fiberglass, rock wool, and slag wool insulation products. NAIMA concentrates its efforts on promoting energy efficiency and environmental preservation through the use of fiberglass, rock wool, and slag wool insulation products, while encouraging safe production and use of these products.

## Resources and Tools

Note: The descriptions accompanying the following sources have generally been taken directly from the publisher, author, or developer. Inclusion of these sources does not imply endorsement by the U.S. Department of Energy.

Several other resources are available that describe current tools, technologies, and practices that can help improve steam system operating efficiency and performance. Many of these resources are intended to increase awareness of the benefits of energy improvement projects and to identify where the industry professional can go for more help.

## Books

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**American Society for Metals**
9639 Kinsman Road
Materials Park, OH 44073-0002

***Induction Heat Treatment of Steel***
*Author:* S.L. Semiatin and D.D. Stutz
*Description:* The book serves as a reference to induction heat treatment of steel. It reviews heat treating operations, induction heating, surface hardening, and equipment selection. Case studies are also included.

***Elements of Induction Heating: Design Control and Applications***
*Author*: S. Zinn, S. L. Semiatin
*Description:* This book describes different types of induction heating applications and includes information on different coil shapes and designs, tips, and data for different heating situations.

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**Battelle Press**
505 King Avenue
Columbus, OH 43201-2693

***Electric Process Heating, Technologies/Equipment/ Applications***
*Author:* Maurice Orfeuil
*Description.* A comprehensive text on electric-based process heating equipment. Detailed coverage of all electric-based process heating systems.

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**CRC Press**
2000 NW Corporate Boulevard
Boca Raton, FL 33431
800-272-7737
*www.crcpress.com*

***Handbook of Induction Heating***
*Author:* Valery I. Rudnev
*Description*: Offering ready-to-use tables, diagrams, graphs, and simplified formulas for at-a-glance guidance in induction heating system design, this book contains numerous photographs, magnetic field plots, temperature profiles, case studies, hands-on guidelines, and practical recommendations to navigate through various system designs and avoid surprises in installation, operation, and maintenance. It covers basic principles, modern design concepts, and advanced techniques engineers use to model and evaluate the different types of manufacturing processes based on heating by induction. The handbook explains the

electromagnetic and heat transfer phenomena that take place during induction heating.

***Heat Transfer in Industrial Combustion***
*Author:* Charles E. Baukal
*Description:* This book covers the heat transfer, thermodynamics, and fluid mechanics involved in industrial combustion practices, including a section on flame impingements. It reviews the basics and general concepts, as well as advanced applications and computer modeling.

***The Microwave Processing of Foods***
*Author:* Helmar Schubert
*Description:* From an international team of contributors, this publication reviews current research on how this technology affects particular foods and how it can be optimized for the food industry. This book discusses advantages in microwave processing such as more rapid heating and preservation of nutritional quality, as well as interactions with the dielectric properties of certain foods and the effects on sensory quality. The text also explores the range of applications of microwave processing including baking, drying, blanching, thawing, and tempering. In addition, it covers packaging issues as well as the key areas of process measurement and control to ensure more uniform heating of food products.

***Optimization of Industrial Unit Processes: Boilers, Chillers, Clean Rooms, Compressors, Cooling Towers, CSTR AND BSTR Reactors, Dryers, Evaporators, Fans, Heat Exchangers, HVAC Systems, Pumps***
*Author:* Bela G. Liptak
*Description:* This book describes ways to maximize the productivity, efficiency and safety of industrial equipment while minimizing the cost, taking into consideration issues such as leaks, plugged sensors, corrosion and cavitation.

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**IEEE: Institute of Electrical and Electronics Engineers**
445 Hoes Lane
Piscataway, NJ 08854-1331
732-981-0060
***www.ieee.org***

***Handbook of Electrical Heating for Industry***
*Author:* C. James Erickson
*Description:* This book provides tips and suggestions on how to specify, install, and operate electrical process heating systems for a broad range of industrial applications.

***Conduction and Induction Heating***
*Author:* John Davies, E. J. Davies
*Description:* This book covers the electrical engineering aspects of resistance and induction heating.

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**John Wiley & Sons**
111 River Street
Hoboken, NJ 07030-5774
201-748-6000
***www.wiley.com***

***Finite Element Method in Heat Transfer Analysis***
*Authors:* R. W. Lewis, H. Randolph Thomas, K. N. Seetharamu, Ken Morgan
*Description:* One of the first books specifically devoted to the application of the finite element method to heat transfer analysis. The authors present computation methods used in the course of their research, which demonstrate how the method works in practice.

***Handbook of Energy Systems Engineering Production and Utilization***
*Author:* Leslie Wilbur (Editor)
*Description:* Covers all aspects of energy system engineering from a user's perspective, from fuels to end-use technologies.

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**Krieger Publishing Company**
P.O. Box 9542
Melbourne, FL 32902-9542
321-724-9542
***www.krieger-publishing.com***

***Handbook of Thermal Insulation Design Economics for Pipes and Equipment***
*Authors:* William C. Turner, John F. Malloy
*Description:* This handbook discusses topics such as: heat transfer, insulation materials properties/selection/application/installation, and energy savings.

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**McGraw-Hill**
1221 Avenue of the Americas
New York, NY 10020
800-352-3566
***www.mhprofessional.com***

***A Working Guide to Process Equipment***
*Authors:* Norman P. Lieberman, Elizabeth T. Lieberman
*Description:* Explains the basic technical issues that need to be known to troubleshoot process equipment problems. Provides diagnostic tips, calculations, practical examples, and illustrations.

***Marks Standard Handbook of Mechanical Engineers***
*Authors:* Eugene Avallone and Theodore Baumeister, III (Editors)
*Description:* Provides descriptions of different heat distribution systems using many diagrams, drawings, graphs, and charts.

***Modeling of Gas-Fired Furnaces and Boilers and Other Industrial Heating Processes***
*Authors:* Jeff M. Rhine, Robert J. Tucker
*Description:* Describes how to model gas-fired furnaces and other process heating equipment.

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**National Academy Press**
500 Fifth Street. N.W.
Washington, D.C. 20001
888-624-8373
*www.nap.edu/*

***Microwave Processing of Materials***
*Author:* National Research Council
*Description:* Introduces the reader to the use of microwaves for processing materials. Identifies gaps, limitations, or weaknesses in the understanding of the use of microwaves in materials processing, and provides an assessment of the state of the art of microwave processing as an industrial technology.

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**Noyes Publications**
Willoughby Road
Bracknell Berkshire
RG12 8DW
UK
(+44)(0)1344 328039
*www.ihsatp.com*

***Electrotechnology: Industrial and Environmental Applications***
*Authors:* Nicholas P. Cheremisinoff
*Description:* A survey of electrotechnologies and their status. Principles of operation and significant applications, both current and potential, are outlined, and an assessment is made wherever possible of the selected topics. Many of the technologies and processes discussed are in their infancy and development stages. Some have developed and are developing rapidly, while all show great future promise.

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**Prentice Hall**
One Lake Street
Upper Saddle River, NJ 07458
800-382-3419
*www.prenhall.com*

***Energy Analysis of 108 Industrial Processes***
*Authors:* Harry Brown, Bernard Hamel, and Bruce Hedman
*Description:* A reference for identifying the quantity and quality of industrial waste energy, which can be economically practical to recover. Presents detailed heat and material balances developed from the process flow diagrams for 108 industrial processes.

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**Springer Science + Business Media**
233 Spring Street
New York, NY 10013-1578
212-460-1501
*www.springer.com*

***Laser Material Processing***
*Authors*: William M. Steen and Kenneth Watkins
*Description:* Lasers now play a major part in the processing of the disparate materials used in engineering and manufacturing. The range of procedures in which they are involved is ever increasing. With this growing prominence comes a need for clear and instructive textbooks to teach the next generation of laser users. The informal style of *Laser Material Processing* (3rd Edition) will guide you smoothly from the basics of laser physics to the detailed treatment of all the major materials processing techniques for which lasers are now essential.

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**Technomic Publishing Company**
851 New Holland Avenue
Box 3535
Lancaster, PA 17604-3535
800-233-9936

***Radio Frequency/Radiation and Plasma Processing: Industrial Applications & Advances***
*Authors:* Paul N. Cheremisinoff, O. C. Farah, R. P. Quellette
*Description:* Overview of various electric-based heating technologies and applications.

## Other Publications (Guides, Manuals, and Standards)

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**IHEA: Industrial Heating Equipment Association**
P. O. Box 54172
Cincinnati, OH 45230
513-231-5613
*www.ihea.org*

***Combustion Technology Manual (fifth edition)***
*Description:* A reference source of combustion engineering principles and practices prepared by many leading authorities involved in combustion processes. It includes in-depth studies of fluid flow, air sources, gas-air ratio control,

premixing, burners, fuel oil systems, measuring of gases, flame safety and sequence controls, sizing mixers, and flowmeters for atmosphere generators.

***IHEA Heat Processing Manual (first edition)***
*Description:* Provides a ready reference source for basic engineering principles and practices related to process heating. Chapters include: Thermal Energy Sources, Basic Heat Transfer, Safety Technology, Special Thermal Applications, Infrared Technology for Industrial Applications, Incineration and Heat Recovery Methods and Environmental Regulations—Impact on Process Heating Equipment.

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**Electric Power Research Institute (EPRI)**
3420 Hillview Avenue
Palo Alto, CA 94303
650-855-2000
*www.epri.com*

***Technology Guide for Electric Infrared Process Heating***
*Description:* This guidebook describes electric infrared process heating as it is used for curing coating and other materials fabrication applications. It is intended to help potential users understand and apply electric infrared technology. This guidebook was published in conjunction with Center for Materials Fabrication and Infrared Equipment Association

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**Vulcan-Verlag GmbH**
Huyssenallee 52-56
D-45128 Essen
Federal Republic of Germany
+49 (0)201 8 20 02-0

***Handbook of Thermoprocessing Technologies***
*Editors:* Axel von Starck, Alfred Mühlbauer, Carl Kramer
*Description:* This comprehensive book covers both fundamentals and cutting edge design principles of industrial thermoprocessing of materials in achieving the required properties, specific shapes and forms desired.

## Software

Section 3 of this sourcebook contains detailed descriptions of several resources and tools developed by the U.S. Department of Energy's Industrial Technologies Program that can be used to identify and assess process heating system improvement opportunities. Information on additional software produced by other organizations is provided in the following pages.

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**HTRI: Heat Transfer Research, Inc.**
150 Venture Drive
College Station, TX 77845
979-690-5050
*www.htri-net.com*

***FH Software***
*Developer:* HTRI
*Description:* Simulates the behavior of fire heaters, designs process heater tubes, and performs combustion calculations.

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**MAYA Heat Transfer Technologies**
4999 Street Catherine Street West
Suite 400
Montreal, Quebec, Canada H3Z 1T3
514-369-5706
*www.mayahtt.com*

***TMG Thermal Simulation Software***
*Developer:* MAYA Heat Transfer Technologies
*Description:* TMG thermal simulation software is a comprehensive heat transfer simulation package, which provides fast and accurate solutions to complex thermal problems. Using advanced finite difference control volume technology, TMG makes it easy to model nonlinear and transient heat transfer processes including conduction, radiation, free and forced convection, duct flow, and phase change.

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**National Insulation Association**
99 Canal Center Plaza
Suite 222
Alexandria, VA 22314
703-683-6422
*www.insulation.org*

***3E Plus Mechanical Insulation Energy Appraisal Program***
*Developer:* National Insulation Association
*Description*: Demonstrates to plant owners, engineers, specifiers, and contractors the enormous energy savings in dollars through the use of insulation on hot and cold piping, ducts, vessels, and equipment in a facility. Savings are also quantified in $CO_2$, $NO_x$, and CE emission levels. Note that 3E Plus is intended for low-temperature applications and does not include data for high temperature refractories and insulation.

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**Oarsman Corporation**
*www.oarsman.com*

***Process Heating Software***
*Developer:* Oarsman Corporation
*Description:* Allows for the side-by-side comparison of different methods of process heating. When combined with other analysis such as combined heat and power, compressed air, or refrigeration, heat recovery savings can also be evaluated.

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**TechniCAL**
2400 Veterans Boulevard
Suite 145
Kenner, LA 70062
504-733-0300
***www.tcal.com***

***CALSoft32 Thermal Processing Software***
*Developer:* TechniCAL
*Description:* Conducts heat penetration and temperature distribution testing, evaluates the collected data, and calculates a thermal process or vent schedule/come-up time.

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**ThermoAnalytics**
23440 Airpark Boulevard
P.O. Box 66
Calumet, MI 49913
906-482-9560
***www.thermoanalytics.com***

***WinTherm Software***
*Developer:* ThermoAnalytics
*Description:* WinTherm is designed for component-level modeling and simulation and provides the user with a complete solution to thermal analysis for models up to 20,000 thermal nodes (typically 10,000 mesh elements). WinTherm runs under Windows 95/98/NT and UNIX and allows users from any engineering background (thermal or other) to analyze their components quickly and accurately. Examples of WinTherm applications are electronics enclosures, fluid tanks, or oven systems. Analysis of heat management techniques such as insulated heat shields, cooling with fans, heat sinks, or surface treatments can be explored.

***RadTherm Software***
*Developer:* ThermoAnalytics
*Description:* RadTherm is full-featured, cross-platform, thermal analysis software for system-level CAE applications. RadTherm utilizes a state-of-the-art Radiation Module and an extremely user-friendly Graphical User Interface to set up boundary conditions for multi-mode heat transfer: multibounce radiation, conduction and convection with one-dimensional fluid flow. Examples of RadTherm applications are complete vehicular systems, aerospace systems, electronic instrument panels, architectural solar analysis, and complex process heating schemes.

## Periodicals

***Chemical Engineering***
Access Intelligence
New York, NY
***www.che.com***

***Chemical Processing***
Putman Media
Itasca, IL
***www.chemicalprocessing.com***

***Energy Engineering***
Association of Energy Engineers
Lilburn, GA
***www.aeecenter.com***

***Energy Matters***
U.S. Department of Energy
Industrial Technologies Program
Washington, D.C.
***www.eere.energy.gov/industry/bestpractices***

***Energy and Power Management***
BNP Media
Troy, MI
***www.energyandpowermanagement.com***

***Industrial Heating: The International Journal of Thermal Technology***
BNP Media
Troy, MI
***www.industrialheating.com***

***Industrial Maintenance & Plant Operation***
Advantage Business Media
Madison, WI
***www.impomag.com***

***Process Heating***
BNP Media
Troy, MI
***www.process-heating.com***

## Reports and Technical Papers

**Gas Technology Institute (GTI)**
1700 S. Mount Prospect Road
Des Plaines, IL 60018
847-768-0500
***www.gastechnology.org***

***General Infrared Process Heating Application Tool***
This report on the infrared application tool presents an overview of infrared process heating technology. It explains the fundamentals of infrared heating, identifies the characteristics of products and heating equipment that should be considered in applying infrared, and describes the different types of infrared heaters, their operation and their characteristic features. Applications discussed in detail include the paper industry, plastics thermoforming, powder coating and curing, and textiles processing.

**U.S. Department of Energy**
Industrial Technologies Program
***www.eere.energy.gov/industry***

***Roadmap for Process Heating Technology: Priority Research and Development Goals and Near-Term Non-Research Goals to Improve Industrial Process Heating***
*Description:* This roadmap summarizes the future technology priorities for increasing the energy efficiency of industrial process heating systems. It is the outcome of a collaborative effort led by the Industrial Heating Equipment Association and DOE to develop a comprehensive plan for meeting industrial process heating needs. The roadmap includes performance targets for the year 2020, barriers to improvement, priority R&D goals, non-research goals, and next steps for implementation. The roadmap may be downloaded at www.eere.energy.gov/industry/bestpractices.

***Process Heating Supplement to Energy Matters Newsletter***
*Description:* A six-page executive summary of the large Roadmap for Process Heating Technology technical report. Articles include: "Process Heating Roadmap to Help U.S. Industries Be Competitive"; "The Big Picture on Process Heating"; "Seven Ways to Optimize Your Process Heat System"; "Indirect-Fired Kiln Conserves Scrap Aluminum and Cuts Costs". Available from the Industrial Technologies Program at www.eere.energy.gov/industry.

## Training Courses and Technical Services

**Association of Energy Engineers**
4025 Pleasantdale Road, Suite 420
Atlanta, GA 30340
770-447-5083
***www.aeecenter.org***

*Area(s) covered:* Seminars offered for various topics of interest, including air distribution systems, energy management, conservation, and economics.

**Center for Professional Advancement**
Box 7077
44 West Ferris Street
East Brunswick, NJ 08816-7077
732-238-1600
***www.cfpa.com***

*Area(s) covered:* The CFPA offers courses in piping design, analysis, and fabrication; pressure vessel design and analysis; project management for plant retrofits; and shutdowns.

**IHEA: Industrial Heating Equipment Association**
P. O. Box 54172
Cincinnati, OH 45230
513-231-5613
***www.ihea.org***

*Area(s) covered:* Annual Combustion Technology and Annual Safety Standards Seminars.

**PHAST Training Seminars**
U.S. Department of Energy and Industrial Heating Equipment Association
***www.eere.energy.gov/industry/bestpractices***

*Area(s) covered:* How to use PHAST software, how to accurately collect and input data for PHAST; what information sources, instruments, and measurement devices to use for collection of necessary data required for use of PHAST; and how to use PHAST to evaluate a process heating system and develop a measurement plan.

**PGS Energy Training**
43 Fawnvue Drive
Suite 700
McKees Rocks, PA 15136
412-521-4737
***www.pgsenergy.com***

*Area(s) covered:* Managing industrial energy procurement.

**TMS: The Minerals, Metals, & Materials Society**
184 Thorn Hill Road
Warrendale, PA 15086-7514
724-776-9000
***www.tms.org***

*Area(s) covered:* Process Heating Systems Optimization Workshop (TMS Annual meeting)

# Appendices

The following appendices have been included in the sourcebook:

- **Appendix A: Glossary of Terms**
  This appendix contains a glossary of terms used in process heating systems.

- **Appendix B: Process Heating Tip Sheets**
  This appendix contains a series of process heating system tip sheets developed by the U.S. Department of Energy's Industrial Technologies Program (ITP). These tip sheets discuss common opportunities that industrial facilities can use to improve performance and reduce fuel use.

- **Appendix C: Technical Briefs**
  This appendix contains a series of process heating technical briefs developed by ITP. These discuss key process heating issues in detail.

- **Appendix D: References**
  This appendix is a list of all the references used throughout the sourcebook.

- **Appendix E: Guidelines for Comments**
  This appendix contains a form that provides a vehicle for submitting comments for improving the sourcebook.

# 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 $6.24 \times 10^{18}$ 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 $H_2$, 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.

**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.

# Appendix B: Process Heating Tip Sheets

The U.S. Department of Energy's Industrial Technologies Program (ITP) has developed this series of tip sheets through its BestPractices program.

1. Preheated Combustion Air (recovery)
2. Check Burner Air to Fuel Ratios (generation)
3. Oxygen-Enriched Combustion (recovery)
4. Check Heat Transfer Surfaces (transfer)
5. Reduce Air Infiltration in Furnaces (containment)
6. Furnace Pressure Controllers (generation)
7. Reduce Radiation Losses from Heating Equipment (containment)
8. Install Waste Heat Recovery Systems for Fuel-Fired Furnaces (recovery)
9. Load Preheating Using Flue Gases from a Fuel-Fired Heating System (recovery)
10. Using Waste Heat for External Processes (recovery)
11. Use Lower Flammable Limit Monitoring Equipment to Improve Oven Efficiency

The tip sheets can also be downloaded from ITP's BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

# Preheated Combustion Air

For fuel-fired industrial heating processes, one of the most potent ways to improve efficiency and productivity is to preheat the combustion air going to the burners. The source of this heat energy is the exhaust gas stream, which leaves the process at elevated temperatures. A heat exchanger, placed in the exhaust stack or ductwork, can extract a large portion of the thermal energy in the flue gases and transfer it to the incoming combustion air. Recycling heat this way will reduce the amount of the purchased fuel needed by the furnace.

Many processes produce dirty or corrosive exhaust gases that will plug or attack heat exchangers. Some exchangers are more resistant to these conditions than others, so if your process is not a clean one, do not give up without investigating all the options. When discussing it with potential vendors, be sure to have a detailed analysis of the troublesome materials in your exhaust gas stream.

Fuel savings for different furnace exhaust gas temperature and preheated combustion air temperature can be found in the table below and can be used to estimate reductions in energy costs.

**Percent Fuel Savings Gained from Using Preheated Combustion Air**

| Furnace Exhaust Temperature, ˚F | Preheated Air Temperature, ˚F | | | | | |
|---|---|---|---|---|---|---|
| | 600 | 800 | 1,000 | 1,200 | 1,400 | 1,600 |
| 1,000 | 13 | 18 | – | – | – | – |
| 1,200 | 14 | 19 | 23 | – | – | – |
| 1,400 | 15 | 20 | 24 | 28 | – | – |
| 1,600 | 17 | 22 | 26 | 30 | 34 | – |
| 1,800 | 18 | 24 | 28 | 33 | 37 | 40 |
| 2,000 | 20 | 26 | 31 | 35 | 39 | 43 |
| 2,200 | 23 | 29 | 34 | 39 | 43 | 47 |
| 2,400 | 26 | 32 | 38 | 43 | 47 | 51 |

Fuel: Natural gas at 10% excess air

Source: IHEA Combustion Technology Manual (see references)

There are two types of air preheaters: recuperators and regenerators. Recuperators are gas-to-gas heat exchangers placed on the furnace stack. Internal tubes or plates transfer heat from the outgoing exhaust gas to the incoming combustion air while keeping the two streams from mixing. Recuperators are available in a wide variety of styles, flow capacities, and temperature ranges. Regenerators include two or more separate heat storage sections, each referred to as a regenerator. Flue gases and combustion air take turns flowing through each regenerator, alternately heating the storage medium and then withdrawing heat from it. For uninterrupted operation, at least two regenerators and their associated burners are required: one regenerator is needed to fire the furnace while the other is recharging.

## Payback Guidelines

Process temperature is customarily used as a rough indication of where air preheating will be cost effective. Processes operating above 1,600˚F are generally good candidates, while preheated air is difficult to justify on processes operating below 1,000˚F. Those in the 1,000˚ to 1,600˚F range may still be good candidates but must be evaluated on a case-by-case basis.

These guidelines are not ironclad. Financial justification is based on energy (or Btu) saved, rather than on temperature differential. If a low temperature process has a high enough exhaust gas flow, energy savings may still exist, even though the exhaust gas temperature is lower than 1,000˚F.

## References

1. *Combustion Technology Manual.* Published by Industrial Heating Equipment Association (IHEA), Arlington, Virginia.
2. *Maintenance and Adjustment Manual for Natural Gas and No. 2 Fuel Oil Burners.* Technical Information Center, U.S. Department of Energy.
3. *Handbook of Applied Thermal Design,* edited by Eric C. Guyer. Published by McGraw Hill Book Company.

**Payback Period = (Cost of combustion air preheating system, obtained from the supplier or contractor) + (Reduction in fuel usage, Million Btu/hr x Number of operating hours per year x Cost of fuel per Million Btu)**

### Example

A furnace operates at 1,600˚F for 8,000 hours per year at an average of 10 million British thermal units (MMBtu) per hour using ambient temperature combustion air. At $9 per MMBtu, annual energy cost is $720,000. Use of preheated air at 800˚F will result in 22% fuel savings, or $158,400 annually. The preheated air system installation is estimated to cost $200,000 to $250,000, with a simple payback period of 15 to 19 months.

## Suggested Actions

- **Using current or projected energy costs, estimate preheated air savings with this example or the Process Heating Assessment and Survey Tool (PHAST) available from the U.S. Department of Energy's Industrial Technologies Program.**
- **Contact furnace or combustion system suppliers to calculate payback period or ROI.**

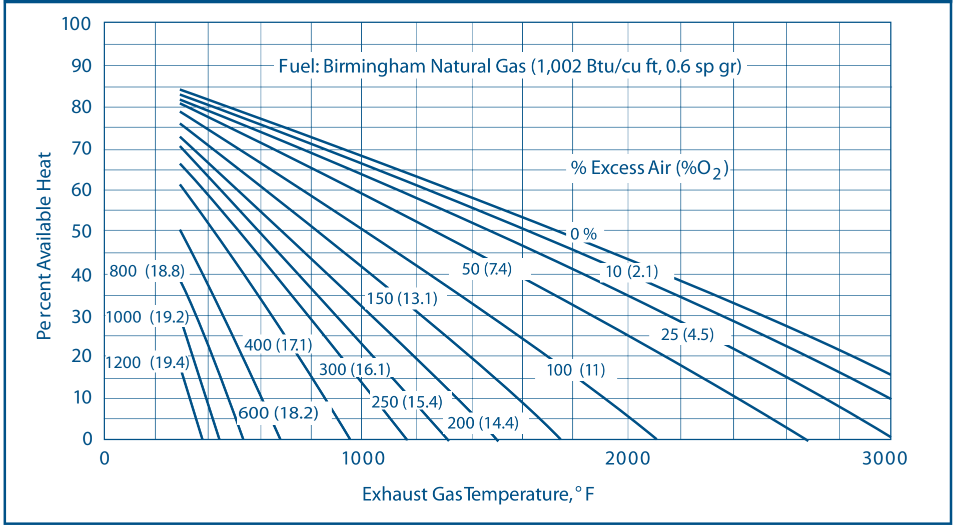
DOE/GO-102007-2482 • October 2007• Process Heating Tip Sheet #1

# Check Burner Air to Fuel Ratios

Periodic checking and resetting of air-fuel ratios for burners is one of the simplest ways to get maximum efficiency out of fuel-fired process heating equipment such as furnaces, ovens, heaters, and boilers. Most high temperature direct-fired furnaces, radiant tubes, and boilers operate with about 10% to 20% excess combustion air at high fire to prevent the formation of dangerous carbon monoxide and soot deposits on heat transfer surfaces and inside radiant tubes. For the fuels most commonly used by U.S. industry, including natural gas, propane, and fuel oils, approximately one cubic foot of air is required to release about 100 British thermal units (Btu) in complete combustion. Exact amount of air required for complete combustion of commonly used fuels can be obtained from the information given in one of the references. Process heating efficiency is reduced considerably if the combustion air supply is significantly higher or lower than the theoretically required air.

Air-gas ratios can be determined by flow metering of air and fuel or flue gas analysis. Sometimes, a combination of the two works best. Use the Available Heat Chart below to estimate the savings obtainable by tuning burner air-gas ratios. The excess air curves are labeled with corresponding oxygen percentages in flue gases.

**Available Heat Chart**



Source: Calculations by Mr. Richard Bennett, published in *Process Heating* magazine, September 1997.

To figure potential savings, you need to know:

- The temperature of the products of combustion as they leave the furnace
- The percentage of excess air or oxygen in flue gases, at which the furnace now operates
- The percentage of excess air or oxygen in flue gases, at which the furnace could operate.

### Factors Affecting Excess Air Level Requirements

Combustion systems operate with different amounts of excess air between high and low fire. Measurement of oxygen and combustibles such as carbon monoxide in flue gases can be used to monitor changes in excess air levels. For most systems, 2% to 3% of oxygen with a small amount of combustibles—only 10 to 50 parts per million—indicate ideal operating conditions.

Processes that evaporate moisture or solvents need large amounts of excess air to dilute flammable solvents to noncombustible levels, to ensure adequate drying rates, and to carry vapors out of the oven. Lowering excess air to minimal levels can slow down the process and create an explosion hazard.

### References

*Combustion Technology Manual.* Published by Industrial Heating Equipment Association (IHEA), Arlington, Virginia 22209.

*Maintenance and Adjustment Manual for Natural Gas and No. 2 Fuel Oil Burners*. Technical Information Center, Department of Energy.

*Handbook of Applied Thermal Design,* edited by Eric C. Guyer.Published by McGraw Hill Book Company.

On the chart, determine the available heat under present and desired conditions by reading up from the flue gas temperature to the curve representing the excess air or $O_2$ level; then, read left to the percentage available heat (AH). Calculate the potential fuel savings:

**% Fuel Savings = 100 X ((%AH Desired - %AH Actual ) / %AH Desired)**

### Example

A furnace operates at 2,400°F flue gas temperature. The optimum ratio is 10% excess air (2.1% $O_2$ in flue gases), but tests show an actual ratio of 25% excess air (4.5% $O_2$ in flue gases). The chart shows an actual available heat of 22% compared to an ideal of 29%.

**Fuel Savings = 100 X (( 29 – 22 ) / 29 ) = 24%**

Note: The graph on the front page is for combustion air at ambient temperature (about 60ºF) using natural gas with specific gas composition. The exact numbers may vary slightly if the natural gas composition is different from the one used for this graph. The available heat will also be different if the combustion air temperature is different. Use the Process Heating Assessment and Survey Tool (PHAST) or other methods to estimate fuel savings if your operating conditions are significantly different from the conditions stated above.

## Suggested Actions

**To get the most efficient performance out of fuel-fired furnaces, ovens, and boilers:**

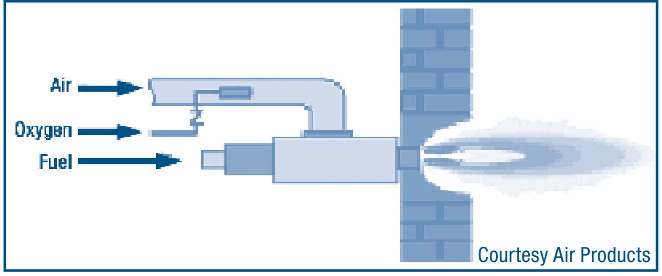
1. **Determine the best level of excess air for operating your equipment.**
2. **Set your combustion ratio controls for that amount of excess air.**
3. **Check and adjust ratio settings regularly.**

DOE/GO-102007-2483 • November 2007 • Process Heating Tip Sheet #2

# Oxygen-Enriched Combustion

When a fuel is burned, oxygen in the combustion air chemically combines with the hydrogen and carbon in the fuel to form water and carbon dioxide, releasing heat in the process. Air is made up of 21% oxygen, 78% nitrogen, and 1% other gases. During air–fuel combustion, the chemically inert nitrogen in the air dilutes the reactive oxygen and carries away some of the energy in the hot combustion exhaust gas. An increase in oxygen in the combustion air can reduce the energy loss in the exhaust gases and increase heating system efficiency.

**Figure 1. Oxygen-enriched burner**



Courtesy Air Products

Most industrial furnaces that use oxygen or oxygen-enriched air use either liquid oxygen to increase the oxygen concentration in the combustion air or vacuum pressure swing adsorption units to remove some of the nitrogen and increase the oxygen content. Some systems use almost 100% oxygen in the main combustion header; others blend in oxygen to increase the oxygen in the incoming combustion air (see Figure 1). Some systems use auxiliary oxy-fuel burners in conjunction with standard burners. Other systems use staged combustion and vary the oxygen concentration during different stages of combustion. Still others "lance" oxygen by strategically injecting it beside, beneath, or through the air–fuel flame.

## Benefits

Oxygen-enriched combustion can:

- **Increase efficiency.** The flue gas heat losses are reduced because the flue gas mass decreases as it leaves the furnace. There is less nitrogen to carry heat from the furnace.
- **Lower emissions.** Certain burners and oxy-fuel fired systems can achieve lower levels of nitrogen oxide, carbon monoxide, and hydrocarbons.
- **Improve temperature stability and heat transfer.** Increasing the oxygen content allows more stable combustion and higher combustion temperatures that can lead to better heat transfer.
- **Increase productivity.** When a furnace has been converted to be oxygen enriched, throughput can be increased for the same fuel input because of higher flame temperature, increased heat transfer to the load, and reduced flue gas.

## Suggested Actions

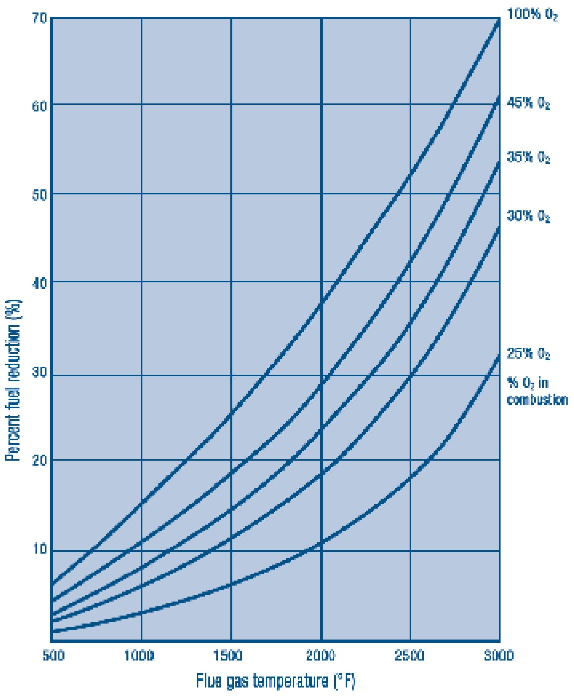
- Use current or projected energy costs with PHAST to estimate energy savings from oxygen-enriched combustion.
- Contact furnace or combustion system suppliers to calculate payback or return on investment.
- Include the cost of oxygen or of the vacuum pressure swing adsorption unit in the calculations.

Using oxygen-enriched combustion for specific applications may improve efficiency, depending on the exhaust gas temperature and percentage of oxygen in the combus-tion air. Figure 2 can be used to calculate energy savings for commonly used process heating applications. The Process Heating Assessment and Survey Tool (PHAST) can also be used to estimate the amount of energy that can be saved by switching to oxygen-enriched combustion.

Conversion to oxygen-enriched combustion is followed by an increase in furnace temperature and a simultaneous decrease in furnace gas flow around the product. Unless there is a sufficient increase in the heat transfer to product, the flue gas temperature will rise above the pre-conversion level and little or no energy will be saved. In radiant heat-governed furnaces, the conversion could increase the radiant heat transfer substantially.

Consequently, the flue gas temperature could drop to or below the pre-conversion level. In convective heat-governed furnaces, the furnace gas velocity may drop because the convective heat transfer coefficient may decrease in a larger proportion than the increase in gas temperature. If this happens, the conversion would do little to increase the overall heat transfer, so reducing
flue gas temperature to pre-conversion level may not be possible.

**Figure 2. Energy savings from oxygen injection**



## Potential Applications

Oxygen-enhanced combustion is used primarily in the glass-melting industry, but other potential applications can be found in Table 1.

**Table 1. Potential Applications for Oxygen- Enhanced Combustion**

| Industry | Applications |
|---|---|
| Steel | Reheat, soaking pits, ladles |
| Aluminum | Melting |
| Copper | Smelting and melting |
| Glass | Melting |
| Pulp and Paper | Lime kilns, black liquor boilers |
| Petroleum | Process heaters, crackers |
| Power Production | Coal-fired steam boilers |
| Chemical | Sulfur |

## Sample Applications

**Theoretical** — A potential application is a PHAST analysis of a forging furnace where the flue gas temperature is 2,100°F and 95% of the combustion air is oxygen. This shows a 42% fuel saving over a conventional system.

**Actual** — The U.S. Department of Energy (DOE) sponsored a performance study (www.eere.energy.gov/industry/glass/pdfs/oxy_fuel.pdf) in which a glass melter was converted to 100% oxygen-enriched combustion. The plant was a 70 ton-per-day end-fired melter. Natural gas consumption was lowered by 10% to 20% and nitrogen oxide emissions were reduced by 90%.

## Reference

*Improving Process Heating System Performance: A Sourcebook for Industry.*
DOE and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

**DOE/GO-102005-2178 • September 2005• Process Heating Tip Sheet #3**

# Check Heat Transfer Surfaces

Industrial process heating systems use various methods to transfer heat to the load. These include direct heat transfer from the flame or heated gases to the load and indirect heat transfer from radiant tubes, muffles, or heat exchangers. Indirect heating systems that use fuel firing, steam, or hot liquids to supply heat are discussed in this tip sheet. In each case, clean heat transfer surfaces can improve system efficiency. Deposits of soot, scale or oxides, sludge, and slag on the heat transfer surfaces should be avoided.

## Contamination from Flue Gas and Heating Medium

Problem areas from flue gas include soot, scale or oxides, sludge, and slag. Soot is a black substance formed by combustion that adheres to heat transfer surfaces. Scale or oxide is formed when metals are oxidized in the presence of oxygen, water vapor, or other oxidizing gases. Sludge is residue from a liquid–solid mixture after the liquid evaporates. Slag is the residue formed by oxidation at the surface of molten metals, which can also adhere to heat transfer surfaces. These contaminants impede the efficient transfer of heat and reduce the efficiency of industrial heating systems.

**Figure 1. Example of a poorly maintained heat exchanger from an aluminum melting furnace**

Problem areas for indirectly heated systems where heating media such as air, steam, or hot liquids are used include scale, dirt, oxide film, or fouling on the heat transfer surfaces that are in contact with the heating medium.

Contamination of heat transfer surfaces is typically the result of:
- Low air:fuel ratios
- Improper fuel preparation
- Malfunctioning burners
- Oxidation of heat transfer surfaces in high temperature applications
- Corrosive gases or constituents in the heating medium
- Stagnant or low-velocity areas in contact with heat transfer surfaces for hot liquid or gas heating systems
- Special atmospheres (such as in heat treating furnaces) that can produce soot during the heating process.

### Suggested Actions—Flue Gases

- Examine your flue-side heat transfer surfaces for deposits.
- Clean heat transfer surfaces periodically.
- Use a soot blower to automatically clean heat transfer surfaces.
- Use a soot burn-out practice for radiant tubes or muffles used in high temperature furnaces.
- Use continuous agitation or other methods to prevent materials from accumulating on the heat transfer surfaces.

### Suggested Actions—Water Supplies

- Examine your water-side heat transfer surfaces for scale and remove the deposits.
- If scale is present, consult with your local water treatment specialist and consider modifying your chemical additives.

As shown in Table 1, a 1/32-inch thick layer of soot can reduce heat transfer by about 2.5%.

**Table 1. Efficiency Reductions Caused by Soot Deposits***

| Soot Layer Thickness | | |
|---|---|---|
| 1/32 inch | 1/16 inch | 1/8 inch |
| 2.5% | 4.5% | 8.5% |

*Extracted from the Application Note – Energy Efficiency Operations and Maintenance Strategies for Industrial Gas Boilers, Pacific Gas and Electric Company, May 1997.

Contamination from flue gas can also shorten equipment life and lead to unscheduled maintenance. The extent to which dirty heat transfer surfaces affect efficiency can be estimated from an increase in stack temperature relative to a "clean operation" or baseline condition. Efficiency is reduced by approximately 1% for every 40°F increase in stack temperature.

## Contamination from Water Supplies

Scale is formed from deposits of calcium, magnesium, or silica from the water supply. Problems occur when these minerals form a continuous layer of material on the water side of heat transfer surfaces; surfaces with scale deposits have much lower thermal conductivity than bare metal. Efficiency losses from scale deposits can range from 1% to 7%. Scale deposits can also lead to decreased heat transfer equipment life, especially because of corrosion. Most scale problems are caused by inadequate water treatment. Scale can be removed mechanically (by manual brushing) or with acid cleaning.

## Reference

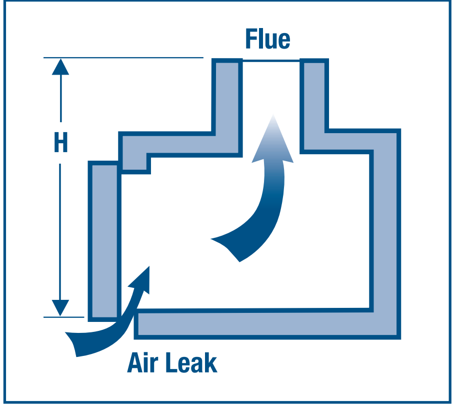
*Improving Process Heating System Performance: A Sourcebook for Industry.*
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

DOE/GO-102005-2179 • September 2005 • Process Heating Tip Sheet #4

# Reduce Air Infiltration in Furnaces

Fuel-fired furnaces discharge combustion products through a stack or a chimney. Hot furnace gases are less dense and more buoyant than ambient air, so they rise, creating a differential pressure between the top and the bottom of the furnace. This differential, known as *thermal head*, is the source of a natural draft or negative pressure in furnaces and boilers.

**Figure 1. Air leakage and gas flow in a typical fuel-fired furnace**



A well-designed furnace (or boiler) is built to avoid air leakage into the furnace or leakage of flue gases from the furnace to the ambient. However, with time, most furnaces develop cracks or openings around doors, joints, and hearth seals. These openings (leaks) usually appear small compared with the overall dimensions of the furnace, so they are often ignored. The negative pressure created by the natural draft (or use of an induced-draft fan) in a furnace draws cold air through the openings (leaks) and into the furnace. The cold air becomes heated to the furnace exhaust gas temperature and then exits through the flue system, wasting valuable fuel. It might also cause excessive oxidation of metals or other materials in the furnaces.

The heat loss due to cold air leakage resulting from the natural draft can be estimated if you know four major parameters:

- The furnace or flue gas temperature
- The vertical distance H between the opening (leak) and the point where the exhaust gases leave the furnace and its flue system (if the leak is along a vertical surface, H will be an average value)
- The area of the leak, in square inches
- The amount of operating time the furnace spends at negative pressure.

Secondary parameters that affect the amount of air leakage include these:

- The furnace firing rate
- The flue gas velocity through the stack or the stack cross-section area
- The burner operating conditions (e.g., excess air, combustion air temperature, and so on).

## Suggested Actions

Taking the following actions can reduce air leakage in a furnace:

1. Repair the air leakage area by replacing or repairing insulation or seals.
2. Close furnace doors properly to maintain a tight seal and avoid opening.
3. Install a pressure control system that maintains balanced, slightly positive (in hundredths of an inch) pressure, at the point of major air leakage.
4. Install a damper in the stack that can be adjusted manually if an automated furnace pressure control cannot be used or justified.
5. Install or use a "draft gage" to monitor furnace pressure at the level of air leakage if it cannot be sealed properly, and adjust the manual damper to maintain balanced, slightly positive (in hundredths of an inch) pressure, at the point of major air leakage.

Note: Actions 3-5 work only in forced and balanced draft furnaces.

## Resources

See also *Improving Process Heating System Performance: A Sourcebook for Industry.* Washington, D.C.: U.S. Department of Energy and Industrial Heating Equipment Association, 2004.

For furnaces or boilers using an induced-draft (ID) fan, the furnace negative pressure depends on the fan performance and frictional losses between the fan inlet and the point of air leakage. In most cases, it would be necessary to measure or estimate negative pressure at the opening.

The amount of air leakage, the heat lost in flue gases, and their effects on increased furnace or boiler fuel consumption can be calculated by using the equations and graphs given in *Industrial Furnaces* (see W. Trinks et al., below). Note that the actual heat input required to compensate for the heat loss in flue gases due to air leakage would be greater than the heat contained in the air leakage because of the effect of available heat in the furnace. For a high-temperature furnace that is not maintained properly, the fuel consumption increase due to air leakage can be as high as 10% of the fuel input.

## Example

An industrial forging furnace with an 8-foot (ft) stack operates at 2,300°F for 6,000 hours per year (hr/yr) on natural gas costing $8.00/ MMBtu. The door of the furnace has an unnecessary 36-square-inch (in.$^2$) opening at the bottom that allows air to infiltrate. The table to the right shows the annual cost of the fuel that would be wasted because of the leak.

| Cost of Air Infiltration in a Furnace | |
|---|---|
| Stack height (ft) | 8 |
| Stack diameter (ft) | 3 |
| Opening size, area (in.$^2$) | 36 |
| Gross input (MMBtu/hr) | 20 |
| Combustion air temperature (°F) | 70 |
| Oxygen in flue gases (%) | 2 |
| Temperature of flue gases (°F) | 2,300 |
| Fuel cost ($/MMBtu) | 8 |
| Operating hr/yr | 6,000 |
| Air infiltration (ft$^3$/hr) | 15,300 |
| Annual cost of wasted fuel ($) | 100,875 |

## Furnace Pressure Controllers

Furnace pressures fluctuate with the burner firing rate and tend to be lowest at the lowest firing rates. To compensate for this constantly changing condition, a furnace pressure control system is used. It consists of a stack damper automatically controlled to maintain a neutral or slightly positive pressure in the combustion chamber. As burner firing rates decrease, the damper throttles the flow out of the stack to hold the pressure constant. Many different types of pressure controllers are available for use with furnaces and boilers. See the tip sheet titled *Furnace Pressure Controllers* for more information.

## References

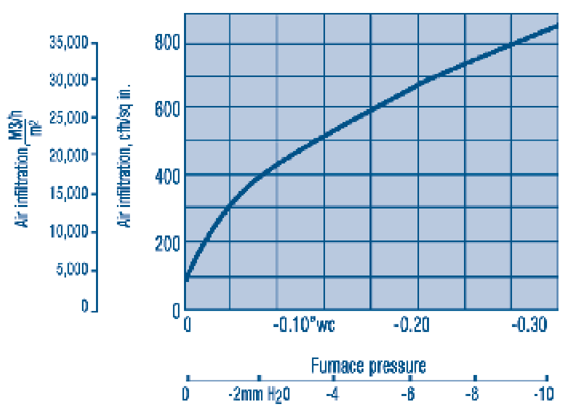
*Fan Engineering.* Robert Jorgensen, ed. New York: Buffalo Forge Company. 1961.

*Gas Engineers Handbook.* George C. Segeler, ed. New York: The Industrial Press. 1968.

W. Trinks et al. *Industrial Furnaces, Sixth Edition.* New York: John Wiley & Sons, Inc. 2003.

# Furnace Pressure Controllers

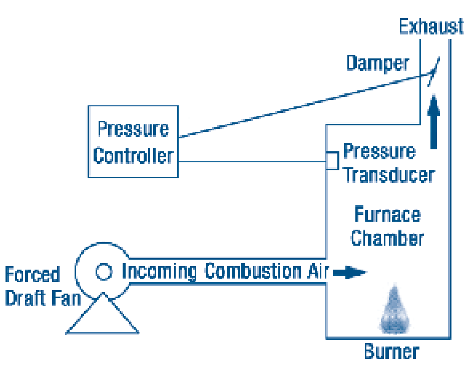
Figure 1. Air infiltration from furnace draft



Furnace draft, or negative pressure, is created in fuel-fired furnaces when high temperature gases are discharged at a level higher than the furnace openings. This is commonly known as the *chimney effect*. The negative pressure in a furnace that operates at a fixed temperature changes with the heat input rate or mass flow of flue gases moving through the stack. This negative pressure causes ambient air to leak into the furnace.

Figure 1 shows rates of air infiltration resulting from furnace draft. This air has to be heated to the flue gas temperature before it leaves the furnace through the stack, which wastes energy and reduces efficiency. The air infiltration can be minimized by reducing or eliminating openings and areas of possible air leaks and by controlling pressure in the furnace. Examples of openings include leakage around burner mountings, seals around heater or radiant tubes, doors that are opened and closed frequently, and observation ports.

Figure 2. Furnace pressure controller



Furnace pressure controllers regulate and stabilize the pressure in the working chamber of process heating equipment. Pressure controllers use a pressure gauge in the furnace chamber or duct and regulate the airflow to maintain a slightly positive pressure (a few inches of water gauge) in the furnace chamber (see Figure 2). Airflow can be regulated by varying the speed of draft fans or by changing damper settings for the incoming combustion air or the exiting flue gas.

## Suggested Actions

- Work with process heating specialists to estimate energy savings from using precise furnace pressure control.
- Contact furnace or combustion system suppliers to obtain cost estimates so you can calculate payback or return on investment.

Pressure controllers can be manual or automatic. An equipment operator typically uses a dial on a control panel to set the pressure in a manual system. An automatic system has a feedback loop and continuously monitors and regulates the pressure through an electronic control system. A barometric damper is an inexpensive option for a natural draft furnace or oven.

Four types of draft systems are used in industrial furnaces:

- **Natural.** Uses the chimney effect. Gases inside the stack are less dense and will rise, creating a vacuum that draws air into the furnace.
- **Induced.** A fan draws air from the furnace to the stack.
- **Forced.** A fan pushes air into the furnace.
- **Balanced.** Uses an induced and a forced draft fan.

Furnace pressure controllers can work with any of these systems. Properly sized stack diameters and dampers (or fan speed control) must be used to control furnace pressure for the entire range of furnace operation or firing rates. For safety reasons, controlled atmosphere furnaces require positive pressure and special pressure controllers; furnaces and ovens with volatile vapors (from operations like paint drying) require slightly negative pressure.

## Benefits

Maintaining slightly positive furnace pressure can have many benefits, including:

- **Energy savings.** Positive pressure eliminates cold air infiltration, which reduces fuel consumption.
- **Improved product quality.** Process heating equipment with regulated pressure control will help maintain a more uniform temperature in the furnaces and avoid cold and hot spots, which can improve product quality. For heat treating applications, positive furnace pressure can reduce oxidation, and for processes like carburizing, create a more stable atmosphere for the diffusion process.
- **Maintenance savings.** Pressure control prevents excessive fluing through cracks and doors in process heating equipment, which can minimize corrosion and crack enlargement.
- **Emissions Reductions.** Improved combustion control can reduce emissions.

## Reference

*Improving Process Heating System Performance: A Sourcebook for Industry.*
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices.

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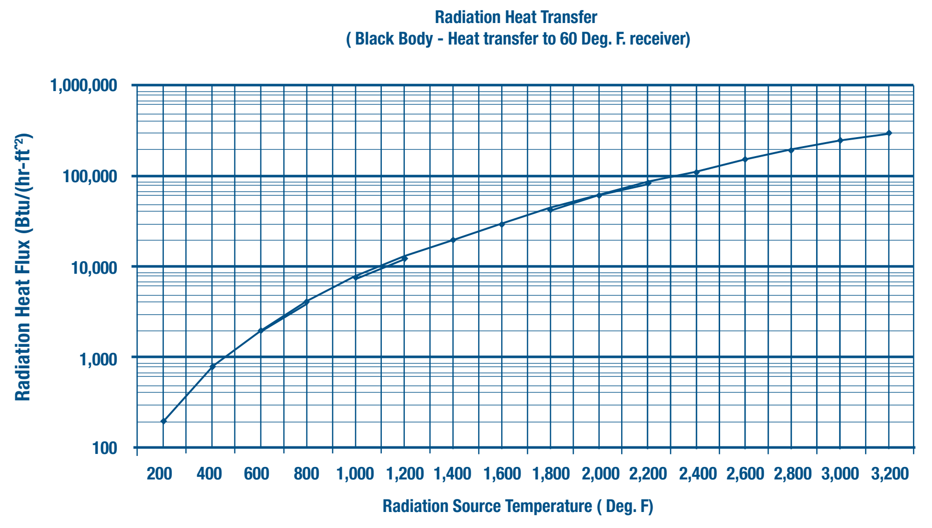
# Reduce Radiation Losses from Heating Equipment

Heating equipment, such as furnaces and ovens, can experience significant radiation losses when operating at temperatures above 1,000°F. Hot surfaces radiate energy to colder surfaces in their line of sight, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. Figure 1 shows radiation heat flux from a heat source at a given temperature to 60°F ambient.

**Figure 1. Radiation heat transfer rates[1]**



The biggest radiant energy loss in furnace operations is caused by doors remaining open longer than necessary, or doors left partially open to accommodate a load that is too large for the furnace. Furnace openings not only waste energy through radiation losses, they also allow ambient air to enter the furnace or hot furnace gases to escape if the furnace pressure is not controlled (see the tip sheets titled *Reduce Air Infiltration in Furnaces*; *Furnace Pressure Controllers*).

Radiation losses are a function of three factors:

- The temperature of the internal furnace surfaces facing the opening.
- The effective area of the opening that the radiation passes through. This is the true opening size corrected for both the thickness of the wall surrounding it and for its height/width ratio. The thicker the wall and the higher the opening's aspect ratio (longer dimension divided by shorter dimension), the smaller its effective area. Figure 2 can be used in calculating effective area for openings in a furnace wall. These graphs give results that are within 5% of the results of using detailed view-factor calculations.
- The length of time the opening permits radiation to escape.

## Suggested Actions

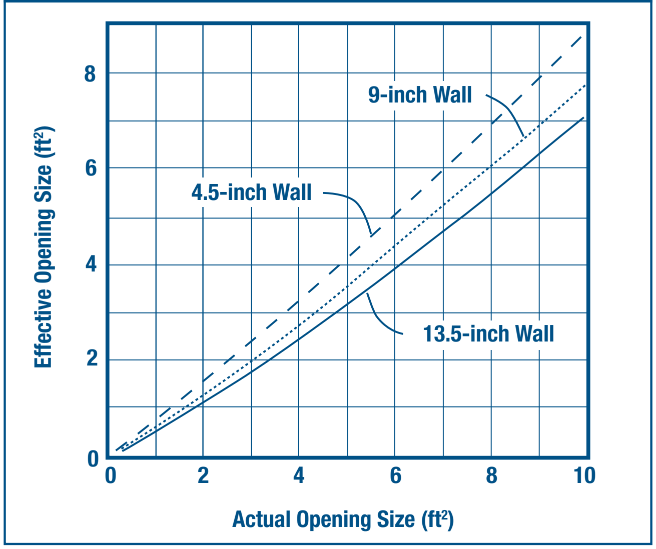
The following actions can prevent or reduce radiations losses:

- Eliminate the furnace opening or keep the furnace door open the shortest possible time.
- For a continuous furnace in which opening size cannot be reduced, you can use flexible materials such as ceramic strips, chains, or ceramic textiles as "curtains." These generally reduce heat loss by half and help reduce infiltration of air into the furnace and leakage of hot furnace gases into the atmosphere. Tunnel-like extensions on the end of the furnace can also reduce the effective opening; shallow inclines in extension tunnels can direct radiation into furnace insulation or incoming cold work. These methods still allow the load to enter the furnace.
- Repair or plug fixed openings. If that is not possible, use a radiation shield such as an alloy sheet or ceramic board. Use proper refractory or insulation to plug holes. For openings such as a sight glass, use a damper or slide valve to block radiation when using the sight glass.

## Resources

See also Robert Siegel and John Howell, *Thermal Radiation Heat Transfer*, New York: McGraw-Hill, 1972; and W. Trinks et al., *Industrial Furnaces*, Sixth Edition, New York: John Wiley & Sons, Inc., 2003.

**Figure 2. Calculation of effective area for openings in a furnace**[2]



Technically, the temperature of the colder (receiving) surface also plays a part. However, this surface is usually the area surrounding the furnace, which can range from 20°F for an outdoor furnace up to 120°F for a hot factory building, and it has little effect on radiation losses.

## Estimating Radiation Heat Losses

Radiation losses can be estimated by using a simple formula:

$Q_{\text{radiation}}$ (Btu/hr) = (black body radiation at the source temperature – radiation at the ambient temperature) x effective area of the opening x fraction of the time an opening (e.g., the furnace door) is open

In most cases, the furnace temperature can be used as a radiation source temperature for estimating radiation losses. Figure 1 can be used to estimate radiation heat flux based on furnace temperature. As mentioned earlier, ambient temperature has very little effect on the losses and can be ignored. The effective area of the opening can be estimated by using Figure 2 along with the dimensions of the opening and the furnace wall thickness. For a fixed opening, the fraction open time would be 1.0. However, for doors opened for loading or unloading, this should be calculated as the time the door is open divided by the cycle time for loading-unloading. In some cases, the door might not be fully closed, and a small gap is constantly maintained. In this case, the fraction open time would again be 1.0.

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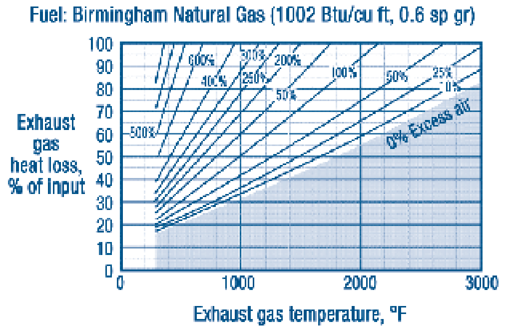
[1] Calculations by Arvind Thekdi, E3M, Inc.

[2] Calculations by Richard Bennett, Janus Technology Group.

# Install Waste Heat Recovery Systems for Fuel-Fired Furnaces

Figure 1. Heat in flue gas



For most fuel-fired heating equipment, a large amount of the heat supplied is wasted as exhaust or flue gases. In furnaces, air and fuel are mixed and burned to generate heat, some of which is transferred to the heating device and its load. When the heat transfer reaches its practical limit, the spent combustion gases are removed from the furnace via a flue or stack. At this point, these gases still hold considerable thermal energy. In many systems, this is the greatest single heat loss. The energy efficiency can often be increased by using waste heat gas recovery systems to capture and use some of the energy in the flue gas.

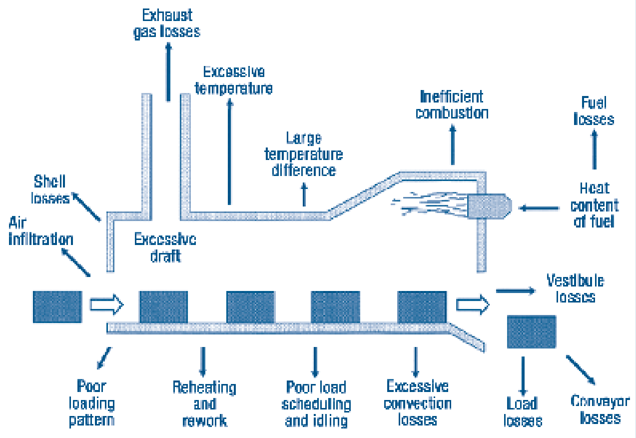
For natural gas-based systems, the amount of heat contained in the flue gases as a percentage of the heat input in a heating system can be estimated by using Figure 1. Exhaust gas loss or waste heat depends on flue gas temperature and its mass flow, or in practical terms, excess air resulting from combustion air supply and air leakage into the furnace. The excess air can be estimated by measuring oxygen percentage in the flue gases.

### Waste Heat Recovery

Heat losses must be minimized before waste heat recovery is investigated. Figure 2 highlights opportunities for energy savings.

The most commonly used waste heat recovery methods are preheating combustion air, steam generation and water heating, and load preheating.

Figure 2. Heat losses



## Suggested Actions

- Use PHAST with current and projected energy costs to estimate energy savings from waste heat recovery.
- Contact furnace or combustion system suppliers to calculate payback or return on investment.

**Preheating Combustion Air.** A recuperator is the most widely used heat recovery device. It is a gas-to-gas heat exchanger placed on the stack of the furnace that preheats incoming air with exhaust gas. Designs rely on tubes or plates to transfer heat from the exhaust gas to the combustion air and keep the streams from mixing.

Another way to preheat combustion air is with a regenerator, which is an insulated container filled with metal or ceramic shapes that can absorb and store significant thermal energy. It acts as a rechargeable storage battery for heat. Incoming cold combustion air is passed through the regenerator. At least two regenerators and their associated burners are required for an uninterrupted process: one provides energy to the combustion air while the other recharges.

**Steam Generation and Water Heating.** These systems are similar to conventional boilers but are larger because the exhaust gas temperature is lower than the flame temperature used in conventional systems. Waste heat boilers can be used on most furnace applications, and special designs and materials are available for systems with corrosive waste gases. Plants that need a source of steam or hot water can use waste heat boilers, which may also work for plants that want to add steam capacity. However, the waste boiler generates steam only when the fuel-fired process is operating.

**Load Preheating.** If exhaust gases leaving the high temperature portion of the process can be brought into contact with a relatively cool incoming load (the material being heated), energy will be transferred to the load, preheating it and reducing the energy consumption. Load preheating has the highest potential efficiency of any system that uses waste gases. Load preheating systems can be difficult to retrofit and are best suited for continuous rather than batch furnaces.

## Benefits

Benefits of waste heat recovery include:

- **Improved heating system efficiency.** Energy consumption can typically be reduced 5% to 30%.
- **Lower flue gas temperature in chimney.** Less heat is wasted.
- **Higher flame temperatures.** Combustion air preheating heats furnaces better and faster.
- **Faster furnace startup.** Combustion air preheating heats furnaces faster.
- **Increased productivity.** Waste heat used for load preheating can increase throughput.

## Potential Applications

Waste heat recovery should generally be considered if the exhaust temperature is higher than 1,000°F, or if the flue gas mass flow is very large.

## References

*Improving Process Heating System Performance: A Sourcebook for Industry.*
U.S. Department of Energy (DOE) and the Industrial Heating Equipment Association (IHEA). This document can be obtained from www.eere.energy.gov/industry/bestpractices

*Waste Heat Reduction and Recovery for Improving Furnace Efficiency.* DOE and IHEA. This document can be obtained from www.eere.energy.gov/industry/bestpractices

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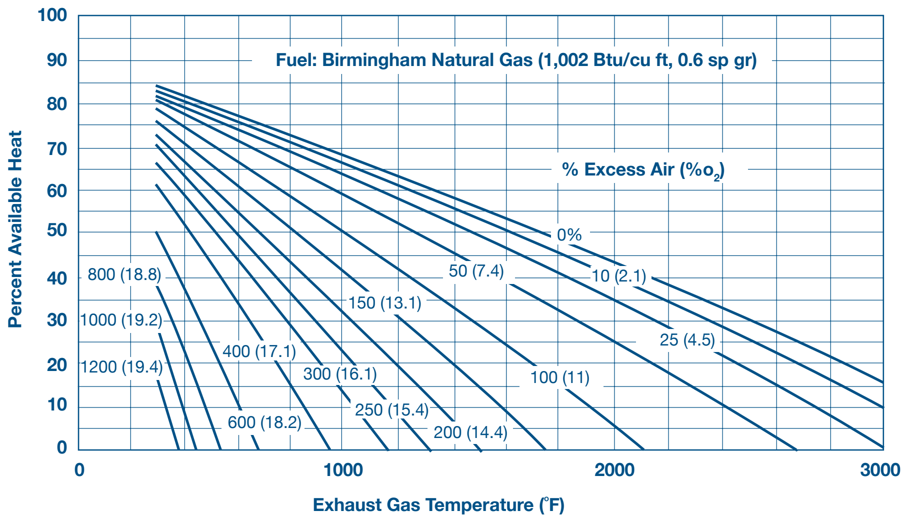
# Load Preheating Using Flue Gases from a Fuel-Fired Heating System

The thermal efficiency of a heating system can be improved significantly by using heat contained in furnace flue gases to preheat the furnace load (material coming into the furnace). If exhaust gases leaving a fuel-fired furnace can be brought into contact with a relatively cool incoming load, heat will be transferred directly to the load. Since there is no intermediate step, like air or gas preheating, in the heat recovery process, this can be the best approach to capturing waste heat. Load preheating is best suited for continuous processes, but it can sometimes also be used successfully with intermittently operated or batch furnaces. Load preheating can be achieved in a variety of ways, including these:

- Use of an *unfired load preheat section*, in which furnace flue gases are brought in contact with the incoming load in an extended part of the furnace.
- Use of an *external box*, in which high-temperature furnace flue gases are used to dry and/or preheat the charge before loading in a furnace.
- Use of a *counter-current* flow design in a furnace or a kiln, in which the burner gases flow in the opposite direction of the load being heated.

**Figure 1. Available Heat Chart**



The amount of energy savings obtained by using load preheating is *higher* than the amount of actual heat transferred to the load. The "net" heat delivered to the load has to account for the efficiency of the furnace. Since the furnace efficiency is always less than 100%, the resulting energy savings exceed the energy picked up by the load. Load preheating can result in higher production from the same furnace.

## Suggested Actions

Questions to ask if your furnace can be adapted to load preheating (not all can be):

1. Would combustion air preheating or some other savings measure be cost-effective?
2. How large a preheating chamber is needed?
3. Do you have enough space for a preheater that size?
4. You might have to restrict exhaust gas paths so they will come in contact with the load. Will this interfere with exhaust gas flow and cause too much backpressure in the furnace chamber?
5. How will incoming parts move through the preheating chamber? If conveying equipment is needed, can it withstand exhaust gas temperatures?

Questions to ask before adding a separate load preheat section or chamber:

1. How would flue gases move to the heating chamber? Will a fan or blower be needed to overcome pressure drops in ducts?
2. Does heat demand equal heat supply during most of the heating cycle time?
3. How would the hot load be transferred to the main furnace? Would the heat loss be considerable?
4. What type of controls are required to maintain the desired temperature in the preheat chamber? Will an auxiliary heating system be needed?

## Example

An aluminum die cast melting furnace has an average production rate of 1,000 lb/hr. As metal is drawn from the furnace at 1,400°F, the molten bath is periodically replenished with ingots at room temperature. The furnace exhaust temperature is 2,200°F. Wall conduction and opening radiation losses average 100,000 Btu/hr. The burners operate at 20% excess air. The graphs and tables in the reference below (and other sources) show that the molten metal requires 470 Btu/lb heat, for a total of 470,000 Btu/hr. Total net input to the furnace equals heat to the load plus wall and radiation losses, or 470,000 + 100,000 Btu/hr = 570,000 Btu/hr.

For 20% excess air and 2,200°F exhaust temperature, the available heat is 31%, based on Figure 1. This means 69% of the heat input is wasted in flue gases. Divide this into the net input: 570,000 Btu/hr ÷ 0.31 = 1, 838,700 Btu/hr total input to the furnace. The exhaust gas loss is 1,838,700 – 570,000 = 1,268,700 Btu/hr.

The furnace is modified to route the exhaust gases to the stack through a slightly inclined, refractory-lined tunnel. Exhaust gases flow counter to the incoming ingots, preheating them. The ingots are heated to an average temperature of 600°F and contain 120 Btu/lb, or 120,000 Btu/hr, for a 1,000 lb/hr production rate. Preheating the cold ingots to 600°F lowers the amount of heat required from the furnace to
(470 – 120) Btu/lb x 1,000 lb/hr = 350,000 Btu/hr.

As an approximation, assume that the flue gas temperature from the melting section of the furnace remains constant at 2,200°F and the available heat remains the same (31%). Total input to the furnace is now (350,000 + 100,000) ÷ 0.31 = 1,451,600 Btu/hr. Savings are (1,838,700 – 1,451,600) / 1,838,700 = 387,100 / 1,838,700 = 0.2105, or 21.1%.

This is a rough estimate. Actual savings will be greater, because lowering the burner firing rate decreases the furnace exhaust gas temperature and volume, resulting in higher available heat with further reductions in fuel input. Because the furnace input could still be 1,838,700 Btu/hr, with net available heat of 470,000 Btu/hr for aluminum, while the heat demand for 1,000 lb/hr aluminum charge is only 350,000 Btu/hr, it is possible to increase production by (470,000 – 350,000)/470,000 = 25.5%. Check the material handling system to see if it is capable of handling the additional load and if the downstream processes can accommodate increased melter production.

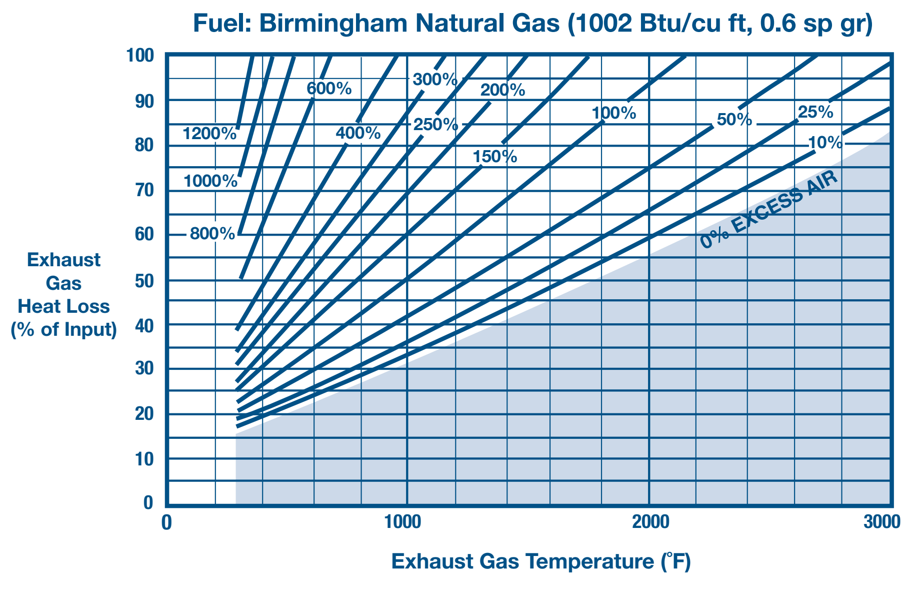
## Reference

W. Trinks et al. *Industrial Furnaces, Sixth Edition*. New York: John Wiley & Sons, Inc. 2003.

# Using Waste Heat for External Processes

The temperature of exhaust gases from fuel-fired industrial processes depends mainly on the process temperature and the waste heat recovery method. Figure 1 shows the heat lost in exhaust gases at various exhaust gas temperatures and percentages of excess air. Energy from gases exhausted from higher temperature processes (primary processes) can be recovered and used for lower temperature processes (secondary processes). One example is to generate steam using waste heat boilers for the fluid heaters used in petroleum crude processing. In addition, many companies install heat exchangers on the exhaust stacks of furnaces and ovens to produce hot water or to generate hot air for space heating.

**Figure 1. Heat loss in exhaust gases at various exhaust gas temperature and excess air percents[1]**



Before attempting to use energy from higher temperature flue gases in lower temperature processes, engineers should take the following technical issues into consideration:

- **Nature or quality of the flue gases.** Flue gases from the primary processes should be clean and free of contaminants such as corrosive gases and particulates. Contaminants pose special handling problems for the gases and might affect the quality of work in the secondary process.
- **Temperature of primary process flue gases.** The temperature difference between the primary and secondary process should be high enough (at least 200°F), and there should be a sufficient amount of usable waste heat.

## Suggested Actions

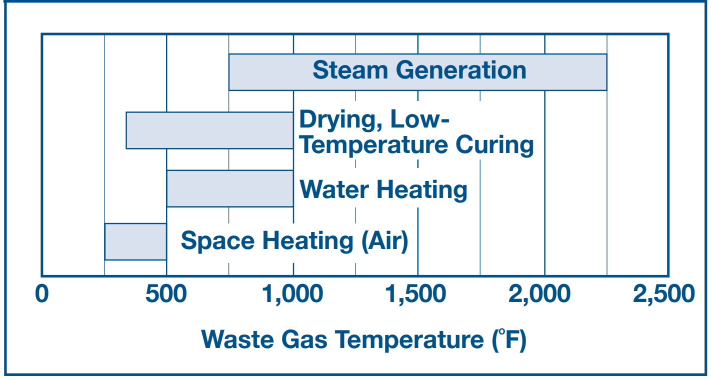
Questions to ask when evaluating the use of waste gases for heating secondary processes:

1. Is there a less expensive way to heat the secondary process?
2. Is the temperature of the flue gases high enough to heat the secondary process?
3. Do the flue gases contain enough transferable energy?
4. Are the flue gases compatible with the secondary process (as to cleanliness, corrosiveness, etc.)?
5. Can the primary process deliver energy to the secondary process in time?
6. Are the two processes close enough together to avoid excessive heat losses during waste gas transport?
7. Will the flue gases leave the secondary process at a high enough temperature to avoid problems with moisture condensation?
8. Can the exhaust ductwork and secondary process be designed to avoid excessive pressure resistance to the flue gases, or are additional means like exhaust fans necessary?

## Resources

See also the *ASM Handbook*, Volumes 1 (1990) and 2 (1991), Materials Park, OH: ASM International; *Combustion Technology Manual,* Fifth Edition, Cincinnati, OH: Industrial Heating Equipment Association (IHEA), 1994; *Handbook of Applied Thermal Design*, E.C. Guyer and D.L. Brownell, eds., London: Taylor & Francis Group, 1999.

Figure 2. Typical secondary processes and approximate exhaust temperatures [2]



- **Matching the heat demand of the secondary process with the heat supply from the primary process.** The heat supply from the primary process should be sufficiently high to meet a reasonably high percentage of the secondary process heat demand.
- **Matching the timing of the heat supply from the primary process and the heat demand in the secondary process.**
- **Placement of primary and secondary heating equipment.** The closer the primary and secondary process can be situated, the better.

Figure 2 shows some heating processes that commonly use waste heat from a higher temperature process, and the approximate range of waste gas temperatures they require. Sometimes lower temperature gases can be used if the heat recovery device is deliberately oversized.

## Example

A plant uses a furnace with a firing rate of 10 MMBtu/hr, which discharges flue gases at 1,400°F (primary process). The plant also has a drying oven that operates at 400°F and requires 2.5 MMBtu/hr of heat (secondary process). The recoverable heat can be estimated using Figure 1. At 1400°F, the heat content of the exhaust gases (at 10% excess air) is about 42% of the heat furnace input. Again using Figure 1, the heat content of exhaust gases at 400°F is approximately 20% (at 10% excess air). The *approximate* amount of heat that can be saved is 42% – 20% = 22% of the heat input to the primary process. The net heat available for the secondary process is approximately 0.22 x 10 MMBtu/hr = 2.2 MMBtu/hr. Actual savings would be greater than this because the available heat at the 400°F exhaust gas temperature is approximately 80% (see Figure 1 in Process Heating Tip Sheet #9, *Load Preheating Using Flue Gases from a Fuel-Fired Heating System*). The actual savings for the oven are thus 2.2/0.8 = 2.75 MMBtu/hr.

In this case, there is more than enough heat to meet the heat demand for the drying oven. It would be necessary to use additional heat in the oven if the exhaust gas heat from the furnace were not sufficient to meet the oven heat demand. At a fuel cost of $8.00 per MMBtu, the company can save $22.00 in fuel costs per hour. Assuming 8,000 hours of operation per year, annual savings are $175,000.

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[1] Calculations by Richard Bennett, Janus Technology Group.

[2] Figure by Richard Bennett, Janus Technology Group.

# Use Lower Flammable Limit Monitoring Equipment to Improve Process Oven Efficiency

Process heating applications involving flammable solvent removal use large amounts of energy to maintain safe lower flammable limits (LFL) in the exhaust air. National Fire Protection Association (NFPA) guidelines require the removal of significant amounts of exhaust air to maintain a safe, low-vapor solvent concentration. If LFL monitoring equipment is used to ensure proper vapor concentrations, these guidelines allow for less exhaust air removal. LFL monitoring equipment can improve the efficiency of the solvent removal process and significantly lower process energy requirements.

Flammable solvents used in industrial production processes are typically evaporated in industrial ovens. Higher oven temperatures evaporate solvent vapors more quickly, allowing for faster production. Because the vapors are flammable, the exhaust air is discharged (along with the heat) to prevent the accumulation of the vapors in the oven. As the oven temperatures increase, plants have to maintain higher ventilation ratios to reduce the solvent vapor concentration levels and maintain the respective LFL.

For example, the NFPA ventilation safety ratio for batch-loaded ovens operating below 250˚F is 10:1 and xylol has an LFL of 1%. Therefore, exhaust ventilation needs to be added to the vapor until the solvent concentration reaches 0.1%, meaning that the plant has to exhaust 10 times the amount of air required by the process to meet the NFPA requirement. If the process operates above 250˚F, the required safety ratio rises to 14:1, the LFL goes down to 0.07%, and the plant has to exhaust 14 times the amount of air required to keep the process from becoming flammable.

The non-uniform rate of solvent vaporization is one of the reasons why LFLs are so stringent. Solvent vaporization is inherently non-uniform mainly because of wall losses and load characteristics; this causes periodically high solvent concentrations in the oven during the vaporization process. As a result, safe ventilation ratios are calculated using the theoretical peak needs of ventilation based on the highest vapor concentrations that can accumulate during the vaporization process.

## LFL Monitoring Equipment

LFL monitoring equipment can reduce energy used in solvent removal by adjusting the ventilation ratio according to the fluctuations in vapor concentration. The equipment continuously tracks the solvent extraction rate in real time and controls the rate of ventilation air based on real needs, thereby maintaining a safe ratio throughout the process. LFL monitoring equipment

### Suggested Actions

- Evaluate energy costs, process load and production requirements to determine the economic feasibility of LFL monitoring equipment.
- Examine process energy requirements to confirm the flammable solvent load. If this load has changed over time, ventilation rates may need to be adjusted.
- Using a booster oven can reduce the evaporation requirements in the main oven, thus reducing its exhaust requirements
- Consider a professional outside evaluation to determine the technical and economic feasibility of additional improvements including reducing wall losses, installing heat exchangers and fume incinerators, and recuperating exhaust air to capture the heat value of exhaust air.
- Check all relevant NFPA and other applicable codes, regulations, and standards before adding equipment or making adjustments and consider consulting with an expert.

### Resources

Hans L. Melgaard, “Substantial Energy Savings are Often Realized by Monitoring Process Oven Exhausts,” *Plant Engineering*, November 1980

*Improving Process Heating System Performance: A Sourcebook for Industry.* U.S. Department of Energy and Industrial Heating Equipment Association. This document can be obtained from *http://www1.eere.energy.gov/industry/bestpractices/techpubs_process_heating.html* can employ several technologies including catalytic systems, infrared sensors, ionization systems and combustion sensors. LFL monitoring equipment has self-check functions and uses a calibrated test gas for periodic self-calibration. Because the vaporization process depends on the intake and exhaust air, linking the LFL controller to an adjustable speed drive on the exhaust system fan can improve process efficiency even further (damper adjustments can also be used).

## Example

The NFPA safety ventilation ratios are significantly lower when LFL monitoring equipment is used than when such equipment is absent. This lowers the energy requirements for the process because less air needs to be exhausted to keep the process from becoming flammable. For a continuous strip coating process requiring 46 gallons of xylol with a maximum oven temperature of 800º F and ambient air temperature of 70º F, the safety ventilation ratio is 4:1 without LFL monitoring equipment. This results in an exhaust requirement of 8,330 standard cubic feet per minute and energy consumption of 6.7 million British thermal units (MMBtu) per hour. At a cost of $8/MMBtu assuming a two-shift operation, this process costs approximately $214,000 annually. Installing LFL monitoring equipment would reduce the ratio to 2:1, halving the exhaust and energy requirements. Annual energy savings would total $107,000. With an installed cost of $12,500 for an LFL controller, the simple payback is very attractive at less than 1.5 months.

# Appendix C: Technical Briefs

1. Materials Selection Considerations for Thermal Process Equipment
2. Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emissions Performance

The technical briefs can also be downloaded from ITP's BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

# Materials Selection Considerations for Thermal Process Equipment

## Introduction

High-temperature metallic materials or alloys used in process heating equipment (furnaces, heaters, ovens, kilns, etc.) have significant effect on thermal efficiency, productivity and operating cost of the equipment. These materials are used in burners, electrical heating elements, material handling, load support, and heater tubes, etc.

A number of factors must be considered to select appropriate materials to improve energy efficiency of the equipment while extending their life at the minimum cost.

These factors include mechanical properties, oxidation or hot corrosion resistance, use of cast or fabricated components, and material availability.

Technical data describing the properties of heat-resistant alloys are necessary guides for selection. However, the behavior of alloys during long exposure to various high-temperature environments is complex. This behavior is not always completely predicted by laboratory tests alone. Service experience with high-temperature equipment is needed to judge the relative significance of the many variables involved.

## Selection Criteria

### Operating Temperature

Temperature is often the first—and sometimes the only—data point given upon which one is supposed to base alloy selection. However, one cannot successfully choose an alloy based on temperature alone. Nevertheless, one simple guide to alloy selection is an estimate of the maximum temperature at which a given alloy might have useful long-term engineering properties. Considering oxidation in air as the limiting factor, several common alloys, in plate form, rate as shown in Table 1. Thin sheets will have a lower limiting temperature because of proportionally greater losses from oxidation.

### Thermal Stability

After long exposure to temperatures in the range of 1,100˚ to 1,600˚F (590˚-870˚C), many of the higher chromium alloys precipitate a brittle intermetallic compound known as sigma phase. Molybdenum contributes to this phase. Sigma reduces room-temperature impact strength and ductility. The quantity and morphology of the sigma phase determines severity of embrittlement. Usually the metal is brittle only near room temperature, and it retains reasonable ductility at operating temperatures between 600˚ and 1000˚F (315˚-540˚C). Higher nickel grades, such as N08811, N08330, N06600 or N06601, are not susceptible to embrittlement by sigma. Because of higher carbon content, which causes carbide precipitation, cast heat-resistant alloys lose ductility in service.

**Glossary of Terms**

| | |
|---|---|
| UNS | Unified Numbering System |
| EN | European Normal |
| W.Nr. | Werkstoff Nummer |
| Al | Aluminum |
| Cb | Columbium (Niobium) |
| Ce | Cerium |
| Co | Cobalt |
| Cr | Chromium |
| La | Lanthanum |
| Mo | Molybdenum |
| Si | Silicon |
| Ti | Titanium |
| Y2O3 | Yttria (Yttrium Oxide) |
| W | Tungsten |
| Zr | Ziconium |

### Strength

Creep-rupture properties at temperature are usually available from the various producers, and many alloys are covered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

### Oxidation

Chromium is the one element present in all heat-resistant alloys, and its protective chromia scale is the basis for high-temperature environmental resistance. Nickel is next in importance, then silicon, aluminum, and rare earths. Oxidation rates in service depend upon thermal cycling and creep, which increase scale spalling. In addition, contaminants, such as alkali metal salts, can damage the chromia scale grain size, which affects chromium diffusion rates, and the particular atmosphere involved also increases oxidation rate. Significant water vapor content usually increases oxidation rates.

**Table 1. High Temperature Alloys (in order of increasing performance)**

| Alloy | Comments |
|---|---|
| Carbon steel, such as ASTM A 387 Grade 22 (2 1/4Cr, 1Mo) | This may be used to 1,200˚F (649˚C); above 950˚F (510˚C) 304H is stronger, and of course, more resistant to oxidation. |
| 409, and 410S stainless (UNS S40900, S41008) 1,200˚F (650˚C) | Limited by oxidation. Both are subject to embrittlement after several years of service above 600˚F (315˚C). |
| 430 stainless (S43000), with useful oxidation resistance to about 1,600˚F (870˚C) | Subject to embrittlement when exposed to the 600˚-1,100˚F (315˚-600˚C) range. |
| 304/304H & 316L stainless (S30400/ S30409, & S31600), cast HF | This is limited by oxidation to 1,500˚F (816˚C). If product contamination by scale particles is a concern, consider 1,200˚F (650˚C) as limitation. |
| 321 (S32100) stainless | This has an advantage of about 100˚F (55˚C) over 304, and is used to 1,600˚F (1202˚C). |
| 309S (S30908), cast HH-2 (J93633) | Useful up to the 1,850-1,900˚F (1010-1038˚C) range. Above 1,900˚F, oxidation performance becomes unsatisfactory. |
| Alloy 800HT®[1] (UNS N08811) | Much stronger, and somewhat more oxidation resistant. A practical upper use limit is about 2,000˚F (1,093˚C). |
| RA 253 MA®[2] alloy (UNS S30815) | Has superior oxidation resistance up to 2,000˚F (1,100˚C). Above this temperature, the oxidation resistance may be adequate, but not exceptional |
| 310 (S31008), and cast HK (J94204) | Very good oxidation resistance to 2,000˚F (1,093˚C), but drops off considerably by 2,100˚F (1,150˚C). The 310's strength is quite low at these temperatures. |
| RA330®[3] alloy (N08330, EN 1.4886) | Combines useful oxidation resistance and a fairly high melting point; it will tolerate rather extreme temperatures through 2,200˚F (1,200˚C). This grade is available in more product forms than almost any other high-temperature alloy. Applications include muffles, retorts, radiant heating tubes, bar frame baskets in heat treat, tube sheets, and tube hangers for petrochemical and boiler applications. |
| RA 353 MA®[4] alloy (S35315, EN 1.4854) | Has a melting point (solidus 2,480˚F/1,360˚C) similar to that of RA330, with better oxidation resistance. Experience with muffles, calciners, vortex finders, and cement kiln burner pipes show it to tolerate extreme temperature better than does RA330. |
| Alloy HR-120®[5] | One of the strongest available wrought alloys up to about 1,900˚F (1040˚C), and is used through 2,100˚F (1,150˚C). |
| RA333®[6] alloy (N06333) | In open-air use has a practical limit of about 2,200˚F (1,204˚C). Applications include retorts, rotary calciners, muffles for brazing, molybdenum, and tungsten oxide reduction. |
| 625 (N06625) | Has high strength, but is limited by oxidation resistance to 1,800˚F (980˚C). |
| 600 alloy (N06600) | A nickel-chromium alloy. Good oxidation resistance through 2,200˚F, good carburization resistance and ductility. |
| 601 (N06601) | Is very oxidation resistant to 2,200˚F (1,204˚C). Applications include muffles, retorts and radiant heating tubes |
| RA 602 CA®[7] (N06025) | Extremely oxidation-resistant grade; one of strongest available at extreme temperature. Used through 2250˚F. Applications include CVD retorts, vacuum furnace fixturing, rotary calciners |
| Alloy X (N06002) | Is designed for gas turbine combustors, in which hot gases continually sweep over the metal surface. Because of its 9% molybdenum content, this grade may be subject to catastrophic oxidation under stagnant conditions, or in open air above 2,150˚F (1,177˚C). |
| Alloy 617 | Very strong. Typical uses include land-based gas turbine combustors and nitric acid catalyst support grids. |
| Alloy 230®[8] | Also a strong alloy, with excellent oxidation resistance and good retention of ductility after intermediate temperature exposure. Gas turbine combustors, nitric acid grids, and CVD retorts are some applications of this alloy. |
| Supertherm®[9], cast 26Cr 35Ni 5W 15Co | Under various trade names, is suited for extreme temperature conditions. The cobalt content is sufficient to minimize high-temperature galling wear when in contact with NiCrFe alloys. |

### Carburization

Chromium, nickel, and silicon are three major elements that confer resistance to carbon absorption. Nickel and silicon lower the maximum solubility of carbon and nitrogen. Carburization is usually of concern, because highly carburized alloys become brittle. Above about 1% carbon content, most wrought heat-resistant alloys have no measurable ductility at room temperature. Metal dusting, also known as catastrophic carburization or carbon rot, is metal waste, not embrittlement. In the right environment, it appears that any alloy can eventually metal dust. Disagreement exists regarding appropriate alloy selection. In the steel heat-treating industry, experience has shown that RA333 and Supertherm are two of the best choices, while 602 CA performs well in some petrochemical applications. However, 310 stainless has been used in petrochemical metal dusting environments. Alloys such as N08830 and N08811 do not perform well in metal dusting environments.

### Sulfidation

Low or moderate nickel with high chromium content minimizes sulfidation attack at high temperatures. With the exception of alloy HR-160, less than 20% nickel content is preferred.

### Fabricability

Typically, fabricability is not a significant issue for conventionally melted wrought alloys. Grades that are strengthened by oxide dispersion, such as MA956®, offer unmatched strength and oxidation resistance at extreme temperatures, but are difficult to fabricate by conventional means.

### Design

Allowable stresses are often based on ASME design codes. For most thermal processing equipment, design stress is either one-half of the 10,000-hour rupture strength, or one-half of the stress to cause a minimum creep rate of 1% in 10,000 hours. Above about 1,000˚F (540˚C), creep or rupture is the basis for setting design stresses. At this temperature, materials are no longer elastic, but deform slowly with time.

### Thermal Expansion

A major cause of distortion and cracking in high-temperature equipment is failure to adequately address the issue of thermal expansion, and differential thermal expansion. Temperature gradients of only 200˚F (110˚C) are sufficient to strain metals beyond the yield point.

### Molten Metals

In industrial applications, low-melting metals such as copper and silver braze alloys, zinc, and aluminum cause problems. As a rule of thumb, low-melting metals attack the higher nickel alloys more readily than low-nickel or ferritic grades.

### Galling

Austenitic nickel alloys tend to gall when they slide against each other. At elevated temperatures, cobalt oxide tends to be somewhat lubricious. Cobalt or alloys with high cobalt content, such as cast Super-therm, are resistant to galling at red heat. For heat treat furnace applications up through 1650˚F, Nitronic® 60[10] (S21800) has resisted galling well.

### Cast Versus Wrought Heat Resistant Alloys

The alloys are offered in two forms: cast form and wrought form. Each has advantages and disadvantages for use in process heating, as shown in Table 2.

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1 Registered trade name of Special Metals, Inc.

2 Registered trade name of Outokumpu

3 Registered trade name of Outokumpu

4 Registered trade name of AvestaPolarit

5 Registered trade name of Haynes International

6 Registered trade name of Rolled Alloys

7 Registered trade name of ThyssenKrupp VDM

8 Registered trade name of Haynes International

9 Registered trade name of Duraloy Technologies, Inc.

10 Registered trade name of AK Steel Corporation

Table 2. Comparison of Cast and Wrought Alloys

| Alloy | Advantages | Disadvantages |
|---|---|---|
| **Cast** | Inherently greater creep strength | Embrittlement frequently occurs in service, making weld repair difficult |
| | Availability of shapes that are inconvenient to fabricate | May have soundness issues, such as porosity, shrink and surface integrity |
| | Chemistries not available as wrought alloys | May incur high costs for creating patterns, if only a few pieces are needed |
| | Some 35% and 50% chromium castings only available as castings | Delivery time may be long even if only a few pieces are needed |
| | | Cast parts may be thicker and heavier than the equivalent fabrication. This increases the dead weight that is heat treated, and reduces efficiency of thermal transfer through the wall. |
| **Wrought** | Availability of broad range of section thicknesses. Wrought alloys are available as thin as foil. | Creep strength—few wrought alloys match the high strength of heat-resistant alloy castings. This must be considered in product design, where creep rupture is a concern. |
| | Thinner sections permit significant weight reduction | Composition—alloys such as 50Cr 50Ni, 28Cr 10Ni or 35Cr 46Ni, all with excellent hot corrosion and/or carburization resistance, are available only as castings. |
| | Smooth surface helps avoid focal point for accelerated corrosion by molten salts or carbon deposits | |
| | Usually free of the internal and external defects, such as shrink and porosity, found in castings | |
| | Availability—fabrications are quickly procured, using stock materials, which minimizes down time. | |

Table 3. Material (Alloy) Composition

**Nominal Chemistry, Ferritic Alloys**

| Alloy | Unified Numbering System (UNS) | European Normal/ Werkstoff Nummer EN/W.Nr | Chromium (Cr) | Silicon (Si) | Aluminum (Al) | Titanium (Ti) | Carbon (C) | Other |
|---|---|---|---|---|---|---|---|---|
| 410S | S41008 | 1.4000 | 12.0 | 0.30 | -- | -- | 0.05 | -- |
| 430 | S43000 | 1.4016 | 16.5 | 0.50 | -- | -- | 0.08 | -- |
| MA956®[11] | S67956 | -- | 19.4 | 0.05 | 4.5 | 0.4 | 0.02 | $0.5Y_2O_3$ |
| 446 | S44600 | 1.4763 | 25.0 | 0.50 | -- | -- | 0.05 | -- |

**Nominal Chemistry, Fe-Cr-Ni Alloys, Nickel 20% and under**

| Alloy | UNS | EN/W.Nr | Cr | Nickel (Ni) | Si | C | Nitrogen (N) | Other |
|---|---|---|---|---|---|---|---|---|
| 304H | S30409 | 1.4301 | 18.3 | 9 | 0.5 | 0.05 | -- | 70Fe |
| RA253 MA® | S30815 | 1.4835 | 21 | 11 | 1.7 | 0.08 | 0.17 | 0.04Ce<br>65Fe |
| 309S | S30908 | 1.4833 | 23 | 13 | 0.8 | 0.05 | -- | 62Fe |
| 310S | S31008 | 1.4845 | 25 | 20 | 0.5 | 0.05 | -- | 52Fe |

**Nominal Chemistry, Fe-Ni-Cr Alloys, Nickel 30% to 40%**

| Alloy | UNS | EN/W.Nr | Cr | Ni | Si | C | Other |
|---|---|---|---|---|---|---|---|
| 800 HT® | N08811 | -- | 21 | 31 | 0.4 | 0.06 | 45Fe 0.6Ti 0.4Al |
| 803 | S35045 | -- | 25.5 | 34.5 | 0.7 | 0.07 | 37Fe 0.4Ti 0.3Al |
| RA330® | N08330 | 1.4886 | 19 | 35 | 1.2 | 0.05 | 43Fe |
| RA353 MA® | S35315 | 1.4854 | 25 | 35 | 1.2 | 0.05 | 36Fe 0.16N 0.05Ce |
| HR-160® 12 | N12160 | -- | 28 | 36 | 2.8 | 0.05 | 30Co 2Fe 0.5Ti |
| HR-120® | N08120 | -- | 25 | 37 | 0.6 | 0.05 | 35Fe 0.7Cb 0.1Ti |

## Table 3. Material (Alloy) Composition (continued)

**Nominal Chemistry, Ni-Cr-Fe Alloys, Nickel 45% to 60%**

| Alloy | UNS | EN/W.Nr | Cr | Ni | Si | C | Other |
|---|---|---|---|---|---|---|---|
| RA333® | N06333 | 2.4608 | 25 | 45 | 1 | 0.05 | 3Co 3Mo 3W 18Fe |
| 617 | N06617 | 2.4663 | 22 | 54 | 0.03 | 0.08 | 12.5Co 9Mo 1Al 0.4Ti 1Fe |
| 230® | N06230 | -- | 22 | 60 | 0.4 | 0.10 | 14W 1.5Mo 0.3Al 0.02La |

**Nominal Chemistry, Nickel over 60%, 15% to 25% Chromium**

| Alloy | UNS | EN/W.Nr | Cr | Ni | Si | C | Other |
|---|---|---|---|---|---|---|---|
| 601 | N06601 | 2.4851 | 22.5 | 61.5 | 0.2 | 0.05 | 1.4Al 14Fe |
| RA 602 | N06025 | 2.4633 | 25 | 63 | -- | 0.2 | 2Al 0.1Y 0.08Zr |
| CA® | | | | | | | 9.5Fe |
| 214™ [13] | N07214 | -- | 16 | 76 | -- | 0.04 | 4.5Al 0.005Y 3.5Fe |
| 600 | N06600 | 2.4816 | -- | 15.5 | 76 | 0.2 | 0.08 0.2Ti 8Fe |

**Nominal Chemistry, Cast Heat Resistant Alloys**

| Alloy | UNS | EN/W.Nr | Cr | Ni | Si | C | Tungsten (W) | Cobalt (Co) | Other |
|---|---|---|---|---|---|---|---|---|---|
| HC | J92605 | -- | 28 | 2 | 0.8 | 0.3 | -- | -- | 67Fe |
| HD | J93005 | -- | 29 | 5 | 1.5 | 0.4 | -- | -- | 63Fe |
| HE | J93403 | 1.4339 | 28 | 9 | 1.5 | 0.3 | -- | -- | 61Fe |
| HF | J | -- | 21 | 10 | 1.4 | 0.3 | -- | -- | 67Fe |
| HH-2 | J93633 | 1.4837 | 25 | 13 | 1 | 0.3 | -- | -- | 60Fe |
| HI | J94003 | -- | 28 | 16 | 1 | 0.4 | -- | -- | 54Fe |
| HK | J94204 | 1.4840 | 25 | 20 | 1.4 | 0.4 | -- | -- | 54Fe |
| HL | J94614 | -- | 30 | 20 | 1.4 | 0.4 | -- | -- | 47Fe |
| HN | J | | 21 | 25 | 1.4 | 0.4 | -- | -- | 52Fe |
| Ten-X | -- | -- | 20 | 30 | 1.4 | 0.4 | 5 | 8 | 35Fe |
| HT | J94605 | -- | 17 | 35 | 1.7 | 0.5 | -- | -- | 44Fe |
| HU | J95405 | 1.4865 | 18 | 38 | 1.7 | 0.5 | -- | -- | 40Fe |
| HP | J95705 | 1.4857 | 26 | 35 | 1.3 | 0.5 | -- | -- | 36Fe |
| MO-RE® 1[14] | -- | -- | 26 | 36 | 1 | 0.45 | 1.6 | -- | 33 |
| Supertherm® [15] | -- | -- | 26 | 35 | 1.5 | 0.5 | 5 | 15 | 13Fe |
| 22H® [16] | -- | 2.4879 | 28 | 48 | 1 | 0.5 | 5 | -- | 16Fe |
| Super 22H [17] | -- | -- | 28 | 48 | 1 | 0.5 | 5 | 3 | 13 |
| MO-RE® 40MA | -- | -- | 35 | 46 | 1 | 0.45 | -- | -- | 14Fe 1.3Cb |
| HX | N06006 | -- | 17 | 66 | 2 | 0.5 | -- | -- | 13Fe |
| IC-221M | -- | -- | 7.7 | 81 | -- | 0.04 | -- | -- | 8Al 1.3Mo 1.7Zr |

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[13] Trade name of Haynes International.

[14] Registered trade name of Duraloy Technologies, Inc.

[15] Registered trade name of Duraloy Technologies, Inc.

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[17] Registered trade name of Duraloy Technologies, Inc.

### Composition of Alloys

Table 3 provides composition of commonly used alloys for industrial heating equipment. The alloy composition contains several elements which are added to iron. The percentages of the elements in each alloy are shown in Table 3.

### Acknowledgements

Special thanks to Dr. James Kelly of Rolled Alloys and Arvind Thekdi of E3M, Inc., for their contributions to this technical brief.

# Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity, and Emissions Performance

## Introduction

Thermal efficiency of process heating equipment, such as furnaces, ovens, melters, heaters, and kilns is the ratio of heat delivered to a material and heat supplied to the heating equipment. For most heating equipment, a large amount of the heat supplied is wasted in the form of exhaust or flue gases. These losses depend on various factors associated with the design and operation of the heating equipment. This technical brief is a guide to help plant operators reduce waste heat losses associated with the heating equipment.

This technical brief supports or complements the software tool Process Heating Assessment and Survey Tool (PHAST) developed jointly by the Industrial Heating Equipment Association (IHEA) and the U.S. Department of Energy's (DOE) Industrial Technologies Program.

## Heat Losses from Fuel-Fired Heating Equipment.

Waste-gas heat losses are unavoidable in the operation of all fuel-fired furnaces, kilns, boilers, ovens, and dryers. Air and fuel are mixed and burned to generate heat, and a portion of this heat is transferred to the heating device and its load. When the energy transfer reaches its practical limit, the spent combustion gases are removed (exhausted) from the furnace via a flue or stack to make room for a fresh charge of combustion gases. At this point, the exhaust flue gases still hold considerable thermal energy, often more than what was left behind in the process. In many fuel-fired heating systems, this waste heat is the greatest source of heat loss in the process, often greater than all the other losses combined.

Reducing these losses should be a high priority for anyone interested in improving the energy efficiency of furnaces and other process heating equipment.

The first step in reducing waste heat in flue gases requires close attention and proper measures to reduce all heat losses associated with the furnace. Any reduction in furnace heat losses will be multiplied by the overall available heat factor. This could result in much higher energy savings. The multiplier effect and available heat factor are explained in greater detail in the following sections.

These furnace losses include:

- Heat storage in the furnace structure
- Losses from the furnace outside walls or structure
- Heat transported out of the furnace by the load conveyors, fixtures, trays, etc.
- Radiation losses from openings, hot exposed parts, etc.
- Heat carried by the cold air infiltration into the furnace
- Heat carried by the excess air used in the burners.

All of these losses can be estimated by using the PHAST software tool or the ITP's Process Heating Tip Sheets, available on the DOE's BestPractices Web site at www.eere.energy.doe.gov/industry/bestpractices.

Reducing waste heat losses brings additional benefits, among them:

- Lower energy component of product costs
- Improved furnace productivity
- Lower emissions of carbon monoxide (CO), nitrogen oxides ($NO_x$) and unburned hydrocarbons (UHCs)
- May contribute to more consistent product quality and better equipment reliability.

## What Determines Waste-Gas Losses?

To answer this, the flow of heat in a furnace, boiler, or oven must be understood. The purpose of a heating process is to introduce a certain amount of thermal energy into a product, raising it to a certain temperature to prepare it for additional processing, change its properties, or some other purpose. To carry this out, the product is heated in a furnace or oven. As shown in Figure 1, this results in energy losses in different areas and forms.

First, the metal structure and insulation of the furnace must be heated so their interior surfaces are about the same temperature as the product they contain. This stored heat is held in the structure until the furnace shuts down, then it leaks out into the surrounding area. The more frequently the furnace is cycled from cold to hot and back to cold again, the more frequently this stored heat must be replaced.

In addition, because the furnace cannot run production until it has reached the proper operating temperature, the process of storing heat in it causes lost production time. Fuel is consumed with no useful output.

**Wall losses.** Additional heat losses take place while the furnace is in production. Wall or transmission losses are caused by the conduction of heat through the walls, roof, and floor of the heating device, as shown in Figure 2. Once that heat reaches the outer skin of the furnace and radiates to the surrounding area or is carried away by air currents, it must be replaced by an equal amount taken from the combustion gases. This process continues as long as the furnace is at an elevated temperature.

**Material handling losses.** Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts or product hangers that enter the heating chamber cold and leave it at higher temperatures drain energy from the combustion gases. In car bottom furnaces, the hot car structure gives off heat to the room each time it rolls out of the furnace to load or remove work. This lost energy must be replaced when the car is returned to the furnace.

**Cooling media losses.** Water or air cooling protects rolls, bearings, and doors in hot furnace environments, but at the cost of lost energy. These components and their cooling media (water, air, etc.) become the conduit for additional heat losses from the furnace. Maintaining an adequate flow of cooling media is essential, but it might be possible to insulate the furnace and load from some of these losses.

**Radiation (opening) losses.** Furnaces and ovens operating at temperatures above 1,000˚F might have significant radiation losses, as shown in Figure 3. Hot surfaces radiate energy to nearby colder surfaces, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. Anyone who has ever stood in front of the open door of a high-temperature furnace can attest to the huge amount of thermal energy beamed into the room.

Figure 1. Heat losses in industrial heat processes.

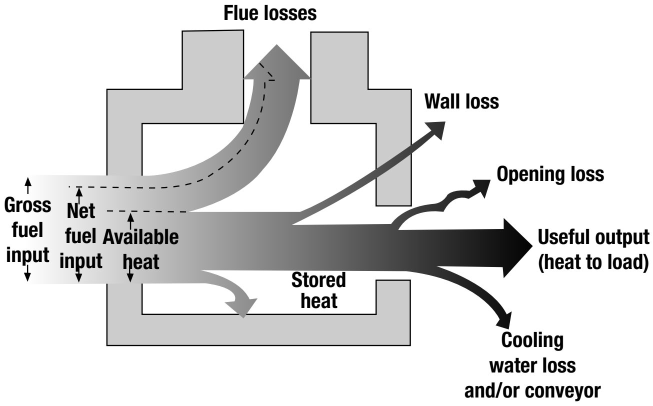


Figure 2. Wall loss.

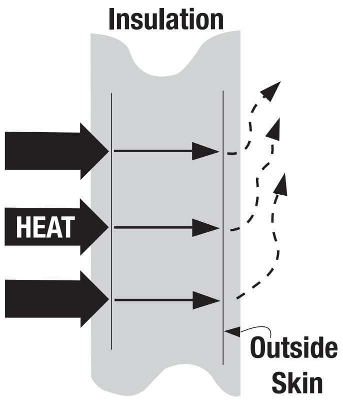


Figure 3. Radiation loss from heated to colder surface.

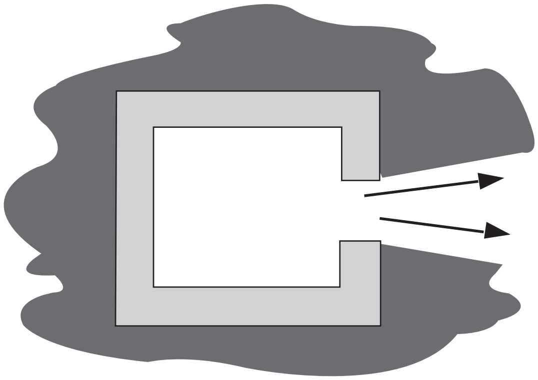
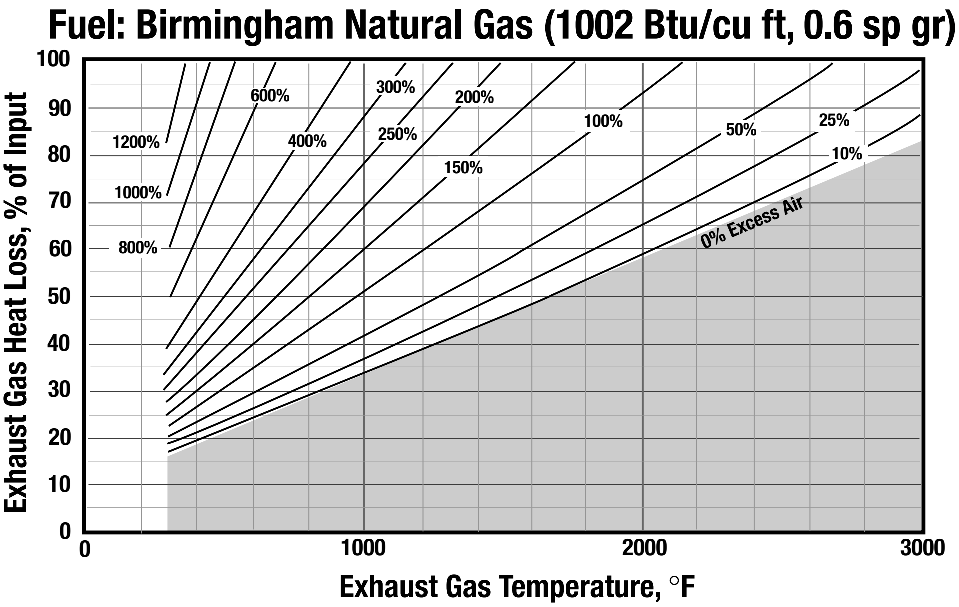


Figure 1. Heat losses in industrial heat processes.



Anywhere or anytime there is an opening in the furnace enclosure, heat is lost by radiation, often at a rapid rate. These openings include the furnace flues and stacks themselves, as well as doors left partially open to accommodate oversized work in the furnace.

**Waste-gas losses.** All the losses mentioned above – heat storage, wall transmission, conveyor and radiation – compete with the workload for the energy released by the burning fuel-air mixture. However, these losses could be dwarfed by the most significant source of all, which is waste-gas loss.

Waste-gas loss, also known as flue gas or stack loss, is made up of the heat that cannot be removed from the combustion gases inside the furnace. The reason is heat flows from the higher temperature source to the lower temperature heat receiver.

In effect, the heat stream has hit bottom. If, for example, a furnace heats products to 1,500˚F, the combustion gases cannot be cooled below this temperature without using design or equipment that can recover heat from the combustion gases. Once the combustion products reach the same temperature as the furnace and load, they cannot give up any more energy to the load or furnace, so they have to be discarded. At 1,500˚F temperature, the combustion products still contain about half the thermal energy put into them, so the waste-gas loss is close to 50% (Figure 4). The other 50%, which remains in the furnace, is called available heat. The load receives heat that is available after storage in furnace walls, and losses from furnace walls, load conveyors, cooling media and radiation have occurred.

This makes it obvious that the temperature of a process, or more correctly, of its exhaust gases, is a major factor in its energy efficiency. The higher that temperature, the lower the efficiency.

Another factor that has a powerful effect is the fuel-air ratio of the burner system.

**Fuel-air ratios.** For every fuel, there is a chemically correct, or stoichiometric, amount of air required to burn it. One cubic foot of natural gas, for example, requires about 10 cubic feet of combustion air. Stoichiometric, or on-ratio combustion will produce the highest flame temperatures and thermal efficiencies.

However, combustion systems can be operated at other ratios. Sometimes, this is done deliberately to obtain certain operating benefits, but often, it happens simply because the burner system is out of adjustment. The ratio, as shown in Figure 5, can go either rich (excess fuel or insufficient air) or lean (excess air). Either way, it wastes fuel. Because there is not enough air for complete combustion, operating the burners at rich combustion conditions wastes fuel by allowing it to be discarded with some of its energy unused. It also generates large amounts of carbon monoxide (CO) and unburned hydrocarbons (UHCs).

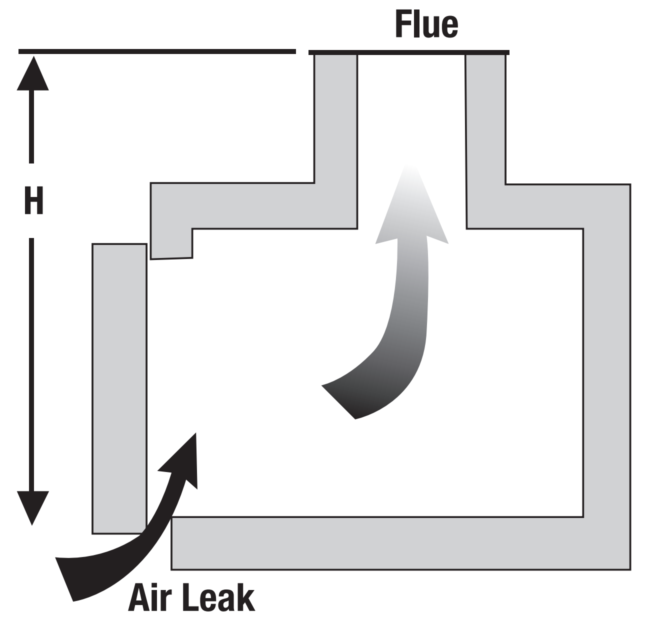
At first glance, operating lean might seem to be a better proposition because all the fuel is consumed. Indeed, a lean operation produces no flammable, toxic by-products of rich combustion, but it does waste energy. Excess air has two effects on the combustion process. First, it lowers the flame temperature by diluting the combustion gases, in much the same way cold water added to hot produces warm water. This lowers the temperature differential between the hot combustion gases and the furnace and load, which makes heat transfer less efficient. More damaging, however, is the increased volume of gases that are exhausted from the process. The products of stoichiometric combustion and the excess are at the same temperature. The excess air becomes one more competitor for the energy demand in the process. Because this is part of the combustion process, excess air goes to the head of the line, taking its share of the heat before the furnace and its contents.

The results can be dramatic. In a process operating at 2,000˚F, available heat at stoichiometric ratio is about 45% (55% goes out the stack). Allowing just 20% excess air into the process (roughly a 12-to-1 ratio for natural gas) reduces the available heat to 38%. Now, 62% of the total heat input goes out the stack, the difference being carried away by that relatively small amount of excess air. To maintain the same temperatures and production rates in the furnace, 18% more fuel must be burned.

**Air infiltration.** Excess air does not necessarily enter the furnace as part of the combustion air supply. It can also infiltrate from the surrounding room if there is a negative pressure in the furnace. Because of the draft effect of hot furnace stacks, negative pressures are fairly common, and cold air slips past leaky door seals and other openings in the furnace. Figure 6 illustrates air infiltration from outside the furnace.

Once in the furnace, air absorbs precious heat from the combustion system and carries it out the stack, lowering the furnace efficiency. A furnace pressure control system may be an effective way to deal with this. See the ITP tip sheet, "Reduce Air Infiltration in Furnaces," for guidelines on estimating infiltration losses.[1]

Figure 6. Air infiltration from furnace opening.



The bottom line is that to get the best possible energy efficiency from furnaces and ovens, reduce the amount of energy carried out by the exhaust and lost to heat storage, wall conduction, conveying and cooling systems and radiation.

### Furnace scheduling and loading

A commonly overlooked factor in energy efficiency is scheduling and loading of the furnace. "Loading" refers to the amount of material processed through the furnace or oven in a given period of time. It can have a significant effect on the furnace's energy consumption when measured as energy used per unit of production, for example, in British thermal units per pound (Btu/lb).

Certain furnace losses (wall, storage, conveyor and radiation) are essentially constant regardless of production volume; therefore, at reduced throughputs, each unit of production has to carry a higher burden of these fixed losses. Flue gas losses, on the other hand, are variable and tend to increase gradually with production volume. If the furnace is pushed past its design rating, flue gas losses increase more rapidly, because the furnace must be operated at a higher temperature than normal to keep up with production.

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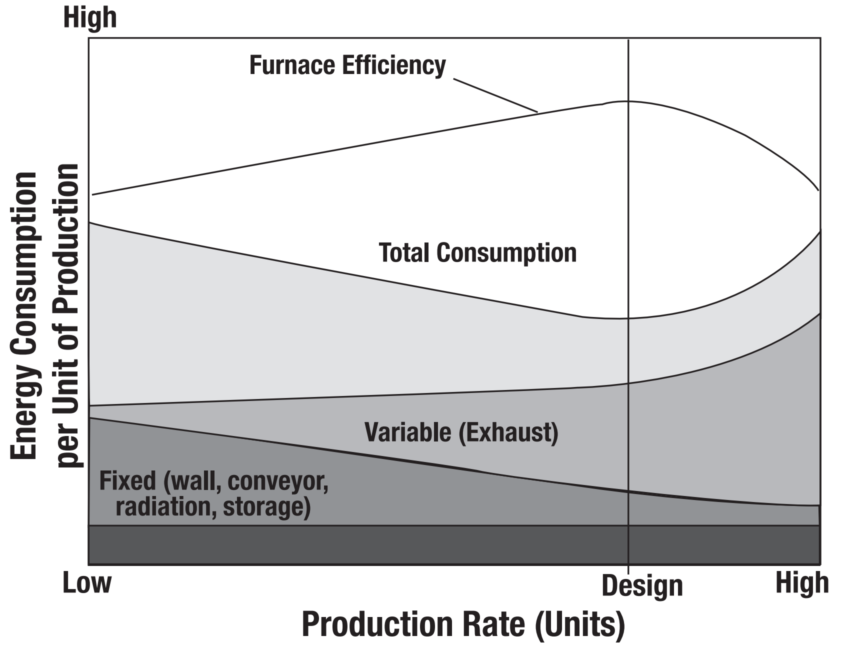
[1] The tip sheet is available online on the ITP BestPractices Web site at www.eere.energy.gov/industry/bestpratices.

Total energy consumption per unit of production will follow the curve in Figure 7, which shows the lowest at 100% of furnace capacity and progressively higher the farther throughputs deviate from 100%. Furnace efficiency varies inversely with the total energy consumption. The lesson here is that furnace operating schedules and load sizes should be selected to keep the furnace operating as near to 100% capacity as possible. Idle and partially loaded furnaces are less efficient.

Figure 7. Impact of production rate on energy consumption per unit of production.



### Steps for increasing energy efficiency through reduction in exhaust gas heat losses.

The exhaust gas heat losses can be calculated by the equation:

Furnace exhaust heat losses = W * Cp * (T exhaust – T ambient)

Where:

- W = Mass of the exhaust gases
- Cp = Specific heat of the exhaust gases
- T exhaust = Flue gas temperature entering the furnace exhaust system (stack)
- T ambient = Ambient temperature (usually assumed 60˚F)

The highest priority is to minimize exhaust gas temperature and mass or volume of exhaust gases.

- The furnace exhaust gas temperature depends on many factors associated with the furnace operation and heat losses discussed above. It can be measured directly or can be assumed to 100˚ to 200˚F above the control temperature for the furnace zone where the flue gases are exhausted.
- The exhaust mass flow depends on the combustion air flow, fuel flow and the air leakage into the furnace. Measurement of fuel flow together with the percentage of oxygen (or carbon dioxide [CO2]) in the flue gases can be used to estimate mass or volume of exhaust gases.
- The flue-gas specific heat (Cp) for most gaseous fuel-fired furnaces can be assumed to be 0.25 Btu/lb per ˚F) or 0.02 Btu/(standard cubic foot per ˚F) for a reasonably accurate estimate of flue gas heat losses.

**Minimize exhaust gas temperatures.** Excessive exhaust gas temperatures can be the result of poor heat transfer in the furnace. If the combustion gases are unable to transfer the maximum possible heat to the furnace and its contents, they will leave the furnace at higher temperatures than necessary. Optimizing heat transfer within the furnace requires different methods for different situations. The ITP tip sheet “Check Heat Transfer Surfaces” will provide greater insight into how transfer takes place and what can be done to improve it.[2]

Overloading a furnace can also lead to excessive stack temperatures. To get the proper rate of heat transfer, combustion gases must be in the heating chamber for the right amount of time. The natural tendency of an overloaded furnace is to run colder than optimal, unless the temperature is set artificially high. This causes the burners to operate at higher than normal firing rates, which increase combustion gas volumes. The higher gas flow rates and shorter time in the furnace cause poor heat

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[2] The tip sheet is available online on the ITP Best Practices Web site at www.eere.energy.gov/industry/bestpractices.

transfer, resulting in higher temperature for the flue gases. Increased volumes of higher temperature flue gases lead to sharply increased heat losses. Overly ambitious production goals might be met, but at the cost of excessive fuel consumption.

**Minimize exhaust gas volumes.** Avoiding overloading and optimizing heat transfer are two ways to lower waste gas flows, but there are others.

The most potent way is to closely control fuel-air ratios. Operating the furnace near the optimum fuel-air ratio for the process also controls fuel consumption. The best part is that it can usually be done with the existing control equipment. All that is required is a little maintenance attention. The ITP tip sheet "Check Burner Air-Fuel Ratios" provides a useful chart for figuring exhaust gas losses and shows how to figure the efficiency improvements that can come from controlling ratios more closely.

Some reduction in exhaust volumes will be the indirect result of efficiencies applied elsewhere. As mentioned above, flue gas losses are a fixed percentage of the total heat input to the furnace. As shown in Figure 8, any reduction in heat storage, wall, conveyor or radiation losses will be multiplied by the available heat factor.
For example, on a furnace operating at 50% available heat (50% exhaust gas loss), lowering wall losses by 100,000 Btu per hour (Btu/hr) will permit a firing rate reduction of 200,000 Btu/hr. That is 100,000 Btu/hr for the wall loss and 100,000 Btu/hr for the accompanying exhaust gas loss.

**Use of oxygen enriched combustion air.** Ambient air contains approximately 21% oxygen with nitrogen and other inert gases as balance. The total volume of exhaust gases could be reduced by increasing the oxygen content of combustion air, either by mixing in ambient air or by using 100% oxygen. Reducing exhaust gases would result in substantial fuel savings. The exact amount of energy savings depends on the percentage of oxygen in combustion air and the flue gas temperature. Higher values of oxygen and flue gas temperature offer higher fuel savings. Obviously, the fuel savings would have to be compared to the cost of oxygen to estimate actual economic benefits.

Figure 8. Multiplying effect of available heat on furnace losses.

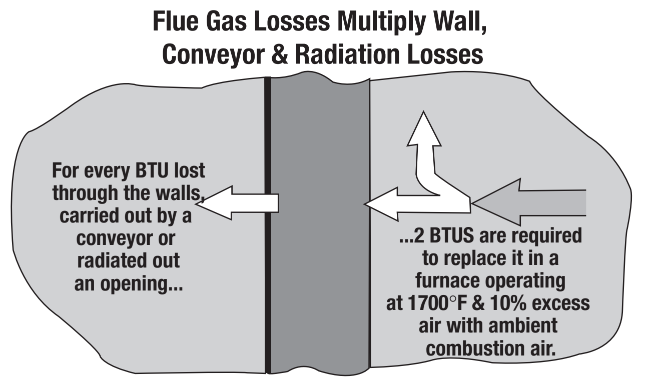


Figure 9. Direct preheating of incoming work.

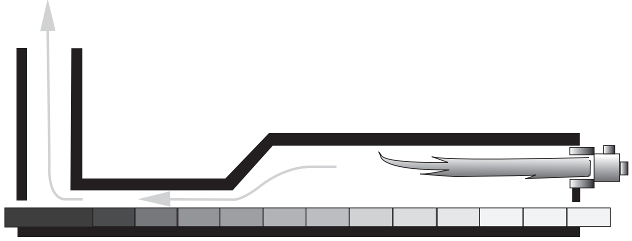
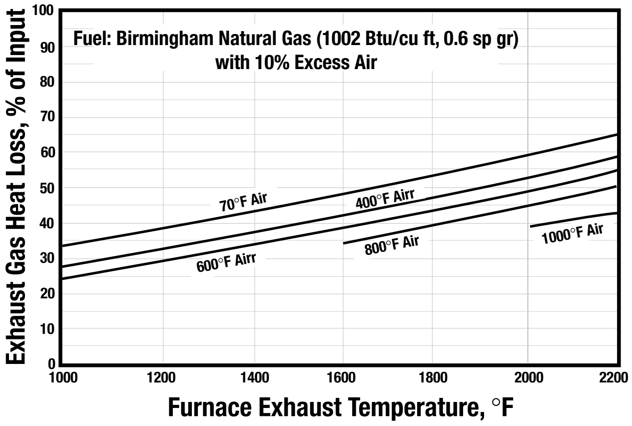


Figure 10. Exhaust gas losses with ambient and preheated air.



**Waste heat recovery.** Reducing exhaust losses should always be the first step in a well-planned energy conservation program. Once that goal has been met, consider the next level – waste heat recovery. Waste heat recovery elevates furnace efficiency to higher levels, because it extracts energy from the exhaust gases and recycles it to the process. Significant efficiency improvements can be made even on furnaces that operate with properly tuned ratio and temperature controls. There are four widely used methods:

1. **Direct heat recovery to the product.** If exhaust gases leaving the high-temperature portion of the process can be brought into contact with a relatively cool incoming load, energy will be transferred to the load and preheats the load. This reduces the energy that finally escapes with the exhaust (Figure 9). This is the most efficient use of waste heat in the exhaust.

   Use of waste heat recovery to preheat combustion air is commonly used in medium- to high- temperature furnaces. Use of preheated air for the burners reduces the amount of purchased fuel required to meet the process heat requirements. Figure 10 shows the effect of preheating combustion air on exhaust gas heat losses.

   Preheating of combustion air requires the use of a recuperator or a regenerator.

2. **Recuperators.** A recuperator (Figure 11) is a gas-to-gas heat exchanger placed on the stack of the furnace. There are numerous designs, but all rely on tubes or plates to transfer heat from the outgoing exhaust gas to the incoming combustion air, while keeping the two streams from mixing. Recuperators are the most widely used heat recovery devices.

3. **Regenerators**. These are basically rechargeable storage batteries for heat. A regenerator (Figure 12) is an insulated container filled with metal or ceramic shapes that can absorb and store relatively large amounts of thermal energy. During the operating cycle, process exhaust gases flow through the regenerator, heating the storage medium. After a while, the medium becomes fully heated (charged). The exhaust flow is shut off and cold combustion air enters the unit. As it passes through, the air extracts heat from the storage medium, increasing in temperature before it enters the burners. Eventually, the heat stored in the medium is drawn down to the point where the regenerator requires recharging. At that point, the combustion air flow is shut off and the exhaust gases return to the unit. This cycle repeats as long as the process continues to operate.

   For a continuous operation, at least two regenerators and their associated burners are required. One regenerator provides energy to the combustion air, while the other recharges. In this sense, it is much like using a cordless power tool; to use it continuously, you must have at least two batteries to swap out between the tool and the recharger. An alternate design of regenerator uses a continuously rotating wheel containing metal or ceramic matrix. The flue gases and combustion air pass through different parts of the wheel during its rotation to receive heat from flue gases and release heat to the combustion air.

4. **Use of waste heat boiler.** Use of a waste heat boiler to recover part of the exhaust gas heat is an option for plants that need a source of steam or hot water. The waste heat boiler is similar to conventional boilers with one exception: it is heated by the exhaust gas stream from a process furnace instead of its own burner. Waste heat boilers may be the answer for plants seeking added steam capacity. Remember, however, that the boiler generates steam only when the process is running.

Figure11. Recuperator system for preheating combustion air looses.

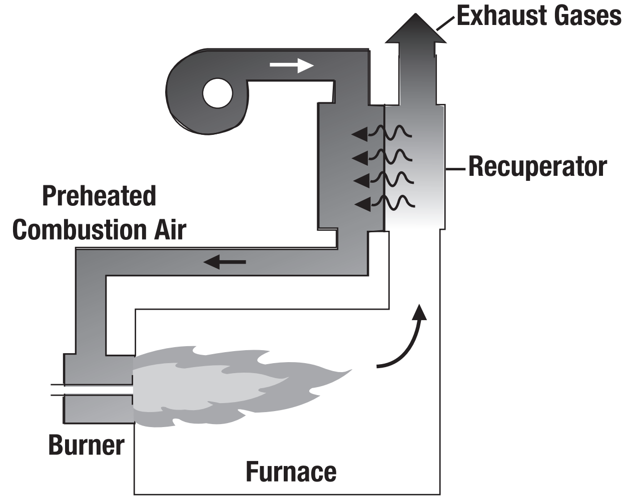


Table 1. Areas of Potential Waste Heat Reduction and Recovery Improvement

| Energy Conservation Technique | Heat Transfer to Load | Reduction of Exhaust Gas Mass | Temperature Uniformity | Productivity |
|---|---|---|---|---|
| *Improving the Performance of Existing Equipment* | | | | |
| Reducing Heat Storage | | √ | | √ |
| Reducing Wall Losses | | √ | | √ |
| Reducing Material Handling Losses | | √ | | √ |
| Reducing Cooling Media Losses | √ | √ | √ | √ |
| Reducing Radiation Losses | √ | √ | √ | √ |
| Optimizing Fuel-Air Ratio | √ | √ | | √ |
| Reducing Air Infiltration | √ | √ | √ | √ |
| Improving Scheduling & Loading | | √ | | √ |
| *Modifying and Upgrading Equipment* | | | | |
| Waste Heat Recovery | | | | |
| - Air Preheating | √ | √ | | √ |
| - Load Preheating | | √ | √ | √ |
| - To External Processes* | | | | |
| Oxygen-Enhanced Combustion | √ | √ | | √ |
| Improving Heat Transfer with Advanced Burners and Controls | √ | √ | √ | √ |

* Process is not directly affected, but energy reduction can be achieved at the plant level.

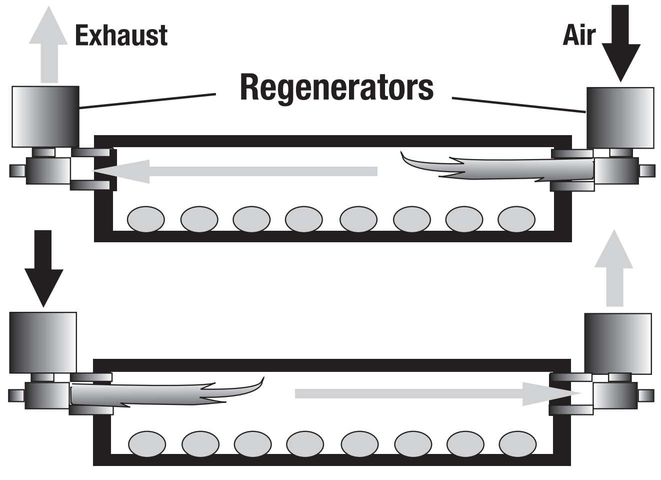
Not all processes are candidates for waste heat recovery. Exhaust volumes and temperatures may be too low to provide financial justification, but if the exhaust temperature is above 1,000˚F, waste heat recovery is worth investigating.

The ITP tip sheet "Preheated Combustion Air" offers guidance on how to estimate the efficiency and economic benefits of preheating combustion air.

### Energy reduction and recovery strategy

A comprehensive program for reducing furnace energy consumption involves two types of activities. The first deals with achieving the best possible performance from the existing equipment. Equipment modifications, if required, are relatively modest. The second involves major equipment modifications and upgrades that can make substantial reductions in energy consumption. These techniques and their benefits are summarized in Table 1.

Figure 12. Regenerator system for storing thermal energy.



## Summary

Obtaining the maximum efficiency and productivity from industrial furnaces and ovens is a two-step process. First, get the equipment up to its peak performance by reducing heat losses, improving production scheduling and closely controlling gas-air ratios. Once the equipment has reached this level of performance, additional significant improvements may come from recapturing waste heat through direct load preheating, combustion air preheating or steam generation.

## Additional Process Heating Resources

For additional information on topics referenced in this tech brief, please see tip sheets and case studies on the ITP BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

## Acknowledgements

Special thanks to Richard Bennett of Janus Technologies and Arvind Thekdi of E3M, Inc., for their contributions to this technical brief.

# Appendix D: References

The following are references used in this Sourcebook.

*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 Industrial Technologies Program, Capital Surini Group International, Inc., Energetics, Incorporated, March 16, 2001.

Presentation titled, *Process Heating, Review of Processes and Equipment Used by the Industry*, Dr. Arvind Thekdi, E3M, Inc.

Figures 1, 2 and 4. Presentation titled, *Process Heating, Review of Processes and Equipment Used by the Industry*, Dr. Arvind Thekdi, E3M, Inc.

Figure 3. *North American Combustion Handbook*, diagram source; numbers from Arvind Thekdi.

# Appendix E: Guidelines for Comments

Comments that can correct and improve this sourcebook are appreciated. Please photocopy this page and provide suggestions to the address listed below.

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