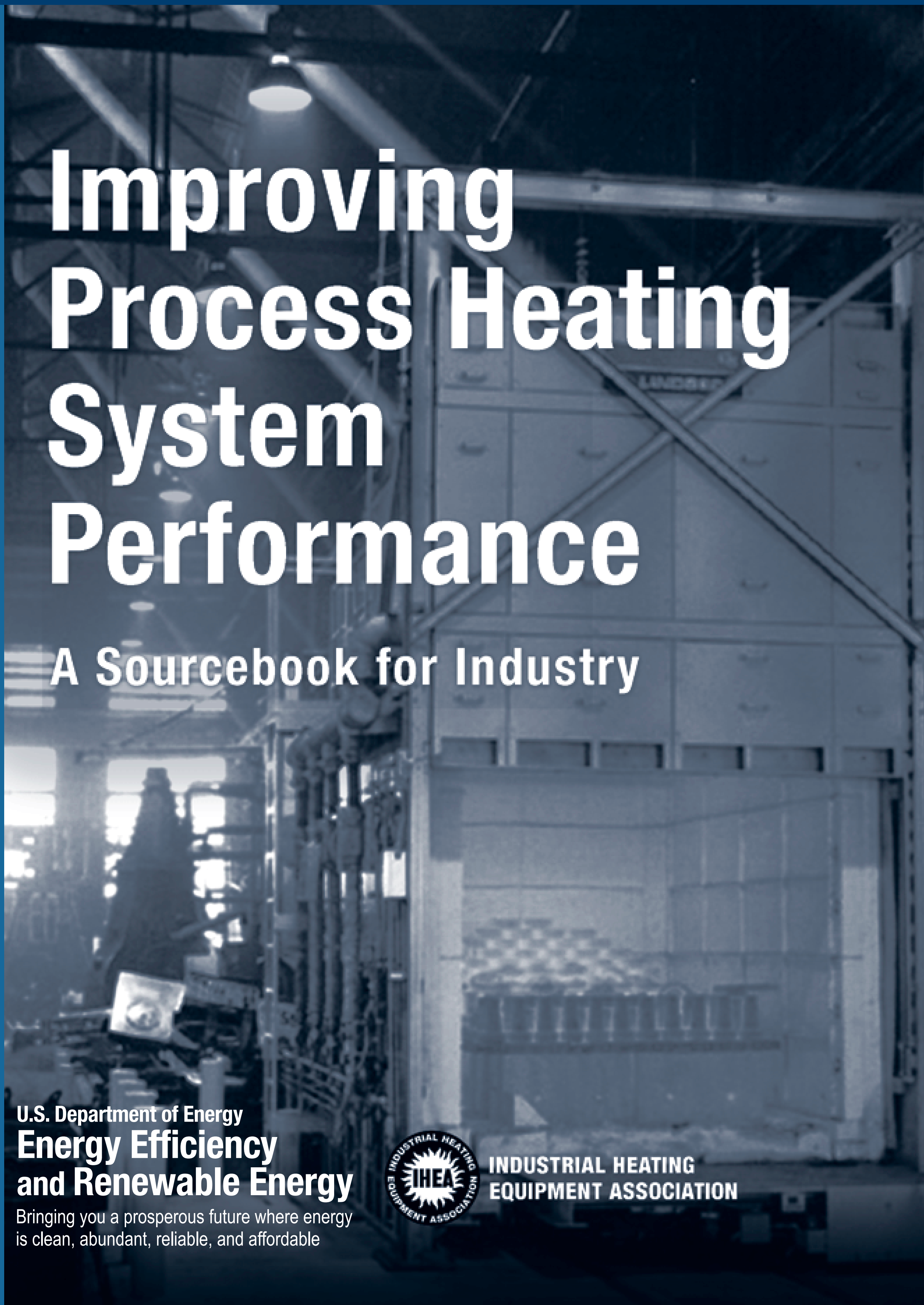
Industrial Technologies Program



Improving Process Heating System Performance

A Sourcebook for Industry

U.S. Department of Energy
Energy Efficiency and Renewable Energy
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INDUSTRIAL HEATING EQUIPMENT ASSOCIATION

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Improving Process Heating System Performance: A Sourcebook for Industry is a development of the BestPractices initiative under the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP) and the Industrial Heating Equipment Association (IHEA). The ITP and IHEA undertook this project as part of a series of Sourcebook publications on industrial utility systems. Other topics in this series include compressed air systems, pumping systems, fan systems, steam systems, and motors and drives.

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 the Industrial Technologies' BestPractices effort and IHEA, see Section 5, "Where to Find Help".

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Quick Start Guide

This Sourcebook provides process heating system stakeholders with a reference describing basic process heating processes and equipment, and outlines opportunities for energy and performance improvements. The Sourcebook 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 as a document that raises awareness of potential performance improvement opportunities, provides practical guidelines, and offers suggestions on where to find additional help. The Sourcebook consists of the following sections:

◆ Section 1: Process Heating System 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

This section discusses key factors for improving the performance of process heating systems.

◆ Section 3: 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 4: Process Heating System Economics

To support the improvement opportunities presented in Section 2, this section provides recommendations to justify process heating improvement projects using economic reasoning.

◆ Section 5: 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 opportunities for improving the efficiency and performance of process heating systems. Appendix C contains technical briefs developed by DOE. Appendix D is a compendium of references used in the Sourcebook. Appendix E provides guidelines for submitting suggested changes and improvements to the Sourcebook.

Section 1: Process Heating System Basics

Overview

Process heating is a fundamental component in the manufacture of most consumer and industrial products, including those made out of metal, plastic, rubber, concrete, glass, and ceramics. Within the U.S., fuel-based process heating (excluding electricity and steam generation) currently accounts for 5.2 quads,[1] which equals roughly 17% of the total industrial energy use. Typically, the energy used for process heating accounts for 2% to 15% of the total production cost.[2]

Depending on the industrial process and the application, process heating is provided by different means. Process temperatures range from under 300°F to more than 5,000°F. Whereas some process heating operations are continuous and heat several tons of material per hour, others are slow, precise, and heat small batches according to very accurate time-temperature profiles. The characterization and description of process heating operations provides a basis to discuss performance issues, to identify improvement opportunities, and to evaluate and compare improvement options.

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

To identify valid improvement opportunities it is important to understand the requirements of the application, common process design deficiencies, limitations of the available equipment, and common causes for reduced system performance and efficiency. General constraints are the requirement of a controlled atmosphere during heat treatment (e.g., oxidizing, reducing, reactive), the temperature range, the available infrastructure (e.g., energy source), and the material handling during processing.

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

Since process heating system performance is fundamental to the quality of a wide range of final 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 this Sourcebook in Section 3, 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 main intention is to help end users identify and prioritize potential improvement opportunities, and implement projects which are technically and economically feasible.

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/knowledge

[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 Office of Industrial Technologies, Capital Surini Group International, Inc., Energetics, Incorporated, March 16, 2001.

transfer, opportunities common to industry segments, applications, and, where possible, equipment type, are identified. References to further reading and other information sources are given where appropriate.

Systems Approach

Depending on the process heating application, system sizes, configurations, and operating practices range widely throughout industry. For a given system, there are usually a variety of improvement opportunities, and consequently, 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 the system 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, optimization of them 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. New products might require adjustments in operating practice, leading to operating conditions barely achievable by the original design. 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 are often focused 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.

A poor condition of refractory or insulation might reduce the furnace efficiency, thereby increasing the amount of fuel and combustion air needed to perform a given process heating task. In addition to an increased cost for fuel, the system is exposed to higher stress which can accelerate wear and subsequently lead to more frequent breakdowns. Other side effects can be a reduced product quality and increased emissions.

Another example 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.

Components of a Typical Process Heating System

Figure 1 shows a schematic of a common 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, this is 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.

The remainder of this section of the Sourcebook will introduce the user to process heating systems by describing:

- Common types of process heating systems and equipment
- Process heating equipment classifications
- Process heating energy sources
- Basic process heating operations.

Common Types of Process Heating Systems and Equipment

Common to all process heating systems is the transfer of energy to the material to be treated. Direct heating methods generate heat within the material itself (microwave, induction, 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 (microwave, 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:

- Combustion-based process heating systems
- Electric process heating systems
- Heat recovery and heat exchange systems.

Boilers and steam generators, which are often considered as a category of their own, are discussed in detail in a companion Sourcebook titled *Improving Steam System Performance: A Sourcebook for Industry*. The following sections discuss heating methods commonly employed in process heating systems.

◆ Combustion-based (Fuel-based) Process Heating

Heat is generated by the combustion of solid, liquid, or gaseous fuels, and transferred either directly or indirectly to the material. Common fuel types are fossil fuels (e.g. oil, natural gas, coal), and biomass (e.g. vegetable oil, wood chips, cellulose, charcoal, ethanol). To enhance combustion, gaseous or liquid fuels are mixed with oxidants (e.g., oxygen, 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, muffle). Solid fuels are utilized in a wide variety of combustion systems, including fluidized bed, grate, and stokers.

Examples of fuel-fired process heating equipment include ovens, heaters, kilns, and melters. The term 'furnace' will be used to describe this broad range of equipment in the following discussion. Combustion-based process heating systems are used in nearly every industry segment, especially in furnaces like ovens, heaters, kilns and melters, but also for surface treatments in ambient air.

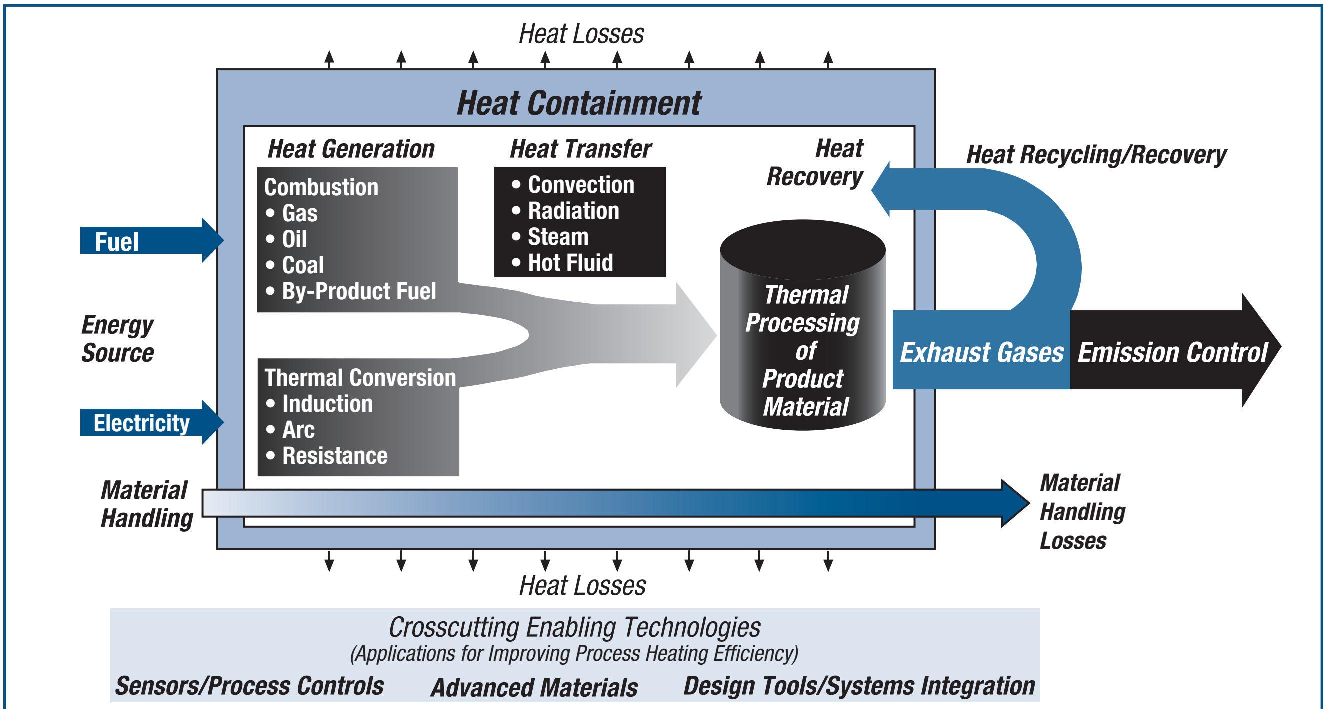


Figure 1. Key Components of a Process Heating System

There are many types of combustion-based furnaces. Examples include:

Atmosphere generators. Used to prepare 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 vs. batch operation, material handling system, or source of heat generation.

Flares. Used to protect the environment by burning combustible waste products in the petro-chemical 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 of the open type (in which the flame comes in contact with ware), or of 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 and annealing.

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

Reverberatory furnaces. Furnaces where 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 incineration. Used to dispose of solid waste materials.

Thermal oxidizers. Used to oxidize volatile organic compounds in various industrial waste streams. Processes include paint and polymer curing/drying.

Furnaces come in many configurations, but can be considered as heating systems consisting of a number of 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 Process Heating (Electrotechnologies)

Electric currents or electromagnetic fields are used to heat the material. 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) by exciting atoms/molecules within the material with electromagnetic radiation (e.g. microwave). Indirect heating methods use one of these three methods to heat a heating element or susceptor, and transfer the heat either by conduction, convection, radiation or a combination of these to the work piece.

Resistance heating. A type of heating system that generates heat by passing current through a conductor, causing it to increase in temperature.

Direct resistance heating. Using electrodes or fixed connectors, an electric current (AC or DC) is passed through the material. Since the heat is generated directly in the work piece or melt, comparably high efficiencies can be achieved. The electrode material has to be compatible with the material to be heat-treated or melted; in industrial applications, consumable and non-consumable electrodes are common. Direct resistance heating is primarily used to heat glass- and metal-melts, and electrical heating elements. The material to be treated must have a reasonable electrical conductivity.

Indirect resistance heating

Conventional. An electrical current is passed through a resistor, and energy is transmitted to the work piece primarily though convection.

Electric infrared heating. An electrical current is passed through a resistor, which could be either solid (metal, ceramic) or gaseous (for example, Ar/He gas column; contained plasma arc), and which in turn emits infrared radiation. Especially with contained plasma arcs, high energy densities in the order of 3.5kW/cm^2 are achievable. Electric infrared heating systems are used where precise temperature control is required to heat treat surfaces, cure coatings, and dry materials. The work piece to be treated must have a reasonable absorption in the infrared part of the spectrum.

Induction heating. Heating by electrical resistance and hysteresis losses induced by subjecting an electrically conducting material to the varying magnetic field surrounding a coil carrying an alternating current.

Direct induction heating. A strong electromagnetic field generated by a water-cooled coil (solenoid) induces an eddy current into an electrically conducting material, for example, steel, graphite, or molten glass. 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, annealing), but has also found applications in the manufacturing of specialty glass, ceramics, and crystals.

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 vessels, to sinter ceramic powders in graphite crucibles, and to heat melts in crystal drawing processes.

Microwave heating. Microwave heating systems use electromagnetic radiation in the microwave band to excite water molecules in the material, or generate heat in a susceptor (for example, made out of graphite). Microwave heating systems are commonly used to dry textiles and polymers, to process foods, and to dry and sinter ceramics. Advantages include the comparably high efficiency, the high energy densities achievable, reasonably good control, and a comparably 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 arc heating and melting. 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 non-transferred arc. In the transferred-arc configuration, the arc is transferred from an electrode to the workpiece, which is connected to a return electrode; heating of the material occurs through radiation, convection, and direct resistance heating. In non-transferred 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 an AC (single phase, three-phase) or a DC current can be used.

Radio frequency (RF) plasma heating. Gas is partially ionized in a strong electromagnetic field. The material to be heated is either introduced into the plasma, for example, as a powder, or the plasma gas is discharged through a nozzle/collimator against it. Applications of RF plasma include the manufacture of nano-powders, the spherulization of powders, and the treatment of surfaces including the deposition of coatings.

◆ Heat Recovery and Exchange 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.

A common type of heat exchange system is 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 without the high pressures that would be required with steam.

This catchall group of process heating applications represents a significant amount of energy. 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.

◆ Boilers and Steam Generators

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]

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.

Boilers generate steam, generally using heat from fuel combustion. 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 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 with respect to other alternatives.

A significant amount of energy is used for industrial steam generation. For example, in 1994, industry used about 5,676 trillion Btu of steam energy, which represents about 34% of the total energy used in industrial applications.

Process Heating Equipment Classification

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. The purpose of this section is to build upon the discussion of common process heating operations by providing broad descriptions of process heating 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

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

improvements are likely to be applicable. This section describes several functional characteristics that can be used in classifying equipment. Process heating equipment can be classified in many different ways, including:

- Mode of operation (batch versus continuous)
- Material handling system
- Type of heating element
- Type of heating method
- Type of energy used.

Table 1 lists these classification characteristics by equipment/application and industry.

◆ 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, the load continually moves into the furnace, and in many cases various process heating steps are carried out in designated zones or locations which are held at a specific temperature or under specific conditions. A continuous furnace generally has the ability to operate on an uninterrupted basis as long as the load keeps feeding into the furnace. In batch mode, all process heating steps (i.e. heating, holding, cooling) are carried out at a single location by adjusting the conditions over time, and single loads of material are heated at a time.

◆ Material Handling System

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. Several 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, belts, buckets, roller systems. Systems in which a material or its container travels through the heating system during the heating and/or cooling. The work piece is moved through the furnace on driven belts or rolls. The work piece could be in direct contact with the transporting mechanism (belt, roller, etc.), or could be supported by a tray or contained in a bucket, which is either in contact 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 "turn-table" while being heated and cooled.

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

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

Continuous strip furnaces systems. Systems in which the material in 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 furnaces, 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 that is manually fed

Table 1. Process Heating Equipment Classification

Furnace Classification Method	Equipment/Application Comments	Primary Industries
Batch and 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 electrically heated furnaces.	Most manufacturing sectors
Indirectly Heated	Heat treating furnaces, chemical reactors, distillation columns, salt bath furnaces	Metals, Chemical
Type of Energy Used		
Fuel Fired	Process heaters, aluminum and glass melting furnaces, reheat furnaces, ovens	Most manufacturing sectors
Electrically Heated	Infrared ovens, induction melting and heating furnaces, electric arc melting furnaces	Metals, Chemical
Steam Heated	Dryers, fluid heating systems, water or slurry heaters, tracing	Pulp and Paper, Chemical, Petroleum Refining, Food
Other	Air heaters, polymerizing heaters, frying ovens, digesters, evaporators.	Chemical, Food
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	Continuous furnaces used for metal heating, heat treating, drying, curing	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, and coal gasifiers	Metals, Petroleum Refining
Rotary Hearth Furnaces	Furnaces used for metal or ceramics heating or heat treating of steel and other metals, iron ore palletizing	Metals
Walking Beam Furnaces	Primarily used for large loads such as reheating of steel slabs, billets, ingots	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	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

material with a pick and place system is a batch furnace, while a pit furnace used for heat treatment of automatically fed material with a vertical material handling system is a continuous furnace.

◆ **Type of Heating Method**

In principle, one can distinguish direct and indirect heating methods. Systems using direct heating methods expose the material to be treated directly to the heat source or combustion products; heating elements can be open burners, or open electrical heating elements. 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). Heating elements include radiant burner tubes, and covered electrical heating elements.

◆ **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, drums, and various types of electric heating elements.

◆ **Type of Energy Used**

The type of energy used in a process heating system is closely related to the type of equipment.

- Combustion based: includes furnaces using gaseous, liquid, or solid fuel burners. The fuel combustion produces heating gases that are used for heating of the material. The heating could be direct or indirect.
- Electric based: includes electrical resistance, induction, arc, or plasma heating.
- Steam: includes boiler or steam generator-based indirect heating process.
- Other: uses hot liquids or gases in direct contact with the material or through indirect heat transfer with a heat exchanger.

Process Heating Energy Sources

Process heating energy is obtained from three major energy sources; electricity, fuel, and steam. The choice of the energy source depends on the availability, cost, and, in direct heating systems, the compatibility of the exhaust gases with the material to be heated.

Although steam is generated by using fuel in boilers, it represents 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 liquids, and water. The secondary sources are generated by a heating system of its own that can fall under the general category of fluid heating.

Some energy sources are more expensive than others. Comparatively expensive energy types tend to promote shorter payback periods for projects that improve system efficiency. In contrast, waste 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 2 illustrates how fuels are used in several process heating applications. The costs of different fuel types can vary widely, which has a significant impact on the payback period of efficiency improvement projects. 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, justifying energy efficiency projects must emphasize performance and reliability benefits that usually accompany improvements in efficiency.

Basic Process Heating Operations

Process heating is used in many industries for a wide range of applications. Many industries use multiple process heating operations. For example, steelmaking facilities often perform a combination of smelting, metal melting, and heat treating processes. Chemical manufacturing facilities often use 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. Although there is a very broad range of process heating operations, some commonalities among these processes allow them to be grouped into nine categories:

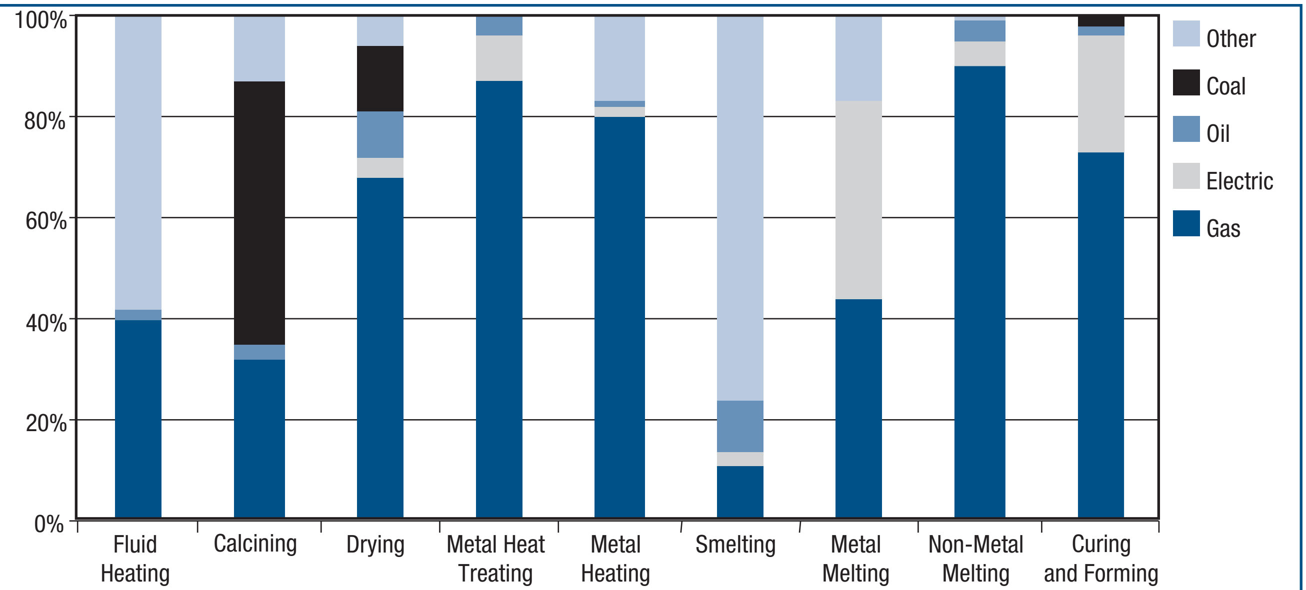


Figure 2. Energy Source Breakdown for Key Industrial Process Heating Applications

- Fluid heating
- Calcining
- Drying
- Smelting
- Agglomeration and sintering
- Heat treating
- Metals reheating
- Metal and non-metal melting and refining
- Curing and forming
- Other process heating operations.

Each of the key process heating operations is discussed below.

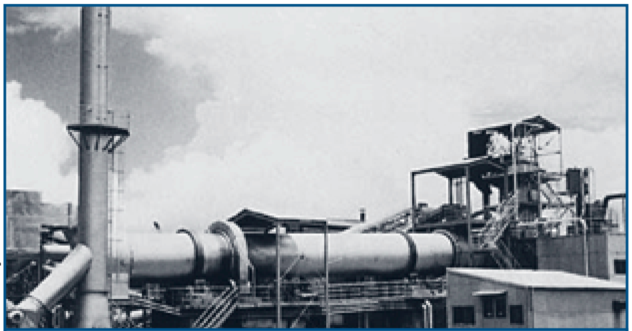
Fluid heating. Fluid heating is used to increase the temperature of a liquid or gas, including the complete or partial vaporization of the fluid, and is performed for a wide range of purposes in many industries, including chemicals, food processing, and petroleum refining. In chemical manufacturing,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

Calcining. Calcining is the removal of chemically bound water and/or gases, such as carbon dioxide, through direct or indirect heating. Calcining is common in the preparation of construction materials such as cement and wallboard. In the pulp and paper industry, calcining is used to recover lime for the kraft pulping process. In the petroleum industry, calcining is also used to produce anodes from petroleum coke for aluminum smelting applications. Calcining is sometimes also used to remove excess water from raw materials for specialty optical materials and glasses.

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. Drying is also common in food processing and textile industries for similar moisture

Courtesy of Foster Wheeler

Fluid Heating in a Petroleum Process Heater


Courtesy of Arvind Thekdi, E3M, Inc.

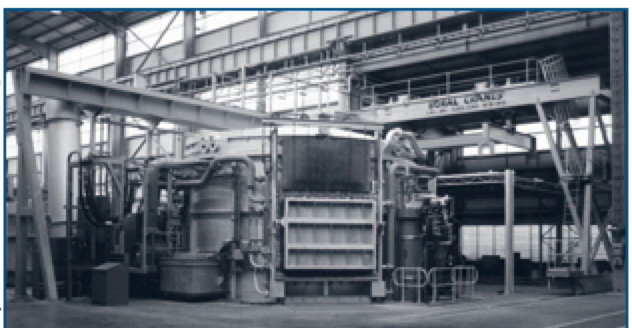
Rotary Dryer


Courtesy of Surface Combustion, Inc.

Quench Furnace Line for Heat Treating


Courtesy of Arvind Thekdi, E3M, Inc.

Walking Beam Furnace for Metal Reheating


Courtesy of SECO/WARWICK Corporation

Tiling Top Aluminum Melting Furnace

reduction purposes. There are several types of dryers, including conveyor, fluidized bed, rotary, and cabinet. Industries that use large amounts of drying energy include stone, glass, pulp and paper, and chemical manufacturing.

Smelting. Smelting is the chemical reduction of a metal from its ore, usually by fusion. Smelting separates impurities, allowing their removal from the reduced metal. A common example is the reduction of iron ore in a blast furnace to produce pig iron. Smelting is also used to isolate aluminum from bauxite in arc furnaces and to produce copper.

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

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.

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

Metal and non-metal melting and refining. Melting is the conversion of a solid to a liquid by applying heat, and is used extensively in the metals and glass industries. In the metals industry, melting processes are used to both make the metals, such as in the conversion of iron into steel, and to produce castings. Melting is often combined with refining processes, which demand the increase of temperature to remove impurities and/or gases from the melt. Additionally, several non-metal melting applications, particularly container glass and flat glass production, use large amounts of process heating energy.

Curing and forming. Curing is the controlled heating of a substance to promote or control a chemical reaction. In plastics applications, curing is the cross-linking reaction of a polymer. Curing is a common process step in the application of coatings to metallic and non-metallic materials, including ceramics and glass. 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, and the hot-shaping of glass.

Incineration/thermal oxidation. Incineration refers to the process of reducing the weight and volume of a solid through process heating. Incineration is usually used to treat waste and render it disposable via landfill. Thermal oxidation refers to heating waste (particularly organic vapors) in excess oxygen at high temperatures.

Other heating processes. Many process heating applications do not fall in the above categories, however, they collectively 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. Table 2 provides a list of the processes and identifies the applications, equipment, and industries where these processes are commonly used.

Table 2. Process Heating Operations

Process	Application	Equipment	Industry
Fluid Heating	Food Preparation, Chemical Production, Reforming, Distillation, Cracking, Hydrotreating, Visbreaking	Various Furnace Types, Reactors, and Heaters	Agricultural and Food Products, Chemical Manufacturing, Petroleum Refining
Calcining	Lime calcining	Various Furnace Types	Cement, Wallboard, Pulp and Paper Manufacturing, Primary Metals
Drying	Water and organic compound removal	Dryers	Stone, Clay, Petroleum Refining, Agricultural and Food Products, Pulp and Paper, Textile
Smelting	Steelmaking	Various Furnace Types, and Ovens	Primary Metals
Agglomeration - Sintering	Metals production	Various Furnace Types, Ovens, Kilns, and Lehrs	Primary Metals
Heat Treating	Coating, Enameling, Hardening, Annealing, Tempering	Various Furnace Types, Ovens, Kilns, and Lehrs	Primary Metals, Fabricated Metal Products, Glass, Ceramics
Metals Reheating	Forging, Rolling, Extruding, Galvanizing, Coating, Joining	Various Furnace Types, Ovens, Kilns, Heaters, and Reactors	Primary Metals, Fabricated Metal Products
Metal and Non-Metal Melting	Casting, Steelmaking, Glass production	Ovens, Kilns, Reactors, and Heaters	Primary Metals, Glass
Curing and Forming	Coatings, Polymer production	Various Furnace Types, Ovens, Kilns, and Lehrs	Ceramics, Stone, Glass, Primary Metals, Chemical Manufacturing, Plastics and Rubber
Incineration/Thermal Oxidation	Waste handling/disposal	Incinerators, Thermal oxidizers	Fabricated Metals, Food Products, Plastics and Rubber, Chemical Manufacturing
Other Heating Processes	Food Production (including Baking, Roasting, and Frying), Sterilization, Chemical production	Various Furnace Types, Ovens, Reactors, and Heaters	Agricultural and Food Products, Glass, Ceramics, Plastics and Rubber, Chemical Manufacturing

Section 2: Performance Improvement Opportunities

This section describes the most common performance improvement opportunities for process heating systems. The performance and efficiency of a process heating system can be described with an energy balance diagram, as shown in Figure 3. The main goal of the performance optimization is reduction of energy losses, and the increase of the energy transferred to the load. It is therefore important to know which aspects of the heating process have the highest impact.

Performance and efficiency improvement opportunities can be grouped into the following categories:

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

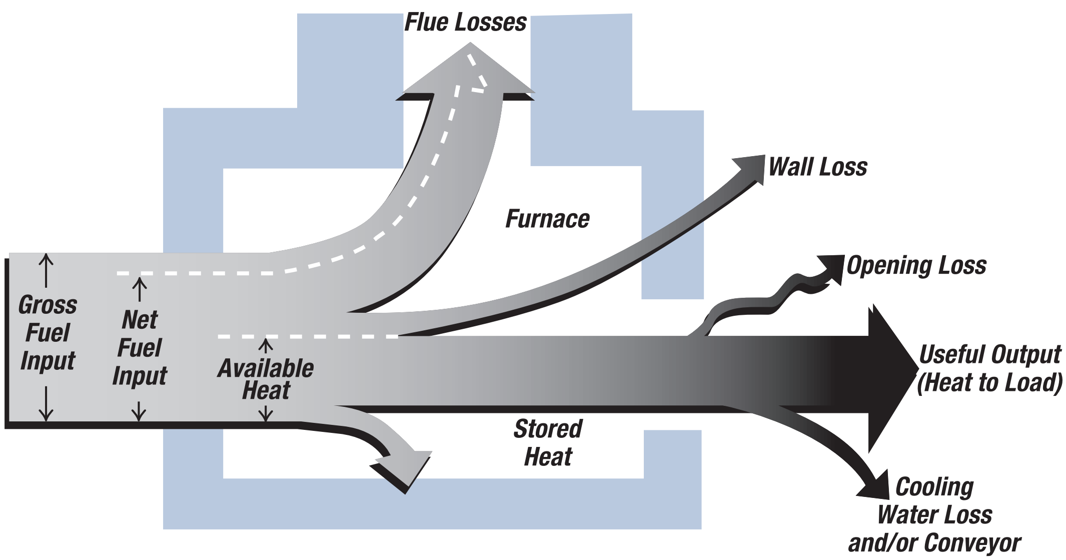


Figure 3. Energy Loss Diagram for a Fuel-Fired Furnace

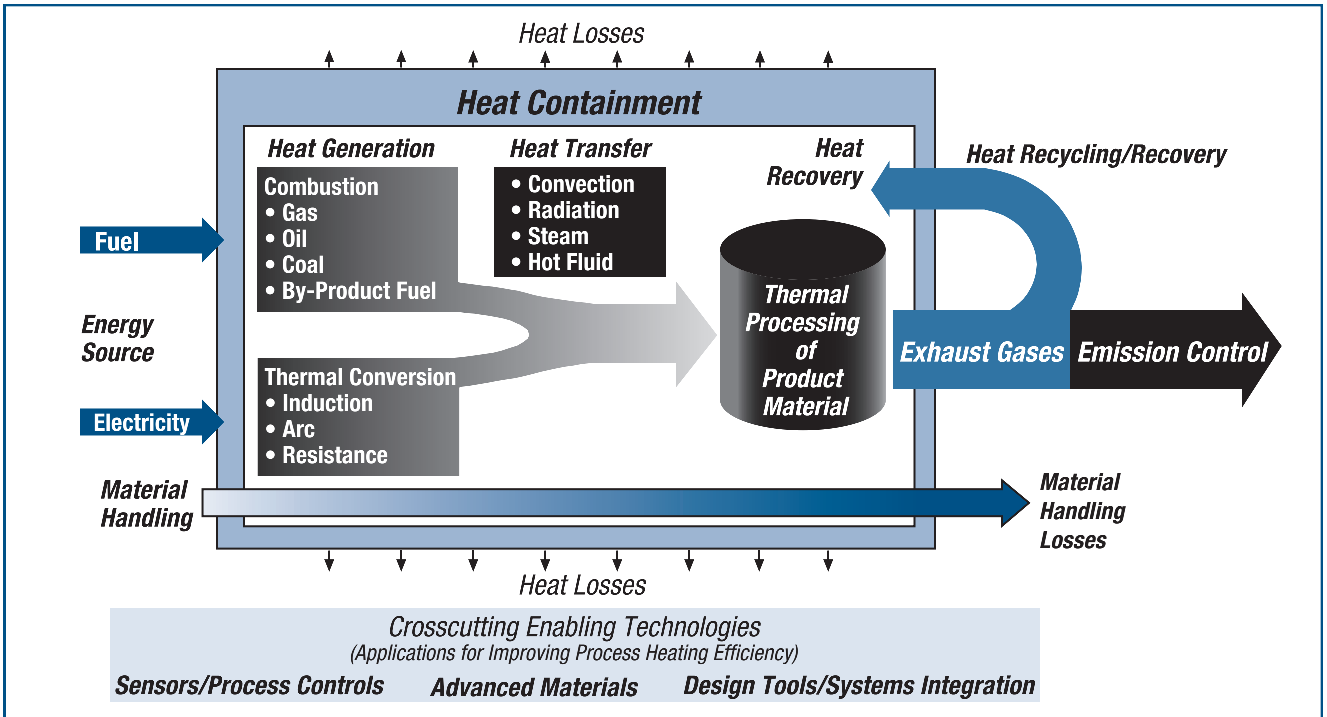


Figure 4. Key Performance Improvement Opportunities

Transferring heat from the exhaust gases to the incoming combustion air 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.

This section of the Sourcebook and the referenced Tip Sheets and Technical Briefs primarily focus on combustion-based process heating systems. Future editions will also include other systems, such as electrotechnologies.

Many opportunities are addressed in a series of Tip Sheets developed by the DOE's Industrial Technologies Program, some of 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 this set of Tip Sheets, two Technical Briefs have been developed, which discuss key issues in greater detail. The first of these Technical Briefs is *Materials Selection Considerations for Thermal Process Equipment*, which discusses how material selection can provide performance and efficiency improvements. The second Technical Brief is titled *Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity and Emission Performance* which discusses the advantages of reducing energy losses to the environment and heat recovery.

The following sections discuss the principal areas of a process heating system, indicating which opportunities are more likely to be found in these areas, things to look for that can indicate these opportunities, and where to seek additional information.

Heat Generation

In basic terms, heat generation converts chemical or electric energy into thermal energy, then transfers this energy to the materials being heated. 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 this fuel to the material. Key improvement areas include:

- Air-to-fuel ratio control
- Reducing excess air
- Preheating of combustion air or oxidant
- Oxygen enrichment.

◆ Air-to-Fuel Ratio Control and Reducing Excess Air

For most process heating applications, combustion burns a hydrocarbon fuel in the presence of air, forming carbon dioxide and water, and releasing heat. One common way to improve combustion efficiency is to ensure the proper air-to-fuel ratio is used, which 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, since a perfect mixing of the fuel with the oxidant (air, oxygen) would be required to achieve complete combustion. Without excess oxidant (air, oxygen), 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 avoidably large amounts of heat.

Caution should be used when reducing excess air. Although this is often an opportunity 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:

- The type of fuel used
- The type of burner used
- The process conditions
- Process temperature.

Heat Generation Opportunities

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

Checklist of Things 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.

References For Additional Information

Check the BestPractices Web site for these and other publications (**www.eere.energy.gov/industry/bestpractices**).

Tip Sheets

- Check Burner Air to Fuel Ratio (Also available in Appendix B)

Technical Brief

- Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity and Emission Performance (Also available in Appendix C)

◆ Preheat 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.

◆ Oxygen Enrichment

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 an 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, due to technological improvements in several areas, oxygen enrichment is being viewed again as a potential means of increasing productivity.

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, using methods such as:
  - 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 Containment

Heat containment refers to the improvement opportunities that reduce energy loss to the surroundings. In most heat generation equipment, significant sources of heat loss are the convection and radiation of energy from the system to the environment. Since convection and radiation losses both depend on the outside temperature of the heating equipment, insulating materials such as brick and refractory materials are essential in minimizing heat lost to the surroundings.

Another important cause for heat loss is air infiltration. Often, furnaces are operated at slightly negative pressure due to non-existent or improper pressure control operation to prevent the loss of furnace gases to the surroundings. The slightly negative pressure can result in air infiltration into the furnace. Air infiltration can result in a significant energy loss as the cool air carries heat away from the product and up the stack. As a result, fixing leaks around the furnace chamber and proper operation of a pressure control system can be a cost-effective effort to improve furnace efficiency.

Heat Transfer Opportunities

Performance Improvement Description	Savings
• Improve Heat Transfer with Advanced Burners and Controls	**5 to 10%**
• Improving Heat Transfer within a Furnace	**5 to 10%**

Checklist of Things to Watch

- ❑ Higher than necessary operating temperature
- ❑ Exhaust gas temperature from heat recovery device
- ❑ Stack temperature

References For Additional Information

Check the BestPractices Web site for current publications (**www.eere.energy.gov/industry/bestpractices**).

Heat Containment Opportunities

Performance Improvement Description	Savings
• Reduce wall heat losses	**2 to 5%**
• 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%**

Checklist of Things 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

References For Additional Information

Check the BestPractices Web site for these and other publications (**www.eere.energy.gov/industry/bestpractices**).

Technical Brief

- Waste Heat Reduction and Recovery for Improving Furnace Efficiency, Productivity and Emission Performance (Also available in Appendix B)

Major loss sources from a 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 slight negative pressure. Under these conditions, air can be drawn into the furnace, especially if integrity of the furnace is not inspected often.
- Presence of openings in the furnace walls or doors due to lack of proper seals at the doors used for material handling.
- Presence of 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.
- Presence of extended parts such as roller shafts from the furnace. These parts get hot and result in heat losses.
- Poor insulation condition. Similar to energy losses from the walls of the furnace, any other surfaces such as piping and ductwork that have poor insulation are sources of energy loss. In many cases, the loss of energy to work spaces that are HVAC conditioned often results in additional burden on cooling systems. This added demand on the cooling system should be accounted for when considering the restoration or installation of the insulation.

Heat Recovery Opportunities

Performance Improvement Description	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%**

Checklist of Things to Watch

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

References For Additional Information

Check the BestPractices Web site for these and other publications (**www.eere.energy.gov/industry/bestpractices**).

Tip Sheets

- Preheat Combustion Air (Also available in Appendix B)

Heat Recovery

Heat recovery is the return of energy, generally from exhaust gases, back 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," where waste heat is utilized several times on subsequent lower levels. Another example of heat recovery is the transfer of exhaust gas energy back to the material being heated, which similarly reduces fuel use. The heat lost from exhaust gases depends on mass flow and temperature of gases. Methods of reducing mass flow rate and exhaust gas temperature would increase overall efficiency of the process heating system.

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 can only extract energy from the combustion gases down to close to this limit. 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 exhaust gas energy back to some other part of the system can be an excellent efficiency improvement. Two common targets for receiving this energy include 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 with 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.

Use of air preheating reduces the exhaust gas temperature and mass flow through the heating system. Use of waste heat from waste or flue gases from high temperature processes to supply heat to lower temperature processes can improve the efficiency of the process. For example, use of flue gases from process heaters to generate steam or to heat feedwater for other boilers can increase the system efficiency significantly.

Enabling Technologies Opportunities

Performance Improvement Description	Savings
• Install high turndown combustion systems	**5 to 10%**
• Programmed heating temperature setting for part load operation	**5 to 10%**
• Monitoring and control of exhaust gas oxygen and unburned hydrocarbon and carbon monoxide emissions	**2 to 15%**
• Furnace pressure control	**5 to 10%**
• Correct location of sensors	**5 to 10%**

Checklist of Things to Watch

- ❑ Frequent and avoidable starting and stopping of the furnace
- ❑ Long periods of idle time between batches
- ❑ Extended periods of avoidably low capacity furnace operation
- ❑ Higher than necessary operating temperature

References For Additional Information

Check the BestPractices Web site for these and other publications (**www.eere.energy.gov/industry/bestpractices**).

Technical Brief

- Material Selection Considerations for Thermal Process Equipment (Also available in Appendix B)

Enabling Technologies

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

◆ Sensors and Process Control

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 attributable 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, an energy loss that can often be minimized with more effective process control is heat storage. 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 de-energized to energized 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 due to combustion instabilities. Generally, when the load on a system drops below its lowest safe operating capacity, the system must be shut down. Frequent shutting down and restarting a system results in heat storage losses, and in purge losses that accompany clearing the remaining combustible gases from the burner area. 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 often improve the performance and efficiency of a process heating system. The high temperatures of many process heating operations often require parts of the system to be cooled to protect against thermal damage. In some cases, advanced materials that can safely withstand higher temperatures may replace conventional materials, avoiding or reducing the energy losses associated with cooling. Use of advanced materials can reduce 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 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 heated material 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 systems with dampers or throttle valves.

DOE has several resources that address the opportunities available from improving motor system performance and efficiency. Notable among these resources is Motor Master+, a software program that helps end users make informed motor selection decisions. Information regarding this program and many other useful resources are available from the DOE'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

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

handling applications to move heated materials. The performance, efficiency, and reliability of fans, as with motors, are significantly affected by sizing and selection decisions and the fan maintenance effort.

Common fan problems and opportunities to improve their performance are discussed in a companion Sourcebook, titled *Improving Fan System Performance: A Sourcebook for Industry*. This resource is available from DOE's BestPractices Web site, 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, titled *Improving Pumping System Performance: A Sourcebook for Industry*. This resource is available from DOE's BestPractices Web site, www.eere.energy.gov/industry/bestpractices.

Section 3: BestPractices Process Heating Performance Improvement Tools

The U.S. Department of Energy BestPractices activity has developed several resources and tools that can be used to identify and assess process heating system improvement opportunities. These are described in this section of the Sourcebook. Additional resources are identified in the "Where to Find Help" section of the Sourcebook.

Process Heating Assessment and Survey Tool (PHAST)

The Industrial Heating Equipment Association (IHEA), through its partnership with DOE, worked with Oak Ridge National Laboratory and representatives from industry and equipment suppliers to develop the Process Heating Assessment and Survey Tool (PHAST). PHAST, with development support by E3M, Inc., is a user-friendly interactive tool that helps process heating equipment users assess how much energy their furnaces, ovens, and heaters use; and model 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. The PHAST software was developed to be useful in almost all industries and is effective for almost any size furnace. Support for the software development is provided by the DOE Industrial Technologies Program through its BestPractices activity, 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.

The PHAST software tool serves three major purposes:

1. 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.
2. Allows users to compare furnace performance across a range of operating conditions.
3. Calculates potential energy savings that may be achievable under different operating conditions.

◆ User-Friendly 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:

- **Energy equivalency:** Calculates heat requirements when the heat source is changed from fuel firing (Btu/hr) to electricity (kWh), or from electricity to fossil-fuel firing.
- **Efficiency improvement:** Calculates available heat for fuel-fired furnaces and expected energy savings when the burner operating conditions (exhaust fuel gas temperature, excess air, and preheated air) are changed for the burners.
- **O_2 enrichment:** Calculates available heat for fuel-fired furnaces and expected energy savings when oxygen in combustion air is changed from standard (21%) to a higher value.

The plant information section of the PHAST tool assists users to survey process heating equipment to identify which equipment consumes the most energy. 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 high-energy-use equipment 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 have an even more detailed assessment of individual pieces of equipment. In this way, PHAST allows users to work almost like a medical specialist equipped 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 operating or design conditions of the furnace. 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. PHAST also offers a "what-if" decision support tool that lets you 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.

NOx Emission Assessment Tool (NxEAT)

This tool is designed to analyze options for NOx (nitrogen oxide) reduction and energy efficiency improvements. The tool was developed jointly by DOE, Oak Ridge National Laboratory, E3M, Inc., and Texas Industries of the Future. An advisory committee consisting of members from chemical and petroleum refining industries provided input on the features and functions of the tool. The equipment suppliers and engineering consultants provided cost and performance data used in the tool database.

The (NxEAT) tool includes:

- A method of taking inventory of NOx sources, utility distribution system and equipment that use energy or the plant utility.
- Information on NOx reduction through the use of currently available combustion systems and other NOx reduction technologies.
- Information on commonly used methods of energy efficiency improvement and NOx reduction using available technologies, hardware, or systems.
- Data on the cost of NOx reduction technologies/equipment and rules-of-thumb for implementation cost obtained from the vendors and E&C firms. Also included is default data for NOx reduction potential and associated cost. The data can be changed by the user to allow for specific situations.
- Information on resources that will enable users to estimate energy reduction for plant equipment and processes.
- A model for consolidating and summarizing results.
- A report showing summary of total NOx reduction, cost of NOx reduction per ton per year, energy savings with cost of efficiency improvement actions, 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.

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

This tool, developed jointly by DOE, E3M, Inc., and Oak Ridge National Laboratory, is designed to evaluate the feasibility of using combined heat and power (CHP) in industrial process heating systems. The heating systems include fuel-fired 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 industry decide whether it is worthwhile to carry out further engineering studies for the project. The tool can be used to estimate payback periods and 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 raise steam in a heat recovery boiler.
- Use of the turbine exhaust gases for combustion of fuels: 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 where residual oxygen from the turbine exhaust gases is used for combustion of the fuel.

Section 4: Process Heating System Economics

Very often, industrial facility managers must convince upper management that an investment in efficiency is an effort worth undertaking. The communication of this message can often 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 Btu 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 the hearts and minds of corporate officers who have the final say over capital investments like 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, if the firm is publicly held). It is the job of these officers to create and grow the equity 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—are assets 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 largest and fastest returns.

This corporate attitude may impose (sometimes unpleasant) priorities on the facility manager: assure reliability in production, avoid unwanted surprises by sticking with familiar technology and practices, and contribute to cost control today by cutting a few corners in maintenance and upkeep. This may result in industrial decision-makers concluding that efficiency is a luxury that cannot be afforded.

Fortunately, our story does not end here. 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 in turn opens up more 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. These analyses capture 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 downtime.

One revelation that typically emerges from this exercise is that fuel costs may represent as much as 96% 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 impacts for the company.

Presenting the Finance 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. Five important factors to remember when calculating a simple payback are:

- It 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 find the best solution (for the two reasons immediately above) when choosing among several project options
- 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 = Present worth of benefits
– Present worth of costs

Another commonly used calculation for determining economic feasibility of a project is internal rate of return, 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 internal rate of return 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

Saving money, in and of itself, 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):

- **A 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—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.
- **Improved worker comfort and safety.** Process heating system optimization requires on-going 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.
- **Improved reliability and capacity utilization.** 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 does the following:

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

Section 5: 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:

- The U.S. Department of Energy Industrial Technologies Program (ITP) and its BestPractices activity, a national effort aimed at improving 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 and reports, other publications, 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 (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.

The Industrial Technologies Program and BestPractices

◆ Overview

Industrial manufacturing consumes 36% of all energy used in the United States. The Industrial Technologies Program (ITP) has initiatives to assist industry in achieving significant energy and process efficiencies. 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.

In particular, BestPractices offers several resources for process heating system energy management. These resources complement technology development programs, which address other industrial systems, such as motor, compressed air, pumping, combined heat and power, and steam, in addition to efforts by the Industrial Assessment Centers and Financing Assistance programs. Collectively, these efforts assist industry in adopting near- and long-term energy-efficient practices and technologies.

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 BestPractices assists industry to identify and realize their best energy efficiency and pollution prevention options from a system and life cycle cost perspective.

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

◆ Plant Assessments

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

Plant-wide assessments help manufacturers develop comprehensive plant strategies to increase efficiency, reduce emissions, and boost productivity. Annual competitive solicitations offer matching funds.

Small- to medium-sized manufacturers can qualify for free assessments from the university-based Industrial Assessment Centers.

◆ 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 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.

◆ Allied Partnerships

Allied Partners are manufacturers, associations, industrial service and equipment providers, utilities, and other organizations that voluntarily work with ITP. Allied Partners seek to increase energy efficiency and productivity for those industries that participate in endorsing and promoting ITP programs, products, and services.

Allied Partnerships help ITP achieve industrial energy efficiency goals by extending delivery channels through the partners' existing networks. In turn, partners realize benefits, such as achieving their own corporate, institutional, or plant goals and objectives by expanding services to customers and suppliers. Allied Partners also gain access to technical resources, such as software, technical publications, and training; and they can gain recognition as leaders in the implementation of energy-efficient technologies and practices. For more on Allied Partnerships, contact the EERE Information Center at 877-337-3463.

◆ Technical Resources

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

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, process heating, and steam. The EERE Information Center can be the first stop in finding out what's available from EERE and ITP. Contact the EERE Information Center at 877-337-3463 or www.eere.energy.gov/informationcenter.

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

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

Industrial Energy Savers Web site. Manufacturers will find a number of resources on this site to implement industrial energy efficiency projects and see immediate savings. Access this site at www.eere.energy.gov/consumerinfo/industry.

◆ Training

Training sessions in industrial systems improvements using DOE software tools are offered periodically through Allied Partners. A particularly useful training session involves the Process

Heating Assessment and Survey Tool (PHAST). See the discussion on the PHAST tool in the Software Tools section. More information on PHAST training and other training offerings can be found on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

◆ Software Tools

ITP and its partners have developed several software tools for systems improvements to help you make decisions about implementing efficient practices in your manufacturing facilities.

- **AirMaster+** is a software tool, developed by EERE BestPractices and jointly sponsored by the Compressed Air Challenge. AIRMaster+ helps end users to assess the potential for efficiency and productivity improvements in compressed air systems without bias to any particular technology, organization, or product. The software allows users to run a number of what-if scenarios to determine which energy efficiency measures have the greatest savings potential for their facility.
- **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)** helps industrial users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.
- The **Steam System Scoping Tool** is designed to help steam system energy managers and operations personnel for large industrial plants. This spreadsheet program will profile and grade steam system operations and management. This tool will help you to evaluate your steam system operations against identified best practices.
- The **Steam System Assessment Tool (SSAT)** uses a graphical model of a generic steam system for up to three steam pressure headers (high, medium, and low). You can enter data for your own plant conditions, including fuel type and cost, electricity, water costs, initial boiler efficiency, header pressures, and turbine efficiencies. The tool allows you to evaluate what-if scenarios for the following types of key improvement opportunities:
  - Boiler efficiency
  - Alternative fuels
  - Cogeneration opportunities
  - Utilizing backpressure turbines to let down steam
  - The true cost of steam
  - Boiler blowdown
  - Condensate recovery
  - Steam trap operating efficiencies
  - Heat recovery
  - Steam quality
  - Vent steam
  - Steam leaks
  - Insulation efficiency.

  The SSAT uses a simple interface to allow you to easily enter data about your steam system and about steam improvement opportunity areas. It also provides the ability to print out the results of energy, cost, and emissions savings for the opportunities that are evaluated.
- **3E-Plus Insulation Appraisal Software-** Because insulation is used in many process heating systems and almost all steam systems, restoration, replacement, and/or installation of missing insulation are common improvement opportunities. A lack of awareness regarding the energy losses and the associated costs often result in a low prioritization of restoring or properly installing insulation on system surfaces. As a result, a software program known as 3E-Plus was developed by the North American Insulation Manufacturers Association (NAIMA) to increase awareness among system operations and management personnel of the benefits of insulation and to assist these stakeholders in assessing insulation opportunities.

  3E-Plus assists the user in assessing important insulation project factors such as energy savings, installation cost, and payback period for various insulation materials and thicknesses. Users of 3E-Plus can estimate energy losses from uninsulated surfaces as well as potential savings from various insulation options.

  The program has general data for insulation costs by type and can analyze insulation cross-sections that use several different insulation types. It also accounts for labor rates and productivity by region, estimating how hard the

DOE Process Heating-Specific Resources

Software: *Process Heating Assessment Tool (PHAST):* This software tool 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, stem, or electricity, and identify the most energy-intensive equipment. You 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.

Training: *Process Heating Assessment and Survey Tool (PHAST) Specialist Qualification*—Industry professionals can earn recognition as Qualified Specialists in the use of the PHAST software tool. Individuals become qualified by taking DOE-sponsored training on the software and passing a rigorous exam.Qualifed PHAST Specialists apply the PHAST tool to accurately gather pertinent system information and provide realistic "what if" scenarios for process heating system operations.

Tip Sheets: Improvement opportunities are available for many different systems. To increase industry awareness of several fundamental improvement opportunities, the Industrial Technologies Program has developed Process Heating tip sheets through its BestPractices activity. These tip sheets provide concise descriptions of common improvement opportunities. BestPractices continues to develop and identify energy improvement programs; additional tip sheets are expected. See Appendix B for current Process Heating tip sheets and check the BestPractices Web site at www.eere.energy.gov/industry/bestpractices for the latest updates.

Technical Briefs: The Industrial Technologies Program has also developed technical briefs that provide an increased level of detail and guidance in identifying and implementing performance improvement opportunities. These technical briefs include:

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

Technical briefs can be found in Appendix C and on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

Fact Sheets: ITP partners with industry to conduct plant-wide assessment at manufacturing facilities. These energy assessments have successfully identified opportunities to improve industrial energy efficiency, productivity, and global competitiveness, and to reduce waste and emissions. The plant-wide assessments are highlighted in fact sheets, and include:

BestPractices Process Heating: Metal and Glass Manufacturers Reduce Costs by Increasing Energy Efficiency in Process Heating Systems

Fact sheets on plant-wide assessments can be found on the BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

installation process will be based on general piping characteristics. Users can quickly determine the economic feasibility of various insulation thicknesses. Since the program also allows the user to evaluate various combinations of insulation types, 3E-Plus can help the user optimize the material thicknesses within an insulation system. The present version of 3E-Plus can be downloaded from the BestPractices Web site, www.eere.energy.doe.gov/industry/bestpractices.

Although 3E-Plus is an effective tool for many applications, it is not as effective in brick, refractory, and lagging work. 3E-Plus was designed primarily for lower temperature applications, such as steam systems, largely due to the significant opportunities for insulation improvements in those systems.

◆ Newsletters

- The **Industrial Technologies Program E-Bulletin** is a monthly e-mail update that spotlights technologies, significant project developments, and program activities; new ITP and BestPractices products; training and events; Web updates; and solicitations. The *E-Bulletin* provides readers with links to source information on the ITP, BestPractices, and IAC Web sites. To subscribe, go to: www.eere.energy.gov/industry/resources/itp_ebulletin.html.
- **Energy Matters** is a bimonthly newsletter written by the Industrial Technologies Program that provides news, technical tips, and case studies. *Energy Matters* informs industrial end users of energy efficiency opportunities, technical issues, new products and services, and events related to process heating systems and other industrial utilities such as motor, steam, and compressed air systems. To subscribe, contact the EERE Information Center (877-337-3463) or subscribe online at: www.eere.energy.gov/industry/bestpractices.
- **Steaming Ahead** is a bimonthly e-mail newsletter published by the Alliance to Save Energy that describes the activities and information products of the BestPractices Steam effort. BestPractices Steam outreach and promotion is performed by the Alliance to Save Energy. *Steaming Ahead* promotes best-in-class practices and technology applications in steam system design and management. Additional information on *Steaming Ahead* can be found at: www.steamingahead.org.

Directory of Contacts

Industrial Heating Equipment Association (IHEA)

1139 Fehl Lane
Cincinnati, OH 45230
513-231-5613
www.ihea.org

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 before 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 industrial 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 energy systems is available from several resources.

National Insulation Association (NIA)

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.

North American Insulation Manufacturers Association (NAIMA)

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/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

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

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. Covers the basics and general concepts, as well as advanced applications and computer modeling.

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.

Institute of Electrical and Electronics Engineers (IEEE)
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.

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.

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.

McGraw-Hill
1221 Avenue of the Americas
New York, NY 10020
212-512-2000
www.bookstore.mcgraw-hill.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.

Prentice Hall/Pearson Education
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.

Other Publications (Guides, Manuals, and Standards)

Industrial Heating Equipment Association (IHEA)
1139 Fehl Lane
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 flow-meters 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.

Software

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

Heat Transfer Research, Inc. (HTRI)
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.

MAYA Heat Transfer Technologies
4999 St. 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.

National Insulation Association (NIA)
99 Canal Center Plaza, Suite 222
Alexandria, VA 22314
703-683-6422
703-549-4838
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 3EPlus is intended for low temperature applications and does not include data for high temperature refractories and insulation.

TechniCAL
250 Plauche Street
New Orleans, LA 70123
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.

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 would be 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 an advanced Radiation Module and a 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 would be complete vehicular systems, aerospace systems, electronic instrument panels, architectural solar analysis, and complex process heating schemes.

Periodicals

Chemical Engineering
Chemical Week Publishing
110 William Street
New York, NY 10138
212-621-4900
www.che.com

Chemical Processing
Putman Media
555 West Pierce Road, Suite 301
Itasca, IL 60143
630-467-1300
www.chemicalprocessing.com

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

Energy Matters Newsletter
U.S. Department of Energy
Industrial Technologies Program
Room 5-F, MS EE-2F
1000 Independence Avenue, SW
Washington, DC 20585
877-337-3463
www.eere.energy.gov/industry/bestpractices

Energy User News
BNP Media
1428-30 Midland Avenue #8
Bronxville, NY 10708
914-776-9241
www.energyusernews.com

Industrial Heating: The International Journal of Thermal Technology
BNP Media
Manor Oak One
1910 Cochran Road, Suite 450
Pittsburgh, PA 15220
412-531-3370
www.industrialheating.com

Industrial Maintenance & Plant Operation
Reed Business Information
100 Enterprse Drive, Suite 600, Box 912
Rockaway, NJ 07866
973-920-7590
www.reedbusiness.com

Process Heating

BNP Media
Manor Oak One
1810 Cochran Road, Suite 450
Pittsburgh, PA 15220
412-531-3370
www.industrialheating.com

Reports and Technical Papers

GTI

1700 South Mount Prospect Road
Des Plaines, IL 60018
847-768-0500
www.gastechnology.org

GTI offers a range of technical reports, journals, brochures, publications, maps, and software products that report on past and current GTI research activities and provide information and tools for various energy markets. Many of these reports address process heating equipment.

U.S. Department of Energy

Room 5-F, MS EE-2F
1000 Independence Avenue
Washington, DC 20585
877-337-3463
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, www.eere.energy.gov/industry.

Training Courses and Technical Services

Association of Energy Engineers (AEE)

4025 Pleasantdale Road, Suite 420
Atlanta, GA 30340
www.aeecenter.com

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

Center for Professional Advancement (CFPA)

P.O. 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.

Industrial Heating Equipment Association (IHEA)

1139 Fehl Lane
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
Carnegie Office Park
600 North Bell Avenue, Building 2, Suite 2708
Carnegie, PA 15106
412-279-9298
www.pgsenergy.com

Area covered: Managing industrial energy procurement.

The Minerals, Metals, & Materials Society (TMS)
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: Tip Sheets**
This appendix contains a series of process heating system tip sheets. Developed by the U.S. Department of Energy, 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. The technical briefs are developed by the U.S. Department of Energy and 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 Comment**
This appendix contains a form that provides a vehicle for submitting comments for improving the Sourcebook.

Appendix A: Glossary of Terms

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 ft3 of air per pound of fuel.

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

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). Can cause difficulties with heat transfer surfaces, refractories, and burner ports.

Atmosphere (atm)—Refers to a mixture of gases (usually within a furnace). Also a unit of pressure equal to 14.7 lb/in2 or 760 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/in2 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 kcal or 0.000293 kWh).

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—Gas, composed primarily of hydrogen and methane, saved for use as a fuel when coke is made from coal in by-product 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.

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.

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

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 ft^3 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.

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 in. x 4.5 in. x 2.5 in. 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 CO_2, H_2O and N_2, but may also include O_2, CO, 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, 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 psi, 760 mm 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.

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

Warm up time—The time required to bring a furnace up to operating temperature.

Appendix B: Tip Sheets

Industrial Technologies Program has developed the following tip sheets through its BestPractices activities.

Currently Available

1. Preheated Combustion Air
2. Check Burner Air to Fuel Ratios

Additional Tip Sheets are under development and will be available on the 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 process temperatures 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. 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 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)

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.

◆ Example

A furnace operates at 1600°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 $5 per MMBtu, annual energy cost is $800,000. Use of preheated air at 800° F will result in 22% fuel savings, or $176,000 annually. The preheated air system installation is estimated to cost $200,000 to $250,000, with a payback period of 13.6 months to 17 months, or an annual return on investment (ROI) of 88% to 70%.

◆ Suggested Actions ◆

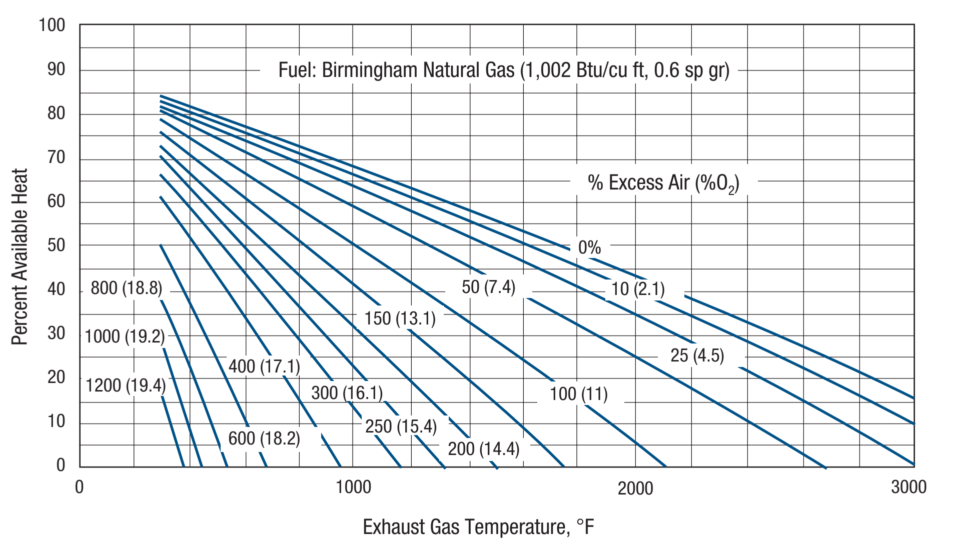
- Using current or projected energy costs, estimate preheated air savings with this example or the Process Heating Assessment and Survey Tool (PHAST) available from the Department of Energy's Office of Industrial Technologies.
- Contact furnace or combustion system suppliers to calculate payback period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

Check Burner Air to Fuel Ratios

Periodic checking and resetting of air-fuel ratios 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 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 air supply is significantly higher or lower than the theoretically required air.

Air-gas ratios can be determined by flow metering 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.

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).

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% 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

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.

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%

◆ 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.

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

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.

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
Y_2O_3	Yttria (Yttrium Oxide)
W	Tungsten
Zr	Zirconium

◆ 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 1,100-1,600°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 600-1000°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.

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) 1200°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 1600°F (870°C)	Subject to embrittlement when exposed to the 600-1100°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 1,850-1900°F (1010-1038°C) range. Above 1900°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 (1100°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 2200°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 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 CA®	N06025	2.4633	25	63	--	0.2	2Al 0.1Y 0.08Zr 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

11 Registered trade name of Special Metals, Inc.
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16 Registered trade name of Duraloy Technologies, Inc.
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 (NOx) 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 heating processes.

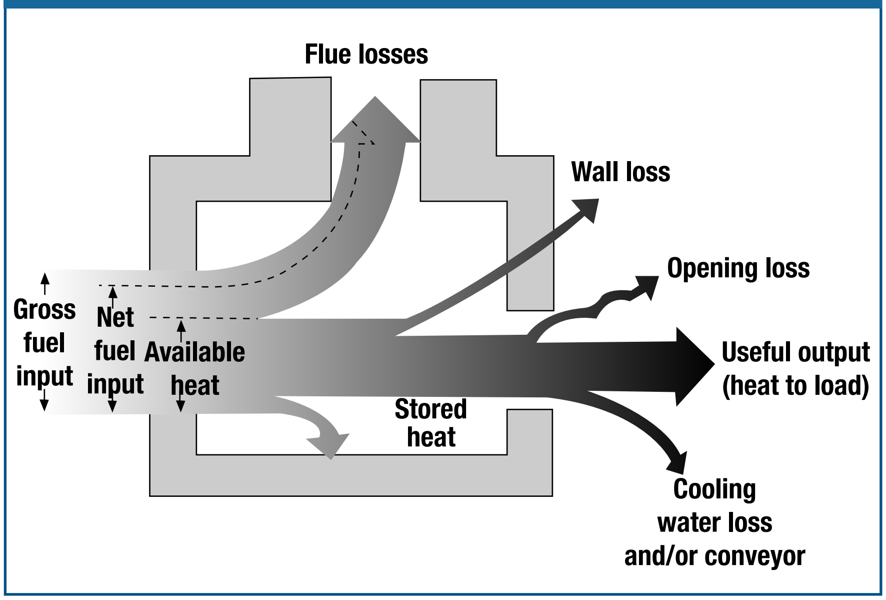


Figure 2. Wall loss.

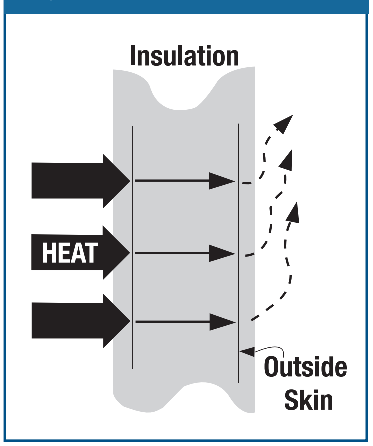
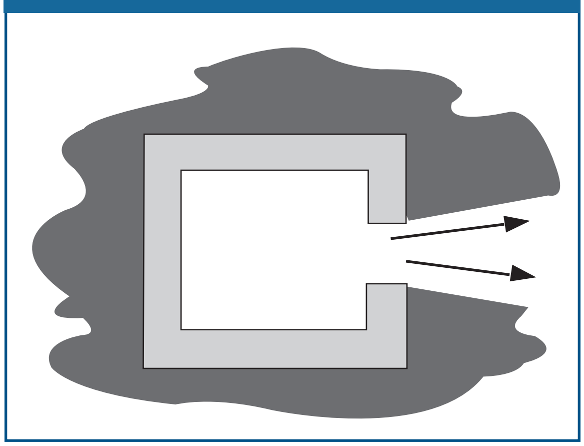
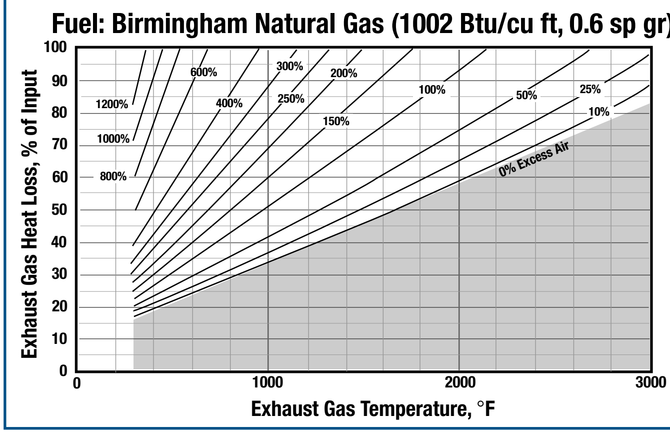


Figure 3. Radiation loss from heated to colder surface.



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.

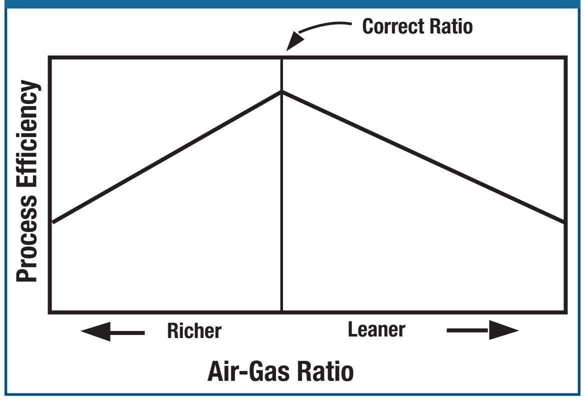
Figure 4. Exhaust gas heat losses vs. exhaust gas temperature and air-gas ratio.



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.

Figure 5. Effect of off-ratio operation on furnace efficiency.



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.

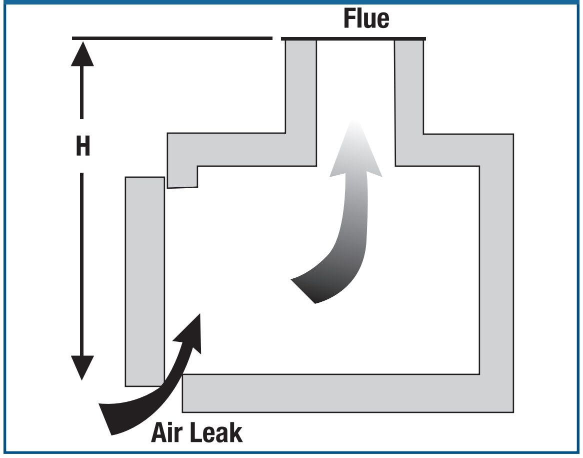
Fuel-air ratios. For every fuel, there is a chemically correct, or stoichiometric, amount of air required to burn it. One cubic foot of natural gas, for example, requires about 10 cubic feet of combustion air. Stoichiometric, or on-ratio combustion will produce the highest flame temperatures and thermal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

Figure 6. Air infiltration from furnace opening.

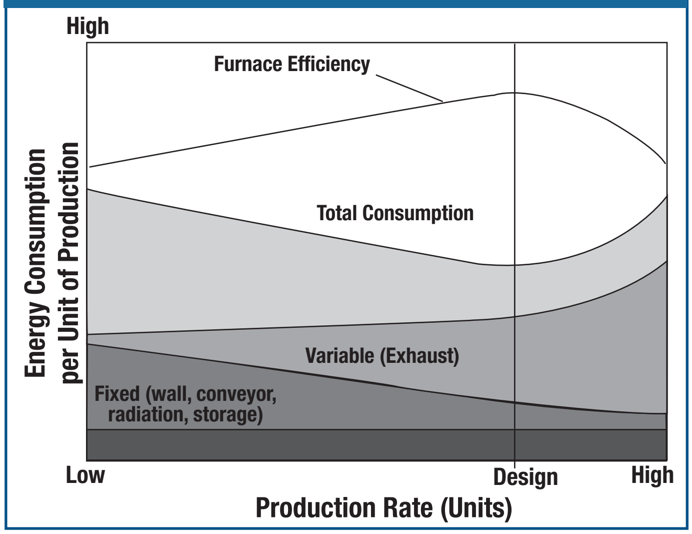


Air infiltration. Excess air does not necessarily enter the furnace as part of the combustion air supply. It can also infiltrate from the surrounding room if there is a negative pressure in the furnace. Because of the draft effect of hot furnace stacks, negative pressures are fairly common, and cold 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]

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.

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



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.

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

1 The tip sheet on Air Infiltration was in development at the time of this publication. The tip sheet will be available online on the ITP BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

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.

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 ºF) 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 on Furnace Heat Transfer 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 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.

2 The tip sheet on Furnace Heat Transfer was in development at the time of this publication. The tip sheet will be available online on the ITP BestPractices Web site at www.eere.energy.gov/industry/bestpractices.

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.

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.

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

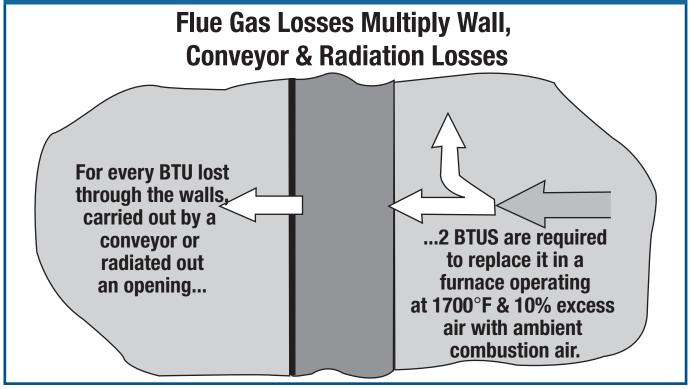


Figure 9. Direct preheating of incoming work.

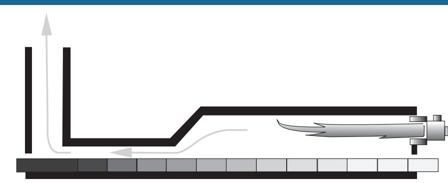
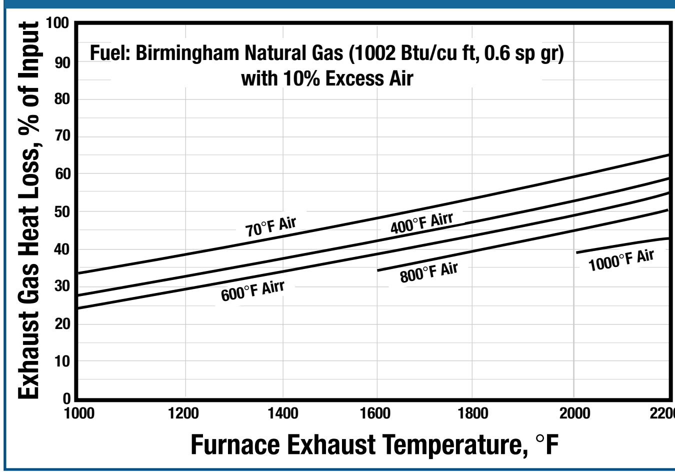


Figure 10. Exhaust gas losses with ambient and preheated air.



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.

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.

Figure 11. Recuperator system for preheating combustion air losses.

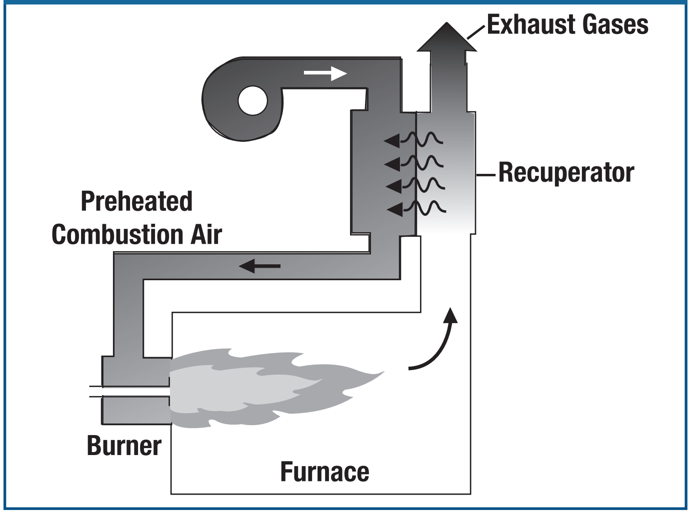
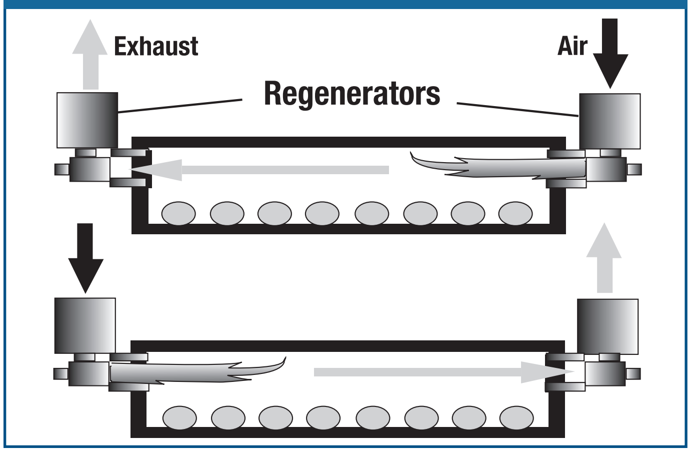


Figure 12. Regenerator system for storing thermal energy.



The ITP tip sheet on 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.

◆ 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.

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.

◆ Additional Process Heating Resources

For additional information on topices referenced in this tech brief, please see tip sheets and case studies on the ITP BestPractices Web site at http://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.

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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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