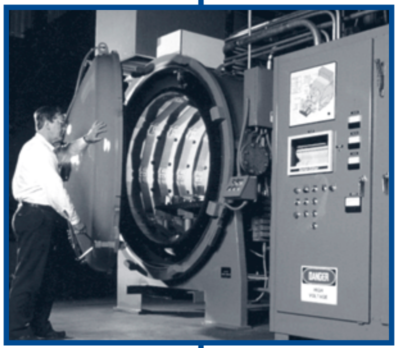
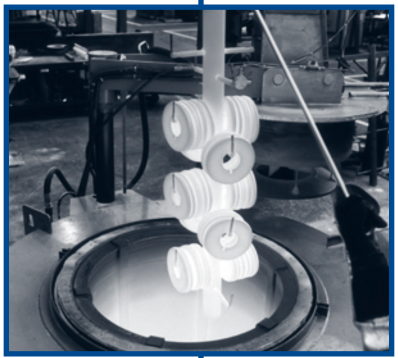
A BestPractices
Process Heating
Technical Brief





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

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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.

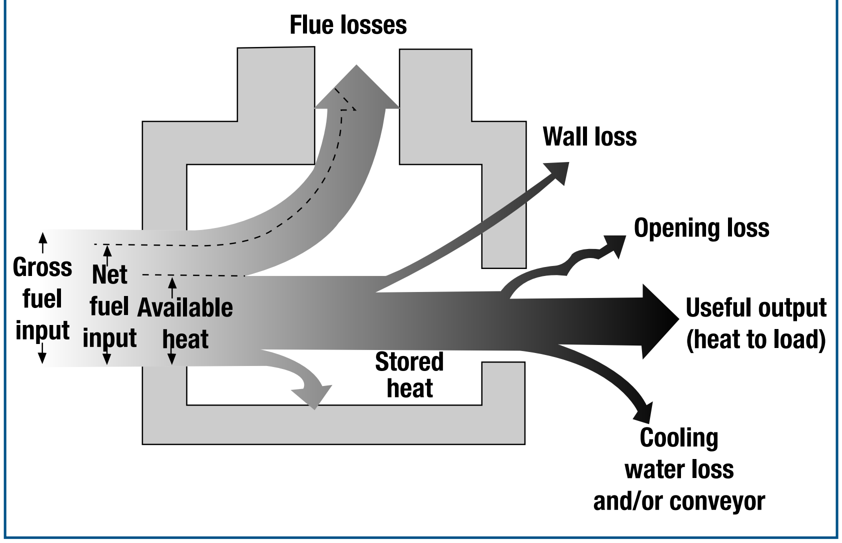
◆ What Determines Waste-Gas Losses?

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.

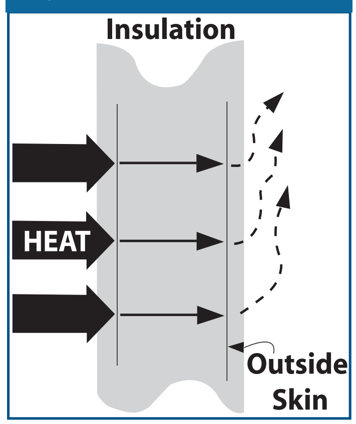
In addition, because the furnace cannot run production until it has reached the proper operating temperature, the process of storing heat in it causes lost production time. Fuel is consumed with no useful output.

Figure 1. Heat losses in industrial heating processes.



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.

Figure 2. Wall loss.



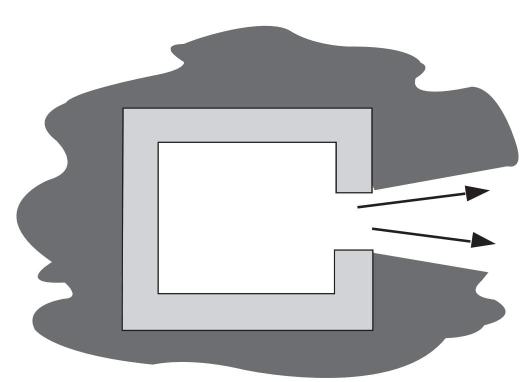
Material handling losses. Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts or product hangers that enter the heating chamber cold and leave it at higher temperatures drain energy from the combustion gases. In car 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.

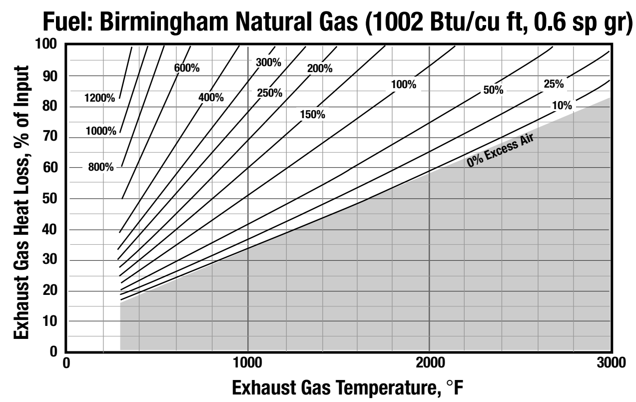
Figure 3. Radiation loss from heated to colder surface.



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.

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.

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



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

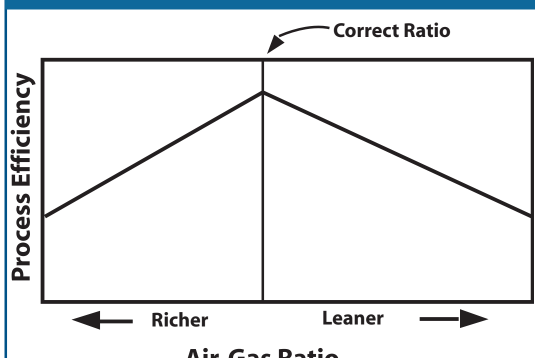
In effect, the heat stream has hit bottom. If, for example, a furnace heats products to 1,500°F, the combustion gases cannot be cooled below this temperature without using design or equipment that can recover heat from the combustion gases. Once the combustion products reach the same temperature as the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

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

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

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

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



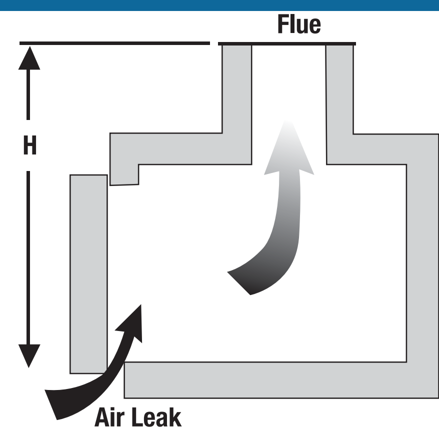
However, combustion systems can be operated at other ratios. Sometimes, this is done deliberately to obtain certain operating benefits, but often, it happens simply because the burner system is out of adjustment. The ratio, as shown in Figure 5, can go either rich (excess fuel or insufficient air) or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

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

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

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

Figure 6. Air infiltration from furnace opening.



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.

Furnace scheduling and loading

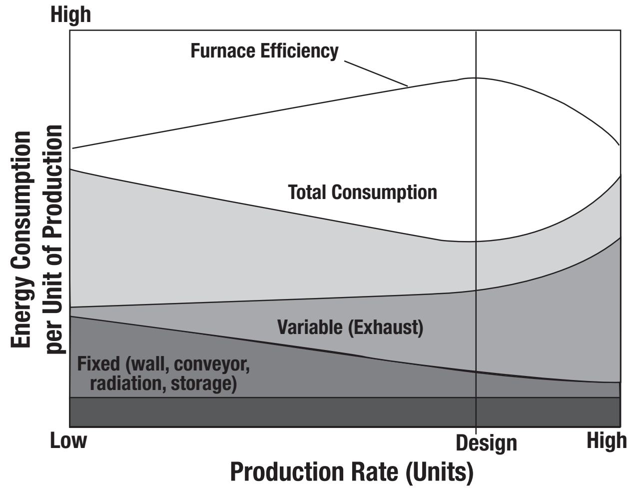
A commonly overlooked factor in energy efficiency is scheduling and loading of the furnace. “Loading” refers to the amount of material processed through the furnace or oven in a given period of time. It can have a significant effect on the furnace's energy consumption when measured as energy used per 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.

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.

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

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



Steps for increasing energy efficiency through reduction in exhaust gas heat losses. The exhaust gas heat losses can be calculated by the equation:

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

Where:

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

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

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

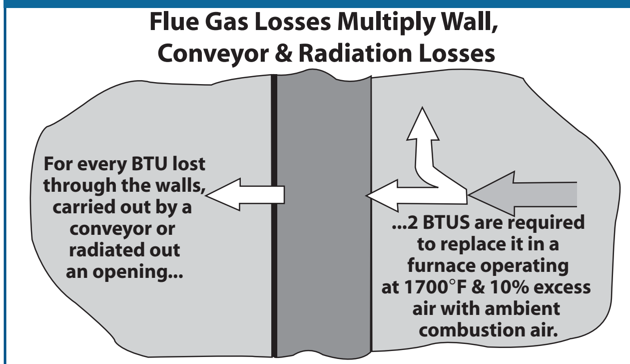
Minimize exhaust gas volumes. Avoiding overloading and optimizing heat transfer are two ways to lower waste gas flows, but there are others.

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.

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" will provide a useful chart for figuring exhaust gas losses and shows how to figure the efficiency improvements that can come from controlling ratios more closely.[3]

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

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



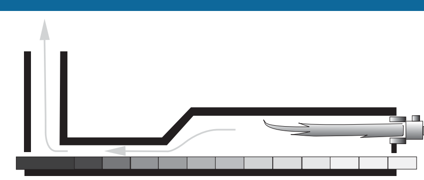
Use of oxygen enriched combustion air. Ambient air contains approximately 21% oxygen with nitrogen and other inert gases as balance. The total volume of exhaust gases could be reduced by increasing the oxygen content of combustion air, either by mixing in ambient air or by using 100% oxygen. Reducing 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.

Figure 9. Direct preheating of incoming work.



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

2. **Recuperators.** A recuperator (Figure 11) is a gas-to-gas heat exchanger placed on the stack of the furnace. There are numerous designs, but all rely on tubes or plates to transfer heat from the outgoing exhaust

3 The tip sheet on Burner Fuel-Air Ratios 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.

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.

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

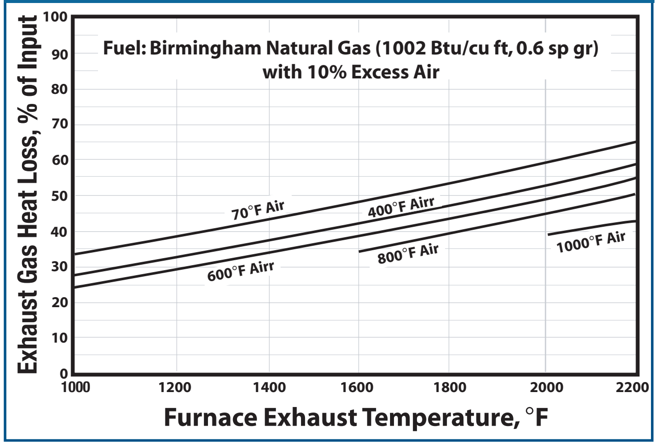


Figure 11. Recuperator system for preheating combustion air losses.

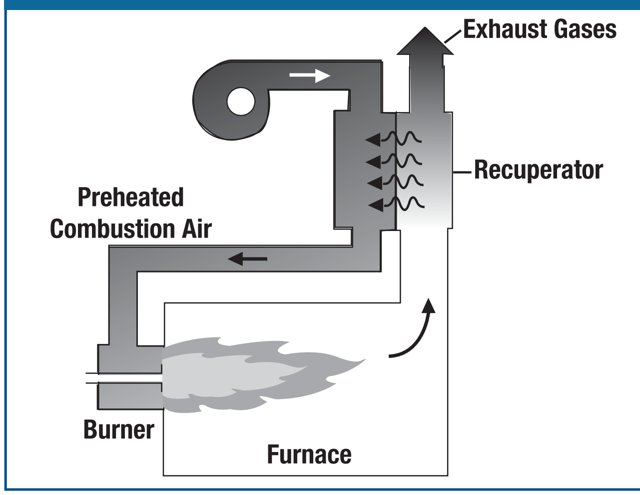
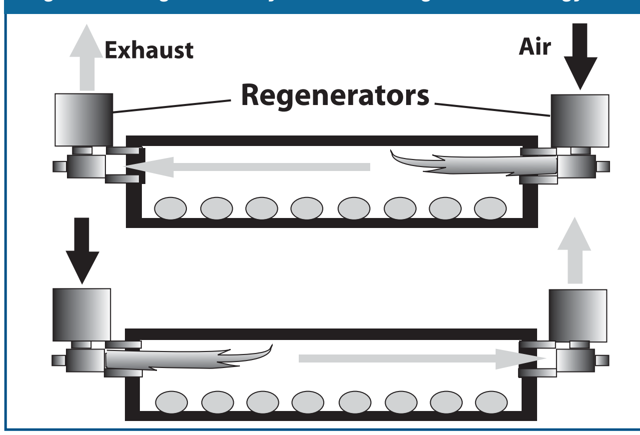


Figure 12. Regenerator system for storing thermal energy.



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

The ITP tip sheet on Preheated Combustion Air will offer guidance on how to estimate the efficiency and economic benefits of preheating combustion air.[4]

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.

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.

◆ Summary

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

◆ Additional Process Heating Resources

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

◆ Acknowledgements

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[4] The tip sheet on Preheated Combustion Air 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.

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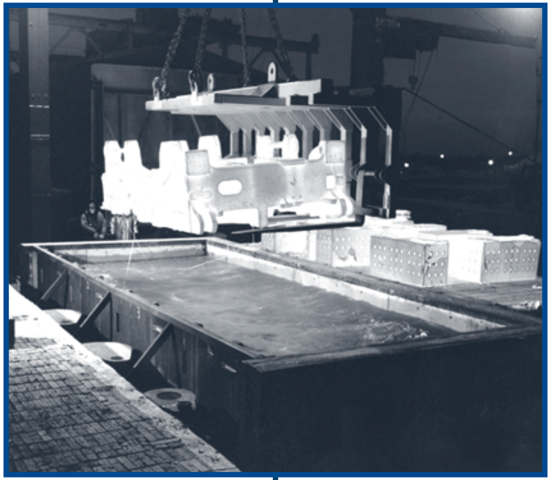
Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.



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