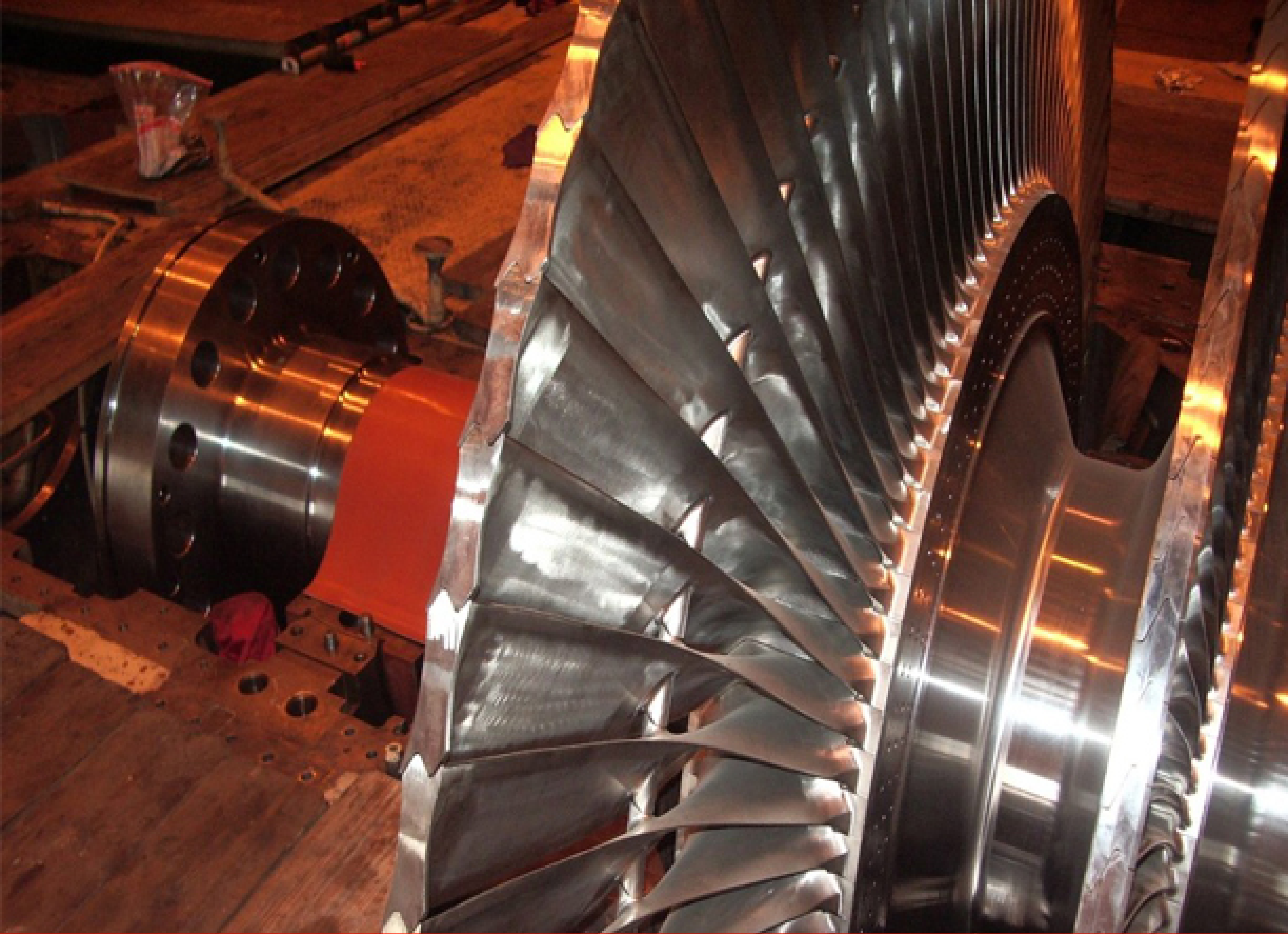

Combustion Engineering

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Bunsen Burner and LO-NOx Burner

Bunsen burner

Bunsen Burner

A Bunsen burner with needle valve. The hose barb for the gas tube is facing left and the needle valve for gas flow adjustment is on the opposite side. The air inlet on this particular model is adjusted by rotating the barrel, thus opening or closing the vertical baffles at the base.

Uses	Heating Sterilization Combustion
Related items	Hot plate Heating mantle Meker-Fisher burner

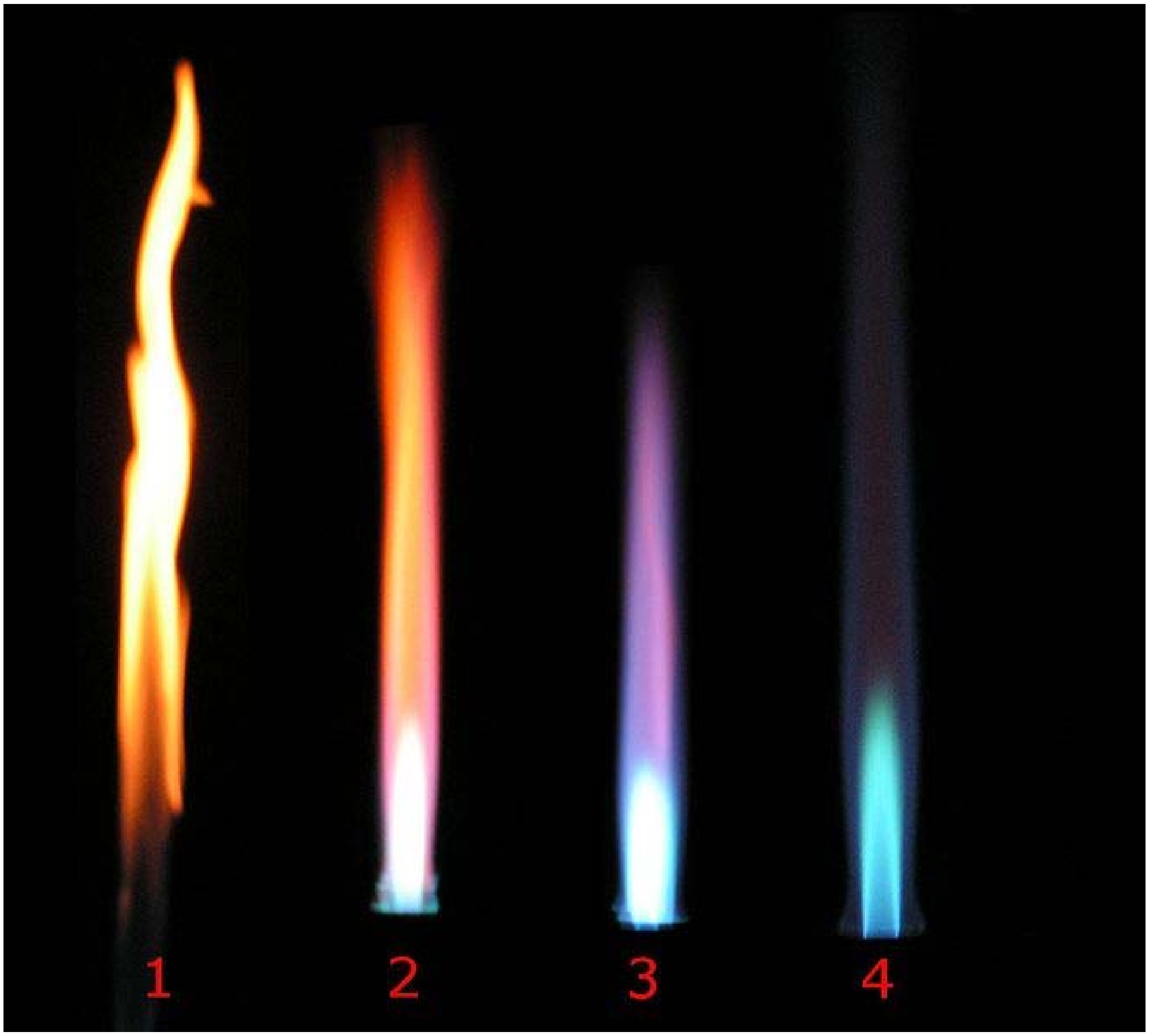
A **Bunsen burner**, named after Robert Bunsen, is a common piece of laboratory equipment that produces a single open gas flame, which is used for heating, sterilization, and combustion.

History

When the University of Heidelberg hired Robert Bunsen in 1852, the authorities promised to build him a new laboratory building. Heidelberg had just begun to install coal-gas street lighting, so the new laboratory building was also supplied with gas. The laboratory required *heating* from the gas as well as illumination. For heating, it was desirable to maximize the temperature and minimize the luminosity. Previous laboratory lamps left much to be desired regarding economy and simplicity, as well as the quality of the flame for a burner lamp.

While his building was still under construction late in 1854, Bunsen suggested certain design principles to the university's mechanic, Peter Desaga, and asked him to construct a prototype. (Similar principles had been used in an earlier burner design by Michael Faraday as well as in a device patented in 1856 by the gas engineer R W Elsner.) The Bunsen/Desaga design succeeded in generating a hot, sootless, non-luminous flame by mixing the gas with air in a controlled fashion before combustion. Desaga created slits for air at the bottom of the first cylindrical burner, the flame igniting at the top. By the time the building opened early in 1855, Desaga had made fifty of the burners for Bunsen's students. Bunsen published a description two years later, and many of his colleagues soon adopted the design. Bunsen burners are now used in laboratories all around the world.

Operation



Different flame types of Bunsen burner depending on flow through the throat holes (holes on the side of the Bunsen burner -- not to be confused with the needle valve for gas flow adjustment).1) air hole closed (Safety flame used for when not in use or lighting).2) air hole slightly open.3) air hole half open.4) air hole almost fully open (this is the roaring blue flame).

The device in use today safely burns a continuous stream of a flammable gas such as natural gas (which is principally methane) or a liquefied petroleum gas such as propane, butane, or a mixture of both.

The hose barb is connected to a gas nozzle on the laboratory bench with rubber tubing. Most laboratory benches are equipped with multiple gas nozzles connected to a central gas source, as well as vacuum, nitrogen, and steam nozzles. The gas then flows up through the base through a small hole at the bottom of the barrel and is directed upward. There are open slots in the side of the tube bottom to admit air into the stream via the

Venturi effect, and the gas burns at the top of the tube once ignited by a flame or spark. The most common methods of lighting the burner are using a match or a spark lighter.

The amount of air mixed with the gas stream affects the completeness of the combustion reaction. Less air yields an incomplete and thus cooler reaction, while a gas stream well mixed with air provides oxygen in an equimolar amount and thus a complete and hotter reaction. The air flow can be controlled by opening or closing the slot openings at the base of the barrel, similar in function to the choke in a carburetor.

If the collar at the bottom of the tube is adjusted so more air can mix with the gas before combustion, the flame will burn hotter, appearing blue as a result. If the holes are closed, the gas will only mix with ambient air at the point of combustion, that is, only after it has exited the tube at the top. This reduced mixing produces an incomplete reaction, producing a cooler but brighter yellow which is often called the "safety flame" or "luminous flame". The yellow flame is luminous due to small soot particles in the flame which are heated to incandescence. The yellow flame is considered "dirty" because it leaves a layer of carbon on whatever it is heating. When the burner is regulated to produce a hot, blue flame it can be nearly invisible against some backgrounds. The hottest part of the flame is the tip of the inner flame, while the coolest is the whole inner flame. Increasing the amount of fuel gas flow through the tube by opening the needle valve will increase the size of the flame. However, unless the airflow is adjusted as well, the flame temperature will decrease because an increased amount of gas is now mixed with the same amount of air, starving the flame of oxygen.

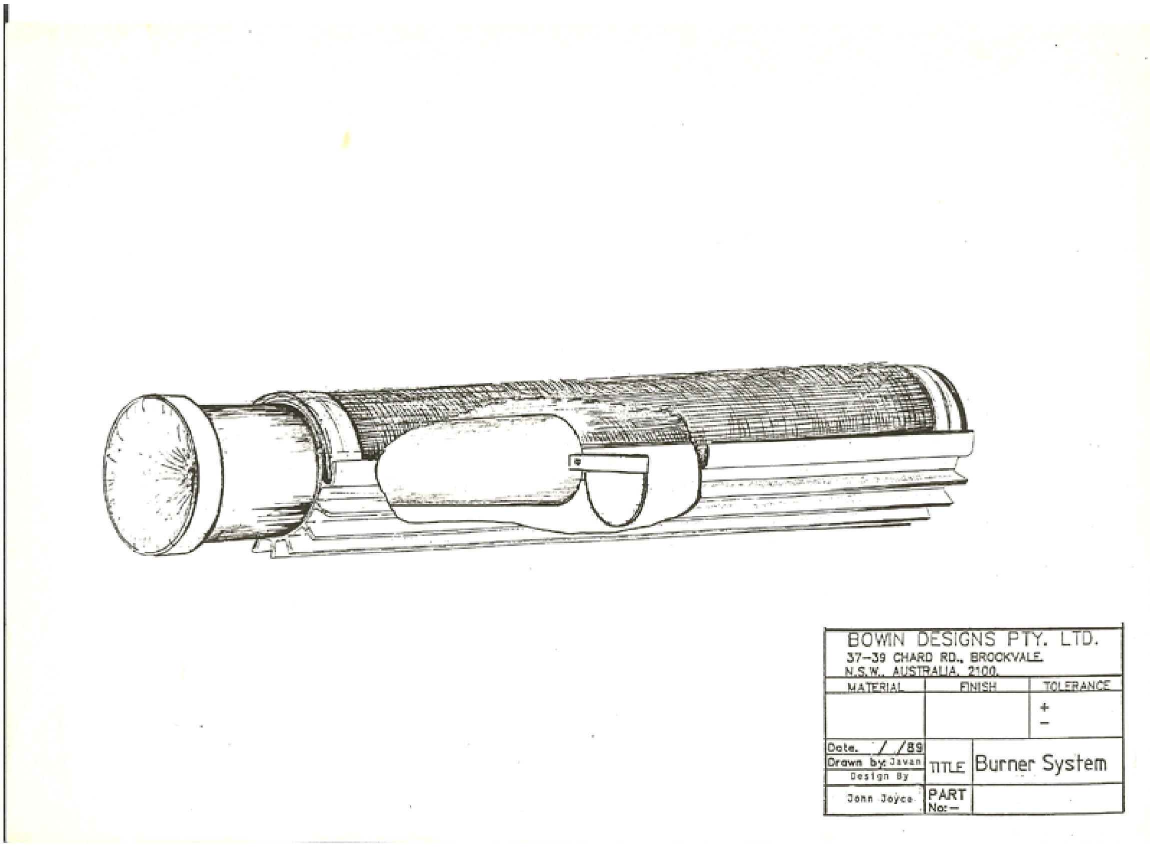
The burner will often be placed on a suitable heatproof mat to protect the laboratory bench surface.

Variants

Other burners based on the same principle exist. The most important alternatives to Bunsen burner are:

- Teclu burner; the lower part of its tube is conical, with a round screw nut below its base. The gap, set by the distance between the nut and the end of the tube, regulates the influx of the air in a way similar to the open slots of the Bunsen burner. The Teclu burner provides better mixing of air and fuel and can achieve higher flame temperatures than Bunsen burner.
- Meker burner; the lower part of its tube has more openings with larger total cross-section, admitting more air and facilitating better mixing of air and gas. The tube is wider and its top is covered with a wire grid. The grid separates the flame into an array of smaller flames with a common external envelope, and also prevents flashback to the bottom of the tube, which is a risk at high air-to-fuel ratios and limits the maximum rate of air intake in a conventional Bunsen burner. Flame temperatures of up to 1,100–1,200 °C (2,012–2,192 °F) are achievable. The flame also burns without noise, unlike the Bunsen or Teclu burners.

LO-NOx burner



One of John Joyce's early sketches of the Low NOx burner

A **LO NOx burner** is a type of burner that is typically used in utility boilers to produce steam and electricity.

Background

John Joyce the inventor of the LO-NOx burner at Australian Gas Association Conference in the early 1990s

The first discovery

Around 1986 John Joyce (of Bowin Cars fame), an influential Australian inventor, first learned about oxides of nitrogen (NO_x) and their role in the production of smog and acid rain. His first introduction to the complexities of the subject was brought about by the work of Fred Barnes and Dr John Bromley from the state Energy Commission of Western Australia.

The vast majority of the research and development stretching back over twenty years was about large scale industrial burners and complex mechanisms which, in the end, did not produce what one would consider low NO_x (2 ng/J or ~ 4 ppm at 0% O_2 on dry basis).

In fact at that time, 15 ng/J NO_2 appears to have been considered low NO_2. The one clear message that did flow through all the mass of information he studied, was the effect of temperature on the formation of NO_x.

Need is the "Mother of Invention"

In the late 1980s, Health and Environment Authorities in Australia raised concerns about the indoor air quality and the extent that particularly older style unflued gas heaters were contributing to higher than acceptable levels of nitrogen dioxide (NO_2). Consequently in 1989 the New South Wales Department of School Education initiated an extensive investigation of nitrogen dioxide in schools throughout New South Wales. As an interim measure the Health Authorities advised that a level of 0.3 ppm NO_2 should become the upper limit for classrooms. The Australian Gas Association in turn reduced the indoor emission rate of NO_2 for unflued gas heaters from 15 to 5 ng/J and this remains the current limit. The New South Wales government, through the Public Works Department, also re-evaluated alternative methods of heating classrooms, to ensure a safe and healthy environment for students.

It was in this context, that John Joyce's company Bowin Technology embarked on a major research & development program aimed at minimising nitrogen dioxide emissions from unflued gas heaters. Bowin Technology set itself the task of solving the emission problem at its source: the gas burner. This was despite a generally long held belief by gas experts, that commercially warranted gas burner improvements could not deliver drastic nitrogen oxides (NO_x) reductions.

In 1989, an immediate call to reduce the indoor nitrogen dioxide (NO_2) level, was triggered by widely publicised articles and media coverage in New South Wales, highlighting the effect this chemical has on respiratory sensitive people, such as asthmatics and those with bronchial problems.

In the heat of the indoor air quality debate various State institutions in Australia were advised to switch to flued gas heaters and electric heating.

New South Wales in contrast, through combined action by Australian Gas Light Company, Health Authorities and the New South Wales Public Works Department, formulated initial indoor air quality guidelines. These guidelines formed the basis for Australian Gas Appliance Code restrictions for nitrogen dioxide NO_2emissions from unflued heaters, now adopted Australia wide.

John Joyce became aware that no other overseas regulatory body made a distinction between NO and NO_2 in their environmental guidelines or codes. Furthermore it appeared that total nitrogen oxides level requirements were in place irrespective of whether emissions were flued or not.

Consequently John Joyce learned that a 'harmless' part of NO_x emissions nitric oxide (NO), in the presence of hydrocarbons (such as household aerosol propellants, possible gas leaks and ingress of vehicle exhaust fume), converts to NO_2. This was found to be the case in the New South Wales school investigation. In a scientific sense it had become practice to calculate both NO + NO_2, when measuring oxides of nitrogen levels in emissions. Hence the now commonly used reference to "total NO_x".

Greenhouse gas and photochemical smog

Natural gas by composition has a distinct advantage over other fossil fuels in terms of carbon dioxide, particulate and sulfur dioxides produced when converting to useful energy. In the early 1990s numerous countries were in the process of substituting oil and coal with natural gas for their energy and electric power needs.

To maintain this advantage as an "environmentally friendly" fuel, Australian gas utilities are effectively reducing gas losses (methane emissions) in their deliveries, and impose strict codes on appliance manufacturers and installers against gas leakage.

Nevertheless environmental experts see the production of oxides of nitrogen as a major menace in the formation of greenhouse gases and photochemical smog. The interaction of NOx with hydrocarbons from vehicle exhausts and sunlight, can also form low level ozone. In the stratosphere (some 25 km up). Ozone is helpful by absorbing the fiercer part of the ultraviolet radiation of the sun, but at ground level it damages materials and vegetation. It irritates throat, lungs and eyes, and strenuous exercise or work can become painful. Furthermore, the effectiveness of nitrous oxide as a greenhouse gas is magnified by its longer life than carbon dioxide, methane and CFC's.

In essence the rate at which low level ozone is formed is determined by hydrocarbons, whilst the availability of oxides of nitrogen influences the amount it produces. At this point the environmental debate takes a surprising turn as individual industries tend to blame each other's emission as a probable cause.

Best Available Control Technology (BACT)

It is well established that conventional "blue flame" or bunsen gas burners produce oxides of nitrogen at levels of 30-50 nanograms per joule and are as such not considered to have potential for NOx reduction. Surface combustion burners or radiant tile burners in comparison produce nitrogen oxides' levels 60-70% less. Therefore John Joyce's research into low NO_x burners revolved primarily around surface combustion techniques. Another issue was the effect combustion temperatures have on the formation of NO_x.

John Joyce's task became even more challenging when he decided not to direct his development towards radiant type surface combustion tiles. The use of radiant heating for most institutional purposes (other than spot heating) is considered impractical as is too hot close to the heater, while the loss of radiant heat over a distance to be reached is quite dramatic.

Investigations into numerous developments of other types of "low NOx" burners showed that so far such burners were either too complex in design or operation, too expensive or unsuitable. John Joyce's plan was to use high temperature steel mesh, and went on to produce scores of prototype burners until one showed "potential".

The scientific innovative nature of John Joyce's LO-NO_x technologies are confirmed by full patent protection in Australia, United States, United Kingdom, Japan, Italy and France.

In 1993 John Joyce received an Australian Design Award and Powerhouse Museum Selection status for his "SLE" heater range, which incorporate LO-NO_x burners.

The Australian Academy of Design selected the SLE unflued gas heater range to be featured in the Design Showcase during the "Innovation by Design" National Conference in October 1994

In the United States, John Joyce's LO-NO_x water heater burners have successfully undergone a series of exhaustive tests to prove that these particular burners do not act as an ignition source in the presence of flammable vapours, resulting from accidental fuel spillage. They have also been extensive tests carried out to verify its reduction of NO_2.

Energy efficiencies

More tangible cost savings are defined when comparing the energy efficiencies of gas heaters with low NO_x emissions with conventional flued types. Gas heaters with emission problems are flued and inherently lose substantial energies in the form of hot flue gases to the atmosphere. In addition, the choice of placement of flued heaters is greatly impaired due to flue installation restrictions.

In contrast, dedicated low emission gas heaters do not require a flue system. Furthermore, with the introduction of oxygen depletion sensors and thermostatic controls, they do not place critical reliance on ventilation as previously was the case. These heaters can be positioned more conveniently and centralised to affect optimum warm air distribution. By definition unflued low NO_x gas heaters are 100% efficient as all heat energy released from the flame is converted to useful heat.

Applications of technology

- Gas-fired unflued gas heaters
- Gas-fired flued gas heaters
- Gas-fired storage water heaters

Chapter 2

Incineration

The Spittelau incineration plant in Vienna, designed by Friedensreich Hundertwasser.

SYSAV incineration plant in Malmö, Sweden capable of handling 25 metric tons (28 short tons) per hour household waste. To the left of the main stack, a new identical oven line is under construction (March 2007).

Incineration is a waste treatment process that involves the combustion of organic substances contained in waste materials. Incineration and other high temperature waste treatment systems are described as "thermal treatment". Incineration of waste materials converts the waste into ash, flue gas, and heat. The ash is mostly formed by the inorganic constituents of the waste, and may take the form of solid lumps or particulates carried by the flue gas. The flue gases must be cleaned of gaseous and particulate pollutants before they are dispersed into the atmosphere. In some cases, the heat generated by incineration can be used to generate electric power.

Incineration with energy recovery is one of several waste-to-energy (WtE) technologies such as gasification, Plasma arc gasification, pyrolysis and anaerobic digestion. Incineration may also be implemented without energy and materials recovery.

In several countries, there are still concerns from experts and local communities about the environmental impact of incinerators.

In some countries, incinerators built just a few decades ago often did not include a materials separation to remove hazardous, bulky or recyclable materials before combustion. These facilities tended to risk the health of the plant workers and the local environment due to inadequate levels of gas cleaning and combustion process control. Most of these facilities did not generate electricity.

Incinerators reduce the solid mass of the original waste by 80–85% and the volume (already compressed somewhat in garbage trucks) by 95-96 %, depending on composition and degree of recovery of materials such as metals from the ash for recycling. This means that while incineration does not completely replace landfilling, it significantly reduces the necessary volume for disposal. Garbage trucks often reduce the volume of waste in a built-in compressor before delivery to the incinerator. Alternatively, at landfills, the volume of the uncompressed garbage can be reduced by approximately 70% by using a stationary steel compressor, albeit with a significant energy cost. In many countries, simpler waste compaction is a common practice for compaction at landfills.

Incineration has particularly strong benefits for the treatment of certain waste types in niche areas such as clinical wastes and certain hazardous wastes where pathogens and toxins can be destroyed by high temperatures. Examples include chemical multi-product plants with diverse toxic or very toxic wastewater streams, which cannot be routed to a conventional wastewater treatment plant.

Waste combustion is particularly popular in countries such as Japan where land is a scarce resource. Denmark and Sweden have been leaders in using the energy generated from incineration for more than a century, in localised combined heat and power facilities supporting district heating schemes. In 2005, waste incineration produced 4.8 % of the electricity consumption and 13.7 % of the total domestic heat consumption in Denmark. A number of other European countries rely heavily on incineration for handling municipal waste, in particular Luxembourg, the Netherlands, Germany and France.

History

The first incinerators for waste disposal were built in Nottingham by Manlove, Alliott & Co. Ltd. in 1874 to a design patented by Albert Fryer. They were originally known as destructors.

Technology

An incinerator is a furnace for burning waste. Modern incinerators include pollution mitigation equipment such as flue gas cleaning. There are various types of incinerator plant design: moving grate, fixed grate, rotary-kiln, and fluidised bed.

Burn pile

The burn pile, or burn pit is one of the simplest and earliest forms of waste disposal, essentially consisting of a mound of combustible materials piled on bare ground and set on fire. Indiscriminate piles of household waste are strongly discouraged and may be illegal in urban areas, but are permitted in certain rural situations such as clearing forested land for farming, where the stumps are uprooted and burned. Rural burn piles of organic yard waste are also sometimes permitted, though not asphalt shingles, plastics, or other petroleum products.

Burn piles can and have spread uncontrolled fires, for example if wind blows burning material off the pile into surrounding combustible grasses or onto buildings. As interior structures of the pile are consumed, the pile can shift and collapse, spreading the burn area. Even in a situation of no wind, small lightweight ignited embers can lift off the pile via convection, and waft through the air into grasses or onto buildings, igniting them.

Burn barrel

The burn barrel is a somewhat more controlled form of private waste incineration, containing the burning material inside a metal barrel, with a metal grating over the exhaust. The barrel prevents the spread of burning material in windy conditions, and as the combustibles are reduced they can only settle down into the barrel. The exhaust grating helps to prevent the spread of burning embers. Typically steel 55-gallon drums are used as burn barrels, with air vent holes cut or drilled around the base for air intake. Over time the very high heat of incineration causes the metal to oxidize and rust, and eventually the barrel itself is consumed by the heat and must be replaced.

Private burning of dry cellulosic/paper products is generally clean-burning, producing no visible smoke, but the large amount of plastics in household waste can cause private burning to create a public nuisance and health hazard, generating acrid odors and fumes that make eyes burn and water. The temperatures in a burn barrel are not regulated, and usually do not reach high enough or for enough time to completely break down chemicals such as dioxin in plastics and other waste chemicals. Therefore plastics and other petroleum products must be separated and sent to commercial waste disposal facilities.

In The United States, private rural incineration is typically permitted so long as it is not a nuisance to others, does not pose a risk of fire such as in dry conditions, and the fire is clean-burning, producing no visible smoke. However, many states, such as New York, Minnesota, and Wisconsin, have laws against private burn barrels due to EPA findings that one household burning their own waste can release more dioxins and furans annually than a modern incinerator processing 1,000 tons per day. People intending to burn waste may be required to contact a state agency in advance to check current fire risk and conditions, and to alert officials of the controlled fire that will occur.

Moving grate

Control room of a typical moving grate incinerator overseeing two boiler lines

The typical incineration plant for municipal solid waste is a moving grate incinerator. The moving grate enables the movement of waste through the combustion chamber to be optimised to allow a more efficient and complete combustion. A single moving grate boiler can handle up to 35 metric tons (39 short tons) of waste per hour, and can operate 8,000 hours per year with only one scheduled stop for inspection and maintenance of about one month's duration. Moving grate incinerators are sometimes referred to as Municipal Solid Waste Incinerators (MSWIs).

The waste is introduced by a waste crane through the "throat" at one end of the grate, from where it moves down over the descending grate to the ash pit in the other end. Here the ash is removed through a water lock.

Municipal solid waste in the furnace of a moving grate incinerator capable of handling 15 metric tons (17 short tons) of waste per hour. The holes in the grate elements supplying the primary combustion air are visible.

Part of the combustion air (primary combustion air) is supplied through the grate from below. This air flow also has the purpose of cooling the grate itself. Cooling is important for the mechanical strength of the grate, and many moving grates are also water cooled internally.

Secondary combustion air is supplied into the boiler at high speed through nozzles over the grate. It facilitates complete combustion of the flue gases by introducing turbulence for better mixing and by ensuring a surplus of oxygen. In multiple/stepped hearth incinerators, the secondary combustion air is introduced in a separate chamber downstream the primary combustion chamber.

According to the European Waste Incineration Directive, incineration plants must be designed to ensure that the flue gases reach a temperature of at least 850 °C (1,560 °F) for 2 seconds in order to ensure proper breakdown of toxic organic substances. In order to comply with this at all times, it is required to install backup auxiliary burners (often fueled by oil), which are fired into the boiler in case the heating value of the waste becomes too low to reach this temperature alone.

The flue gases are then cooled in the superheaters, where the heat is transferred to steam, heating the steam to typically 400 °C (752 °F) at a pressure of 40 bars (580 psi) for the electricity generation in the turbine. At this point, the flue gas has a temperature of around 200 °C (392 °F), and is passed to the flue gas cleaning system.

In Scandinavia scheduled maintenance is always performed during summer, where the demand for district heating is low. Often incineration plants consist of several separate 'boiler lines' (boilers and flue gas treatment plants), so that waste can continue to be received at one boiler line while the others are subject to revision.

Fixed grate

The older and simpler kind of incinerator was a brick-lined cell with a fixed metal grate over a lower ash pit, with one opening in the top or side for loading and another opening in the side for removing incombustible solids called clinkers. Many small incinerators formerly found in apartment houses have now been replaced by waste compactors.

Rotary-kiln

The rotary-kiln incinerator is used by municipalities and by large industrial plants. This design of incinerator has 2 chambers: a primary chamber and secondary chamber. The primary chamber in a rotary kiln incinerator consist of an inclined refractory lined cylindrical tube. Movement of the cylinder on its axis facilitates movement of waste. In the primary chamber, there is conversion of solid fraction to gases, through volatilization, destructive distillation and partial combustion reactions. The secondary chamber is necessary to complete gas phase combustion reactions.ē

The clinkers spill out at the end of the cylinder. A tall [[flue g as stack]], fan, or steam jet supplies the needed draft. Ash drops through the grate, but many particles are carried along with the hot gases. The particles and any combustible gases may be combusted in an "afterburner".

Fluidized bed

A strong airflow is forced through a sandbed. The air seeps through the sand until a point is reached where the sand particles separate to let the air through and mixing and churning occurs, thus a fluidised bed is created and fuel and waste can now be introduced.

The sand with the pre-treated waste and/or fuel is kept suspended on pumped air currents and takes on a fluid-like character. The bed is thereby violently mixed and agitated keeping small inert particles and air in a fluid-like state. This allows all of the mass of waste, fuel and sand to be fully circulated through the furnace.

Specialized incineration

Furniture factory sawdust incinerators need much attention as these have to handle resin powder and many flammable substances. Controlled combustion, burn back prevention systems are essential as dust when suspended resembles the fire catch phenomenon of any liquid petroleum gas.

Use of heat

The heat produced by an incinerator can be used to generate steam which may then be used to drive a turbine in order to produce electricity. The typical amount of net energy that can be produced per tonne municipal waste is about 2/3 MWh of electricity and 2 MWh of district heating. Thus, incinerating about 600 metric tons (660 short tons) per day of waste will produce about 400 MWh of electrical energy per day (17 MW of electrical power continuously for 24 hours) and 1200 MWh of district heating energy each day.

Pollution

Incineration has a number of outputs such as the ash and the emission to the atmosphere of flue gas. Before the flue gas cleaning system, the flue gases may contain significant amounts of particulate matter, heavy metals, dioxins, furans, sulfur dioxide, and hydrochloric acid.

In a study from 1994, Delaware Solid Waste Authority found that, for same amount of produced energy, incineration plants emitted fewer particles, hydrocarbons and less SO_2, HCl, CO and NO_x than coal-fired power plants, but more than natural gas fired power plants. According to Germany's Ministry of the Environment, waste incinerators reduce the amount of some atmospheric pollutants by substituting power produced by coal-fired plants with power from waste-fired plants.

Gaseous emissions

Dioxin and furans

The most publicized concerns from environmentalists about the incineration of municipal solid wastes (MSW) involve the fear that it produces significant amounts of dioxin and furan emissions. Dioxins and furans are considered by many to be serious health hazards.

In 2005, The Ministry of the Environment of Germany, where there were 66 incinerators at that time, estimated that "...whereas in 1990 one third of all dioxin emissions in Germany came from incineration plants, for the year 2000 the figure was less than 1 %. Chimneys and tiled stoves in private households alone discharge approximately 20 times more dioxin into the environment than incineration plants."

According to the United States Environmental Protection Agency, incineration plants are no longer significant sources of dioxins and furans. In 1987, before the governmental regulations required the use of emission controls, there was a total of 10,000 grams (350 oz) of dioxin emissions from US incinerators. Today, the total emissions from the 87 plants are 10 grams (0.35 oz) annually, a reduction of 99.9 %.

Backyard barrel burning of household and garden wastes, still allowed in some rural areas, generates 580 grams (20 oz) of dioxins annually. Studies conducted by the US-

EPA demonstrate that the emissions from just one family using a burn barrel produced more emissions than an incineration plant disposing of 200 metric tons (220 short tons) of waste per day by 1997 and five times that by 2007 due to increased chemicals in household trash and decreased emissions by municipal incinerators using better technology.

Dioxin cracking methods and limitations

Generally, the breakdown of dioxin requires exposure of the molecular ring to a sufficiently high temperature so as to trigger thermal breakdown of the strong molecular bonds holding it together. Small pieces of fly ash may be somewhat thick, and too brief an exposure to high temperature may only degrade dioxin on the surface of the ash. For a large volume air chamber, too brief an exposure may also result in only some of the exhaust gases reaching the full breakdown temperature. For this reason there is also a time element to the temperature exposure to ensure heating completely through the thickness of the fly ash and the volume of waste gases.

There are trade-offs between increasing either the temperature or exposure time. Generally where the molecular breakdown temperature is higher, the exposure time for heating can be shorter, but excessively high temperatures can also cause wear and damage to other parts of the incineration equipment. Likewise the breakdown temperature can be lowered to some degree but then the exhaust gases would require a greater lingering period of perhaps several minutes, which would require large/long treatment chambers that take up a great deal of treatment plant space.

A side effect of breaking the strong molecular bonds of dioxin is the potential for breaking the bonds of nitrogen gas (N_2) and oxygen gas (O_2) in the supply air. As the exhaust flow cools, these highly reactive detached atoms spontaneously reform bonds into reactive oxides such as NO_x in the flue gas, which can result in smog formation and acid rain if they were released directly into the local environment. These reactive oxides must be further neutralized with selective catalytic reduction (SCR) or selective non-catalytic reduction (see below).

Dioxin cracking in practice

The temperatures needed to break down dioxin are typically not reached when burning of plastics outdoors in a burn barrel or garbage pit, causing high dioxin emissions as mentioned above. While plastic does usually burn in an open-air fire, the dioxins remain after combustion and either float off into the atmosphere, or may remain in the ash where it can be leached down into groundwater when rain falls on the ash pile.

Modern municipal incinerator designs include a high temperature zone, where the flue gas is ensured to sustain a temperature above 850 °C (1,560 °F) for at least 2 seconds before it is cooled down. They are equipped with auxiliary heaters to ensure this at all times. These are often fueled by oil, and normally only active for a very small fraction of the time.

For very small municipal incinerators, the required temperature for thermal breakdown of dioxin may be reached using a high-temperature electrical heating element, plus a selective catalytic reduction stage.

CO_2

As for other complete combustion processes, nearly all of the carbon content in the waste is emitted as CO_2 to the atmosphere. MSW contains approximately the same mass fraction of carbon as CO_2 itself (27%), so incineration of 1 ton of MSW produces approximately 1 ton of CO_2.

If the waste was landfilled, 1 ton of MSW would produce approximately 62 cubic metres (2,200 cu ft) methane via the anaerobic decomposition of the biodegradable part of the waste. Since the global warming potential of methane is 21 and the weight of 62 cubic meters of methane at 25 degrees Celsius is 40.7 kg, this is equivalent to 0.854 ton of CO_2, which is less than the 1 ton of CO_2 which would have been produced by incineration. In some countries, large amounts of landfill gas are collected, but still the global warming potential of the landfill gas emitted to atmosphere in the US in 1999 was approximately 32 % higher than the amount of CO_2 that would have been emitted by incineration.

In addition, nearly all biodegradable waste has biological origin. This material has been formed by plants using atmospheric CO_2 typically within the last growing season. If these plants are regrown the CO_2 emitted from their combustion will be taken out from the atmosphere once more.

Such considerations are the main reason why several countries administrate incineration of the biodegradable part of waste as renewable energy. The rest – mainly plastics and other oil and gas derived products – is generally treated as non-renewables.

Different results for the CO_2 footprint of incineration can be reached with different assumptions. Local conditions (such as limited local district heating demand, no fossil fuel generated electricity to replace or high levels of aluminum in the waste stream) can decrease the CO_2 benefits of incineration. The methodology and other assumptions may also influence the results significantly. For example the methane emissions from landfills occurring at a later date may be neglected or given less weight, or biodegradable waste may not be considered CO_2 neutral. A study by Eunomia Research and Consulting in 2008 on potential waste treatment technologies in London demonstrated that by applying several of these (according to the authors) unusual assumptions the average existing incineration plants performed poorly for CO_2 balance compared to the theoretical potential of other emerging waste treatment technologies.

Other emissions

Other gaseous emissions in the flue gas from incinerator furnaces include sulfur dioxide, hydrochloric acid, heavy metals and fine particles.

The steam content in the flue may produce visible fume from the stack, which can be perceived as a visual pollution. It may be avoided by decreasing the steam content by flue gas condensation and reheating, or by increasing the flue gas exit temperature well above its dew point. Flue gas condensation allows the latent heat of vaporization of the water to be recovered, subsequently increasing the thermal efficiency of the plant.

Flue gas cleaning

The quantity of pollutants in the flue gas from incineration plants is reduced by several processes.

Particulate is collected by particle filtration, most often electrostatic precipitators (ESP) and/or baghouse filters. The latter are generally very efficient for collecting fine particles. In an investigation by the Ministry of the Environment of Denmark in 2006, the average particulate emissions per energy content of incinerated waste from 16 Danish incinerators were below 2.02 g/GJ (grams per energy content of the incinerated waste). Detailed measurements of fine particles with sizes below 2.5 micrometres ($PM_{2.5}$) were performed on three of the incinerators: One incinerator equipped with an ESP for particle filtration emitted 5.3 g/GJ fine particles, while two incinerators equipped with baghouse filters emitted 0.002 and 0.013 g/GJ $PM_{2.5}$. For ultra fine particles ($PM_{1.0}$), the numbers were 4.889 g/GJ $PM_{1.0}$ from the ESP plant, while emissions of 0.000 and 0.008 g/GJ $PM_{1.0}$ were measured from the plants equipped with baghouse filters.

Acid gas scrubbers are used to remove hydrochloric acid, nitric acid, hydrofluoric acid, mercury, lead and other heavy metals. Basic scrubbers remove sulfur dioxide, forming gypsum by reaction with lime.

Waste water from scrubbers must subsequently pass through a waste water treatment plant.

Sulfur dioxide may also be removed by dry desulfurisation by injection limestone slurry into the flue gas before the particle filtration.

NO_x is either reduced by catalytic reduction with ammonia in a catalytic converter (selective catalytic reduction, SCR) or by a high temperature reaction with ammonia in the furnace (selective non-catalytic reduction, SNCR). Urea may be substituted for ammonia as the reducing reagent but must be supplied earlier in the process so that it can hydrolyze into ammonia. Substitution of urea can reduce costs and potential hazards associated with storage of anhydrous ammonia.

Heavy metals are often adsorbed on injected active carbon powder, which is collected by the particle filtration.

Solid outputs

Operation of an incinerator aboard an aircraft carrier

Incineration produces fly ash and bottom ash just as is the case when coal is combusted. The total amount of ash produced by municipal solid waste incineration ranges from 4 to 10 % by volume and 15-20 % by weight of the original quantity of waste, and the fly ash amounts to about 10-20 % of the total ash. The fly ash, by far, constitutes more of a potential health hazard than does the bottom ash because the fly ash often contain high concentrations of heavy metals such as lead, cadmium, copper and zinc as well as small amounts of dioxins and furans. The bottom ash seldom contain significant levels of heavy metals. In testing over the past decade, no ash from an incineration plant in the USA has ever been determined to be a hazardous waste. At present although some historic samples tested by the incinerator operators' group would meet the being ecotoxic criteria at present the EA say "we have agreed" to regard incinerator bottom ash as "non-hazardous" until the testing programme is complete.

Other pollution issues

Odor pollution can be a problem with old-style incinerators, but odors and dust are extremely well controlled in newer incineration plants. They receive and store the waste in an enclosed area with a negative pressure with the airflow being routed through the boiler which prevents unpleasant odors from escaping into the atmosphere. However, not all plants are implemented this way, resulting in inconveniences in the locality.

An issue that affects community relationships is the increased road traffic of waste collection vehicles to transport municipal waste to the incinerator. Due to this reason, most incinerators are located in industrial areas. This problem can be avoided to an extent through the transport of waste by rail from transfer stations.

Debate

Use of incinerators for waste management is controversial. The debate over incinerators typically involves business interests (representing both waste generators and incinerator firms), government regulators, environmental activists and local citizens who must weigh the economic appeal of local industrial activity with their concerns over health and environmental risk.

People and organizations professionally involved in this issue include the U.S. Environmental Protection Agency and a great many local and national air quality regulatory agencies worldwide.

Arguments for incineration

Kehrichtverbrennungsanlage Zürcher Oberland (KEZO) in Hinwil, Switzerland

- The concerns over the health effects of dioxin and furan emissions have been significantly lessened by advances in emission control designs and very stringent new governmental regulations that have resulted in large reductions in the amount of dioxins and furans emissions.

- The U.K. Health Protection Agency concluded in 2009 that "Modern, well managed incinerators make only a small contribution to local concentrations of air pollutants. It is possible that such small additions could have an impact on health but such effects, if they exist, are likely to be very small and not detectable.".
- Incineration plants can generate electricity and heat that can substitute power plants powered by other fuels at the regional electric and district heating grid, and steam supply for industrial customers. Incinerators and other waste-to-energy plants generate at least partially biomass-based renewable energy that offsets greenhouse gas pollution from coal-, oil- and gas-fired power plants. The E.U. considers energy generated from biogenic waste (waste with biological origin) by incinerators as non-fossil renewable energy under its emissions caps. These greenhouse gas reductions are in addition to those generated by the avoidance of landfill methane.
- The bottom ash residue remaining after combustion has been shown to be a non-hazardous solid waste that can be safely put into landfills or recycled as construction aggregate. Samples are tested for ecotoxic metals.
- In densely populated areas, finding space for additional landfills is becoming increasingly difficult.

The Maishima waste treatment center in Osaka, designed by Friedensreich Hundertwasser, uses heat for power generation.

Fine particles can be efficiently removed from the flue gases with baghouse filters. Even though approximately 40 % of the incinerated waste in Denmark was incinerated at plants with no baghouse filters, estimates based on measurements by the Danish Environmental Research Institute showed that incinerators were only responsible for approximately 0.3 % of the total domestic emissions of particulate smaller than 2.5 micrometres ($PM_{2.5}$) to the atmosphere in 2006.

- Incineration of municipal solid waste avoids the release of methane. Every ton of MSW incinerated, prevents about one ton of carbon dioxide equivalents from being released to the atmosphere.

- Incineration of medical waste and sewage sludge produces an end product ash that is sterile and non-hazardous.
- Most municipalities that operate incineration facilities have higher recycling rates than neighboring cities and counties that do not send their waste to incinerators. This is in part due to enhanced recovery of ceramic materials reused in construction, as well as ferrous and in some cases non-ferrous metals that can be recovered from combustion residue. Metals recovered from ash would typically be difficult or impossible to recycle through conventional means, as the removal of attached combustible material through incineration provides an alternative to labor- or energy-intensive mechanical separation methods.
- Volume of combusted waste is reduced by approximately 90%, increasing the life of landfills. Ash from modern incinerators is vitrified at temperatures of 1,000 °C (1,830 °F) to 1,100 °C (2,010 °F), reducing the leachability and toxicity of residue. As a result, special landfills are generally no longer required for incinerator ash from municipal waste streams, and existing landfills can see their life dramatically increased by combusting waste, reducing the need for municipalities to site and construct new landfills.

Arguments against incineration

Decommissioned Kwai Chung Incineration Plant from 1978. As of late February 2009, it has been demolished.

- The Scottish Protection Agency's (SEPA) comprehensive health effects research concluded "inconclusively" on health effects in Oct. 2009. The authors stress, that even though no conclusive evidence of non-occupational health effects from incinerators were found in the existing literature, "small but important effects might be virtually impossible to detect". The report highlights epidemiological deficiencies in previous UK health studies and suggests areas for future studies. The U.K. Health Protection Agency produced a lesser summary in September 2009. Many toxiocologists criticise and dispute this report as not being comprehensive epidemiologically, thin on peer review and the effects of fine particle effects on health.

- The highly toxic fly ash must be safely disposed of. This usually involves additional waste miles and the need for specialist toxic waste landfill elsewhere. If not done properly, it may cause concerns for local residents.
- Some people are still concerned about the health effects of dioxin and furan emissions into the atmosphere from old incinerators; especially during start up and shut down, or where filter bypass is required.
- Incinerators emit varying levels of heavy metals such as vanadium, manganese, chromium, nickel, arsenic, mercury, lead, and cadmium, which can be toxic at very minute levels.
- Incinerator Bottom Ash (IBA) has elevated levels of heavy metals with ecotoxicity concerns if not reused properly. Some people have the opinion that IBA reuse is still in its infancy and is still not considered to be a mature or desirable product, despite additional engineering treatments. Concerns of IBA use in foam concrete have been expressed by the UK Health and Safety Executive in 2010 following several construction and demolition explosions. In its guidance document, IBA is currently banned from use by the UK Highway Authority in concrete work until these incidents have been investigated.
- Alternative technologies are available or in development such as Mechanical Biological Treatment, Anaerobic Digestion (MBT/AD), Autoclaving or Mechanical Heat Treatment (MHT) using steam or plasma arc gasification (PGP), which is incineration using electrically produced extreme high temperatures, or combinations of these treatments. Erection of incinerators compete with the development and introduction of other emerging technologies. A UK government WRAP report, August 2008 found that in the UK median incinerator costs per ton were generally higher than those for MBT treatments by £18 per metric ton; and £27 per metric ton for most modern (post 2000) incinerators.
- Building and operating waste processing plants such as incinerators requires long contract periods to recover initial investment costs, causing a long term lock-in. Incinerator lifetimes normally range 25–30 years. This was highlighted by Peter Jones, OBE, the Mayor of London's waste representative in April 2009.
- Incinerators produce fine particles in the furnace. Even with modern particle filtering of the flue gases, a small part of these is emitted to the atmosphere. $PM_{2.5}$ is not separately regulated in the European Waste Incineration Directive, even though they are repeatedly correlated spatially to infant mortality in the UK (M.Ryan's ONS data based maps around the EfW/CHP waste incinerators at Edmonton, Coventry, Chineham, Kirklees and Sheffield). Under WID there is no requirement to monitor stack top or downwind incinerator $PM_{2.5}$ levels. Several European doctors associations (including cross discipline experts such as physicians, environmental chemists and toxicologists) in June 2008 representing over 33,000 doctors wrote a keynote statement directly to the European Parliament citing widespread concerns on incinerator particle emissions and the absence of specific fine and ultrafine particle size monitoring or in depth industry/ government epidemiological studies of these minute and invisible incinerator particle size emissions.

- Local communities are often opposed to the idea of locating waste processing plants such as incinerators in their vicinity (the Not In My Back Yard phenomenon). Studies in Andover, Massachusetts strongly correlated 10% property devaluations with close incinerator proximity.
- Prevention, waste minimisation, reuse and recycling of waste should all be preferred to incineration according to the waste hierarchy. Supporters of zero waste consider incinerators and other waste treatment technologies as barriers to recycling and separation beyond particular levels, and that waste resources are sacrificed for energy production.
- A 2008 Eunomia report found that under some circumstances and assumptions, incineration causes less CO_2 reduction than other emerging EfW and CHP technology combinations for treating residual mixed waste. The authors found that CHP incinerator technology without waste recycling ranked 19 out of 24 combinations (where all alternatives to incineration were combined with advanced waste recycling plants); being 228% less efficient than the ranked 1 Advanced MBT maturation technology; or 211% less efficient than plasma gasification/autoclaving combination ranked 2.
- Some incinerators are visually undesirable. In many countries they require a visually intrusive chimney stack.
- If reusable waste fractions are handled in waste processing plants such as incinerators in developing nations, it would cut out viable work for local economies. It is estimated that there are 1 million people making a livelihood off collecting waste.

Trends in incinerator use

The history of municipal solid waste (MSW) incineration is linked intimately to the history of landfills and other waste treatment technology. The merits of incineration are inevitably judged in relation to the alternatives available. Since the 1970s, recycling and other prevention measures have changed the context for such judgements. Since the 1990s alternative waste treatment technologies have been maturing and becoming viable.

Incineration is a key process in the treatment of hazardous wastes and clinical wastes. It is often imperative that medical waste be subjected to the high temperatures of incineration to destroy pathogens and toxic contamination it contains.

Incineration in North America

The first incinerator in the U.S. was built in 1885 on Governors Island in New York. In 1949, Robert C. Ross founded one of the first hazardous waste management companies in the U.S. He began Robert Ross Industrial Disposal because he saw an opportunity to meet the hazardous waste management needs of companies in northern Ohio. In 1958, the company built one of the first hazardous waste incinerators in the U.S. The first full-scale, municipally operated incineration facility in the U.S. was the Arnold O. Chantland Resource Recovery Plant, built in 1975 and located in Ames, Iowa. This plant is still in operation and produces refuse-derived fuel that is sent to local power plants for fuel. The first commercially successful incineration plant in the U.S. was built in Saugus, Massachusetts in October 1975 by Wheelabrator Technologies, and is still in operation today.

There are several environmental or waste management corporations that transport ultimately to an incinerator or cement kiln treatment center. Currently (2009), there are three main businesses that incinerate waste: Clean Harbours, WTI-Heritage, and Ross Incineration Services. Clean Harbours has acquired many of the smaller, independently run facilities, accumulating 5–7 incinerators in the process across the U.S. WTI-Heritage has one incinerator, located in the southeastern corner of Ohio (across the Ohio River from West Virginia).

Several old generation incinerators have been closed; of the 186 MSW incinerators in 1990, only 89 remained by 2007, and of the 6200 medical waste incinerators in 1988, only 115 remained in 2003. No new incinerators were built between 1996 and 2007. The main reasons for lack of activity have been:

- Economics. With the increase in the number of large inexpensive regional landfills and, up until recently, the relatively low price of electricity, incinerators were not able to compete for the 'fuel', i.e., waste in the U.S.
- Tax policies. Tax credits for plants producing electricity from waste were rescinded in the U.S. between 1990 and 2004.

There has been renewed interest in incineration and other waste-to-energy technologies in the U.S. and Canada. In the U.S., incineration was granted qualification for renewable energy production tax credits in 2004. Projects to add capacity to existing plants are underway, and municipalities are once again evaluating the option of building incineration plants rather than continue landfilling municipal wastes. However, many of these projects have faced continued political opposition in spite of renewed arguments for the greenhouse gas benefits of incineration and improved air pollution control and ash recycling.

Incineration in Europe

In Europe, with the ban on landfilling untreated waste, scores of incinerators have been built in the last decade, with more under construction. Recently, a number of municipal governments have begun the process of contracting for the construction and operation of incinerators. In Europe, some of the electricity generated from waste is deemed to be from a 'Renewable Energy Source (RES)' and is thus eligible for tax credits if privately operated. Also, some incinerators in Europe are equipped with waste recovery, allowing the reuse of ferrous and non-ferrous materials found in landfills. A prominent example is the AEB Waste Fired Power Plant.

Incineration in the United Kingdom

The technology employed in the UK waste management industry has been greatly lagging behind that of Europe due to the wide availability of landfills. The Landfill Directive set down by the European Union led to the Government of the United Kingdom imposing waste legislation including the landfill tax and Landfill Allowance Trading Scheme. This legislation is designed to reduce the release of greenhouse gases produced by landfills through the use of alternative methods of waste treatment. It is the UK Government's position that incineration will play an increasingly large role in the treatment of municipal waste and supply of energy in the UK.

In the UK in 2008, plans for potential incinerator locations exists for approximately 100 sites. These have been interactively mapped by UK NGO's.

Small incinerator units

An example of a low capacity, mobile incinerator

Small scale incinerators exist for special purposes. For example, the small scale incinerators are aimed for hygienically safe destruction of medical waste in developing countries. Small incinerators can be quickly deployed to remote areas where an outbreak has occurred to dispose of infected animals quickly and without the risk of cross contamination.

Chapter 3

Furnace

Industrial Furnace from 1907

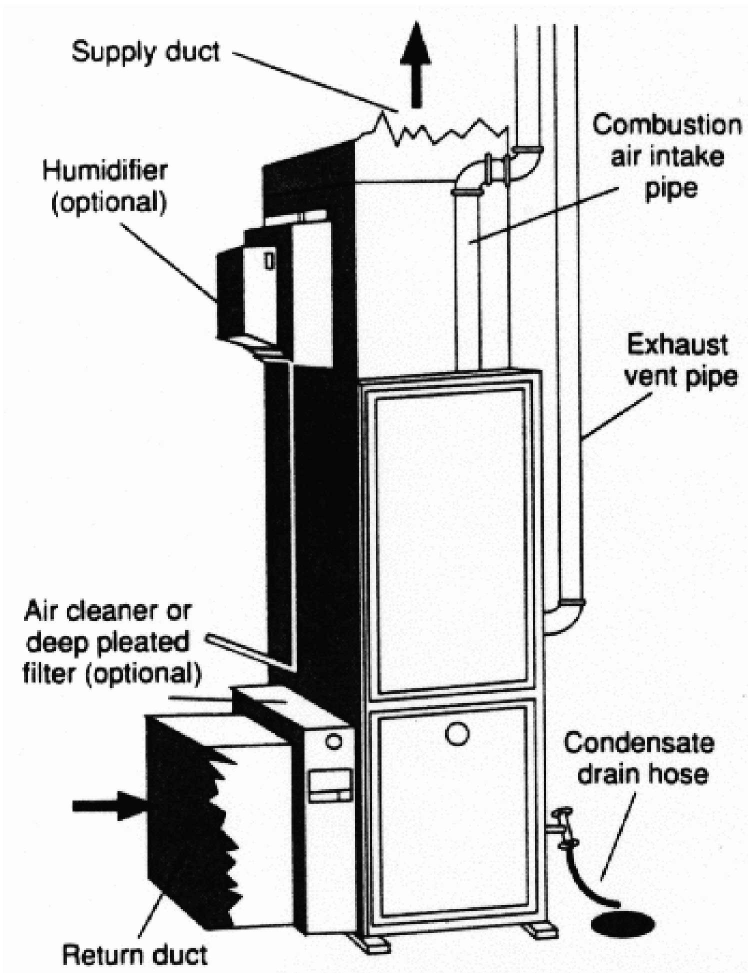
A **furnace** is a device used for heating. The name derives from Latin *fornax*, oven.

In American English and Canadian English, the term *furnace* on its own is generally used to describe household heating systems based on a central furnace (known either as a boiler or a heater in British English), and sometimes as a synonym for kiln, a device used in the production of ceramics. In British English the term *furnace* is used exclusively to mean industrial furnaces which are used for many things, such as the extraction of metal from ore (smelting) or in oil refineries and other chemical plants, for example as the heat source for fractional distillation columns.

The term *furnace* can also refer to a direct fired heater, used in boiler applications in chemical industries or for providing heat to chemical reactions for processes like cracking, and is part of the standard English names for many metallurgical furnaces worldwide.

The heat energy to fuel a furnace may be supplied directly by fuel combustion, by electricity such as the electric arc furnace, or through Induction heating in induction furnaces.

Household furnaces



Schematic of a condensing furnace.

A condensing furnace

A household furnace is a major appliance that is permanently installed to provide heat to an interior space through intermediary fluid movement, which may be air, steam, or hot water. The most common fuel source for modern furnaces in the United States is natural gas; other common fuel sources include LPG (liquefied petroleum gas), fuel oil, coal or wood. In some cases electrical resistance heating is used as the source of heat, especially where the cost of electricity is low.

Combustion furnaces always need to be vented to the outside. Traditionally, this was through a chimney, which tends to expel heat along with the exhaust. Modern high-efficiency furnaces can be 98% efficient and operate without a chimney. The small amount of waste gas and heat are mechanically ventilated through a small tube through the side or roof of the house.

- "High-efficiency" in this sense may be misleading, because furnace efficiency is typically expressed as a "first-law" efficiency, whereas the energy efficiency of a typical furnace is much lower than the first-law thermal efficiency. By comparison, cogeneration has a higher energy efficiency than is realizable from burning fuel to generate heat directly at a moderate temperature. However, as the vast majority of consumers (as well as many government regulators) are unfamiliar with exergy efficiency, Carnot efficiency, and the second law of thermodynamics, the use of first-law efficiencies to rate furnaces is well-entrenched.

Modern household furnaces are classified as *condensing* or *non-condensing* based on their efficiency in extracting heat from the exhaust gases. Furnaces with efficiencies greater than approximately 89% extract so much heat from the exhaust that water vapor in the exhaust condenses; they are referred to as condensing furnaces. Such furnaces must be designed to avoid the corrosion that this highly acidic condensate might cause and may need to include a condensate pump to remove the accumulated water. Condensing furnaces can typically deliver heating savings of 20%-35% assuming the old furnace was in the 60% Annual Fuel Utilization Efficiency (AFUE) range.

Modern Furnace components

The furnace components can be divided into three categories.

1. The burners, heat exchanger, draft inducer, and venting.
2. The controls and safety devices.
3. The blower and air movement.

The flame originates at the burners and is drawn into the heat exchanger by the negative pressure produced by the draft inducer. The hot gases produced by the combustion of the flame pass through the chambers of the heat exchanger and heat the metal walls of the heat exchanger. The gases cool as they transfer the heat to the heat exchanger and are at about 120 ℉ (49 ℃) as they exit on a high efficiency furnace. The cooled gases then enter the draft inducer blower and are pushed into the venting pipes. The exhaust gases then are directed out of the house through the vent pipes.

The controls include the gas valve, ignition control, ignitor, flame sensor, transformer, limit control, blower control board, and flame roll out switch. The transformer provides 24 volts of electricity to power the controls. 24 volts is applied to the thermostat that is installed in the living space.

The thermostat is basically an automatic switch that closes and completes the electrical circuit when the room temperature drops below the heat setting. This then allows 24 volts to the circuit board which initiates the heat sequence. The circuit board has a relay that closes to power up the motor on the draft inducer blower. Then the circuit board ignitor relay is energized which sends 120 volts to the hot surface ignitor and makes it glow bright and get extremely hot.

Next the gas valve relay in the circuit board is energized. This allows voltage to the gas valve and energizes a solenoid coil in the gas valve which opens the valve to allow gas to flow to the burners. The gas flows into the burners and is ignited by the hot surface ignitor. The ignition control circuit board applies an AC voltage to the flame sensor which is just a stainless steel rod. An interesting thing occurs inside a burning flame, which is called ionization. That is, free electrons are produced which can conduct electricity through the flame itself. The electrons will normally flow from the flame sensor, through the flame when present, and back to ground through the grounded burners.

The ignition system must prove that a flame is present to continue the gas flow, or if there's no flame, then shut off the gas flow through the gas valve to prevent a possible explosion. It also must not be fooled into thinking there is a flame present by a flame sensor that is touching the ground from being broken or bent. The way it does this is by a diode effect where the sensor surface area is less than 10% of the ground surface area. This produces a half-wave of electrical current from each full wave. The ignition control circuit detects the half-wave to determine if the sensor is merely touching ground. If the ignition control receives this half wave signal from the flame sensor then combustion will continue.

Now the circuit board timer counts a determined amount of time and energizes the blower relay. This relay powers up the blower motor and air is then pushed through the heat exchanger where it removes the heat from the hot metal and enters the ductwork to go to the various rooms in the house. The limit control is a safety device that will open the electrical circuit to the ignition control and stop the gas flow if the furnace overheats. The flame roll-out switch does the same thing if the flame was rolling out of the heat exchanger instead of being completely induced into it by the draft inducer.

The blower creates a negative pressure on the intake side which draws air into the ductwork return air system and blows the air out through the heat exchanger and then into supply air ductwork to distribute throughout the home.

Heat distribution

The furnace transfers heat to the living space of the building through an intermediary distribution system. If the distribution is through hot water (or other fluid) or through steam, then the furnace is more commonly termed a boiler. One advantage of a boiler is that the furnace can provide hot water for bathing and washing dishes, rather than requiring a separate water heater. One disadvantage to this type of application is when the boiler breaks down, both heating and domestic hot water is not available.

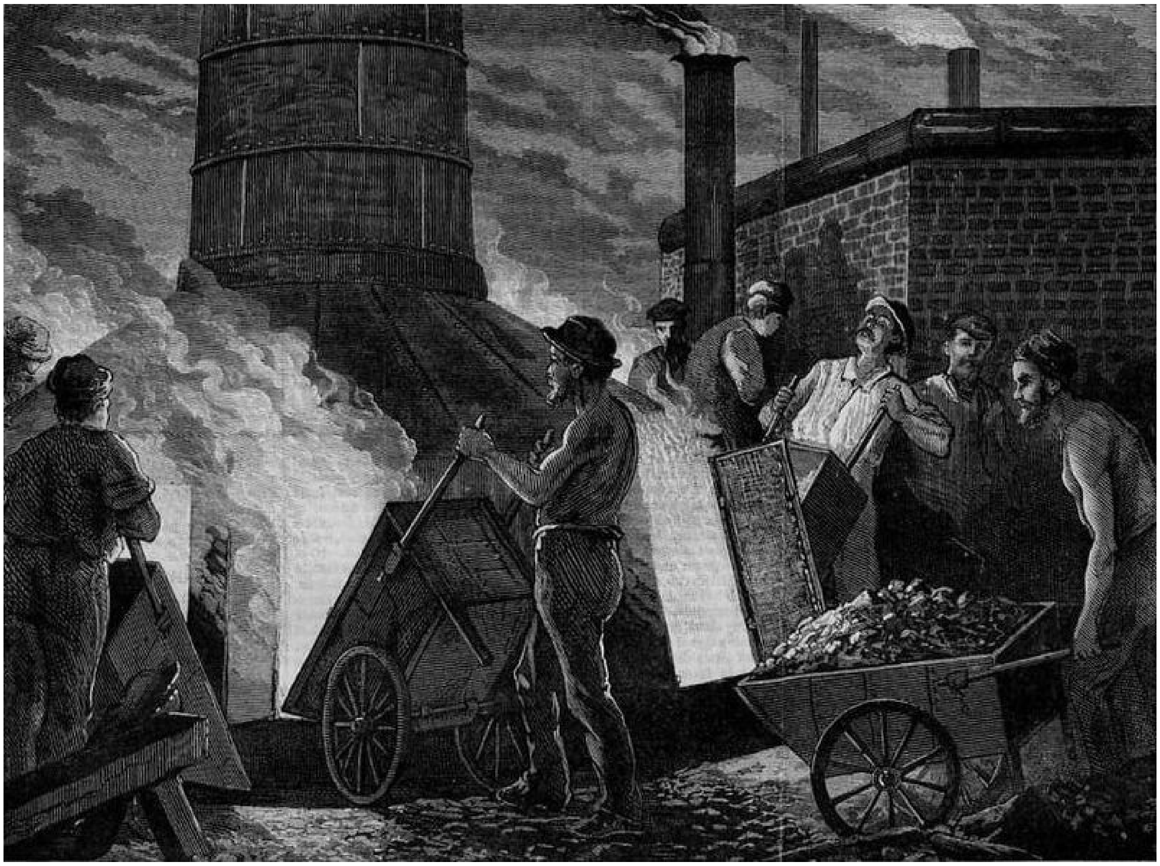
Air convection heating systems have been in use for over a century, but the older systems relied on a passive air circulation system where the greater density of cooler air caused it to sink into the furnace, and the lesser density of the warmed air caused it to rise in the ductwork, the two forces acting together to drive air circulation in a system termed "gravity-feed; the layout of the ducts and furnace was optimized for short, large ducts and caused the furnace to be referred to as an "octopus" furnace.

By comparison, most modern "warm air" furnaces typically use a fan to circulate air to the rooms of house and pull cooler air back to the furnace for reheating; this is called forced-air heat. Because the fan easily overcomes the resistance of the ductwork, the arrangement of ducts can be far more flexible than the octopus of old. In American practice, separate ducts collect cool air to be returned to the furnace. At the furnace, cool air passes into the furnace, usually through an air filter, through the blower, then through the heat exchanger of the furnace, whence it is blown throughout the building. One major advantage of this type of system is that it also enables easy installation of central air conditioning by simply adding a cooling coil at the exhaust of the furnace.

Air is circulated through ductwork, which may be made of sheet metal or plastic "flex" duct and insulated or uninsulated. Unless the ducts and plenum have been sealed using mastic or foil duct tape, the ductwork is likely to have a high leakage of conditioned air, possibly into unconditioned spaces. Another cause of wasted energy is the installation of ductwork in unheated areas, such as attics and crawl spaces; or ductwork of air conditioning systems in attics in warm climates.

The following rare but difficult-to-diagnose failure can occur. If the temperature inside the furnace exceeds a maximum threshold, a safety mechanism with a thermostat will shut the furnace down. A symptom of this failure is that the furnace repeatedly shuts down before the house reaches the desired temperature; this is commonly referred to as the furnace "riding the high limit switch". This condition commonly occurs if the temperature setting of the high limit thermostat is set too close to the normal operating temperature of the furnace. Another situation may occur if a humidifier is incorrectly installed on the furnace and the duct which directs a portion of the humidified air back into the furnace is too large. The solution is to reduce the diameter of the cross-feed tube, or install a baffle that reduces the volume of re-fed air.

Metallurgical furnaces



The Manufacture of Iron -- Filling the Furnace, an 1873 wood engraving

In metallurgy, several specialised furnaces are used. These include:

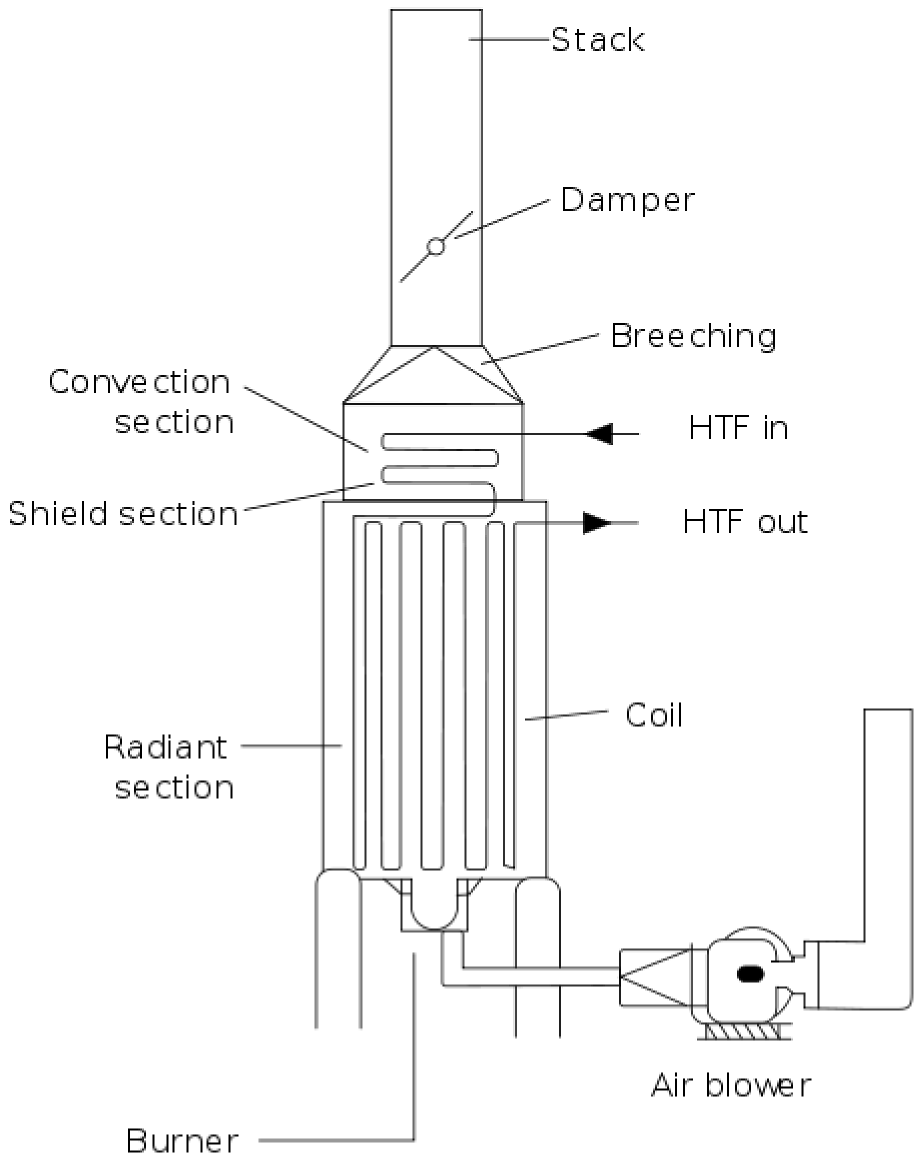
- Furnaces used in smelters, including:
    - The blast furnace, used to reduce iron ore to pig iron
    - Steelmaking furnaces, including:
        - Puddling furnace
        - Reverberatory furnace
        - Bessemer converter
        - Open hearth furnace
        - Basic oxygen furnace
        - Electric arc furnace
        - Electric induction furnace

- Furnaces used to remelt metal in foundries.

- Furnaces used to reheat and heat treat metal for use in:
    - Rolling mills, including tinplate works and slitting mills.
    - Forges.

- Vacuum furnaces

Industrial process furnaces



Schematic diagram of an industrial process furnace

An industrial furnace or direct fired heater, is an equipment used to provide heat for a process or can serve as reactor which provides heats of reaction. Furnace designs vary as to its function, heating duty, type of fuel and method of introducing combustion air. However, most process furnaces have some common features.

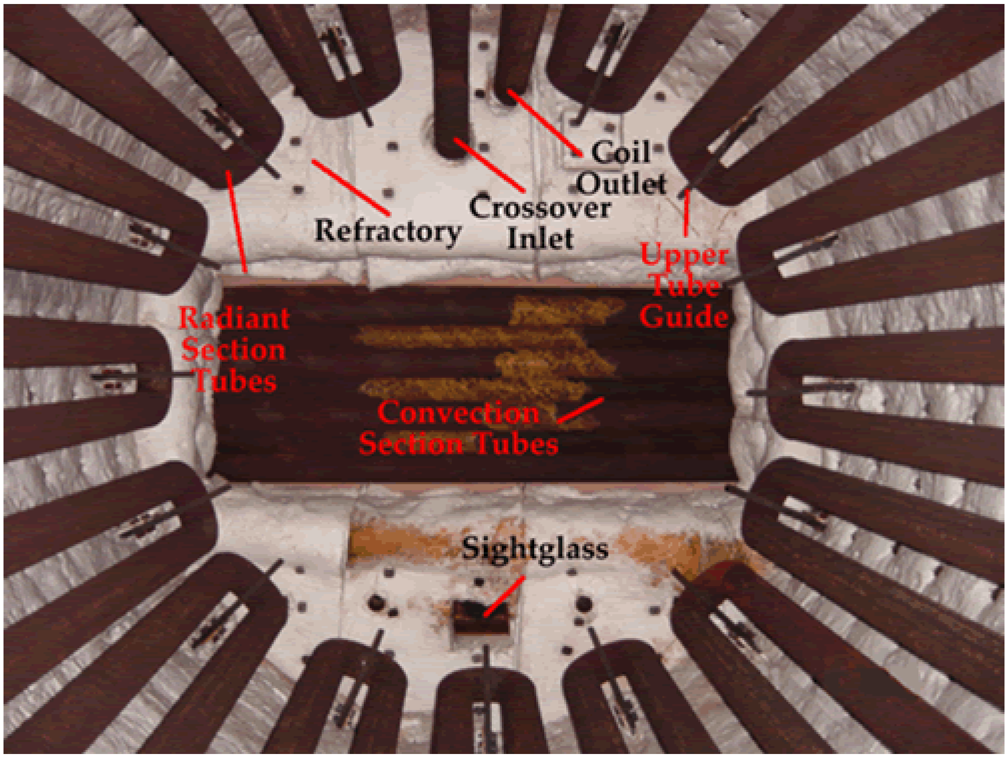
Fuel flows into the burner and is burnt with air provided from an air blower. There can be more than one burner in a particular furnace which can be arranged in cells which heat a particular set of tubes. Burners can also be floor mounted, wall mounted or roof mounted depending on design. The flames heat up the tubes, which in turn heat the fluid inside in the first part of the furnace known as the radiant section or firebox. In this chamber where combustion takes place, the heat is transferred mainly by radiation to tubes around the fire in the chamber. The heating fluid passes through the tubes and is thus heated to the desired temperature. The gases from the combustion are known as flue gas. After the flue gas leaves the firebox, most furnace designs include a convection section where more heat is recovered before venting to the atmosphere through the flue gas stack. (HTF=Heat Transfer Fluid. Industries commonly use their furnaces to heat a secondary fluid with special additives like anti-rust and high heat transfer efficiency. This heated fluid is then circulated round the whole plant to heat exchangers to be used wherever heat is needed instead of directly heating the product line as the product or material may be volatile or prone to cracking at the furnace temperature.)

Radiant section

Middle of radiant section

The radiant section is where the tubes receive almost all its heat by radiation from the flame. In a vertical, cylindrical furnace, the tubes are vertical. Tubes can be vertical or horizontal, placed along the refractory wall, in the middle, etc., or arranged in cells. Studs are used to hold the insulation together and on the wall of the furnace. They are placed about 1 ft (300 mm) apart in this picture of the inside of a furnace. The tubes, shown below, which are reddish brown from corrosion, are carbon steel tubes and run the height of the radiant section. The tubes are a distance away from the insulation so radiation can be reflected to the back of the tubes to maintain a uniform tube wall temperature. Tube guides at the top, middle and bottom hold the tubes in place.

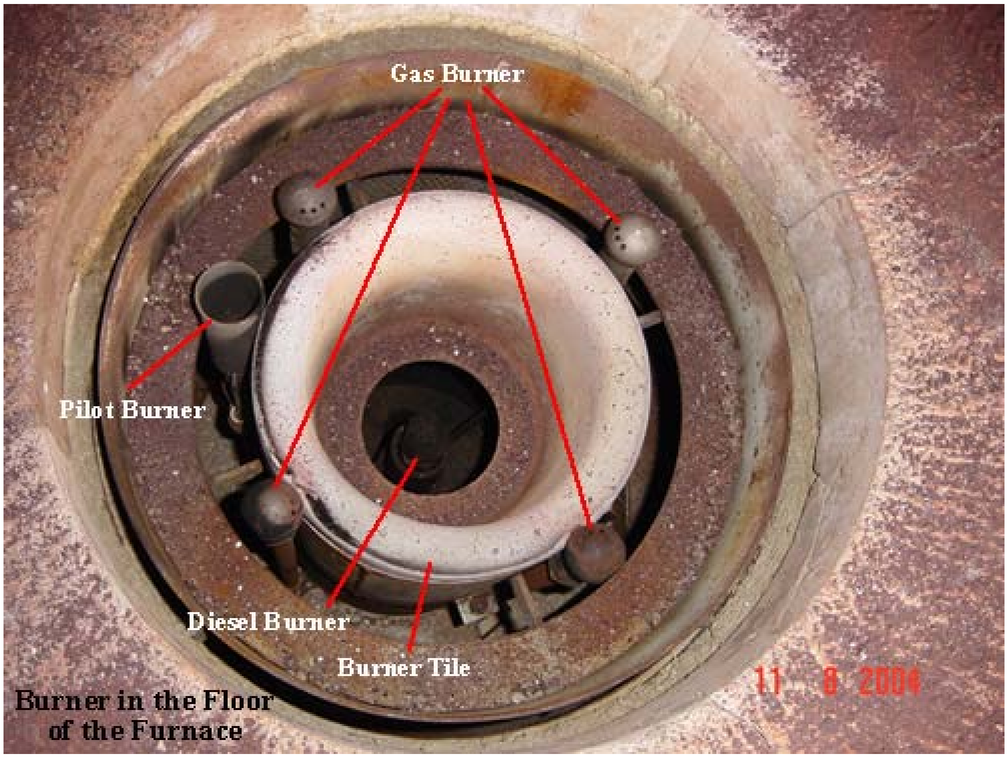
Convection section



Convection section

The convection section is located above the radiant section where it is cooler to recover additional heat. Heat transfer takes place by convection here, and the tubes are finned to increase heat transfer. The first two tube rows in the bottom of the convection section and at the top of the radiant section is an area of bare tubes (without fins) and are known as the shield section, so named because they are still exposed to plenty of radiation from the firebox and they also act to shield the convection section tubes, which are normally of less resistant material from the high temperatures in the firebox. The area of the radiant section just before flue gas enters the shield section and into the convection section called the bridgezone. Crossover is the term used to describe the tube that connects from the convection section outlet to the radiant section inlet. The crossover piping is normally located outside so that the temperature can be monitored and the efficiency of the convection section can be calculated. The sightglass at the top allows personnel to see the flame shape and pattern from above and visually inspect if flame impingement is occurring. Flame impingement happens when the flame touches the tubes and causes small isolated spots of very high temperature.

Burner



Furnace burner

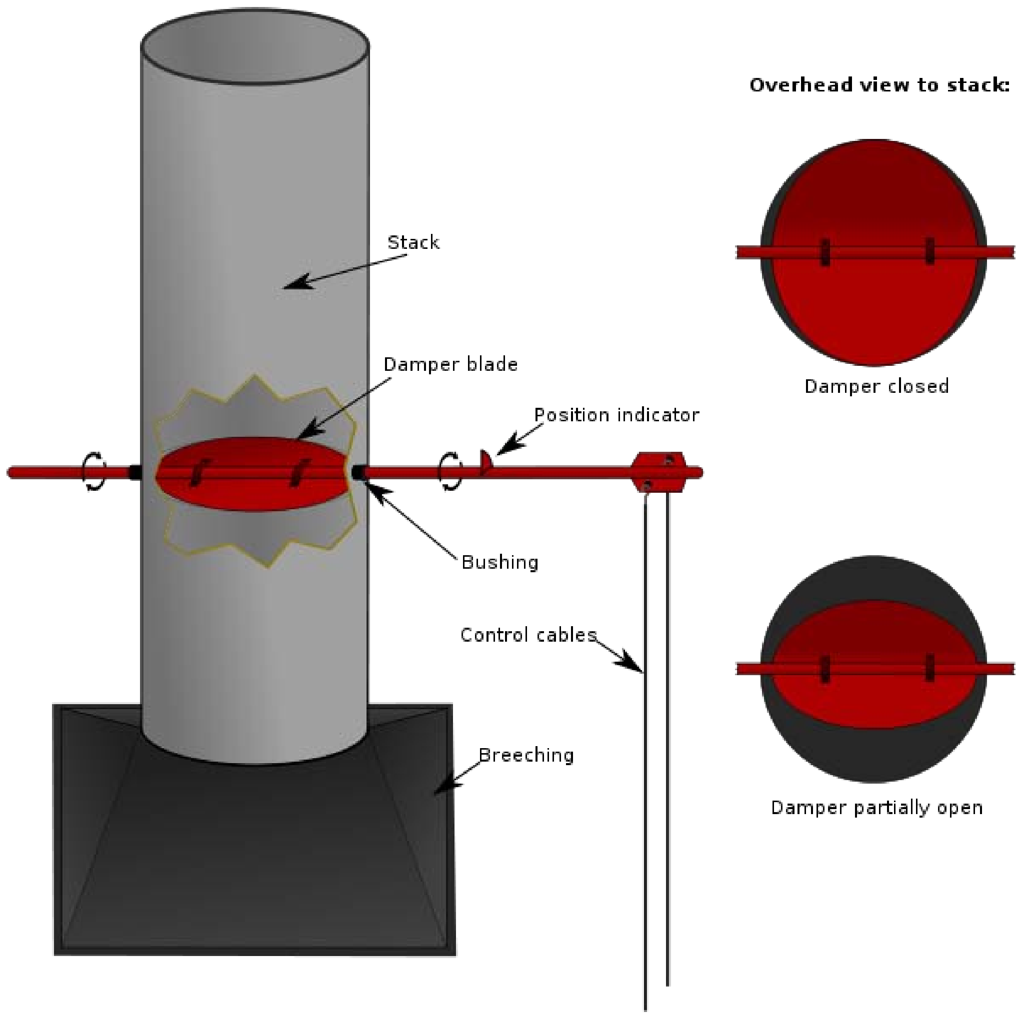
The burner in the vertical, cylindrical furnace as above, is located in the floor and fires upward. Some furnaces have side fired burners, such as in train locomotives. The burner tile is made of high temperature refractory and is where the flame is contained in. Air registers located below the burner and at the outlet of the air blower are devices with movable flaps or vanes that control the shape and pattern of the flame, whether it spreads out or even swirls around. Flames should not spread out too much, as this will cause flame impingement. Air registers can be classified as primary, secondary and if applicable, tertiary, depending on when their air is introduced. The primary air register supplies primary air, which is the first to be introduced in the burner. Secondary air is added to supplement primary air. Burners may include a premixer to mix the air and fuel for better combustion before introducing into the burner. Some burners even use steam as premix to preheat the air and create better mixing of the fuel and heated air. The floor of the furnace is mostly made of a different material from that of the wall, typically hard castable refractory to allow technicians to walk on its floor during maintenance.

A furnace can be lit by a small pilot flame or in some older models, by hand. Most pilot flames nowadays are lit by an ignition transformer (much like a car's spark plugs). The pilot flame in turn lights up the main flame. The pilot flame uses natural gas while the main flame can use both diesel and natural gas. When using liquid fuels, an atomizer is used, otherwise, the liquid fuel will simply pour onto the furnace floor and become a hazard. Using a pilot flame for lighting the furnace increases safety and ease compared to using a manual ignition method (like a match).

Sootblower

Sootblowers are found in the convection section. As this section is above the radiant section and air movement is slower because of the fins, soot tends to accumulate here. Sootblowing is normally done when the efficiency of the convection section is decreased. This can be calculated by looking at the temperature change from the crossover piping and at the convection section exit. Sootblowers utilize flowing media such as water, air or steam to remove deposits from the tubes. This is typically done during maintenance with the air blower turned on. There are several different types of sootblowers used. Wall blowers of the rotary type are mounted on furnace walls protruding between the convection tubes. The lances are connected to a steam source with holes drilled into it at intervals along its length. When it is turned on, it rotates and blows the soot off the tubes and out through the stack.

Stack



Stack damper

The flue gas stack is a cylindrical structure at the top of all the heat transfer chambers. The breeching directly below it collects the flue gas and brings it up high into the atmosphere where it will not endanger personnel.

The stack damper contained within works like a butterfly valve and regulates draft (pressure difference between air intake and air exit)in the furnace, which is what pulls the flue gas through the convection section. The stack damper also regulates the heat lost through the stack. As the damper closes, the amount of heat escaping the furnace through the stack decreases, but the pressure or draft in the furnace increases which poses risks to those working around it if there are air leakages in the furnace, the flames can then escape out of the firebox or even explode if the pressure is too great.

Insulation

Insulation is an important part of the furnace because it prevents excessive heat loss. Refractory materials such as firebrick, castable refractories and ceramic fibre, are used for insulation. The floor of the furnace are normally castable type refractories while those on the walls are nailed or glued in place. Ceramic fibre is commonly used for the roof and wall of the furnace and is graded by its density and then its maximum temperature rating. For example, 8# 2,300 °F means 8 lb/ft^3 density with a maximum temperature rating of 2,300 °F. An example of a castable composition is kastolite.

First fire

The **first fire** is the moment when a furnace or another heating device (usually for industrial use such as metallurgy or ceramics) is first lit after its construction. The refractory of the furnace walls should be as dry as possible and the first fire should be done slowly with a small flame as the refractory of the still unfired furnace has a minimal amount of moisture. Gradually or during subsequent firings, the flame or heat source (e.g. Kanthal heating elements) can be turned up higher.

After first fire some adjustments should be done usually to fine-tune the furnace. Despite this, a first fire is always a moment of great excitement for the people who designed and built the furnace.

Outdoor wood-fired boilers

Description

An outdoor wood-fired boiler (OWB) also known as a waterstove or outdoor wood furnace or simply a wood boiler, is a heating technology that has grown in popularity in the Northern United States. OWBs in most cases look like a small shack with metal siding. They are self-contained, and are only connected to the building they heat through underground insulated water pipes. OWBs contain a metal combustion chamber for a wood fire, which is surrounded by a water tank or water jacket. The fire heats the water, which is then circulated through the insulated water pipes into the heated building. Once the hot water from the boiler reaches the building, the heat from the hot water can be transferred to most existing heating systems and the building's hot water supply.

A damper and fan on the boiler interacts with a thermostat inside the building. If the building's temperature falls, the thermostat will trigger the damper to open, letting oxygen enter the combustion chamber, which causes the fire to burn more intensely. The fire will then raise the temperature of the water which increases the heat supplied to the home.

Benefits

OWBs have several benefits that increase their popularity. Their large combustion chamber accommodates more fuel than many other forms of wood heat, decreasing the number of times an owner has to add fuel to the fire. Home insurance may cost more for people who heat with an indoor form of wood heat than with an OWB. Finally, for people with a large supply of free wood and willing to invest the time to prepare the wood and stock the OWB, an OWB can be less expensive than heating with gas, oil, or electricity.

Controversy

OWBs are not without controversy, as their emissions sometimes bother neighbors. Some states and municipalities have regulated the devices. They are not currently regulated by the United States Environmental Protection Agency (EPA), unlike other forms of wood heat. However, recently the EPA has worked with manufacturers to develop a method for manufacturers to identify OWBs that meet a voluntary emissions standard. Studies conducted on OWBs suggest that these devices may produce more emissions, most notably particulate matter under 2.5 micrometers (PM2.5) than other heating technologies, though manufacturers dispute these assessments . Exposure to elevated levels of PM2.5 has been associated with cardiopulmonary health effects and premature death.

As of July 2006, the HPBA, along with many of the major OWB manufactures, have requested users of their products follow the "Outdoor Wood Furnace Best Burn Practices". These guidelines have been set up by the HPBA to help cut down on problems associated with OWBs.

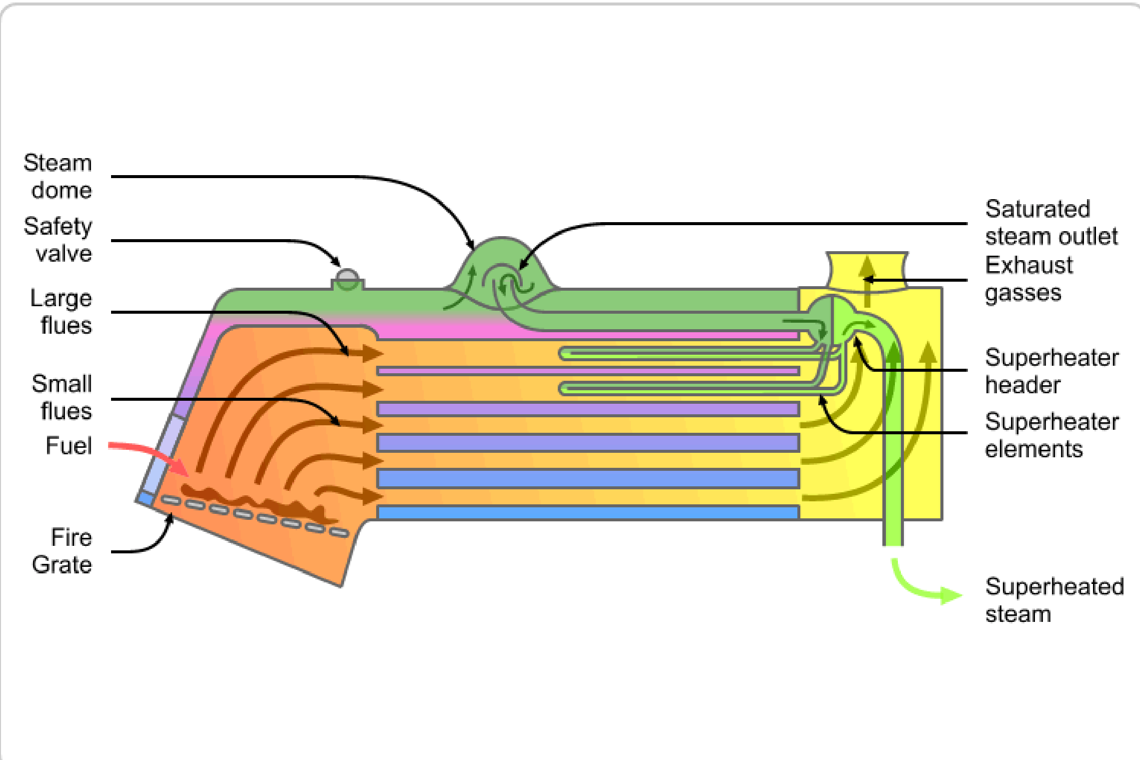
Early in January 2007, the United States Environmental Protection Agency (EPA) initiated a voluntary program for manufacturers of outdoor wood furnaces. The EPA's primary intent is to encourage manufacturers to produce cleaner Outdoor Wood-fired Hydronic Heaters (OWHH) models. The EPA also wants those who buy an OWHH / OWB to buy the cleanest models available, which are those that meet EPA performance verified levels. To participate in this program, manufacturers commit their best efforts to develop cleaner models with goals of distributing their units starting in April 2007.

The EPA now publishes a list of all OWHH / OWB units that pass the new voluntary program. These furnaces come with either an orange EPA tag, signifying Level 1 certification, or a white EPA tag, signifying Level 2 certification, to notify the customer of the units particular emission level output. (One beneficial aspect of this process to consumers is that outdoor wood boilers that are EPA-certified are usually more energy efficient than those that are not, extracting more energy per unit of wood, and thus reducing costs to the owner. Plus, consumers benefit by knowing that such boilers are far less likely to annoy their neighbors.)

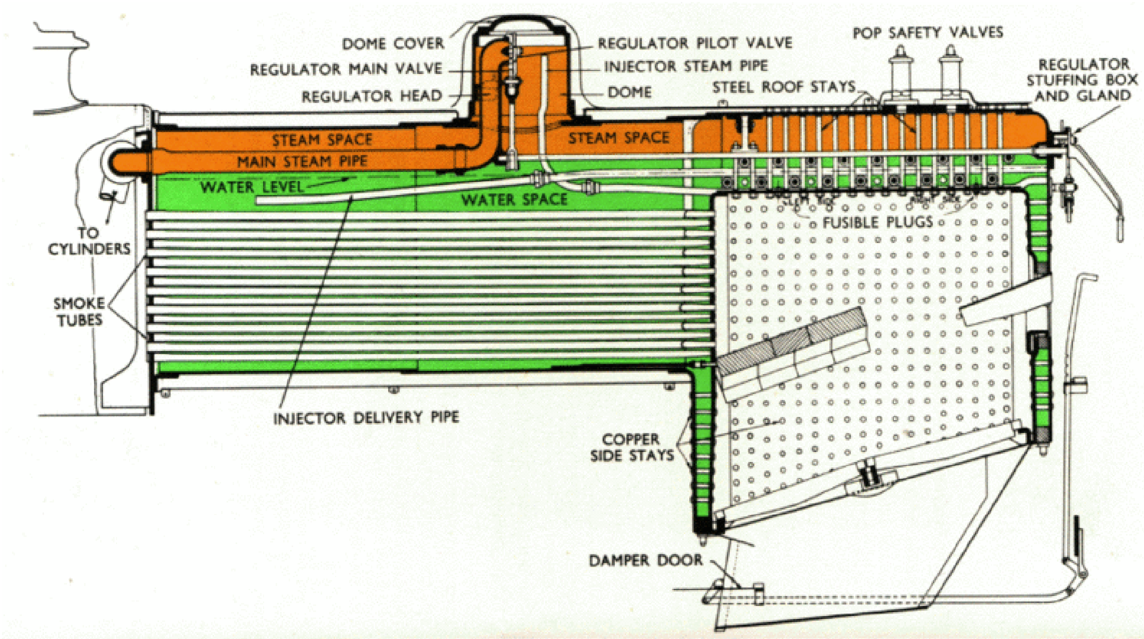
Boilers that do pollute enough to cause a public nuisance (such as by smoke wafting into the house of a neighbor) can be subject to lawsuits by nearby people who are impacted by the smoke nuisance in question, an ancient right under the common law for the abatement of nuisance. This is in addition to local and state regulations, laws, or ordinances that cause restrictions on operation to or even compel removal of excessively polluting boilers. For example, the Commonwealth of Massachusetts Department of Environmental Protection has barred the sale, installation, or use of new outdoor wood boilers that are not Level 2 certified by the EPA, though old boilers remain grandfathered so long as they do not cause a public nuisance or manifestly impact health and safety.

Chapter 4

Firebox (Steam Engine)



Components of a locomotive boiler, firebox at the left



Section of typical boiler and firebox

In a steam engine, the **firebox** is the area where the fuel is burned, producing heat to boil the water in the boiler. Most are somewhat box-shaped, hence the name.

Railway locomotive firebox

The firedoor into the firebox of a steam locomotive

In the standard steam locomotive firetube type boiler, the firebox is surrounded by water space on five sides. The underside is not so surrounded. If the engine burns solid fuel, there is a grate covering most of the bottom of the firebox to hold the fuel. An ashpan collects the solid combustion waste below. Combustion air generally enters at the base, and the airflow is usually controlled by damper doors.

Brick arch

There is a large brick arch (made from fire brick) at the front of the box which directs heat and flames back towards the firedoor at the rear. Without the arch, flames would be sucked straight into the firetubes, and only the front of the box would receive heat. The brick arch and the bars of the grate require periodic replacement due to the extreme heat they endure.

Firetubes

Firetubes are attached to one wall of the firebox (the front wall for a longitudinal boiler, the top for a vertical boiler) and carry the hot gaseous products of combustion through the boiler water, heating it, before they escape to the atmosphere.

Sheets and stays

Cutaway of locomotive firebox and boiler. Note the stays to support the "sheets" (plates) against pressure, the fusible plugs and the "mudhole" to allow access for scraping away scale

The metal walls of the firebox are normally called *sheets*, which are separated by *stays*. Since any corrosion is hidden, the stays may have longitudinal holes, called *tell-tales*, drilled in them which leak before they become unsafe. The *crown sheet* is the top of the firebox.

Belpaire firebox

Normally the top of the firebox is semicircular to match the contour of the boiler, however the Belpaire firebox has more of a square shape and is usually made as large as possible within the loading gauge, to offer the greatest heating surface where the fire is hottest.

Wootten firebox

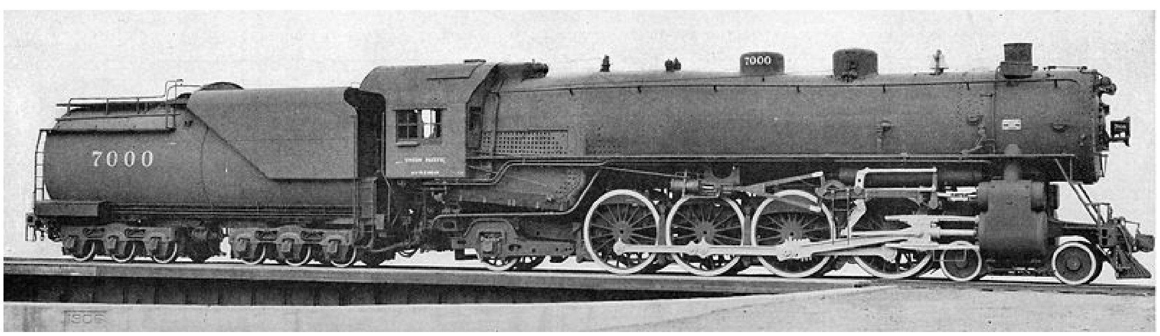
The Wootten firebox was very tall and wide to allow combustion of anthracite coal waste. Its size necessitated unusual placement of the crew, examples being camelback locomotives.

Combustion chamber

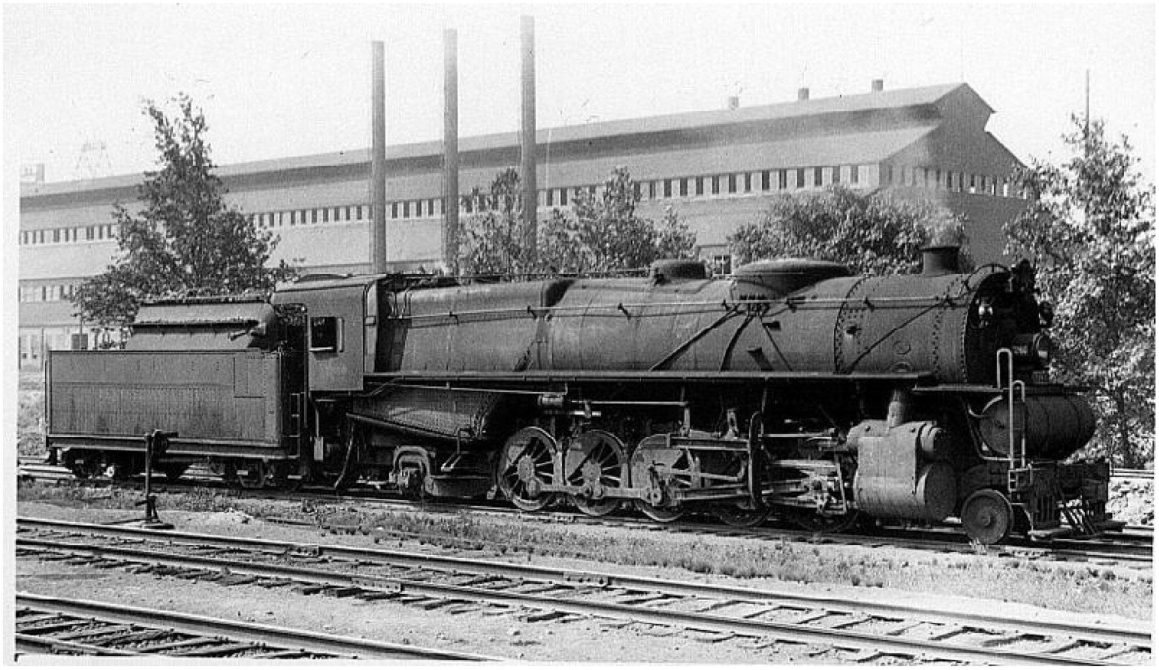
Some fireboxes were equipped with a so-called combustion chamber which placed additional space between the fire and the boiler. This allowed more complete combustion and thus greater heat.

Fireman's duties

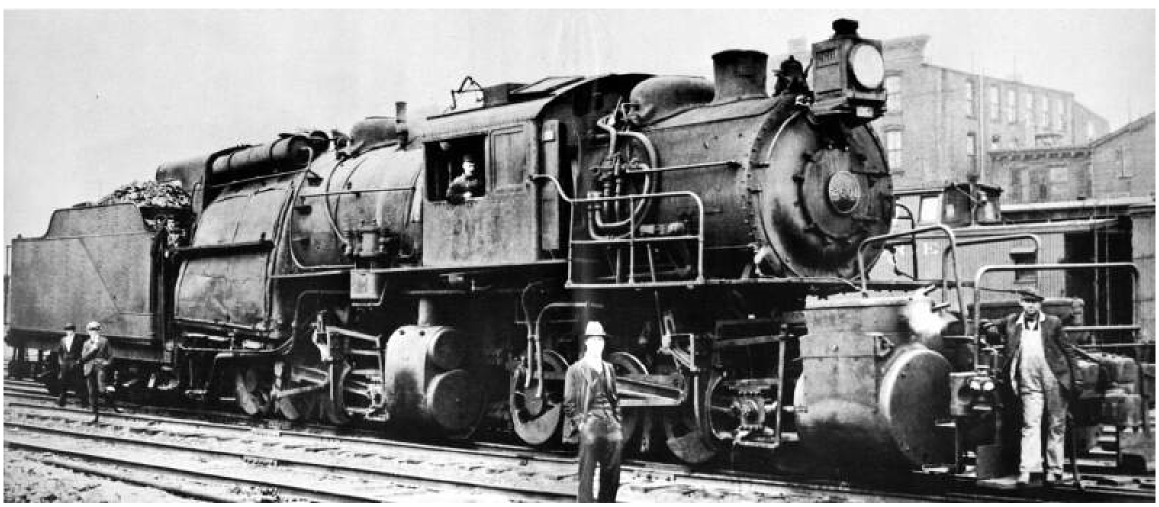
The fireman's role on a steam locomotive is to ensure the driver (engineer) has an adequate supply of steam at his disposal at all times. This is achieved by maintaining a supply of fuel to the fire, and by maintaining the boiler water level so that it covers the firebox crown sheet at all times – otherwise, the latter will overheat and weaken, and a boiler explosion may result. In addition, the fireman also serves as a backup for the driver, keeping a lookout ahead.



Locomotive with a normal firebox. The round top of the firebox makes attaching the boiler easier



The flat sides and square corners show the shape of the Belpaire firebox. This offers a greater heating surface, increasing the efficiency of the engine



The Wootten firebox can be seen as the large construction just in front of the tender. Note the unusual position of the drivers cab. The fireman was left exposed between firebox and tender

Road locomotive firebox

Road locomotives, such as traction engines, usually had fireboxes similar to those on railway locomotives but there were exceptions, e.g. the Sentinel steam waggon which had a vertical water tube boiler.

Stationary boiler firebox

There were, and are, many different designs of firebox for stationary boilers. In flue-type boilers (e.g. the Lancashire boiler) the flues themselves form the firebox. In water-tube boilers, the firebox is usually a firebrick-lined compartment below the water tubes.

Marine boiler firebox

In marine boilers there are also various different types of firebox. The main distinction is, again, between fire-tube types (e.g. the Scotch boiler, with internal firebox) and water-tube types (e.g. the Yarrow boiler, with external firebox).

Chapter 5

Round-Topped Boiler and Pistol Boiler

Round-topped boiler

Round-topped boiler from 'Austerity' saddle tank locomotive 3809, removed for overhaul. The 'waisted' firebox is at the far end of the boiler

A **round-topped boiler** is a type of boiler used for some designs of steam locomotive and portable engine. It was an early form of locomotive boiler, although continuing to be used for new locomotives through to the end of steam locomotive manufacture in the 1960s.

They use the early form of firebox, where the outer wrapper of the firebox is a semi-circular continuation of the cylindrical boiler barrel. They are relatively simple in shape and manufacture, but their design and service is complicated by the difference in shape between the outer and the flat-topped inner wrapper of the firebox. This requires complex staying to support it.

The first boilers of this form had raised fireboxes that were considerably larger, particularly higher, than the boiler barrel. In the extreme case, this gave rise to the Gothic boiler, where the firebox was raised into a vaulted dome. In most cases though, the firebox was merely larger by the width of the internal iron framing section. Around 1850, at the instigation of Crampton, the firebox adopted the flush-topped firebox casing, where it was of the same diameter as the boiler barrel and joined to it by riveted lap strips.

The early boiler fireboxes had flat parallel sides (see figure 1). As locomotives grew in power their boilers expanded in diameter, but the width of the firebox grate was still constrained by the need to fit between the locomotive frames, which were themselves constrained by the gauge between the wheels. This led to the development of the "waisted" form (see figure 2), where a narrow firebox flared upwards and outwards to meet the boiler barrel. Staying of these firebox side walls could still use simple short rod stays, although these were progressively tilted in the middle of the firebox, so as to remain perpendicular to the sheets.

Because the shape of the firebox follows the shape of the boiler barrel, they are used for saddle tank locomotives. The Hunslet *Austerity*, the last production steam locomotives to be constructed in the UK, used this form.

Staying

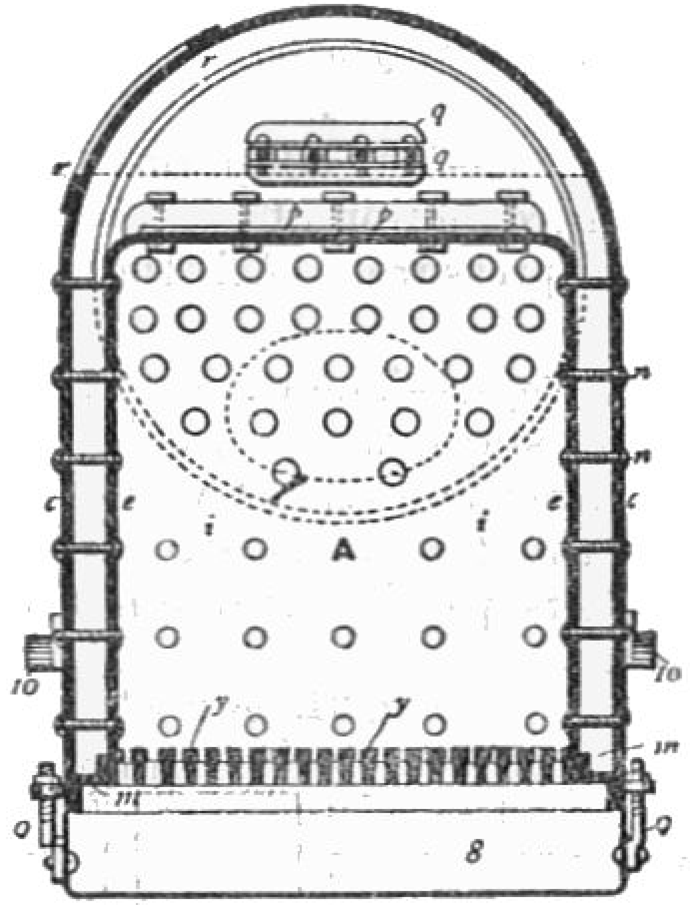


Figure 1 – Early flat-sided girder-stayed boiler

The upper crown sheet of the inner firebox is, as with most locomotive boilers, approximately flat and horizontal, so as to maintain a constant depth of water over this hottest part of the firebox. This flat surface, with steam pressure on its upper side, requires stays to support it. As it is not a constant distance from the boiler barrel, unlike the firebox sides, this staying is difficult to arrange.

Girder stays

Early examples soon used girder stays to support the inner firebox crown. These are iron girders spanning the length or width, on the outside of the inner firebox (i.e. in the water space). The crown sheet is bolted to these. The force on the ends of the girder stays is supported by the ends or sides of the *inner* firebox. The upper part of the boiler barrel is unconnected to the firebox. This has the advantage that a large hole may be cut in the boiler directly above the firebox, to mount the steam dome.

Rod and sling stays

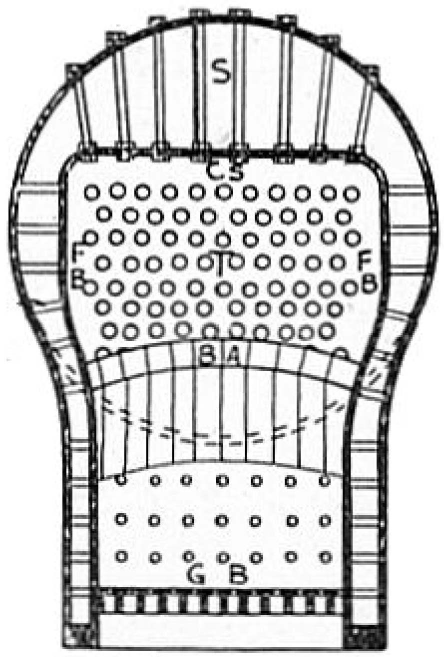


Figure 2 – Section through "waisted" round-topped boiler firebox with long rod stays

Larger boilers could not support their firebox crowns entirely on the inner firebox and required a means to support it from the boiler barrel. As this is also forced outwards by the steam pressure, the total force could be shared between many small stays. Each stay carried enough force on each end to balance itself, avoiding the large bending forces at the ends of the girder stays

Thermal expansion was a problem for these long rod stays, both in their expansion tending to elongate them and reduce their staying effect . Also as the inner firebox expanded in length, this would bend the stays forwards. Where a long firebox was stayed, the forward rod stays were replaced with sling stays, a rod stay with a hinge at the upper end, allowing it to move forwards with the firebox.

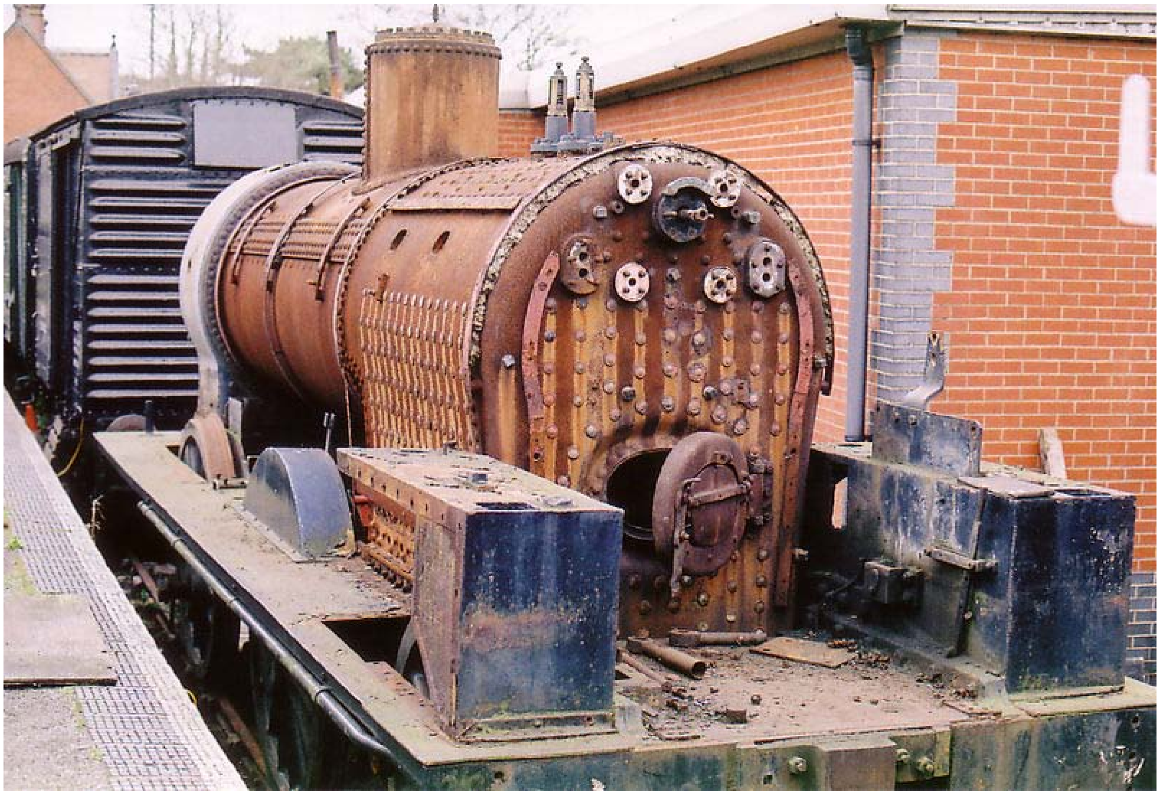
These stays were also placed in the most active part of the boiler, where corrosion was at its worst. Careful inspection and periodic replacement of them was needed, to avoid the risk of a boiler explosion.

The main difficulty of rod stays was that it required a large number of rod stays, each of which was placed at a different angle to its neighbour. The complexity of this rod staying was what drove Alfred Belpaire to develop his Belpaire firebox. This used a more complicated squared-off outer firebox, which was more difficult to manufacture, but could now use simple short rod stays throughout, as for the firebox sides.

Examples

Locomotive designs fitted with round-topped boilers:

NER Class C1 876 at Beamish Museum in 2001



Same locomotive, 876, dismantled for overhaul in 2008

Pistol boiler

Robey & Co 'Express' steam tractor, with Robey's pistol boiler

1925 Robey tandem roller #42693, now owned by the Robey Trust

A **pistol boiler** is a design of steam boiler used in light steam tractors and overtype steam wagons. It is noted for the unusual shape of the firebox, a circular design intended to be self-supporting without the use of firebox stays.

The name 'pistol boiler' derives from the smooth curve of the outer firebox flowing into the boiler barrel, and a supposed resemblance to the stock of an early 19th century pistol.

The locomotive boiler had become well established since Stephenson's day; although the cost and complexity of its firebox remained a drawback, particularly for small boilers. If the top crown sheet of the inner firebox was made flat, so as to maintain a constant water depth above it, this required complex and expensive girder stays to support it. These stays were also a safety-critical part of the boiler and many past boiler explosions had been caused by their failure. This was especially so for boilers that were likely to be used at all carelessly, or by crews who were less skilled or well-trained.

Clearly the market for small steam traction engines could make use of a novel boiler design that avoided these problems. Following the lead of the London & Birmingham Railway's Bury locomotives, some small portable engines were already using cylindrical stayless fireboxes. These combined a cylindrical vertical drum with a domed top, both shapes that could support themselves well under pressure. In extreme cases for larger railway locomotives, these became the massive brass-clad 'Gothic' fireboxes that were so distinctive on early Great Western Railway locomotives.

The firm of Robey & Co, well-known builders of both large stationary engines and small steam tractors, developed its own version of this stayless domed firebox as the **pistol boiler**.

As the boiler was small, with a barrel diameter of only 2', it was practical to form the deeply curved plates for the inner and outer firebox with a hydraulic press. The inner firebox was formed in one piece as a truncated cone with a domed top. The front face of this cone was flattened inwards, to form the firebox tubeplate. 54 1½inch fire-tubes were used. The boiler barrel was cylindrical, but the lower part of the rear end was cut on a diagonal, rather than straight across. The lower part of the outer firebox was also conical and wrapped over this diagonal edge. The foundation ring was circular, avoiding the problems of mud build-up in the corners. The upper corner of the outer firebox was a separate plate, approximately a quarter of a sphere. Rather than the time-consuming and costly flanging of flat plates, these curved plates could be pressed and riveted together almost immediately. The number of boiler plates was also reduced, from the usual eight to only five.

The firebox door was also of novel design. As the backplate sloped so steeply, the door was top-hinged and opened inwards, rather than outwards. This also had the effect of acting as a deflector plate, directing the cold draught down onto the firebed, rather than directly across and into the tubes.

Robey used this design of boiler on their 6-ton steam wagons and 'Express' steam tractors, also their tandem steam rollers. One of these rollers was the first artefact to be preserved by the Robey Trust. When the boiler was re-barreled in 1988, this was the last boiler to be constructed by the Robey factory before closure. On their larger engines, Robey used a conventional boiler.

Chapter 6

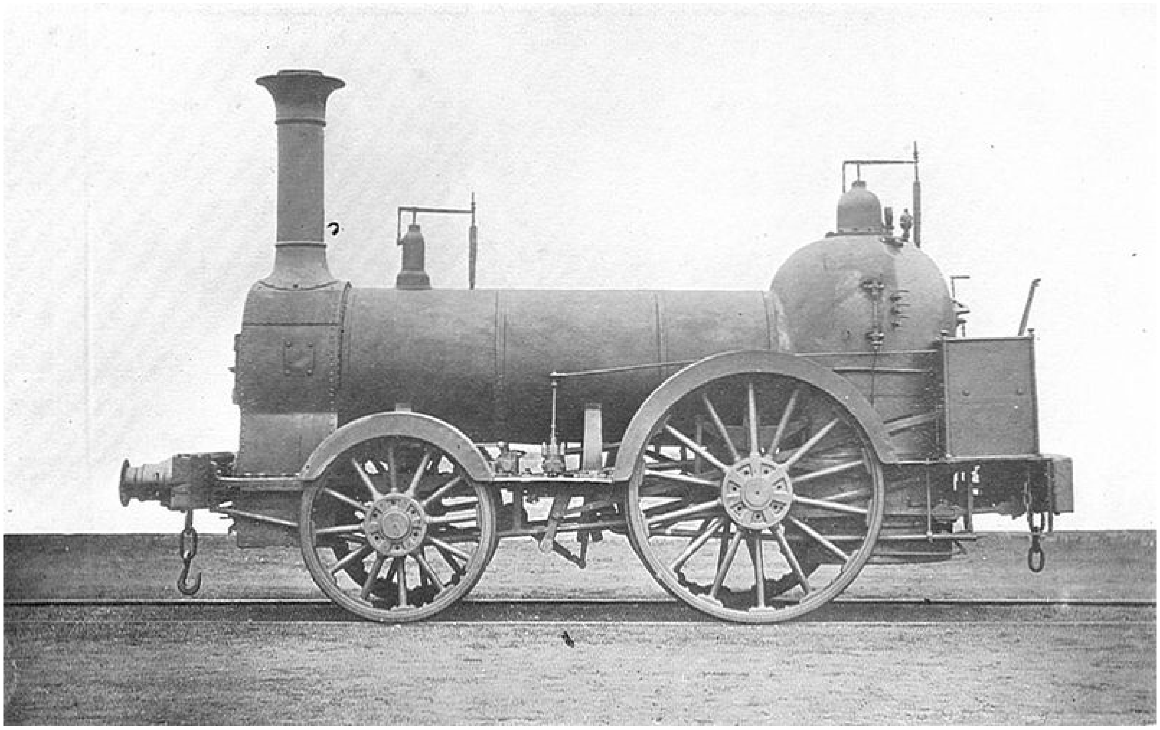
Gothic Boiler and Flue Gas Stack

Gothic boiler

French locomotive *L'Aigle*

A **gothic boiler** is an early form of steam locomotive boiler with a prominently raised firebox of "Gothic arch", "haystack", or "coppernob" shape. The term haystack is most commonly used, but is avoided here as it is confusingly used for three quite different forms of boiler. This particularly large outer firebox served as the steam dome and was often highly decorated with polished brass. These were popular for early railway locomotives, from 1830 to around 1850.

Haystack firebox



London & Birmingham Railway 2-2-0 Bury locomotive

The prominently raised firebox first appeared in 1830, in Bury's 0-4-0 locomotive *Liverpool*. This was the progenitor of his bar-frame locomotives and shared their distinctive boiler design. The inner firebox was D-shaped in plan, with a flat tubeplate. Fireboxes of this time did not yet have a brick arch and so the Bury firebox was relatively short in length but tall, to give an adequate length of combustion path. The outer firebox was a vertical cylinder, formed into a tall hemispherical dome above it. Later Bury designs were flattened on top and became known as "haystacks".

Gothic arch firebox

A regular problem with early steam locomotives was that of priming, the carry-over of water with the steam. Many varieties of steam dome on the boiler barrel were tried to avoid this, by taking the steam outlet from as high as possible above the waterline. Stephenson's *Rocket* of 1829 had used such a small steam dome. In the 1830s, domes became extravagantly large. A drawback to fitting such large domes was the weakening of the boiler shell where such a large hole was cut into it.

In 1840, Stephenson produced their 2-2-2 design which avoided the dome altogether, in favour of a raised firebox in the Bury style of ten years earlier. Boiler power had increased considerably over the decade, now requiring a larger fire grate area. The inner and outer fireboxes were square in plan, with flat sides that required staying. At the top these four sides were vaulted inwards to a point, having a profile approximating a thenfashionable Gothic arch. These provided a large steam space above the waterline, but their flat surfaces limited working pressure.

Stephenson used the Gothic arch firebox for their long-boiler locomotives as well, including their 2-2-2 *North Star* of 1841 and outside-cylindered 2-2-2s for the Yarmouth and Norwich Railway in 1844.

GWR *Firefly* class

The *Gothic arch* firebox was also notably used by a number of Gooch's Great Western Railway broad-gauge locomotives, including the *Firefly*, *Leo* and *Hercules* classes of 1840-1842.

One well-known locomotive that did *not* use a Gothic boiler, despite its appearance, was the L&MR *Lion* of 1838. This used a semi-cylindrical raised firebox, hidden beneath a purely decorative brass facsimile of the Gothic boiler.

Other makers of haystack fireboxes

Some makers retained the Bury pattern of a hemispherical firebox. The American-built 4-2-0 Norris locomotives for the Birmingham and Gloucester Railway resembled an enlarged Bury design with outside cylinders and still retained their small D-shaped inner firebox. Kitson also built a number of long-boiler 0-6-0s around 1845, also using the hemispherical haystack firebox.

Coppernob

Bury also built Furness Railway Nº 3 of 1846, one of the few surviving locomotives of this style and period. This locomotive acquired the name "Coppernob", on account of its polished copper outer cladding, which it then gave generically to this style of boiler.

Demise

By around 1850 the haystack and Gothic boiler had fallen from favour. Boiler working pressures had risen from 80 psi to the 120 psi of the *Jenny Lind*, making the flat surfaces of the Gothic firebox unsupportable. Future locomotives returned to the use of the steam dome.

Flue gas stack

Flue gas stack at GRES-2 Power Station in Ekibastusz, Kazakhstan

A **flue gas stack** is a type of chimney, a vertical pipe, channel or similar structure through which combustion product gases called flue gases are exhausted to the outside air. Flue gases are produced when coal, oil, natural gas, wood or any other fuel is combusted in an industrial furnace, a power plant's steam-generating boiler, or other large combustion device. Flue gas is usually composed of carbon dioxide (CO_2) and water vapor as well as nitrogen and excess oxygen remaining from the intake combustion air. It also contains a small percentage of pollutants such as particulate matter, carbon monoxide, nitrogen oxides and sulfur oxides. The flue gas stacks are often quite tall, up to 400 metres (1300 feet) or more, so as to disperse the exhaust pollutants over a greater area and thereby reduce the concentration of the pollutants to the levels required by governmental environmental policy and environmental regulation.

When the flue gases are exhausted from stoves, ovens, fireplaces, or other small sources within residential abodes, restaurants, hotels, or other public buildings and small commercial enterprises, their flue gas stacks are referred to as chimneys.

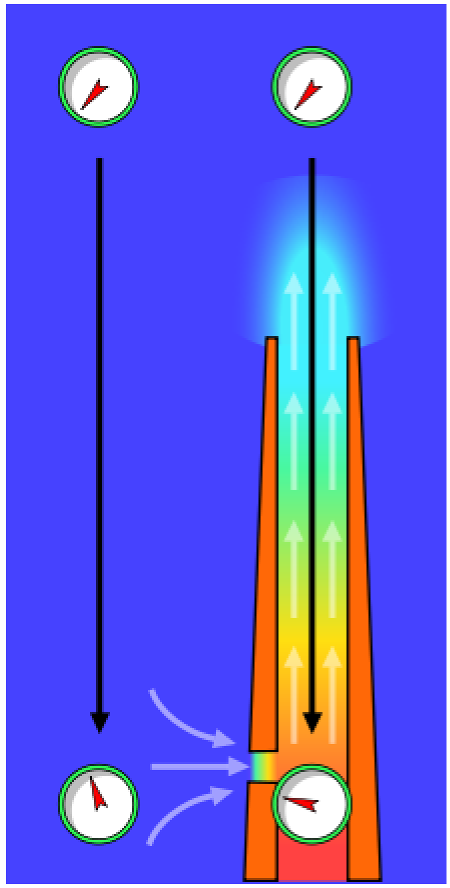
History

The first industrial chimneys were built in the mid-17th century when it was first understood how they could improve the combustion of a furnace by increasing the draught of air into the combustion zone. As such, they played an important part in the development of reverberatory furnaces and a coal-based metallurgical industry, one of the key sectors of the early Industrial Revolution. Most 18th century industrial chimneys (now commonly referred to as **flue gas stacks**) were built into the walls of the furnace much like a domestic chimney. The first free-standing industrial chimneys were probably those erected at the end of the long condensing flues associated with smelting lead.

The powerful association between industrial chimneys and the characteristic smoke-filled landscapes of the industrial revolution was due to the universal application of the steam engine for most manufacturing processes. The chimney is part of a steam-generating boiler, and its evolution is closely linked to increases in the power of the steam engine. The chimneys of Thomas Newcomen’s steam engine were incorporated into the walls of the engine house. The taller, free-standing industrial chimneys that appeared in the early 19th century were related to the changes in boiler design associated with James Watt’s "double-powered" engines, and they continued to grow in stature throughout the Victorian period. Decorative embellishments are a feature of many industrial chimneys from the 1860s, with over-sailing caps and patterned brickwork.

The invention of fan-assisted forced draught in the early 20th century removed the industrial chimney's original function, that of drawing air into the steam-generating boilers or other furnaces. With the replacement of the steam engine as a prime mover, first by diesel engines and then by electric motors, the early industrial chimneys began to disappear from the industrial landscape. Building materials changed from stone and brick to steel and later reinforced concrete, and the height of the industrial chimney was determined by the need to disperse combustion flue gases to comply with governmental air pollution control regulations.

Flue gas stack draught



The stack effect in chimneys: the gauges represent absolute air pressure and the airflow is indicated with light grey arrows. The gauge dials move clockwise with increasing pressure.

The combustion flue gases inside the flue gas stacks are much hotter than the ambient outside air and therefore less dense than the ambient air. That causes the bottom of the vertical column of hot flue gas to have a lower pressure than the pressure at the bottom of a corresponding column of outside air. That higher pressure outside the chimney is the driving force that moves the required combustion air into the combustion zone and also moves the flue gas up and out of the chimney. That movement or flow of combustion air and flue gas is called "natural draught", "natural ventilation", "chimney effect", or "stack effect". The taller the stack, the more draught is created.

The equation below provides an approximation of the pressure difference, ΔP, (between the bottom and the top of the flue gas stack) that is created by the draught:

$$\Delta P = C\,a\,h\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

where:

ΔP = available pressure difference, in Pa

C = 0.0342

a = atmospheric pressure, in Pa

h = height of the flue gas stack, in m

T_o = absolute outside air temperature, in K

T_i = absolute average temperature of the flue gas inside the stack, in K

The above equation is an approximation because it assumes that the molar mass of the flue gas and the outside air are equal and that the pressure drop through the flue gas stack is quite small. Both assumptions are fairly good but not exactly accurate.

The flue gas flow rate induced by the draught

As a "first guess" approximation, the following equation can be used to estimate the flue gas flow rate induced by the draught of a flue gas stack. The equation assumes that the molar mass of the flue gas and the outside air are equal and that the frictional resistance and heat losses are negligible:

$$Q = C\ A\ \sqrt{2\ g\ H\ \frac{T_i - T_o}{T_i}}$$

where:

Q = flue gas flow rate, m^3/s

A = cross-sectional area of chimney, m^2 (assuming it has a constant cross-section)

C = discharge coefficient (usually taken to be from 0.65 to 0.70)

g = gravitational acceleration at sea level, 9.807 m/s^2

H = height of chimney, m

T_i = absolute average temperature of the flue gas in the stack, K

T_o = absolute outside air temperature, K

Designing chimneys and stacks to provide the correct amount of natural draft involves a great many factors such as:

- The height and diameter of the stack.
- The desired amount of excess combustion air needed to assure complete combustion.
- The temperature of the flue gases leaving the combustion zone.
- The composition of the combustion flue gas, which determines the flue gas density.
- The frictional resistance to the flow of the flue gases through the chimney or stack, which will vary with the materials used to construct the chimney or stack.
- The heat loss from the flue gases as they flow through the chimney or stack.

- The local atmospheric pressure of the ambient air, which is determined by the local elevation above sea level.

The calculation of many of the above design factors requires trial-and-error reiterative methods.

Governmental agencies in most countries have specific codes which govern how such design calculations must be performed. Many non-governmental organizations also have codes governing the design of chimneys and stacks (notably, the ASME codes).

Stack design

The design of large stacks poses considerable engineering challenges. Vortex shedding in high winds can cause dangerous oscillations in the stack, and may lead to its collapse. The use of helical faring is common to prevent this process occurring at or close to the resonant frequency of the stack.

Other items of interest

Some fuel-burning industrial equipment does not rely upon natural draught. Many such equipment items use large fans or blowers to accomplish the same objectives, namely: the flow of combustion air into the combustion chamber and the flow of the hot flue gas out of the chimney or stack.

A great many power plants are equipped with facilities for the removal of sulfur dioxide (i.e., flue gas desulfurization), nitrogen oxides (i.e, selective catalytic reduction, exhaust gas recirculation, thermal deNOx, or low NOx burners) and particulate matter (i.e., electrostatic precipitator)s. At such power plants, it is possible to use a cooling tower as a flue gas stack. Examples can be seen in Germany at the Power Station Staudinger Grosskrotzenburg and at the Rostock Power Station. Power plants without flue gas purification, would experience serious corrosion in such stacks.

In the United States and a number of other countries, atmospheric dispersion modeling studies are required to determine the flue gas stack height needed to comply with the local air pollution regulations. The United States also limits the maximum height of a flue gas stack to what is known as the "Good Engineering Practice (GEP)" stack height. In the case of existing flue gas stacks that exceed the GEP stack height, any air pollution dispersion modelling studies for such stacks must use the GEP stack height rather than the actual stack height.

Chapter 7

Cofiring

Cofiring is the combustion of two different types of materials at the same time. One of the advantages of cofiring is that an existing plant can be used to burn a new fuel, which may be cheaper or more environmentally friendly. For example, biomass is sometimes cofired in existing coal plants instead of new biomass plants. Cofiring can also be used to improve the combustion of fuels with low energy content. For example, landfill gas contains a large amount of carbon dioxide, which is non-combustible. If the landfill gas is burned without removing the carbon dioxide, the equipment may not perform properly or emissions of pollutants may increase. Cofiring it with natural gas increases the heat content of the fuel and improves combustion and equipment performance. As long as the electricity or heat produced with the biomass and landfill gas was otherwise going to be produced with non-renewable fuels, the benefits are essentially equivalent whether they are cofired or combusted alone. Also, cofiring can be used to lower the emission of some pollutants. For example, cofiring biomass with coal results in less sulfur emissions than burning coal by itself.

Origin of cofiring and meaning according to present technology framework

Cofiring (also referred usually as co-firing or co-combustion) is the combustion of two different fuels in the same combustion system. Fuels can be solid fuels, Liquid fuels or gaseous, and its nature either fossil or renewable. Therefore use of heavy fuels assisting coal power stations may be considered technically co-firing. However the term cofiring is used in the present technological framework to designate combined combustion of two (or more) fuels sustained in the time, as a normal daily practice.

The interest for cofiring and the use of this term sprung in the 80's in the U.S. and Europe, and referred specifically to the use of waste solid residues (paper, plastic, solvents, tars, etc.) or biomass in coal power stations that were initially designed for combustion of sole coal, and attempted, because of existence of those new opportunity fuels, to carry out a combined combustion in order to increase benefit margins. As a matter of fact, this interest on cofiring has grown in the last decade mainly due to the increasing social concerns on global warming and greenhouse gas (GHG) emissions.

Consequences of this concern are the new policies on energy and environment aiming at reducing emissions. Cofiring is regarded as a great opportunity for replacing coal (solid fossil fuel) used for power generation easily with renewable fuels (biomass) with low costs and a direct repercussion in the decrease of greenhouse gas emissions. During the last decades research has provided very diverse solutions for cofiring biomass in coal power stations with a limited impact in efficiency, operation and lifespan.

Under this present context the definition of cofiring could be as next: together use of two (or more) fuels being the principal fossil and the secondary from other nature (renewable or residual) into the boiler originally designed for the fossil fuel, either using same combustion system or additional devices.

Types of cofiring

The concept of cofiring is quite simple. It consists in the use of two or more fuels inside the same combustion device. It is applicable to all kind of combustion systems traditionally used for power generation (pulverized fuel, fluidized bed combustion and grate firing). Cofiring in cement kilns is already a quite widespread solution for valorization of waste materials mostly, as well as for biomass. Iron industry (uses blast furnace)and domestic sector (coal stoves) are also sectors where cofiring could be implemented.

The use of a secondary fuel (biomass or waste) replacing a share of the original fossil fuel may involve from trivial changes in the facility to a complete retrofitting with important reforms. Modifications will depend on the characteristics of the fuels, the original combustion technology, the plant layout and the type and location of auxiliary systems. The percentage of original fuel replaced, also known as cofiring rate (either expressed in mass or in energy basis) is furthermore a definitive parameter limiting the technical solutions valid for a specific plant.

The co-firing systems, according to the current state of the art and the future perspectives, can be classified into **direct** and **indirect** cofiring technologies. The former refer to those systems where combustion of both fuels takes place at the same combustion device or into the same boiler simultaneously. The secondary fuel (biomass, waste) may be either mixed with coal before the combustion starts or fed by a separate device, e.g. specific biomass burners. Indirect cofiring, on the contrary, separates the combustion of both solid fuels, though Combustion Gasses may be mixed afterwards.

Direct biomass **cofiring** systems entail advantages of simplicity and economics. However direct cofiring systems are also more sensitive to variations in fuel quality and heterogeneity. Additionally other problems limit the rate of secondary fuel replacing the original fossil fuels. In example ash deposition (fouling and slagging) and corrosion usually increase with the use of biomass and wastes replacing coal, what may shorten the lifespan of diverse devices in contact with Combustion Gasses like superheaters, heat exchangers, selective catalytic reduction (SCR), etc. Direct cofiring systems include next technological solutions:

- *Co-milling* (in case of solid fuels): blending of primary (coal) and secondary (biomass or waste) fuel, combined milling (in original system) and injection through the coal burners (or feeding system)
- *Co-feeding:* separate treatment of primary and secondary fuels (milling in case of solid fuels), and incorporation of secondary fuel to the main flow. In case of solid fuels the mixture takes place downstream the coal mill.
- *Combined burner:* fuels are treated separately (milled in case of solid fuels) and transported to the burner, where primary fuel uses the original ports and secondary fuel uses new ports or unused ducts. In this case, though feeding does not involve fuel physical mixing, combustion stages takes place simultaneously and with similar aerodynamics to original design.
- *New burners:* fuels use independent feeding lines. Primary fuel uses original injection system, whereas secondary fuel is transported to specific dedicated burners or inlet ports penetrating into the combustion chamber. New burners (injection systems) may replace former burners of primary fossil fuel, or may be installed in new positions in the combustion chamber. This option may involve the use of different combustion systems. In example in a pulverized coal power station a grate firing system may be installed at the bottom of the combustion chamber, though this solution is not frecuent.

Indirect cofiring systems imply usually more complex and expensive solutions, but they reduce usually problems related with corrosion, fouling, slagging, etc. This, a priori, allows cofiring rates larger than direct systems, that is, larger percentages of coal substituted by biomass or waste. As well indirect cofiring systems are in general better for fuel mixtures where secondary fuel may include potential contaminants like heavy metals or other dangerous inorganic compounds.

Main indirect cofiring systems are listed next:

- *Separated burning:* burning of secondary fuel in a separate boiler or system and introduction of flue gases downstream the radiant section of the original boiler.
- *Coupled plant:* separate burning in a new boiler specially designed and built for firing the secondary fuel. Original and new system couple their heating fluid circuits. Combustion gases are not mixed and Exhaust gas must be treated separately.
- *Gasification systems:* the secondary fuel is transformed into gas (with heating value) by means of a gasifier. The resulting syngas is either directly or with a previous treatment, injected in the original combustion chamber or boiler through new dedicated ducts.
- *Pyrolisis:* biomass is transformed into a mixture of gas, bio-oils and char by means of pyrolisis. Fractions may be separated and introduced into the boiler in different sites.

Advantages of cofiring

Use of biomass in co-firing incorporate additional environmental, socio-economic and strategy advantages respect the use of biomass in dedicated biomass plants. In case of waste residues advantages are same, but, however the combustion of waste may change the emissions regulations to satisfy more strict regulations. In example limits in emissions from environmental regulations for large scale combustion facilities are more permissive than regulations for incineration plants. Except for the previous drawback related to waste cofiring, next advantages are common for waste and biomass cofiring:

- *Specific investment (per unit of installed power):* reduced respect conventional biomass facilities since plant using fossil fuel already exists and only diverse modifications are required
- *Power generation with better efficiency:* generally biomass power plants produce electricity with relative low efficiency (18 to 22%) respect the huge coal units (32 to 38%) with optimised cycles given the economy of scale
- *Flexible operation:* original plant can operate still at 100% load with fossil fuel. Co-firing facility is less sensitive to seasonality in biomass production and to biomass availability and price
- *Carrot for development of biomass markets:* diverse European countries have proven the promotion of co-firing is a key for the development of biomass markets as well as for the creation of expertise on biomass handling and combustion

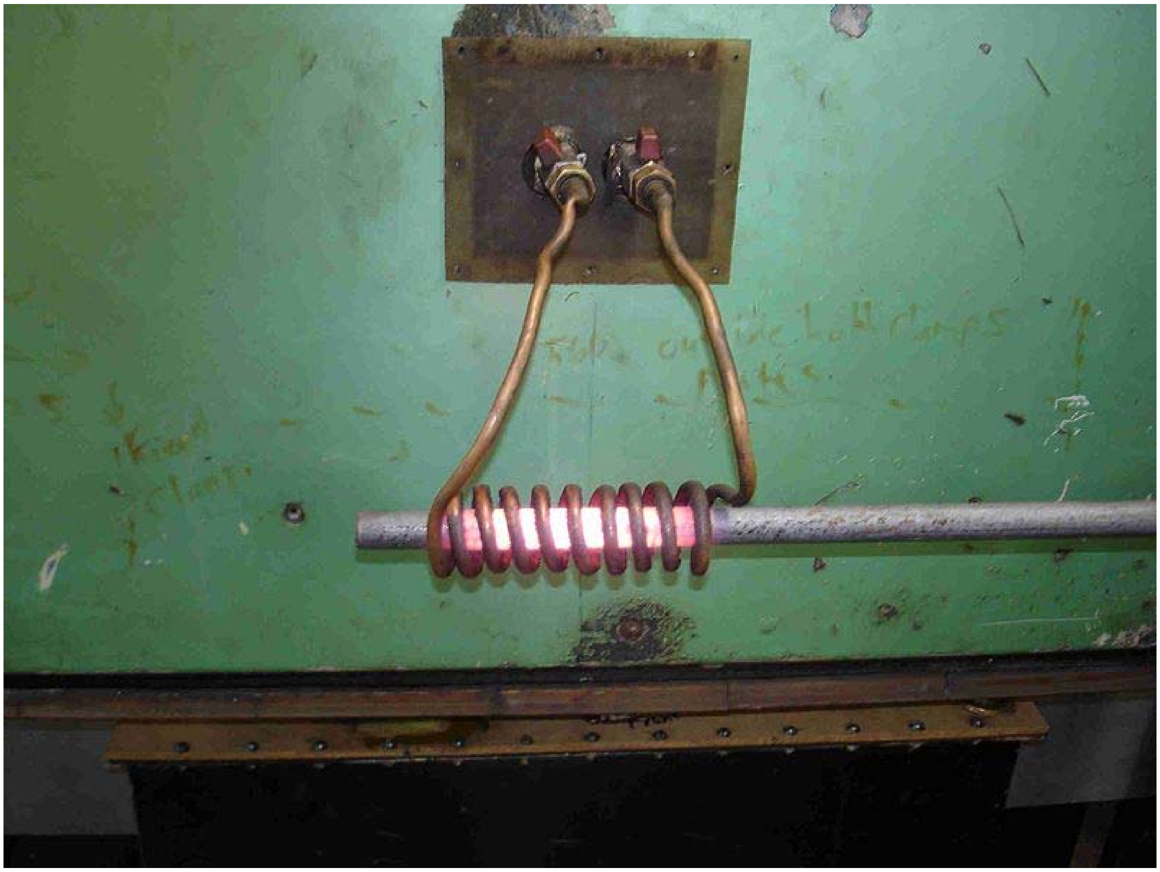
Chapter 8

Induction Heating

Component of Stirling radioisotope generator is heated by induction during testing

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where eddy currents (also called Foucault currents) are generated within the metal and resistance leads to Joule heating of the metal. An induction heater (for any process) consists of an electromagnet, through which a high-frequency alternating current (AC) is passed. Heat may also be generated by magnetic hysteresis losses in materials that have significant relative permeability. The frequency of AC used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth.

Applications



Induction heating of 25 mm metal bar using 15 kW at 450 kHz.

Induction heating allow the targeted heating of an applicable item for applications including surface hardening, melting, brazing and soldering and heating to fit. Iron and its alloys respond best to induction heating, due to their ferromagnetic nature. Eddy currents can, however, be generated in any conductor, and magnetic hysteresis can occur in any magnetic material. Induction heating has been used to heat liquid conductors (such as molten metals) and also gaseous conductors. Induction heating is often used to heat graphite crucibles (containing other materials) and is used extensively in the semiconductor industry for the heating of silicon and other semiconductors. Supply frequency (mains, 50/60 Hz) induction heating is used for many lower cost industrial applications as inverters are not required.

Induction furnace

An induction furnace uses induction to heat metal to its melting point. Once molten, the high-frequency magnetic field can also be used to stir the hot metal, which is useful in ensuring that alloying additions are fully mixed into the melt. Most induction furnaces consist of a tube of water-cooled copper rings surrounding a container of refractory material. Induction furnaces are used in most modern foundries as a cleaner method of melting metals than a reverberatory furnace or a cupola. Sizes range from a kilogram of capacity to a hundred tonnes capacity. Induction furnaces often emit a high-pitched whine or hum when they are running, depending on their operating frequency. Metals melted include iron and steel, copper, aluminium, and precious metals. Because it is a clean and non-contact process it can be used in a vacuum or inert atmosphere. Vacuum furnaces make use of induction heating for the production of specialty steels and other alloys that would oxidize if heated in the presence of air.

Induction welding

A similar, smaller-scale process is used for induction welding. Plastics may also be welded by induction, if they are either doped with ferromagnetic ceramics (where magnetic hysteresis of the particles provides the heat required) or by metallic particles.

Seams of tubes can be welded this way. Currents induced in a tube run along the open seam and heat the edges resulting in a temperature high enough for welding. At this point the seam edges are forced together and the seam is welded. The RF current can also be conveyed to the tube by brushes, but the result is still the same — the current flows along the open seam, heating it.

Induction cooking

In induction cooking, an induction coil in the cook-top heats the iron base of cookware. Copper bottomed pans, aluminium pans and other non-ferrous pans are generally unsuitable.

The heat induced in the base is transferred to the food via conduction. Benefits of induction cookers include efficiency, safety (the induction cook-top is not heated itself) and speed. Drawbacks include the fact that non-metallic cookware such as glass and ceramic cannot be used on an induction cook-top. Both installed and portable induction cookers are available.

Induction brazing

Induction brazing is often used in higher production runs. It produces uniform results and is very repeatable.

Induction sealing

Induction heating is often used in *cap sealing*.

Heating to fit

Induction heating is often used to heat an item causing it to expand prior to fitting or assembly. Bearings are routinely heated in this way using mains frequency (50/60 Hz) and a laminated steel transformer type core passing through the centre of the bearing.

Heat treatment

Induction heating is often used in the heat treatment of metal items. The most common applications are induction hardening of steel parts, induction soldering/brazing as a means of joining metal components and induction Annealing_(metallurgy) to selectively soften a selected area of a steel part.

Induction heating can produce high power densities which allow short interaction times to reach the required temperature. This gives tight control of the heating pattern with the pattern following the applied magnetic field quite closely and allows reduced thermal distortion and damage.

This ability can be used in hardening to produce parts with varying properties. The most common hardening process is to produce a localised surface hardening of an area that needs wear-resistance, while retaining the toughness of the original structure as needed elsewhere. The depth of induction hardened patterns can be controlled through choice of induction-frequency, power-density and interaction time.

There are limits to the flexibility of the process - mainly arising from the need to produce dedicated inductors for many applications. This is quite expensive and requires the marshalling of high current-densities in small copper inductors, which can require specialized engineering and 'copper-fitting'.

Details

The basic setup is an AC power supply that provides electricity with low voltage but very high current and high frequency. The workpiece to heat is placed inside an air coil driven by the power supply, usually in combination with a resonant tank capacitor to increase the reactive power. The alternating magnetic field induces eddy currents in the workpiece.

Applications of frequency ranges

Frequency (kHz)	Workpiece type
5–30	Thick materials
100–400	Small workpieces or shallow penetration
480	Microscopic pieces

Magnetic materials improve the induction heat process because of hysteresis. In essence materials with high permeability (100–500) are easier to heat with induction heating. Hysteresis heating occurs below the Curie temperature where materials lose their magnetic properties.

So high permeability and temperatures below Curie temperature in the workpiece is useful. Also temperature difference, mass, and specific heat influence the workpiece heating.

The energy transfer of induction heating is coupled to the distance between the coil and the workpiece. Energy losses occur through heat conduction from workpiece to fixture, natural convection, and thermal radiation.

The induction coil is usually made of 3.175–4.7625 mm diameter copper tubing and fluid cooled. Diameter, shape, and number of turns influence the efficiency and field pattern.

Core type furnace

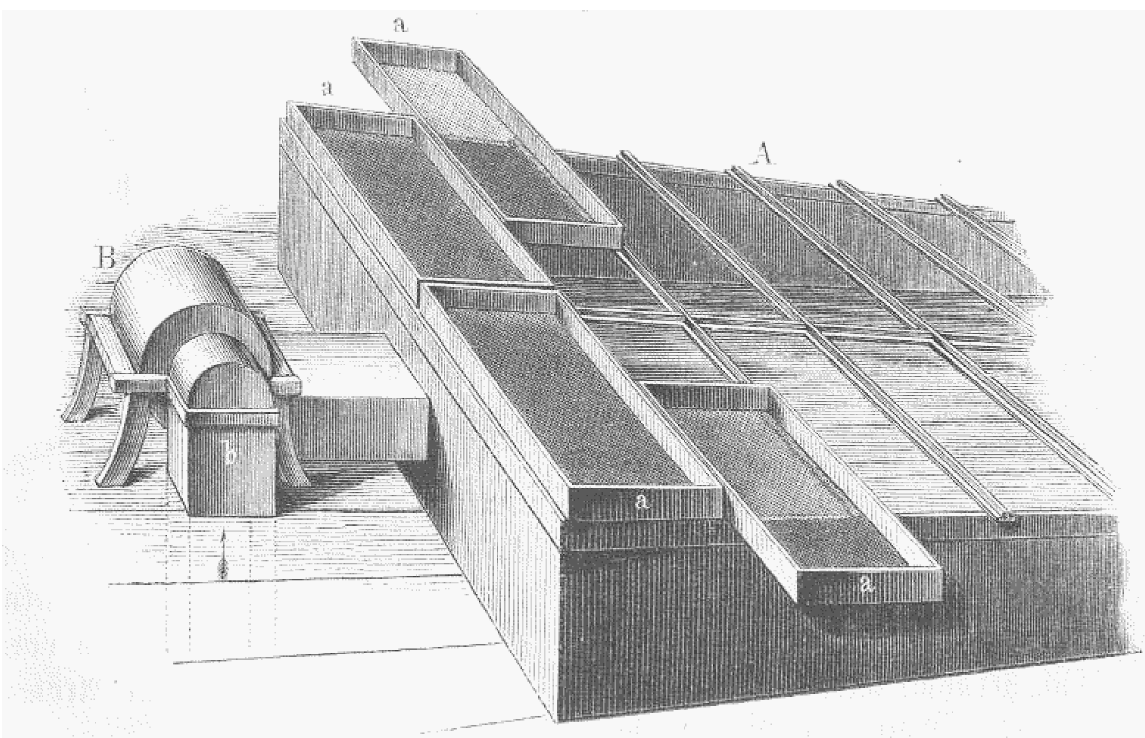
The furnace consists of circular hearth which contains the charge to be melted in the form of angular ring. The metal ring is large in diameter and is magnetically interlinked with an electrical winding energized by an AC source.

Chapter 9

Kiln

Charcoal Kilns, California

Gold Kiln, Victoria, Australia



Hop kiln.

Anagama kiln firing.

Farnham Pottery, Wrecclesham, Surrey with the preserved **bottle kiln** on the right of photo

Catenary arch kiln under construction

An empty, intermittent kiln; note the decorated vase having just been removed from kiln

A **kiln** is a thermally insulated chamber, or oven, in which a controlled temperature regime is produced. Uses include the hardening, burning or drying materials. Kilns are also used for the firing of materials, such as clay and other raw materials, to form ceramics (including pottery, bricks etc.).

Specific other uses include:

- To dry green lumber so that the lumber can be used immediately
- Drying wood for use as firewood
- Heating wood to the point of pyrolysis to produce charcoal
- For annealing, fusing and deforming glass, or fusing metallic oxide paints to the surface of glass
- For cremation (at high temperature)
- Drying of tobacco leaves
- Drying malted barley for brewing and other fermentations
- Drying hops for brewing (known as a hop kiln or oast house)
- Smelting ore to extract metal
- Heating limestone with clay to make cement
- Heating lime to make quicklime or calcium oxide

Ceramic kilns

Kilns are an essential part of the manufacture of all ceramics, which, by definition, require heat treatment, often at high temperature. During this process, chemical and physical reactions occur which cause the material to be permanently altered. In the case of pottery, clay materials are shaped, dried and then fired in a kiln. The final characteristics are determined by the composition and preparation of the clay body, by the temperature at which it is fired, and by the glazes that may be used. Although modern kilns often have sophisticated electrical systems to control the firing temperatures, pyrometric devices have been used to provide visual indication of the firing regime since around 1000 AD.

Clay consists of fine-grained particles, that are relatively weak and porous. Clay is combined with other minerals to create a workable clay body. Part of the firing process includes sintering. This process heats the clay until the particles partially melt and flow together, creating a strong, single mass, composed of a glassy phase interspersed with pores and crystalline material. Through firing, the pores are reduced in size, causing the material to shrink slightly. This crystalline material is a matrix of predominantly silicon and aluminium oxides, and is very hard and strong, although usually somewhat brittle.

Types of kiln

In the broadest terms, there are two types of kiln, both sharing the same basic characteristics of being an insulated box with controlled inner temperature and atmosphere.

In using an **intermittent** kiln, the *ware* to be fired is loaded into the kiln. The kiln is sealed, and the internal temperature increased according to a schedule. After the firing process is completed, both the kiln and the ware are cooled.

A **continuous** kiln, sometimes called a *tunnel* kiln, is a long structure in which only the central portion is directly heated. From the cool entrance, ware is slowly transported through the kiln, and its temperature is increased steadily as it approaches the central, hottest part of the kiln. From there, its transportation continues and the temperature is reduced until it exits the kiln at near room temperature. A continuous kiln is the most energy-efficient, because heat given off during cooling is recycled to pre-heat the incoming ware.

A special type of kiln, common in tableware and tile manufacture, is the *roller-hearth kiln*, in which ware placed on bats is carried through the kiln on rollers.

Kiln technology is very old. The development of the kiln from a simple earthen trench filled with pots and fuel, pit firing, to modern methods happened in stages. One improvement was to build a firing chamber around pots with baffles and a stoking hole, this allowed heat to be conserved and used more efficiently. The use of a chimney stack improves the air flow or *draw* of the kiln, thus burning the fuel more completely. Early examples of kilns found in Britain include those made for the making of roof-tiles during the Roman occupation. These kilns were built up the side of a slope, such that a fire could be lit at the bottom and the heat would rise up into the kiln.

With the advent of the industrial age, kilns were designed to utilize electricity and more refined fuels, including natural gas and propane. The majority of large, industrial pottery kilns now use natural gas, as it is generally clean, efficient and easy to control. Modern kilns can be fitted with computerized controls, allowing for refined adjustments during the firing cycle. A user may choose to control the rate of temperature climb or *ramp*, *hold* or *soak* the temperature at any given point, or control the rate of cooling. Both electric and gas kilns are common for smaller scale production in industry and craft, handmade and sculptural work.

- **Anagama kiln** - the Asian anagama kiln has been used since medieval times and is considered the oldest style of production kiln, brought to Japan from China via Korea in the 5th century. This kiln usually consists of one long firing chamber, pierced with smaller stacking ports on one side, with a firebox at one end and a flue at the other. Firing time can vary from one day to several weeks. Traditional anagama kilns are also built on a slope to allow for a better draft.

- **Bottle kiln** - a type of intermittent kiln, usually coal-fired, formerly used in the firing of pottery; such a kiln was surrounded by a tall brick hovel or cone, of typical bottle shape.

- **Catenary arch kiln**, typically used for the firing of pottery using salt, these by their form (a catenary arch) tend to retain their shape over repeated heating and cooling cycles, whereas other types require extensive metalwork supports.

- **Electric kilns** - kilns operated by electricity were developed in the 20th century, primarily for smaller scale use such as in schools, universities, and hobby centers. The atmosphere in most designs of electric kiln is rich in oxygen, as there is no open flame to consume oxygen molecules, however reducing conditions can be created with appropriate gas input.

- **Feller kiln** brought contemporary design to wood firing by re-using the unburnt gas from the chimney in order to heat the air up before entering the firebox. This leads to an even shorter firing cycle and less wood consumption. This design requires external ventilation to prevent the in-chimney radiator from melting, being typically in metal. The result is a very efficient wood kiln firing one cubic meter of ceramics with one cubic meter of wood.

- **Microwave assisted firing** - this technique combine microwave energy with more conventional energy sources such as radiant gas or electric heating in order to process ceramic materials to the required high temperatures. Microwave-assisted firing offers significant economic benefits.

- **Noborigama kiln** - the Noborigama is an evolution from Anagama design as a multi-chamber kiln, usually built on a slope, where wood is stacked from the front firebox at first, then only through the side-stoking holes with the benefit of having air heated up to 600 °C from the front firebox, enabling more efficient firings.

- **Sèvres kiln** was invented in Sèvres, France and enabled to reach efficiently high-temperature (1280 °C) in order to have fully water-proof ceramic bodies and easy to obtain glazes. It features a down-draft design that enabled to reach high temperature in shorter time, even with wood-firing.

- **Top-hat kiln** - an intermittent kiln of a type sometimes used in the firing of pottery. The ware is set on a refractory hearth, or plinth, over which a box-shaped cover is then lowered.

Wood-drying kiln

A variety of wood drying kiln technologies exist today: conventional, dehumidification, solar, vacuum and radio frequency.

Conventional wood dry kilns (Rasmussen, 1988) are either package-type (sideloader) or track-type (tram) construction. Most hardwood lumber kilns are sideloader kilns in which fork trucks are used to load lumber packages into the kiln. Most softwood lumber kilns are track types in which lumber packages are loaded on kiln/track cars for loading the kiln.

Modern high-temperature, high-air-velocity conventional kilns can typically dry 1-inch-thick (25 mm) green lumber in 10 hours down to a moisture content of 18%. However, 1-inch-thick green Red Oak requires about 28 days to dry down to a moisture content of 8%.

Heat is typically introduced via steam running through fin/tube heat exchangers controlled by on/off pneumatic valves. Less common are proportional pneumatic valves or even various electrical actuators. Humidity is removed via a system of vents, the specific layout of which are usually particular to a given manufacturer. In general, cool dry air is introduced at one end of the kiln while warm moist air is expelled at the other. Hardwood conventional kilns also require the introduction of humidity via either steam spray or cold water misting systems to keep the relative humidity inside the kiln from dropping too low during the drying cycle. Fan directions are typically reversed periodically to ensure even drying of larger kiln charges.

Most softwood lumber kilns operate below 240 °F (116 °C) temperature. Hardwood lumber kiln drying schedules typically keep the dry bulb temperature below 180 °F (82 °C). Difficult-to-dry species might not exceed 140 degrees F.

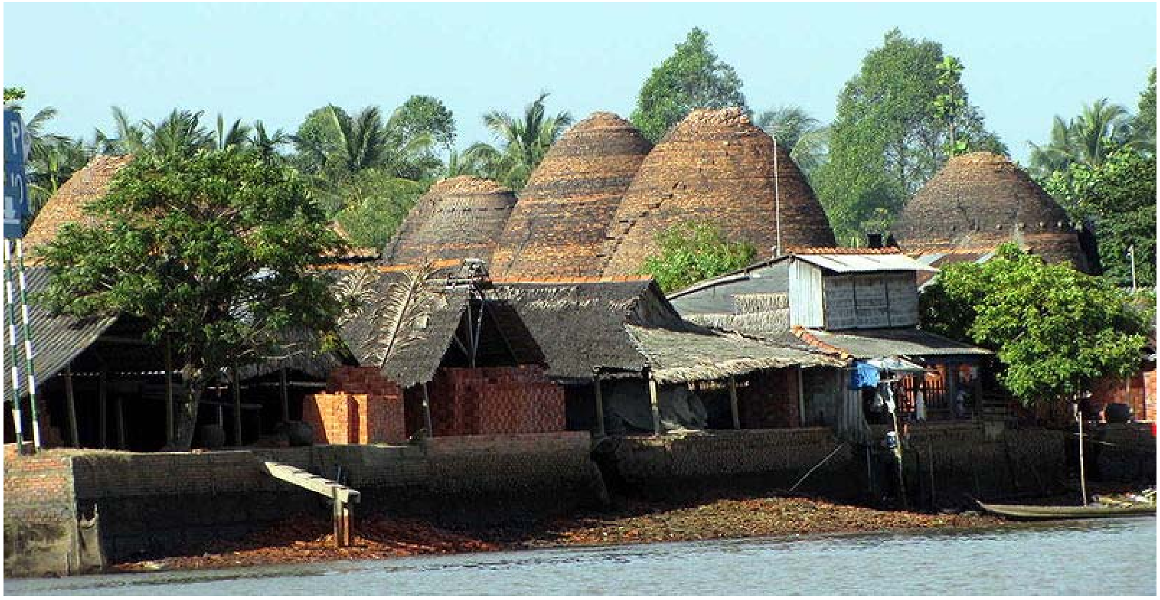
Dehumidification kilns are very similar to conventional kilns in basic construction. Drying times are usually comparable. Heat is primarily supplied by an integral dehumidification unit which also serves to remove humidity. Auxiliary heat is often provided early in the schedule where the heat required may exceed the heat generated by the DH unit.

Solar kilns are conventional kilns, typically built by hobbyists to keep initial investment costs low. Heat is provided via solar radiation, while internal air circulation is typically passive.

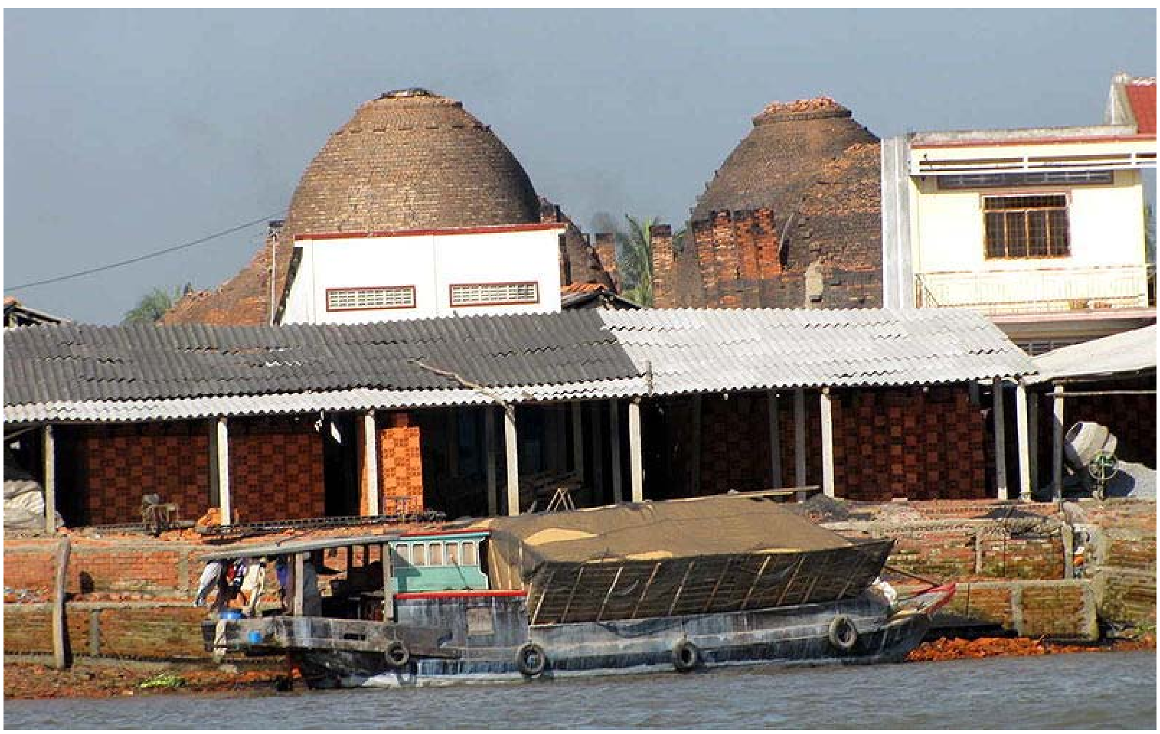
Newer wood drying technologies have included the use of reduced atmospheric pressure to attempt to speed up the drying process. A variety of vacuum technologies exist, varying primarily in the method heat is introduced into the wood charge. Hot water platten vacuum kilns use aluminum heating plates with the water circulating within as the heat source, and typically operate at significantly reduced absolute pressure. Discontinuous and SSV (super-heated steam) use atmosphere to introduce heat into the kiln charge. Discontinuous technology allows the entire kiln charge to come up to full atmospheric pressure, the air in the chamber is then heated, and finally vacuum is pulled. SSV run at partial atmospheres (typically around 1/3 of full atmospheric pressure) in a hybrid of vacuum and conventional kiln technology (SSV kilns are significantly more popular in Europe where the locally harvested wood is easier to dry versus species found in North America). RF/V (radio frequency + vacuum) kilns use microwave radiation to heat the kiln charge, and typically have the highest operating cost due to the heat of vaporization being provided by electricity rather than local fossil fuel or waste wood sources.

Valid economic studies of different wood drying technologies are based on the total energy, capital, insurance/risk, environmental impacts, labor, maintenance, and product degrade costs for the task of removing water from the wood fiber. These costs (which can be a significant part of the entire plant costs)involve the differential impact of the presence of drying equipment in a specific plant. An example of this is that every piece of equipment (in a lumber manufacturing plant) from the green trimmer to the infeed system at the planer mill is the "drying system". Since thousands of different types of wood products manufacturing plants exist around the globe, and may be integrated (lumber, plywood, paper, etc.) or stand alone (lumber only), the true costs of the drying system can only be determined when comparing the total plant costs and risks with and without drying.

The total (harmful) air emissions produced by wood kilns, including their heat source, can be significant. Typically, the higher the temperature the kiln operates at, the larger amount of emissions are produced (per pound of water removed). This is especially true in the drying of thin veneers and high-temperature drying of softwoods.



Brick and roof tile making kilns on a branch of the Mekong in the Delta region of Vietnam.

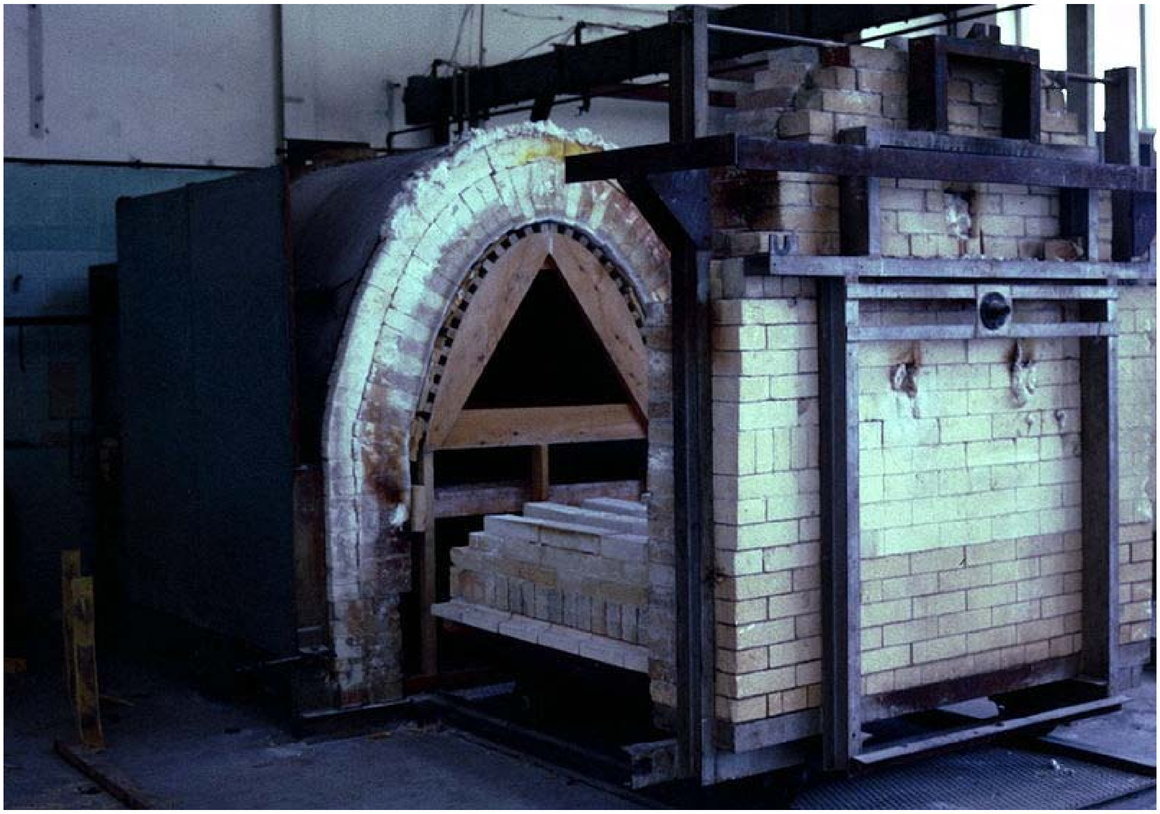


Brickmaking kilns, Mekong delta. The cargo boat in the foreground is carrying the rice chaff which is the fuel for the firing.

A wood fired pottery kiln in Hoi An Vietnam.

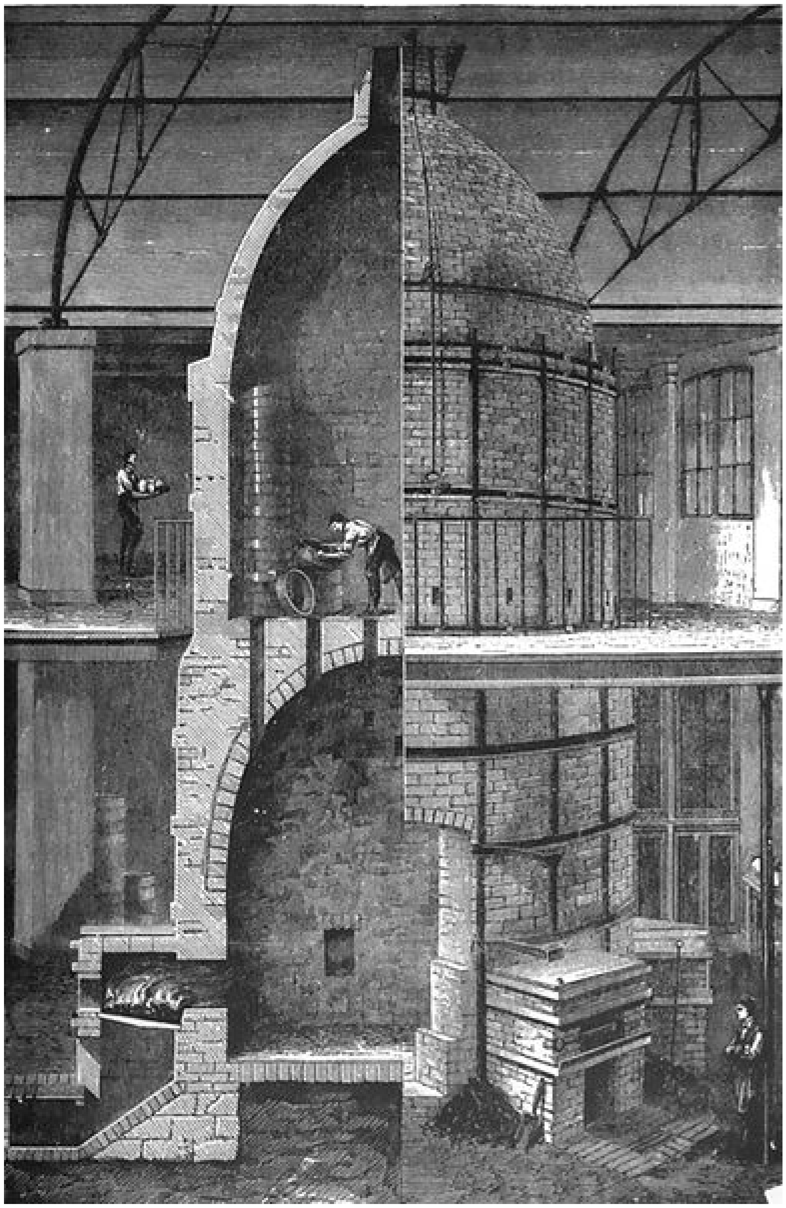
Remains of a ceramics producing kiln just north of Sukothai, Thailand.

Same kiln as previous shot. Glazed pottery produced in this area's kilns, dated from around the 14th - 15th century AD



A Catenary Arch kiln used for firing high temperature electron tube grade aluminium oxide ceramics

Kiln from previous picture while being relocated



A two-story porcelain kiln with furnaces *á alandier* in Sèvres, France circa 1880

Chapter 10

Blast Furnace

Blast furnace in Sestao, Spain. The actual furnace itself is inside the central girderwork.

A **blast furnace** is a type of metallurgical furnace used for smelting to produce industrial metals, generally iron.

In a blast furnace, fuel and ore are continuously supplied through the top of the furnace, while air (sometimes with oxygen enrichment) is blown into the bottom of the chamber, so that the chemical reactions take place throughout the furnace as the material moves downward. The end products are usually molten metal and slag phases tapped from the bottom, and flue gases exiting from the top of the furnace.

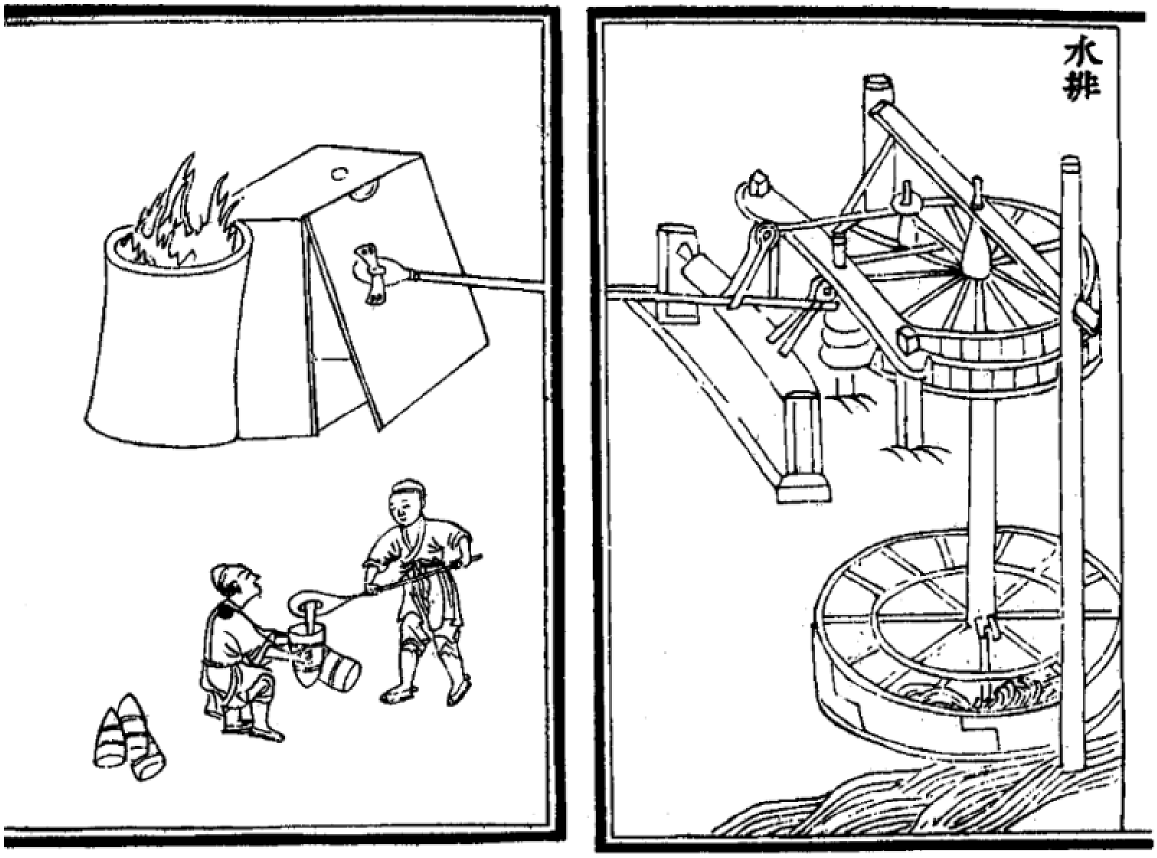
Blast furnaces are to be contrasted with air furnaces (such as reverberatory furnaces), which were naturally aspirated, usually by the convection of hot gases in a chimney flue. According to this broad definition, bloomeries for iron, blowing houses for tin, and smelt mills for lead, would be classified as blast furnaces. However, the term has usually been limited to those used for smelting iron ore to produce pig iron, an intermediate material used in the production of commercial iron and steel.

History

Blast furnaces existed in China from about the 5th century BC, and in the West from the High Middle Ages. They spread from the region around Namur in Wallonia (Belgium) in the late 15th century, being introduced to England in 1491. The fuel used in these was invariably charcoal. The successful substitution of coke for charcoal is widely attributed to Abraham Darby in 1709. The efficiency of the process was further enhanced by the practice of preheating the blast, patented by James Beaumont Neilson in 1828.

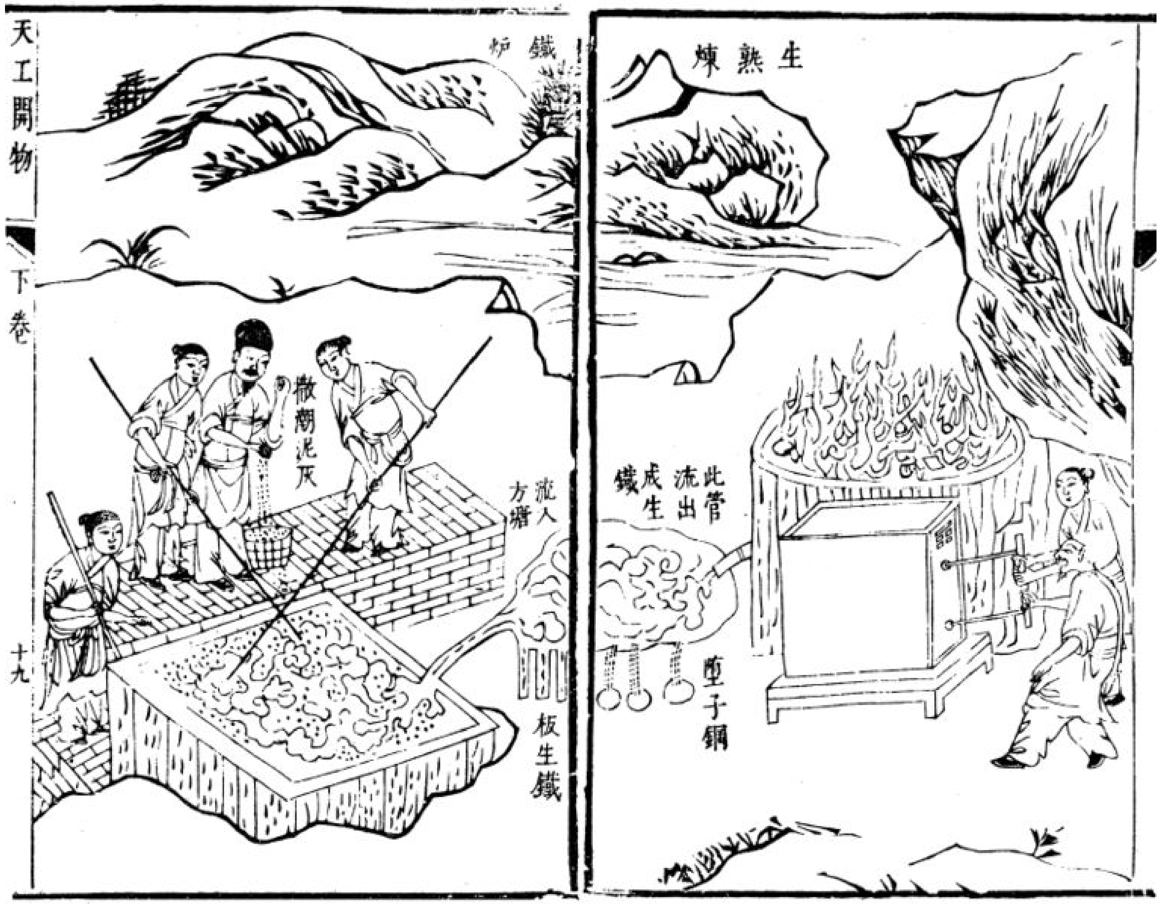
The blast furnace is distinguished from the bloomery in that the object of the blast furnace is to produce molten metal that can be tapped from the furnace, whereas the intention in the bloomery is to avoid it melting so that carbon does not become dissolved in the iron. Bloomeries were also artificially blown using bellows, but the term "blast furnace" is normally reserved for furnaces where iron (or another metal) is refined from ore.

China



An illustration of furnace bellows operated by waterwheels, from the *Nong Shu*, by Wang Zhen, 1313 AD, during the Yuan Dynasty of China.

The oldest extant blast furnaces were built during the Han Dynasty of China in the 1st century BC. However, cast iron farm tools and weapons were widespread in China by the 5th century BC, while 3rd century BC iron smelters employed an average workforce of over two hundred men. These early furnaces had clay walls and used phosphorus-containing minerals as a flux. The effectiveness of the Chinese blast furnace was enhanced during this period by the engineer Du Shi (c. 31 AD), who applied the power of waterwheels to piston-bellows in forging cast iron.



The left picture illustrates the fining process to make wrought iron from pig iron, with the right illustration displaying men working a blast furnace, of smelting iron ore producing pig iron, from the *Tiangong Kaiwu* encyclopedia, 1637.

While it was long thought that the Chinese had developed the blast furnace and cast iron as their first method of iron production, Donald Wagner (the author of the above referenced study) has published a more recent paper that supersedes some of the statements in the earlier work; the newer paper still places the date of the first cast iron artifacts at the 4th and 5th century BC, but also provides evidence of earlier bloomery furnace use, which migrated in from the west during the beginning of the Chinese Bronze Age of the late Longshan culture (2000 BC). He suggests that early blast furnace and cast iron production evolved from furnaces used to melt bronze. Certainly, though, iron was essential to military success by the time the State of Qin had unified China (221 BC). By the 11th century, the Song Dynasty Chinese iron industry made a remarkable switch of resources from charcoal to bituminous coal in casting iron and steel, sparing thousands of acres of woodland from felling. This may have happened as early as the 4th century AD.

Ancient World elsewhere

Other than in China, there is no evidence of the use of the blast furnace (proper). Instead iron was made by direct reduction in bloomeries. These are not correctly described as blast furnaces, though the term is occasionally misused in referring to them.

In Europe, the Greeks, Celts, Romans, and Carthaginians all used this process. Several examples have been found in France, and materials found in Tunisia suggest they were used there as well as in Antioch during the Hellenistic Period. Though little is known of it during the Dark Ages, the process probably continued in use. Similarly, smelting in bloomery-type furnaces in West Africa and forging for tools, appears in the Nok culture in Africa by 500 BC. The earliest records of bloomery-type furnaces in East Africa are discoveries of smelted iron and carbon in Nubia and Axum which date back between 1,000-500 BCE. Particularly in Meroe, there are known to have been ancient blast furnaces which produced metal tools for the Nubians/Kushites and produced surplus for their economy.

Medieval Europe

The first blast furnace of Germany as depicted in a miniature in the Deutsches Museum

An improved bloomery, named the Catalan forge, was invented in Catalonia, Spain during the 8th century. Instead of using natural draught, air was pumped in by bellows, resulting in better quality iron and an increased capacity. This pumping of airstream in with bellows is known as *cold blast*, and it increases the fuel efficiency of the bloomery and improves yield. The Catalan forges can also be built bigger than natural draught bloomeries.

Modern experimental archaeology and history re-enactment has shown there is only a very short step from Catalan forge to the true blast furnace, where the iron is gained as pig iron in liquid phase. Usually obtaining the iron in liquid phase is actually undesired and the temperature is intentionally kept below the melting point of iron, since while removing the solid bloom mechanically is tedious and means batch process instead of continuous process, it is almost pure iron and can be worked immediately. On the other hand, pig iron is the eutectic mixture of carbon and iron, and needs to be decarburized to produce steel or wrought iron, which was extremely tedious in the Middle Ages.

The oldest known blast furnaces in the West were built in Dürstel in Switzerland, the Märkische Sauerland in Germany, and at Lapphyttan in Sweden where the complex was active between 1150 and 1350. At Noraskog in the Swedish county of Järnboås there have also been found traces of blast furnaces dated even earlier, possibly to around 1100. These early blast furnaces, like the Chinese examples, were very inefficient compared to those used today. The iron from the Lapphyttan complex was used to produce balls of wrought iron known as osmonds, and these were traded internationally – a possible reference occurs in a treaty with Novgorod from 1203 and several certain references in accounts of English customs from the 1250s and 1320s. Other furnaces of the 13th to 15th centuries have been identified in Westphalia.

Knowledge of certain technological advances was transmitted as a result of the General Chapter of the Cistercian monks. This may have included the blast furnace, as the Cistercians are known to have been skilled metallurgists. According to Jean Gimpel, their high level of industrial technology facilitated the diffusion of new techniques: "Every monastery had a model factory, often as large as the church and only several feet away, and waterpower drove the machinery of the various industries located on its floor." Iron ore deposits were often donated to the monks along with forges to extract the iron, and within time surpluses were being offered for sale. The Cistercians became the leading iron producers in Champagne, France, from the mid-13th century to the 17th century, also using the phosphate-rich slag from their furnaces as an agricultural fertilizer.

Archaeologists are still discovering the extent of Cistercian technology. At Laskill, an outstation of Rievaulx Abbey and the only medieval blast furnace so far identified in Britain, the slag produced was low in iron content. Slag from other furnaces of the time contained a substantial concentration of iron, whereas Laskill is believed to have produced cast iron quite efficiently. Its date is not yet clear, but it probably did not survive until Henry VIII's Dissolution of the Monasteries in the late 1530s, as an agreement (immediately after that) concerning the "smythes" with the Earl of Rutland in 1541 refers to blooms. Nevertheless, the means by which the blast furnace spread in medieval Europe has not finally been determined.

Early modern blast furnaces: origin and spread

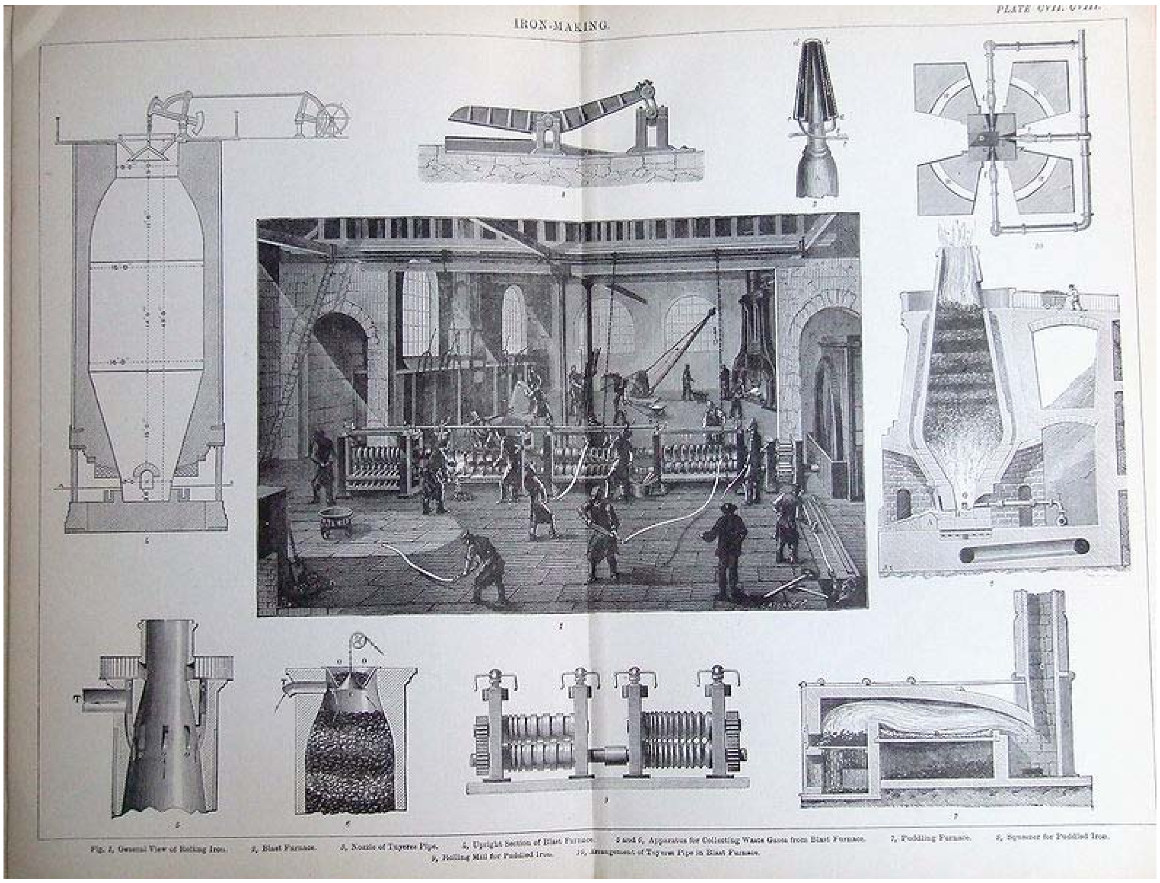
Luisenhuette at Balve

The direct ancestor of these used in France and England was in the Namur region in what is now Wallonia (Belgium). From there, they spread first to the Pays de Bray on the eastern boundary of Normandy and from there to the Weald of Sussex, where the first furnace (called Queenstock) in Buxted was built in about 1491, followed by one at Newbridge in Ashdown Forest in 1496. They remained few in number until about 1530 but many were built in the following decades in the Weald, where the iron industry perhaps reached its peak about 1590. Most of the pig iron from these furnaces was taken to finery forges for the production of bar iron.

The first British furnaces outside the Weald appeared during the 1550s, and many were built in the remainder of that century and the following ones. The output of the industry probably peaked about 1620, and was followed by a slow decline until the early 18th century. This was apparently because it was more economic to import iron from Sweden and elsewhere than to make it in some more remote British locations. Charcoal that was economically available to the industry was probably being consumed as fast as the wood to make it grew. The Backbarrow blast furnace built in Cumbria in 1711 has been described as the first efficient example.

The first blast furnace in Russia opened in 1637 near Tula and was called the Gorodishche Works. The blast furnace spread from here to the central Russia and then finally to the Urals.

Blast furnaces have also been discovered and recorded to have been created in medieval West Africa with some of the metalworking Bantu civilizations such as the Bunyoro Empire and the Nyoro people.



Representation of blast furnaces and other ironmaking processes from the 19th century

Coke blast furnaces

In 1709, at Coalbrookdale in Shropshire, England, Abraham Darby began to fuel a blast furnace with coke instead of charcoal. Coke iron was initially only used for foundry work, making pots and other cast iron goods. Foundry work was a minor branch of the industry, but Darby's son built a new furnace at nearby Horsehay, and began to supply the owners of finery forges with coke pig iron for the production of bar iron. Coke pig iron was by this time cheaper to produce than charcoal pig iron. The use of a coal-derived fuel in the iron industry was a key factor in the British Industrial Revolution. Darby's old blast furnace has been archaeologically excavated and can be seen in situ at Coalbrookdale, part of the Ironbridge Gorge Museums. Cast iron from the furnace was used to make girders for the world's first iron bridge in 1779. The Iron Bridge crosses the River Severn at Coalbrookdale and remains in use for pedestrians.

A further important development was the change to hot blast, patented by James Beaumont Neilson at Wilsontown Ironworks in Scotland in 1828. This further reduced production costs. Within a few decades, the practice was to have a "stove" as large as the furnace next to it into which the waste gas (containing CO) from the furnace was directed and burnt. The resultant heat was used to preheat the air blown into the furnace.

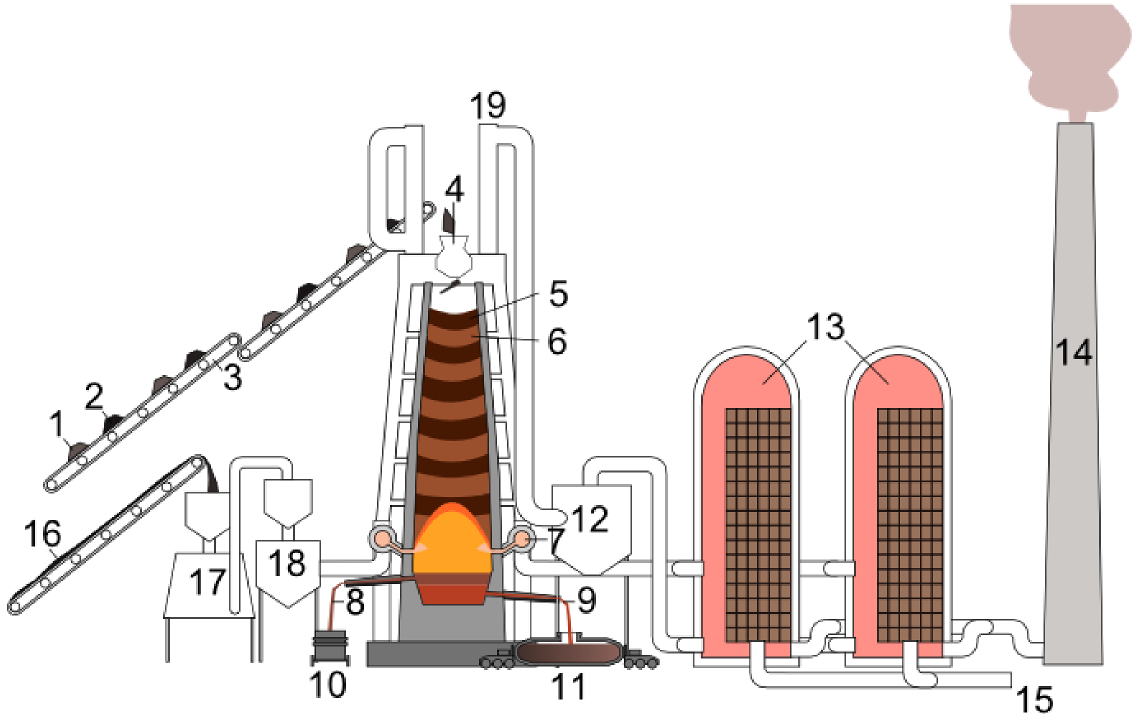
A further significant development was the application of raw anthracite coal to the blast furnace, first tried successfully by George Crane at Ynyscedwyn ironworks in south Wales in 1837. It was taken up in America by the Lehigh Crane Iron Company at Catasauqua, Pennsylvania in 1839.

Modern furnaces

The blast furnace remains an important part of modern iron production. Modern furnaces are highly efficient, including Cowper stoves to pre-heat the blast air and employ recovery systems to extract the heat from the hot gases exiting the furnace. Competition in industry drives higher production rates. The largest blast furnaces have a volume around 5580 m^3 (190,000 cu ft) and can produce around 80,000 tonnes (88,000 short tons) of iron per week.

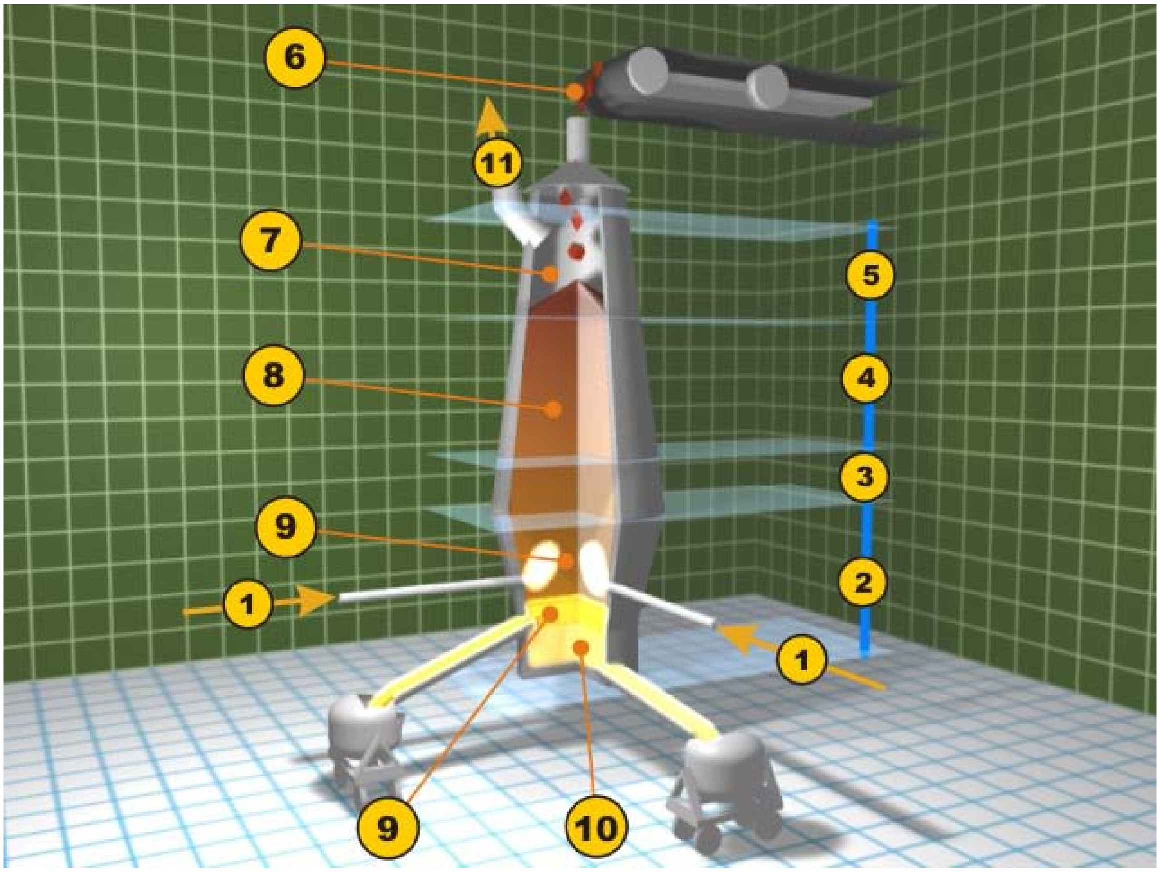
This is a great increase from the typical 18th-century furnaces, which averaged about 360 tonnes (400 short tons) per year. Variations of the blast furnace, such as the Swedish electric blast furnace, have been developed in countries which have no native coal resources.

Modern process



Blast furnace placed in an installation

1. Iron ore + limestone sinter
2. Coke
3. Elevator
4. Feedstock inlet
5. Layer of coke
6. Layer of sinter pellets of ore and limestone
7. Hot blast (around 1200°C)
8. Removal of slag
9. Tapping of molten pig iron
10. Slag pot
11. Torpedo car for pig iron
12. Dust cyclone for separation of solid particles
13. Cowper stoves for hot blast
14. Smoke outlet (can be redirected to carbon capture & storage (CCS) tank)
15: Feed air for Cowper stoves (air pre-heaters)
16. Powdered coal
17. Coke oven
18. Coke
19. Blast furnace gas downcomer



Blast furnace diagram
1. Hot blast from Cowper stoves
2. Melting zone (*bosh*)
3. Reduction zone of ferrous oxide (*barrel*)
4. Reduction zone of ferric oxide (*stack*)
5. Pre-heating zone (*throat*)
6. Feed of ore, limestone, and coke
7. Exhaust gases
8. Column of ore, coke and limestone
9. Removal of slag
10. Tapping of molten pig iron
11. Collection of waste gases

Modern furnaces are equipped with an array of supporting facilities to increase efficiency, such as ore storage yards where barges are unloaded. The raw materials are transferred to the stockhouse complex by ore bridges, or rail hoppers and ore transfer cars. Rail-mounted scale cars or computer controlled weight hoppers weigh out the various raw materials to yield the desired hot metal and slag chemistry. The raw materials are brought to the top of the blast furnace via a skip car powered by winches or conveyor belts.

There are different ways in which the raw materials are charged into the blast furnace. Some blast furnaces use a "double bell" system where two "bells" are used to control the entry of the raw material into the blast furnace. The purpose of the two bells is to minimize the loss of hot gases in the blast furnace. First the raw materials are emptied into the upper or small bell. The bell is then rotated a predetermined amount in order to distribute the charge more accurately. The small bell then opens to empty the charge into the large bell. The small bell then closes, to seal the blast furnace, while the large bell dispenses the charge into the blast furnace. A more recent design is to use a "bell-less" system. These systems use multiple hoppers to contain each raw material, which is then discharged into the blast furnace through valves. These valves are more accurate at controlling how much of each constituent is added, as compared to the skip or conveyor system, thereby increasing the efficiency of the furnace. Some of these bell-less systems also implement a chute in order to precisely control where the charge is placed.

The iron making blast furnace itself is built in the form of a tall chimney-like structure lined with refractory brick. Coke, limestone flux, and iron ore (iron oxide) are charged into the top of the furnace in a precise filling order which helps control gas flow and the chemical reactions inside the furnace. Four "uptakes" allow the hot, dirty gas to exit the furnace dome, while "bleeder valves" protect the top of the furnace from sudden gas pressure surges. When plugged, bleeder valves need to be cleaned with a bleeder cleaner. The coarse particles in the gas settle in the "dust catcher" and are dumped into a railroad car or truck for disposal, while the gas itself flows through a venturi scrubber and a gas cooler to reduce the temperature of the cleaned gas.

The "casthouse" at the bottom half of the furnace contains the bustle pipe, tuyeres and the equipment for casting the liquid iron and slag. Once a "taphole" is drilled through the refractory clay plug, liquid iron and slag flow down a trough through a "skimmer" opening, separating the iron and slag. Modern, larger blast furnaces may have as many as four tapholes and two casthouses. Once the pig iron and slag has been tapped, the taphole is again plugged with refractory clay.

The tuyeres are used to implement a hot blast, which is used to increase the efficiency of the blast furnace. The hot blast is directed into the furnace through water-cooled copper nozzles called tuyeres near the base. The hot blast temperature can be from 900 °C to 1300 °C (1600 °F to 2300 °F) depending on the stove design and condition. The temperatures they deal with may be 2000 °C to 2300 °C (3600 °F to 4200 °F). Oil, tar, natural gas, powdered coal and oxygen can also be injected into the furnace at tuyere level to combine with the coke to release additional energy which is necessary to increase productivity.

Chemistry

Blast furnaces of Třinec Iron and Steel Works

The main chemical reaction producing the molten iron is:

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$

This reaction might be divided into multiple steps, with the first being that preheated blast air blown into the furnace reacts with the carbon in the form of coke to produce carbon monoxide and heat:

$2\ C(s) + O_2(g) \rightarrow 2\ CO(g)$

The hot carbon monoxide is the reducing agent for the iron ore and reacts with the iron oxide to produce molten iron and carbon dioxide. Depending on the temperature in the different parts of the furnace (warmest at the bottom) the iron is reduced in several steps. At the top, where the temperature usually is in the range between 200 °C and 700 °C, the iron(III) oxide is reduced to iron(II) iron(III) oxide, Fe_3O_4.

$3\ Fe_2O_3(s) + CO(g) \rightarrow 2\ Fe_3O_4(s) + CO_2(g)$

At temperatures around 850 °C, further down in the furnace, the iron(II) iron(III) is reduced to iron(II) oxide:

$$Fe_3O_4(s) + CO(g) \rightarrow 3\ FeO(s) + CO_2(g)$$

Hot carbon dioxide, unreacted carbon monoxide, and nitrogen from the air pass up through the furnace as fresh feed material travels down into the reaction zone. As the material travels downward, the counter-current gases both preheat the feed charge and decompose the limestone to calcium oxide and carbon dioxide:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

As the iron(II) oxide moves down to the area with higher temperatures, ranging up to 1200 °C degrees, it is reduced further to iron metal:

$$FeO(s) + CO(g) \rightarrow Fe(s) + CO_2(g)$$

The carbon dioxide formed in this process is re-reduced to carbon monoxide by the coke:

$$C(s) + CO_2(g) \rightarrow 2\ CO(g)$$

The main reaction controlling the gas atmosphere in the furnace is called the Boudouard reaction:

$$C + O_2 \rightarrow CO_2$$
$$CO_2 + C \rightarrow 2CO$$

The decomposition of limestone in the middle zones of the furnace proceeds according to the following reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

The calcium oxide formed by decomposition reacts with various acidic impurities in the iron (notably silica), to form a fayalitic slag which is essentially calcium silicate, $CaSiO_3$:

$$SiO_2 + CaO \rightarrow CaSiO_3$$

The "pig iron" produced by the blast furnace has a relatively high carbon content of around 4–5%, making it very brittle, and of limited immediate commercial use. Some pig iron is used to make cast iron. The majority of pig iron produced by blast furnaces undergoes further processing to reduce the carbon content and produce various grades of steel used for tools and construction materials.

Although the efficiency of blast furnaces is constantly evolving, the chemical process inside the blast furnace remains the same. According to the American Iron and Steel Institute: "Blast furnaces will survive into the next millennium because the larger, efficient furnaces can produce hot metal at costs competitive with other iron making technologies." One of the biggest drawbacks of the blast furnaces is the inevitable carbon dioxide production as iron is reduced from iron oxides by carbon and there is no economical substitute – steelmaking is one of the unavoidable industrial contributors of the CO_2 emissions in the world.

The challenge set by the greenhouse gas emissions of the blast furnace is being addressed in an on-going European Program called ULCOS (Ultra Low CO_2 Steelmaking). Several new process routes have been proposed and investigated in depth to cut specific emissions (CO_2 per ton of steel) by at least 50%. Some rely on the capture and further storage (CCS) of CO_2, while others choose decarbonizing iron and steel production, by turning to hydrogen, electricity and biomass. In the nearer term, a technology that incorporates CCS into the blast furnace process itself and is called the Top-Gas Recycling Blast Furnace is under development, with a scale-up to a commercial size blast furnace under way. The technology should be fully demonstrated by the end of the 2010s, in line with the timeline set, for example, by the EU to cut emissions significantly. Broad deployment could take place from 2020 on.

Manufacture of stone wool

Stone wool or Rock wool is a spun mineral fibre used as an insulation product and in hydroponics. It is manufactured in a blast furnace fed with diabase rock which contains very low levels of metal oxides. The resultant slag is drawn off and spun to form the rock wool product. Very small amounts of metals are also produced which are an unwanted by-product and run to waste.

Decommissioned blast furnaces as museum sites

For a long time, it was normal procedure for a decommissioned blast furnace to be demolished and either be replaced with a newer, improved one, or to have the entire site demolished to make room for follow-up use of the area. In recent decades, several countries have realized the value of blast furnaces as a part of their industrial history. Rather than being demolished, abandoned steel mills were turned into museums or integrated into multi-purpose parks. The largest number of preserved historic blast furnaces exists in Germany; other such sites exist in Spain, France, the Czech Republic, Japan, Luxembourg, Poland, Romania, Mexico, Russia and the United States.

Chapter 11

Electric Arc Furnace

Steel mill with two arc furnaces

An **electric arc furnace** (**EAF**) is a furnace that heats charged material by means of an electric arc.

Arc furnaces range in size from small units of approximately one ton capacity (used in foundries for producing cast iron products) up to about 400 ton units used for secondary steelmaking. Arc furnaces used in research laboratories and by dentists may have a capacity of only a few dozen grams. Industrial electric arc furnace temperatures can be up to 1,800 degrees Celsius, while laboratory units can exceed 3,000 °C. Arc furnaces differ from induction furnaces in that the charge material is directly exposed to an electric arc, and the current in the furnace terminals passes through the charged material.

History

In the 19th century, a number of men had employed an electric arc to melt iron. Sir Humphry Davy conducted an experimental demonstration in 1810; welding was investigated by Pepys in 1815; Pinchon attempted to create an electrothermic furnace in 1853; and, in 1878–79, Sir William Siemens took out patents for electric furnaces of the arc type.

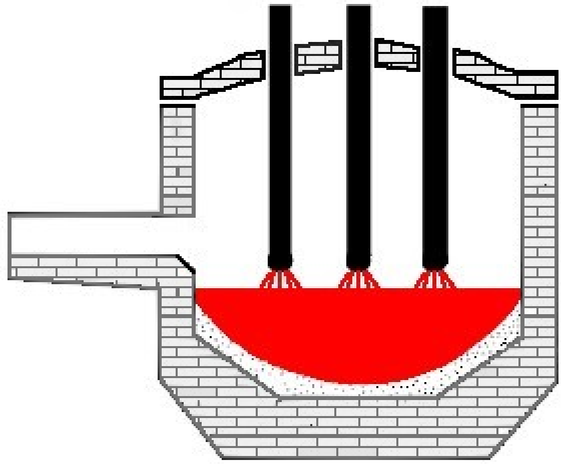
The first electric arc furnaces were developed by Paul Héroult, of France, with a commercial plant established in the United States in 1907. The Sanderson brothers formed The Sanderson Brothers steel Co. in Syracuse, New York, installing the first **electric arc furnace** in the U.S. This furnace is now on display at Station Square, Pittsburgh, Pennsylvania.

Initially "electric steel" was a specialty product for such uses as machine tools and spring steel. Arc furnaces were also used to prepare calcium carbide for use in carbide lamps. The *Stessano electric furnace* is an arc type furnace that usually rotates to mix the bath. The *Girod furnace* is similar to the *Héroult furnace*.

While EAFs were widely used in World War II for production of alloy steels, it was only later that electric steelmaking began to expand. The low capital cost for a mini-mill—around US$140–200 per ton of annual installed capacity, compared with US$1,000 per ton of annual installed capacity for an integrated steel mill—allowed mills to be quickly established in war-ravaged Europe, and also allowed them to successfully compete with the big United States steelmakers, such as Bethlehem Steel and U.S. Steel, for low-cost, carbon steel "long products" (structural steel, rod and bar, wire, and fasteners) in the U.S. market.

When Nucor—now one of the largest steel producers in the U.S.—decided to enter the long products market in 1969, they chose to start up a mini-mill, with an EAF as its steelmaking furnace, soon followed by other manufacturers. Whilst Nucor expanded rapidly in the Eastern US, the companies that followed them into mini-mill operations concentrated on local markets for long products, where the use of an EAF allowed the plants to vary production according to local demand. This pattern was also followed globally, with EAF steel production primarily used for long products, while integrated mills, using blast furnaces and basic oxygen furnaces, cornered the markets for "flat products"—sheet steel and heavier steel plate. In 1987, Nucor made the decision to expand into the flat products market, still using the EAF production method.

Construction



A schematic cross-section through an EAF. Three electrodes (black), molten bath (red), tapping spout at left, refractory brick movable roof, brick shell, and a refractory-lined bowl-shaped hearth.

An electric arc furnace used for steelmaking consists of a refractory-lined vessel, usually water-cooled in larger sizes, covered with a retractable roof, and through which one or more graphite electrodes enter the furnace. The furnace is primarily split into three sections:

- the *shell*, which consists of the sidewalls and lower steel "bowl";
- the *hearth*, which consists of the refractory that lines the lower bowl;
- the *roof*, which may be refractory-lined or water-cooled, and can be shaped as a section of a sphere, or as a frustum (conical section). The roof also supports the refractory delta in its centre, through which one or more graphite electrodes enter.

The hearth may be hemispherical in shape, or in an eccentric bottom tapping furnace (see below), the hearth has the shape of a halved egg. In modern meltshops, the furnace is often raised off the ground floor, so that ladles and slag pots can easily be maneuvered under either end of the furnace. Separate from the furnace structure is the electrode support and electrical system, and the tilting platform on which the furnace rests. Two configurations are possible: the electrode supports and the roof tilt with the furnace, or are fixed to the raised platform.

A typical alternating current furnace has three electrodes. Electrodes are round in section, and typically in segments with threaded couplings, so that as the electrodes wear, new segments can be added. The arc forms between the charged material and the electrode, the charge is heated both by current passing through the charge and by the radiant energy evolved by the arc. The electrodes are automatically raised and lowered by a positioning system, which may use either electric winch hoists or hydraulic cylinders. The regulating system maintains approximately constant current and power input during the melting of the charge, even though scrap may move under the electrodes as it melts. The mast arms holding the electrodes carry heavy busbars, which may be hollow water-cooled copper pipes carrying current to the electrode holders. Modern systems use "hot arms", where the whole arm carries the current, increasing efficiency. These can be made from copper-clad steel or aluminium. Since the electrodes move up and down automatically for regulation of the arc, and are raised to allow removal of the furnace roof, heavy water-cooled cables connect the bus tubes/arms with the transformer located adjacent to the furnace. To protect the transformer from heat, it is installed in a vault.

The furnace is built on a tilting platform so that the liquid steel can be poured into another vessel for transport. The operation of tilting the furnace to pour molten steel is called "tapping". Originally, all steelmaking furnaces had a tapping spout closed with refractory that washed out when the furnace was tilted, but often modern furnaces have an eccentric bottom tap-hole (EBT) to reduce inclusion of nitrogen and slag in the liquid steel. These furnaces have a taphole that passes vertically through the hearth and shell, and is set off-centre in the narrow "nose" of the egg-shaped hearth. It is filled with refractory sand, such as olivine, when it is closed off. Modern plants may have two shells with a single set of electrodes that can be transferred between the two; one shell preheats scrap while the other shell is utilised for meltdown. Other DC-based furnaces have a similar arrangement, but have electrodes for each shell and one set of electronics.

AC furnaces usually exhibit a pattern of hot and cold-spots around the hearth perimeter, with the cold-spots located between the electrodes. Modern furnaces mount oxygen-fuel burners in the sidewall and use them to provide chemical energy to the cold-spots, making the heating of the steel more uniform. Additional chemical energy is provided by injecting oxygen and carbon into the furnace; historically this was done through lances in the slag door, now this is mainly done through multiple wall-mounted injection units.

A mid-sized modern steelmaking furnace would have a transformer rated about 60,000,000 volt-amperes (60 MVA), with a secondary voltage between 400 and 900 volts and a secondary current in excess of 44,000 amperes. In a modern shop such a furnace would be expected to produce a quantity of 80 metric tonnes of liquid steel in approximately 60 minutes from charging with cold scrap to tapping the furnace. In comparison, basic oxygen furnaces can have a capacity of 150–300 tonnes per batch, or "heat", and can produce a heat in 30–40 minutes. Enormous variations exist in furnace design details and operation, depending on the end product and local conditions, as well as ongoing research to improve furnace efficiency—the largest scrap-only furnace (in terms of tapping weight and transformer rating) is in Turkey, with a tap weight of 300 metric tonnes and a transformer of 300 MVA.

To produce a ton of steel in an electric arc furnace requires approximately 400 kilowatt-hours per short ton of electricity, or about 440 kWh per metric tonne; the theoretical minimum amount of energy required to melt a tonne of scrap steel is 300 kWh (melting point 1520°C/2768°F). Therefore, the 300-tonne, 300 MVA EAF mentioned above will require approximately 132 MWh of energy to melt the steel, and a "power-on time" (the time that steel is being melted with an arc) of approximately 37 minutes, allowing for the power factor. Electric arc steelmaking is only economical where there is plentiful electricity, with a well-developed electrical grid. In many locations, mills operate during off-peak hours when utilities have surplus power generating capacity.

Operation

An arc furnace pouring out steel into a small ladle car. The transformer vault can be seen at the right side of the picture. For scale, note the operator standing on the platform at upper left. This is a 1941-era photograph and so does not have the extensive dust collection system that a modern installation would have, nor is the operator wearing a hard hat or dust mask.

- Scrap metal is delivered to a scrap bay, located next to the melt shop. Scrap generally comes in two main grades: shred (whitegoods, cars and other objects made of similar light-gauge steel) and heavy melt (large slabs and beams), along with some direct reduced iron (DRI) or pig iron for chemical balance. Some furnaces melt almost 100% DRI.
- The scrap is loaded into large buckets called baskets, with "clamshell" doors for a base. Care is taken to layer the scrap in the basket to ensure good furnace operation; heavy melt is placed on top of a light layer of protective shred, on top of which is placed more shred. These layers should be present in the furnace after

charging. After loading, the basket may pass to a scrap pre-heater, which uses hot furnace off-gases to heat the scrap and recover energy, increasing plant efficiency.

- The scrap basket is then taken to the melt shop, the roof is swung off the furnace, and the furnace is charged with scrap from the basket. Charging is one of the more dangerous operations for the EAF operators. There is a lot of energy generated by multiple tonnes of falling metal; any liquid metal in the furnace is often displaced upwards and outwards by the solid scrap, and the grease and dust on the scrap is ignited if the furnace is hot, resulting in a fireball erupting. In some twin-shell furnaces, the scrap is charged into the second shell while the first is being melted down, and pre-heated with off-gas from the active shell. Other operations are continuous charging—pre-heating scrap on a conveyor belt, which then discharges the scrap into the furnace proper, or charging the scrap from a shaft set above the furnace, with off-gases directed through the shaft. Other furnaces can be charged with hot (molten) metal from other operations.
- After charging, the roof is swung back over the furnace and meltdown commences. The electrodes are lowered onto the scrap, an arc is struck and the electrodes are then set to bore into the layer of shred at the top of the furnace. Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs. Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap, the voltage can be increased and the electrodes raised slightly, lengthening the arcs and increasing power to the melt. This enables a molten pool to form more rapidly, reducing tap-to-tap times. Oxygen is also supersonically blown into the scrap, combusting or cutting the steel, and extra chemical heat is provided by wall-mounted oxygen-fuel burners. Both processes accelerate scrap meltdown.
- An important part of steelmaking is the formation of slag, which floats on the surface of the molten steel. Slag usually consists of metal oxides, and acts as a destination for oxidised impurities, as a thermal blanket (stopping excessive heat loss) and helping to reduce erosion of the refractory lining. For a furnace with basic refractories, which includes most carbon steel-producing furnaces, the usual slag formers are calcium oxide (CaO, in the form of burnt lime) and magnesium oxide (MgO, in the form of dolomite and magnesite). These slag formers are either charged with the scrap, or blown into the furnace during meltdown. Another major component of EAF slag is iron oxide from steel combusting with the injected oxygen. Later in the heat, carbon (in the form of coke or coal) is injected into this slag layer, reacting with the iron oxide to form metallic iron and carbon monoxide gas, which then causes the slag to foam, allowing greater thermal efficiency, and better arc stability and electrical efficiency. The slag blanket also covers the arcs, preventing damage to the furnace roof and sidewalls from radiant heat.
- Once flat bath conditions are reached, i.e. the scrap has been completely melted down, another bucket of scrap can be charged into the furnace and melted down, although EAF development is moving towards single-charge designs. After the second charge is completely melted, refining operations take place to check and correct the steel chemistry and superheat the melt above its freezing temperature

in preparation for tapping. More slag formers are introduced and more oxygen is blown into the bath, burning out impurities such as silicon, sulfur, phosphorus, aluminium, manganese, and calcium, and removing their oxides to the slag. Removal of carbon takes place after these elements have burnt out first, as they have a greater affinity for oxygen. Metals that have a poorer affinity for oxygen than iron, such as nickel and copper, cannot be removed through oxidation and must be controlled through scrap chemistry alone, such as introducing the direct reduced iron and pig iron mentioned earlier. A foaming slag is maintained throughout, and often overflows the furnace to pour out of the slag door into the slag pit. Temperature sampling and chemical sampling take place via automatic lances. Oxygen and carbon can be automatically measured via special probes that dip into the steel, but for all other elements, a "chill" sample—a small, solidified sample of the steel—is analysed on an arc-emission spectrometer.

- Once the temperature and chemistry are correct, the steel is tapped out into a preheated ladle through tilting the furnace. For plain-carbon steel furnaces, as soon as slag is detected during tapping the furnace is rapidly tilted back towards the deslagging side, minimising slag carryover into the ladle. For some special steel grades, including stainless steel, the slag is poured into the ladle as well, to be treated at the ladle furnace to recover valuable alloying elements. During tapping some alloy additions are introduced into the metal stream, and some more lime is added on top of the ladle to begin building a new slag layer. Often, a few tonnes of liquid steel and slag is left in the furnace in order to form a "hot heel", which helps preheat the next charge of scrap and accelerate its meltdown. During and after tapping, the furnace is "turned around": the slag door is cleaned of solidified slag, repairs may take place, and electrodes are inspected for damage or lengthened through the addition of new segments; the taphole is filled with sand at the completion of tapping. For a 90-tonne, medium-power furnace, the whole process will usually take about 60–70 minutes from the tapping of one heat to the tapping of the next (the tap-to-tap time).

Advantages of electric arc furnace for steelmaking

The use of EAFs allows steel to be made from a 100% scrap metal feedstock, commonly known as "cold ferrous feed" to emphasise the fact that for an EAF, scrap is a regulated feed material. The primary benefit of this is the large reduction in specific energy (energy per unit weight) required to produce the steel. Another benefit is flexibility: while blast furnaces cannot vary their production by much and are never stopped, EAFs can be rapidly started and stopped, allowing the steel mill to vary production according to demand. Although steelmaking arc furnaces generally use scrap steel as their primary feedstock, if hot metal from a blast furnace or direct-reduced iron is available economically, these can also be used as furnace feed.

A typical steelmaking arc furnace is the source of steel for a mini-mill, which may make bars or strip product. Mini-mills can be sited relatively near to the markets for steel products, and the transport requirements are less than for an integrated mill, which would commonly be sited near a harbour for access to shipping.

Environmental issues

Although the modern electric arc furnace is a highly efficient recycler of steel scrap, operation of an arc furnace shop can have adverse environmental effects. Much of the capital cost of a new installation will be devoted to systems intended to reduce these effects, which include:

- enclosures to reduce high sound levels
- Dust collector for furnace off-gas
- Slag production
- Cooling water demand
- Heavy truck traffic for scrap, materials handling, and products
- Environmental effects of electricity generation

Because of the very dynamic quality of the arc furnace load, power systems may require technical measures to maintain the quality of power for other customers; flicker and harmonic distortion are common side-effects of arc furnace operation on a power system.

Other electric arc furnaces

For steelmaking, direct current (DC) arc furnaces are used, with a single electrode in the roof and the current return through a conductive bottom lining or conductive pins in the base. The advantage of DC is lower electrode consumption per ton of steel produced, since only one electrode is used, as well as less electrical harmonics and other similar problems. However, the size of DC arc furnaces is limited by the available electrodes and maximum allowable voltage. Maintenance of the conductive furnace hearth is a bottleneck in extended operation of a DC arc furnace. However, Danieli—makers of steel plant equipment—are preparing to install a 420-tonne DC furnace, powered by two 160 MVA transformers, in a Japanese steel mill. Instead of an upper graphite electrode and a lower conductive hearth, this EAF would have two upper graphite electrodes.

In a steel plant, a ladle furnace (LF) is used to maintain the temperature of liquid steel during processing after tapping from EAF or to change the alloy composition. The ladle is used for the first purpose when there is a delay later in the steelmaking process. The ladle furnace consists of a refractory roof, a heating system, and, when applicable, a provision for injecting argon gas into the bottom of the melt for stirring. Unlike a scrap melting furnace, a ladle furnace does not have a tilting or scrap charging mechanism.

Electric arc furnaces are also used for production of ferroalloys and other non-ferrous alloys, and for production of phosphorus. Furnaces for these services are physically different from steel-making furnaces and may operate on a continuous, rather than batch, basis. Continuous process furnaces may also use paste-type, Søderberg electrodes to prevent interruptions due to electrode changes. Such a furnace is known as a submerged arc furnace because the electrode tips are buried in the slag/charge, and arcing occurs through the slag, between the matte and the electrode. A steelmaking arc furnace, by comparison, arcs in the open. The key is the electrical resistance, which is what generates the heat required: the resistance in a steelmaking furnace is the atmosphere, while in a submerged-arc furnace the slag or charge forms the resistance. The liquid metal formed in either furnace is too conductive to form an effective heat-generating resistance.

Amateurs have constructed a variety of arc furnaces, often based on electric arc welding kits contained by silical blocks or flower pots. Though crude, these simple furnaces are capable of melting a wide range of materials and creating calcium carbide etc. An example is shown here.

Plasma arc furnace

A plasma arc furnace (PAF) uses plasma torches instead of graphite electrodes. Each of these torches consists of a casing provided with a nozzle and an axial tubing for feeding a plasma-forming gas (either nitrogen or argon), and a burnable cylindrical graphite electrode located within the tubing. Such furnaces can be referred to as "PAM" (Plasma Arc Melt) furnaces. They are used extensively in the titanium melt industry and similar specialty metals industries.

Vacuum arc remelting

Vacuum arc remelting (VAR) is a secondary remelting process for vacuum refining and manufacturing of ingots with improved chemical and mechanical homogeneity.

In critical military and commercial aerospace applications, material engineers commonly specify VIM-VAR steels. VIM means Vacuum Induction Melted and VAR means Vacuum Arc Remelted. VIM-VAR steels become bearings for jet engines, rotor shafts for military helicopters, flap actuators for fighter jets, gears in jet or helicopter transmissions, mounts or fasteners for jet engines, jet tail hooks and other demanding applications.

Most grades of steel are melted once and are then cast or teemed into a solid form prior to extensive forging or rolling to a metallurgically sound form. In contrast, VIM-VAR steels go through two more highly purifying melts under vacuum. After melting in an electric arc furnace and alloying in an argon oxygen decarburization vessel, steels destined for vacuum remelting are cast into ingot molds. The solidified ingots then head for a vacuum induction melting furnace. This vacuum remelting process rids the steel of inclusions and unwanted gases while optimizing the chemical composition. The VIM operation returns these solid ingots to the molten state in the contaminant-free void of a vacuum. This tightly controlled melt often requires up to 24 hours. Still enveloped by the vacuum, the hot metal flows from the VIM furnace crucible into giant electrode molds. A typical electrode stands about 15 feet (5 m) tall and will be in various diameters. The electrodes solidify under vacuum.

For VIM-VAR steels, the surface of the cooled electrodes must be ground to remove surface irregularities and impurities before the next vacuum remelt. Then the ground electrode is placed in a VAR furnace. In a VAR furnace the steel gradually melts drop-by-drop in the vacuum-sealed chamber. Vacuum arc remelting further removes lingering inclusions to provide superior steel cleanliness and further remove gases such as oxygen, nitrogen and hydrogen. Controlling the rate at which these droplets form and solidify ensures a consistency of chemistry and microstructure throughout the entire VIM-VAR ingot. This in turn makes the steel more resistant to fracture and/or fatigue. This refinement process is essential to meet the performance characteristics of parts like a helicopter rotor shaft, a flap actuator on a military jet or a bearing in a jet engine.

For some commercial or military applications, steel alloys may go through only one vacuum remelt, namely the VAR. For example, steels for solid rocket cases, landing gears or torsion bars for fighting vehicles typically involve the one vacuum remelt.

Vacuum arc remelting is also used in production of titanium and other metals which are reactive or in which high purity is required.