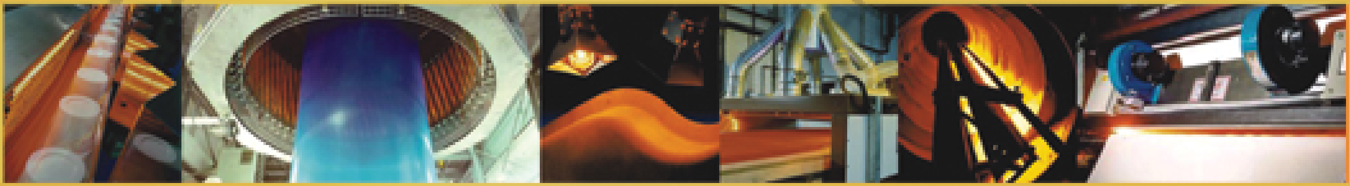
# understanding INFRARED HEATING

$$W_{\lambda,T} = C_1\lambda^{5}\exp-\left[\frac{C_2}{\lambda T}\right]$$

$$f = \frac{1}{t} \qquad \lambda = v/f$$

$$W = \sigma T^4\,(W/m^2)$$



Heraeus

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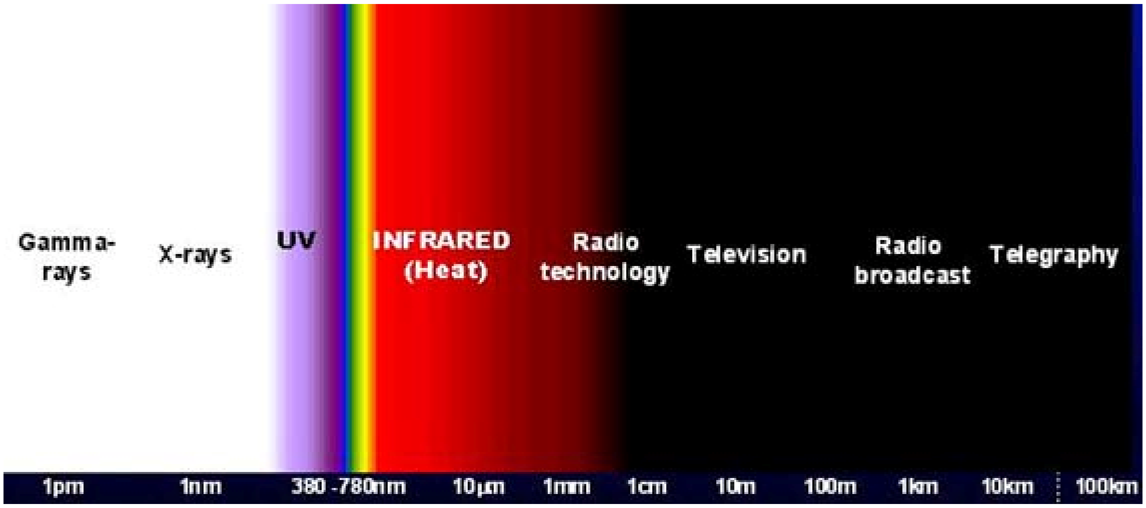
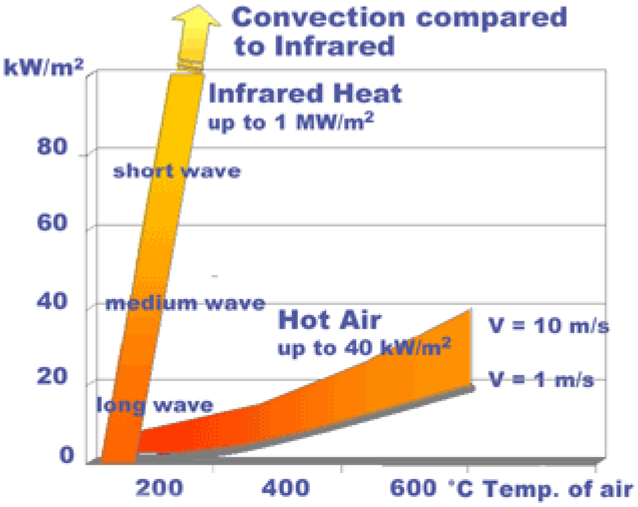
# Introduction to Infrared Technology



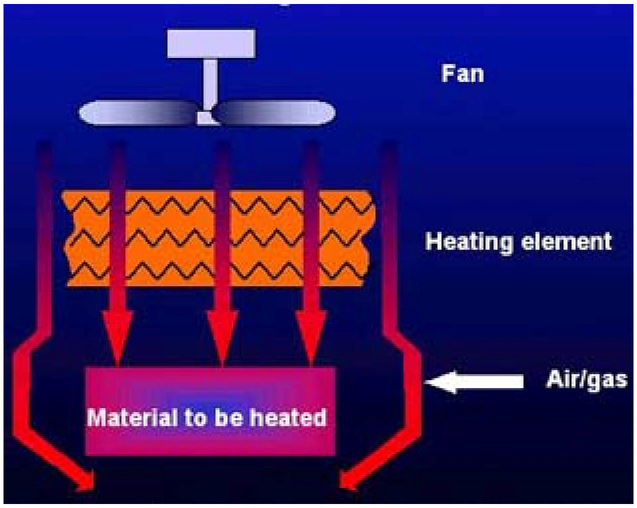
There are two basic means of heating a product electrically, by direct and indirect methods. With direct heating, heat is generated within the mass of the material (e.g. by microwave and radio frequency energy in the case of dielectric materials or by induction or resistance heating in the case of electrically conducting materials). With indirect heating, heat is transferred to an article by any of the three familiar methods of *conduction*, *convection*, and *radiation*.



*Conductive heating* is achieved by placing an article into touch contact with a heat source. The rate of heat transfer is determined by several factors, not just the thermal properties and temperatures of the two bodies.

The surface conditions over the contact area, the pressure of contact and the nature of any gas, liquid or solid films at the interface all play a part in the conductive process. Radiation can also contribute to heat transfer across the interface.

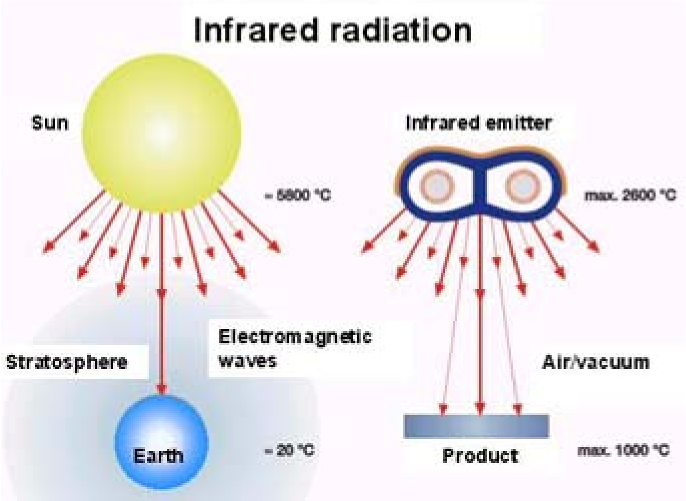
*Convective heating* relies on the movement of a hot fluid or gas, such as air, which acts as a carrier of heat from one body to another. Natural convection occurs when different zones of the gas or liquid have different temperatures and densities. Industrial process heating commonly makes use of forced (air) convection, whereby the air is directed towards the substrate by a fan.



The rate of heat transfer depends on many factors including the temperature differential between the heating air and the substrate, and the density and rate of movement of the air.

In the context of heat transfer, *radiation* refers to the thermal variety (non-ionizing radiation), and should not be confused with radiation produced at wavelengths shorter than the visible spectrum (e.g. X-rays).

Thermal radiation takes place without the need for an intermediary agent such as air because energy is transmitted as electromagnetic rays emitted from a heated body. The rate of heat transfer depends on such factors as the temperatures of the heater and the receiver, the ability of each to emit and absorb radiant heat, their geometrical shape, their active areas, and relative positions or proximity.



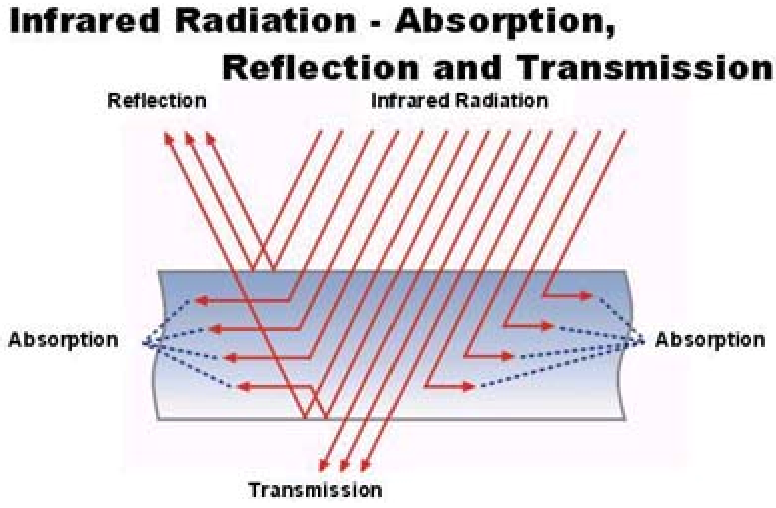
The human eye differentiates between light-producing or glowing sources and invisible emissions. Infrared radiation occupies a waveband immediately adjacent to the red end of the visible spectrum. "Black heat" is a term sometimes used to describe the infrared band.

Heaters of visible radiation produce thermal radiation within the IR band as well as the visible band. Even at the very intense light producing temperatures in the order of 5000°C, an heater produces more energy in the infrared than in the visible band. Heaters that produce some light energy are also classified as infrared, although in scientific terms the description is not absolutely accurate.

## History of infrared process heating

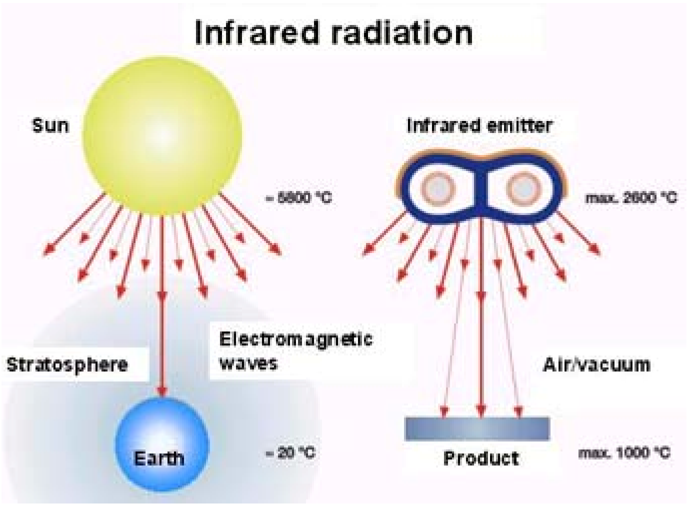
Electric infrared process heating is not a new technique. It has been in use -- in one form or another -- for over half a century. But only in recent years have a wide choice of radiant heat sources - infrared heaters - become available.

The term *infrared heating* as applied to industrial heating processes originated in the late 1930s when experiments took place in the use of heat radiation produced by commercial lighting bulbs fitted with special external reflectors.



The technique was very successful for curing the new synthetic resin enamels on car bodies, so it was applied to production lines. Carbon-filament lamps were used at first, and later tungsten-filament lamps with internal reflectors. In each case the lamps were rated to operate at a reduced filament temperature. As the reduction in filament temperature had the effect of moving the peak wavelength of the emitted radiation further into the infrared portion of the spectrum, it was logical to differentiate between lamp bulbs used for lighting and those used for heating by calling the latter infrared lamps and the process in which they were used infrared heating. The early lamp systems were only capable of providing power intensities in the order of 5 kW/ m$^2$; modern designs can provide up to 105 kW/ m$^2$, and with improved directional properties. When other types of even more powerful radiant heat source were later developed (e.g. linear quartz lamps and metal sheathed elements), the term infrared heating was retained.

This undoubtedly had some commercial value in persuading industrialists to investigate this heating process in relation to their own problems. As a result, industry has enjoyed significant savings in time and money. The concept of the infrared oven became firmly established. Infrared heaters, reflective walls, roof and floor, together with entrapped warm air were combined to optimize the heating of a wide range of products, including three-dimensional shapes. Infrared heating has proved its worth over many years, having evolved into a sophisticated industrial tool to become an acknowledged and indispensable branch of engineering practice.

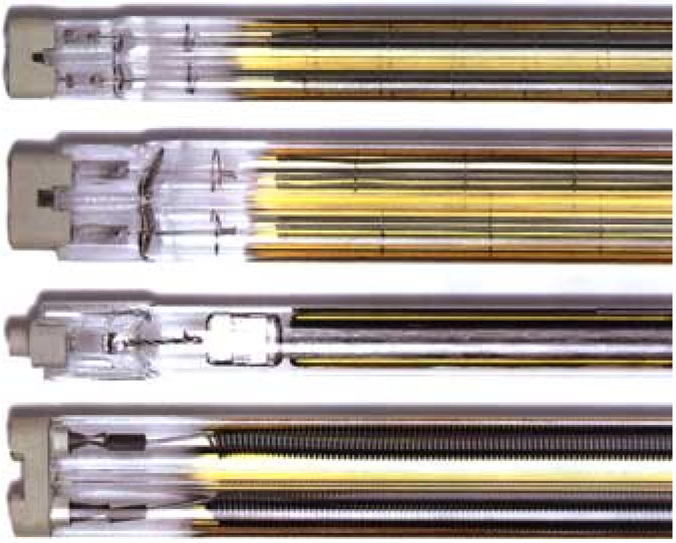


## Infrared heating in everyday life

There is a popular misconception that infrared radiation is something new and mysterious. The emotive word *radiation* is usually associated with nuclear physics, medical X-ray, and ultra-violet tanning lamp equipment, so it is hardly surprising that infrared radiation is treated with some suspicion by the general public. Some typical examples of how and where IR is encountered in everyday life should help dispel these myths.

Infrared radiation exists around us at all times: in fact any body having a temperature above the absolute zero (- 273°C) emits infrared radiation in an elaborate exchange with its surroundings.

In addition to being below the level of appreciation by the senses, these low levels of radiation are of limited practical application. However, even the human body emits infrared radiation, as does a candle, hot fluids and foods, a flame, a light bulb, and of course the sun.



With electric infrared sources, heat is normally produced by passing a current through a coiled resistive element. To be applicable to domestic and industrial processes, source temperatures in the range of 500°C to 2200°C are normally required. The domestic quartz tube radiant heater, popular for bathroom heating, falls within this range. It operates with an element temperature of around 950°C and produces a bright orange glow from the element spiral.

Similarly, the tubular metal sheathed element rings and grill elements on electric cookers emit a substantial amount of infrared radiation, operating with a cherry red glow at around 700°C The latest quartz halogen infrared heaters used for cooking operate at a maximum temperature of 2200°C resulting in luminous emission. In the medical field, infrared radiant heat lamps are used in osteopathy for the treatment of muscle and limb disorders.

Infrared thermography for diagnostic purposes is now commonplace. In medical diagnosis the technique provides a multicolored contour plot of the heat radiation patterns from the human body from which medical specialists can locate areas of abnormality. A similar technique is used for the detection of heat losses from the external surfaces of buildings thus indicating where additional insulation could be used to conserve heat and thereby reduce space heating costs.

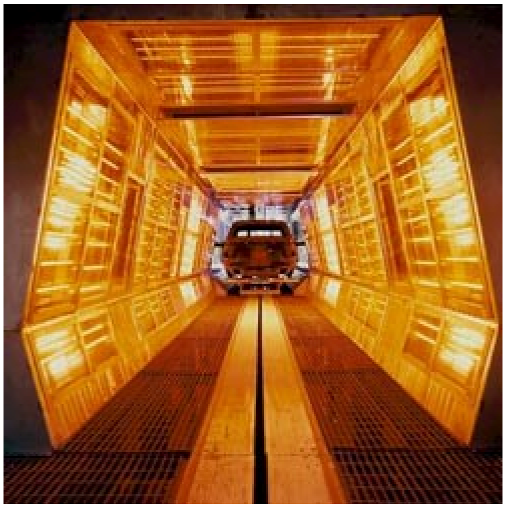
Special video cameras sensitive to the IR heat emitted by a scene can be used to good effect in darkness to produce remarkably clear pictures. These have applications in the military, security, and entertainment fields. Domestic television remote control units make use of infrared signals for program selection etc. while certain types of burglar alarms detect the presence of intruders by responding to the infrared content of body heat. In a more specialized application, heat seeking missiles home in on the infrared emission from the hot exhaust gases of enemy devices.

A wide range of appliances and devices rely on infrared radiation for their operation; we use these in ever-increasing numbers with complete confidence.

## Developments in process heating

During World War II infrared heating became more widely recognized. The main applications were in the metal finishing fields, notably in the curing and drying of paints and lacquers on military equipment. Banks of lamp bulbs were used very successfully, and although by today's standards the power intensities were very low, the technique offered much faster drying than the fuel-fired convection ovens of the time. Production bottlenecks were overcome and military supplies to the armed forces were maintained.

After the urgency of war production had passed, the adoption of infrared heating techniques continued, albeit on a much slower basis. As industries reverted to normal peace time operations, prewar methods of production were reinstated in order to resume full output as quickly as possible, and to provide immediate employment for the returning members of the armed forces.



However, in the mid 1950s the motor vehicle industry again began to show interest in the capabilities of infrared for paint curing, and a number of production line infrared tunnels came into use. The familiar lamp bulbs were by now being complemented by a new tubular lamp of higher radiant intensity but smaller in physical size. This allowed a much higher packing density to be achieved, hence a higher power intensity over a given area of radiant emission.

With the interest in infrared heating now renewed, new types of heat sources (heaters) were developed to fill the ever widening needs of industry. There now exists a variety of types, shapes and sizes with an extensive range of intensities and operating temperatures. This flexibility enables the equipment designer to meet a vast range of process heating requirements, such as paint curing, moisture evaporation, printing ink drying and heating of solid materials. Thus the technique is not restricted to a unique heating condition but may be as powerful or as gentle as a particular process requires.

## Summary of benefits

The growth in popularity of infrared systems over the past 30 years stems not only from numerous production benefits provided by this form of heating but also from more mechanized production processes and new heat setting materials being deployed in industry. Certain benefits are, of course, common to all infrared systems, but additional specific benefits are often obtained depending on the process under consideration.

In general infrared systems provide the following:

- Rapid heating of the product. In all but a few exceptional cases radiative transfer of heat is much faster than convection. A more constant rate of heating is obtained because the source temperature is normally much higher than that of the product,

even at the end of the heating cycle.
- Low energy costs because of short heating times, and the ability to apply the heat only where and when it is required.
- Cleanliness in operation as the heat sources do not cause contamination.
- Elimination of atmospheric pollution due to the absence of combustion products.
- Ease of control combined with safe operation.

# Advantages of Infrared Heating

Since its development some 70 years ago, IR heating has been successfully applied to hundreds of different process heating applications, such as curing metal finishes and protective coatings; fusing thermoset and thermoplastic powder coatings; forming molded plastics; bonding adhesives and metals; drying papers, inks, and fabrics; and processing foods.

### Advantages of Electric IR Heating

A number of features make electric IR heating advantageous:

- Flexibility of control and configuration
- High speed and high efficiency
- Compact footprint and relatively low weight
- Consistent product quality
- Low environmental impact both inside and outside the plant
- Value for investment.

### Flexibility of Control and Configuration

One of the primary reasons for the success of electric IR heating is the high degree of control available to users. Electric IR heating equipment can be switched on and off in a matter of seconds. Thus electric IR can be programmed to provide a heat-up and cool-down profile well suited to a given product. In a setting where products are sensitive to overheating, the quick control and low thermal inertia of IR elements can be vital, quickly reducing the heat delivered to a product after an interruption in line movement.

Electric IR ovens can be "zoned" to provide a high heating rate in one zone and a lower heating rate in another. This may be important, for example, when curing a paint or powder. It may also be desirable to apply a high heating rate at first to set the paint or powder, then a lower heating rate to cure the finish without overheating.

IR heaters can deliver a range of heating rates to the product, from the very low rates characteristic of a convection oven to heating rates of 80 kW/ $m^2$, or roughly 20 times greater than possible in a convection oven. Heating rates greater than 80 kW/ $m^2$ are sometimes necessary.

### High Speed and High Efficiency

As a result of the greater heating rates and the high degree of control available with electric IR process heating, most products can be heated much more rapidly than in a convection oven. Thus, it is possible to decrease the product's residence time in the heating unit and increase the throughput of products. This enables manufacturers to make better use of their production facilities.

For example, an electric IR oven can provide a high heating rate to cure paints (including hard-to-cure, water-based paints) in a fraction of the time required in a convection oven. High heating rates are possible for curing paint in an IR oven because the short-wave IR radiation may be partially transmitted through certain coatings to heat the substrate.

The times to heat various materials in both An electric IR oven can heat many materials far more quickly than can a convection. For example, for steel and aluminum, the time to heat 0.05 inch thick panels to 300°F (149°C) is more than six times faster in the electric IR oven.

For plastic and wood, the time differences are even more dramatic. The higher heating rate supplied by an IR oven causes the surface temperature to rise to 300°F (149°C) without fully heating the interior of the material. In a convection oven, it takes much longer to reach 300°F (149°C) because of the lower heating rate and because the product is heated throughout.

For curing a coating on plastic or wood, an IR oven has an advantage in that the coating can be heated to the curing temperature without appreciably heating the material in depth. Thus, a coating could be cured without overheating and damaging the material. Furthermore, the cool-down time would be less because the material would not be heated in depth.

Electric IR heating is capable of delivering a higher percentage of the input energy to the product than convection oven heating. Due to the higher efficiencies of the IR system, the per-product processing cost can be comparable to -- or lower than -- gas convection. Furthermore, the long preproduction heat-up times required for convection ovens waste energy that would, in an IR system, be put into heating the product. Electric IR heating is efficient because more heat is delivered to the product, not lost to the surrounding air and not up a flue.

### Compact Footprint and Relatively Low Weight

Electric IR ovens can deliver heat more rapidly to a product than convection ovens can. This means that IR ovens are generally much smaller than convection ovens. Manufacturers can make more productive use of their floor space. Because heat delivered by electric IR heaters is not dependent on convection, IR ovens usually require less insulation and fewer bulky construction materials. In fact, some manufacturers suspend IR ovens from the ceiling to save floor space.

IR radiation can also be precisely aimed or directed to heat only selected parts of an assembly without overheating other parts that may be temperature-sensitive. Electric IR ovens tend to be reliable, with no moving parts or motors, and they are usually modular, making it possible to expand an existing oven or to add IR modules to an existing convection oven. Depending on the application, portable IR units can also be used for localized heating.

If the product finishing line has a convection oven in good working order, its capacity can be increased by adding an electric IR preheat section. For example, by adding an IR preheat oven, a manufacturer can double the product speed versus a convection oven alone. The added capacity of an IR preheat section can enable water-based paints to be cured in a convection oven designed for solvent-based paints. In other applications, an IR preheat oven can gel powder coatings before they enter a convection oven. The moving air and dust in a convection oven might disturb such coatings before they gel.

### Consistent Product Quality

Electric IR heating units can be controlled, directed, and instrumented for more precise temperature control than is possible in convection ovens, which are prone to temperature stratification (especially when heating large objects or surfaces). Because IR heats materials selectively, water-based coatings can be dried more efficiently. Especially with short-wavelength IR heaters, the energy can penetrate coatings to heat the underlying surface itself. Thus the coatings are evaporated more readily, preventing blisters that might occur with convection heating.

For paint curing, the quality of the finish may be improved because of the reduced air turbulence and generally cleaner conditions in an IR oven. For example, the high airflow rates characteristic of a convection oven sometimes displace powder coatings and can introduce unwanted airborne particles before the coatings cure. An electric IR unit does not require convection currents to heat the object; thus, a higher quality, more predictable product finish is possible.

### Low Environmental Impact Both Inside and Outside the Plant

Electric IR heating can help manufacturers respond to more stringent environmental regulations. Many manufacturers and finishers are replacing solvent-based paints with water-based paints and powder coatings to satisfy the emission restrictions imposed by new air quality standards. It generally takes longer to cure water-based paints and powders than those that are solvent-based. Because electric IR can increase the heating rate of the coated surface, manufacturers can recover the production efficiencies lost in the switch to water based paints and powders.

Compared to forced-air convection ovens, electric IR heating units draw less air from surrounding space. The environment in and around the electric IR oven is cleaner, because coatings (such as powder) stay on the product. This means less make-up air and a lower space conditioning bill if the manufacturing facility is conditioned. IR units also deliver less waste heat to their surroundings, which can be a significant benefit in warm climates, and they are much quieter, with no burner or large blowers. They do not produce any on-site $NO_X$ or $SO_X$ emissions.

### Value for Investment

Because of its relatively low capital cost, easy installation, reliable operation and efficient use of energy, electric IR heating provides an excellent value for your investment.

## Summary of Benefits

In summary, electric IR units offer many advantages to manufacturers:

- Heating rate can be controlled from very low values to very high values
- Higher heating rates mean faster production using less floor space
- Heating rate can be switched on or off in a matter of minutes or seconds, meaning no off-cycle losses
- Heating rate profile through the oven can be varied to optimize product processing
- IR ovens can be zoned to apply heat only where needed without heating the entire product
- Electric IR is an environmentally friendly process, with no on-site $NO_X$ or $SO_X$ emissions, far less thermal emissions than convection ovens, and virtually no noise emissions
- Electric heating is inherently cleaner than fossil fuel heating; thus, less clean-up is required
- Electric IR can dry/cure coatings very rapidly when the radiation penetrates the coating and heats from within
- In some cases, a coating can be dried/cured in an electric IR oven without heating the entire product, thus protecting heat-sensitive areas and saving energy
- In many cases, drying/curing of coatings with IR results in higher quality finish
- Electric IR is efficient because the energy is transferred directly from the heat source to the product.

# Engineering Aspects of IR Heating

## What is Infrared Heating?

All bodies above zero temperature (-273°C) emit infrared radiation in the form of waves which pass through space and are partly absorbed by bodies they strike. This radiation forms a part of the electromagnetic spectrum and has the strongest heating effect of all. The nature of the radiation is the same in essence as that of x-rays, ultraviolet, visible light and radio waves.

It has been known since the mid nineteenth century that infrared radiation, or group of rays, behave in a similar manner to visible light as far as transmission, reflection and absorption are concerned. The concept of radiation is not easy to define, as both corpuscular and oscillatory aspects are involved.

The electromagnetic energy that is emitted from the surface of a heated body is called thermal radiation, and consists of a continuous spectrum of frequencies extending over a wide range. The spectral distribution and the amount of energy radiated depend chiefly on the temperature of the emitting surface.

Careful measurements show that for a given temperature there is a definite frequency at which the radiated power is maximum. Furthermore the frequency of the maximum is found to vary in direct proportion to the absolute temperature. At room temperature, for example, the maximum occurs in the far infrared region of the spectrum and there is no perceptible visible radiation emitted. But at higher temperatures the maximum power is radiated at correspondingly higher frequencies, and at about 500°C a body begins to glow visibly. The rate at which energy is radiated by a hot body is also found to be dependent on temperature.

Electromagnetic radiation is created by oscillatory electric charges, and the frequency of oscillation determines the kind of radiation emitted. Radio waves and microwaves exist at the lower frequencies and x-rays and gamma rays exist at the higher frequencies. In between these is a range of frequencies known as the optical spectrum, with infrared, visible light and ultraviolet light.

The optical spectrum is characterized by the fact that the radiation can be directed, focused and controlled by mirrors and lenses and that prisms and gratings can be used for dispensing it into a spectrum.

Ordinary sources of radiation in the optical spectrum, such as tungsten filament lamps, fluorescent lamps and flames consist of a very great number of molecules which have electric charges that oscillate independently of each other, producing a range of frequencies.

Unlike these sources, excited individual atoms and molecules give out radiation at various discrete frequencies, which are characteristic of the particular kinds of atom or molecules involved. The optical spectra of most atoms are quite complex, but a few elements such as the hydrogen and the alkali metals have relatively simple spectra.

The most simple of all is the hydrogen atom which consists of an electron and a proton. The electron may be considered as being able to inhabit only certain levels about the proton and to move from one level to another it needs to gain or lose an amount of energy, called a quantum.

Small quantities of energy are measured in electron-volts (eV), and for radio waves a quantum is about 0.000004 eV, for infrared a quantum is about 0.004 eV, and for x-rays and gamma rays it is about 40,000 eV.

When an electron moves to a lower energy level a discrete amount of energy in the form of a photon is emitted from the atom. This photon takes the form of electromagnetic radiation. Movement between the lowest levels produces a photon of far ultraviolet, movement between the next lowest levels produces visible light and near ultraviolet; movement between the middle levels produces infrared.

A photon may be considered as having a cross sectional area, like that of a ball; the larger the ball the greater the chance of it hitting something. Similarly, atoms and molecules can be considered as having a cross sectional area and materials made of larger atoms and molecules are likely to absorb photons more quickly than materials made of small ones. However, materials absorb infrared selectively. Virtually all transparent solids show broad absorption bands that extend into the visible frequencies.

### Reflection, Absorption and Color

Solids have atoms that are fixed in position relative to each other, and each atom has electrons that are tightly bound to it. These are known as polarization ions.

A low frequency electromagnetic field falling on the surface of a solid would cause the electrons near the surface to become more energetic and to oscillate at the applied frequency. After a time of perhaps less than a second the energy is given off as a photon.

The solid does not absorb energy unless the frequency of the electromagnetic field is close to the resonant frequency of the electrons. At this frequency the magnitude of the electrons' oscillation is sufficiently large for them to "bump" into one another electrons, so the solid gains energy.

An electromagnetic wave always transports the same amount of energy per second. When the wave enters a solid the increase in the electrons' oscillations causes the energy density to increase, so the wave travels more slowly. An electric field is set up by the oscillating electrons and this causes a part of the electromagnetic field to be reflected.

Materials made only of atoms with only tightly bound electrons absorb very little energy. They are good insulators.

In many solids some of the electrons are not tightly bound, and some solids contain electrons that can move freely. These are called conduction electrons. An electromagnetic wave causes conduction electrons to oscillate in anti-phase with it, and this decreases the wave's energy density. The wave cannot increase its velocity so energy must be reflected. The electrons screen the solid, and it takes only a few conduction electrons to reflect the wave totally.

The polarization electrons resonate at frequencies in the infrared and visible radiation bands and energy from infrared and visible electromagnetic waves is absorbed by solids at these frequencies.

At higher frequencies the conduction electrons undergo smaller and smaller oscillations, so the wave penetrates more deeply.

As the frequency increases through the visible range and the penetration increases the overall absorption before the wave is completely reflected stays roughly the same. This is why most metal looks grey and not blue or red. The higher conductivity of a solid the more light it reflects and the whiter it appears.

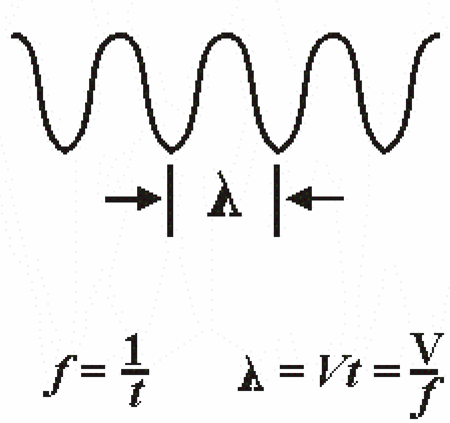
Very white surfaces are usually prepared from very transparent materials powdered into small particles. The light entering the particles is reflected by the randomly oriented surfaces

A solid appears a certain color because IR reflects one part of the optical spectrum preferentially to another part. A paint achieves its color by mixing a fine transparent powder with other particles which absorb particular frequencies in the visible spectrum. To make colored films the transparent powder is omitted.

To assess the reflection and absorption properties of paints, coatings and nonmetallic solids in the infrared spectral region it will always be necessary to rely on empirical measurements. Properties vary not only with chemical composition but also with fine structure, surface roughness and temperature. Where objects are heated with short wave infrared lamps as much as 20% of the radiation can be in the red end of the visible spectrum. This inevitably leads to blue paints absorbing more radiant energy than red paints.

**Laws of Radiation and Their Practical Significance**

Turning now to the oscillatory nature, the radiation passes through successive identical states at precise time intervals measured in seconds. The rate at which the states recur, or frequency, is measured in cycles per second so that frequency is equal to the reciprocal of time. The velocity of propagation (in a vacuum) for all radiation is 3 x 108 meters per second: the speed of light. From this we can deduce that the distance between successive identical states -- the wavelength -- is the product of velocity and time [see figure at right].



Expressing these statements mathematically, t = time interval in seconds which separates the passage of radiation through two successive identical states; f = frequency in cycles/second; λ= wavelength in meters/second, and V = speed of light in meters/second.

Infrared and visible wavelengths are normally expressed in microns (or micro-meters), this unit being one millionth of a meter. Radiation visible to the human eye occurs over a very narrow band, form 0.4 to 0.76 microns. The broad region occupied by infrared extends from 0.76 microns (that is just beyond the red end of the visible end of the spectrum) to 400 microns. However, the radiation used for process heating occurs between wavelengths of 1 and 5 microns in order to obtain adequate source temperatures. This represents a temperature range of 2200°C to 300°C.

Continuing well beyond the infrared or thermal region to much longer wavelengths of the

order of centimeters and meters, the spectrum is occupied by microwave, radar, television and radio communications equipment.

The radiation emitted by a body can be determined if the temperature and nature of its surface (emissivity) are known.

These are the key parameters required to calculate the radiation emitted by a surface at a particular wavelength or over a band of wavelengths.

the starting point in the discussion on the laws of thermal radiation is the concept of the "black body" or Planckian radiator. This is an ideal body which totally absorbs all incident radiation at all wavelengths. The reflectivity is therefore zero (Note that the term "black body" does not have any color connotation in the visual sense). In addition to being a perfect absorber, it is also a perfect radiator: it will radiate the maximum amount of energy at any given temperature. This concept is very convenient in the mathematical and graphical treatment of infrared theory and the development of relationships.

A near approximation to the black body is provided by an isothermal enclosure, which represents a hollow metal sphere with a small radial hole through its wall. Any radiation entering this hole undergoes multiple internal reflections and absorptions until total absorption is achieved. Conversely, if the sphere is heated, the hole will radiate as if it were a black body. This applies even if the sphere is heated to an incandescent temperature.

From this theoretical phenomenon, it is possible, for example, to visualize the interior of an enclosed furnace with all the walls at a constant temperature behaving almost as a black body. However, in practice all bodies are less than perfect radiators or absorbers, and are therefore referred to as "grey bodies," or more strictly "nonblack bodies." The maximum radiation intensity W produced by a black body unit interval of wavelength is obtained from Planck's Law, which (in slightly simplified form) can be written::

$$W_{\lambda}, T = C_1 \lambda^{5} exp - \left[ \frac{C_2}{\lambda T} \right]$$

Where the left-hand side of the equation represents emission at wavelength λ; $C_1 = 3.741 \times 10^{16}$ W/$m^2$, $C_2 = 1.439 \times 10^{-2}$ mK, λ = wavelength in microns, and T = absolute temperature.

In practice this formula is seldom used in the process heating field as total emission is a more meaningful quantity. The total emission from a black body is obtained by integrating Planck's Law for all wavelengths. This is known as the Stefan-Boltzmann Law:

W = σT4 (W/ $m^2$)
where σ = 5.67 x 10-8 (Wm-2 K4)

σ is known as the Stefan Boltmann constant.

The Stefan-Boltzmann Law shows that the total energy radiated by a black body is proportional to the fourth power of the absolute temperature. For example, by doubling the absolute temperature of a black body the total radiated energy increases, theoretically, by a factor of sixteen. Although the radiation at all wavelengths increases, the bulk of the excess is at the short end of the spectrum.

The emission from a surface of a nonblack body is always lower than that from an ideal black body, the ratio which relates the two values being known as the emissivity of the surface.

If E = emissivity (E < 1)
WNB = emission from a nonblack body at temperature T
WS = emission from a black body at temperature T

then $E = W_{NB} / W_B$

Using the term E in the Stefan Boltzmann formula above, we obtain the emission for a nonblack body:

W = ET4 (W/ $m^2$)

and for a body of area A,

Radiant heat = A x E x T4 x σ W

The equation above shows that the total radiation is directly proportional to the surface area of the emitting surface, an important factor in oven design.

The value of the emissivity is strictly wavelength dependent, but for practical purposes it is taken as being constant. Again, by doubling the absolute temperature the total radiation increases sixteen fold.

At best only 1% or 2% emission or absorption of radiation is possible with these metals unless they are alloyed or contaminated with more able elements. However, the emissivity value for metals normally increase with temperature, the relationship being substantially proportional. Nonconductors usually have much higher values of emissivity at lower temperatures but they can fall with rising temperatures, in certain cases by an inverse ratio.

Absorption characteristics are defined in a similar manner to emission characteristics. The absorptivity or a nonblack body is the ratio of the nonblack absorption to the black absorption at the same surface temperature.

The absorptivity of a grey body is equal in value to its emissivity, a grey body having constant spectral emissivity at all wavelengths. Absorptivity values are often assumed to be constant as this helps to simplify oven design problems. This is true only if the source and workplace temperatures do not alter substantially during operation. However, if a different temperature were to be considered particularly if there is a major change in the source temperature, a new value of absorptivity might well be applicable, as shown earlier for emissivity.

### Wien's Law

The relationship between the absolute temperature T of a heat emitting body and the peak wavelength of emission, $\lambda m$, is given by Wien's displacement law:

$\lambda m T = \text{constant}$
If $\lambda m$ is expressed in microns
Then $T\lambda m = 2898$

An important aspect of this effect is that as the temperature of an heater is changed, for example, by varying the supply voltage, the peak wavelength of emission changes in inverse ratio. Therefore, as the temperature increases the peak wavelength decreases and vice versa.

For example, an heater operating at a typical temperature of 2200°C (2473K) would have a radiation peak at 2898/2473 = 1.17 microns, whereas an heater operating at 650°C (923K) would have a radiation peak at 2898/923 = 3.14 microns.

We therefore have a means of selecting an heater whose emission spectrum is best matched to the absorption spectrum of a receiving body wherever this is a critical factor in optimizing the rate of heat transfer. It should be remembered, however, that in the infrared process heating field the transmission and absorption wavebands are usually sufficiently broad to utilize the side-bands of the emitted radiation in addition to the peak wavelength. The basic types of heaters which have become established over many years in industrial process applications are designed to operate within defined limits of temperature determined by their construction and materials.

### Reflectivity

This is defined as the fraction of the incident radiation which is reflected by a surface. It therefore makes no immediate contribution to the heating at the surface. The property of reflection is however used extensively in infrared heating both to orientate the energy and to provide enclosures in which the radiant energy can also take indirect paths to the surface requiring to be heated.

## Transmissivity

This is defined as the fraction of the incident radiation which is transmitted through the receiving surface. Many substances, particularly those in the liquid and gaseous state, transmit infrared. Thickness of the layer is an important factor. As illustrated by the greenhouse effect, transmission of visible and short wave energy does not necessarily extend to the longer wavelengths.

## Accounting for Total Radiation

Infrared radiation striking a body is dispersed in three ways: by reflection, absorption and transmission. The summation of these three quantities is equal to the value of the incident radiation, but it is normally the aim in infrared process heating to make the value of the absorbed radiation as high as possible.

## Lambert's Cosine Law

This is one of the basic laws of photometry which states that the intensity of radiation falling onto a flat surface from a small radiant source is a maximum when the receiving surface is normal to the source. However, if the receiving surface is turned away from the normal by an angle X, the intensity of the radiation received is proportional to the cosine of the angle X between the normal to the receiving surface at that point and the direction of the radiation.

This law applies only to a small source radiating over a relatively large distance, for example in illumination engineering. In infrared engineering the sources usually occupy substantial areas, sometimes larger than the individual receiving surfaces of the workpieces and the distances between the source and receiver are usually comparatively small. The cosine law is therefore not universally valid in the process heating field, but it does underline the need to arrange for the radiation to strike the receiver at right angles for the best efficiency of heat transfer. Conversely, if a thin metal panel, for example, is placed with its edge towards the source of radiation (that is, when $\cos X = 0$) it would not, in theory, receive any heat. However, this directional effect does not present a problem in a well designed infrared oven, and in certain cases it can even be put to good use.

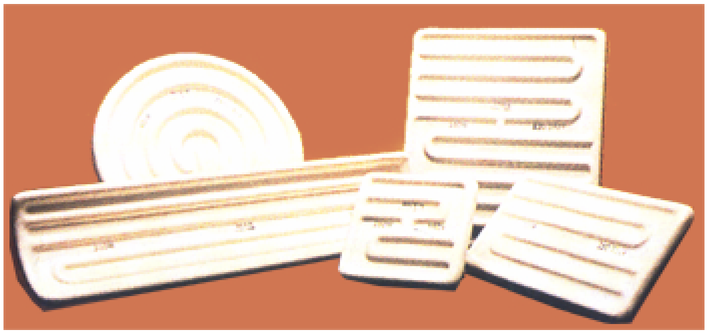
## The Inverse Square Law

This law is also based on the concept of a point source of radiation and is more appropriate to illumination engineering. It states that the radiant intensity at a receiving surface varies inversely as the square of its distance from the point source of radiation. On the other hand, radiation between two infinitely large parallel plates is independent of the distance between them. Another example not conforming to the Inverse Square Law is that of radiation to a sphere from a larger spherical shell surrounding it. For comparatively large radiant source areas such as those commonly employed in infrared ovens the surface-to-surface relationship between distance and intensity is found not to conform to the inverse square law. In practice the intensity can be almost independent of distance over very small distances of the order of a few centimeters, increasing to an almost linear relationship at greater distances.

## Industrial Heaters and Modules

Electric infrared heaters produce radiant heat through the ohmic heating effect of an electric current flowing through a spiral coil of wire such as a tungsten filament or a suitable heating element alloy. The hot wire itself may radiate or alternatively conduct its heat to a surrounding material which then becomes the source of radiant heat. Heater surface temperatures in the range of 400°C to 2200°C are normally required to produce acceptable heating rates for the wide variety of processes to which infrared systems are commonly applied. For a given radiant output low temperature heaters have a far larger radiant area than those of higher temperature. Each type of industrial heater in the long, medium and short wave bands has a role to play in the process heating held. Infrared radiation is generally classified as: short wave - less than 2 microns, medium wave - between 2 and 4 microns, and long wave - longer than 4 microns.

### Ceramic elements



Starting at the low temperature end of the working range there is the sealed ceramic heater, a typical example being the trough type shown at right. It normally operates with a surface temperature in the range of 300°C to 700°C. The large emitting area provides substantial radiation, but also allows a significant proportion of the input power to emerge as heat to the surrounding air by convection. This can be beneficial in certain applications.

A coiled heating element of nickel chrome alloy is embedded in a glazed ceramic body, which gives protection against thermal shock, and prevents attack by atmospheric oxygen. An operational life of several years is therefore normal. The refractory material has a high emissivity value in the region of 0.9 which approaches the ideal black body conditions required for efficient radiation. The radiated energy is in the long wave band with peak emission wavelengths between 3 and 5 microns (See Wien's Law, Chapter 3).

Typical element ratings for the trough type are from 125 W to 1000 W. An even pattern of radiation is obtained from the ceramic surface, and the elements can be mounted adjacent to each other to give an even spread of radiation over a large area. This is used to advantage when heating static products such as plastic sheets. When required, profiled heat patterns can be easily obtained by zoning a combination of elements of different power ratings.

The combined masses of the element spiral and the refractory material result in a high thermal inertia compared with some infrared sources.

Thus heat-up and cool-down times can be 3-4 minutes. During this time the amount of residual heat remaining after switching off the power may necessitate the element panels or modules being fitted with quick acting baffles or retraction devices to prevent damage to heat sensitive products on conveyor lines during unscheduled stoppages. On the other hand, the slow response of the elements can be exploited to smooth the on-off periods of simple pulse type electromechanical regulators, or burst firing SCR units.

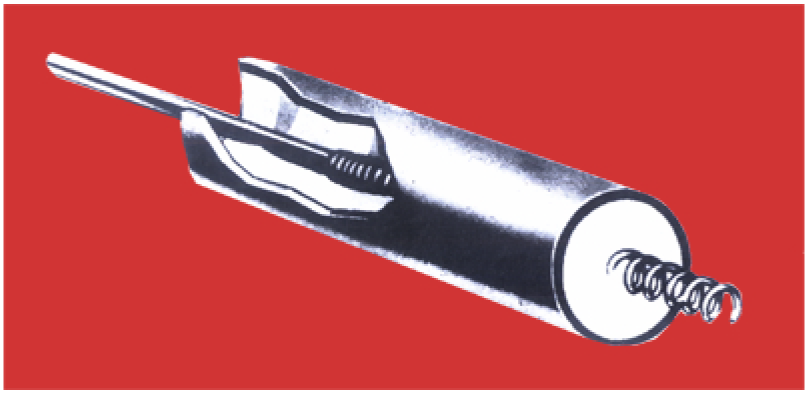
**Applications**

Flat elements are normally built into panels, to provide blanket heating for either stationary or conveyorized products. Trough units are particularly suitable for tubular ovens. Applications include the following:

- Preheating of plastic sheet for vacuum forming
- Drying silk screen printing inks
- Activation of adhesives
- Drying textiles
- Preheating embossing rollers
- Drying paints and lacquers
- Animal husbandry and rearing

**Metal sheathed elements**

Elements in the form of tubular rods are probably best known for their widespread use as boiling rings and grill elements on electric cookers. Surface temperatures up to 850°C (depending on the sheath material are obtainable, although a limit of 750°C is recommended where a long operating life is required. Typically, the metal sheathed element runs at a dull red heat along its working length, but running conditions from true "black heat" to orange can be selected, bridging the medium and long wavebands. The elements consist of a nickel-chrome resistance spiral mounted concentrically inside a tubular metal sheath. Electrical insulation between the two parts is provided by compacted magnesium oxide powder so that the sheath can operate safely at ground potential.



The elements are extremely robust and will withstand a fair amount of thermal and mechanical shock. An operational life of several years is therefore quite normal. When used as infrared heaters the sheath material is usually nickel-chrome alloy. The radiated energy is in the long wave band with peak emission in the region of 4 microns. As the radiating surface is in direct contact with the surrounding air a significant proportion of the input power emerges as convected heat.

In order to concentrate this energy in the desired direction, polished metal such as aluminum or stainless steel reflectors are used. Care must be taken to keep reflectors clean for maximum efficiency.

The combined masses of the element spiral, the magnesium oxide, and the metal sheath result in a comparatively high thermal inertia, so that the heat up and cool down times can be about 2 minutes or more. The residual heat remaining after switching off the power means that the reflectors or element panels might need to be fitted with quick-acting baffles or retraction devices to prevent damage to sensitive products on conveyor lines during unscheduled stoppages. On the other hand, the slow response of the elements can be exploited to smooth the on-off periods of simple pulse type electromechanical regulators, or burst firing thyristor units.

### Applications

The applications of metal sheathed element heaters are very widespread and include the following:

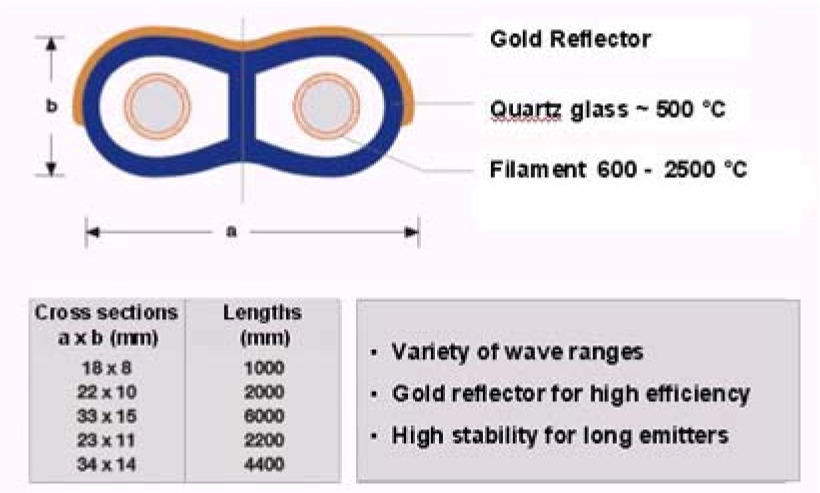
- Paint curing
- Curing of powder coatings
- Moisture removal
- Cooking or browning of food products
- Curing carpet backing
- Curing water-based adhesives
- Soft soldering metal components
- Drying silk-screen printing inks

### Mediumwave Quartz heaters

The most common type of medium wave heater is the tubular fused quartz unit. An alloy spiral element is housed inside a linear quartz tube, which is open ended. There is minimal contact between the spiral and the inner wall of the tube. In many respects it resembles the tubular element of a domestic bathroom heater, and operates at the same bright orange color temperature, up to 950°C. The peak wavelength is around 2.5 microns, and as quartz transmits infrared radiation efficiently up to 4 microns the quartz temperature is cooler than the spiral element. This means that convective losses from the quartz outer surface are minimized, while the secondary radiation from this source at a temperature of 650°C contributes to the total output from the heater.

Approximately 60% of the input power is converted into radiant heat, the emissivity of the unit being that of the wire spiral, around 0.8 when in use.

Twin-tube heaters [see figure at right] are constructed in a figure-of-eight cross-section, which gives extra rigidity over long lengths and enables all connections to be made at one end. Lengths of this type of heater are available up to 2.5 m, with ratings up to 8 kW. When built into modular form, with



| Cross sections a x b (mm) | Lengths (mm) |
|---|---|
| 18 x 8 | 1000 |
| 22 x 10 | 2000 |
| 33 x 15 | 6000 |
| 23 x 11 | 2200 |
| 34 x 14 | 4400 |

- Variety of wave ranges
- Gold reflector for high efficiency
- High stability for long emitters

multiple elements a power intensity of 50 kW/ $m^2$ is possible. Process temperatures up to 500°C can be achieved, and the heat output can be easily controlled either by element selection or by solid state thyristor controllers.

Full heat output after switching on takes from 20 to 60 seconds depending on the type of unit and mass of the element spiral. Heat conduction to the inner wall of the tube is minimal due to the small contact areas, therefore the relatively large mass of the tube scarcely affects the heat up time. The cooling time, however, is somewhat longer because of the residual heat in the combined masses of the quartz tube and the spiral.

Heat output is transmitted radially in all directions from the tube therefore reflectors have to be used to concentrate the radiation in a forward direction. Aluminum or stainless steel reflectors, either flat, parabolic or semi-elliptical are used, especially with the single tube units. The twin-tube units are available with the rear surface gold-plated to give a unidirectional beam of radiation.

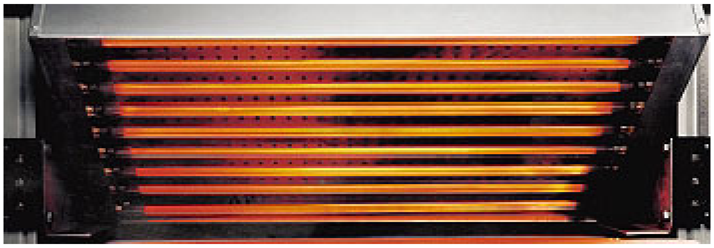
All medium wave tubes in common use can be expected to have an operational life of several years provided they are not subjected to undue mechanical shock or vibration, However, replacement is a relatively simple task and can often be carried out during natural short breaks in production.

**Applications**

- Drying of paints, varnishes and lacquers
- Curing mirror backing
- Glass moulding and lamination
- Curing sound deadening coatings
- Solder reflow for printed circuits
- Drying of battery plates
- Curing adhesives
- Floor tile heating and manufacture
- Vehicle paint and underseal drying
- Moisture removal

**Mediumwave Panel Heaters**

In panel form, [see photo below], medium wave emission is obtained from an element mounted in channels on the rear side of a quartz window, the whole assembly being contained in a steel case. A uniform distribution of heat is obtained across the emitting surface, with temperatures in the range of 500 to 950°C and power intensities about 40 kW/ $m^2$. The units can be close mounted to form a robust radiant wall which is resistant to thermal shock such as water splashes.



Due to the heater's comparatively large mass, heating and cooling times can be as long as 5 to 15 minutes. Retraction devices have to be considered when used for drying delicate or flammable materials such as paper.

### Applications

The main uses of panel heaters are for supplementary drying in paper mills, wallpaper production, heating of plastics or any material in web form.

### Molybdenum disilicide heaters

Molybdenum disilicide heaters were originally made for use in furnaces. They consist of a mixture of molybdenum disilicide and ceramic compounds.

Their ability to withstand oxidation at high temperatures depends on the formation of a thin layer of silicon material which adheres to the surface and prevents oxidation. When operated at high temperatures for extended periods the protective layer increases in thickness, and may tend to flake off when cooled. The protective layer is reformed as soon as the element re-attains a high temperature. If operated at temperatures below 800°C the protective layer does not develop.

The main reasons for failure are:

- Mechanical damage during maintenance or operation reaction with foreign substances either by direct contact or by dust, fumes or gases
- Mechanical stresses during cooling to room temperature
- Mechanical shocks due to magnetic forces. If the heaters are switched on at a low temperature at too high a voltage, or without a current limiting device, the shock from the resulting high electromagnetic forces may cause element breakage overheating of the element.

### Reflector heat lamps

An infrared heat lamp is similar to a normal incandescent lamp, but is designed to project its radiant heat in the forward direction. The envelope is parabolic in shape, and is internally silvered to give a high reflective efficiency for the whole life of the lamp. The various types of infrared lamps all have coiled tungsten filaments and are gas filled. Typical ratings for industrial use are 250, 300 and 375 watts. They differ from normal incandescent lamps in that their operating temperature is around 2200°C compared with 2900°C for lighting purposes. Peak wavelength is therefore 1.2 microns. The borosilicate hard glass envelope, as used for oven ware, transmits infrared energy efficiently up to 2 microns, and about 80% of the input power is converted into useful radiation. A lamp life of 5000 hours is claimed when operated at the normal voltage, but this can be extended considerably by under-running. Tungsten filaments have a positive resistance-temperature coefficient and therefore have a low cold resistance. At the instant of switching on an inrush of current of up to 14 times the normal rated value can flow, depending on the source impedance, so on large installations zone switching is often used to limit the inrush current.

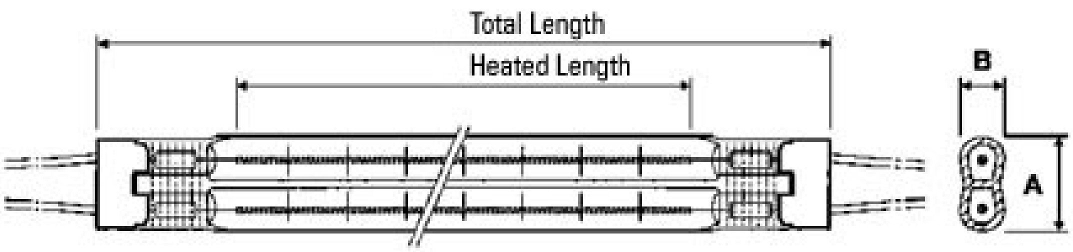
Alternatively, series-parallel switching or a solid-state soft starting arrangement can be used. For short duration stoppages the lamps are normally switched down to an idling mode. Full radiant output is obtained within a fraction of a second of switch-on, likewise the decay of heat on switching off is equally rapid. Because of the rapid response phase angle controllers must be used in preference to burst firing controllers to avoid lamp flicker. Only a small amount of heat is retained by the glass envelope as its normal running temperature is no higher than 300°C. An Edison screw-cap provides the means of connection and fixing so that lamp changing is a simple task.

A point to note in the design and application of multilamp panels is that the lamps, being 12.6 cm diameter at their widest point, cannot be mounted closer than 13 cm between centers. As the filament of each lamp is small in area compared to the frontal area of the lamp envelope an appreciable lateral gap exists between adjacent filaments. Sufficient distance should therefore be allowed between the lamp faces and the workpiece to avoid hot spots from the filament images.

Process temperatures up to 300°C can be obtained although in the majority of applications such as the drying-curing of coatings, temperatures exceeding 200°C are seldom required. Where solvents are being evaporated the lamp housings can be purged with clean air, which bleeds out from the annular spaces between the housing and the lamp faces. This ensures that solvent vapors cannot enter the lamp housing, it helps to keep the lamp faces clean, and provides cooling for the lamps.

### Shortwave Quartz Tube Heaters

Short wave tubular heaters in basic form comprise a linear coiled filament surrounded by a clear quartz glass tube, [see figure below]. The tube is evacuated, the electrical connections being taken through seals at the ends. The four typical types of heater to be described are: basic air-cooled units, tungsten halogen high intensity units, water-cooled units and spot heaters. They are suitable for many industrial and research applications.



### Basic air- cooled units

These are the most commonly used short-wave heaters, and are manufactured in single and twin-tube versions, single tubes of around 10 mm outside diameter and up to 1 meter in heated length have power ratings from 0.5 to 5 kW. Twin tube heaters are nominally 11 mm by 23 mm in cross section but have longer heated lengths up to 3000 mm. Power ratings are from 0.25 to 15 kW.

In general, short wave tubes operate with a filament temperature of 2200°C corresponding to a peak wavelength of 1.2 microns.

The coiled diameter of the filament is appreciably less than the internal diameter of the quartz tube, therefore spacers are used to hold the filament central in the tube. The spacers in conjunction with raised projections on the inner wall prevent the element from sagging when used vertically. A reflective coating can be deposited over half the circumference of the tube to provide unidirectional radiation, or alternatively external aluminum or gold linear reflectors in semi-elliptical or parabolic form can be used to give a converging or parallel radiation pattern.

The nominal working life of the heaters is 5000 hours provided they are not subjected to severe vibration or mechanical shocks. Frequent switching on and off can also shorten the working life, but this situation can be alleviated by switching the heaters between idling and full load. As with reflector heat lamps, a high inrush of current is obtained at the instant of switching on to the full rated voltage, so that slow acting fuses are required or a soft-start arrangement made.

Over 80% of the input power is converted into radiant heat, but some convection losses are inevitable due to the fact that the quartz tube can operate at a temperature as high as 400°C. Precautions must be taken in the design of heater panels to ensure that the metal-to-quartz seals at. the end connections do not exceed a temperature of 300°C, otherwise the seals could fail due to differential expansion. This cooling requirement can be easily achieved with air blowers, or by using tubes with special end caps incorporating heat sink features. Process temperatures up to 600°C can be obtained, while the control of temperature is normally achieved by bank or zone selection of heaters or by phase angle controllers. Pulsed energy regulators or burst firing controllers are not suitable because of the flicker produced at low power levels. Moreover, repetitive inrush current pulses would shorten the heater life and possibly interfere with other sensitive equipment fed by the same supply cable.

Power Intensities achievable with short wave tubes are capable of providing intense and rapid heating. Single bore tubes close mounted on a reflective panel with forced air cooling can produce power intensities up to 300 kW/ $m^2$, while twin tubes can achieve up to 150 kW/ $m^2$.

Applications include the drying of fast moving paper webs, textiles, and metal finishing such as coil coating or any process where intense heat is required with the capability of rapid removal of heat during process line stoppages.

### Tungsten Halogen High Intensity Heaters

As with the basic short wave heaters described above, the tungsten halogen units comprise a linear coiled tungsten filament surrounded by a clear quartz glass tube.

However, with the basic type the tungsten slowly evaporates from the filament when the heater is in use. This causes progressive blackening of the inner wails of the tube causing a steady loss of short wave output. The addition of a halogen such as iodine or bromine to the gas-filled tube prevents this blackening by combining with the tungsten particles to form a tungsten halide. This would normally condense on the inner wall of the tube, but if the wall is maintained above 300°C it will not condense, but will be returned to the vicinity of the filament. The high temperature of the filament causes the tungsten halide to break down into tungsten and halogen, the tungsten being deposited on to the filament, and the halogen released to repeat the cycle.

The filament temperature of tungsten halogen tubes is around 2700°C, equivalent to a peak wavelength of 1 micron. The color temperature is therefore similar to an incandescent lamp bulb.

The main applications for this concentrated high intensity heat source are in the research field for materials testing.

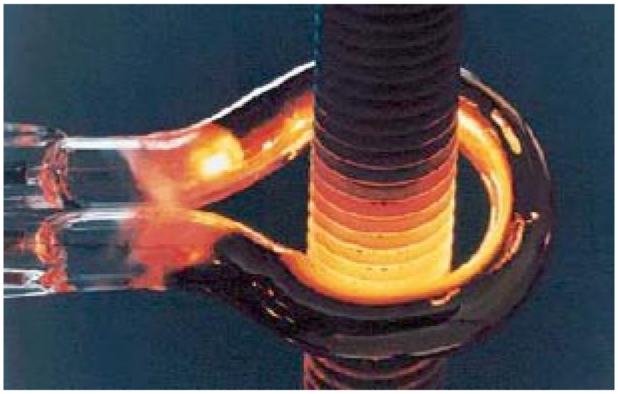
**Water cooled units**
These are used where extremely high radiant intensities are required, for example for materials testing and space research. They are seldom used in industrial processes as sufficiently high heating rates are possible with basic air cooled panels.

Water cooled units are based on the conventional tungsten-in- quartz configuration, but their successful operation depends to a large extent on the design of the housing and reflector system.

A simple form of water cooling is achieved with a double bore quartz tube, one bore being used to contain the filament, the other to carry a constant flow of water.

Gold reflectors are used to concentrate the radiation onto the work surface, and power intensities of up to 400 kW/ $m^2$. Certain materials can be heated up to 1000°C in a matter of seconds, the heater responding rapidly to switching on and off.

**Spot heaters**



For heating very small areas rapidly and without contact, short wave spot heaters are often used. A small tungsten halogen lamp, similar to those used in film projectors, is mounted at the focus of a semi- elliptical reflector. A concentrated beam of radiation is projected to the external focal point where the workpiece is placed. Spot sizes as small as 6 mm in diameter are possible. Using a 200 W lamp, workpiece temperatures up to 1000°C are possible depending on absorptivity, mass and losses. A 1000 W lamp with a spot size of 7.5 mm x 10 mm can provide workpiece temperatures up to 1600°C Applications include soldering and unsoldering, glass to metal sealing, and micro-brazing.

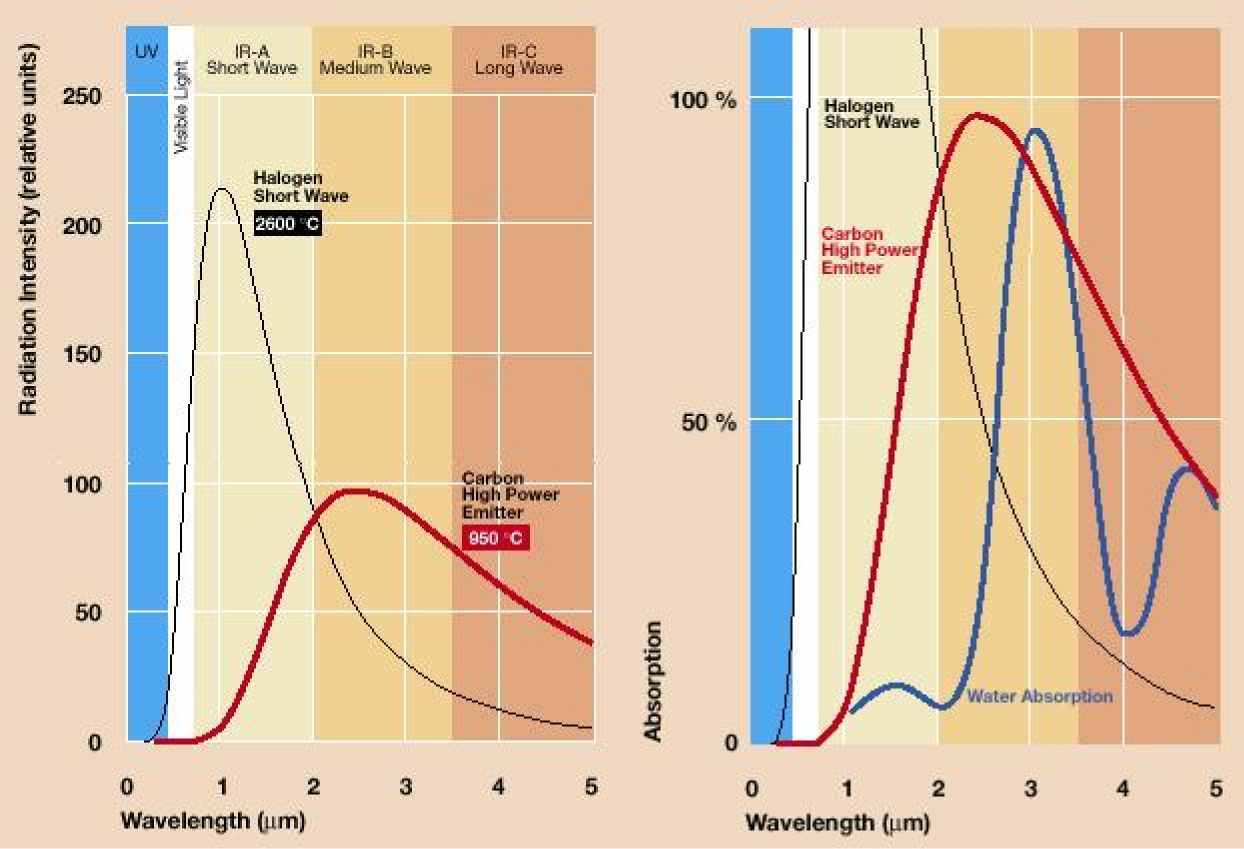
**Carbon Heaters**
High heating efficiency and rapid cool down make the mediumwave infrared carbon heater an excellent choice when shortwave response times are required. Suitable for all

medium-wave applications, carbon heaters also offer the capability to match temperatures to the optimum absorption wavelength for each application. These features eliminate overheating and contamination of sensitive substrates.

A particular large portion of medium wave radiation is absorbed in water, solvents and plastics and converted into heat. This allows significant benefits: carbon heaters dry printing inks, with less stress for the paper because the radiation acts more intensively on the ink. The high power heater increases print drying speed and reduces drying time. It also heats plastics in a targeted manner, with less heating of the surrounding environment.

Various types of infrared heaters have different maximum output at different wavelengths – Halogen IR heaters at 1 µm, Carbon heaters at about 2.5 µm. Therefore at 3 µm the a high power carbon heater can provide three times the irradiance of a Halogen heater.

Only that part of the spectrum which covers the absorption curve of water is effective for the drying process – not the whole IR radiation. The infrared radiation of a carbon heater is almost ideally matched to the absorption spectrum of water. In comparison, only a small fraction of short wave radiation covers the absorption curve.



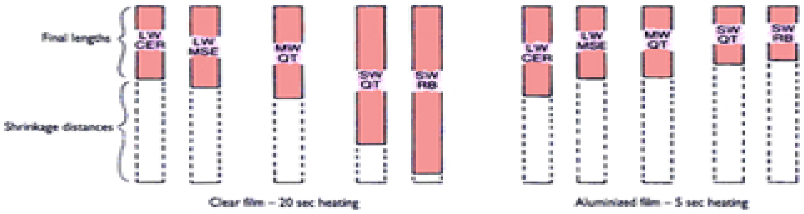
Thus, a short wave heater at the same power density supplies less than 50 % of the power of a carbon heater in drying processes. For example, at an irradiation of 120 watts/in2, the effective power density of a carbon heater is around 28 watts/ $m^2$; that of a short wave heater is around 14 watts/in2.

Some manufacturers offer carbon technology in a twin-tube configuration for even greater heating density. This configuration can also be employed in modular systems.

## Workpiece Characteristics and Their Effects

In modern industry, infrared equipment is being used to heat a vast range of products, varying in size and complexity. Each different product or material will respond in a different way to infrared heat depending on such factors as mass, surface area, geometrical shape, surface condition, color and conductivity.

Probably the easiest product to heat with infrared is a flat metal sheet with a matt black surface because for a given mass it has a large surface area compared with its thickness. Moreover, it can be placed very close to an infrared panel to receive uniformly the vast majority of the heat available. Its ability to absorb heat is very considerable as a matt black surface has a high emissivity value near to unity, The direction of the projected radiation would be normal to the receiving surface, thus any losses due to the Cosine Law would be eliminated. The simple conditions for rapid and very efficient heating are therefore all easily met. However, in the real world infra- red systems have to be designed to cope with products and situations which can be far more complex than this ideal example, and the aim of this chapter is to give an insight into the behavior of a representative sample of materials and products.



Heating trials with each new product or material remain a prudent step as the results provide a basis for the specification of an efficient and correctly sized oven.

**Effect of wavelength**

Plastic film

An industrial application that illustrates the effect of heater wavelength is the use of infrared to heat shrink-wrap film. In trials two such films of the same thickness, one virtually clear the other aluminum colored were exposed to different heater panels. Aluminum colored film shrank rapidly with all wavelengths, but because of the lack of pigment in the clear film, the long wave heaters took three times longer to achieve the same shrinkage, the medium wave heaters took four times as long while the short wave types were the least effective.

**Powder coatings and absorptivity**

The curing of coatings on metal substrates has great relevance to the choice of wavelength for corridor ovens. For powder coating with thermosetting epoxy and polyester materials heat transfer does not need to take account of solvent release.

One might expect a fine white powder covering the surface of a metal to have an insulating effect on radiant heat transfer. However, polished metals, exemplified in trials by brass billets, absorb infrared heat very much faster with such a covering than without. This result applies equally before fusion of the powder and at the higher temperatures after fusion.

Long and medium wave infrared unlike short wave are almost blind to color difference.

Metallic powders are an exception to this rule, just as bright metals are more reflective to the longer Wavelengths than to the short. Prior to fusion of the metallic powders, heat absorption occurs at the level of the other coatings. However, a step change in the heating rate occurs at the point of fusion. The eight remaining powders indicate that little if any adjustment would be needed to allow for a change of color or texture in a medium or long wave oven.

### Effect of power intensity

The flexibility of the corridor type of oven to change the heating condition significantly by altering power intensity can be used to good effect in several ways. For example, reduced power intensity is more suitable for workpieces of mixed gauges. Different heat settings along the length of an oven may suit the curing of certain solvent-based coatings. The heat transfer falls with distance as an inverse linear law, that is heat flux is inversely proportional to wall separation.

### Effect of conductivity

No significant temperature differences can be expected to occur when heat at the level experienced in an infrared corridor oven flows into the core of a heavy metal item or across a section heated on one side only.

### Effect of product rotation

For the general case the number of revolutions made by a workpiece or loaded jig while in the oven is the important criterion rather than the speed of rotation. A value of approximately 10 revolutions produces a very acceptable temperature uniformity which is comparable with that to be expected in convection oven practice.

### Heating time compared to conveyor speed and product thickness

The time required to cure powder coating is virtually proportional to thickness of the workpiece. A variable speed conveyor provides a method of maintaining maximum production over a range of metal gauges.

### Velocity and temperature of air

The main advantage of introducing fan circulation into an infrared oven is not to increase heat transfer but to ensure uniform air temperatures from hearth to roof. The natural tendency for air to stratify into hot and cooler layers is therefore negated. Circulation of air at or close to the required temperature also has the advantage of optimizing temperature uniformity on the product. It can also be observed on the trace of the run that the workpiece starts to heat before entering the oven, This is encouraged by having extended entry and exit reflective vestibules or doors of a reflective material which can be adjusted to enhance reflectivity, Even in the open state parallel to the track the doors form an effective infrared vestibule. For narrow work such as thin sheets they may be almost closed to enhance heating inside the oven.

## Process Control of Workpieces

Unlike convection ovens, which are controlled by reference to the air temperature within them, infrared radiant ovens do not  have an operating temperature as such. In practice, only the temperature of the heaters themselves would be known because of their type and operating characteristics. In fact, the amount of heat transferred to the workpieces and their rate of temperature rise are related to such factors as absorptivity, mass, jigging arrangements, power intensity, heater-to-workpiece distance, and time of residence in the oven.

It follows that any temperature readings obtained from a sensor probe placed within an infrared oven would be totally meaningless, as the sensor would only produce readings related to its own absorptivity, mass and mounting position. (However, it will be seen in Chapter 7 that the measurement of product temperature is possible in certain cases.) It is fortunate therefore that infrared ovens and systems lend themselves to many forms of heat control which are easy to incorporate and economical to run.

The following methods of product temperature control are in common use:

- Manual switching of heaters, individually or in groups
- Variation of input power to heaters, either manually or automatically
- Variation of heater-to-workpiece distance
- Variation of residence time, for example by altering the conveyor speed.

### Manual switching of heaters, individually or in groups

Manual switching of heaters or groups is a low cost method of heat control and enables a wide variation of heat patterns to be selected. In corridor ovens with heaters mounted on the inner facing walls, the heat intensity can be selected from top to bottom, and also along the length of the oven. These features, for example, allow for complex masses, and various heights of workpieces placed on the conveyor hangers, and can provide a high intensity entry zone for rapid heating followed by a holding zone at lower intensity. Thus a controlled heat profile is obtained for curing the vast majority of paints and electrostatic powder coatings in common use today.

The switches used for heater selection are usually installed on a free-standing control console, and arranged to form a mimic diagram of the heater layout. Where short wave tungsten aliment heaters are used the switches must be rated to handle the high inrush currents at the moment of switching on. (Tungsten has a positive temperature coefficient). These currents can be as high as 14 times the normal full load value, depending on the impedance of the cables supplying the oven. Stable running conditions are normally restored after about 200 milliseconds, but care should be taken to ensure that any sensitive apparatus, such as computers, photographic or printing equipment connected to the same phase will not be affected by a momentary voltage drop.

This effect can be minimized by switching on the heaters in small groups rather than energizing the whole oven by closing a main breaker. In static ovens such as those used for softening plastic sheets for vacuum forming into wash basins, baths, hot tubs etc, it is advantageous to control certain areas of heaters where the depth of draw differs appreciably within a sheet. Heaters heating low profiled areas can be selectively switched on later than those heating deep draw areas, therefore individual switching provides a high degree of versatility, combined with simplicity and economy.

**Variation of Input power to heaters, either manually or automatically**

Variation of input power to heaters, in its simplest form, consists of a timer and contactor to vary the on/off times. A similar effect can be achieved with energy regulators. These are electromechanical devices in which control is effected by periodically switching the power on and off. The ratio of "on" time to total time determines the average power supplied to the heaters, which can be varied between 0 and 100%. For reproducible results several cycles should ideally occur during the heating of a product. Because the intervals are of the order of seconds or minutes, these regulators are only suitable for slow response heaters such as metal sheathed elements or ceramic heaters because these loads have natural smoothing capabilities. (Medium and short wave heaters would tend to follow the on-off switching periods and produce a modulated or flashing output mode, making such a system unsuitable for process heating.)

Therefore, continuously variable control of input voltage is often used, employing phase angle firing solid state electronic devices, (thyristors) or triacs. These provide even greater flexibility of control, and at reasonable cost as the base load of the oven would still be selected by switches, and only a relatively small portion of the load, for exampled up to 25% controlled manually or automatically by solid state devices. The controller therefore arts as a trimming or final tuning facility. Such control systems can be applied to all types of heaters irrespective of their response times.

The alternative burst firing solid state devices (or zero switching units) supply discrete bursts of complete sine waves to the load. These units are eminently suitable for slow response heaters, but should be used with caution on fast response systems where a substantial tum-down factor is likely to be required. As with energy regulators, flicker can result due to Prolonged "off" periods equivalent to several hundreds of cycles of the supply waveform. The main benefit of these control systems is that the waveform is not adversely affected, and therefore little harmonic distortion is introduced into the supply mains. For this reason they should be used whenever practicable in preference to phase angle bring types, especially on heavy loads of the order of tens of kilowatts. In certain cases a ramped version of burst firing might prove an effective compromise.

Both phase angle and burst firing controllers can be used in fully automatic closed loop control systems. The temperature of the product is monitored by a non-contact type radiation thermometer and its output compared with a voltage representing the desired product temperature. (The basic principles of non-contact radiation thermometers are covered in Chapter 7.) Moisture content or other product condition may be monitored instead of temperature. Any deviation from the desired value is amplified to cause the solid state controller to increase or decrease its output to the heaters, keeping the product within the specified limits.

Such systems are only practicable for products which produce a continuous temperature or moisture level signal, such as paper and textile webs or any material in sheet form without large gaps between the sheets. In corridor ovens carrying individual workpieces in a range of shapes and sizes on hangers, the temperature signals would be intermittent, and in addition, such products could not be guaranteed to present a sufficiently large and regular target area for the radiation thermometer to view from a point in a side wall. The temperature readings would also be affected by direct and reflected radiation from the opposite wails of the oven.

### Variation of heater-to-workpiece distance

Variation of heater-to-workpiece distance is easily achieved with corridor ovens as the wails are usually mounted on castors which run on rails. Variations in working width are typically up to 50% extension on the minimum separation. On flat bed belt conveyor ovens facilities can be provided to raise or lower the radiant roof of the oven to vary the intensity of radiation falling on the products. Other systems using on-machine panels may also have some built in adjustment, We have seen from Chapter 6 under "Proximity Effect" that the heat intensity falls with distance as an approximate inverse linear relationship in corridor and box ovens. Flat bed conveyor systems and on-machine panels have been found in practice to behave in a similar way. Thus a fine control of product temperature is easily achieved with this facility, but overall efficiency can, of course, be reduced.

### Variation of residence time

Variation of residence time by variation of the conveyor speed is normally a built-in feature using variable speed drives on the conveyors. It allows products of different thicknesses to be correctly and adequately heated. Earlier it was shown that the residence time required is virtually proportional to the mass to surface area ratio. Hence the effect of slowing down the conveyor is to lengthen the oven and give a longer heating period.

A timer can also be used to allow heavier workpieces, for example, to come to rest inside the oven for a specific period. Thus a short conveyorized oven can be effectively "lengthened" by selecting a suitable dwell time for each type of workpiece.

## Non-contact Temperature Measurement and Control

In recent years infrared ovens and systems used to dry or heat materials in continuous web form or sheets running edge to edge have become more sophisticated by using automatic (closed loop) control systems. The temperature of the moving material is continuously measured with a non-contact radiation thermometer known as a radiation pyrometer, and the reading compared with a stabilized voltage representing the desired temperature, or set point. Any difference between the two voltages is amplified and fed to a thyristor solid state controller to correct the infrared intensity, and thereby hold the temperature of the product within specified limits.

Such is the importance of the concept of non-contact temperature measurement that this chapter is devoted to explaining the basic principles of these instruments and their application.

All bodies above the absolute zero temperature of -273°C emit infrared radiation. Measurement of this emitted radiation makes it possible to determine the surface temperature of a body, provided its emissivity value is taken into account. The transmitted radiation is received by a sensitive instrument containing an optical system, to focus the radiation onto a sensor which produces a small electrical signal related to temperature. This is the basis of non-contact thermometry. It is worth noting that even temperatures below 0°C can be measured with these instruments, but as the radiant energy varies as the fourth power of the absolute temperature, the signals are very weak.

In the process heating field, the vast majority of applications are in the range of 50°C to 600°C, but even so, the signals produced are of the order of just a few micro-volts per degree centigrade. In theory the viewing distance between the hot body and the instrument is immaterial provided the target area required by the optical system is of an adequate size to fill the viewing aperture. The viewing angle is also immaterial provided the target area is filled. The air space between the product and the thermometer should not contain water vapor or carbon dioxide as these absorb infrared radiation at certain wavelengths.

However there are convenient windows in the infrared spectrum which allow these absorption bands to be avoided. The most useful band of spectral response for infrared process heating applications is from 8 to 14 microns; sufficient energy is available in that segment. Moreover, only relatively low gain amplifiers are required to drive the control system, and allow for emissivity compensation.

Linearizing circuits can also be used when necessary to remove the fourth power component from the temperature signal, otherwise the readings produced by an indicator or recorder would be cramped at the lower end of the temperature scale and expanded at the top end.

The detectors which convert temperature readings to electrical signals are available in various forms, each one containing features relating to the spectrum of operation, temperature range, and time response.

1. The thermopile, which is an adaptation of the thermocouple, uses multiple low mass hot junctions in series placed at the focal point of the instrument lens system. The micro-volt outputs of each thermocouple in the pile are therefore additive, giving good overall sensitivity for driving an indicating instrument or recorder direct, or a temperature controller via a built-in solid state amplifier. Response time is in the range 50 milliseconds to one second, depending upon the mass of the thermopile.
2. Resistive detectors normally use a Wheatstone Bridge arrangement with a thermistor (temperature sensitive resistor) in one arm of the bridge. The bolometer falls within this group of instruments. The thermistor alone receives focused heat energy via the instrument's lens system causing the bridge to become unbalanced. A millivolt output is then obtained across the appropriate arms of the bridge. Being a thermal filament device, the response time is in the range of 100 to 200 milliseconds.
3. Photon detectors employ the same basic optical system as in 1 and 2 above. Photo-conductive, photovoltaic or photo-emissive cells are used to produce electrical signals. Fast response is a feature of these detectors, being of the order of a few milliseconds.

In addition to the temperature control systems described above variations are available for processes such as moisture removal from paper or textiles. One or more detectors convert moisture content across the width of the web to electrical signals which act on the heaters via solid state controllers.

**Selection of temperature sensors**

As the temperature of an object increases the wavelength at which the peak energy occurs decreases. So the temperature sensor should be most sensitive to the wavelengths at which the maximum energy is emitted.

For an object at a given temperature the error in temperature measurement is inversely proportional to the wavelength at which the temperature sensor operates. So generally the pyrometer chosen should be the one operating at the longest possible wavelength.

The amount of energy radiated from a body at a particular temperature depends on the characteristics of the body. Generally, polished metals radiate a smaller proportion of their energy than nonmetals. This property is known as the emissivity, and the lower the emissivity the lower will be the temperature measured.

In simple cases where the emissivity is known the measured temperature can be corrected by dividing by the emissivity.

For cases where the emissivity is low or variable it may be acceptable to paint a surface with a coating of high, constant emissivity. This should be done with caution as the heat lost by radiation will be different for the coated and uncoated surfaces and they will be at a different temperature.

The temperature of a surface can be measured with two pyrometers each viewing different wavelength bands and the ratio of their readings gives an indication of temperature. This type of thermometer is best for targets which are partially obscured by dust or fumes, but if the particles of dust are of the same size as the wavelength being measured the results will be inaccurate so care is needed in choosing suitable applications.

Some of the radiation reaching the surface of a body is reflected and thermometers can not distinguish between this and the radiation from inside the body, except by differences in wavelength between the two.

Thus the most difficult circumstance for measuring temperature occurs when the temperature of a reflective body to be measured is close to the temperature of the surroundings. Very large errors may result if account is not taken of the ambient radiation.

It may be possible to screen off the ambient radiation form the measured area by independent screens or by screens incorporated in the sighting system of the pyrometer. These screens would need to be kept cool. Putting them in good thermal contact with a water jacket may help, but in most cases water cooling is required.

By introducing a second pyrometer to measure the incident radiation from the hot surroundings and comparing this measurement with the first thermometer measurement (for the temperature of the body) electronically, the body temperature can be estimated. This requires that the second thermometer is carefully positioned to obtain an average figure for the incident radiation, from both hot heaters and the cooler reflectors.

Most of the radiation from heaters with quartz envelopes is emitted at wavelengths of less than 5 microns, so a thermometer sensitive to wavelengths above 5 microns would be unaffected by the hot surroundings.

### Filters

infrared pyrometers can be fitted with filters to look only at a segment of the spectrum and integrate the energy falling on the detector from that segment. Filter types include narrow bandpass, wide bandpass and both long wave and short wave pass. Some pyrometers cover most of the infrared spectrum and consequently become sensitive to the atmospheric absorption bands. Many general purpose low cost pyrometers avoid these absorption bands and still provide sufficient energy to make use of low gain amplifiers by accepting the large amount of energy in the range 8-14 microns.

### Some Special Applications

Some materials have characteristics that lead to the use of special temperature measuring techniques. Reference is being made here to basic pure material without body or surface coloring agents.

### Metals

Most metals, unless well oxidized tend to be reflective and have low emissivities. Some of these emissivities are so low that a large portion of the sensed energy is reflected radiation, and this can result in varying and unreliable readings. The problem generally increases at the longer wavelengths; the emissivity of most metals is greater for the shorter wavelengths, so the shortest possible measurement wavelength should be used. Also a smaller change in indicated temperature results from the same change in emissivity at shorter wavelengths, producing more accurate measurements when emissivity variations are present.

It is vital to screen off all radiation from the metal sensing area whether direct radiation from the heaters or reflected and re-radiated from the walls.

The amount of energy available at the short wavelength of the black body radiation curve is small and as the energy level difference between two given temperatures increases an amplifier with wide range capabilities is required. The availability of a suitable amplifier may prove a limitation on the use of very short wavelengths.

**Plastics**

Generally temperatures of plastics thicker than 2.5 mm can be measured using 8-14 micron instruments, but thin films of plastic are partially transparent in this waveband. However the characteristics of molecular bonding eliminate the transmitted energy completely at certain wavelengths. Polyethylene, polypropylene, nylon and polystyrene are opaque at 3.43 microns. Polyester polyurethane, Teflon, FEP, cellulose and polyamide are opaque at 7.9 microns.

**Glass**

Pane glass is generally opaque beyond 5 microns and becomes progressively transparent at shorter wavelengths. For panes, bottles and other thin glass the 8-14 micron waveband can be used with an emissivity setting of 0.85. Reflectivity averages 15%. Between 5 and 8 microns reflectivity is low, but the cooling effect of surface convection currents is reduced if 5.1 microns is chosen, as the temperature sensed is mainly that just below the surface. If surface temperature is required 7.9 microns minimizes reflectance.

**Controllers**

Controllers compare the signal from the temperature sensor with a set reference signal and take action to bring it within the prescribed limits. Types include:

- Simple on-off switching, where the heaters are switched on until the set point temperature is reached and then switched off
- Time proportioning controllers which enable control of the proportion of time the heaters are switched on within a given cycle time of between 1 and 30 seconds.
- Phase angle controllers which enable the heaters to be switched on for a controlled part of each supply cycle.

A controller can only switch the power either on or off. If the temperature is below the set temperature the controller switches the power fully on. If the temperature is above the set temperature the controller switches the power fully off.

To avoid constantly changing between these two conditions the controller has a small range in which it does not change from its existing condition. This is called the dead band. Too wide a dead band results in inaccurate control; too narrow a dead band produces relay chatter.

If the power available is much greater than required the temperature will be higher than required for most of the time. If the power available is slightly less than required the workpiece will spend most of its time below the required temperature.

### Control for short wave quartz lamp and quartz tube elements

*Switch-on*

After the voltage is applied the current through the filament heats it up. The tungsten filament has a low resistance at ambient temperature, so the current just after switch-on is high, and is broadly related to the thickness of the filament, and therefore to the rated current; the initial current is about 14 times the rated current.

As tungsten becomes hotter its resistance increases and the current is reduced to its rated value. The starting current falls rapidly and will be reasonably stable after 0.2 seconds.

In practice, the wires, switches and contacts may be sufficient to limit the initial current to about 10 times the rated current. The use of surge limiting devices will reduce the very high initial current but the time taken to stabilize will be increased.

*Switch-off*

The prime source of radiation is the filament, the quartz sheath being a secondary source of radiation. The percentage of radiation from the filament becomes quite low within two to four seconds of shutdown, but the quartz envelope continues to radiate over a longer decay time scale.

*Control for medium and long wave heating elements*

Various heating elements take between about 5 and 10 minutes to cool to 100°C, according to rating and construction.

In some cases, for example moving webs of sensitive materials, special safety measures are necessary. The driving mechanism and the supply to the ceramic heater elements could be coupled, and the heaters could be moved away from the material, or a screen interposed between the elements and the material.

# Application: Paint

**Paint Finishing**

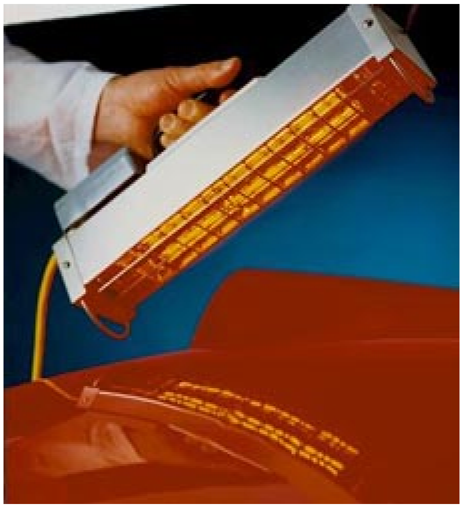
Industrial paints are put to an extensive range of uses and are often designed to meet highly specific requirements, from providing a high gloss, durable corrosion resistance for motor cars to providing a flexible, durable finish for continuous sheets of metal.

Though heat can be used to accelerate the curing of all paints, stowing paints will not cure without heat. infrared can be used to cure paint in two ways, either isothermally or by superheat.

For isothermal storing the temperature of the painted product is raised to the minimum necessary for curing in the first part of the oven and then maintained as the product passes through the rest of the oven. Less radiant heat is needed in the isothermal part of the oven. If an oven is used for painted products of different shape or size there will be a tendency for the product temperature to rise as the product passes through the isothermal region. In comparison with a convection heating system the product is heated to the curing temperature slightly more quickly, usually resulting in a saving of a few minutes in the curing time.

Superheat curing raises the temperature of the painted product to the maximum which provides a complete cure in the time available without causing degradation. Reductions in curing time of up to 90% of the convection curing time can be obtained.

Raising the temperature is a more effective method of accelerating paint curing than reducing the heating time for isothermal curing.



**Solvent based paints**

Solvent based curing paints have four prime components: resins, pigment and solvents for spraying and for coalescing. The solvent content may be as much as 80% of the paint or as little as 5%. The spraying solvent enables the resins and pigment to be sprayed onto the product and ensures that an even, smooth finish is obtained. On exposure to the atmosphere and gentle heating the solvents evaporate, leaving a thin layer of resins and pigment. As the resins reach the curing temperature they absorb oxygen from the atmosphere and combine chemically to form a solid surface which encompasses the pigment and adheres to the product.

## Motor vehicle panting

As a large user of paint the motor vehicle manufacturing industry has developed new painting systems aimed at providing a better quality finish which could be matched in a vehicle repair shop. Modern vehicle finishes are typically baked in the factory at approximately 130°C for 30 minutes for full hardening to take place. Two-pack coatings which cure at approximately 80°C are also available for subsequent rectification work.

The increasing use of infrared systems in place of, or in conjunction with, convection ovens is providing the vehicle producer and refinisher with an immediate solution to the drying needs of thermosetting paint systems in current use.

Either complete vehicles or discrete areas of paintwork can be heated. A suitable infrared panel placed at the recommended distance from a painted surface can provide fast heating without discoloration or solvent boil. The ability of infrared energy to penetrate through the paint layer to the underlying metal means that they both heat up more uniformly. Thus solvents are driven off before the outer skin is formed, minimizing the risk of blistering, even with overlapping coats. Moreover, blooming is prevented by enduring that the metal temperature is not lowered below ambient by the process of solvent evaporation.

The wide range of applications of infrared heating for paint finishing can be illustrated by the following examples.

### Entry zones for convection ovens

Infrared tunnel ovens are being used increasingly as entry zones in convection ovens in order to bring the thermosetting top coats on body shells to a dust-free state rapidly on all outside surfaces. This ensures a high quality outer finish before the body proceeds to the forced convection section where the longer heat soaking period allows all unexposed areas and uneven masses to reach an equilibrium storing temperature of around 130°C. A significant reduction in oven length is possible through use of infrared. The rapid cooling after switch off eliminates the risk of overbake if the line stops.

### Vehicle body repairs

Infrared offers significant operational benefits and savings to vehicle body shops. As the requirements of customers, vehicle manufacturers and insurance companies become ever more demanding, the vehicle body repair trade is turning increasingly to infrared techniques to improve efficiency and quality.

Primer-sealers, top coats and clear lacquers can usually be cured in less than ten minutes. Body shops have been organized into mini- production lines for fast throughput and many shops are now refinishing up to 100 cars per week.

**Painting plastics**

Modern plastics offer ease of fabrication and can be injection moulded into intricate shapes. They resist corrosion and offer savings in mass while reducing costs.

They are frequently painted to provide suitable color, gloss and texture, to hide surface defects such as injection points and flow lines, to protect the plastic from light and weathering, and to give a more abrasion and scratch resistant coating. The most commonly painted plastics are; polyamide (nylon), glass fiber-reinforced plastics and polyurethane.

Curing of painted plastics depends on the paint reaching its curing temperature before the plastic reaches its deformation temperature. A temperature difference of about 70°C between the paint curing temperature and the plastic deformation temperature is desirable; smaller temperature differences may lead to slower production speeds.

**Polyamide (Nylon)**

Polyamide molded parts have good resistance to solvents and show no stress crazing or cracking tendency.

Surface absorbed moisture can amount to between 2 and 8%. For this reason the most suitable paint systems are those which combine with water or are relatively hydrophilic.

**Glass fiber-reinforced plastics**

Glass fiber-reinforced plastics generally require degreasing and removal of adherent dirt before painting. A solvent such as isopropanol can be used for this purpose but a check should be made to ensure there has been no attack on the surface of the moulding which could give rise to defects in the paint coating. Washing equipment which produces a watery spray has been found particularly effective.

Where a high quality finish is required such as for external parts of motor vehicles the surface to be painted should be of quality indistinguishable from metal surfaces. Moulding defects may be filled with suitable stopper compounds and painted over with normal curing finish systems.

### Polyurethane

In the motor vehicle industry semi-rigid polyurethane foam is being used to an increasing extent. The main reasons are the elastic deformation behavior, the weight saving and the ease of shaping.

Blisters and pores may be present in the surface layer of the foam moulded components. Release agents, usually waxes are used to facilitate demolding and these may result in a poor paint finish. After cleaning is indispensable, and a degreasing plant may be the most effective route for large scale operation.

A suitably flexible priming coat is used on to which a two-coat metallic finish is applied.

### Water Based Paints

There are water based paints for practically all applications, Like solvent based paints, water based paints consist of pigment, resins and coalescing solvent. However, the resins are soluble in water rather than in solvent, and the paint contains water to ensure an even coating is applied.

Because water based paints use water rather than solvent they are less tolerant of unclean surfaces. It is more important to ensure that oil and grease contamination have been removed. Ideally, for ferrous articles a chemical pre-treatment with a phosphate bath should be used. This provides protection against rust and ensures a smooth surface so the paint adhesion is enhanced. This may be particularly important with galvanized surfaces.

# Application: Powder Coating

Two types of powder coating are available: thermoplastic (nylon, PVC) and thermosetting. Thermoplastic powder coating is a form of finish that is applied without the use of solvents. It is paint which has been blended in a hot molten state, cooled and solidified and is ground into a fine powder of a specific particle size distribution. This powder can be applied to surfaces and fused into a tough and resilient continuous paint film.

Thermosetting powder coatings are blends of pigment, resin and hardeners which are passed through an extrusion process at elevated temperatures, The resins used are stable at temperatures of around 40°C, but melt at around 70-80°C. They have suitable melt viscosity to enable them to flow sufficiently quickly to provide a smooth finish, and a curing temperature of around 160-200°C.

Most thermosetting powders used in the United Kingdom are based on epoxy resin. Polyester resin powders have a high resistance to the sun's ultra violet and are used almost entirely for external environments on items such as architectural aluminum extrusions for double glazing and patio doors.

**Thermosetting Powder Coatings**

For metal work pieces, powder coatings are mainly applied with an electrostatic spray gun. The powder is fluidized with air into a cloud from which powder is sucked to the gun. As the cloud of powder passes through the gun it receives a negative electrostatic charge of about 60 kV, and disperses into a fine spray as it leaves the gun. This is because the particles of powder each have the same charge, and repel one another.

The work piece is grounded and attracts the particles, which form a smooth coating of uniform thickness. As the powder is an electrical insulator it prevents further particles from being attracted to the already coated parts. Powder that is traveling past the workpiece is attracted back, providing a degree of coating to the far side of the workpiece.

As much as 97 percent of the powder leaving the spray gun adheres to the work piece, because of the static charge, and is then fused to the workpiece by the application of heat. Infrared heating for about 1 or 2 minutes is usually sufficient to form a tough cured film, but on heavy sections 10 minutes may be required.

**Color changes**

When changing from one color powder to another it is necessary to clean the spray equipment and feed lines to avoid color contamination.

Powder recovery systems are available to recover the 3 per cent powder which does not adhere to the work piece, but on changing color, these must also be scrupulously cleaned to avoid color contamination.

If several color changes per day are required and a full powder recovery system is operated then cartridge type recovery booths, which remove the need to clean the booth and recovery system, are available. With this type of unit, cartridge recovery systems for each color are used, so clean down only extends to guns, lines and main booth casing, which is much quicker.

## Film Thickness

Powder coatings are typically about 40 microns thick, and a coverage of between 10 and 15 $m^2$/Kg. For some uses this may be too thick to be economic, and for these the use of powder coatings may be questionable. For other uses an overall film thickness of 40 microns may be needed, and for coating a flat panel where a uniform film thickness can be virtually guaranteed powder coating may prove to be the ideal finish.

For applications where the workpiece has an irregular shape and where a coating of minimum thickness 40 microns is required it may be that by using standard spraying techniques it is necessary to apply a higher average thickness of film to achieve the minimum in recesses and inaccessible corners.

Powder spray guns are available that facilitate control of cloud shape and size, powder output, particle velocity and position relative to the workpiece.

These spray guns give a significant improvement in the cost effectiveness of the process by reducing waste, through more efficient transfer of powder onto complex items, resulting in a more uniform coating and higher quality finish.

## Powder application techniques

### *Tribocharging*

By causing sufficient friction between powder particles and the walls of a non-conducting tubes, a potential of about 10 kv can be applied. Known as tribocharging, this process is a commonly used technique for powder application guns. The powder is transported through the non-conducting tube by compressed air.

### *Electrostatic powder spraying*

Powder is conveyed from the hopper to the gun by air flow or gravity.

The gun has a sharp corona point at its tip, connected to a high tension voltage generator. Here, charged air molecules are created and these bombard the powder particles, imparting an intense charge. The powder particles then move from the gun head to the earthed work piece. Once the nearest parts of the work piece are coated a repulsion effect is established which drives subsequent incidental particles to the more remote parts of the work piece.

### *Electrostatic Fluidized Beds*

Fluidization of a powder can be achieved by blowing air through a porous floor on which the powder will be charged by electrodes. The grounded workpiece is dipped into the fluidized, charged powder and becomes coated, This application technique is commonly used only for small workpieces.

A further development is available, offering a method of coating large objects on a conveyor.

Electrodes are arranged on the floor of a plastic cabin and are charged to a maximum of 50 kV. These electrodes give a charge to the powder particles which rest on the bottom of the cabin, further electrodes, also immersed in the powder particles, are charged with alternating current, causing the powder particles to oscillate vertically, so they remain in suspension. When an earthed workpiece passes through the plastic cabin it attracts powder particles. This system does not require a cyclone or other collector.

*Ionizer*

Ionizer guns contain a corona electrode and charging rings, placed close to it so they collect all the ions and stop the electric field from emanating out of the gun. The powder particles are charged as they pass through the space between the corona electrode and the charging rings.

### Powder Blanks Systems

Components that can be made from a single steel sheet can now be coated and cured before being shaped. Either thick or thin films can be applied depending on the end use; for deep drawing a thick film would be used, a thin film would be used for economy. Primer coats can normally be eliminated and textured metal can be coated without loss of definition. Appliance, architectural and automotive grades of powder coating are available.

Flat sheets are easy to coat, with no Faraday cages or hard to reach areas. There is no need to rely on conduction and convection to cure the powder in shaded areas so faster curing is possible than with preformed sheets. After curing the sheets can proceed directly to the forming operation. The floor space taken by a flat sheet coating line is only a third of that taken by a traditional coating line, and since the sheets require minimum storage space the process is ideal for just-in-time inventory control. With less overspray and a reduced number of application guns the efficiency of spraying is high.

Industry has developed powder coatings that cure in one minute while still retaining appearance and mechanical properties. For most applications sheets can be post forward at room temperature. The powder coatings provide excellent corrosion resistance without the use of heavy metal pigments and can be tailored to meet customers' specific requirements because of the special resins used.

Depending on the substrate and end-use requirements pretreatment can be of the conventional phosphate, chromate or no- rinse types. The horizontal steel sheets can be easily cleaned and pretreatment can be applied by roller.

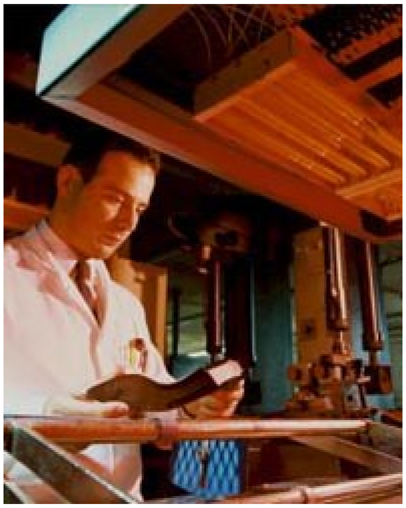
The pretreatment dries in place and enhances corrosion resistance while providing excellent paint adhesion.

Based on experience outside the United Kingdom an infrared oven to cure the powder would be perhaps 20 ft. long including the lead-in and exit conveyor and would be able to heat the powder to about 160°C very rapidly and maintain that temperature across the sheet for a minute. A typical convection oven for this process would be 400 to 500 ft. long.

# Application: Plastics Molding and Processing

Polymers used for thermoforming have to become suitably plastic to flow when heated and have sufficient strength to maintain integrity as a sheet. Amorphous polymers such as ABS, polystyrene and acrylic are ideal for both vacuum forming and high pressure forming as they give high viscosity melts over a broad temperature range.

Highly crystalline polymers such as nylons and polyesters, which normally soften to a low viscosity melt are extensively used for thin film packaging.



Thermoforming of polymers with a mixture of crystalline and amorphous characteristics, such as polypropylene and polyethylene is more difficult. A further consideration is that some materials such as polycarbonates are highly hygroscopic and must be thoroughly dried before thermoforming.

Selection of the appropriate wavelength is particularly important for processing plastics, as most thermoplastic polymers have similar but selective absorption characteristics.

Short wave radiation for clear and translucent sheet is mainly transmitted while medium wave and long wave are strongly absorbed. (Pigmented sheets are more problematical due to reflection and scatter of the radiation, Sample testing is therefore strongly recommended using each infrared wavelength.) However the following guidelines may be helpful:

- Long wave and medium wave heaters will heat both clear or tinted plastics fast and efficiently. Short wave will be effective only on tinted sheet,
- For sheet material over 2 mm thickness, medium or short wave will penetrate plastic more readily and therefore reduce the possibility of scorching the surface.
- Short wave is useful for drying screen printed plastics, as high intensities will quickly dry the ink but pass through the substrate.

Typical applications involving plastics heating include:

- softening acrylic sheet before forming
- vacuum forming and high pressure forming of plastic sheet
- preheating PVC tubes or mouldings prior to fitting

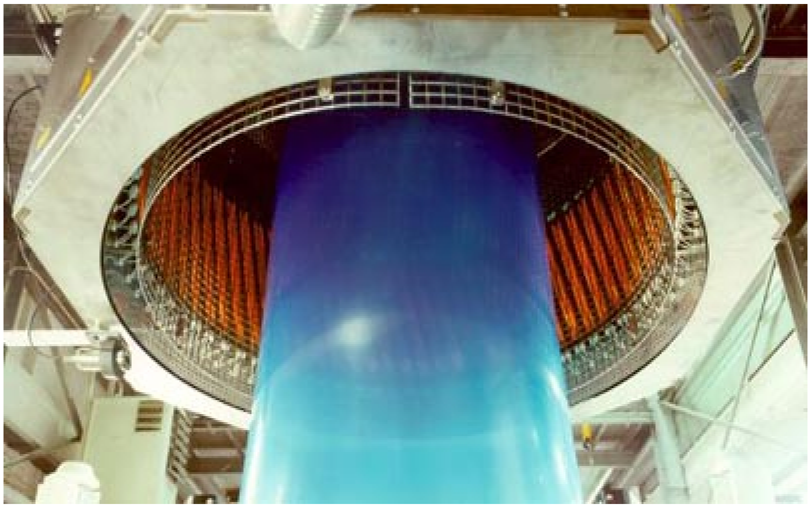
**Vacuum Forming**

A heated thermoplastic sheet is placed over a mould and the air between the sheet and the mould is evacuated so that atmosphere pressure forces the sheet into contact with the mould, where it cools, solidifies and is removed.

## High Pressure Forming

High pressure forming is similar to vacuum forming but produces moulds with much sharper features. The air between the mould and the heated sheet is evacuated but in this case compressed air at pressures of up to about 100 lb./in2 is used to force the sheet in contact with the mould surface where it cools and solidifies.

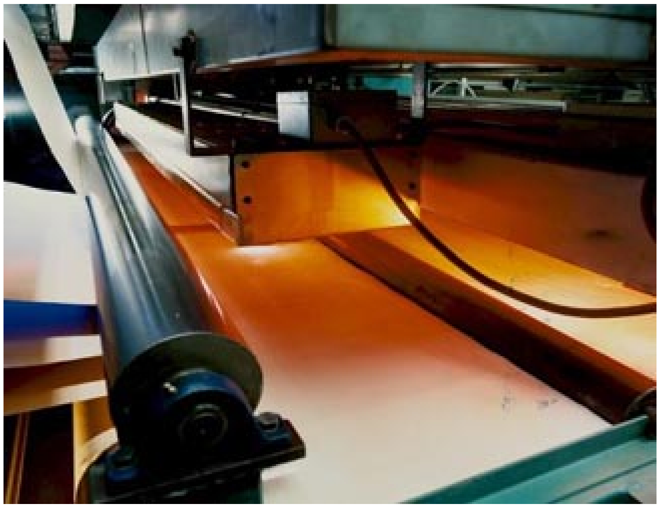
High pressure forming is most frequently applied for limited production runs and where fairly frequent design modifications are likely to be made. For parts which are large in area the cost of tools for high pressure forming may be less than for injection moulding.



The kinds of part which have been successfully produced by high pressure forming include bezels, keyboards, instrument casings, terminals, machine side and top panels, cases, guards and precision packaging.

High pressure forming machines clamp the polymer sheet at the edges and apply heat from above and below. Different plastics have different infrared absorption characteristics and respond to several combinations of infrared heaters. The heaters are arranged to provide even heating from above and below the sheet and may either be mounted on a frame which retracts when the sheet has reached working temperature so the top and bottom moulding tools may be brought together, or may be arranged in a separate bay at the side of the moulding tools, If retractable heating frames are used care should be taken to ensure that the heaters will be cushioned against vibration, or that only robust heaters are used. The heaters are controlled either individually or in banks to accommodate different sheet sizes.

## Application: Adhesives



Hot-melt adhesives depend upon thermoplastic polymers for their formulation. The adhesive is solid at normal temperatures, becomes liquid when heated, usually to temperatures well over 100°C, loses heat to the surfaces being joined and sets, Hot melt adhesives provide the most rapid method of securing adhesion as neither solvent loss nor chemical staring are involved. The materials from which the adhesive is formulated have a low heat content and easily lose sufficient heat to solidify in seconds if the surface to be bonded is cold.

While hot the layer of adhesive in immediate contact with the surface "wets" the microscopic irregularities of the surface, or its molecules move into the most desirable configuration and orientation. Materials with a low heat conductivity are more suitable for these adhesives than those with a high heat conductivity, as these enable the bonding surface to be heated momentarily to the same temperature as the adhesive.

Hot melt adhesives can be applied as sheets, as liquids or as powders.

### Powder Bonding

Powder bonding can be used to produce fabrics from any cardable thermoplastic or non-thermoplastic fiber or blend of fiber types. A range of thermoplastic polymeric binders can be used in varying proportions to produce fabrics with properties that can be refined to suit particular requirements.

Some examples of the features which can be created are the ability to laminate to a variety of substrates using heat and pressure only, customized fluid control, and conversion to high loft, low density structures by the simple application of infrared.

### Instant heating - close temperature control

The polyester fibers are opened before carding and polyester powder is added to the resulting web. As it passes under metal foil infrared heaters the powder melts, but not the fiber.

The melted powder flows round the fibers in contact with it. Under the pressure of cool calendering, the fibers are locked in compression by the now solidified powder. Up to three webs can be produced together and combined on a single roll.

The low thermal mass of the metal foil medium wave infrared heaters ensures they provide full product heating from the instant the line is started. Optical pyrometers provide a signal to the electronic control system which matches the output from file heaters to the web speed and ensures that the web temperature is kept within the required limits. When the web slows down or stops the heaters cool rapidly to avoid overheating.

The ease of installation of electric infrared heating systems has led to further opportunities for exploiting the benefits of powder bonding.

### High bulk fabrics

If highly crimped polyester fibers are used in the web a completed fabric can be made which will increase in thickness by about ten times when the polyester powder is reheated. These fabrics can for example be transformed into high bulk structures for use in insulated clothing. After incorporation into a garment. heating the finished article increases its bulk and often this is conveniently done using an easy to install, low cost electric infrared tunnel oven.

### Latent Bondings

An adhesive manufacturer was asked to supply large flocked PVC sheets, but found that production was limited to sheets of just one square meter. Development of a new production technique using electric infrared has enabled the company to supply flocked PVC sheeting to customers' requirements. Flock is usually applied electrostatically to material which has previously been coated with adhesive. PVC sheet can not be flocked by this method as it does not readily accept an even electrostatic charge. It is also difficult to heat without causing deformation. So the flock is first put on adhesive-coated paper which does accept an even electrostatic charge and then stuck to the PVC sheet with polyurethane adhesive. When the glue is set, the paper is peeled off.

Polyurethane adhesive will cross-bond if sufficient heat is applied or if put under pressure. As traditional machines for performing this operation rely on the application of high pressure, they can handle only small sheet of up to one square meter. They are expensive and are usually operated by specialist contractors.

Tests indicated that short wave electric infrared heaters could be used to heat the delicate PVC sheet if they were arranged to radiate first through the polyurethane adhesive. Sufficient flock could be transferred to the PVC with only a small pressure being applied by forming a heated sandwich of PVC, adhesive. flock and paper.

Based on these results a new flocking machine was designed and built to handle 2m wide PVC at a rate of 5m/min. The machine was fitted with two 30 kW short wave infrared heater banks, one heating the adhesive and PVC, the other heating the flocked paper. .A. further 6 kW of short wave infrared heating was directed into the pinch of two pinch rollers. The machine was producing production quality material within 15 minutes of first being switched on. Setting up adjustments enabled the speed to be increased to 7m/min. Subsequently, different color PVC has been processed without the need to adjust the operating conditions.

The cost of flocking PVC with the new machine is a tiny fraction of the outside contract price for the same operation. The cost of the flocking machine was recovered in a day. Production times have been drastically cut as production is now all in-house. Management of the company is delighted with the successful development.

**Water Based Adhesives**

The basic ingredient of water-based adhesives is often a material with a glass transition temperature that is above room temperature, such as polyvinylacetate (PVA), and a plasticizer is added to allow the PVA to form a film on the work surface. Heat-setting water- based adhesives are applied to the surfaces to be joined and then dried before being heated to form a join. As the adhesive film dries particles of the basic ingredient coagulate and water is exuded. Further additives speed the loss of water from the coagulant. Electric infrared heating can be used to remove the exuded water.

# Application: Metals

## Reflow Soldering

Smaller printed circuit boards use less materials, have shorter circuits and take up less space. One limitation on how small they can be made is the size of the soldered connection between the printed circuit and the component. Reflow soldering enables printed circuit boards of a third of the size possible with wave soldering.

Accurate temperature control is required to enable the solder to be melted without damaging the delicate heat sensitive components. The components are fixed in position on the printed circuit board with a suitable adhesive before entering a four zone tunnel oven. In the first zone the solder paste is heated to 50°C to release the solvents which were used to facilitate printing the circuits. The second zone causes the fluxes to flow, by raising the temperature to 120°C; this temperature is critical since a drop in temperature can limit their effectiveness. The third and fourth zones increase the temperature to 180°C as a final preheat, and to 210°C to 220°C at which temperature reflow occurs. For good grain formation the solder is gently cooled to 180'C. Rapid cooling is then used to avoid component damage. Although short wave, medium wave or long wave heaters could be used for reflow soldering the need to prevent components from being damaged by high temperatures, together with the variety of colors used for components favors the use of long wave heaters.

Trough type ceramic elements enable the long wave infra-red to be focused, and by mounting several of these heaters together suitable temperature rises can be achieved. The ceramic elements also heat the ambient air, producing convection currents which could reduce the degree of temperature control achieved. Extractor fans can be used to remove convection currents and to provide a heated air curtain between the temperature zones.

Thermocouples at the surface of the elements enable the temperature of the printed circuit boards to be monitored. Temperature conditions are controlled by computer program. The program enables adjustment of conveyor speed, zone temperatures and tolerances, and rates of change of temperature.

## Application: Paper

In the making of paper a mixture of fibers and water is sprayed evenly on to a mesh conveyor where much of the water drains away. The resulting web is then dried by steam heated rollers, but because of uneven heating there are large variations in the moisture content of the web. These variations can be removed by applying heat selectively to the wetter parts of the web. This profiling is a particularly effective way to increase production. Given that a machine is drying to an average moisture value, or ensuring that moisture peaks are below an upper limit, high intensity infrared has the advantages of being more efficient than steam at the dry end, and can be selectively applied to peaks, whereas steam dries both the peaks and the valleys.

Like any energy source infrared requires the correct safety precautions to be taken. All exposed surfaces including the front quartz window between the lamps and the sheet should be below the ignition temperature of the paper. This, together with the low thermal mass of the filaments themselves, will ensure that the unit is safe immediately after it is switched off.

Correct choice of break detectors should provide safe operation on web loss. Reflection break detectors tend to be "fail-safe," so that paper scraps, misalignment or malfunction all tend to cause the unit to fail indicating no sheet present. The detectors should be placed both before and immediately after the infrared unit. Rotation sensors can be used to switch the infrared off below a certain machine speed. This prevents heat being applied to an area of a stationary dryer cylinder or a stationary unbroken sheet.

Visual inspection to ensure that no combustible material is left around the infrared unit will be facilitated if the switches for the unit are positioned to allow the operator a clear view of the profiler.

### Reduction in Moisture Spread

The weight and surface reflection are the dominating factors affecting absorption efficiency. Light weight sheets require a reflector or dryer cylinder surface as a reflector to return the energy transmitted through the sheet. Heavier grades such as board do not allow transmitted energy. Most energy reflected from the paper surface gets returned to the infrared heater.

It is possible to have an infrared heater at the entry to the dryers that results in less steam condensing in the dryer cylinders, but causing only a small change in moisture at the final profile. Increased production will result since steam is saved, but this will not help profiling. By placing the prowler after the dryer, this interaction is reproved.

Adequate ventilation is needed to remove the evaporated moisture.

At moisture contents below five or six percent   the water molecules become increasingly bound to the fiber molecules, and although infrared is more effective than dryer cylinders in this region, its ability to get moisture out of the sheet begins to be reduced.

Infrared profiling systems are typically supplied with 300 or 150mm mm zones across the width of the web, and the effectiveness of zoning is determined by the resolution of the moisture measurement system.

Savings in steam or production increases can be obtained through the use of infrared. Reducing moisture peaks with infrared reduces the moisture average and a closed loop control system returns the average to target, either by reducing steam or by increasing production. Further steam savings and production increases can result from raising the target moisture content , and for some papers such as newsprint fiber usage can be reduced by raising the target moisture content.

# Application: Printing

**Litho printing**

Natural drying of litho inks may take up to two days to complete. Infrared heating assists the ink to penetrate the paper more rapidly, though absorption rates depend on the type of paper. It also accelerates drying by increasing the stack temperature; the greatest benefits being obtained with a stack temperature of between 35° and 40°C.

Infrared can be used with virtually all conventional printing inks, except those designed for UV curing. Water cooled reflectors are available to keep the heat to the machine and its surroundings to a minimum. Papers with densities as low as 50-60 g/ $m^2$ can be dried.

The greatest advantage can be achieved with multicolor presses. Short-run, double-sided print work of improved quality can be produced giving increased productivity. The risk of sticking can be greatly reduced, even if the ink quantity is increased simultaneously with a reduction or elimination of spray powder. From the point of view of production, it is irrelevant whether the spraying takes place before or after the drying process. Printed product can be stacked to greater heights, reducing storage space and increasing production.

Moisture absorbs medium and long wave infrared more readily than short wave infrared. By using an efficient cooling system short wave infrared can heat the paper without removing the moisture from it, thus avoiding register problems caused by paper shrinkage.

Medium wave infrared driers rely on matching the emission characteristics of the heater with the absorption characteristics of the ink, so absorbing the maximum amount of heat directly to the ink to dry it without relying on the heat in the paper.

Dark inks will warm up more than reflective inks such as yellows, but where one color predominates the dryer output can be adjusted; temperature variations across the print as it emerges from the dryer are quickly equalized in the stack.

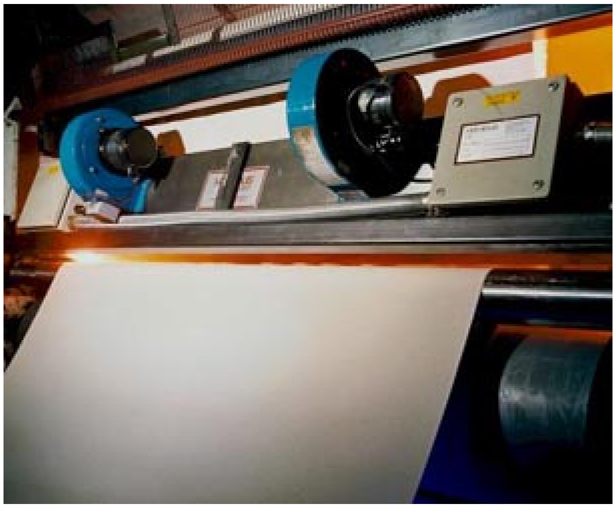
The need for set-off powder can be considerably reduced and in some cases completely discontinued, giving less wear of machinery and helping to produce a cleaner environment.

Heaters are usually arranged diagonally to the direction of the print, with spacing so that alternate lamps can be switched off to give two intensities without fear of 'striping' and ensure even drying across the print width.

### Litho inks

Lithographic inks dry by absorption and auto-oxidation. They consist of resin, pigment, driers and a distillate. The distillate reduces tile viscosity of the ink so it soaks into the paper more readily; it then sets but the drying reactions may take two days to complete. To prevent sheets from sticking together and spoiling, anti-set off powder is used to separate them and allow air to assist oxidation.

Infrared reduces the viscosity of the ink while in its liquid phase so it penetrates the paper more rapidly though absorption rates depend on the type of paper. It also accelerates drying by increasing the stack temperature and so increasing the rate of oxidation. The greatest benefits are obtained with a stack temperature of between 35°C and 40°C.



Infrared can be used with all conventional printing inks, except UV curing ones. Water cooled reflectors are available to keep the heat to the machine and its surrounding area to a minimum. Papers with densities as low as 50-60 g/$m^2$ can be dried.

The greatest advantage can be achieved with multicolor presses. Improved quality and faster production can lead to quicker deliveries and increased prints.

Water cooled reflectors are available, and these require leak proof circulation and controlled water supplies, but more importantly, it is difficult to arrange satisfactory cooling of the tube terminals. Air cooled reflectors are also available, operating at a slightly higher than atmospheric pressure to ensure that anti-set off powder does not settle on the lamps.

Planer reflectors are often used but elliptical and parabolic reflectors are available.

### Screen Printing

Screen printing is a stenciling process sometimes described as silk- screen printing or serigraphy. The process has grown considerably in importance during the last few years. Specific characteristics of the process have made it attractive outside the more established display and poster industries.

Screen printing on materials other than textiles began to attract attention in the 1920s, especially as an economic method of producing short-run posters. The process developed slowly, finding applications mainly in the display and point-of-sale market. The simplicity of the process combined with the thick ink film deposited governed its applications. These characteristics were particularly advantageous in the printing of fluorescent posters, water-slide transfers, display panels, traffic signs and PVC window stickers.

During the 1950s screen printing was found to be a useful printing process for the decoration of polyethylene bottles and for the production of printed circuits. The growth of the plastics and electronic industries provided new substrates and techniques ideally suited to screen printing.

New applications continue to be found for this versatile printing process. Examples have been the incredible growth of the membrane touch switch industry, the printing of rub-removable metallic inks for lottery tickets, the printing of black borders on car windshields in preparation for sealing by robot, and the printing of heater circuits on car rear windows where heat is needed on only one side.

The longer wavelength radiation suffers from three characteristic properties which are detrimental to its use in the curing of printing inks:

- It is readily scattered and is thus difficult to focus and direct towards the substrate using simple reflectors.
- It is extensively absorbed by air molecules, thus lowering the level of effective radiation that reaches the substances and also giving rise to stray convection heating.
- Its penetration into an ink film is limited.

Medium wave infrared heating is potentially more attractive for use by the industry. Focusing is comparatively efficient and absorption by air molecules, although still a problem, is much less than occurs at the longer wavelengths. Medium wave infrared can penetrate to a considerable depth into an ink film, but without excessive amounts of energy passing through and overheating the substrate.

Theoretically medium wave infrared heating should be ideally suited to enhancing the rate of cure of printing ink. Chemical bonds in the molecules of which the ink vehicle is comprised absorb radiation in this region without subsequent stretching or bending deformations, Deformation is a stage in the process that can lead to complete disruption of the molecular bond and result in a chemical reaction. It should be noted that many important chemical groups absorb into the long-wave infrared region.

Short-wave infrared radiation is virtually unattenuated by air. It is readily reflected and focused by simple polished reflectors. Infra- red photons at short wavelengths readily penetrate the 2-3 micron film thickness that is typical for lithographic printing. On absorption by the substrate its temperature is raised and it is the increase in heat that is responsible for the enhanced rate of cure.

It is debatable as to which of the two effective infrared bands is the most suitable to use for curing inks. On the one hand medium- wave infrared supplies energy directly into the ink film and specifically into certain chemical bonds. On the other, short-wave infrared provides the heat energy more efficiently and stray radiation is less of a problem. In both cases, however, the desired rise in temperature is attained more rapidly and more evenly than can be achieved by convection or conduction and this factor permits faster production rates.

An unexpected drop in gloss level is sometimes reported with medium wave infrared drying. This has been attributed to the general lowering of viscosity, as the ink film warms up, which may result in excessive amounts of ink penetrating into the substrate prior to cure. Shortwave infrared which produces a more even heating of the ink and substrate is less prone to this problem.

However, short wave infrared shows a greater discrimination between color and surface texture than is evident at the longer wavelengths. Consequently dark and matt areas of print are prone to overheating while, conversely, insufficient absorption may occur in lighter, glossy, regions. One of the attributes of infrared curing is that special formulations are unnecessary. Any of the formulations for oxidation, headset or penetration inks will give enhanced drying rates under infrared heating.

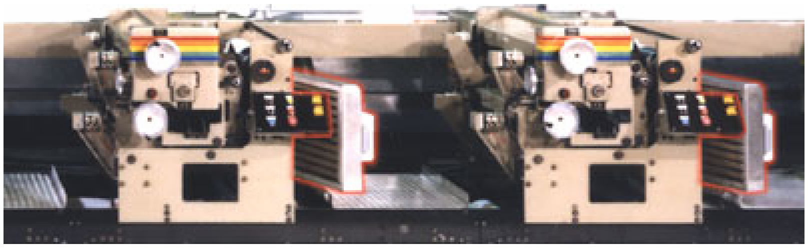
Formulations which cure by thermally induced chemical polymerization, polyester, alkyd-amino and epoxy-based inks for example, are particularly suited to infrared drying.

## Flexographic Printing

Flexography is a process in which the printing images stand up in relief, like that in the letterpress process. A liquid ink is used which is mostly solvent-based, and dries mainly by solvent evaporation. Water-based inks can also be used.

Fast printing speeds can be achieved on non-absorbent materials such as films and foils through the use of liquid inks that dry rapidly by solvent evaporation. The 'soft' and flexible relief printing plates can be mounted and registered on a plate cylinder away from the printing press. Proofs can also be obtained. Individual plates can easily be changed or repaired, and a portion of a plate can be removed to enable items such as price or expiration date to be changed.

Ink can be applied to the surface of the printing plate by means of a screened roller. The result is a simple ink feed system that consists of not more than two rollers. Although most flexographic printing is reel to reel, the machines enable changes in the print repeat length to be made simply.



For in-line flexo, an ink drying system which usually blows hot air on to the web is situated on top of the machine. This is to ensure that the inks dry rapidly enough to enable printing and rewinding at a suitable speed without set-off and sticking.

For printing on textiles the inks are printed on a carrier web (usually paper) and are formulated with disperse dyes which sublime at high temperatures on to fabric held in contact with the web. Print quality has to be of a high standard and both solvent and water based inks can be used. The print on the carrier web must not rub and the resin used should not interfere with the subliming properties of the dyes. The selection of the dyes and binder is influenced by the type of fabric to be transfer printed and the specification of the final print.

# Application: Mass Heating

### Heat setting of fabrics or yarns

Heat setting is a process for making fabrics or yarns dimensionally stable. Fabrics are stretched gradually to the desired value as they travel through a stenter. The temperature of the polymers in the fabric is taken through the glass transition temperatures. The polymers reorganize structurally with great crystallizing which has less potential for further deformation, and then only at temperatures over the heat setting temperature.

The man made fibers involved are principally polyester and nylon, which are drawn after extrusion. This tends to align the molecules parallel to the fiber axis, so shrinkage is in the length of the fiber.

Heat setting temperatures range from 150°C to 230°C and in a traditional convection oven between 15 and 60 seconds may be needed for the fabric to reach that temperature. Recent work has shown that efficient setting of years can be achieved within times as short as 40 milliseconds.

Using medium wave electric infrared, grey nylon fabric shrinks by about 9% at 220°C, 7% at 200°C and less than 1% at 100°C. Polyester shrinks 15% at 220°C, and 6% at 100°C.

### Fabric drying

As wet fabric dries by infrared heating its temperature rises to about 60°C, and remains more or less constant as water evaporates until the fabric is almost dry, when its temperature rises rapidly. Fabrics of the same color may have different cover factors and densities. The amount of water held by the fabric affects the drying time and the cover affects the final dry temperature as more radiation can be absorbed.

### Medium wave heating

Medium wave infrared heating is suitable for processing multicolored fabrics and produces a uniform temperature throughout the fabric. This is because the reflectance of the various colors is more or less the same for medium wave. Medium wave infrared produces surface heating which leads to conduction to dry the inner parts of the fabric. The surface of the fabric dries, and as heat is transferred to the interior by conduction the internal moisture diffuses outwards.

### Short wave heating

For short wave infrared heating the reflectance of white fabric is greater than that of colored fabric, so colored fabrics dry more quickly than white ones. This effect can be minimized by positioning reflectors to produce absorption of the reflected radiation by a process of multiple reflection. Short wave infrared heats the fabric evenly through its thickness, and does not rely on conduction to heat the central region.

### Yarn coating and Bonding

Stretch-free frictionless sewing threads for use in high speed garment manufacture without seam distortions require fully stabilized heat-stretched coated and bonded yarns. Electric infrared heating can provide close temperature control, facilitating low temperature heating to evaporate solvents from the bonding liqueur so as to prevent yarn blistering, and to heat-set the yarn prior to stretching and lubrication. Medium wave metal ribbon heaters are mounted above the yarns on slides. Other applications include braids, tire cords, dental floss, shoelace threads and yarns for a wide range of industrial textiles.

### Glass toughening

The range of materials which can be toughened by electrical heating techniques includes float, rolled, patterned, colored and enameled glasses. There is a choice of techniques with the following benefits:

- Accurate zoned temperature control
- Uniform glass temperature
- Consistent product quality
- A cool clean environment
- Computerized supervision, if required

Toughening is achieved by heating the glass to approximately 650°C, followed by a rapid air quench from truth sides of the sheet. This treatment leaves the outer layers in compression and increases impact strength by 5 to 6 times. Additionally toughened glass fractures into small cubes instead of the dangerous shards formed by annealed glass.

Electric plant is available for toughening glass in either the vertical or horizontal plane. Heating chambers are usually of a low thermal mass design with a high level of insulation provided by ceramic fiber.

Edge marking and length increase are avoided by conveying the glass continuously and horizontally through the furnace on rollers. Heating elements and quench jets are positioned above and below the rollers in the heating and quenching zones respectively. In order to preserve the flatness of the glass, it must travel fast enough to avoid sagging between rollers. This requires long heating and quench chambers particularly where thick sheets are to be processed and plant length may be as long as 60m. This type of equipment is therefore only commercially justified for very high throughputs of standard products.

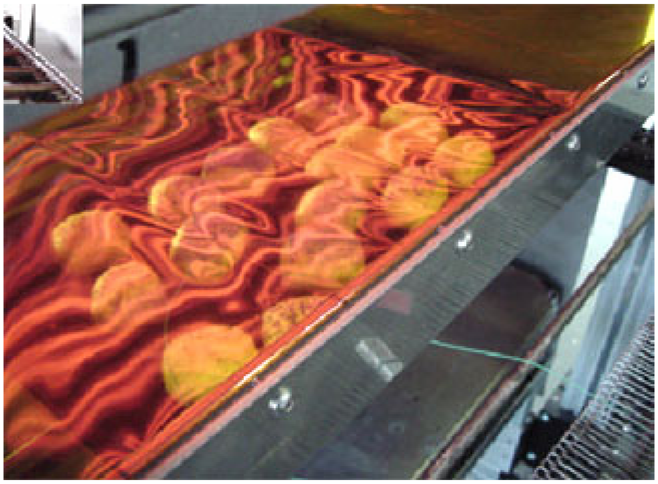
Oscillating horizontal plants have the advantage of horizontal treatment but avoid the need for long heat and quench chambers. This is achieved by oscillating the support rollers so that the glass moves backwards and forwards at a speed fast enough to avoid sagging.

After heating, the rollers transfer the glass to the quench chamber, where it is again oscillated. The free choice of charge layout without the need for jigging makes this design very suitable for jobbing work.

A supply of air for quenching is usually provided by suitable cooling fans and ducting tp the quench chamber. In some plants the air supply is boosted by air from a receiver during the initial part of the quench period.

A wide range of control systems can be offered. For the simplest vertical plants, the heating zones are controlled to preset temperatures. More sophisticated mircroprocessor or computer systems may be offered, particularly with horizontal oscillatory plant.
These can include monitoring and control of all parameters including zone temperature, heating time, roll-speeds, amplitude of oscillation, quench flows, quench cycle etc. The facility to select parameters to suit incoming glass dimensions and loads, in order to optimize productivity and minimize energy consumption, can also be provided. It is possible to monitor temperature profiles across the width of the glass by radiation pyrometer, if required.

In-house infrared toughening reduces material cost. Any surplus capacity can be profitably taken up by offering a subcontracting service. Avoidance of long delivery periods and damage in transit increases productivity. Problems of last minute changes in dimensions or breakages are easily overcome. The modern infrared toughening plant provides a contamination free process together with accurate and uniform heating to ensure a high quality product. The high level of thermal insulation coupled with the inherent cleanliness of electricity ensnares a comfortable and fume free working environment.



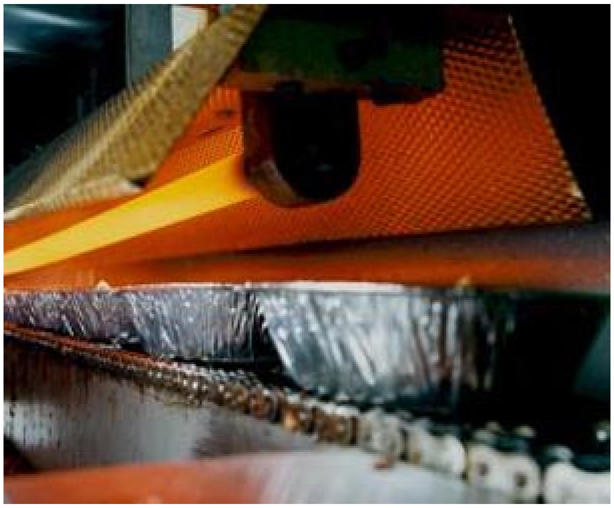
**Biscuit Baking**

In experiments in the use of infrared for baking biscuits (reported in the *Journal of Food Engineering*) identically prepared samples of biscuit dough were baked either in a forced-convection oven or in a short wave infrared oven. The infrared oven, which was only 60% of the length of the forced convection oven, baked the biscuits in about half the time taken by the forced convection oven.

The biscuits from the convection oven had a greater moisture content in the centre than on the outside. This is a well known phenomenon and as the moisture migrates during storage mechanical stresses are produced within the biscuit. If the moisture content is greater than about 1.5% these stresses can result in spontaneous breakage. The biscuits baked in the infrared oven had a higher, more evenly distributed moisture content than those from the forced convection oven and did not suffer from spontaneous breakage.

## Browning

When a food is subject to infrared heating its bulk temperature distribution depends largely on its surface reflectivity and bulk transmissivity for that wavelength of radiation.



Toasting of thin slices of food may be best done with infrared mainly in the range 1.5 to 5 microns, as this range heats the food's surface without greatly penetrating into the food. Within the range 2.8 to 3.4 microns the rate of evaporation of water from the food's surface is likely to be high. The need to carry out trials to determine the most suitable arrangement of infrared heaters for a particular requirement is illustrated by the different toasting needs of thin slices of bread and muffins. Muffins should be heated thoroughly before they attain a brown surface color, while thin bread should be browned rapidly on the surface to avoid excessive dehydration from within.

Foods undergo several complicated chemical reactions when heated. When bread is heated reactions occur between the free sugars and the nitrogenous compounds such as the amino groups in amino acids or proteins. Then brown colored polymers and compounds with characteristic cooking odors and flavors are produced at rates which tend to increase rapidly with temperature. At high temperatures the carbohydrates particularly break down, producing caramelization products with that characteristic aroma. Carbon dioxide and water vapor are evolved within the food and some of the infrared impinging on the food will be absorbed and subsequently convected away.

Browning accelerates once the color of the food's surface begins to change, as part of the visible spectrums is absorbed slightly more rapidly at this stage.

# Chapter 9 – Is IR Right for My Application?

Electric IR is a special kind of heat source, in that it is a relatively high-temperature source that can be turned on and off almost instantaneously.

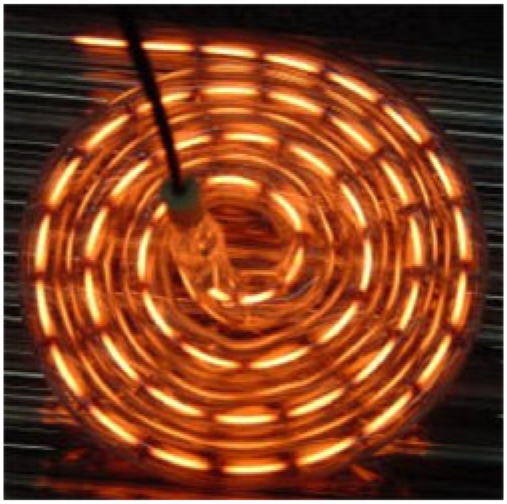
**Is electric IR right for my application**?
Wherever a heat source is needed, electric IR can probably be used. Within each of the categories previously discussed, major categories are literally hundreds of specific applications. In fact, the number of specific applications is growing as more uses are found for this special heat source. In addition to more traditional uses for electric IR, such as automobile body finishing, relatively new uses, such as drying silk-screened inks on clothing continue to be developed.

**Assessment of Your Application**
When choosing an electric IR system for your application, you should evaluate both the technical and the economic feasibility.

**Technical Aspects**
To determine the technical feasibility, gather certain information about your product and your process. This information will help you determine the size (length and height) of the oven, the power density required, and other aspects needed to specify the correct oven.

**Economic Considerations**
To evaluate the economic feasibility of electric IR, a number of issues need to be considered. The following issues must be addressed to determine the cost of doing business with and without electric IR:

1. Remaining life of the current heating equipment
2. Current heating capacity
3. Energy source for the current heating method
4. Annual energy costs of the current heating method
5. Current energy charge
6. Percentage of material wasted by the current heating method
7. Scrap value of the material
8. Embedded cost in the scrapped part; material
9. Annual labor costs associated with the heating operation
10. Annual production throughput
11. Space requirements for the current heating equipment
12. Annual cost of floor space



13. Installed replacement cost for the current heating process
14. Payback period required to justify the installation of a new electric IR system
15. Expected capacity of the plant in five years

These economic issues can be condensed into five basic costs associated with electric IR heating:

- Equipment
- Labor
- Energy
- Scrap
- Floor space.

## Chapter 10 – Additional Resources

This reference has been compiled by Heraeus Noblelight as an informational tool for those in business and industry.

When it comes to the mastery of lamp technology, competence, problem-solving potential and productivity all go by the name of Heraeus Noblelight.

It is not easy to be outstanding in the highly competitive international arena. And yet Heraeus Noblelight has been just that for over three decades thanks to its masterful grasp of fundamental technologies coupled with creativity and flexibility.

Heraeus Noblelight is a subsidiary of Heraeus Noblelight GmbH, one of the world's leading producers of Infrared and Ultraviolet solutions for the Specialty Lighting market.

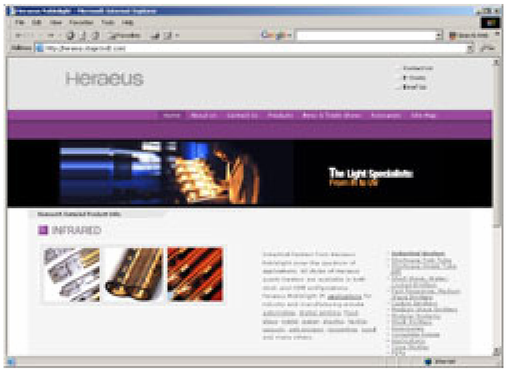
The different physical properties of chemical elements and materials cause each substance to respond to a very specific section of the sun irradiation (absorbing it). The remaining part either passes through the medium unhindered, or is reflected. This selective behavior opens up the possibility of producing targeted light processes.

The transfer of energy represents a particularly interesting capability of light (without contact and without assistance by a medium). This capability produces technologies that operate rapidly, simply and cleanly with light. Additionally, there are the environmentally friendly aspects: the possibility of tailor-making light spectra not only increases the efficiency but also saves energy. Light can initiate chemical reactions and thus can reduce the use of chemicals. Intensive UV radiation can "crack" chemical compounds that are not biologically and chemically degradeable.

Heraeus Noblelight is one of the few specialists that can supply tailor-made light sources for the entire scientific and industrial spectrum--from ultraviolet (UV) to infrared (IR)--for use in research, engineering, medicine, chemical analysis, production and environmental protection.

Part of the Heraeus company, Heraeus Noblelight is the expert for special technical and scientific lamps. The in-house research and development cooperates extensively with the R&D divisions of the other Heraeus areas, domestically and abroad. In this manner, synergistic effects are utilized with company-wide knowhow.

Special lamps require special quartz glass which is developed at Heraeus in-house and stems from our own production with high quality requirements. Also, the knowhow for the high-temperature processes of decisive importance in quartz lamp manufacture is available at Heraeus in-house. Highly modern test centers and comprehensive application engineering experience strengthen its performance potential.



For more information please visit Heraeus Noblelight online at [http://noblelight.net](http://noblelight.net) or telephone (770) 418-0707.

# Bibliography

O'Connell, J.R., Croft, E.F.B. and Hankins, W.C. *Electric Infra-Red Heating for Industrial Processes*, London: Electricity Association Services Limited, 1991.

--- , *Technology Guidebook for Electric Infrared Process Heating*, Cincinnati: Infrared Equipment Association, 1993.

Battelle Columbus Division, *Electric Infrared Process Heating: State-of-the-Art Assessment*, Columbus: Electric Power Research Institute, 1987.

Heraeus Noblelight. December 2005. http://www.noblelight.net/

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