# INDUSTRIAL HEATING

Electricity is a form of energy that can be converted into heat, another form of energy. Electricity is a convenient source of heat because it is readily available, has no local emissions, can be directed, and is easy to control.

## FUNDAMENTALS

### Heat Transfer

The user of electrical heating must have some understanding of the fundamentals of heat transfer in order to apply it properly.

**Conduction.** Heat flows from a high-temperature region of a body to a lower-temperature region. This flow of energy is similar to the flow of electricity in a conductor. The amount of energy transferred is

$$Q = kA\frac{dt}{dl} \qquad (1)$$

where:

$Q$ = quantity of heat transferred (W)
$k$ = coefficient of thermal conductivity for material [W/(m · °C)]
$A$ = cross sectional area of conductor (m$^2$)
$dt$ = temperature increment along flow path (°C)
$dl$ = increment of flow path over which temperature increment is measured (m)

This is a general equation that can be modified to fit specific installations.

**Convection**

***Natural.*** The contact of most fluids with a hotter surface reduces the density of the fluid, causing it to rise through more dense fluid. Colder surfaces have the opposite affect. This circulation carries energy from the hotter surface to the colder, transferring heat.

***Forced.*** If a fluid is forced over a surface hotter than the fluid, the surface removes heat at a more rapid pace than in natural convection, especially if the flow is turbulent. A general equation for quantity of heat transferred is

$$Q = hA(T_1 - T_2) \qquad (2)$$

where:

$Q$ = quantity of heat transferred (W)
$h$ = surface coefficient (film conductance) [W/(m$^2$ · °C)]
$A$ = surface area (m$^2$)
$T_1$ = temperature on hot side of boundary layer (°C)
$T_2$ = temperature on cold side of boundary layer (°C)

***Change of State.*** A special case of convective heat transfer is when the fluid changes state. A common example of this is water changing to a vapor (steam). Vaporization removes heat very rapidly, since it requires 110 W · h/kg of energy to convert water to vapor.

**Radiation.** Any body will emit radiant energy proportional to the body's temperature, and receive energy from other bodies to which it is exposed. This energy is emitted at all wavelengths, but the higher the body temperature, the shorter the wavelength at which the maximum energy is emitted. Figure 1 illustrates this graphically, the area below the curves representing the total energy emitted. Radiation between any two bodies can be described by the following relationship:

$$E_r = \alpha F_A F_\epsilon A(T_1^4 - T_2^4) \qquad (3)$$

where:

$E_r$ = net energy radiated from the high-temperature body to the low-temperature body (nW) = W · 10$^{-9}$)
$\alpha$ = Stefan–Boltzmann constant, 57.3 nW/(m$^2$ · K$^4$)
$F_A$ = configuration factor that allows for the spatial relationship and radiating areas of the bodies (see Ref. 1 for values for various common configurations)
$F_\epsilon$ = emissivity factor that allows for body surfaces being less than perfect emitters (blackbodies have an emissivity of 1); (see Ref. 1 for values for various common surfaces)
$A$ = area of the lesser or equal of the two body surfaces (m$^2$)
$T_1$ = temperature of high-temperature body (K)
$T_2$ = temperature of low-temperature body (K)

### Specific Heat

The specific heat of a substance is the heat required to heat a unit mass through a unit temperature:

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 1999 John Wiley & Sons, Inc.

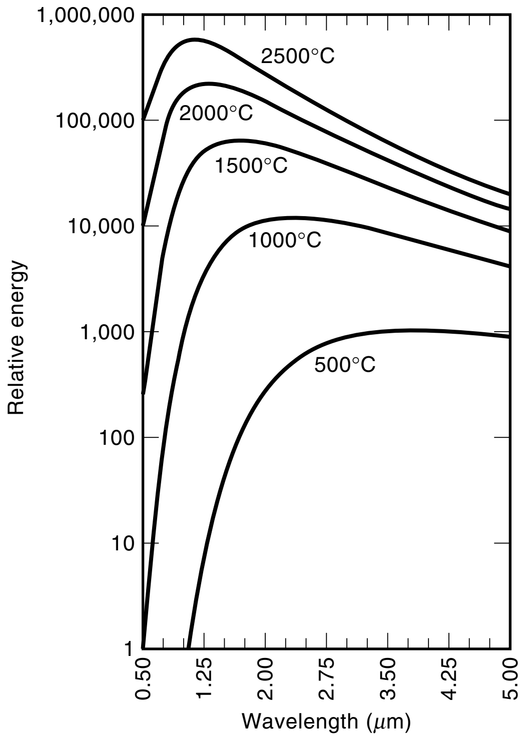


**Figure 1.** The distribution of radiant energy as related to the temperature of the distributing body

$$C_\mathrm{p} = \frac{Q}{M(T_\mathrm{f} - T_\mathrm{i})} \tag{4}$$

where:

$C_p$ = specific heat of substance [W · h/(kg · °C)]
$Q$ = heat absorbed (W)
$M$ = mass (kg/h)
$T_\mathrm{f}$ = final temperature (°C)
$T_\mathrm{i}$ = initial temperature (°C)

See Table 1 for specific heats of common substances.

## RESISTANCE HEATING

The most common form of electrical heating is *resistance heating*. Heat is generated by passing a current through an electrically conductive or semiconductive material. The material may be solid or a fluid. The current may be direct (dc) or alternating (ac). The heat generated is directly proportional to the resistance and the square of the current:

**Table 1. Specific Heats of Common Materials**

| Material | Density (kg/m$^3$) | Specific Heat (W · h/kg · °C) |
|---|---|---|
| Carbon | 2211 | 0.23 |
| Coal | 1281 | 0.26 |
| Concrete | 1602 | 0.19 |
| FEP | 2162 | 0.33 |
| Glass | 2643 | 0.23 |
| Graphite | 2082 | 0.23 |
| Ice | 913 | 0.53 |
| MgO | 3044 | 0.24 |
| Petroleum | 878 | 0.59 |
| Quartz | 2211 | 0.30 |
| Water | 1000 | 1.16 |
| Wood | 801 | 0.66 |

$$Q = I^2R \tag{5}$$

where:

$Q$ = heat generated (W)
$I$ = current in conductor (A)
$R$ = resistance of conductor (Ω)

### Resistance Elements

Many metallic and some nonmetallic substances are used to make resistance elements in the form of wires, coils, rods, or bars to generate heat for applications ranging from comfort heating to metal melting.

**Nichrome.** The most commonly used metal for heating elements is nichrome. It consists of an alloy of nickel, chromium, and sometimes iron, the composition being varied to impart different characteristics. Table 2 shows the characteristics of three commonly used nichrome alloys. Nichrome is used frequently because:

- It can operate for long periods of time at a high temperature in air or an inert atmosphere.
- Its high resistivity allows the use of large-cross-section elements at a given voltage, so the elements are sturdy.
- Its resistance remains nearly constant over the usable temperature range (Fig. 2). This allows the designer to predict accurately the voltage and current requirements and the power output.
- It develops a chromium oxide layer at high temperature to protect the element against oxidation.

**Iron Alloy.** This alloy is used as an alternative to nichrome where higher element operating temperatures are required. Its mechanical characteristics are not quite as good as nichrome's, so it must be supported more carefully.

**Nickel–Iron (Ni–Fe) Alloy.** This alloy is used in special applications where its resistivity (lower than that of nichrome) and its positive temperature coefficient of resistance (as shown in Fig. 2) are advantageous. The low resistivity allows longer elements at a given voltage, and the positive coefficient of resistance provides protection against overheating, since as the resistance increases, current and wattage produced are reduced. Its maximum operating temperature is low because it oxidizes rapidly at high temperatures.

**Copper.** Copper has characteristics similar to Ni–Fe alloy, except that its resistivity and maximum operating temperatures are lower. It is used where very long circuits are required.

**Molybdenum.** Molybdenum has a very high operating temperature in an inert atmosphere, but a very low operating temperature where subject to oxidation. It is useful where high element temperatures are required.

**Table 2. Characteristics of Heating Elements**

| Material | Nominal Analysis (%) | Resistivity at 20°C ($\mu\Omega \cdot$cm) | Temp. Coeff. of Res., 0–100°C (per unit/°C) | Specific Heat (W·h/kg·°C) | Approx. m.p. (°C) | Max. Oper. Temp. (°C) In Air | Max. Oper. Temp. (°C) In Inert Atm. |
|---|---|---|---|---|---|---|---|
| Nichrome | 35Ni,20Cr,bal.Fe | 102 | 0.00014 | 0.14 | 1390 | 1100 | 1100 |
| | 60Ni,20Cr,bal.Fe | 112 | 0.00014 | 0.133 | 1390 | 1125 | 1125 |
| | 80Ni,20Cr | 108 | 0.00008 | 0.128 | 1400 | 1200 | 1200 |
| Iron alloy | 22Cr,5a1,0.5Co,bal.Fe | 139 | 0.00001 | 0.128 | 1510 | 1330 | 1330 |
| Ni–Fe | 70Ni,30Fe | 19.9 | 0.0045 | | 1425 | 600 | 1100 |
| Copper | 100Cu | 1.73 | 0.0039 | 0.116 | 1083 | 600 | 800 |
| Molybdenum | 100Mo | 5.7 | 0.0033 | 0.071 | 2625 | 200 | 1700 |
| Tungsten | 100W | 5.48 | 0.0045 | 0.037 | 3410 | 150 | 2700 |
| SiC | | 150,000 | See Fig. 2 | 0.233–0.268 | | 1500 | 1500 |

**Tungsten.** Tungsten is similar to molybdenum, with an even higher operating temperature (useful in incandescent lamps).

**Silicon Carbide.** This material is available in rods and ribbons with a large cross-sectional area, necessary because of its high resistivity. It has a high allowable surface temperature, but is brittle and has to be protected from mechanical damage. Its resistance has a negative coefficient to about 600°C, and then starts to increase (Fig. 2). The resistance also may undergo a long-term increase in operation.

### Resistance Heaters

**Open Elements.** Coils, ribbons, or rods can be made of any of the element materials and supported on insulators or ceramics. They are furnished in standard modules, which can be assembled to furnish required heat. Heat can be radiated to the work, or a nonconductive fluid, such as air, can remove the heat by convection.

**Strip Heaters.** Strip and band heaters are thin, flat heaters that contain a strip or wire heating element, electrical insulating material, and may have a metal sheath. They are used to conduct heat efficiently to flat or curved surfaces.

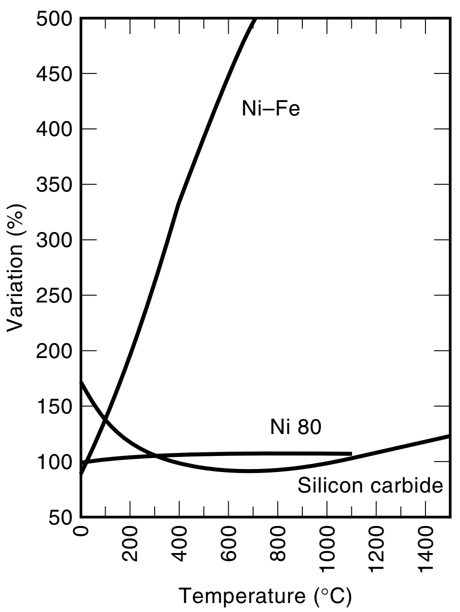


**Figure 2.** The relationship of the resistivity of common heating elements to element temperature

**Tubular Heaters.** Tubular heaters are round or triangular heaters that contain a heating coil, a ceramic powder insulating material, and a metal sheath. They are made by inserting the coil in a tube, filling with ceramic powder, and swaging to a smaller cross-sectional area to compact the ceramic material. They are the most frequently used resistance heaters, because they are available in various diameters and lengths, they are well protected from mechanical damage, the metal sheath can be made from any available material to resist corrosion, if kept dry their dielectric strength is high, and they can be operated at sheath temperatures up to 900°C.

### Resistance Heater Applications

#### Gases

***Duct Heaters.*** Heaters are mounted in the passageway through which the gas is flowing. The heaters may be open elements transferring heat directly to the gas, or strip or tubular heaters where the element is protected from the gas by a metal sheath.

***Circulation Heaters.*** Heaters are purchased in a separate vessel, and the gas is routed from its passageway, heated in the circulation heater, and returned to its original path. This allows the heater manufacturer to do all the mounting and wiring required, and minimizes the field installation.

#### Liquids

***Immersion Heaters.*** Bundles of tubular heaters are immersed directly in the liquid to be heated. They can be inserted in the top of an open vessel, or through a flange in a closed vessel. This is a very efficient way of transferring heat from the heater to the liquid, allowing high power densities. The sheaths can be designed to be compatible with the liquids to be heated.

***Circulation Heaters.*** These are similar to circulation heaters used for heating gasses.

***Vessel Wall Heating.*** The wall of the vessel containing the liquid can be heated by any of the heaters mentioned previously, transferring heat to the liquid in the vessel. This allows heating without penetrating the vessel.

***Vaporizers (Boilers).*** Immersion heaters are normally used to vaporize liquids, which are then routed to the work to be heated. Vapors have a high heat density and can be closely controlled for uniform temperature. Water and commercially available thermal fluids are commonly used liquids.

#### Solids

***Surface Heaters.*** Strip or tubular heaters can be clamped to the surface of the solid to be heated. The closer the contact, the better the heat transfer and the higher the power density that can be used for the heater.

***Insertion Heaters.*** Tubular (cartridge) heaters can be inserted in holes drilled in the solid to be heated. If the tolerance of the fit is low, heat will be transferred efficiently to the interior of the solid and will result in a lower heater operating temperature.

***Cast-In Heaters.*** Castings can be custom made with tubular heaters in the casting, to fit almost any solid. The efficient heat transfer from the sheath to the casting allows for high power densities. Casting materials commonly used are aluminum and bronze (for its higher temperature rating).

***Enclosed (Cozy) Heaters.*** Fabricated to fit around the solid to be heated, these are complete assemblies of weather barrier, thermal insulation, and heater. Commonly they have a metal enclosure with thermal insulation sealed inside, and tubular heaters fastened to the inner surface. They are made in sections so that they can easily be assembled around the work. The heater sheath and enclosure can be made of any materials required for environment and mechanical protection.

***Heating Mantles.*** These are blankets made of high-temperature materials such as fiberglass, with a heating wire woven into the cloth. They can be made in any size or shape to fit the application.

***Fluidized Bed Heating.*** A heated gas, commonly air, is blown through a bed of particulates (sand), heating the sand. The solid to be heated is imbedded in the sand. The fluidized sand reaches all parts of the solid, allowing for efficient heat transfer.

**Radiant Heating.** Resistance heating elements are often used to radiate heat to the body to be heated. Several different types of elements are used, with the maximum element temperature the most important factor.

***Open Elements.*** Open elements are efficient because there is no barrier between the element and the work, so they can radiate at the maximum element temperature. They can be mounted in a reflector to direct radiation, fastened to refractories, or encapsulated in ceramic fibers. The elements have no protection from the atmosphere of the furnace.

***Encapsulated Elements (Lamps).*** The element can be protected from the furnace atmosphere and still radiate efficiently if it is mounted in a translucent envelope, such as a quartz tube. If the tube is sealed, containing an inert atmosphere or vacuum, a high temperature element such as tungsten can be used, greatly increasing the amount of heat radiated.

***Area Heaters.*** Elements are mounted in an enclosure with thermal insulation on the back side, and a quartz window or woven refractory cloth on the side facing the work. These are physically robust, but the radiating face is necessarily cooler than the element temperature, limiting the radiation per unit area.

***Tubular and Strip Heaters.*** Tubular heaters can be used for radiant heating, mounted either on a refractory or on a reflector. The sheath (the radiating body) is necessarily cooler than the internal heating element. Such heaters are robust.

***Silicon Carbide.*** Silicon carbide rods can radiate at a higher temperature than metallic elements in an oxidizing atmosphere.

## INDUCTION HEATING

Induction heating allows the heating of the workpiece to very high temperatures, in some cases exceeding the melting temperature of the piece being heated, without any of the electrical components of the system being exposed to high temperatures. If considering the use of induction heating. ANSI/IEEE Std 844 (2) should be reviewed.

### Theory

An electromotive force is induced in any conductive material in a changing electromagnetic field. If the conductive material offers a complete path for the flow of current, the induced electromotive force produces a current along this path. In overcoming the resistance of this path, work is done, proportional to $I^2R$, and this work appears as heat. In addition, in magnetic materials, there are losses due to the thermal effect of magnetic hysterisis, although these are usually small in comparison with eddy current losses.

*Proximity (skin) effect* causes the eddy currents to concentrate near the surface facing the induction coil creating the electromagnetic field. The distribution of current can be described by

$$i_d = i_0 e^{-d/k_f} \tag{6}$$

where:

$i_d$ = current density at distance $d$ from surface (A/mm$^2$)
$i_0$ = current density at surface (A/mm$^2$)
$d$ = distance from surface (mm)
$k_f$ = constant highly dependent on frequency

Figure 3 shows the current distribution variation for magnetic and nonmagnetic materials at 60 Hz. Magnetic materials channel most of the current in a small layer near the surface, heating more effectively. To simplify the solution of induction heating problems, the exponential current density shown in Fig. 3 is replaced by a constant current to a depth of penetration that will develop equal eddy current power. This depth is the point where the actual current density is approximately 37% of the surface current density. It is also the point where the exponent in Eq. (6), $d/k_f$, is equal to $-1$. The following equation gives the equivalent depth of current penetration for a solid cylindrical workpiece where the diameter is much larger than the depth of current penetration; it is also appropriate for hollow cylinders where the wall thickness exceeds the depth of penetration:

$$d_w = 50{,}330 \left(\frac{\rho_w}{\mu_w f}\right)^{1/2} \tag{7}$$

where:

$d_w$ = depth of penetration (mm)
$\rho_w$ = resistivity of workpiece at operating temperature ($\Omega \cdot$cm)

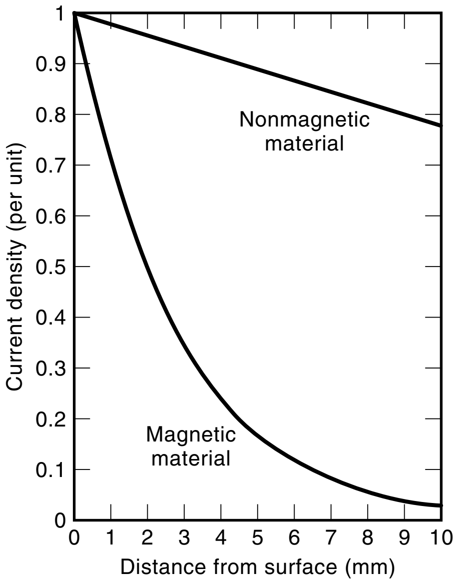


**Figure 3.** The variation of current density for 60 Hz induced currents, in magnetic and nonmagnetic materials, with the distance from the surface

$\mu_w$ = relative permeability of workpiece (see below)
$f$ = electrical supply frequency (Hz)

For carbon steel the relative permeability is given by

$$\mu_w = \frac{34.4 B_s^{4/3} f^{1/3} \rho_w^{1/3} L_c^{2/3} D_w^{2/3}}{W_t^{2/3} \times 10^3} \tag{8}$$

where:

$B_s$ = saturation flux density of the steel used in the piece to be heated (G) (18,000 G = 1.8 T may be used if better information is not available)
$L_c$ = length of workpiece to be covered with heating coil (m)
$D_w$ = outside diameter of workpiece (m) (must exceed 0.05 m for these formulas to be reasonably accurate)
$W_t$ = power required to be induced in the workpiece (kW) (power density should not exceed 40 W/cm$^2$ for these formulas to be used.)

Figure 4 shows the effect of frequency on the effective depth of penetration in typical heating applications of carbon steel. When the magnetic material reaches the Curie temperature, about 735°C for carbon steel, the material becomes nonmagnetic and can no longer be effectively heated by line frequency power supplies.

### Induction Heating Components

**Coil.** The coil is placed in close proximity of the workpiece, to carry alternating current that provides a changing magnetic field around the coil. This magnetic field induces an electromotive force in the workpiece, which causes a current to flow. The coil can be any conductive material, from insulated cables in low-temperature applications to hollow copper tubes for water cooling in high-temperature applications. The coil should be placed as close to and cover as much of the workpiece as possible for efficiency.

**Support System.** It is necessary to support the coil in position and minimize movement due to electromotive forces, and to insulate the turns from each other and ground.

**Magnetic Yokes (Shunts).** Magnetic lamination stacks are placed to confine stray field flux by providing a low-reluctance return path for the magnetic flux generated by the induction coil. The insulated laminations minimize the power loss in the yokes.

**Susceptors.** A susceptor is an electrically conductive medium in which heat is generated by induced currents, and then transferred to the work piece by conduction, convection, or radiation.

**Generators.** A generator is used to take line frequency power and increase its frequency to a value suitable for efficient heating of the workpiece.

***Rotary Generator.*** A three-phase drive motor is driven by line frequency power, and drives a single-phase alternator with an constant output frequency anywhere from 250 to 10,000 Hz.

***Static Generator.*** Thyristors are used to convert line frequency power to an output of 250 to 10,000 Hz.

### Applications

**Metal Melting.** Metal to be melted is placed in a crucible, and a coil wound around the crucible. The crucible can be refractory material, in which case the power is induced directly in the metal to be melted; or a conductive material, which is heated and transfers heat to the metal by conduction.

**Heat Treating**

***Hardening.*** The surface of a workpiece can be hardened by heating to a critical temperature and quenching. Induction

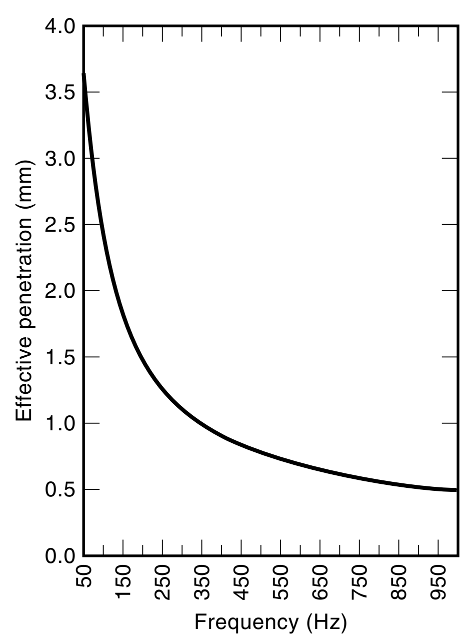


**Figure 4.** The variation of effective induced current penetration, in carbon steel, with applied frequency

heating does this well, because the depth of heating can be controlled by adjusting the frequency.

***Annealing.*** Steels can be heated through, held at temperature, and cooled in the required cycle. Induction heating is a rapid method of heating through.

**Forging.** Metal billets can be rapidly raised to forging temperature by induction heating, because the heat does not all have to be transferred from the surface.

**High-Temperature Furnances.** The use of susceptors with high temperature capabilities, such as graphite, enables the furnance to reach higher temperatures than if any resistance heating elements were used.

**Vessel and Pipeline Heating.** Metallic vessels and pipelines can be heated inductively to heat the contents, or to replace losses so as to maintain the temperature of the contents. If the wall material is carbon steel, it is usually possible to use line frequency power on the coil, saving the cost of a generator.

## ELECTRIC ARC HEATING

Electric arc heating is most commonly applied to metal-melting furnaces where its ability to transfer a large amount of energy directly to the metal to be melted is useful. All but very small furnaces use three-phase power applied to three consumable graphite electrodes. The electrodes are brought in contact with or very close to the metal to be melted to strike an arc, and then the distance from electrode to load is controlled to equalize phase currents and deliver the required power. Currents of up to 100,000 A are used in the larger furnances. The electrodes have couplings to supply additional lengths to replace the electrode consumed.

The high loads involved and power fluctuations cause disturbances to the power system, which will disturb other customers unless compensated. A very high-capacity system is needed for large furnaces.

Electric arc welding is the most common form of arc heating.

## PLASMA HEATING

Ionization of a gas, usually by the application of a radio-frequency field, creates a plasma with ionized particles and free radicals. The particles and free radicals are unstable and react with any foreign matter they contact, creating heat. Lightning is a naturally occurring plasma. Plasmas are used for pyrolysis of wastes, for reduction of ores, for melting of refractories, and to treat organic workpieces to impart specialized properties.

## DIELECTRIC HEATING

Dielectric heating uses the electromagnetic spectrum of 10 MHz to 30,000 MHz to heat nonconducting materials. This form of heating develops heat inside the material by rapidly distorting electron alignment, eliminating the lengthy and inefficient process of conducting heat from the surface of the material.

**Table 3. Common Dielectric Heating Frequencies and Wavelengths**

| Type of Heating | Frequency (MHz) | Wavelength (m) |
|---|---|---|
| RF | 13.5 | 22.17 |
| | 27 | 11.09 |
| | 40.5 | 7.39 |
| Microwave | 915 | 0.327 |
| | 2,450 | 0.122 |
| | 5,800 | 0.0516 |
| | 22,125 | 0.0135 |

### Radio Frequency

Radio-frequency (RF) heating is a subgroup of dielectric heating most often used in industrial applications. RF heating uses frequencies of 10 MHz to 300 MHz. Table 3 shows RF bands in common usage.

**Power Development.** If material characteristics, power source, and electrode configuration are known, an attempt may be made to calculate energy released in the work, using

$$W = \frac{5.55V^2\epsilon_r \tan\Phi \cdot A}{t \times 10^{14}} \tag{9}$$

where:

$W$ = power generated in work (W)
$V$ = voltage applied across work (V)
$\epsilon_r \tan \Phi$ = loss factor (LF), available in Ref. 1 for common materials
$A$ = area of material between electrodes (mm$^2$)
$t$ = thickness of material (mm)

**RF Generator.** A commercial generator should include a three-phase transformer to increase the voltage to anywhere from 1000 V to 15,000 V, a dc rectifier, one or more oscillator tubes for the required power, a tank circuit, and a tuning inductance to match output to load. Generators have a nominal output frequency, but can be operated over a range about that frequency.

**Electrodes.** Electrodes apply the electrical field across the work. They can be in the form of parallel plates or tubes.

**Connections.** The transmission of high-frequency power requires consideration of the connections used, because their inductance is proportional to the frequency. Coaxial cables are often used for RF heating connections.

**Regulations.** Many countries have regulations limiting stray field radiation, and many have adopted IEC Publication 215 (3). The manufacturer should warrant his equipment to comply, and should also be consulted on arrangement of electrodes and field testing to assure compliance. IEEE Std 140 (4) provides methods for minimizing stray field radiation.

#### Applications

- Through heating of insulation materials that have temperature limitations that rule out high temperature oven storage: polymerization of fibers, vulcanization of rubber
- Insulating materials where time for heating in the process is short: molding of plastics or elastomers
- Composite materials where selective heating is desirable: plywood glue drying
- Materials where it is important to equalize moisture content: paper webs
- Selective area heating: plastic welding

### Microwave Heating

Microwave heating is similar to RF heating except that higher frequencies are used (300 MHz to 30,000 MHz) and voltages can range up to 30 kV. Table 3 shows microwave bands in common usage. Equation (9) can also be used to calculate energy released in the workpiece by microwave heating. The depth of field penetration is less for microwave than for RF heating, so it is more effective in heating thin work, such as films.

**Microwave Generator.** The generator is similar to an RF generator, except that the rectified dc is fed to resonator tube(s), magnetrons, or klystrons. The frequency output is determined by the tube design, with some variations from tube tolerances.

**Connections.** Waveguides are used to transmit the power from the generator to the applicator. Waveguides are conductive enclosures that propagate the wave by reflection from the inner surface, to channel power and prevent broadcasting of power in all directions. The dimensions of the waveguide are determined by the wavelength of the power to be transmitted. See Table 4.

**Applicators.** Applicators are the antennas used to apply the microwave energy to the product to be heated.

***Cavity.*** Resonant cavities are used to confine energy and reflect it through the product. Residential microwave ovens use a cavity.

***Slotted Waveguides.*** Slots can be made in the side of square or rectangular waveguides, and the product conveyed through.

***Radiating Waveguides.*** Waveguides may be slotted one or two sides to emit energy. Rueggeberg (5) gives a method of sizing the slots.

#### Applications

- Heating of materials that have a very low loss factor (e.g. polyethylene)
- Continuous heating of thin films to polymerize or dry them
- Curing coatings on film
- Rapid thawing of frozen food products
- Vacuum heating of food products to dehydrate them for storage

## JOULE HEATING

### Theory

Joule heating, for the purposes of this section, means the release of thermal energy when an electric current flows in a liquid conductor. The power released is proportional to the resistance to current flow and the square of the current:

$$W = RI^2 = R(V/Z)^2 \tag{10}$$

where:

$W$ = power released (W)
$R$ = resistance to current flow (Ω)
$I$ = current (A)
$V$ = voltage applied across liquid (V)
$Z$ = total impedance to current flow (Ω)

### Requirements for Use

- The liquid to be heated must be electrically conductive.
- If heating is to be uniform, the liquid must have uniform resistance characteristics and flow path area.
- The liquid enclosure must be electrically insulated.
- There must be two or more electrodes immersed in the liquid, across which the voltage may be applied.

### Advantages

- The heat is generated in the liquid to be heated, so there are no heat transfer losses.
- The conversion efficiency is high, since the only losses are in the power supply system.
- High power densities may be used.
- There are no external heating elements to have limited life.

**Table 4. Microwave Waveguide Dimensions**

| | | Rectangle | | Square | Circle |
|---|---|---|---|---|---|
| Frequency (MHz) | Wavelength (cm) | Long Side (cm) | Short Side (cm) | Side (cm) | Diameter (cm) |
| 915 | 32.7 | 22.9 | 11.4 | 22.9 | 19.1 |
| 2450 | 12.2 | 8.6 | 4.3 | 8.6 | 7.6 |
| 5800 | 5.16 | 3.56 | 1.78 | 3.56 | 3.05 |
| 22,125 | 1.35 | 1.02 | 0.51 | 1.02 | 0.76 |

### Applications

- Steam boilers
- Water heaters
- Salt bath heaters
- Heating of galvanizing baths
- Molten metal heating
- Concrete curing
- Chemical reactions
- Glass melting

## PIPELINE HEATING

### Types

**Solidification Prevention.** Supplementary heating may be used on pipelines to prevent the fluid in the pipeline from solidifying. If this is not done, flow is stopped and expansion may damage the pipeline.

**Viscosity Maintenance.** Viscous fluids are heated to achieve pumping efficiency and reduce pipeline size requirements. If the pipeline is not heated, losses will reduce the fluid temperature and increase the viscosity.

**Process Heating.** Process fluids require the maintenance of an operating temperature.

**Condensation Prevention.** If a gas is transported, the pipeline walls must be maintained at a temperature above its dew point to prevent condensation.

**Remelting.** Systems may be used to heat pipelines to remelt liquids that have been allowed to solidify in the pipeline.

### Methods

**Thermal Insulation.** Thermal insulation may restrict losses from pipelines so that supplementary heating is not necessary. It is required with any form of supplementary heating to minimize losses.

**Environment.** If the pipeline is installed in a heated space at a temperature equal to or above that required for the pipeline, no form of supplementary heating will be required.

**Jacketed Pipelines.** A heated fluid in the jacketed cavity of a pipeline will provide uniform temperature around the pipeline, and along it if the flow is sufficient. The fluid used should have a high specific heat.

**Tracers.** Supplementary tubing can be fastened to the pipeline to carry hot liquid or vapor to heat the pipeline. Condensing vapor gives off much heat.

**Electrical Systems.** Electrical energy can be supplied to the pipeline by many different systems. Electrical systems can be directed and controlled accurately. References 2, 6, and 7 should be reviewed if electrical heating is being considered.

### Electrical Resistance Cables

**Series Resistance Wire.** Current is caused to flow through a conductor to cause heating by $I^2R$ losses in the conductor. The conductor is electrically insulated to isolate it from the pipe wall, and the insulation needs to withstand high temperature if meaningful heat is to be transferred to the pipe. The conductor will increase in temperature until it is able to dissipate all the heat created, so care must be taken to see that there is no barrier to heat transfer, such as burying the conductor in the thermal insulation. The heat created is controlled by controlling the current in the conductor.

***Insulating Materials.*** Insulating heating cables involves a compromise between good electrical insulating properties and high thermal conductivity. Manufacturers try to optimize their systems for good heat transfer and electrical isolation.

*Polyolefins.* One polyolefin is a flame-retardant, heat-resistant thermoplastic (THHN in Ref. 8) with good electrical characteristics, rated for use up to 90°C.

*Silicone Rubber (SA).* Silicone rubber is a rubberlike material rated for use up to 138°C. Its dielectric characteristics are not as good as those of THHN, so it must be a thicker.

*Fluorinated Ethylene Propylene (FEP).* This is a fluoropolymer with good dielectric strength, rated for use up to 200°C.

*Perfluoroalkoxy (PFA).* This is a fluoropolymer similar to FEP, but rated for use up to 250°C.

*Polytetrafluoroethylene (TFE).* This is another fluoropolymer rated for use up to 250°C in dry applications. It is not easily extruded, so it is usually tape-wrapped and sintered.

*Ethylene Tetrafluoroethylene (ZW).* This is a fluoropolymer with exceptional mechanical properties, rated for use up to 150°C.

*Fiberglass.* This is a glass fiber insulation rated for exposure up to 538°C. A woven insulation, it provides no moisture resistance.

*Magnesium Oxide (MgO).* This is a ceramic powder rated for use up to 800°C. It has good thermal conductivity but must be isolated from moisture, as it is hygroscopic. It is the insulation in mineral-insulated cables.

***Conductors.*** Conductor material and size are selected to generate the required amount of heat over the optimum circuit length. See Table 2 for commonly used conductor materials.

*Nichrome.* As discussed above, this is nickel–chromium alloy formulated to have a minimum resistance change with change of conductor temperature. See Fig. 2. The power output is controlled by controlling circuit currents. With modern controllers it is possible to vary the circuit voltage to provide the necessary current on any circuit length less than the maximum allowable, minimizing design effort.

*Ni–Iron.* This is a nickel–iron alloy formulated to have a large resistance change with a change of conductor temperature. See Fig. 2. This resistance change reduces current flow and heat output at constant voltage, protecting the cable from burnout. Because of the resistance change, current flow is not a good measurement of heat output. It is advisable to have temperature feedback to control the pipeline heating. The resistivity is approximately 20% of the resistivity of nichrome at room temperature, so it can be used on longer circuits at the same voltage.

*Copper.* Copper has a positive coefficient of resistance similar to Ni–iron, so it has the same advantages. It has less than 2% the resistivity of nichrome, so it can be used on circuits miles long.

***Metal Covering.*** The National Electrical Code (NEC) (8, Sec. 427-23) requires that all heating assemblies for pipelines or vessels have a grounded metal covering. This is required for personnel and mechanical protection.

*Stainless Steel Braid.* This provides good protection from mechanical damage and corrosion, but is difficult to work with and is not a low-resistance ground path. It is used in specialized applications where its characteristics are necessary.

*Copper Braid.* Nickel-plated copper braid provides a good ground path and is easy to work with. It must be protected from corrosion in certain areas.

*Solid Metal Sheath.* A solid metal sheath is used on mineral-insulated (MI) cables to provide mechanical protection and exclude moisture from the MgO ceramic powder. Any available tubing material can be used.

*Copper.* Copper is easy to work with but must be protected from corrosion, and its temperature must be kept below about 190°C to limit oxidation.

*Stainless Steel.* This material gives better corrosion and mechanical protection than copper, but is stiffer and more difficult to work. The temperature limit is 800°C.

*Inconel.* Inconel is used where its unique corrosion resistance characteristics are required. Its other characteristics are similar to those of stainless steel, but it is more expensive.

***Overjacket.*** An overjacket can be applied over the metal sheath to protect the sheath from corrosion and to provide additional mechanical protection for the cable. The overjacket should be impervious to moisture, easy to bend, and resistant to mechanical damage.

*Nylon.* Nylon has good mechanical properties, but it is stiff and has a low temperature rating. It is used to protect MI cables from corrosion in underground or cement pad installations.

*Polyolefins.* THHN has the same characteristics as nylon, except it is easier to work.

*Silicone Rubber (SA).* This has better mechanical properties and temperature rating than THHN. Its cut resistance is not as good as that of some other plastics.

*Ethylene Tetrafluoroethylene (ZW).* This is extremely durable and has an intermediate temperature rating. It is the most widely used overjacket material.

*Fluorinated Ethylene Propylene (FEP).* This material is used where temperature rating higher than ZW is required. It is not as mechanically resistant.

*Perfluoroalkoxy (PFA).* This material is used for the highest temperature requirements. Its mechanical characteristics are similar to those of FEP.

***Applications.*** Series resistance wires were the first type applied for electrical heating of pipelines. At first regular building wire was used, and then wires especially constructed for this service. This type of heater is still used for very long circuits where low-resistance conductors minimize voltage requirements.

Any level of heat energy can be generated by controlling the current flow, but care must be used that the heat can be dissipated before the conductor reaches an unacceptable temperature. An estimate of the heat that can be safely dissipated is given by

$$Q = UA(T_w - T_p) \tag{11}$$

where:

$Q$ = heat loss per meter of cable (W/m)
$U$ = heat transfer coefficient [W/(m$^2 \cdot$°C)], generally taken as 14 to 17 when wire is installed on a metal pipeline
$A$ = surface area per meter of cable (m$^2$/m)
$T_w$ = temperature of cable surface (°C)
$T_p$ = temperature of pipeline (°C)

***Limitations***

- Pipeline maintained temperature limited by insulation system of cable: FEP, 121°C; PFA, 175°C; MI, 425°C.
- Applied voltage no more than 600 V rms.
- Wattage limited at higher pipeline temperatures to avoid overheating cable.

**Constant-Wattage Heaters.** A constant-wattage (CW) heater is an assembly of two insulated bus wires run in parallel with a heating conductor spiral-wrapped around them and connected to alternate bus wires at regular intervals. The assembly is insulated and covered with a metal jacket, and usually an overjacket. A voltage is applied across the bus wires, which in turn applies the voltage across the heating conductor.

***Insulation.*** The same characteristics are required as are required for series resistance cables.

***Bus Conductors.*** Copper is usually used because of its low resistivity and economy. The size varies from 12 to 18 AWG. The larger sizes reduce voltage drop and effect on wattage produced.

***Heating Conductor.*** Both nichrome and Ni–iron have been used; each has its advantages. A fine wire is used to minimize the connection intervals, so that the cable can be cut to fit the installation without excessive waste.

***Metal Covering.*** The same characteristics are required as are required for series resistance cables.

***Overjacket.*** The same characteristics are required as are required for series resistance cables.

***Applications.*** CW cables were developed to eliminate some of the constraints involved in using series resistance cables. Each separate heating zone, commonly 0.5 to 2 m long, is a circuit designed to deliver rated wattage when rated voltage is applied to the bus wires. This allows the cable to be cut at the interface of any two zones, without affecting the wattage developed in any of the zones. This in turn allows the application of these cables to circuits without knowing the exact circuit length or providing a variable source of circuit voltage.

***Limitations***

- Applied voltage no more than 480 V rms
- Pipeline maintained temperature limited by insulation system as with series resistance cables. CW heaters are available with fiberglass insulation that allows maintained temperatures up to 260°C.

**Self-Limiting Cables.** A self-limiting cable is an assembly of two bare bus wires run in parallel with a semiconductive polymeric material extruded between them and electrically connected to them. The assembly is insulated and covered with a metal jacket, and usually an overjacket. A voltage is applied across the bus wires, which in turn applies the voltage across the polymeric material, generating heat. The semiconductive material has a positive coefficient of resistance, reducing the dissipated power as it heats up, and thus preventing cable burnout.

***Insulation.*** The same characteristics are required as are required for series resistance cables.

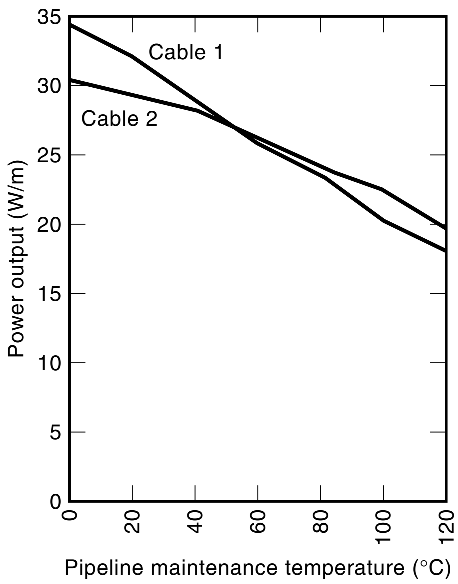


**Figure 5.** The variation of power output of self-limiting heating cables with the temperature of the pipeline to which they are attached

***Bus Conductors.*** Copper is usually used because of its low resistivity and economy. The size varies from 14 to 18 AWG. The larger sizes reduce the voltage drop and the effect on wattage produced.

***Heating Materials.*** Each manufacturer has a proprietary blend of carbon particles dispersed in a polymeric material. The material is tailored for each cable type and rating to produce the proper heat output.

***Metal Covering.*** The same characteristics are required as are required for series resistance cables.

***Overjacket.*** The same characteristics are required as are required for series resistance cables.

***Applications.*** This cable type was developed to eliminate cable burnout and minimize design effort, because it may be cut to fit any pipeline length, up to a maximum, while still delivering rated output. Figure 5 shows the curves of cable output versus pipeline temperature published by two prominent manufacturers of this type of cable, with the cable mounted on a steel pipeline. On nonmetallic pipelines the cable output will be reduced significantly, so the manufacturer should be consulted for application information.

***Limitations***

- Applied voltage no more than 277 V rms
- Maximum pipeline maintenance temperature of 121°C
- Maximum exposure temperature of 204°C
- Reduced wattage output at higher pipeline temperatures. (It is often wise to use the highest-temperature, highest-wattage cable available and control the pipeline temperature to assure adequate heat. The cost of these premium cables is not much above the cost of low-output cables, and the installation costs, the bigger portion of the costs, remain the same.)

**Heat Transfer Aids**

***Heat Transfer Mastic.*** Commercial heat transfer mastics (HTMs) are available that can increase the safe output of cables by up to 10 times the heat available without them. Commercial HTMs are usually carbon particles dispersed in a polymer base, and are applied as a paste, which may harden or maintain its flexibility. It is important to assure that the cable is completely covered if an HTM is to be depended upon to keep the cable within temperature limitations. This is especially difficult to do on complex surfaces such as valves, and to maintain when routine maintenance is done on the piping system.

***Metal Tapes or Mesh.*** Aluminum or copper tapes can be wrapped around the cable and pipeline to assist in transferring heat from the cable. They are not as effective as HTMs except on plastic pipes, where they will conduct heat around the pipeline.

***General.*** The use of heat transfer aids increases initial costs significantly, and they are subject to breakdown in service due to damage or age. For this reason they are not recommended unless there is no other solution available.

**Heat Sinks.** Heat sinks are devices installed in or attached to the pipeline that will cause higher than usual heat losses. Extra cable must be attached at heat sinks to replace these extra losses. Exact losses are difficult to control, so maintenance temperatures at these heat sinks will vary. Common heat sinks are:

- Flanges (Provisions should be made for breaking flanges without cutting cable.)
- Valves (Water leakage around valve stems can make maintaining temperature impossible.)
- Pumps (Provisions must be made for maintenance without destroying cable.)
- Filters (Provisions for cleaning must be incorporated.)
- Supports (When possible the pipeline should be supported outside the thermal insulation to eliminate support losses, which can be major when supports are attached directly to the pipe.) (6)

### Impedance Heating

The following definition is from the NEC (8, Sec. 427-2)

> Impedance Heating System: A system in which heat is generated in a pipeline or vessel wall by causing a current to flow through the piepline or vessel wall by direct connection to an ac voltage source from a dual-winding transformer.

The heat is generated by and is proportional to the $I^2R$ losses in the pipe wall. It is called impedance rather than resistance heating because the circuit return conductors run parallel to the pipeline, and the magnetic flux causes skin effect in the pipeline, reducing the effective cross-sectional area and increasing the wall resistance. If considering the use of impedance heating. ANSI/IEEE Std 844 (2) should be reviewed.

**Considerations for Use.** Impedance heating should be considered if some of the following conditions are met:

- Uniformity of pipe wall heating is required.
- High pipe wall temperatures are required. The only temperature limitations are the melting point of pipe wall

materials, withstand temperature of the thermal insulation, and temperature limits of the heated fluid.
- A large amount of heat energy is required to maintain high temperature, melt solidified lines rapidly, or change temperature quickly.
- The chance of heating element failure is minimized because the pipe itself is the element.
- Existing insulated lines can be converted to impedance heating with a minimum amount of modification.
- The economies and reliability of a factory-installed thermal insulation system are desired.

**Restraints of Use.** The following conditions must be considered before committing to impedance heating:

- The pipeline material must be conductive.
- Large pipe diameters, say over 150 mm, and thick walls may require excessive currents, making other forms of heating more economical.
- The pipe size and cross-sectional area must be the same for each circuit.
- The pipeline should be welded. Flanged pipelines require jumpers at flanges and sacrifice temperature uniformity.
- In-line heat sinks such as valves and pumps must be jumpered, and require supplemental heating.
- The pipeline must be insulated from ground, except at designated points, and isolated from personnel contact. The thermal insulation system usually meets these requirements.
- If the fluid in the pipeline is electrically conductive, this must be taken into consideration when designing the system.

### Circuit Configurations

***End-Feed System.*** This is the simplest system, and the one originally used, as shown in Fig. 6. The low-voltage winding of the dedicated transformer is connected across the pipeline to be heated. One side of the low-voltage winding is grounded where it connects to one end of the circuit. At the other end of the circuit, full voltage to ground is impressed on the pipeline, so it must be insulated from the remainder of the piping system by an insulated flange. The voltage across the pipeline causes a current to flow in the pipe wall, generating heat.

***Midpoint-Feed System.*** One end of the low-voltage transformer winding is connected to both ends of the pipeline, while the other winding end is connected to the electrical midpoint of the pipeline, as shown in Fig. 7. This eliminates the necessity of insulated flanges, which are a frequent cause of system failure in service. It also doubles the circuit length that can be used on a given secondary voltage. Since there are minor differences in circuit impedance to either end of the pipeline, it is wise to interconnect the ends with a ground path to confine stray ground currents.

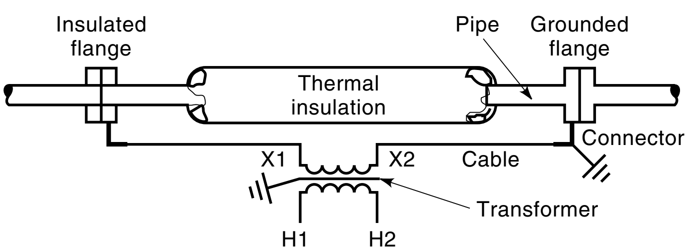


**Figure 6.** A diagram of an impedance heating system where the voltage is applied across the complete length of the pipe section to be heated

***Multiphase Systems.*** Where the pipeline configuration can be arranged as shown in Fig. 8, a three-phase transformer can be used to give a balanced load on the distribution system. The electrical connection length can be minimized to reduce circuit impedance. This is a valuable system for impedance heat exchangers. The entry and exit flanges are at ground potential, so no insulation is required to isolate the rest of the piping system.

**Transformers.** The transformers needed for impedance heating systems are special dual-winding transformers with low-voltage, high-current secondary windings.

***Secondary Voltage.*** The NEC (8, Sec. 427-26) limits the transformer secondary voltage to 30 V, unless ground fault protection is provided. If ground fault protection or ground fault alarm is provided, the transformer secondary voltage shall not exceed 80 V.

There is general agreement that an ac voltage that does not exceed 30 V to ground poses no shock hazard to personnel. Because pipelines are accessible to all types of personnel, not just those trained to deal with electricity, it is preferable to limit voltage to 30 V whenever possible. Use of midpoint or multiphase systems allows circuit lengths of 100 to 125 m, so higher voltages are hard to justify. If higher voltages are to be used, the application should be carefully reviewed for safety hazards.

The primary winding should have at least two 5% taps above and below normal to compensate for changes in circuit impedance and supply system voltage.

***Isolation.*** The NEC (8, Sec. 427-27), requires that the transformer be a dual-winding transformer with a grounded metal shield between the primary and secondary windings. This provision is to prevent the primary voltage from being imposed on the pipeline due to a failure of the transformer winding insulation system.

***Service Factor.*** The transformer shall be a heavy-duty type to correspond with the remainder of the heating system. For long life and energy efficiency it is recommended that the transformer have a Class B temperature rise at full load, and a Class F or H insulation system.

***Enclosure.*** The transformer enclosure shall be suitable for the ambient conditions in which it is to be installed. In most cases this means a weatherproof enclosure.

***Connection Compartments.*** Both the primary and secondary compartments shall have sufficient space to train the cables and install any metering or protective equipment. Since the secondary cables are normally large because of the high currents involved, consideration should be given to a large bending radius to avoid stressing the secondary connections. Since the secondary cables are normally run separately because of size, the panel through which they enter the compartment shall be nonmagnetic to minimize inductive heating.

**Secondary Cables.** The secondary cables are the connections from the transformer secondary winding to the pipeline.

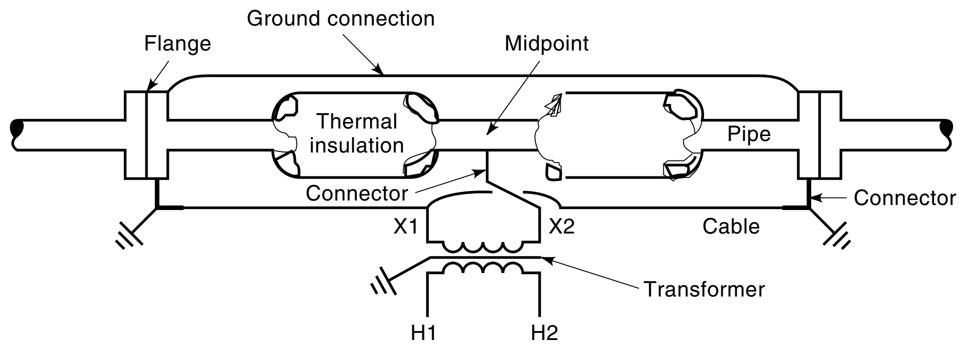


**Figure 7.** A diagram of an impedance heating system where the pipe section to be heated is divided into two equal lengths, with equal voltage from one circuit applied to each length

***Cable Sizing.*** The NEC (8, Sec. 427-30) requires the cables' ampacity to be at least 100% of the total load of the heater. When the ampacity required exceeds the rating of a single 500 kcmil (320 mm$^2$) cable, it is advisable to use parallel cables. Larger cables are difficult to run and support. Consideration should be given to using larger than required cables to minimize power loss and voltage drop.

***Cable Routing.*** The cables are to be run as close as practical to the weather jacket of the thermal insulation system to minimize circuit impedance. Where more than one cable is required, they should be evenly distributed around the pipeline to equalize skin effect in the pipe wall. There shall be no magnetic materials, such as hangers, supports, jacketing, etc., between the cable and the pipeline in which currents can be induced.

Where the cables leave the pipeline to be connected to the transformer, they shall be routed together to minimize impedance. Cables from either side of the secondary winding shall be alternated to minimize impedance. In multicable, midpoint-feed, or multiphase systems the cables must have the same size and the same length and be routed in the same configuration to balance currents.

**Connectors.** The connectors between the cables, or bus, and the pipe are a critical part of the system. They are usually made from the same material as the pipe and welded to the pipe, and must carry high current without overheating the cable fastened to them. They must be long enough to extend beyond the thermal insulation. If fastened to the bottom of horizontal pipelines, they will minimize the heat conducted to the cable termination. The current in the connector must generate enough heat that the connector does not become a heat sink for the pipe. A finite-element analysis can be used to design a connector shape that meets all these criteria.

When a midpoint-feed system is used, the center connector must be located to balance currents in each end of the system. A pipe saddle may be installed at the measured midpoint, a low current run through the system, and the saddle moved in the direction of the lower current until the currents are balanced. A reputable manufacture will give detailed instructions for accomplishing this. When the midpoint is determined, a permanent connector can be welded to that spot.

**Connector Enclosures.** Where the connector exits, the thermal insulation weather barrier will be an entrance for moisture unless steps are taken to exclude moisture. A fabricated box installed around the connector and pipeline is the usual solution. It must be separable so that the cable-to-connector bolt torques can be checked periodically. The side panel where the cables enter the box must be nonmagnetic to minimize inductive heating.

**Applications**

***Fluid Transportation.*** This method of heating is applicable to long lines that must transport high-temperature fluids without cooling, or in some cases heat the fluid. A midpoint-feed system will minimize the number of circuits required. The transformers must be located near the midpoint of each circuit. The primary voltage should be chosen to minimize primary cable size and voltage drop. Power controls can be located in the primary, at a more environmentally friendly location.

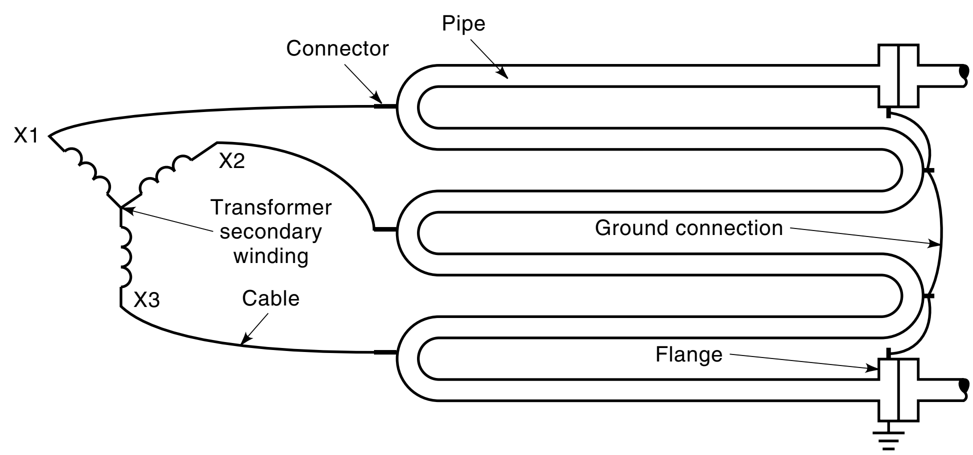


**Figure 8.** A diagram of an impedance heating system where the pipe section to be heated is divided into three equal lengths, with voltage from a three-phase circuit applied so that phase voltage is across each length

***Heat Exchangers.*** Multiphase systems can be used to heat pipe to heat fluids. The transformer should be located near the connector end of the heat exchanger to minimize cable or bus length and associated losses. Primary control is preferred to minimize the currents controlled. A heat transfer consultant should be used to calculate the required pipe wall temperature and pipe length.

**Special Considerations.** It must be recognized that all attachments to the pipeline at any place but a grounded circuit end will be electrically energized. This means that all such devices, including pipe wall temperature sensors, must be electrically insulated from the pipeline to avoid sneak circuits that will destroy the temperature uniformity. Water in the thermal insulation will not only cause excessive heat loss, but provide a conductive path to ground.

### Skin Effect Heating

According to the NEC (8, Sec. 427-2), skin effect heating is

> A system in which heat is generated on the inner surface of a ferromagnetic envelope attached to a pipeline and/or vessel. FPN: Typically, an electrically insulated conductor is routed through and connected to the envelope at the other end. The envelope and the electrically insulated conductor are connected to an ac voltage source from a dual winding transformer.

The heat is generated by current flowing through the conductor and returning in the envelope wall. It is called skin effect heating because the current flowing through the conductor pulls the current in the envelope wall to the inner surface by skin effect. This effect decreases the effective cross-sectional area of the envelope wall, increasing path resistance, and the heat generated by $I^2R$ losses. The conductor losses also generate heat, but they are small in comparison with the envelope losses in a properly designed system. If considering the use of skin effect heating, ANSI/IEEE Std 844 (2) should be reviewed.

**Considerations for Use.** Skin effect heating should be considered if some of the following conditions are met:

- The pipeline is long without much complexity.
- The required pipe wall temperature does not exceed 250°C. This limitation is imposed by the conductor insulation system.
- The heat energy required is moderate (if not, multiple systems must be used). The limitation of a single system is perhaps 150 W/m.
- A reliable system is required. The only part of the system at hazard is the conductor, and it can be readily replaced by pulling a new conductor in the envelope.
- The economies and reliability of a factory installed thermal insulation system are desired.

**Restraints of Use.** The following conditions must be considered before committing to impedance heating:

- Circuit voltage requirements limit the circuit length to a few kilometers, unless high-voltage shielded cables are used, and they require special care. The length may be doubled by using a midpoint-feed system.
- The conductor will be the hottest component of the system, so its insulation must be carefully selected.
- Pipeline complexity will require complicated envelope paths, making it difficult to pull the conductor.
- The pipeline length must be sufficient to justify the costs of this system. Lengths as short as 100 m or even less may be considered for special applications.
- If the pipeline is not welded, flanges require supplemental heating, as do in-line devices such as valves and filters.

#### Components

***Conductor***

- The conductor must have an insulation system suitable for the temperatures to be expected, and should be tough enough or jacketed to withstand the long pulls required by this system.
- "Conductor Ampacity. The ampacity of the electrically insulated conductor inside the ferromagnetic envelope shall be permitted to exceed the values given in Article 310, provided it is identified as suitable for this use." [NEC (8, Sec. 427-45)]

***Ferromagnetic Envelope***

- The envelope must be ferromagnetic with side walls thick enough (3 mm is a generally accepted thickness) to confine the magnetic flux.
- "Single Conductor in Enclosure. The provisions of Section 300-20 shall not apply to the installation of a single conductor in a ferromagnetic envelope (metal enclosure)." [NEC (8, Sec. 427-47)]
- "Grounding. The ferromagnetic envelope shall be grounded at both ends and, in addition, it shall be permitted to be grounded at intermediate points as required by its design. The ferromagnetic envelope shall be bonded at all joints to ensure electrical continuity." [NEC (8, Sec. 427-48)]
- The ferromagnetic envelope should be sized so that the conductor cross-sectional area does not exceed 33% of the internal cross-sectional area of the envelope, for ease of pulling.

***Boxes and Sleeves***

*Service Terminal Box.* This box is to be ferromagnetic, weatherproof, and welded to the ferromagnetic envelope. It will have a welded conduit hub for service cable entrance. One conductor of the service cable will be fastened to the heating conductor, while the second conductor will be terminated on a lug welded inside the box.

*End Terminal Box.* This box is to be ferromagnetic, weatherproof, and welded to the ferromagnetic envelope. The heating cable will be terminated on a lug welded inside the box.

*Pull Boxes.* These boxes are to be ferromagnetic, weatherproof, and welded to the ferromagnetic envelope on two sides. The heating cable will be pulled through the boxes. Boxes are to be located at all radical changes of direction of the pipeline, and no further than 130 m apart. If splices are necessary in the heating cable, they will be done in a pull box. According to the NEC (8, Sec. 427-46):

Pull Boxes. Pull boxes for pulling the electrically insulated conductor in the ferromagnetic envelope shall be permitted to be buried under the thermal insulation, provided their locations are indicated by permanent markings on the insulation jacket surface and on drawings. For outdoor installations, pull boxes shall be of watertight construction.

*Ferromagnetic Sleeves.* Ferromagnetic sleeves are to be welded to each end of the ferromagnetic envelope at each pipeline section joint to provide electrical continuity and mechanical protection for the heating cable.

***Transformers.*** The transformers needed for skin effect heating systems are special dual-winding transformers with secondary windings designed to provide the required circuit voltage.

*Secondary Winding.* When two secondary windings are provided for a mid-feed system, the secondary windings are to have taps to allow voltage adjustment to balance currents in the two circuits.

*Primary Winding.* The primary winding should have at least two 5% taps above and below normal to compensate for changes in circuit impedance and supply system voltage.

*Service Factor.* The transformer shall be a heavy duty type to correspond with the remainder of the heating system. For long life and energy efficiency it is recommended that the transformer have a Class B temperature rise at full load, and a Class F or H insulation system.

*Enclosure.* The transformer enclosure shall be suitable for the ambient conditions in which it is to be installed.

### Special Considerations

- Consideration must be given to the relative expansion of the long pipeline, the ferromagnetic envelope, and the thermal insulation system and its affect on supports.
- Plastic pipelines may be heated by this method if the power density is kept low and the insulation is oversized to allow heat dissipation from the ferromagnetic envelope by convection. The ferromagnetic envelope is strapped to the pipe.
- Skin effect heating is efficient because the heat is developed in the envelope and conducted directly to the pipe, and the power factor is usually 0.9 or better.

## THERMAL INSULATION

Thermal insulation is of such critical importance that it must be included in any discussion of electrical heating. It has been estimated that as much as 95% of the failures of electrical heating systems can be attributed to the failure of the thermal insulation system. The $k$ factor given for commercial insulation by the manufacturer is a laboratory-measured number and does not necessarily reflect practical numbers in field installations. Thermal insulation systems consist of the insulating material and a weather barrier to exclude moisture. References 6 and 9 should be reviewed for more extensive information.

Thermal insulation serves two functions:

- To protect personnel from contact with hot surfaces. It is advisable to limit the insulation outer surface temperature to 60°C.
- To reduce heat losses from the surface insulated so as to allow the heating system to maintain the required temperature and to reduce energy loss costs. There is a point beyond which increasing insulation thickness is not economically justified. Figure 9 clearly indicates this.

### Insulating Material

Table 5 lists some of the commercially available thermal insulations and some of their more important characteristics.

**Insulation Type.** The insulation type is a general description of the material in the insulation. Most insulations will also have fillers that provide structural stability. All insulation should be specified as asbestos-free.

**Thermal Conductivity.** The $k$ factor is an indication of the effectiveness of the insulation in providing a barrier to heat flow. The lower the $k$ factor, the more efficient the insulation. All insulations become less efficient as their mean temperature rises.

**Maximum Temperature.** This is the temperature to which the insulation may be exposed without physical or thermal degradation.

**Compression Strength.** The ability of the insulation to resist changes in dimensions from external forces can in some applications be critical to the performance of the insulation. Insulation with high compression strength is generally more resistant to abuse in installation and service.

**Water Resistance.** The ability to withstand limited exposure to moisture without degrading the thermal conductivity

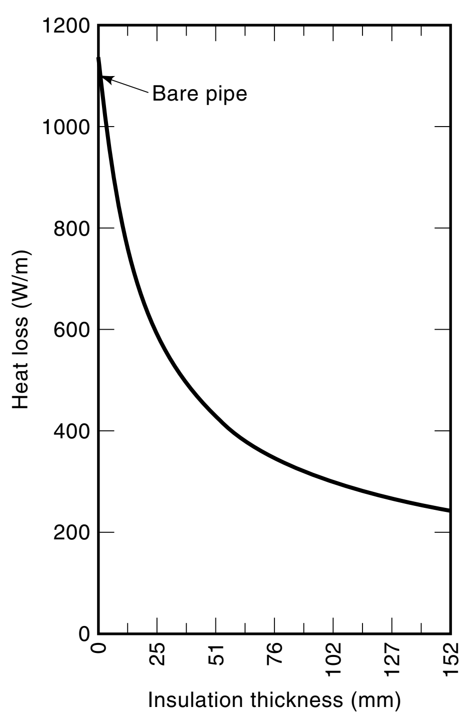


**Figure 9.** The variation of energy loss with insulation thickness from a 10 cm (4 in.) pipe insulated with expanded silicate thermal insulation, when the pipe operating temperature is 88°C above ambient temperature

**Table 5. Thermal Insulation**

| Insulation Type | ASTM No. | $k$ Factor [W/(m · °C)] | Mean Temperature (°C) | Maximum Temperature (°C) | Compression Strength (Pa) | Water Resistance |
|---|---|---|---|---|---|---|
| Glass fiber | C547 | 0.033 | 38 | 454 | None | Poor |
| | | 0.052 | 149 | | | |
| | | 0.069 | 232 | | | |
| Calcium silicate | C533 | 0.063 | 93 | 649 | 700,000 | Poor |
| | | 0.079 | 204 | | | |
| | | 0.095 | 316 | | | |
| Expanded perlite | C610 | 0.063 | 93 | 649 | 420,000 | Good |
| | | 0.079 | 204 | | | |
| | | 0.095 | 316 | | | |
| Cellular glass | C552 | 0.048 | 10 | 482 | 700,000 | Excellent |
| | | 0.050 | 24 | | | |
| | | 0.052 | 38 | | | |
| Mineral wool | C553 | 0.052 | 93 | 649 | Low | Poor |
| | | 0.065 | 204 | | | |
| | | 0.087 | 316 | | | |
| Polyurethane foam | C591 | 0.022 | 10 | 82 | 175,000 | Fair |
| | | 0.022 | 24 | | | |
| | | 0.023 | 38 | | | |
| Polyisocyanurate foam | C591 | 0.026 | 10 | 121 | 175,000 | Fair |
| | | 0.027 | 24 | | | |
| | | 0.029 | 38 | | | |

characteristics is very important, since most insulation is exposed to moisture at least some of the time.

**Chemical Resistance.** The insulation must be compatible with chemicals to which it may be exposed in any particular service.

### Weather Barrier

The weather barrier is required to exclude moisture from the insulating material. Wet insulation has almost no insulating value, and is impossible to dry unless baked for a long time in a high-temperature oven. The better weather barriers also provide mechanical protection for the thermal insulation.

**Mastics.** Mastics are cheap, but their application is labor-intensive, they provide no mechanical protection, and they need frequent renewal because of drying cracks and mechanical damage. They are not recommended except for very irregular surfaces where there is no other acceptable choice.

**Aluminum.** Sheet aluminum is furnished flat-rolled into cylinders to fit pipelines and small vessels. The material costs exceed those for mastics, but the installation is less expensive, and the aluminum provides a long service life and some mechanical protection. It may require corrosion protection against some chemicals, which will increase the cost.

**Plastics.** Various plastic materials provide excellent corrosion protection, and some mechanical protection if thick enough. Installation costs depend on the form and thickness. Factory-installed foamed-in-place insulation with performed plastic pipes on the outside are excellent systems with long life expectancy. Factory-installed systems are also considerably cheaper than field-installed systems where they can be used—usually on long lengths of pipe with minimum complexity.

**Galvanized Steel.** Suitable in some areas where aluminum will degrade, it provides more mechanical protection than aluminum. It is more difficult to work, so it costs more to install.

**Stainless Steel.** Stainless steel is suitable for severe corrosive areas. It is more expensive than all the other materials, and more difficult to install. It is sometimes required for fire protection.

### Vessels

**Installation.** Smaller cylindrical vessels can have their side walls covered with preformed insulation manufactured to insulate pipelines. The heads and larger vessels can be covered with flat panels bent to shape and held in place. Another option is to foam insulation on the surfaces. This allows the effective covering of complex surfaces with many penetrations.

Usually on vessels heat losses through piping connections and supports will be extensive. They should be insulated also to minimize these losses. These penetrations also make it difficult to seal the weather barrier to exclude moisture. Special care should be taken at these places, or the thermal insulation will become ineffective. Side-wall penetrations are easier to seal than roof penetrations, if the option is available.

When the vessels sit directly on a concrete pad, consideration should be given to a layer of high compression strength insulation under the vessel. High-compression-strength materials usually have a much higher $k$ factor than ordinary insulations, but concrete has almost no insulating value.

The losses may be calculated from the equation

$$Q = \frac{Ak_{\mathrm{i}}(T_{\mathrm{v}} - T_{\mathrm{a}})}{t_{\mathrm{i}}} \tag{12}$$

where

$Q$ = total heat loss from vessel (W)
$A$ = total surface area of vessel ($m^2$)
$k_i$ = insulation thermal conductivity [W/(m · °C)]
$T_v$ = vessel temperature (°C)
$T_a$ = ambient temperature (°C)
$t_i$ = insulation thickness (m)

Equation (12) will give conservative results (maximum losses), because the surface convection and radiation coefficients have not been included in the loss path.

**Corrosion.** There have been many cases of corrosion under thermal insulation that have led to vessel failure. Corrosion will not occur if the insulation is kept dry. The following practices are recommended:

- Keep insulation in dry storage before application. Do not apply it in wet weather. Install the weather barrier as soon as the insulation is installed.
- Use flashing and silicon caulking compound where the weather barrier is penetrated. Penetrate sides instead of top wherever possible.
- Where there are protrusions through the top, install rain shields to divert water.
- Overlap weather barrier seams to shed water.
- Inspect the weather barrier frequently, and recaulk joints as required.
- When the weather barrier is damaged, replace it and the wet insulation immediately.
- Use water-resistant insulation.
- Paint carbon steel, and coat stainless steel with sodium silicate, before insulation is applied in places where keeping the insulation dry is a problem.

Vessels subject to frequent heatup and cooldown are especially subject to insulation water absorption through osmosis.

### Pipelines

**Installation.** Piping insulation can be soft or can be rigid and preformed to fit each pipe size. While the soft insulation is easy to install, rigid insulation has many advantages, which will be detailed later. Rigid insulation to be used with an external heat tracer should be one pipe size larger than require for the pipe, to allow room for the tracer without burying the tracer or leaving a gap where the two halves of the insulation meet. Insulation should be trimmed to fit around heat sinks in the pipeline such as valves, flanges, and supports. The use of "mud" is not recommended. It has a very high $k$ factor, and it contracts and cracks as it ages. Water resistance is a prime criterion for selecting insulation.

Vertical or sloped pipelines should be given special consideration if heated. There will be convective currents in the fluid being heated, and in the air space between the pipeline and the thermal insulation where oversized insulation is used, which will make the top warmer than the bottom. Rings of heat transfer mastic around the pipeline at periodic intervals will stop convection outside the pipe, but convection in the pipe must be allowed for in the design.

**Supports.** Wherever possible, pipeline supports should be installed outside the thermal insulation and weather barrier. This avoids weather barrier penetration and a heat sink. Rigid insulation with good compression strength must be used for this service. If supports must be attached to the pipeline, they should be insulated as well as possible, weather barrier penetrations sealed, and extra heat provided on heated pipelines.

**Composite Systems.** Insulation systems may be composed of two or more layers. The layered system has several advantages:

- The joints of the two layers may be staggered. This prevents the opening of joints by poor installation or thermal cycling from exposing bare pipe.
- An insulation with high-temperature capabilities may be used next to the pipe, and a superior-heat-transfer insulation can be used on the outer layer where it is protected from high temperatures.
- The outer layer may have superior moisture resistance.

**Thermal Loss Calculations.** We have

$$Q = \frac{2\pi k_{\mathrm{i}}(T_{\mathrm{p}} - T_{\mathrm{a}})}{\ln(D_2/D_1)} \tag{13}$$

where:

$Q$ = heat loss from pipe (W/m)
$k_i$ = insulation thermal conductivity [W/(m · °C)]
$T_p$ = pipe temperature (°C)
$T_a$ = ambient temperature (°C)
$D_2$ = insulation outside diameter (m)
$D_1$ = insulation inside diameter (m)

Equation (13) will give conservative results (maximum losses), because the surface convection and radiation coefficients have not been included in the loss path.

## HEATING CONTROLS

Since one of the major advantages of electrical heating as opposed to other forms of heating is the ability to control it accurately, it is well to know the types of control available, and the advantages and disadvantages of each.

### Types of Control for Electrical Heating

**Manual On–Off Control.** This is the simplest and most economical form of control. A switch or plug and receptacle can be used. This method is suitable for processes that are closely observed. It requires the constant attention of an operator, and human responses lead to a comparatively wide *dead zone* (difference between turn-on and turnoff temperatures).

Operator interaction with a switch or plug breaking full voltage poses a safety hazard.

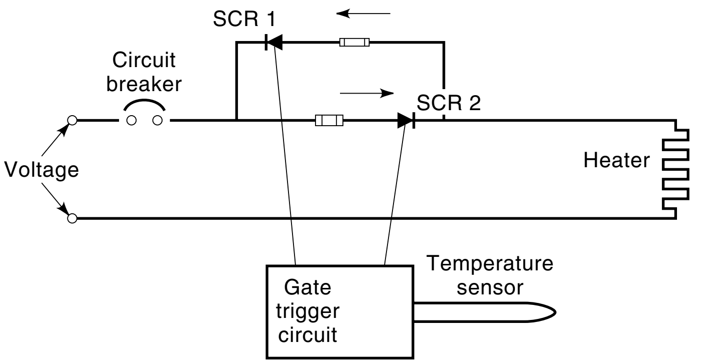


**Figure 10.** A simplified diagram of a static controller (SCR) controlling an electrical heater

**Automatic On–Off Control.** This method eliminates the operator, but a wide dead zone is still necessary to minimize the control operations and required maintenance. Several types of devices are used.

***Thermostat.*** This device combines the sensing and control functions in one package. While economical to use, it is limited to the control of small heaters because of current and voltage limitations of the contacts. Because thermostats are mechanical devices, they must be inspected and calibrated at regular intervals, no less frequently than yearly. If in dirty or corrosive atmospheres, they should be maintained more frequently. There are two types.

*Bimetal.* A bimetal thermostat has two dissimilar metals with different coefficients of expansion combined in such a way that exposure to increased temperature causes movement that operates an internal switch. Such thermostats are subject to fatigue failure, and must be protected from corrosive atmospheres. They must be selected for a limited operating range.

*Fluid-Filled.* A sensing bulb is filled with a fluid that expands as the exposure temperature increases, operating a switch. The bulb may be included in the switch enclosure, or connected to it by a tube. This allows a limited separation of the thermostat from the work to be controlled—usually not over 2 m. These thermostats must also be selected for a limited operating range.

***Contactor.*** Contactors are able to control large heaters because of their high current and voltage ratings. They require a separate temperature-sensing device to initiate their operation. Because they are also mechanical devices, they also require frequent maintenance and entail a discrete dead zone. There are three types.

*Air Break.* The most common type, the air break is economical and readily available in different ratings. It requires the most maintenance, and is noisy when operating.

*Vacuum.* Vacuum contactors require less maintenance, but are more expensive than air break contactors.

*Mercury.* Mercury contactors have been used in the past for heater control because of their ability to confine the arc and reduce contact resistance. They are costly and pose environmental problems when they must be replaced.

**Static Controllers.** Where accurate control, maximum reliability, and low maintenance costs are needed, static controllers (SCRs) should be considered. They are more expensive than mechanical devices initially, but their long-term costs are less. Figure 10 is a simplified wiring diagram of a static controller and electrical heater.

***On–Off Controllers.*** Static controllers can be used as a solid-state contactors to energize and deenergize heaters manually or automatically. This eliminates the noise and maintenance problems associated with mechanical contactors. However, for only slightly more investment, static controllers can be made more flexible.

***Burst (Zero) Fired Controllers.*** These controllers conduct current for discrete cycles. The thyristors start to conduct when the ac voltage increases through zero, and can be set to conduct for any number of full cycles. The circuit voltage is determined by the number of on and off cycles in any given period. Most commercial controllers can be set to vary the conducting period from one cycle to a few seconds.

Figure 11 shows the output of a burst-fired controller with a period of three cycles, where it is desired to provide 67% of full rms voltage to the heater. The thyristors conduct for two cycles, and block the current for one cycle. By varying the cycle length and conduction periods, any rms voltage from zero to full can be impressed on the heater. This is essentially stepless control for any heater with reasonable thermal mass. Advantages and disadvantages of this type of control:

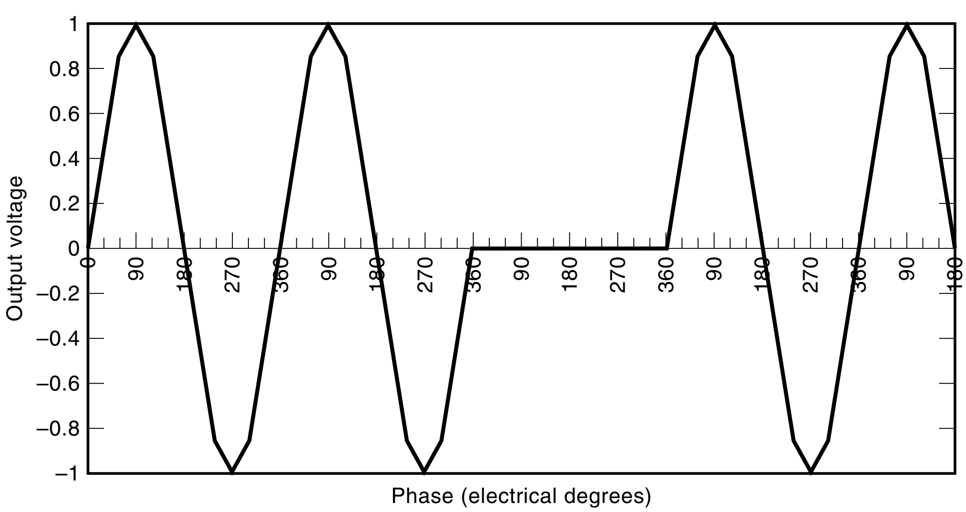


**Figure 11.** The output of a burst-fired static controller set to deliver 67% voltage to an electrical heater

- It has a marginally lower price than for phase-fired controllers.
- Conduction for discrete cycles assures unity power factor on resistive loads.
- The technique eliminates high-frequency harmonic currents associated with phase-fired controllers.
- It is not suitable for control of inductive loads such as transformers, where repetitive inrush currents will lead to thermal failure.
- Low-thermal-mass heaters such as radiant lamps will reflect on–off periods in thermal output.
- The repetitive full-on, full-off currents cause application and relaxation of mechanical forces, which lead to premature failure at connection and terminal points.
- Three-phase controllers inject dc currents into the distribution system, which cause overheating of transformers and impaired readings from instrument transformers.

***Phase-Fired Controllers.*** Phase-angle firing controls the output rms voltage by controlling the conduction time for the thyristor for each half cycle of the sine wave from a typical ac power supply. When thyristors are triggered for full output, the output will be a sine wave, with typically 0.5% loss due to forward resistance. Figure 12 shows the output when each thyristor is triggered at 90 electrical degrees and conducts for half a cycle. The output is approximately half of full rms voltage. The conduction angle can be varied smoothly from zero to 180° to provide zero to full rms voltage output. Advantages and disadvantages of this type of control:

- The short time between on and off, less than half cycle, allows control of very low-thermal-mass heaters without affecting output.
- It can have soft start features to allow energization of high inrush current loads without exceeding circuit contraints.
- It is suitable for use with inductive loads such as transformer primaries.

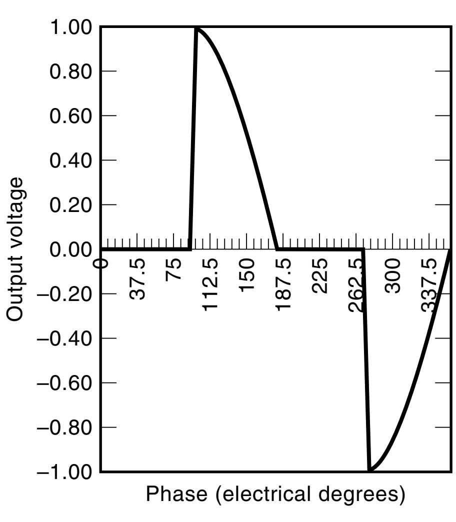


**Figure 12.** The output of a phase-fired static controller set to deliver 50% voltage to an electrical heater

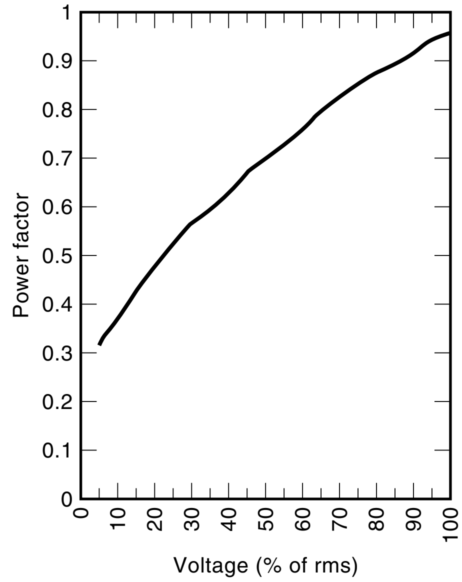


**Figure 13.** The apparent power factor of a phase-fired static controller as it varies with the voltage output of the controller

- Current-limiting circuits can be provided to limit the load current to any desired value for variable-resistance loads.
- The chopping action of the controller produces high-frequency harmonics in the distribution system, which may be a source of problems.
- When phased back, the apparent power factor of the load degrades as shown in Fig. 13.

***Application.*** When applied correctly, static controllers have essentially unlimited life.

*Current.* Static devices have very little thermal mass, so means must be found to dissipate the heat generated when current flows through the forward resistance, typically 1% of the power transmitted. To dissipate this heat the devices are ordinarily mounted on a heat sink. The device is given a current rating by the manufacturer based on the type of heat sink and cooling methods in the installation. This current rating should not be exceeded under any circumstances. Some of the factors to be considered when selecting thyristors are:

- *Convection cooling.* The enclosure must allow entrance of cooling air and exit of heated air. Provision should be made to assure clean air so that the heat sinks are not fouled. Heat sinks must be mounted to allow optimum cooling, and devices should be protected from effects of adjacent devices.
- *Forced-air cooling.* This is more efficient than convection cooling, but also more subject to contaminated air unless a clean source and/or filters are provided. It reduces the reliability of the system because it depends on rotating equipment for operation.
- *Water cooling.* This is an order of magnitude more efficient than air cooling. The water must be treated and recirculated, so this is an expensive option, but one required when high currents are to be controlled.

- *Parallel thyristors* can be used to increase the current rating, but care must be taken to assure that the current divides equally.

*Transient Current.* Because conduction is initiated in a small area of the thyristor, high currents cannot be conducted until the current has had time to spread across the whole conduction area. For this reason, loads with no initial impedance, such as capacitors, cannot be controlled directly by thristors unless some inductance is placed in series with them.

*Voltage.* Thyristors are rated to withstand peak forward and reverse voltages without breaking down. These limits must be respected. A typical industry standard calls for application of thyristors with ratings 250% of rms system voltage, or 175% of peak system voltage. Surge protection should be provided to limit surges to 200% of rms system voltage as a further precaution. Some thyristors have the additional protection of breaking down in the forward direction for half a cycle when receiving a surge.

*Transient Voltage.* High-rate-of-rise voltage spikes (large $dv/dt$) can damage thyristors. A protective circuit to slope such spikes will prevent damage.

***Protection***

*Fault.* Since thyristors have very little thermal mass, high-speed current-limiting fuses are required to limit let-through energy to less than 75% of the manufacturer's withstand rating.

*Overload.* Thermal switches mounted on the heat sink near the device can provide overload protection.

*Failure.* While not as prone to failure as mechanical devices, static devices will fail if not properly applied. The most common mode of failure is breakdown in the forward direction, applying full voltage to the heater with no method of control. A separate mechanical device, circuit breaker or contactor, and overtemperature sensor should be applied to prevent this hazard.

### Discussion

The selection of a controller for any application depends on a review of the complete system.

**Workpiece.** The piece to be heated has characteristics such as thermal mass and accessibility that need to be determined.

***Thermal Mass.*** A piece with low thermal mass will change temperature rapidly, while a piece with high thermal mass will react much more slowly. Mechanical devices with a small deadband are suitable for control of high thermal masses. Since the temperature changes slowly, the number of operations will be reduced, leading to long life and less maintenance. Low-thermal-mass pieces, however, will change temperature so rapidly that the deadband must be increased to reduce operations to a more acceptable level. Static controllers that vary their voltage, instead of full-on, full-off application, will be much more suitable for this application.

***Accessibility.*** If the heater is allowed to be mounted directly on or in the workpiece, heat will be transferred to the piece efficiently, and the piece temperature will rapidly reflect changes in heater output. If however the heater is separated from the workpiece by air or a more dense medium, the piece temperature will lag in response to a change in heater output. Mechanical devices may be suitable on high-thermal-mass devices where the heat is applied directly to the workpiece. When the heater is isolated, the lag in workpiece temperature will cause significant over- and undertemperatures if on–off control is used.

**Heater.** The heater power output is dependent on the process requirements. If it is desired only to maintain a temperature, or to change the work temperature slowly, a heater sized to deliver 125% of losses will suffice. If temperatures must be changed rapidly or the heater must respond quickly to significant changes in ambient conditions or work load, a much larger heater will be required. Mechanical devices will suffice for the control of the smaller heaters, but the larger heaters will respond so rapidly that static devices are the better choice.

**Controller Selection.** From the foregoing discussion it is apparent that static devices are much more flexible, and if service life is taken into consideration are the more economical choice for control of heaters. The most flexible static device is the phase-fired unit. It does generate harmonics in the distribution systems, which can affect the operation of sensitive equipment. It is industry experience, however, that the power level of heaters, compared to that of the total industrial system, is so low as to make these harmonics inconsequential. In addition, there are other sources of harmonics on the distribution system that cannot be controlled, so sensitive equipment should in any case be isolated by its own harmonic barriers.

### Sensors

See Table 6 for the characteristics of various sensors.

**Personnel.** An operator can control temperature by sight or feel. This is coarse temperature control subject to failure because of inattention.

**Thermostats.** Thermostats have already been discussed as controllers, since they perform dual functions of sensing and control. They are manufactured for a limited range and must be calibrated frequently to combat drift. Since they must be mounted near the work to be controlled, calibration can be difficult and at times dangerous.

**Thermocouples.** Probably the most widely used temperature-sensing devices in industry are thermocouples. They are small, so they do not act as heat sinks on the surface being measured. They are also low-cost, although they must be connected to the controller with special wire, which is expensive. Table 7 gives the characteristics of commonly used thermocouples.

**Thermistors.** Thermistors are nonmetallic sensing elements that display a large change of resistance with a small change in temperature; the resistance usually decreases as the temperature increases. They are available in the range of −73°C to 150°C, and must be selected to match the desired temperature. The large change in resistance allows small changes in temperature to be accurately measured. Figure 14 gives characteristics for some common thermistors.

**Resistance Temperature Detectors.** Resistance temperature detectors (RTDs) can be made of any metal that shows a

**Table 6. Temperature Sensor Characteristics**

| Sensor Type | Signal | Accuracy | Response | Mechanical Durability | Interchangeability | Stability | Range |
|---|---|---|---|---|---|---|---|
| Thermostat | On–off | Fair | Fair | Good | Good | Fair | Limited |
| Thermocouple | mV | Good | Excellent | Excellent | Very good | Good | Broad |
| Thermistor | kΩ | Very good | Very good | Fair | Good | Very good | Narrow |
| RTD | Ω | Excellent | Good | Excellent | Very good | Excellent | Broad |
| Pyrometer | mV, mA | Fair | Excellent | Good | Fair | Fair | Broad |
| Heater element | Ω | Good | Fair | Excellent | N/A | Fair | Broad |

change of resistance with temperature, but platinum is the metal of choice for high-accuracy RTDs. Figure 15 shows the resistance-versus-temperature characteristics for a platinum RTD manufactured to international standards. Note that the resistance is 100 Ω at 0°C. Thermistors change resistance much more rapidly that RTDs, allowing them to reflect smaller changes in temperature, but the repeatability and tolerances of RTDs are much better.

**Pyrometers.** Pyrometers measure the radiant energy emitted from a surface and determine the surface temperature from this measurement. Their advantage is that they do not have to contact the surface to measure its temperature. The accuracy is dependent on the calibration for surface emissivity and an unrestricted line of sight to the surface.

**Heater Elements.** Heater elements made from materials that change resistance with element temperature can be used as temperature-sensing elements for the system (7,10). This has the advantage of requiring no separate sensing element and wiring. In most systems the element temperature can be related to the work temperature.

Figure 16 shows some common materials that have been used as temperature sensors in appliances and for pipeline heating. Self-limiting (SL) cable is the cable of choice for most pipeline heating installations up to a maintain temperature of 120°C and circuit lengths of 75 m or less. The nickel–iron (Ni–Fe) alloy is suitable for longer circuit lengths and higher temperatures when properly insulated, and is used in appliance heaters for much higher temperatures. Copper has been used in pipeline heating circuit lengths up to 1.6 km (1 mi) long.

### Monitoring

It is usually a requirement for heater systems that there be some form of monitoring to allow the user to evaluate effectiveness.

**Switch Position.** The switch position will indicate when the heater is energized, unless there is a circuit failure.

**Lights.** Lights can be arranged to indicate that there is voltage to the circuit or voltage to the heater. They will not indicate a failure in the heater itself.

**Ammeter.** Ammeters indicate the power being drawn by the system.

**Temperature Meter.** Measuring the temperature of the system indicates the status of the property usually being controlled. The temperature is usually measured in only one place, which should be carefully selected to reflect the status of the whole system. When temperature is the control feedback, adding a readout is usually economical.

**Ground Leakage Currents.** All heating systems will have capacitive leakage currents to ground. If these currents are monitored, they will indicate incipient failures by an increase.

## SAFETY AND ELECTRICAL HEATING

### Burn Hazards

Electrical heaters have a special hazard compared to other electrical equipment: high surface temperatures. It is generally accepted that 60°C is the maximum temperature a person can contact without damage. Most heaters must operate well above that temperature if any significant heat is to be supplied. Heaters should be isolated or insulated to prevent personnel contact. Even when deenergized, some heaters will remain hot for a long time. The best protection for personnel is awareness.

### Shock Hazards

Electrical heaters are more likely to present a shock hazard to personnel than other equipment for several reasons:

**Table 7. Thermocouple Characteristics**

| | Temperature Range | Materials | | ANSI Color Code Extension Grade Wire | | |
|---|---|---|---|---|---|---|
| Type | (°C) | + | − | + | − | Jacket |
| T | −185 to 260 | Copper | Constantan | Blue | Red | Blue |
| J | −18 to 760 | Iron | Constantan | White | Red | Black |
| E | −185 to 870 | Chromel | Constantan | Purple | Red | Purple |
| K | −18 to 1260 | Chromel | Alumel | Yellow | Red | Yellow |
| R | −18 to 1480 | Pt + 13% Rh | Pt | Black | Red | Green |
| S | −18 to 1480 | Pt + 10% Rh | Pt | Black | Red | Green |
| B | −18 to 1650 | Pt + 6% Rh | Pt + 30% Rh | Gray | Red | Gray |

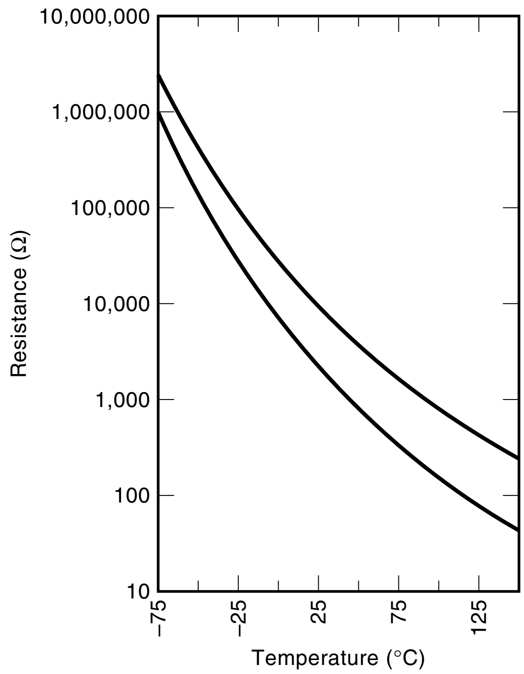


**Figure 14.** The resistance variation with temperature of two commonly available thermistors for use as temperature sensors

- The heater insulation must transfer heat as well as prevent transfer of electricity, conflicting requirements that sometimes reduce the electrical insulation value.
- Heaters must be close to the work to be heated, and thus are exposed to untrained personnel.
- Heaters often use local controls, exposing them to untrained personnel.
- Connections must be made in a high-temperature environment, making them more likely to fail.

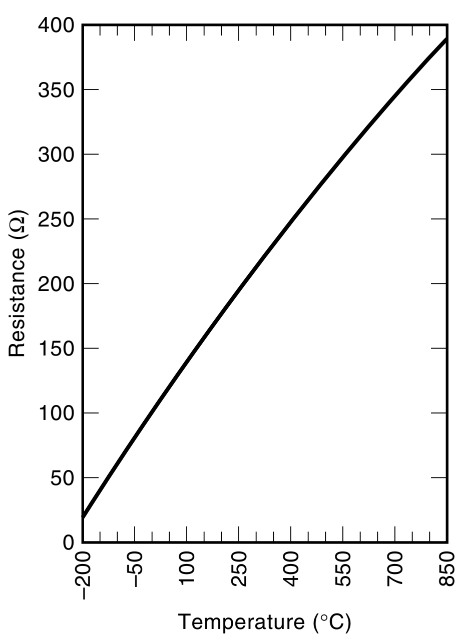


**Figure 15.** Variation of the resistance of a platinum resistance temperature detector (RTD) with its temperature

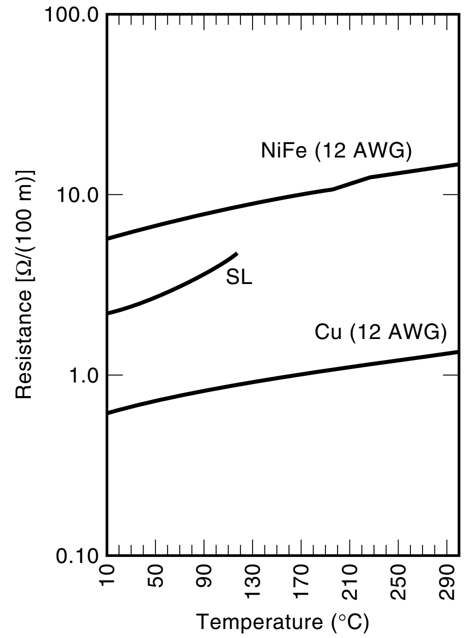


**Figure 16.** Variation of the resistance of 100 m of one type of self-regulating cable and 12 AWG nickel–iron and copper wire with temperature

**Voltage.** Voltage applied to heaters should always be the minimum required to provide the proper heat. Vendors have wide latitude in designing elements for different voltages. Insulation resistance requirements for heaters are usually set at 10 MΩ to 20 MΩ, which compares unfavorably with the requirements of general-purpose equipment for hundreds of megohms.

**Fire Hazards.** Most electrical heaters are constant-power devices. As long as voltage is provide to the heater, the heater temperature will rise until it is able to dissipate all the heat generated. When heaters are placed in a position where they can not dissipate the heat, the temperature will rise until it ignites a fire. Care must be taken not to prevent the dissipation of heat or to mount near flammable materials.

Another source of fires is a fault to ground in some portion of the heater, where the portion of the heater still in service restricts current to something less than that required to trip circuit overcurrent protection. Ground fault protection of the circuit will eliminate this hazard and is required by the NEC (8), Sec. 427-22 for fixed electrical heating equipment for pipelines and vessels.

**Hazardous (Classified) Areas.** Many industrial heaters have to be mounted in hazardous areas to accomplish their task. The following sections of the NEC (8) should be followed.

- Sections 501-10(a) where volatile flammable liquids or gases can normally exist (Class I, Division 1); 502-10(a) and (b)(1), where combustible dusts can be present (Class II); 503-8(a), where easily ignitable fibers are stored or handled (Class III): heaters must be approved for the appropriate class and division. Approval can be granted by an independent testing laboratory by a local code-enforcing agency, or in some industrial facilities by the responsible engineer.

- Section 501-10(b)(1), where volatile flammable liquids or gases are in the area but normally confined (Class I, Divison 2): the heater shall conform with either (a) or (b) below:
  (a) "The heater shall not exceed 80 percent of the ignition temperature in degrees Celsius of the gas or vapor involved on any surface which is exposed to the gas or vapor when continuously energized at the maximum rated ambient temperature. If a temperature controller is not provided these conditions shall apply when the heater is operated at 120 percent of rated voltage."
  (b) "The heater shall be approved for Class I, Division 1 locations."

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