

## Wire alloys and their use in electrical resistance furnaces

This article reviews a variety of wire alloys that can be used as heating elements for electrical-resistance furnaces, noting which ones make most sense for a given application and why.

By James Brocklehurst

This presentation looks at the use of wire alloys in electrical resistance furnaces, but it is fitting to begin by noting that wire-wound electric furnaces have been in commercial use for more than a century and as a concept for nearly two centuries.

An article by R.C. Mackenzie in the October 1982 issue of *Platinum Metals Review*, "The Story of the Platinum-Wound Electrical Resistance Furnace," notes that circa 1815, an Englishman, William Pepys, used soft iron wire powered by a large battery to heat iron and diamond powder to see if he could create steel. Mackenzie also cited Frenchman Georges Charpy, who in 1893 constructed a platinum-wound furnace that was used in studies of annealing and physical properties of brass. By 1894 he had developed a unit that was capable of operating between 500°C and 1300°C. The article also lists William Candler Roberts-Austin as using an iron wire furnace for thermocouple calibration in 1897. In 1899, the team of Holburn and Day were using a unit for the same application that employed nickel wire. Mackenzie attributes the first com-

mercial platinum wire furnace to a German firm, W.C. Heraeus, around 1900, with the company advertising a platinum ribbon-wound unit in 1902 that could heat to 1400°C in 5 minutes, run at 1500°C for hours and could reach 1700°C for short periods. In the roughly 200 years since inception, resistive electric furnaces have seen many advances in controls, insulation and heating materials but the basic concept is fairly close to that first recorded system used by Pepys: a resistance heater, electrical current, some insulation and a product to be heated. With this in mind, what follows is a review of the various wire alloys typically used today on a commercial basis, along with their advantages and limitations.

### Overview of materials

A variety of materials are available for use as heating elements in the field of electrical resistance heating. They range from metallic alloys through ceramic-metal based and graphite/carbon materials. However, even though some of the cermet (a strong alloy of a heat-resistant com-

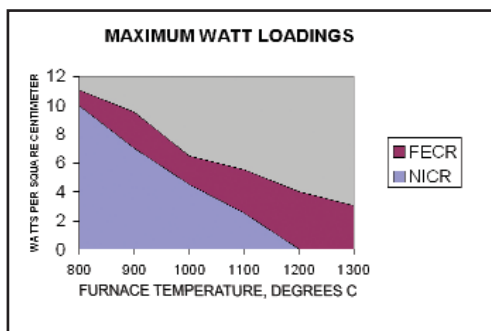


Fig. 1. Comparison of maximum watt loadings for FeCr and NiCr materials.

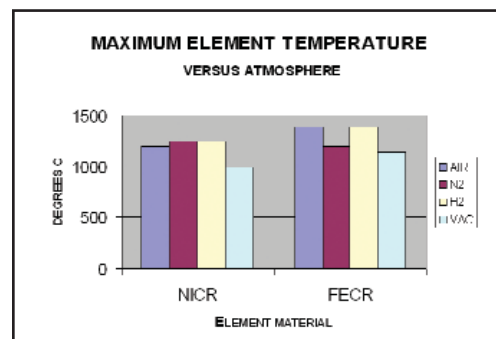


Fig. 2. Maximum element temperatures for FeCr and NiCr materials.

pound) are available in what could be construed as being a wire form, this article will concentrate on traditional wire metallic alloys, the most common being nickel-chrome (NiCr), iron-chrome-aluminum (FeCr), tungsten, molybdenum, tantalum, platinum and platinum-rhodium alloys. These alloys typically are categorized into materials that can work in the presence of oxygen and those that must be protected from oxygen, the latter category including tungsten, molybdenum and tantalum. This restriction somewhat limits use of these materials (as does the cost of platinum-based or precious metal alloys), so they are only given a cursory examination here as the focus is on the more common nickel-chrome and iron-chrome-aluminum materials.

Much of the information presented in this paper comes from available sales literature and specification sheets such as those published by Kanthal AB, Hallstahammar, Sweden; Thermcraft Inc., Winston-Salem, North Carolina, USA; and others.

A brief explanation of how these materials function, their limitations and basic design considerations, will provide the reader a basic understanding as to why a given material was chosen for a given application. It should be noted that a variety of factors not covered in this paper could affect operational characteristics of these materials: therefore, the reader is urged to contact a reputable furnace vendor to discuss any specific applications they might have.

Factors that should be examined in choosing a heating element include temperature, atmosphere, life and power or the required heat-load. The temperature referred to is actual element operating temperature, which is based on the inter-relationship of furnace temperature, element watt loading and the ability of the element to radiate the heat generated. Design information, available from a variety of sources, shows the effects of element placement on radiation ability and the relationship of furnace temperature versus element watt loading. An energized element always operates at a higher temperature than its surrounding “ambient” temperature. The higher the watt loading, the greater the temperature differential or “head” generated. As the furnace temperature increases, the watt loading must

decrease to prevent element overheating. Fig. 1 shows this relationship for freely radiating elements in air.

Atmosphere is important in that at increasing temperatures, materials react differently to various compounds. A system that works very well at one temperature in air, may fail quickly if applied in a different atmosphere at the same temperature. Fig. 2 shows the maximum element temperatures in various atmospheres for freely radiating elements.

Service life of the element is also an important economic consideration. One must determine whether the elements are to last for years, months or weeks. With any given element, the higher its operating temperature, the shorter its lifetime. Thus, for a long life, it is implied that the element should have a low head temperature with respect to furnace temperature. This is accomplished by decreasing the watt loading. The downside of this equation is that when lowering the element loading, one may need to add more elements to meet the heat load requirements of the furnace. These additional elements yield higher initial cost, and their number may be restricted due to space limitations in the furnace. This restriction may dictate conversion to a higher power/temperature rated material not covered in the scope of this paper.

Finally, consider the power or heat load requirements of the furnace. The power required is determined by process temperature, amount of material to be heated, heating rates and furnace losses. Restrictions are normally placed on the amount of power (KW or kilowatts) that can be placed on the furnace walls.

These restrictions are based on element configuration, placement, material type, and furnace temperature.

Fig. 3 shows this relationship for a freely radiating iron-chrome-aluminum element (ROB), versus one housed in grooves in the furnace wall.

### Review of materials

A general review of materials indicates their advantages and limitations.

*Metallic alloys.* These materials (nickel-chrome and

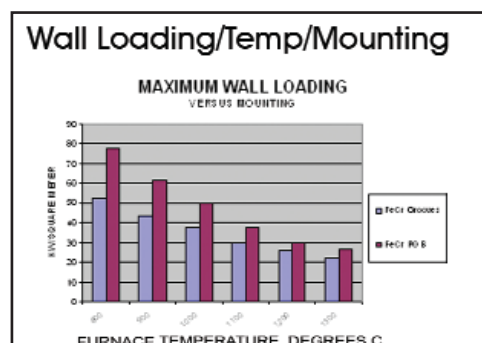


Fig. 3. Relationship between wall loading and mounting for FeCr and NiCr materials.

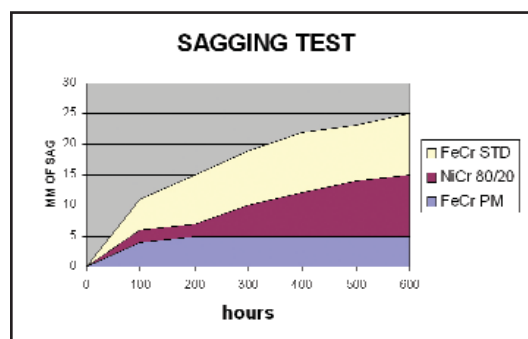
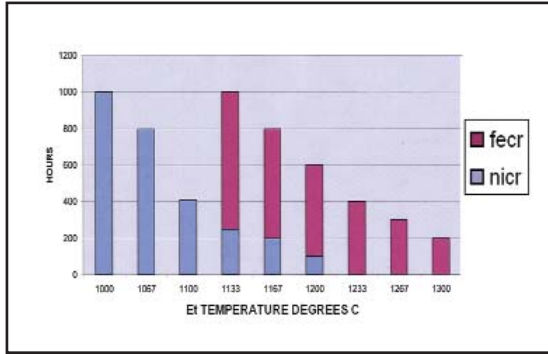


Fig. 4. Sag Test comparison for APM, FeCr and ASTM-grade NiCr material



**Fig. 5. Life Index comparison of NiCr and FeCr materials.0**

iron-chrome-aluminum) are often the easiest to use and the least expensive. Unfortunately, they also have the lowest operating temperature in an oxidizing atmosphere.

Metallic alloy materials are fairly rugged with respect to mechanical and thermal shock. Their resistance remains relatively constant in relation to element temperature and service life. These two factors combine to produce a product that is very easy to control, yielding what is generally a rather simple and inexpensive power supply. This fact, in turn, can have a significant effect on the overall capital costs of a project, making this class of materials very attractive.

Thermal cycling does not present a significant problem. Most of these alloys are available in wire, strip, rod and tube forms. Typical element configurations are coils, either in grooves or on ceramic tubes; a free radiating design commonly referred to as an ROB or sinuous loop element; or as part of a packaged system in which the alloy is either embedded in or mounted on an insulation or ceramic panel for mounting on furnace walls, floors or roofs.

*Nickel-chrome alloys.* These groups of alloys are among the oldest electrical heating materials and are still widely used today. They are fairly ductile, have good form stability, and hot strength. The three most common compositions used for heating applications are ASTM “A” grade (80% nickel, 20% chromium), ASTM “C” grade (60% nickel, 26% chromium, balance iron), and ASTM “D” grade (35% nickel, 20% chromium, balance iron). There is a fourth, rather recent, alloy gaining widespread use that has a typical mix of 70% nickel and 30% chromium. It should be noted that the above ASTM grades are specified minimum mixtures and the actual alloy compositions can vary widely among vendors. Of these various alloys, the 70/30 material is listed as having the highest maximum element temperature of 1250°C in air, and in most cases would be limited to a maximum chamber temperature of 1150°C. It generally has poorer ductility than the more common ASTM “A” grade alloy, and was developed primarily to combat “Green rot” (an intergranular oxidation of chromium experienced by other ASTM grades of nickel-chrome materials

when used in either exothermic or endothermic atmospheres in the temperature range of 1500 to 1800°F). As indicated, the ASTM “A” grade material is the more common alloy and is limited to a maximum element temperature of 1200°C with a maximum chamber temperature of 1100°C.

This is the material listed as NICR in the enclosed charts and graphs. The “C” grade material is rated for 1125°C with chamber temperatures typically 1000°C maximum. The “D” grade is listed at 1100°C with chamber temperatures around 950°C maximum.

*Iron-chrome-aluminum.* These alloys are typified by a composition of 72.5% iron, 22% chrome and 5.5% aluminum. The higher grades made by traditional melt technology have limiting temperatures of 1400°C on the element with chamber temperatures typically 1300°C. There are other grades available with lower use temperatures in which the aluminum content has been reduced and the balance is made up with iron. These alloys were introduced in Scandinavia in the early 1930s and their use as a replacement material for nickel-chromes has been on the increase. Iron-chrome-aluminum alloys typically have a higher use temperature, higher resistance and lower density than nickel-chromes. Generally, when properly applied, these features yield a less expensive, longer-lived element than a comparable nickel-chrome design. On the down side, Iron-chrome-aluminum alloys suffer from a lower hot strength, reduced ductility, and embrittlement with use.

*Iron-chrome-aluminum, PM grades.* In the past few years, iron-chrome-aluminum alloys have been introduced that use powder metal (PM) technology in their manufacturing process. Typically, these materials start with a high-grade iron-chrome-aluminum alloy made by conventional melt technology. The resulting ingot is then turned into a powder and compressed into a billet, either by a hot isostatic press or, more rarely, a cold isostatic press operation. This billet is then used to produce the final wire, strip or tube product. The advantage gained by this extended and fairly expensive process is that an iron-chrome-aluminum product has greatly improved hot strength and a higher end-use temperature. In one case, the resultant maximum element temperature is listed at 1425°C while the parent alloy is listed at 1400°C.

Fig. 4 shows the results of a sag test comparing one of these powder metal-based, iron-chrome-aluminum alloys (APM), a standard high temperature iron-chrome-aluminum (FECR) and an ASTM Grade “A” nickel-chrome (NICR) material. The tests were performed on 4 mm diameter rods in a horizontal position, supported at 200 mm intervals and exposed to 1200°C. The results are shown in millimeters of sag plotted on the vertical axis against time on the horizontal axis. As indicated, the PM grade material is superior to its parent alloy.

## Oxide formation

One of the most important considerations in the use of any heating material is reaction with oxygen at elevated

temperatures. With some materials—such as molybdenum, tungsten or graphite—this oxidation process continues until the material is consumed.

In other materials, a protective oxide layer forms which, unless disturbed, inhibits further oxidation and may offer protection against attack by other compounds. Oxide formation is dependent on time and temperature. Generally, for iron-chrome-aluminum alloys, temperatures above 1000°C should be used to ensure a good oxide formation; while for nickel-chrome alloys, 800 to 900°C should suffice.

*Nickel-chrome.* This material forms a chromium oxide layer when heated in the presence of air. The oxide layer is relatively thick and greenish in color and has a propensity to flake off during cycling. This flaking exposes the base metal to further oxidation. Eventually the chrome is depleted, leading to element failure. This flaking can also lead to product contamination unless the elements are either located in such a position that falling oxide will not land on the product or the elements are encased in protective tubes. The oxide offers little protection against carbon infiltration and is highly reactive to sulphur.

*Iron-chrome-aluminum.* These alloys form an oxide comprised mainly of alumina ( $\text{Al}_2\text{O}_3$ ). Like the chromium oxide, iron-chrome-aluminum oxide is very stable. However, it has one very important difference. It is very thin and adheres tightly to the base metal, making it less likely to flake off and lead to product contamination. As the element is thermally cycled, small cracks may develop in the oxide, which eventually will lead to aluminum depletion in the base metal. Generally, this aluminum depletion occurs at a much slower rate than the chromium depletion in nickel-chrome materials of similar configuration. The oxide is very resistant to carbon infiltration and is particularly stable in the presence of sulphur. The oxide is also an excellent electrical insulator, which is beneficial should element sections inadvertently touch. This situation can be disastrous in the case of chromium oxide-protected materials.

*Element life.* As mentioned, element life is based on factors such as temperature, atmosphere, mechanical shock, and chemical attack. Because of differences in mounting, operating cycles and other variables, it is difficult to give an accurate figure for the life of a given element.

*Metallic alloys.* In general, the flaking of the chromium oxide on nickel-chrome materials has a greater effect on base material depletion than the cracking of the alumina oxide on iron-chrome-aluminum materials. This, coupled with a higher use temperature, indicates that in oxidizing atmospheres, for a given watt loading, atmosphere composition, and furnace temperature, the iron-chrome-aluminum material should last longer. Fig. 5 shows a “life index” for the two alloys in air.

Although it cannot be directly translated into hours, an element with a life index of 400 should last twice as long as elements with a life index of 200.

## Packaged systems

The above discussion has been based on “free standing” elements that are designed for mounting independently of the insulation system. Various systems are available that combine the elements and a suitable insulation package in one unit. Generally, these systems use either nickel-chrome or iron-chrome-aluminum alloys for elements. The standard shapes are cylindrical, half rounds or flat panels in a variety of sizes, power and voltage. General construction is either a cast/pressed ceramic support with an optional insulation package or a vacuum cast form that provides both support and insulation. Maximum chamber temperatures range from 1100 up to 1400°C for specialized packages with rather stringent operating limitations. Wire can also be found inside metallic sheath heaters (a type of a package system) without the insulation panels normally associated with the packaged system concept.

*Oxygen-sensitive materials.* As indicated, these materials include molybdenum, tungsten, tantalum and graphite. Oxygen-sensitive materials can have fairly high use temperatures and watt loading as long as they are protected from exposure to oxygen by either an inert atmosphere or proper vacuum levels. These items all exhibit substantial increases in resistance with increasing temperature. This characteristic dictates using a power supply that can limit current to protect the elements as well as the furnace and power supply from excessive power during cold start up conditions. Several of these items also exhibit sensitivity to both mechanical and thermal shock. An unfortunate aspect of most applications using these materials is that even for those items not particularly susceptible to thermal or mechanical shock, they use support and structural components that are. Therefore a slow, controlled ramping function from one operational set point to another is desirable.

Finally, most of these materials operate at levels lower than available standard line voltages. This generally translates into a fairly high amperage requirement from the power supply. All these characteristics indicate the need for a complex and expensive power supply.

*Molybdenum.* This material was first used in industrial furnaces around 1930 with increasing usage after 1940. It is available in many forms with the most common element shapes being wire, rod, strip, and on occasion, tubes.

Molybdenum has a strong affinity for oxygen at elevated temperatures and can only be heated in the presence of a vacuum, reducing (dry hydrogen or cracked ammonia), or pure inert atmosphere. This material starts to oxidize between 250 to 300°C with the formation of molybdenum dioxide ( $\text{MoO}_2$ ), which will offer a limited amount of protection against further oxidation up to approximately 600°C. The molybdenum dioxide then converts to molybdenum trioxide ( $\text{MoO}_3$ ), which becomes dominant.

Molybdenum trioxide is very volatile and readily boils off, exposing the base metal to further oxidation. At around 800°C catastrophic oxidation occurs with clouds of molybdenum trioxide being generated. In regard to atmosphere purity, an argon atmosphere containing 45 to 50 PP of oxy-

gen will lead to rapid oxidation of molybdenum at temperatures around 1200 to 1300°C. Decreasing the oxygen content to 4 to 5 PP should lead to a successful application. In general, to prevent oxidation problems, never expose molybdenum to oxygen at temperatures over 400°C.

As indicated earlier, molybdenum has a rather significant increase in resistance from room temperature to operating temperature. Depending on specific composition, this increase could be on the order of ten (10) times or more from 20°C to 1900°C.

Most common forms of molybdenum are made from a powder that is compressed and then either extruded, drawn or molded into the desired shape. When new, the material is fairly ductile and easy to work with. However, when molybdenum has been heated to around 950°C to 1000°C it starts to re-crystallize and at 1500°C spontaneous crystal growth occurs. While at temperature, the material remains ductile but once cooled, this crystal growth phenomenon causes the material to become quite brittle. Depending upon the actual temperature reached and time spent at temperature, the ductile to brittle transition point can range from as low as 20°C for unheated material up to 150°C for completely re-crystallized molybdenum. Thus, after heating, molybdenum becomes very sensitive to both mechanical and thermal shock.

When properly applied, molybdenum can be used in applications having chamber temperatures up to 1900°C. However, it experiences a sharp reduction in strength and hardness at elevated temperatures. The creep strength is also strongly dependent on temperature. These characteristics indicate the requirement for a significant amount of physical support for the elements to ensure proper operation. Unfortunately, molybdenum also has a marked propensity to react strongly with many common furnace ceramics at elevated temperatures, leading to element failure. As a result, firebrick is typically limited to a maximum of 1200°C when used with molybdenum while very pure  $Al_2O_3$  has a history of very successful usage at 1700°C. When used with high purity  $Al_2O_3$  ceramic panels, molybdenum can be supplied as part of a prepackaged system.

This material is commonly used in dry hydrogen, dry cracked ammonia and very pure inert (argon or helium) atmospheres to 1900°C and, in some instances, even higher temperatures. In vacuum levels of less than  $10^{-2}$  torr molybdenum can be used to 1700°C but in high vacuum applications, such as less than  $10^{-4}$  torr, molybdenum evaporation becomes considerable between 1600 to 1700°C and excessive around 1800°C. Oxidation is also a problem around 700°C when exposed to water vapor and at 1000°C in the presence of carbon dioxide ( $CO_2$ ). Carbon monoxide (CO) and many hydrocarbons will cause surface carbonization starting between 1000 to 1200°C.

Molybdenum can be supplied in a prepackaged form which uses high purity aluminum ceramic plates.

*Tungsten.* Tungsten exhibits many of the same characteristics as molybdenum in its electrical, mechanical, chemical and thermal properties. It is available in the same gen-

eral physical forms as molybdenum. Tungsten is somewhat less ductile than molybdenum and is therefore harder to work with. It has embrittlement, mechanical and thermal shock problems that are caused by the same re-crystallizing process that effects molybdenum.

One important difference is a much higher melting point for tungsten. This yields both higher use temperatures and higher vacuum levels than are possible for molybdenum. When correctly applied with the above defined reducing and inert atmospheres, maximum use temperatures of 2500°C are quite common. In vacuum levels of less than  $10^{-2}$  torr it can be used up to 2000°C. In levels of less than  $10^{-4}$  torr strong tungsten evaporation occurs around 2400°C and above. Oxidation starts around 500°C with catastrophic oxidation occurring around 1200°C.

*Tantalum.* Tantalum can only be heated in an inert atmosphere or in a vacuum of less than  $10^{-4}$  torr. This substance shows a strong affinity for bonding with many of the gas molecules found in common industrial heating atmospheres. When heated in the presence of hydrogen, oxygen, nitrogen or carbon, both gas absorption and chemical reactions occur, leading to the formation of hydrides, oxides, nitrides, or carbides. These reactions result in tantalum erosion and/or embrittlement. Of these compounds, the hydride formation is reversible so that heating in a high vacuum can soften tantalum that has become brittle due to exposure to hydrogen. To some extent, tantalum oxide can also be removed in a similar fashion, because of its high vapor pressure characteristic.

Since it has a high reactivity to certain gasses and the fact it can be somewhat “recycled” in addition to being used as heating elements and heat shields, tantalum is often used as a “getter” in critical applications.

Tantalum is very ductile and, if protected from exposure to the above-mentioned gases, it maintains this ductility even after repeated heating and complete re-crystallization. Therefore, mechanical shock is generally not a concern unless getter usage or improper usage has led to the described gas embrittlement phenomena.

When used in vacuum levels of less than  $10^{-4}$  torr, tantalum can be used up to 2400°C. Above this point, strong evaporation occurs. Use as a heating element in vacuum levels of less than  $10^{-2}$  torr is not recommended due to tantalum’s strong getter action. In very pure argon or helium atmospheres, tantalum can be used up to 2400°C.

It should be noted that tantalum is very expensive compared to either molybdenum or tungsten. An average price is approximately one half of that currently listed for platinum. Therefore, except for specialized or very restrictive applications, tantalum’s usage is somewhat limited by economic considerations.

*Precious metals.* This category’s most common metals are pure platinum, platinum/rhodium alloys, and on occasion pure rhodium. They all experience significant increases in resistance with temperature. Depending upon the alloy, these increases can range from just below three times to five times when comparing 20°C and 1500°C readings.

These resistance changes can result in excessive amperages being drawn during cold startup conditions unless proper care is taken. Although the metals are not overly sensitive to rapid thermal cycling, many of their support structures used in the actual furnace are. This indicates the desirability of a ramping function in the control system when making changes in the operating temperature set points. Any power supply must be able to limit amperage to design specifications and should have the ramping function to protect the entire system against damage.

Pure platinum has a rather low melting temperature (around 1770°C), suffers from a rather high vapor pressure, and is prone to losing material through oxide volatilization at high temperatures. Typical use temperatures for pure exposed platinum are listed around 1450°C. By embedding the platinum in approved refractory cement, it is possible to reduce metal and oxide losses. This allows for an increase in operating temperatures, typically up to 1600°C on a regular basis and up to 1700°C in special cases with very stringent operating parameters. Pure platinum becomes brittle with use due to grain growth, which occurs above 1600°C element temperature. Rhodium has a higher melting point (approximately 1960°C), improved vapor pressure and oxide evaporation rates, significantly better hot strength, and a higher temperature for grain growth inception. Although these features would indicate pure rhodium would be the better choice for heating elements, its very poor ductility and adverse resistance curve makes it very difficult to work with. By alloying various percentages of rhodium with platinum, it is possible to create new compounds with marked improvements in use temperature, vapor pressure, oxidation rates and brittleness with some degradation in ductility when compared to pure platinum. Standard alloys typically contain 10, 20, 30 or 40% rhodium with a platinum balance. These alloys have published use temperatures of 1550, 1650, 1720 and 1770°C respectively, compared to 1450°C for pure platinum and 1850 to 1900°C for pure rhodium. The 10 and 20% rhodium/platinum alloys are most commonly used because of ductility, temperature and cost.

Due to the high cost of these materials, their usage for heating elements is on the decrease as less expensive solutions become available. Main areas of usage tend to be in small research and development equipment and specialized applications in the glass industry.

## Summation

The proceeding discussion concentrates only on the more common forms of wire heating elements for industrial applications. As can be seen, there are many options available and there may be multiple good choices depending on the desired application.

While this paper discusses use of wire for use as heating elements in the field of electrical resistance heating, it would be remiss to not mention other uses for wire products in furnaces in general. Wire is often used as reinforcing in cast refractory parts such as lentils or vestibules. It is

also used to support either insulation panels, packaged systems, or in many cases, the heaters themselves. From these internal furnace parts, one could also consider their use for baskets used to hold parts, woven wire for mesh belts and hangers for conveyor systems. In short, the use of wire in the electrical furnace is legion and has been so for nearly two centuries. ■



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