NICEL CHROMIUM ALLOYS FOR ELECTRIC RESISTANCE HEATING

No. 10041


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Design with confidence: select a nickel-chromium alloy heating element

by John Milne and Roger Giler

The family of nickel-chromium (Ni-Cr) alloys has a long and successful history with heating element applications dating back to the early 1900s. Thus the actual field experience of appliances and industrial furnaces provides a base for confidence in the use of these alloys, for new and existing design applications.

Primary producers of the nickel-chromium family of alloys in North America, Europe and Japan include:

**North America**

**Europe**
- British Driver-Harris Ltd., United Kingdom and Italy; Deutsche Nickel AG, West Germany; Imphy SA, France; Inco Alloys Ltd., United Kingdom; Kanthal AB, Sweden; Thyssen Edelstahlwerke AG, West Germany; and VDM Vereingte Deutsche Metallwerke AG, West Germany.

**Japan**
- Furukawa Special Metal Corp.; Nippon Metal Industry Co., Ltd.; Riken Corp.; Sumitomo Special Metals Co., Ltd.; Taihei Metal Industries Co., Ltd.; and Totoku Electric Co., Ltd.

There are also other manufacturers that do not melt the alloys but roll and draw them from material melted by others.

The experience of these suppliers is available to you for guidance in the selection of the appropriate grade of the nickel-chromium alloy for specific applications.
Introduction to resistance heating alloys

Materials for electric heating depend upon an inherent resistance to the flow of electricity to generate heat. Copper wire does not get appreciably hot when carrying electricity because it has good electrical conductivity. Thus for an alloy — as wire, ribbon, or strip — to perform as an electric heating element, it must resist the flow of electricity.

Most of the common steels and alloys such as stainless steel do resist the flow of electricity. The measure of this characteristic is termed Resistivity. In North America the convention is to use ohms/CMF (ohms per circular mil ft) to express resistivity, and this notation has been used in the data that follow. The technically correct designation would be ohm cmil/ft or ohm times circular mils per foot. In Europe, the most common unit of resistivity is ohms mm²/m (ohm millimetre square per metre).

If resistivity alone was the prime factor for an electric heating element, the choice could be from many alloy candidates in a broad spectrum of cost. By its very nature, however, an electric heating element does get hot — usually red hot — and the common alloys will simply not endure that heat for long. It fails and this is termed to be poor life as a heating element.

Families of alloys were developed many years ago with a proper blend of two specific properties:

1. High resistivity (resistance to flow of electricity)
2. Good life, or endurance capability as a heating element

These families of alloys can be classified in six main groups. While all of the alloy families are listed for completeness, this report deals only with the nickel-chromium alloys. This is because they are, by far, the most widely used in the U.S. and Canada. They are listed by family, with the main grades shown, including their composition and resistivity. Please see Table 1.

A listing of the applicable specifications from the American Society for Testing and Materials (ASTM) is presented in Table 2.
### Table 1

**Materials used for electric heaters**

#### Nickel-chromium:
- **A-Grade**: 80 Ni 20 Cr, 650 Ω-CMF
- **70-30**: 70 Ni 30 Cr, 710 Ω-CMF
- **C-Grade**: 60 Ni 16 Cr balance Fe, 675 Ω-CMF
- **D-Grade**: 35 Ni 20 Cr balance Fe, 610 Ω-CMF

#### Iron-chromium-aluminum*:
- **875 Alloy**: 22 Cr 5 Al balance Fe, 875 Ω-CMF
- **815 Alloy**: 22 Cr 4 Al balance Fe, 815 Ω-CMF
- **750 Alloy**: 15 Cr 4 Al balance Fe, 750 Ω-CMF

#### Copper-nickel: for low-temperature use
- **300 Ohm Alloy**: 45 Ni, balance Cu, 300 Ω-CMF
- **180 Ohm Alloy**: 22 Ni, balance Cu, 180 Ω-CMF
- **90 Ohm Alloy**: 11 Ni, balance Cu, 90 Ω-CMF
- **60 Ohm Alloy**: 6 Ni, balance Cu, 60 Ω-CMF
- **30 Ohm Alloy**: 2 Ni, balance Cu, 30 Ω-CMF

#### Stainless, Monel & miscellaneous: for relatively low-temperature use
- **Nickel-manganese**: 94 Ni 5 Mn, 102 Ω-CMF
- **Pure nickel**: 99.98 Ni, 45 Ω-CMF
- **Monel**: 67 Ni 30 Cu, 290 Ω-CMF
- **Nickel-silicon**: 3 Si balance Ni, 190 Ω-CMF
- **UNS S 30400**: 18 Cr 8 Ni balance Fe, 433 Ω-CMF

#### Alloys for vacuum operation:
- **Molybdenum**
- **Tungsten**
- **Tantalum**: Large resistivity change with temperature

#### Nonmetallic materials for special applications:
- **Silicon carbide**
- **Molybdenum disilicide**
- **Lanthanum chromite**

*The numbers 875, 815 and 750 refer to the room-temperature resistivity of the alloy.*
Table 2

American Society for Testing and Materials — specifications

B-63 Resistivity of metallically conducting resistance and contact materials
B-70 Test method for change of resistance with temperature of metallic materials for electric heating
B-76 Method of accelerated life test of nickel-chromium and nickel-chromium-iron alloys for electric heating
B-78 Method of accelerated life test of iron-chromium-aluminum alloys for electric heating
B-344 Specification for drawn or rolled nickel-chromium and nickel-chromium-iron alloys for electrical heating elements
B-603 Specification for drawn or rolled iron-chromium-aluminum alloys

Alloys and Properties

To be useful as an electrical heating element, a material must have the following characteristics:

[a.] A fairly high electrical resistivity, so that the cross section need not be unduly small.
[b.] Good strength and ductility at operating temperatures.
[c.] A low-temperature coefficient of resistance so that resistance at operating temperature does not deviate too greatly from that exhibited at room temperature.
[d.] Good resistance to progressive oxidation in air during intermittent operation.
[e.] Good workability and capacity for being formed into the desired shape.

Four basic compositions have been found to have these desired characteristics — 80 Ni, 20 Cr; 70 Ni, 30 Cr; 60 Ni, 16 Cr, balance Fe; 35 Ni, 20 Cr, balance Fe). A comparison of the characteristics of these alloys is shown in Table 3.

Table 3

Basic average properties of the major nickel-chromium heating alloys in air

<table>
<thead>
<tr>
<th>Typical properties</th>
<th>A-Grade</th>
<th>70-30</th>
<th>C-Grade</th>
<th>D-Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNS number</td>
<td>N 06003</td>
<td>N 06008</td>
<td>N 06004</td>
<td>None</td>
</tr>
<tr>
<td>Maximum use (°C)</td>
<td>1 200</td>
<td>1 260</td>
<td>1 150</td>
<td>1 100</td>
</tr>
<tr>
<td>Maximum use (°F)</td>
<td>2 200</td>
<td>2 300</td>
<td>2 100</td>
<td>2 000</td>
</tr>
<tr>
<td>Melting temperature (°C)</td>
<td>1 400</td>
<td>1 380</td>
<td>1 390</td>
<td>1 390</td>
</tr>
<tr>
<td>Melting temperature (°F)</td>
<td>2 550</td>
<td>2 520</td>
<td>2 530</td>
<td>2 530</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>8.41</td>
<td>8.11</td>
<td>8.25</td>
<td>7.95</td>
</tr>
<tr>
<td>Density lb/in³</td>
<td>0.304</td>
<td>0.293</td>
<td>0.298</td>
<td>0.287</td>
</tr>
<tr>
<td>Specific heat Btu/lb/F</td>
<td>0.107</td>
<td>0.110</td>
<td>0.107</td>
<td>0.110</td>
</tr>
<tr>
<td>Tensile strength MPa</td>
<td>830</td>
<td>900</td>
<td>760</td>
<td>620</td>
</tr>
<tr>
<td>Tensile strength ksi</td>
<td>120</td>
<td>130</td>
<td>110</td>
<td>90</td>
</tr>
<tr>
<td>Yield strength .2% MPa</td>
<td>415</td>
<td>485</td>
<td>380</td>
<td>345</td>
</tr>
<tr>
<td>Yield strength .2% ksi</td>
<td>60</td>
<td>70</td>
<td>55</td>
<td>50</td>
</tr>
<tr>
<td>Elongation %</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Elongation %</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Reduction of area</td>
<td>% 55</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>
Developed and patented by A.L. Marsh in 1906, the first successful resistance alloy comprised 80% nickel, 20% chromium. This alloy is still widely used, although extensive research has led to some modifications of the basic composition. By the addition of small amounts of iron, manganese and silicon, and minute quantities of rare earths and other elements, compositions are available which can be used up to 1 200°C (2 192°F).

In the 1960s, the 70% nickel, 30% chromium composition was developed to provide improved life in air up to 1 260°C (2 300°F). It is also excellent in preventing preferential oxidation in the low oxygen atmospheres, a phenomenon commonly called green rot because of the green color of the oxide.

The alloy containing essentially 60% nickel-16% chromium-balance iron, is generally selected where operating temperatures do not exceed about 1 100°C (2 012°F), such as in electric flat irons.

An alloy — containing mainly 35% nickel, 20% chromium and the balance iron — has been developed primarily for industrial controlled-atmosphere furnaces operating in the 800°C to 1 000°C (1 472°F-1 832°F) range. This alloy has proved useful in combating the deterioration which may occur with the other two alloys when operated in the same temperature range in atmospheres that are reducing or fluctuate between reducing and oxidizing. The 80 nickel-20 chromium alloy can not be used in atmospheres that are reducing to nickel and oxidizing to chromium.

The Ni-Cr family of alloys — a detailed look

In reviewing the four major alloys in the nickel-chromium family, please compare their basic characteristics shown in Table 3. Additional information on all heating alloys may be found in Volume 3 of the American Society for Metals (ASM) Handbook. All of these heating alloys have good life if the heating element is properly designed with the correct alloy, wire size and coil configuration (for coiled wire elements).

Resistance alloy wire and strip product forms are generally supplied in the annealed condition, unless specifically requested otherwise. In the annealed condition, they are easily fabricated by coiling or bending. Satisfactory life as a heating element begins with the manufacture of the alloy, and further results from the proper care of the alloy — wire, ribbon or strip — while it is being fabricated into an element and installed into the end-use device. The nickel-chromium alloys are inherently corrosion-resisting (like stainless steels), but they can be detrimentally affected by certain circumstances and reasonable precautions must be taken to keep the elements clean. This aspect is covered in greater detail further on.

Types of resistance elements

There are many ways to use resistance elements. Here is a review of the most common methods and applications.

Wire or ribbon can be exposed or protected. An exposed heater transfers the heat more efficiently, allowing it to operate at higher temperature while at the same time requiring less material. On the other hand, it is not protected from outside effects such as corrosion and short circuits, and may present hazards of electrical shock for the user.

The method of mounting the wire or strip is of paramount importance. It can be suspended, supported or embedded. A typical suspension application would be in air heaters where a coil of wire is threaded through a series of doughnut-shaped beads supported by a wire frame.

Supported elements are used mostly in furnaces where continuous support is provided for the coil to rest upon, along the walls. In general, this supported type of heater is geared more toward the iron-base alloys (Fe-Cr-Al) which have little hot strength. They are more sluggish in thermal response because the supporting material also has to be heated. The prime reason for using these alloys is their lower cost.

There is a large class of heaters known as tubular or sheathed, where the wire is inside a stainless steel or heat-resisting alloy sheath. The wire is a small-diameter helix surrounded by magnesium oxide powder packed inside a tube. The powder provides the electrical insulation as well as the heat transfer by conduction to the outside. These heaters cover a broad spectrum — all the way from the highest grades used in range-top and oven applications to inexpensive small heaters for immersion in a cup of coffee. The latter typically use stainless wire coiled inside a fibreglass sleeve inserted into aluminum tubing.

Heater design concepts

There are a small number of general concepts, which when grasped, can take all the mystery out of the design of an electric resistance heater. Most are self-evident, but often forgotten.

Resistivity is a property of the material, while resistance is determined by the physical shape of the conductor. And resistance can readily be changed by varying the material cross-section.

Resistance wire is actually manufactured and sold on an ohms/foot basis. It is not manufactured to a specific gauge, although, in the U.S. and Canada, resistance wire is commonly specified by Brown & Sharpe (B&Ś) gauge, to obtain a nominal resistance value. The diameter is adjusted to take into account the minor variations in resistivity. Trying to specify both resistance and diameter is not a realistic or acceptable practice. When a gauge is specified, the corresponding resistance for that size is implied. Actual wire diameter variations from nominal are minimal.

It is the hottest part of a heating element that determines its life. Hot spots on the element can be caused by an accidental change in cross section (nicks, stretching, kinks), or frequently by shielding where the element cannot dissipate its heat freely. The hottest area will fail first, and this is why values such as average temperature, or even power density alone, cannot be used as a barometer of element life.

While wire is drawn to resistance, it is usually ordered in B&Ś gauges. These gauges are in a geometric progression. If the wire diameter is decreased by three B&Ś gauges, the resistance in ohms per foot doubles. If it is decreased by six gauges, the diameter will be exactly half the original.

Temperature, under similar external conditions, is directly affected by the surface area of the heater. It is determined by the ability of the material to dissipate the power. This will be
obvious by comparing the same wattage dissipated in a light bulb or in an electric blanket. The difference is in the area over which that power is spread.

On wire and strip, the concept of power density, often referred to as watts/in² is used. With a coil, there is a heating effect between the adjacent turns. The power density when the stretch ratio is less than three (two wire diameters between adjacent loops), is determined not by the wire surface area, which remains constant, but by the coil envelope area. This effect can be dramatically illustrated by using an almost close-wound coil of wire running extremely hot and progressively stretching it. It can be seen that the surface temperature reaches the point where the heat is no longer visible. In that case, the power density on the wire has not significantly changed, but the surface area of the coil has.

There are three ways in which heat leaves the heater: radiation, convection, and conduction. At the higher temperatures, radiation is the leading method of heat transfer. In furnaces operating over 900°C (1652°F), heat transfer by the other two methods can be ignored in the calculations.

In lower-temperature furnaces — often called ovens — convective heat transfer, using a fan that moves the atmosphere directly over the elements and the charge, is the most effective. In this case, effective means that the ratio of heat generated to the weight of material used is maximal, while the temperature gradient between heater and furnace load is minimal.

The most difficult heater to calculate theoretically is the tubular or sheathed heater, where the wire is embedded in insulating material and all heat transfer from the wire is by conduction. Heat dissipation from the sheath, however, is by convection and radiation. In those applications, using empirical data is the safest method of design.

Service failure of heaters, disregarding accidental damage, is generally not due to end-of-life of the material because of the thermal effect alone. Depending on the design, burnouts are localized. The most common problems, where the material is exposed, occur at the supporting points. Terminations are frequently a weak point.

Control of the temperature of the heater by means of an external device, such as a thermostat or thermistor, is helpful. But it is by no means a foolproof method. It is most important to ascertain that the sensor truly reflects the temperature of the material. In furnaces the usual method is to use a thermocouple, connected to a controller which regulates the electric power to the elements.

One of the first determinations to be made in designing a heater is to establish how much power will be required. With all portable appliances, this is simple as the maximum allowable is established (in the United States by Underwriter Laboratories, Inc., as 1500W at 120V). Similar requirements are stipulated by the Canadian Standards Association (CSA) in Canada. Whenever higher power is needed, and the current exceeds 15A, special outlets and wiring are required by most U.S. codes.

Similar limits are established for 240V devices such as ranges and clothes dryers. When it comes to industrial applications, however, the processes determine the need.

**Figure 1** Power to heat 1 metric ton of steel per hour from room temperature
Figure 1 shows a typical chart that is used to determine the power requirements for a steel heat-treating furnace. The power given is what is needed to heat the steel, and the rule of thumb is to allow 50% above theoretical for heat losses and a control factor.

When the power required has been established, it is necessary to determine whether it is possible to place enough heating elements on the wall surface available. In addition, the method of mounting of the elements comes into play. A typical range of so-called wall loading is shown in Figure 2. Note that the highest power is possible with heavy exposed corrugated strip elements, and the lowest loading will be for wire supported on brick ledges in grooves along the wall of the furnace.

![Figure 2 Recommended wattage per square metre of furnace wall surface area](image-url)

*For kw/sq.ft. divide by 10.76
Terminals, leads and connections for heating devices

Careful design of terminals, leads and connections for electrical heating elements cannot be overlooked. By proper selection of the type of connector and alloy for such applications, premature failures can be minimized. Nickel and nickel-containing alloys should be considered where there is a need for an alloy with:

1. Suitable electrical properties.
2. Good mechanical strength at elevated temperatures.
3. Excellent heat and corrosion-resisting properties.

Properties of common nickel-containing materials, used for these applications, are shown in Table 4. These alloys have traditionally been used for terminals. It is also possible to use the same alloy as the heating element, but with greater cross section so that it will run cooler than the actual element.

General principles that need consideration are:

[a] The operating temperature should be minimized by using large terminals of high thermal conductivity metal.

[b] Oxidation resistance is needed in the metal at the operating temperature.

c] If mechanical joints are required, the pressure should be distributed over as large an area as possible — washers should be used under rivets and nuts, and ferrules should be swaged rather than crimped at local points. Avoid the use of brass or tin-plated hardware; use nickel-plated material.

[d] Since nickel oxide has a relatively high electrical insulating value, nickel or nickel-plated terminals might not be adequate at the higher temperatures. Consideration should be given to the use of nickel-copper alloy Unified Numbering System (UNS) N 04400, nickel-chromium-iron alloy UNS N 06600, nickel-chromium-iron alloy N 07750 or the austenitic stainless steels.

[e] The heating element should not contact the terminal assembly at any spot other than at the designed area.

[f] When forming the heating element, it is imperative that no damage be done to the wire, such as nicks. Special brass tools are used in commercial practice.

Leads and Terminal Designs

The following requirements should be considered for the leads or connections between the heating element and the power supply or some other component:

[a] The FR losses in the lead must not be high enough to result in a temperature in the lead that exceeds the safe operating temperature of the lead material.

[b] If the unit requires flexibility, the ductility of the lead wire may be important.

### TABLE 4 Properties of alloys used for terminals

<table>
<thead>
<tr>
<th>Material</th>
<th>UNS N 02200</th>
<th>N 02211</th>
<th>N 04400</th>
<th>S 30400</th>
<th>N 08800</th>
<th>N 06600</th>
<th>N 07750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal analysis</td>
<td>99Ni</td>
<td>Ni-5Mn</td>
<td>70Ni-30Cu</td>
<td>Fe-18Cr-9Ni</td>
<td>Fe-32Ni-20Cr</td>
<td>Ni15Cr-8Fe</td>
<td>Ni-15Cr-7Fe-2.5Ti-0.7 Al-1Cb</td>
</tr>
<tr>
<td>Tensile strength at 20°C (68°F) in psi</td>
<td>60 000-135 000</td>
<td>60 000-135 000</td>
<td>70 000-150 000</td>
<td>1000 000-3000 000</td>
<td>70 000-90 000</td>
<td>91 000-122 000</td>
<td>175 000-2000 000</td>
</tr>
<tr>
<td>Resistivity at 20°C (68°F)</td>
<td>Ohms-CMF</td>
<td>60</td>
<td>120</td>
<td>290</td>
<td>438</td>
<td>559</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>Microhm-cm</td>
<td>10</td>
<td>20</td>
<td>48.2</td>
<td>73</td>
<td>93</td>
<td>98.1</td>
</tr>
</tbody>
</table>
Simple wire connection

For a simple but convenient connection, the end of a spiralled wire can be bent over and twisted with another piece of wire to make a firm terminal. This is frequently used with a porcelain connector (Figure 3).

![Figure 3](image)

Crimping

A crimped joint is formed by crushing a metal ferrule onto the lead (Figure 4). The ferrule may be flattened at one end to form a spade terminal or it may be joined to the termination by welding or brazing. Nickel N 02211 is most frequently used for the braided lead and termination in this application but in corrosive conditions at temperatures up to 500°C (932°F) nickel-copper alloy N 04400 is recommended.

![Figure 4](image)

Welding and brazing

Brazed or welded joints are most suitable for units operating at temperatures above 500°C (932°F). Such joints ensure low electrical resistance, good current flow and good thermal conductivity.

For joining stranded leads to terminal rods where great flexibility is not required, butt-welding makes a good joint. Where flexibility is important, welding, brazing or silver soldering should be used (Figure 5).

![Figure 5](image)

Threading

A screwed joint is frequently used to join a sheathed element to the power supply. A screw thread is machined on one end of a terminal rod which is then screwed into the element wire inside the sheath (Figure 6). This provides a good mechanical contact. A stranded lead may be joined to the other end of the terminal by brazing, arc welding or butt welding.

![Figure 6](image)

The terminal rod is not likely to get hotter than 450°C (842°F) and should be made of nickel-copper alloy N 04400. The braided leads should be made of N 02211.

A variant of this form of joint does not use the screwed terminal end. The end is machined into a flat shank which is pushed into the tightly wound coils of the element wire. A flat terminal with a hole for a bolted joint may be spot welded to the rod as an alternative to the brazed or welded lead connection (Figure 7).

![Figure 7](image)

Elements for units such as convection heaters and clothes driers are nearly always connected to the power supply by a bolted joint. A bolt is secured to the insulating material and the element wire is then wound round the bolt between two washers. A nut, screwed on to make the contact firm, separates the nickel-chromium element wire from the copper wire input. A further nut makes the whole joint secure. Washers are used between both contacts to distribute pressure over as large an area as possible to avoid failure through localized high stresses (Figure 8).

![Figure 8](image)
Since the unit will often operate in a humid atmosphere and the element wire will conduct heat to the joint, a corrosion-resisting material is essential. Long life can be obtained by using nickel-copper alloy N 04400 for the bolt, nuts and washers.

Porcelain connectors

This common type of screw connection is usually made of steel or brass which is adequate for most conditions. With brass, however, faulty connections may arise if the terminal gets hot. In these conditions nickel-copper alloy N 04400 fittings should be used (Figure 9).

How electric resistance alloys work

It has been explained that an electric resistance alloy produces heat because, based on its composition, it resists the flow of electricity. The alloy must be capable of carrying electricity to a reasonable degree, however, in order to function as a heating element.

Temperature coefficient of resistance

The resistance to the flow of electricity, expressed in ohms, for a particular alloy will change as the temperature of the alloy changes. This change is typically expressed as a percentage change from the original room temperature resistance. Generally, as the temperature goes up so does the resistance, thus an alloy that has, as wire, a resistance of 1.00 ohms at room temperature (20°C, 68°F) may have a resistance of 1.08 ohms at say 650°C (1202°F), or an 8% increase due to the heating. Figure 10 shows typical values for the four major alloys.

![Figure 10 Temperature coefficient of resistance for the basic nickel-chromium alloys](image-url)
Inasmuch as heating elements function (obviously) while hot, this change in resistance must be taken into account when designing an element: Design to the hot condition, then work backward to arrive at the room temperature resistance to which an element must be made. Resistance wire, ribbon and strip is always labelled with room temperature resistance unless specifically requested otherwise by the customer.

**Oxide formation and element life**

Any metallic material can function as a heating element. If it does not have a reasonably high resistivity, however, its cross section must be made too small to be practical. Once an alloy is selected for a heating element it must have the proven capability of forming a protective oxide layer when hot. Such an oxide layer must be tightly adherent to the alloy even during repeated hot-cold cycling.

The oxide serves to protect the metal under it from catastrophic oxidation to the point of destruction. An analogy is the way that rust actually protects the underlying steel from rapid rusting — when the surface rust is removed, then the newly exposed surface of the steel rusts and so on. It is important that the surface oxide on a heating element remain intact to protect the underlying metal.

When manufacturers produce the alloys, a sample wire is made and tested before the melt is released for production. This test is conducted by a method described in ASTM B-76 and results in a life figure expressed in hours. These numbers should not be used for design purposes but the typical results, as shown on Figure 11 for three alloys, give an indication of the effect of temperature on life.

![Figure 11](image-url)

Relative life versus temperature, experimental data*

*These data are for information only
Effect of processing on resistivity

Specific electrical resistance is an intrinsic characteristic of each metal, governed not only by composition but also by the physical structure of the material. The resistance can be affected by normal fabricating and processing procedures, such as cold working and annealing treatments, to the degree that they alter the physical structure through order-disorder reactions. For example, if the cooling rate, from the temperature used for annealing after cold working, is quite slow, the electrical resistance will be near the maximum, but if the cooling rate is rapid the resistance will be lower.

Variation of resistivity with cooling rate is especially noticeable with bright annealed material, in which processing involves an anneal in a protective atmosphere followed by rapid cooling. When such material is first operated at temperatures above about 300°C (572°F), resistivity may be subsequently changed from its original value, particularly if the elements cool slowly. The following changes will likely occur:

- **A-Grade**: 6% increase
- **70-30**: 4% decrease
- **C-Grade**: 2% decrease
- **D-Grade**: Insignificant increase

Also, the tendency for a change in resistivity of bright annealed wire or ribbon is influenced by section size. Since light sections will cool more rapidly than heavier sections, light sections show more pronounced effects of cooling rate on electrical resistivity. The effect is greatest with the 80-20 and 70-30 alloys, and intermediate with 60-16 alloy. No significant size effect has been found with the 35 Ni-20 Cr-balance Fe alloy.

When accurate calibration of a heater is necessary prior to installation, an oxidized surface may be specified for the wire or strip because, in producing the oxidized surface, the metal is slowly cooled in an air atmosphere from the annealing temperature. No great change in electrical resistance will take place during service because its starting resistance will have been stabilized by the original annealing treatment near the maximum value for the alloy.

The original resistance of annealed wire can be altered by the coating operation in the production of a heating element, since the coating involves cold work. The amount of cold work must be kept uniform throughout the coil in order to keep the uniform resistance, as well as to produce coils having uniform stretch characteristics. The coating tension must be held as constant and uniform as possible during the coating operation without any sudden jerks on the wire. Uniformity of stretch is an indication of uniformity of cold work and diameter consistency (roundness) throughout the coiled wire.

Coils of very low or very high arbor-to-wire diameter ratios are extremely difficult to make with uniform stretch characteristics. The easiest to make have ratios of between 2:1 and 5:1. Arbor coating speeds should be as high as possible within the limitations of the equipment used. In general, 16 gauge (Brown and Sharpe - .051 in., 1.3mm, diameter) wire, on 1/4 in., 6.35mm, arbors having lengths up to 36 in., 91cm, may be coiled at speeds up to 5 000 rpm. Longer coils, formed from heavier wire or coils made from much finer wire, such as Brown and Sharpe 32 and 35 gauge (.008 in., 0.2mm, to .005 in., 127mm, diameter) wire, should be coiled at substantially slower speeds.

Nickel-chromium alloy heating elements

In general practice, electric resistance heating has been around for a long time. For this reason, most of the designs are modifications of a previous application that had been proved empirically to perform satisfactorily.

An objective approach is required and many practical factors need to be considered. It is necessary to investigate all the factors that will lead to the design of a heater that will provide satisfactory performance at a reasonable cost. In order to accomplish this task, the following points must be considered:

**Application:** Not all heating elements are alike. They must be divided into two major categories: industrial furnaces and appliances. In furnaces, including industrial heaters, the cost of the heating element is not as critical as in mass-produced appliance items. In appliances, a minor mistake that will result in an early burnout is critical, as it could lead to the recall of a large number of devices. A 1% failure rate may be deemed acceptable for some companies, but to the purchaser who gets the defective unit, that rate is 100%. The allowable level of end-product failure is a serious policy decision determined by the management philosophy of the manufacturer.

The design engineer is always working toward avoiding any failure at all. Planning a 20-year life for a major heating appliance essentially falls into that classification. In furnace and industrial oven design, failures of a properly designed unit are almost always due to user error, generally caused by lack of adherence to good operating practice. It is rare for an element to fail in normal use. These problems will be reviewed separately.

**Mechanical effects:** If the heated device is to be subjected to serious mechanical shock, the method of installing the elements becomes most important. The various possibilities are covered in greater detail in the section on the types of heaters available.

**Temperature:** This is the major consideration when selecting the alloy, and the size of the heating material. The application is what determines the needed temperature. It is also necessary to differentiate between the ambient temperature and that of the resistance wire. In a furnace, they may be quite close, but at the other extreme, say in an electric teapot, the water goes to 100°C (212°F) while the wire itself may be driven up to 1 000°C (1 832°F). The same is true in a space heater.

**Space requirement:** The space available for installing the heater is generally limited. This means that the optimum arrangement may not be practical. For even toasting of bread in a toaster, the elements must be some distance away from the surface, yet counter space available for the device must be reasonable.

**Atmosphere:** This refers to the gases or solids likely to come in contact with the heater. The protective atmosphere in a furnace, or the splattering in a broiler are generally predictable, but what about the unexpected corrosive effect of sea air on the element terminations in a duct heater? The answer is that units are designed for widespread use, but without provision being made for locations near the shore.

**Thermal cycling:** The ideal operating condition for a heating element is to remain at constant temperature. This is generally impractical. At the higher operating temperature (800°C, 1 472°F and higher), laboratory tests have shown that...
a continuously energized heater will have a longer total life than one that cycles. Because of the excellent life of a non-cycling heater, most tests are designed to cycle at a high rate. The cycle time is determined by the duration required to cycle the unit between stabilized test temperature heat, and room temperature.

**Safety:** In a time of large awards in product liability cases, a catastrophic failure could spell the end of a company. For this reason, appliances have to be made fully idiot-proof, and Underwriter Laboratories, Inc., approval is a must in the United States where either high heat, or exposed electrical conductors are involved. Installing the elements behind barriers can lead to temperatures higher than originally calculated.

**Appearance:** This may seem bizarre, but for the most part buyers of consumer appliances place a premium on having the wire or ribbon appear bright. This means that the device that is being sold can generally not be tested at operating temperature, as it would then take on an oxidized finish. For this reason, it is necessary to find correlating factors that can give good certainty of performance for an untested device.

**Power density:** One of the most useful, yet least understood concepts, power density is simply a number expressing watts dissipated per unit area, and is frequently named watt-loading. For any application, the greater the loading, the higher the temperature. It is good design practice to choose the highest value, as it means the lowest amount of material, resulting in the most economical system, while still providing acceptable life. This is obtained through a combination of the smallest conductor cross-section and the appropriate resistivity. Figure 12 shows the relative effect of wire diameter on life, under constant conditions, for an element operating in air.

![Figure 12 Wire diameter versus life factor](image)
Determining the power density for a given application is complex, and often inaccurate. The difficulties can be attributed to the great variations in the heat dissipation of any specific device. The best method is to start from a known value in a similar application. The range of power densities can vary by a factor of 100, and still yield the same temperature. In one case the wire operates in water, while in the other it might be well insulated. That is why the starting point should be the application, with the power density based on an existing similar use.

In the case of coils, and some furnace ribbons, there is self-heating between loops (due to radiation from turn to turn). As a general rule, when determining the watt loading, if the stretch ratio is less than three the surface of the coil shape, rather than the wire surface, should be used in the calculations.

C-Grade versus A-Grade (for properties: Table 3)

Since A-Grade nickel-chromium alloy, also known as 80-20, was invented, efforts have been made to reduce the cost of the material by lowering the nickel and chromium content. Many alloys have been tried, most have been abandoned. One of them, C-Grade (60 Ni-16 Cr) has shown great promise. This has not always been so.

In recent years, improvements in the control of the alloy melting process, as well as cleaner raw materials have allowed the production of C-Grade material with life characteristics close to, and sometimes even better than those of the more costly A-Grade for many temperatures. The A-Grade is recommended when the material has to be pushed to its temperature limit. However, in the majority of applications, the C-Grade alloy can be used successfully, and it presents the user with an opportunity to reduce cost.

The practice of testing any material for each specific application is the best way to evaluate materials. This is why it is advisable to run tests when selecting an appropriate alloy. Savings attainable with the lower alloy grade can be substantial.

Since heater alloys are drawn, or rolled, to resistance, it is not uncommon for users to request that an order for C-Grade alloy be drawn to yield the same resistance, in ohms per foot, as A-Grade. Because C-Grade has a slightly higher resistivity, the wire diameter will be a little larger in order to accomplish this. This means that the operating temperature, which is determined by the power density (watts per unit surface area) will be reduced. This decrease of temperature is small but in the right direction, since life is inversely proportional to temperature.

For industrial furnaces, the C-Grade material is not used. The reason is that the overall cost of the complete furnace setup overshadows the cost of the heating elements. Thus the A-Grade, 70 Ni Grade, or D-Grade alloys (where contamination is a problem) are commonly used in furnaces.

Failure analysis — what to look for

In industrial applications, the true answer for the actual circumstances that led to the failure can be expected less than 20% of the time. The end user of the product often feels guilty about the failure, and will not admit exactly what he did. There is often an accompanying claim for a warranty replacement. So before an objective analysis can be made, the examiner has to be convinced that all the facts are at hand. This requires a sharp eye. An experienced laboratory technician can find the cause of failure in most cases using only simple tools, the most important one being a binocular microscope.

The nickel-chromium heating element alloys are normally non-magnetic, thus a small magnet is a useful tool. If the wire has become magnetic, this is an indication of a major application problem. In such instances, chemical analysis of the failed alloy can be helpful.

Often the mechanism of failure has disappeared because the element burned up at the site of the problem, destroying the evidence. It is then necessary to extend the analysis to adjacent areas.

With consumer appliances, there is little information relative to the failure provided with the product. The first and main step is to determine the type of failure.

[a] Bona fide element failure. What is the failure? Is it really a heater failure, or did another part of the circuit give out? Do not overlook the possibility that the heating element proper was not even involved.

[b] Mechanical. Is the damage due to physical damage, in no way related to the material? Such as a knife stuck in a toaster? Was the element physically abused, as in a broken quartz tube heater? Are there any physical marks? Look for broken insulators that might have created a short circuit to ground. In that case, a part of the element will look normal.

[c] Thermal. Is there sign of a burn-out at a given point? Does it look like the element has seen a lot of service at high temperature? Is the problem localized? Can something have rested on the element causing overheating, and subsequently have been removed?

[d] Chemical attack. Does the whole element have a poor surface appearance, without evidence of overheating? A common problem is the use of chlorinated cleaners in ovens.

[e] Material. Is the material used in the application suitable? Often, the manufacturer may be using a lower grade material because of cost constraints. Has a change of supplier to brand X, which supposedly is essentially identical to that formerly used, been made?

Possibly the wrong material was accidentally substituted along the way. Check for proper resistance for the wire size used and also T.C. (temperature coefficient of resistance) to determine if they meet nominal catalog values.

[f] Others. This could be an unexplained break. Is there any necking down at the point of failure? This indicates stretching. Look for signs of liquid in the device. Did the failure occur at the terminals because of a loose contact? Is the proper material used for that application? Is the actual operating voltage correct? There are frequent problems where a manufacturer redesigns a U.S. product for overseas service. In many cases, the resistance is correct but the power density has become excessive. Could a loose piece of wire, or other conductor have shorted the element?
Basic calculations

For all engineering design, it is desirable to know the basic formulas used for calculations. Because there are many different areas of expertise, it is difficult for engineers to remember all of them and they are listed here. Using these formulas, it is possible to create the complex tables given in the alloy manufacturers' handbooks. The only data needed to generate these tables are the electrical resistivity and density of each alloy.

The variables used here are:

- \( E \) = Voltage
- \( I \) = Current in amperes
- \( R \) = Resistance in ohms
- \( R_c \) = Cold resistance
- \( R_h \) = Hot resistance
- \( W \) = Power in watts
- \( C_t \) = Temperature factor
- \( d \) = Density
- \( D \) = Diameter - in. 1 mil = 1/1000 in.
- \( G \) = B & S wire gauge
- \( p \) = Resistivity
- \( A \) = Area

Ohm's law can take many forms, but the basic one is

\[
E = I R
\]

\[
W = E I = F R = W / R
\]

Using simple algebra, other forms can readily be created:

\[
I = E / R
\]

\[
R = E / I
\]

\[
R = W / F = F / W, \text{ and so on.}
\]

It is handy to be able to convert diameters to gauges, and vice-versa. For some reason, these formulas are not as well known and most users assume that the gauge numbers need to be looked up in a table. They follow the formula:

\[
G = (-.4883 - \log(D)) / .05035
\]

or conversely

\[
D = .325 / 1.123^G.
\]

The resistance of a conductor is a function of its shape (length and cross-section) and electrical resistivity.

\[
R = p / A
\]

When dealing with a wire, \( p \) is expressed in ohms-CMF and the area in circular mils (diameter of the wire expressed in mils, squared). If the conductor is a ribbon, the resistivity is in ohms mil² per ft and the area is in mil².

The hot resistance, \( R_h \) is always higher than at room temperature. This change is represented by the temperature coefficient. This information is always shown in the manuals. Thus when designing a heater, the resistance at operating temperature must be calculated first to give the proper wattage and then the cold resistance determined by calculation.

\[
R_h = R_c C_t = R_c / C_t
\]

As an example, calculate the weight of 12 gauge C-Grade wire required for a coil to operate at 650°C (1202°F) and generate 5kW at 240V, single phase. The following data will be used:

\[
p = 675 \Omega \text{-CMF}
\]

\[
C_t = 1.1 @ 650^\circ C \text{ (1202°F)}
\]

(from Figure 1)

\[
d = .298 \text{ lbs/inch}^3
\]

Density (from Table 3)

The hot resistance \( R_h \) is \( E^2 / W \text{ or } 240^2 / 5000 = 11.52 \text{ ohms} \)

making the room temperature resistance \( R = R_h / C_t \text{ or } 11.52 / 1.1 = 10.47 \text{ ohms} \).

If a table of B&S gauges is not readily available, use the diameter calculation to determine that 12 gauge wire has a diameter of .0808 inches or 81 mils. Its resistance is 675 \( / \) 81² = .0297 Q/ft which means that in order to get the required resistance, 10.47 / .0298 = 101.7 feet are required.

To calculate the weight, multiply the volume by the density. The volume is 101.7 12 .081 2 /4 = 6.29 cubic inches = 1.87 lb (848 g).

Now calculate a coil size using geometry to see how long the element would be.

Dividing the 5 000W by the surface of the wire will give the power density on the wire, but a more meaningful power density would be determined by the envelope area of the coil. The power density on this wire would be 5 000 / (101.7 12 .081) = 16.1.

Calculate the area of a coil 1/2 inch diameter with a stretch ratio of two (one wire diameter of space between loops). Determine the number of loops by dividing the total length of the wire by the length of each loop. 101.7 12 / ((.5 - .081) \pi) = 927 loops giving us a close-wound coil length of 927 .081 = 75.1 inches. This gives an envelope (or coil surface area) 75.1 2 .5 = of 236 in² for a power density (watt-loading) on the coil of 5 000 / 236 = 21.2 watts/in². If the coil were stretched to a pitch of 3, the power density on the coil envelope would decrease to 2/3 or 14.1.

Without knowing the specific application, it is not possible to be sure that it is a good design. The main purpose of the above calculation sequence was to present a quick run through the calculations.