Selecting Heating Elements for Electrically Heated Furnaces & Kilns

By Mac McGinnis

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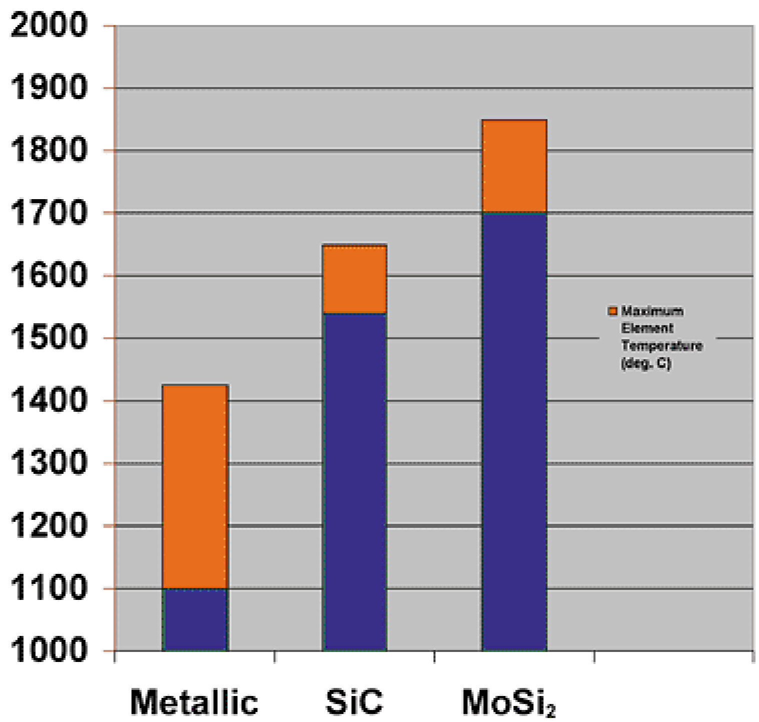

Figure 1: Maximum element temperature vs. element type.

Today's designers, specifiers and end users of electric furnaces and kilns are presented with a wide range of choices with respect to heating elements. As always, the details of any given application can influence the final selection and design of the appropriate electric heating element. However, by understanding the different classes and characteristics of the most often used heating elements, as well as the general guidelines for their selection, users can be certain that they choose the right elements for their application.

Limitations

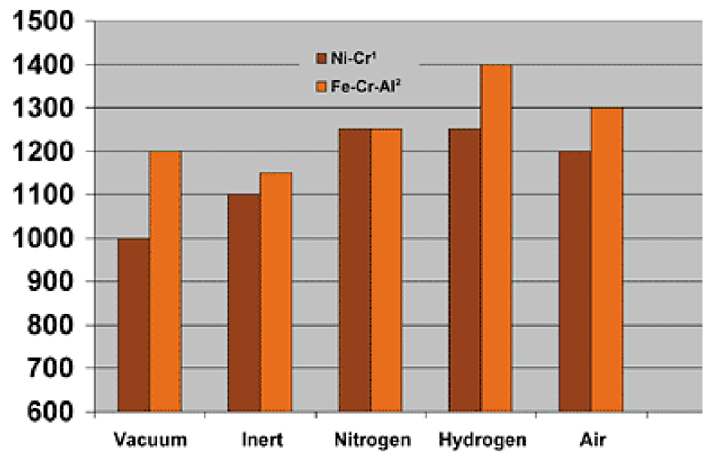

Figure 2: Maximum element temperatures for metallic elements in selected atmospheres.

Nikrothal 80; 2. Kanthal AF

The fundamental operational limitation of any electric heating element is the maximum element surface temperature (MET). The maximum surface temperature is reached either when the basic element material begins to decompose (or change phase) or when the reaction of the element material with the furnace atmosphere proceeds so rapidly that it makes the element life unacceptably short. In general, limitations of elements are given in terms of the MET in a specific atmosphere.

Since an electric heating element transfers heat by convection and radiation to the interior of the furnace and to the load, the element surface temperature is always higher than the furnace / process temperature during the heat-up and soak portions of the firing curve. The element surface temperature may even be higher than the furnace/process temperature during portions of the cool-down curve in order to compensate for heat losses to other areas of the furnace. Therefore, it is important to recognize that the maximum element surface temperature for a specific application will always be higher than the maximum furnace/process temperature (MFT). The difference can range from a few degrees to several hundred degrees, depending on the furnace power requirements and the design/sizing of the element. When screening element types for a specific application, only those types with a MET well above the expected maximum furnace/process temperature should be considered.

A secondary, but nevertheless important, limitation is the maximum specific power loading of the element, which is generally specified in watts/cm2 or watts/in2 of element radiating surface area. This parameter is often simply referred to as the watt loading. In general, the higher the MET, the higher the maximum allowable watt loading. However, each type of element has an absolute maximum watt loading regardless of the element temperature. This limit is based on experience and relates to the deterioration of the basic element material on a microscopic level.

Other practical limitations depend on the form and shape of the element, the element support system and the distortion of the element under mechanical/electro-magnetic load. Some of these limitations will be discussed further with respect to specific classes of elements.

Classes of Elements and Basic Design Considerations

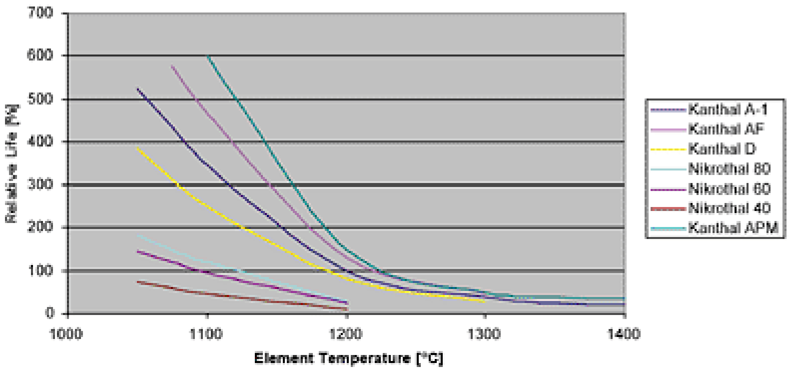

Figure 3: Relative life of metallic alloys (air atmosphere, Kanthal A-1 at 1200 degrees C = 100%).

For the purposes of this discussion, three classes of elements are most often used in ceramic processing applications:

- Metallic (nickel-chromium [Ni-Cr] and iron-chromium-aluminum [Fe-Cr-Al])
- Silicon carbide (SiC)
- Molybdenum disilicide (MoSi2)

Other classes of elements include those made from refractory metals (molybdenum and tungsten) and graphite. Such elements are generally used only in vacuum or protective atmospheres and seldom are found in the ceramic industry.

The METs in dry air for these three classes of elements are shown in Figure 1. The values are shown as bands corresponding to the range of METs for the different qualities of material within each class.

Since the maximum furnace temperature (MFT) will always be less than the MET, one can draw the following general conclusions from Figure 1:

- If the MFT is below 1425 degrees C, all three classes of elements may be technically viable, meaning the selection will depend on the application and economic considerations.
- If the MFT is in the range of 1425 to 1650 degrees C, SiC and MoSi2 are both possibilities.
- If the MFT is above 1650 degrees C, a MoSi2 element is the only possibility.

With the exception of a few special conditions, which will be mentioned later for specific element classes, there are technically no lower limits on element temperature. However, using an element from a class with a high MET in an application where the MFT is far below the MET can be unnecessarily costly.

Typical absolute maximum (dry air) watt loadings for the three classes of elements are as follows:

- Metallic 8 to 12 W/cm2
- SiC 10 to 15 W/cm2
- MoSi2 20 to 30 W/cm2

These recommended maximums can vary from manufacturer to manufacturer and for element quality within each element type. Practical design limit watt loadings will always be lower due to the influences of MET, furnace atmosphere and element geometry.

All types of electric heating elements share the requirement that the necessary process heat be generated by the portion(s) of the element within the kiln or furnace and that the heat generated in the cold ends of the element, which extend through the furnace wall, be relatively small to avoid overheating and excessive heat losses. This requirement is met by reducing the electrical resistance of the cold ends by one of several techniques. For metallic, MoSi2 and some SiC elements, cold ends are used that are larger in diameter than the hot zone. For constant diameter SiC elements, the required resistance ratio is achieved by lowering the resistance of the cold ends. This is accomplished by siliconizing the ends to reduce the resistance or by ceramically joining cold ends of a different, low resistance SiC composition to the hot section(s).

Metallic Elements

Table 1. Characteristics of a family of resistance heating alloys.

Property	Kanthal® APM	Kanthal® A-1	Kanthal® AF	Kanthal® D	Nikrothal® 80	Nikrothal® 70	Nikrothal® 60	Nikrothal® 40
Max. Continuous Operating (Element) Temperature, °C	1425	1400	1300	1300	1200	1250	1150	1100
°F	2600	2550	2370	2370	2190	2280	2100	2010
Nominal Composition, %Cr	22	22	22	22	20	30	15	20
%Al	5.8	5.8	5.3	4.8	0	0	0	0
%Fe	72.2	72.2	72.7	73.2	0	0	25	45
%Ni	0	0	0	0	80	70	60	35
Electrical Resistivity, at 20°C, Ω mm^{-2} m^{-1}	1.45	1.45	1.39	1.35	1.09	1.18	1.11	1.04
at 68°F, Ω/circular mil ft.	872	872	836	812	655	704	668	626
Density, gm/cm^3	7.10	7.10	7.15	7.25	8.3	8.1	8.2	7.9
lb/in^3	0.256	0.256	0.259	0.262	0.300	0.296	0.296	0.285

Metallic elements have the advantage of being available in both a wire and strip form, which enables them to be formed and fabricated by conventional metal-forming techniques into a variety of shapes and sizes. Additionally, heating systems employing metallic elements can be designed to operate on line voltage, while systems using SiC and MoSi2 elements generally require transformers. Metallic elements are also typically less expensive than SiC and MoSi2 elements for the same power output.
However, metallic elements also have a relatively low MET; they are not self-supporting; and their resistance increases with time due to reduction in cross-section by oxidation and elongation (creep), resulting in decreased power output and eventual failure. The effects of these limitations can be minimized by selecting the appropriate element material and element configuration for the MFT and the furnace atmosphere, and by avoiding operation outside of the design envelope.

The physical properties of a family of resistance heating alloys are shown in Table 1. Within each series, composition variations and manufacturing subtleties result in a range of quality in terms of MET and electrical resistivity. In general, the higher the MET, the higher the cost of the material. For a specific application, the information in Table 1 can be used to identify one or two candidate alloy qualities that have METs somewhat above the MFT for the application, but not so far above it as to be unnecessarily costly.

Effects of selected furnace atmospheres on MET are shown in Figure 2 for a Fe-Cr-Al alloy and a Ni-Cr alloy. The limits shown for the Fe-Cr-Al alloy correspond to pre-oxidized material. In general, the performance of Fe-Cr-Al alloys is improved by pre-oxidation, especially if the furnace atmosphere is neutral (nitrogen or exothermic) or reducing (hydrogen or endothermic). Ni-Cr alloys should not be used in furnaces having exothermic or endothermic (carburizing) atmospheres because they are subject to preferential oxidation of the chromium (green rot) in the 800-950? C temperature range. The lowest METs correspond to operation in vacuum, because the protective oxides on the surface of the element are more readily decomposed at elevated temperature under high vacuum conditions.

Metallic element life is primarily a function of temperature, atmosphere and thickness of the element material (wire or strip). The larger the wire diameter and the thicker the strip, the longer it takes for the element to oxidize to the end of its life. Typically, resistance heating alloy manufacturers recommend the use of a minimum of 3 mm diameter for wire and a minimum of 2 mm thick for strips in industrial heating applications.

Another important influence on the life of a metallic element is the type of service continuous or intermittent. Heating and cooling cycles cause thermal stress that can damage the protective oxide surface on the element, thus exposing un-oxidized material, accelerating the rate of oxidation and shortening the life of the element. Spalling of the surface oxide of Ni-Cr elements can contaminate the product, while the oxide of Fe-Cr-Al is more adherent and tends to resist spalling.

The effect of temperature on the relative life of the various members of a Fe-Cr-Al/Ni-Cr resistance heating alloy family is shown in Figure 3. The MFT is 1200 degrees C, and the reference point is the Fe-Cr-Al alloy. The superior life of the Fe-Cr-Al alloys is apparent. Since in-depth economic analyses typically indicate the first cost of a Fe-Cr-Al element to be less than that of a Ni-Cr element for the same application, Ni-Cr elements have a much higher life-cycle cost and are therefore used primarily as replacements in existing Ni-Cr element systems or in special applications.

Silicon Carbide Elements

Table 2. Characteristics of a family of equal-diameter silicon carbide heating elements.

Characteristic	Globar® LL	Hot Rod®	Silit® ED	Crusilite® X	Globar® SG
Max. Element Temperature					
In Dry Air, °C	1540	1625	1625	1575	1650
Element Construction	3-piece	1-piece	1-piece	1-piece spiral	1-piece spiral
Application	standard element	high-perf. element	high-perf. element	standard spiral element	high-perf. spiral element
Maximum Dimensions					
Diameter (mm/in.)	54/2.125	44/1.75	54/2.125	35/1.38	54/2.125
Overall Length (mm/in.)	3300/130	3000/118	3300/130	1600/63	2200/87

Silicon carbide elements are available in a wide range of shapes and sizes (see Photo #1). They are also self-supporting, which enables them to be used in furnaces that are too wide or too long to be spanned by metallic or MoSi2 heating elements. They are capable of higher operating temperatures and higher watt loadings than metallic elements and are relatively easy to change while the furnace is hot.

Disadvantages of SiC elements include the fact that they require more costly power control equipment than metallic elements (multi-tap transformer required); their electrical resistance increases with time (aging), meaning more maintenance attention (transformer tap changing and group replacement) is required than for metallic or MoSi2 elements; and they are made of a ceramic material, so there is a risk of fracture.

Silicon carbide element manufacturers typically produce a family of elements using different grades of material and different manufacturing techniques to tailor each product to a specific range of application. Some characteristics of a typical family of SiC elements are shown in Table 2.

Effects of furnace atmosphere on SiC element MET are shown in Figure 4 for a standard element and two similar high-performance elements. Again, the lowest METs correspond to operation in vacuum, both because any protective silicon dioxide layer formed by pre-oxidation will deteriorate under hard vacuum and because SiC actually vaporizes at elevated temperature under high vacuum conditions.

As noted previously, all SiC heating elements oxidize (or otherwise react with the furnace atmosphere) and increase in resistance during their life in operation. Eventually they either can no longer generate sufficient heat or they fail mechanically, and in either case they must be replaced. Traditionally, SiC heating element power supplies have been designed to supply full rated power even if the element increases in resistance to four times the new element resistance (a 300% resistance increase). Practically speaking, such a high resistance increase is seldom reached. An allowance for a factor of two to three increases (100-200%) is usually sufficient.

When a group of SiC heating elements is exposed to the same temperature and atmosphere, the resistance increase after a given period of operation will differ among the elements due to manufacturing variances and local variations in the environment. As long as the elements are connected electrically in parallel, the effects of this variation are minimal. However, if the elements are connected in series, the situation is potentially unstable. The current (I) is the same through all elements in series, so the element with the highest resistance (R) will generate more heat (I2R). This causes the element to run hotter and age more rapidly, and this process continues until the element fails. The best electrical arrangement is a straight parallel connection of all elements in a group; if a series connection is necessary, best practice dictates it should consist of no more than two elements.

The factors that influence the life of a SiC heating element are generally the same as those that determine the life of metallic heating elements. Temperature and composition of the furnace atmosphere, watt loading, type of service (continuous or intermittent), and operation and maintenance techniques all come into play. Assuming the element selection conforms to good practice based on furnace temperature and atmosphere considerations, operation and maintenance practices become very important. An in-depth review of these considerations is beyond the scope of this article, but matching of element resistances and, if necessary, group replacement to accomplish such matching, are key factors.

In especially aggressive atmospheres, SiC element life can be improved by applying special glazing and coating treatments. In extreme cases, SiC elements can be encased in metallic or ceramic tubes to protect them from the surrounding environment.

Molybdenum Disilicide Elements

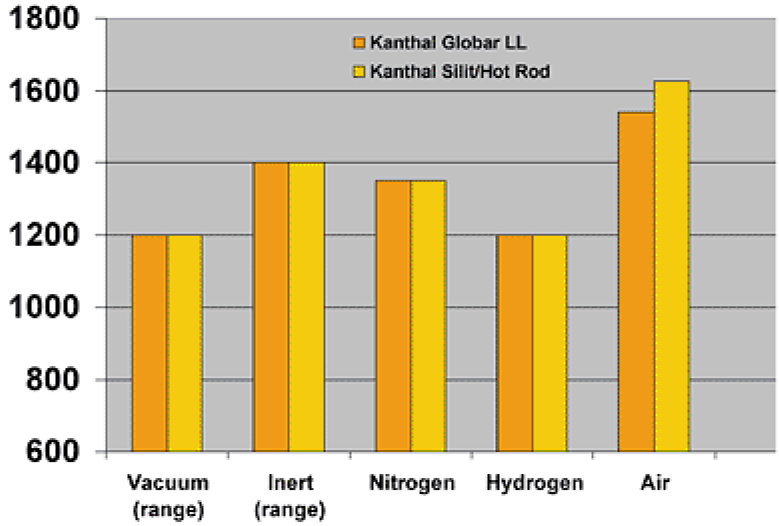

Figure 4: Maximum element temperatures for silicon carbide elements in selected atmospheres.

Molybdenum disilicide elements are available in a variety of shapes and sizes (see Photo #2) and feature the highest operating temperatures and watt loadings of the elements under consideration. They also have stable resistance, which allows new and old elements to be connected in series. Fast thermal cycling is possible without element degradation, and the elements are relatively easy to change while the furnace is hot. MoSi2 elements also offer the longest inherent life of all electric heating elements.

One disadvantage of MoSi2 elements is that more costly power control equipment is required compared to metallic elements (low voltage/high startup current, transformer required). MoSi2 elements are also the most expensive of the elements under consideration, and, like SiC elements, they are made of a ceramic material so there is a risk of fracture.

Molybdenum disilicide element manufacturers also typically produce several grades of elements, with the primary difference being the MET. Effects of furnace atmosphere on the MET of one family of MoSi2 elements are shown in Figure 5. As indicated, the elements have METs of 1700, 1800, and 1850 degrees C, respectively, in air. The METs in non-air atmospheres and vacuum are significantly higher than those for metallic or SiC elements due to the stability and regeneration characteristics of the protective layer that forms on the surface. If the elements are used at low temperature in air, an oxidation can occur at around 550 degrees C that produces a yellowish powder on the element surface. This so-called pest oxidation has no detrimental effect on the performance of the MoSi2 heating element, but is a potential source for product contamination, so operation in this temperature range should be avoided.

If the element design conforms to good practice based on furnace temperature and atmosphere considerations, the life of MoSi2 elements can be very long. More often than not, element replacement is brought on by mechanical damage during loading/unloading and maintenance operations or by improper installation, which introduces mechanical stresses and results in breakage. Another major reason for replacement is overheating and/or electrical/arcing damage to the terminal area. Proper maintenance of the element sealing provisions and the electrical connections will minimize replacements due to such damage.

In recent years, new MoSi2 elements have been introduced to meet the rapidly evolving needs of furnace temperature cycles and atmospheres (and other requirements, such as cleanliness).* These elements feature qualities that are optimized for specific applications such as high temperatures in reactive atmospheres (e.g., nitrogen), extreme temperatures with changing atmospheres, high temperatures and rapid cycling in laboratory and high-temperature sintering furnaces, and contamination- sensitive high temperature processes and represent a significant advancement in MoSi2 element technology. Such elements provide the furnace designer and the end-user with a fresh set of options for solving problems and reducing operating costs associated with new and existing furnaces using MoSi2 elements.

Selecting the Right Elements

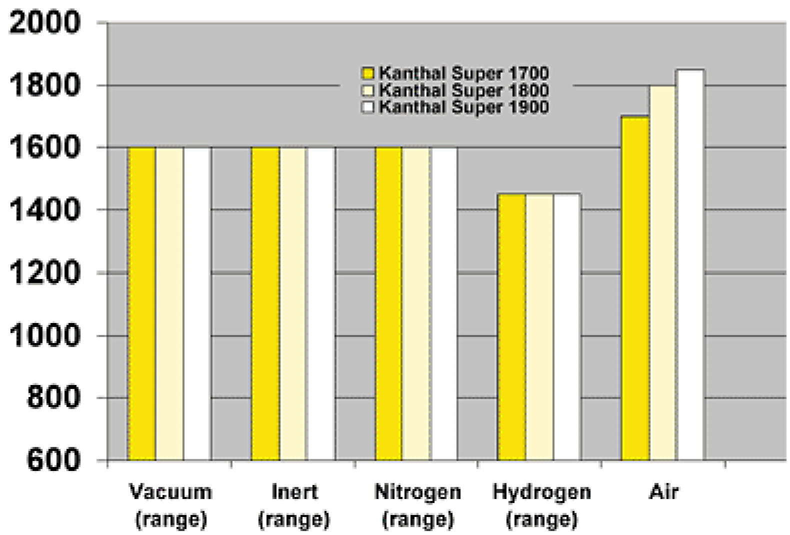

Figure 5. Maximum element temperature for molybdenum disilicide elements in selected atmospheres.

The number of options within a given heating element class is ever increasing, and the overlap in the range of application of the classes is growing as well. The information and guidelines presented here are intended to be sufficient to narrow the range of heating element options for a specific application and/or to enable a general assessment of the validity of a proposed solution. However, the detailed specification and design of electric heating elements is best left to either a highly-qualified electric furnace/kiln builder, an experienced and unbiased electric heating system consultant, or a full-range electric heating element supplier who has no bias toward a particular class of element.

Heating Elements at a Glance

Metallic Elements

Advantages:

- Available in wire and strip form, so they can be formed and fabricated by conventional metal-forming techniques into a variety of shapes and sizes
- Heating systems employing them can be designed to operate on line voltage, while systems using SiC and MoSi2 elements generally require transformers
- Typically less expensive than SiC and MoSi2 elements for the same power output

Disadvantages:

- Relatively low MET
- Not self-supporting
- Resistance increases with time due to reduction in cross-section by oxidation and elongation (creep), resulting in decreased power output and eventual failure

Silicon Carbide Elements

Advantages:

- Available in a wide range of shapes and sizes
- Self-supporting they can be used in furnaces that are too wide or too long to be spanned by metallic or MoSi2 heating elements
- Capable of higher operating temperatures and higher watt loadings than metallic elements
- Relatively easy to change while the furnace is hot

Disadvantages:

- More costly power control equipment than for metallic elements (multi-tap transformer required)
- Electrical resistance increases with time (aging), meaning more maintenance attention (transformer tap changing and group replacement) is required than for metallic or MoSi2 elements
- Ceramic material risk of fracture

Molybdenum Disilicide Elements

Advantages:

- Available in a variety of shapes and sizes
- Highest operating temperatures and watt loadings of the elements under
- consideration
- Stable resistance new and old elements can be connected in series
- Fast thermal cycling possible without element degradation
- Relatively easy to change while the furnace is hot
- Longest inherent life of all electric heating elements

Disadvantages:

- More costly power control equipment than for metallic elements (low voltage/high startup current, transformer required)
- Most expensive of the elements under consideration
- Ceramic material risk of fracture