Efforts are being made to increase the operating temperature of low-mass furnaces beyond the current 1700°C limit. Factors which limit the maximum operating temperature of these units, include high-temperature stability of thermal insulation and power density of heating elements. New insulation materials, installation techniques, and heating-element configurations have been successfully incorporated in the construction and testing of a 1750°C continuously rated furnace. This design can be extended for moderate-size furnaces operating at 1800°C. In addition, the size of 1700°C furnaces has been increased for production applications.

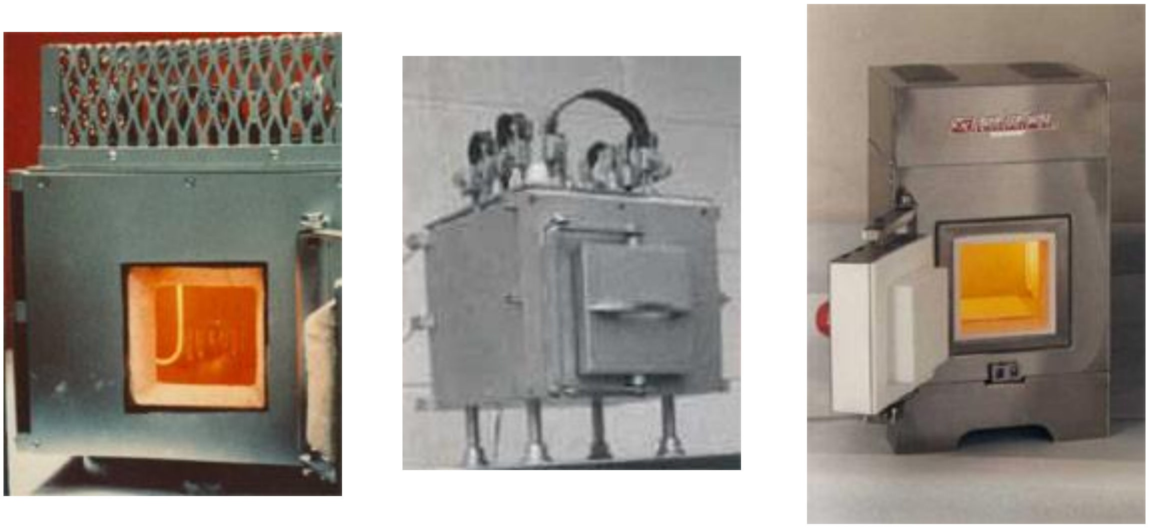


Fig. 1. Changes in design and materials have improved the rapid-cycle furnaces from the first generation (left), to the second generation (center), and finally to the modern furnace, (right).

From Research to Manufacturing

Rapid-cycle furnaces, which use ceramic-fiber insulation and molybdenum disilicide $MoSi_2$ heating elements have been in the marketplace for ≈ 20 years. The first units were constructed under a cooperative effort between Kanthal Corp. and Union Carbide Corp. These units used a fibrous zirconia insulation in combination with small, "U" -shaped $MoSi_2$ heating elements. A second larger furnace, with chamber volume of 3.4 L, was built at Union Carbide Corp. and was the model for future units constructed by furnace builders. CM Furnaces, Inc. was the first to commercialize such furnaces. These served as the model for many furnace builders throughout the world as commercialization continued.

Electrical Data for High-Temperature Furnaces						
Stage	1750°C			1800°C		
	Volts (1 Vm)	Amps (1 Am)	Power kVA	Volts (1 Vm)	Amps (1 Am)	Power kVA
Startup	5	75	0.4	2	150	0.3
Heating	77	54	4.2	36	103	3.7
Soak	65	42	2.7	31	84	2.6

Furnaces that operate to 1700°C are generally used for crystal growth and sintering of powder metal and ceramic components for refractory, structural, and electronic applications. These rapid-cycle units are particularly useful in fast firing of components at high temperatures with short firing cycles. The low thermal mass of the furnaces provides for fast response in both heats up and cool down.

New advances in insulation materials and heating-element design have stretched the current 1700°C limit to ≥1800°C. These 1800°C furnaces will initially be used in R&D efforts to develop new materials and processes and have the potential for eventual commercial application.

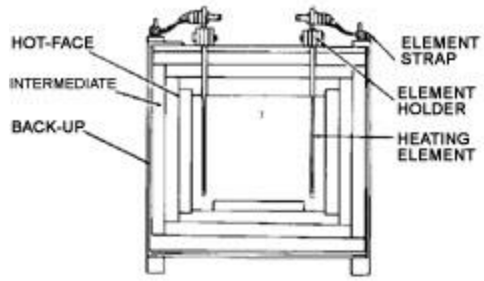


Fig. 2. Schematic for the insulation configuration is shown, which consists of three layers of different temperature grades. The elements are installed through the roof.

Configuration and Performance Factors

Typically, a graded insulation design of three layers is used. These layers consist of high-performance insulation as the hot face, an intermediate layer, and a lower-temperature backup insulation as the cold face. Early furnace models used a zirconia fiber insulation because of its availability and refractory performance. In the last decade, alumina fiber products have surpassed zirconia in terms of high-temperature capabilities, although zirconia still has better chemical resistance.

The industry standard in 1700° C furnace hot-face insulation has been an 80% Al_2O_3 20% SiO_2 composition with a density of 481 kg/m^3 (30 lb/ft^3). This hot-face material can be used from ≈1720°C to 1750°C. A recent developed, improved version of this material with better high-temperature stability, i.e., less shrinkage and greater sag resistance, has pushed the ultimate operating temperature to > 1800° C.

Molybdenum disilicide heating elements available on the market have maximum element temperatures of 1800°C. Operating these elements at their maximum temperature has yielded maximum furnace temperatures of 1700°C to 1750°C. The top temperature that can be obtained in the chamber is mainly a function of the watt loading on the heating elements. Recently, an improved $MoSi_2$ heating element was introduced, which has a maximum operating temperature of 1900°C, thereby yielding furnace temperatures to 1820°C.

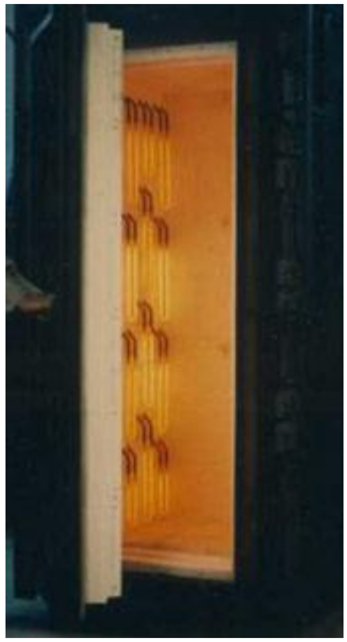
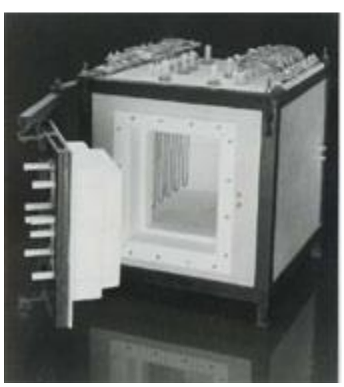


Fig. 3. The chamber of the 1700° C furnace has been increased almost 20 times the original size, allowing for production applications.

Factors that affect the performance of these low-mass furnaces include: chamber size, thermal cycle, insulation type and configuration, and heating element size, orientation, and watt loading. Fibrous insulation can be installed in various configurations. Perhaps the most conventional is the positioning of flat boards parallel to the chamber walls. On the other hand, the butcher-block configuration uses stacked strips of insulation. This design is limited to small chambers and can have shrinkage problems which lead to lining failure. In addition, the properties of the insulation material itself affect furnace performance. These include chemical resistance, high-temperature shrinkage, sag resistance, and thermal- and mechanical-stress resistance.



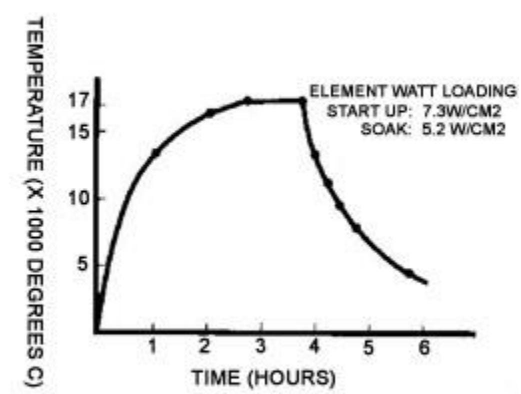


Fig. 4. A 1750° C furnace typically has a chamber 254 mm wide by 280 mm deep by 229 mm high. The typical firing schedule for this type of furnace shows that the element watt loading is critical for optimum performance.

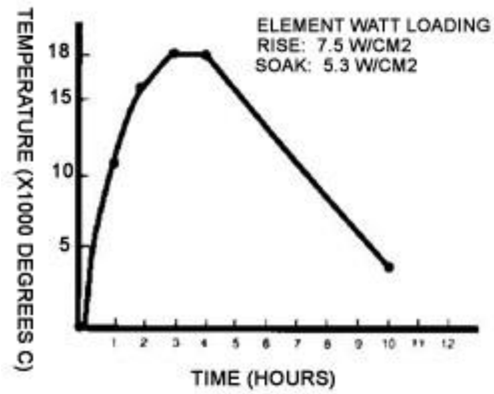


Fig. 5 The typical firing schedule for an 1800° C furnace is shown; again, the element watt loading must be carefully controlled for best performance.

Another important factor is the heating element. Conventional $MoSi_2$ heating elements, although able to withstand the rapid cycling of these furnaces, pose limitations on the size and performance of chambers. The maximum use temperature is a function of the element watt loading, size (length), and orientation of the furnace. For instance, the practical length limit for 1700°C furnace elements is ≈600 mm. Longer elements suffer from sag and elongation under their own weight at the elevated temperatures at which they soften. These elements are usually installed through the roof of the furnace and thus pose problems in terms of maximum obtainable chamber height. Elements can be installed with entry through the chamber wall, but again the use temperature is limited by their tendency to sag and distort. Once sagging occurs, the elements become impaled in the insulation and fail.

Fig. 6. An 1800 °C furnace is shown prior to the first firing (left). The chamber is 229 mm wide by 254 mm deep by 203 mm high. The volume is 11.8 L (0.4 ft^3). After 1 h of soak at 1800°C, the heating elements become distorted (center). After five cycles, with the fifth at a 24-h hold, the insulation shows minimal degradation (right). (See Fig. 8.)

Optimizing Chamber Design

Recent improvements in design of 1700°C furnaces have increased chamber size from 250 L (9ft^3) to 450 L (16 ft^3). The design combines a unique hanger system that supports the insulation with a method to prevent the wall-entry elements from sagging into the insulation. This method uses a horizontal support that contacts the element at the top of the vertical section of the bent element shank. This prevents the element from slumping into the furnace wall.

The insulation hanger system uses fully reinforced insulation panels, generally 225 by 300 mm, that are independently suspended from the furnace-lining exterior. These panels are more

resistant to thermal shock than larger panels because they can expand and contract independently of other panels in the system. Because of the relatively small size of the panels, no great thermal stresses occur. The independent suspension also prevents mechanical loading that occurs with self-supported insulation layers. This combination has resulted in successful rapid-cycle operation of the larger furnace on a daily basis.

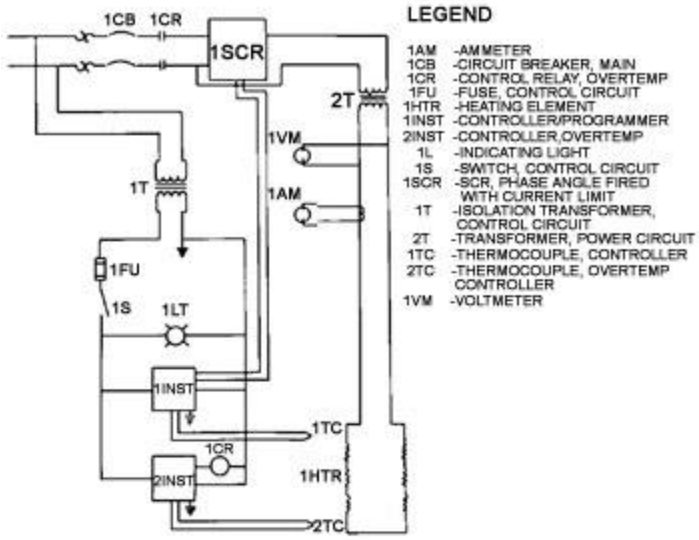


Fig. 7. The diagram shows a typical wiring arrangement for a single-phase furnace. This arrangement is important for controlling the element watt loading and controlling the unit at temperature.

A chamber for continuous cycling to 1750°C was constructed. this unit is similar in design to the lower-temperature furnace. However, higher temperatures are possible by minimizing the mechanical and thermal stresses in the insulation by incorporating small hot-face panels. The chamber temperature is maximized by lowering the heat flow through the walls which minimizes the element watt loading. An element watt loading of 7.3 w/cm^2 is used, which is well below the maximum recommended by the manufacturer. This chamber was successfully cycled 49 times to 1750°C with a total of 100 h of soak and is still fully operational.

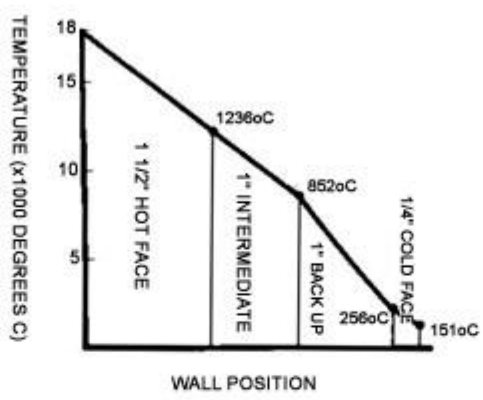


Fig. 8. During the fifth cycle, shown in Fig. 6., the insulation interface temperatures were measured and are shown in the accompanying figure.

A 12-L (0.4-ft^3) laboratory furnace also was designed for 1800°C use. This unit was the improved insulation material and the 1900°C heating elements. The design is similar to the lower-temperature furnaces. Again, small insulation panels are suspended using the hanger system, and the heating elements are powered so that the watt loading on the elements is minimized to ≈ 7 w/cm^2 . The unit was put through a rigorous cycling schedule with 1800°C soaks. During the first cycle, the heating elements distort, and after several more cycles, they sag under their own weight and re-straighten. After four cycles and a total of 4 h of soak, the insulation survived the extreme temperature. After the fifth cycle at a 24-h hold, the insulation showed minimal degradation. To date, this furnace survived 16 cycles with a total of 39 h at soak.

With optimum design of insulation type and configuration, heating-element size, orientation, and watt loading, increases in maximum furnace temperatures become possible. Continued increases in chamber size may also be realized, and, therefore, production units operating at 1800°C may soon be available.

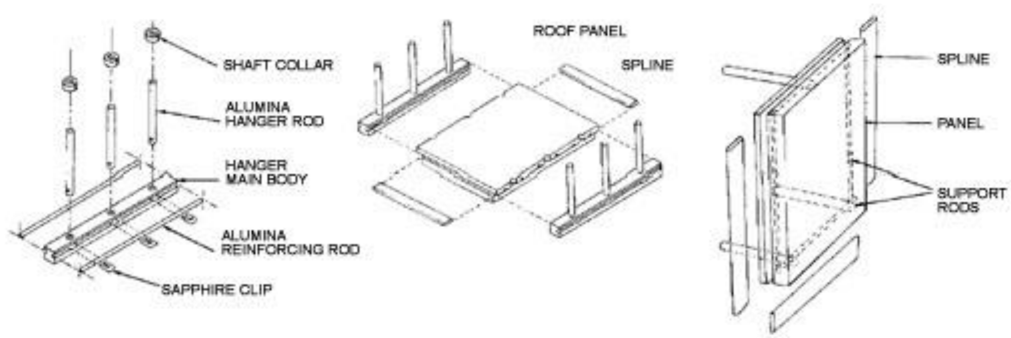


Fig. 9. The insulation hanger assembly (left) permits design of larger chambers. Two hanger assemblies are used to support a single roof panel (center). Reinforced wall panels (right) are suspended from the furnace-lining exterior in a manner slightly different from the roof panels. Alumina hanger rods with through holes drilled to accept support rods are used in a "split-rail fence" configuration. Adjacent panels are joined with splines to block direct-line radiation through the butt joints.