



1700°C Rapid Cycle Furnace Design

Ceramic fiber insulation is made in a variety of shapes, sizes, densities, and compositions. These materials possess a range of characteristics, properties, and utility. Successful applications of fibrous ceramic thermal insulation in rapid cycle furnace chambers operating at 1700°C (3092°F) is critically dependent on its proper use. Consideration must be given to the unique physical, thermal, and chemical properties of these materials and their fabricability.

CERAMIC FIBER INSULATION

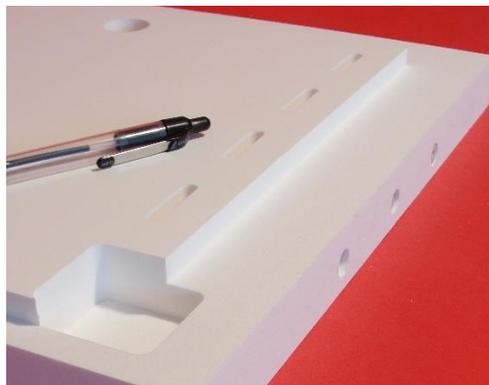
Fabrication

Different shapes of ceramic fibers are formed, by drawing water base slurry of fiber and binders onto a screen.



Producing vacuum formed ceramic fiber insulated heater.

Typically, flat board and cylinder shapes are produced using this method, although an unlimited number of custom shapes can be formed. Once dried, and/or fired, these simple pieces can be machined into very complex geometries for a specific application.



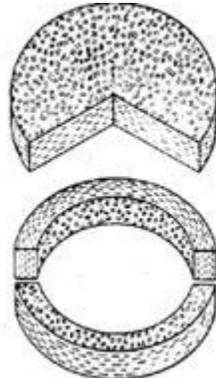
CNC milling enables the rapid and efficient production of complex shapes.

During the forming process, colloidal binders adhere to the fiber surfaces. This bonds fiber to fiber and facilitates the build-up of large volumes.



This 30 pcf density ceramic insulation shows a typical structure with open porosity.

Vacuum-formed fibrous ceramic insulation has a laminar type internal structure, with the fiber generally oriented parallel to the vacuum-formed surface. This results in the fiber plane being perpendicular to the board or cylinder thickness, Fig. 4, thus creating anisotropy with respect to physical properties.



Orientation of ceramic fiber shapes is laminar internally and parallel to formed surfaces.

Chemistry

ZIRCAR Ceramics' Vacuum-formed shapes can be made in combination with alumina or silica binders. Virtually, any combination is possible with certain variations being preferable for any given application.

Product	Composition	Density (LB./Cu.FT.)	Application
SALI	80% Al ₂ O ₃ 20% SiO ₂	30	Hot-Face Insulation for continuous duty at 1700°C in air.
ZAL-15	85% Al ₂ O ₃ 15% SiO ₂	15	Hot-Face or Back-up Insulation for use to 1650°C in air.
ASH	66% Al ₂ O ₃ 34% SiO ₂	20	Back-up insulation.

Table above shows the most common ceramic fiber insulation materials currently used in high temperature laboratory furnace construction

The high temperature stability of fibrous materials can be greatly influenced by the presence of impurities or by the atmosphere in the furnace chamber. Silica-bonded alumina insulating materials exhibit the greatest high temperature stability. They can be adversely affected by impurities or atmospheric conditions, which attack silica. All alumina variations of these materials have been produced; they are

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used primarily in vacuum or reducing conditions where, silica in the insulation is attacked by the furnace atmosphere, or where the presence of silica cannot be tolerated with respect to load contamination.

Thermal Shock Resistance

Fibrous ceramic insulation is extremely low density relative to traditional furnace refractories. Porosities range from 70%-93%. The low density and associated low thermal mass imparts excellent thermal shock resistance (TSR). When used as furnace insulation, material TSR is affected by factors including chemistry, density, temperature cycle and geometrical configuration.

As insulation panel size is increased the overall thermal shock resistance decreases. Insulation panels of 80% Al_2O_3 – 20% SiO_2 that are larger than 12" x 12" (30.4 cm x 30.4 cm), tend to exhibit thermal shock cracking. Thus, for rapid cycle furnace application it is important to limit the size of the hot-face insulation panel. Small panels are more resistant to thermal shock and mechanical failure due to their ability to expand and contract independently of other panels in the system.

Thermal Shrinkage

Thermal shrinkage of fibrous insulating materials is due mainly to the sintering and consolidation of the porous network of fibers, which occurs at elevated temperatures.

Shrinkage, as determined for specimens under no load conditions in an isothermal soak, begins immediately upon exposure to elevated temperatures and continues for some time (up to or in excess of 100 hours). Shrinkage under these conditions is largely due to the chemistry and associated phase changes.

The shrinkage of fibrous ceramic insulating materials is greatest in the direction perpendicular to the fiber plane. This is believed due mainly to the sintering of adjacent fibers and linear contraction perpendicular to the fibers. Certain materials, such as 80% Al_2O_3 – 20% SiO_2 insulation, exhibit expansion parallel to the fiber plane due to the formation of Mullite in the body during exposure to elevated temperatures.

Mechanical Stability

The mechanical stability of fibrous ceramic furnace insulation is highly influenced by the chemistry of the insulating material and furnace, as well as the use temperature, material shrinkage, and mechanical stress placed on the material. These low-density insulating materials are generally soft and non-self-supporting in large configurations at elevated temperatures. In their successful application in furnace chambers operating at 1700°C (3092°F), consideration must be given to all the factors mentioned above.

Furnace roofs, which experience bending stress, usually are the first part of the furnace lining to fail. Furnace walls under compressive loading, when relied on to support the roof, can buckle and slump.

High Temperature Sag Resistance

Fibrous ceramic insulation becomes pyro-plastic at elevated temperatures. Materials exposed to isothermal soak conditions approaching their ultimate use temperature, will fail due to slumping under their own weight. The magnitude of slumping or sag increases dramatically as the span, load and temperature are increased and as the thickness of the material is decreased.

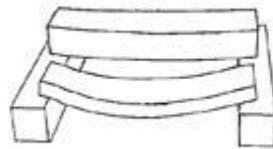


Figure above shows the sag characteristics of simply supported beams of a 30 pcf density alumina insulation exposed to a 24-hour isothermal soak at 1600°C (2912°F). The thinner beam shows much more sag than the thicker one.

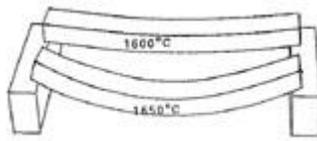
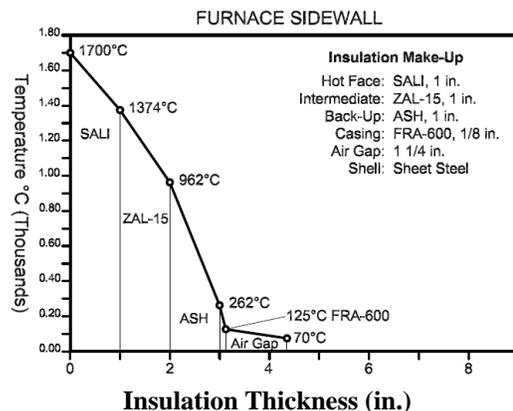
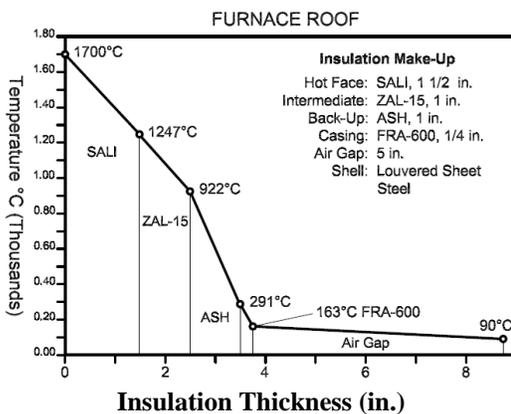


Figure above shows the sag of a 30 pcf density alumina insulation beams of equal size, subjected to isothermal soaks of one (1) hour @ 1600°C & 1650°C (2912°F & 3000°F).

Fibrous insulating materials subjected to isothermal conditions will fail at temperatures well below their recommended maximum use temperatures. In furnace system designs that address this high temperature softening, insulation in furnace roofs and walls do not show the severe slumping of isothermally soaked beams because a temperature gradient will exist through the thickness of the material.

Temperature Gradient

Due to the "low hot strength" nature of these materials an appropriate thermal gradient must be maintained through the thickness of the furnace wall. This thermal gradient assures that a sufficient portion of any insulating layer exists at a cool enough temperature to provide mechanical support to the pyro-plastic "hot-face." The charts below, show the temperature gradient that exists in the walls and roof of a typical laboratory furnace designed and built with a graded system of insulation layers. Note that the temperature drops sharply in both roof and sidewall, and that the cold face side of the hot-face insulation operates at a temperature well below that at which slumping will occur. The data presented below shows temperature gradients achieved with fan assisted cooling. Such cooling can be achieved if sufficient natural convective is facilitated by the furnace housing.



Shown above are temperature gradients established in roof and wall of rapid cycle laboratory furnace with a working chamber size of 12in.W x 12in.D x 1in.H.

There are several common problems associated with improper application of insulation including: (1) Use of minimum thickness hot-face insulation causes "hot-face/intermediate" interface temperatures to run too high. This often results in instability and failure of the hot-face lining. (2) The addition of excess back-up insulation, to lower the furnace shell temperature and minimize heat losses, often raises the hot-face insulation interface temperature to unacceptable levels. This also can result in instability and failure of the hot-face insulation. One of the best ways to achieve low shell temperatures is by the use of an air gap between the back-up insulation and furnace shell. Natural convective cooling or forced air can be employed. (3) Use of excessively thick hot-face insulation in an attempt to provide a "more stable" configuration often results in differential thermal expansion induced cracking and requires more "costly" hot-face insulation than is required. (4) Installing of hot-face roof insulation in a configuration where the edges extend from the hot-face all the way to the cold exterior. This often produces gradients in excess of 600°C/in. (1112°F/in.), often resulting in insulation cracking. The hot-face insulation should be fully encapsulated by the intermediate and back-up insulation layers where possible.

Thermal Conductivity

Porous ceramic fiber insulation possesses low thermal conductivity. Thermal conductivity is a function of product type (chemistry and density), operating temperature and fiber orientation. Thermal conductivities of ZIRCAR Ceramics' fibrous ceramic material range from a low of .07 W/m²K (.5Btu/hr ft²F/in.)@400° C (1000°F) to .52 W/m²K (3.7Btu/ft²F/in.)@1650° C (3000°F). Slightly higher thermal conductivities have been measured in the direction of the fiber plane. The direction of lowest conductivity is perpendicular to the plane of fiber or perpendicular to the thickness of the board or cylinder wall.

As thermal conductivity for a given material in any application is often difficult to arrive at, due to its permeability, losses at element terminals, and losses around door openings, temperature drop data is often accumulated for given configurations of insulation. Wall losses have been determined to range from 3.1-3.5 w/sq in. of chamber hot-face surface area. This is an average value, which is independent of insulation orientation and wall configuration.

SMALL FURNACE DESIGN

Basic Configuration

The insulation configuration and panel layout in the design and construction of high temperature, rapid cycle box furnaces is based on experience with chambers providing heating rates on the order of 60°C/min (140°/min) and extended soak at 1700°C (3092°F). Less rigorous design can be used for units operating at lower temperatures and with slower heating rates. The basic chamber utilizes a multi-layer fibrous ceramic insulation system enclosed in a furnace shell, which provides an air space for convective or forced air-cooling of the cold-face. Molybdenum Disilicide heating elements are installed through the roof of the chamber.

The most refractory, highest cost material, is used as the hot-face layer. It is backed-up with less refractory, lower cost intermediate, and back-up insulation layers.

A proper thermal gradient is important to maintain so that an acceptable degree of rigidity exists in the furnace insulation layers. The table below shows the recommended hot-face, intermediate, and back-up insulation thicknesses in roof and wall panels required achieving the proper thermal gradient and stable insulation layers.

INSULATION	INSULATION THICKNESS			
	ROOF		WALL	
Hot-Face, SALI (80% Al ₂ O ₃ -20% SiO ₂)	1 in.	1 1/2 in.	3/4 in.	1 in.
Intermediate, ZAL-15 (85% Al ₂ O ₃ -15% SiO ₂)	3/4 in.	1 in.	3/4 in.	1 in.
Back-Up, ASH (66% Al ₂ O ₃ -34% SiO ₂)	3/4 in.	1 in.	3/4 in.	1 in.

Recommended Insulation Layer Thicknesses in a 1700°C Rapid-Cycle Furnace.

In small chambers, monolithic hot-face panels are adequate. As the chamber size increase, the magnitude of mechanical stress the panels are subjected to and the severity of thermal expansion induced stress increase. Due to these factors and the pyro-plastic nature of the materials there is a practical limit to the size and thickness of hot-face panels that can be utilized. Additional reinforcement in the form of internal support rods is required in larger chambers.

80% Al ₂ O ₃ -20% SiO ₂ Hot Face Panel Dimension	Hot-Face Insulation Thickness		Internal Support Required
	Roof	Wall	
Up to 8 in.	1 in	3/4 in.	Short rod sections between element slots
8 in. to 12 in.	1 1/2 in.	1 in.	Long rod sections running full width of roof span (SALI-R)
Above 12 in.	1 1/2 in	1 in.	Panels (SALI-R) in roof and wall supported from furnace exterior

Table above relates recommended insulation thickness and internal support requirements to hot-face panel dimensions.

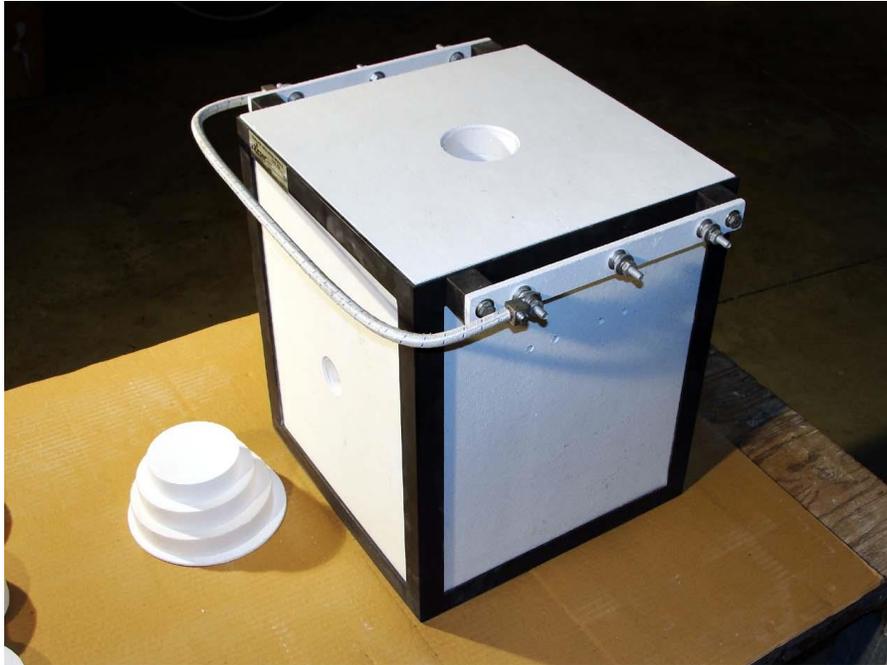
Embedded Reinforcing Rods

In 80% Al₂O₃ -20% SiO₂ panels (SALI), reinforcing rods are installed inside the hot-face insulation layer. These are located near the cold face side of the hot-face insulation panels where lower temperatures exist. In this location, they provide substantial support to the distortion prone hot-face insulation. Fig. 9 shows a typical roof panel.

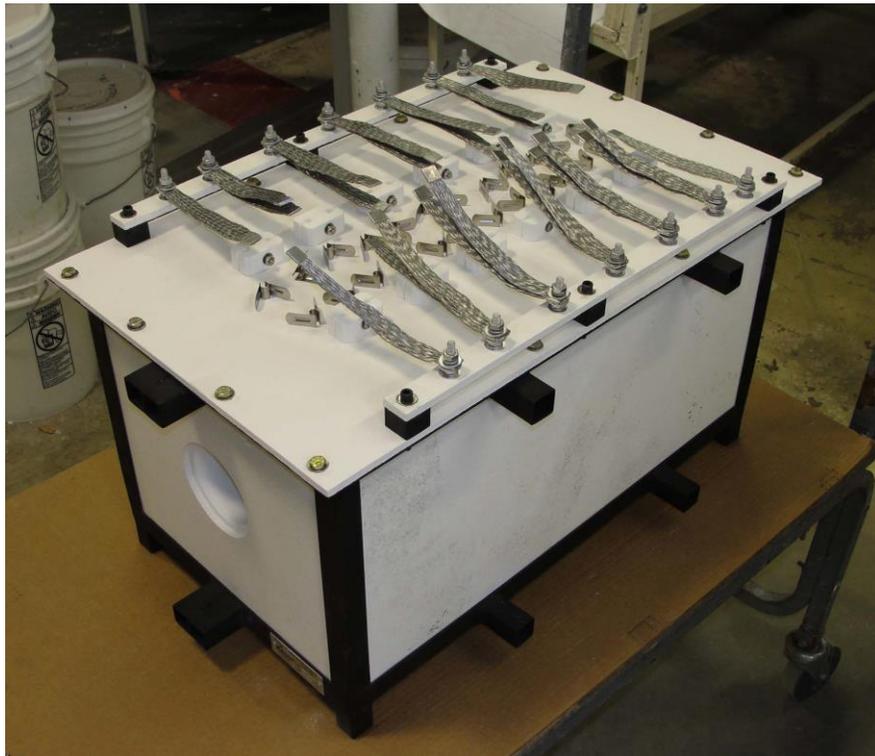
There is a practical limit to the span allowable for furnace roofs comprising these panels. Roofs with spans greater than 12 in. tend to slump after extended service at 1700°C (3092°F). Roof collapse is perhaps the most common cause of lining failure in large furnace chambers.



Typical roof panel with embedded reinforcing rods.



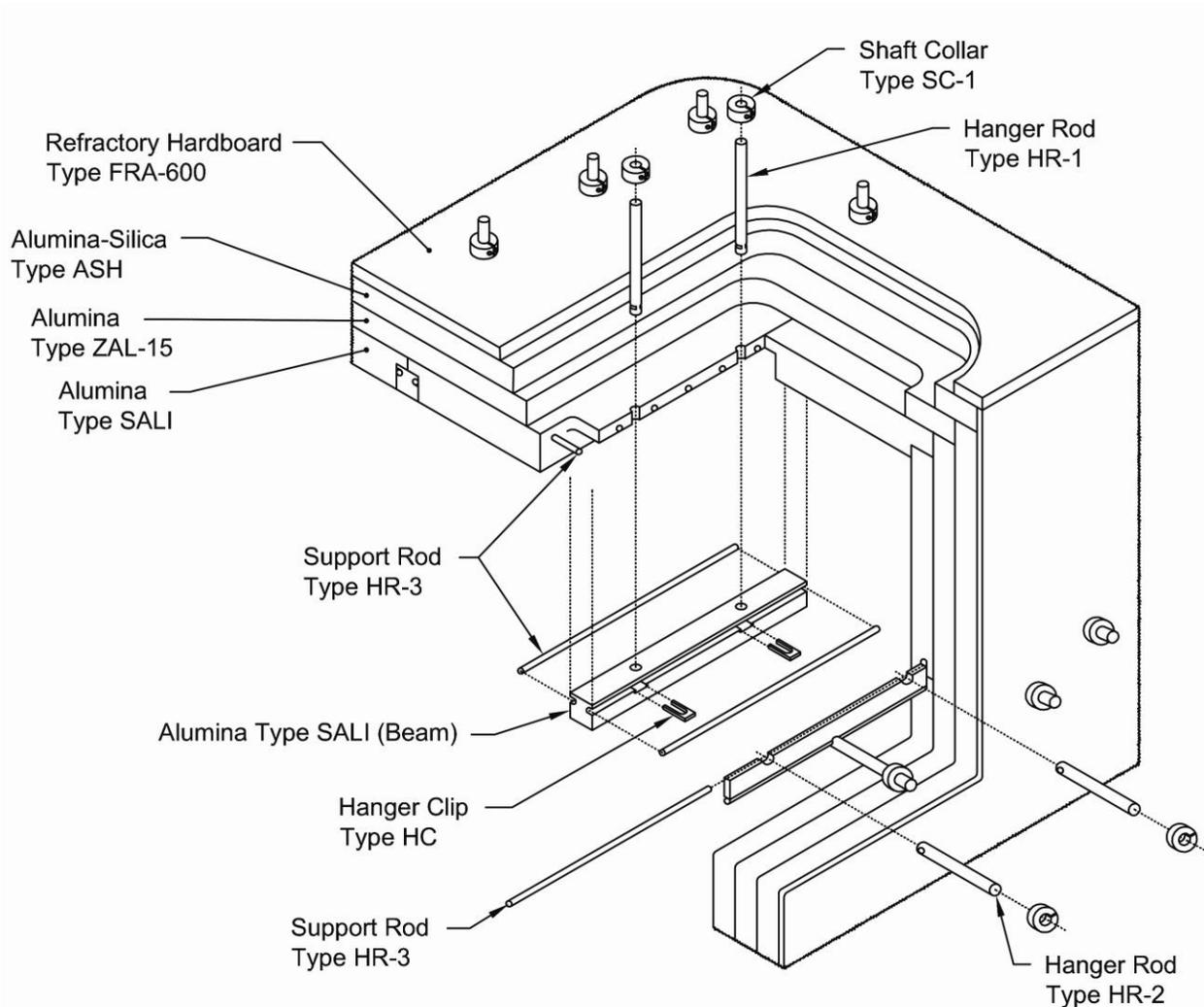
This lab-scale 1700°C rated Furnace Insulation Module utilizes a multi-layer insulation system with 3.5" of insulation in its roof and 3.0" of insulation in its walls and floor.



This lab-scale 1700°C rated Horizontal Tube Furnace Insulation Module utilizes reinforcing rods embedded in its roof. Its relatively small size and gradual heat up/cool duty cycle permit the use of Non-reinforced walls and floor insulation panels.

LARGER CHAMBER DESIGN

A new insulation hanger system, ZIRCAR Ceramics' FIM System, has been developed whereby fully reinforced 80% Al_2O_3 -20% SiO_2 insulation panels are independently suspended from the furnace-lining exterior. Generally, 9" x 12" panels (a multiple of standard commercially available boards) are used. These panels are more resistant to thermal shock than large panels, because they are allowed to expand and contract independent of other panels in the system. Due to the relatively small size, the large thermal expansion induced stresses, inherent in large panels do not occur. As they are independently suspended from the furnace-lining exterior, they are not subject to the mechanical loading incurred by "self-supported" insulation layers.



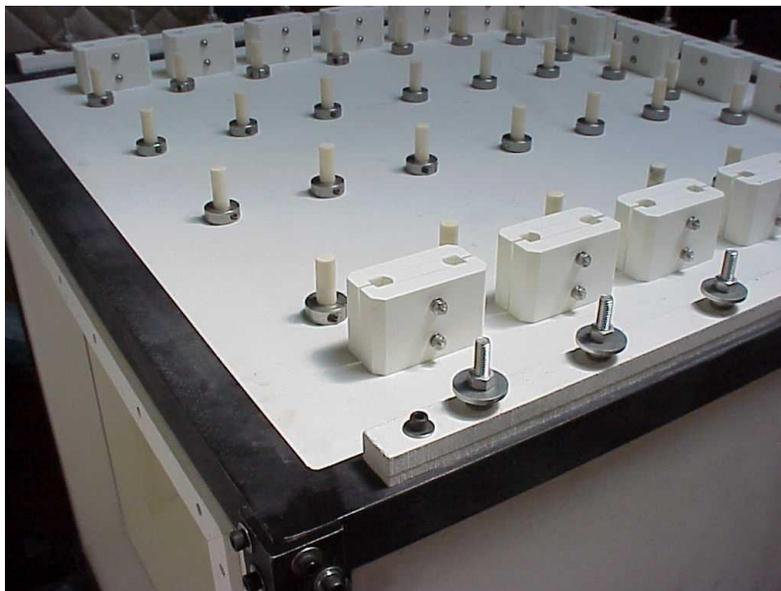
The Furnace Insulation Module Accessories Map above, details the relative locations of the ceramic reinforcement and hanger components in ZIRCAR Ceramics' FIM Furnace Insulation Module System.

Roofs

In Rapid-Cycle furnaces utilizing this FIM system, multiple reinforced insulation panels are configured to cover large roof expanses. Since each panel is reinforced and individually supported from the exterior shell, the span of any roof section is limited to that of each panel. Very large roof spans and very large furnaces can be manufactured with this system.



Shown above is the ceiling of an FIM system that is cycled rapidly to 1740°C. Its small hot face panels control the stresses such aggressive operation imparts on the insulation lining.



Pictured above is the roof of a large front loading 1700°C FIM showing how the reinforced insulation system is suspended from a strong external FRA-600 shell.

Walls

Reinforced wall panels are suspended from the furnace lining exterior in a manner similar but slightly different from the roof panels. Alumina hanger rods ($\frac{1}{2}$ "Ø) with through holes drilled to accept $\frac{1}{4}$ "Ø support rods are used in a "split rail fence" manner. Adjacent panels are joined with splines to block direct line radiation through the butt joints.



Pictured above are walls of an FIM system under construction. Shown are small hot face panels reinforced and joined with rods and splines. This technique strengthens the hot face layer while allowing it to expand and contract during cycling.

Doors

Door panels are configured similar to wall panels. They are supported using "split rail fence" type support rods. These panels must be supported around their entire perimeter since they do not have the edge support many wall panels get from the furnace roof and floor.



Shown above is the door being constructed for a 1700C FIM with a working chamber of 18in.D x 18in.W x 52in.H. Its reinforced insulation system is suspended from its FRA-600 shell.



Pictured above is a 1700°C Shuttle Kiln. This kiln uses the FIM technology and is cycled from room temperature to 1700°C and back in 38 hours.



The Furnace Chambers shown above are used in the sintering of PTC Thermistors who's dielectric properties can only be achieved through extremely fast thermal cycling.



The 1700°C Furnace Insulation Module shown above utilizes the FIM technology.

SUMMARY

Vacuum-formed ceramic fiber insulation possesses a highly ordered internal structure. This structure plus other characteristics impart unique physical and chemical properties that impact on its utility as furnace insulation. These properties must be carefully considered in the design of high temperature furnace chambers.

Large rapid-cycle furnace chambers have been designed and constructed using a revolutionary embedded insulation hanger system.