

March 23, 1954

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2,673,228

INDUCTION FURNACE WITH HIGH-TEMPERATURE RESISTOR

Filed Sept. 15, 1950

2 Sheets-Sheet 1

Fig. 1

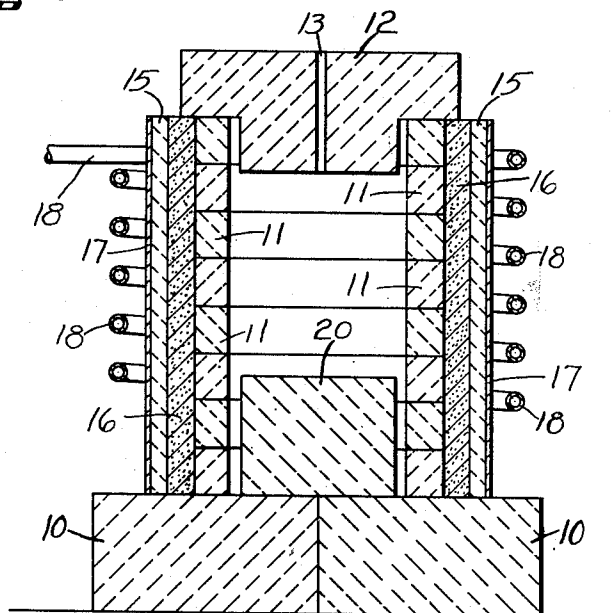


Fig. 2

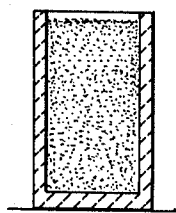
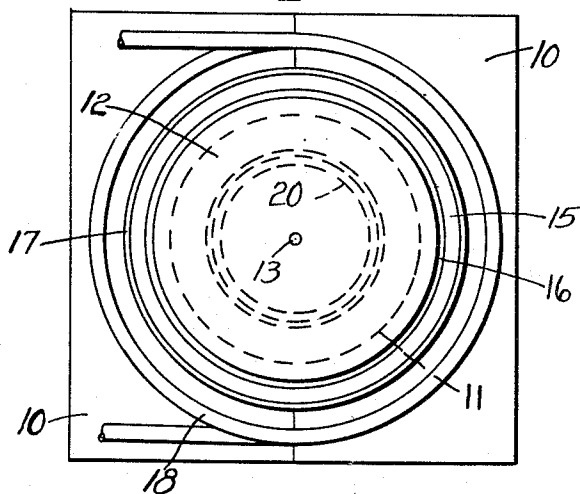


Fig. 3

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2 Sheets-Sheet 2

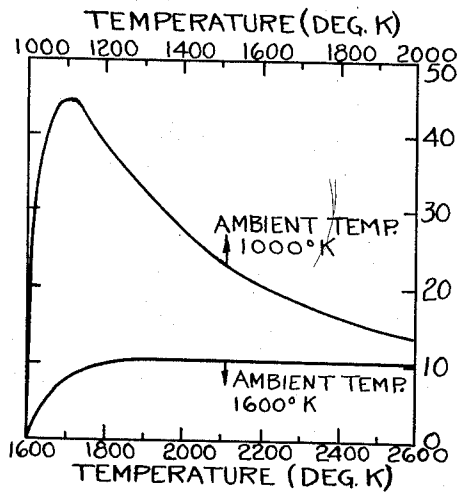


Fig. 4

VOLTAGE / CENTIMETER

CRITICAL
TEMPERATURE
(DEG. K)

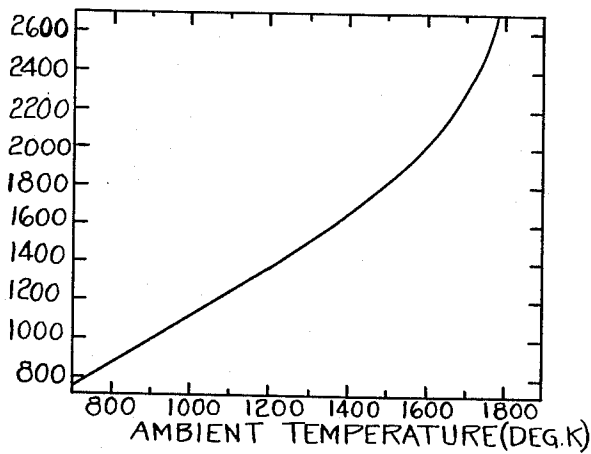
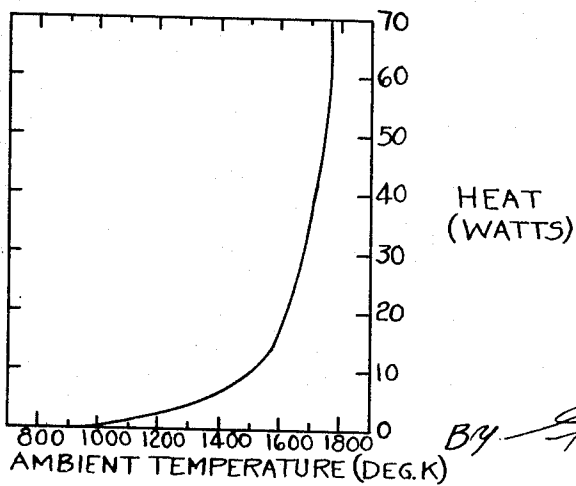


Fig. 5



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INDUCTION FURNACE WITH HIGH-TEMPERATURE RESISTOR

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Application September 15, 1950, Serial No. 184,928

6 Claims. (Cl. 13—26)

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The invention relates to high temperature electrical heating resistors.

One object of the invention is to provide a satisfactory high temperature furnace without any terminals. Another object of the invention is to provide an oxide resistor furnace wherein the resistor can be maintained at top operating efficiency at very small expense. Another object of the invention is to provide a highly refractory resistor capable of reaching temperatures up to almost 2700° C. in an air atmosphere and in many other atmospheres. Another object is to provide a high temperature resistor of very simple construction in a plurality of pieces whereby a piece that has deteriorated can easily be replaced. Another object of the invention is to provide an electric furnace capable of operating at high temperatures over a long period of time. Another object of the invention is to provide a resistance element of such material, shape and characteristics that it can be operated at high temperatures without channeling and without burning out.

Another object of the invention is to provide heating resistors and furnaces utilizing them of particular utility in research laboratories for the attainment of high temperatures.

Other objects will be in part obvious or in part pointed out hereinafter. The invention accordingly consists in the features of construction, combinations of elements and arrangements of parts, as will be exemplified in the structure to be hereinafter described and the scope of the application of which will be indicated in the following claims.

In the accompanying drawings, illustrating one of many possible embodiments of the mechanical features of this invention:

Figure 1 is a vertical axial sectional view of a furnace having a resistor constructed in accordance with the invention,

Figure 2 is a plan view of the furnace,

Figure 3 is a vertical sectional view of a crucible and material therein for starting the furnace,

Figure 4 is a graph illustrating stable and unstable conditions in such a furnace under different loads and at different temperatures,

Figure 5 is a graph of critical temperatures for a zirconia resistor in different ambient temperatures,

Figure 6 is a graph of the heat radiated per square centimeter of a zirconia resistor at the critical temperature for different ambient temperatures.

As conducive to a clearer understanding of certain features of the present invention it is pointed

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out that while it has long been known that many oxides are electrical conductors at elevated temperatures, these oxides in general have negative temperature coefficients of resistance, especially those which seem from all standpoints to indicate usefulness as heating resistors. Since zirconium oxide, also referred to as zirconia, doesn't melt until the extremely high temperature of about 2700° C. is reached, it would at first blush appear to be an excellent material for a heating resistor; but besides having a negative temperature coefficient of resistance, it undergoes a sharp volume change upon heating and cooling. Also it is such a poor conductor at low temperatures that it must be heated by another source of heat before it will operate. Hence when used as a heating resistor, the furnace has to be heated by another means in order to make the zirconia resistor or resistors conducting. Furthermore the negative temperature coefficient results in a decreasing resistance as the temperature rises and on a constant potential source the resistor either becomes progressively hotter and hotter until it burns out, or it cools off and ceases to conduct. Moreover the negative temperature coefficient of zirconia has caused rods made thereof to become molten along the axis because the current always tends to flow wherever the material is hottest. This phenomenon is known as channeling and has been pronounced in cases where furnaces have been provided with large oxide heating resistors. Channeling can also occur in tubular resistors, the material heating more along one side or axial strip, with consequent failure. Other difficulties have heretofore been encountered. One of the objects of this invention is to overcome such disadvantages and difficulties.

Referring now to Figures 1 and 2, the furnace has a pair of supporting blocks 10 which can be made of any suitable refractory material but I have found that sintered zirconia blocks give very good results in actual practice. As shown these supporting blocks 10 are rectangular parallelepipeds and two of them together form a square in plan view. I have not found it necessary to cement them together; they can be merely laid together on any flat surface.

Supported by the supporting blocks 10 is a column of zirconium oxide resistor rings 11 which collectively form a hollow cylinder, each ring 11 being rectangular in cross section so that it will fit nicely on the ring below it and the ring above it can fit nicely on it. These rings 11 are preferably not cemented together. The bottom ring 11 rests upon the supporting blocks 10 and the top ring 11 supports a furnace cap 12 having a

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sight hole 13. This furnace cap 12 is also preferably made of sintered zirconia but can be made of other refractory material. It is cylindrical with two diameters as shown, the smaller diameter portion extending downward into the space bounded by the hollow cylinder formed of the rings 11, for example to a depth of a little over one ring and leaving a reasonable clearance between itself and the rings, all as clearly illustrated in Figure 1.

Outside of and spaced from the cylinder of rings 11 is a hollow cylinder 15 of refractory material, preferably of sintered alumina although other material could be used. This cylinder 15 has a height the same as that of the cylinder of rings 13. Between the hollow cylinder 15 and the cylinder of rings 11 is a packing of zirconia grain 16. Fitting the outside of the hollow cylinder 15 is an asbestos sleeve 17. Outside of and spaced from the asbestos sleeve 17 is a coil 18 of copper tubing which is connected to a high frequency induction heater, for example a fifteen kilowatt, 10 megacycle oscillator. In these induction heating coils cooling water flows through the tubing. I preferably provide a sintered zirconia hearth block 20 resting on the supporting blocks 10. This may be a cylinder of a diameter somewhat less than the inside diameter of the rings 11 to allow a reasonable clearance as shown.

Especially for the resistor rings 11 and the hearth block 20 and preferably for the supporting blocks 10, the cap 12, and desirably for the zirconia grain, I use stabilized zirconia ZrO_2 preferably stabilized with from 3% to 6% lime, CaO , and the material may be made in the following manner. An electric arc furnace of the type disclosed in U. S. Letters Patent No. 775,654 patented November 22, 1904 to Aldus C. Higgins is provided. Furnaces of this type comprising iron shells cooled all over with a cascade of water have been in use practically ever since the date of the above patent and are well known to electro-chemists and therefore need not be further described herein. A furnace mixture of zirconia ore, coke, iron, carbon, and lime (CaO) is prepared. Various zirconia ores or partially purified zirconia powder can be used. In general these are the zircon and baddeleyite ores. However chemically purified zirconia can equally well be used but is of course more expensive.

The quantity of carbon provided in the furnace mixture should be two-thirds of the theoretical quantity of carbon required completely to reduce the silica plus 100% of the theoretical quantity required to reduce all the other oxides (except the zirconia) to metal plus about 20% excess over all of these quantities. This quantity can be varied from the above with no excess to the above or with 40% excess. The reason why only two-thirds of the theoretical quantity of carbon required completely to reduce the silica is provided is that about one-third of the silica is volatilized during the furnacing operation. On the other hand the excess mentioned is provided because some of the coke is used up by combining with oxygen other than that provided by the oxides to be reduced.

The quantity of iron should be enough to form with the silicon that is reduced from silica a ferro-silicon having an iron content of from 75% to 85%. The purpose of the iron is to combine with the silicon to form a ferro-silicon alloy which has a much higher specific gravity than elementary silicon and therefore will go to the bottom of the furnace and, after solidification, form a

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ferro-silicon button containing also other reduction products than can readily be separated from the rest of the ingot. The amount of iron to add is enough to make with two-thirds of the silicon present in the ore a ferro-silicon having an iron content of from 75% to 85% minus the amount of iron obtained by the reduction of the iron oxide in the ore to iron and this of course must take into account that a small percentage of iron oxide remains in the final product.

The quantity of lime as a stabilizing agent to be added should be from 3% to 6% of the amount of ZrO_2 in the ore. The reason for providing the stabilizing agent in the above percentages is that less will not satisfactorily stabilize the zirconia, and more will form a eutectic thus making the product less refractory. The stabilizing agent in the range given causes the zirconia to crystallize predominantly in the cubic system, but when less of the stabilizing agent is used the crystals are predominantly monoclinic. Orthorhombic or natural baddeleyite is monoclinic whereas the product of this invention is predominantly cubic. The monoclinic form of zirconia will not withstand many cycles of heating to over 2000° C. and cooling to 100° C. and even lesser temperature changes may cause cracking or fracturing of the heating element if it is made of monoclinic zirconia. A zirconia of predominantly cubic crystal form will, however, withstand heat shock for many cycles. When the lime is as much as 6% the crystals are nearly all cubic, when the lime is as low as 2.7% about 35% of the crystals are cubic. Zirconia having 3% to 6% of lime on the ZrO_2 is referred to as stabilized zirconia; the expression "stabilized" means that the zirconia does not have a detrimental volume change at the critical temperature of inversion of baddeleyite, normally about 1000° C. However I do not want to be limited to lime stabilized zirconia nor to the precise furnace operation described herein since magnesium oxide (3% to 6%) is likewise a stabilizing agent and other processes of combining the stabilizing agent with the zirconia can be effectively used. However the best material now known to me for the manufacture of the resistor heating elements is that above described.

For the manufacture of the supporting blocks 10, the hearth block 20 and the furnace cap 12 I may take zirconia grain, press it in a mold to produce the desired shape, and then fire it. I may proceed in the same manner to form the rings 11 and they can be ground to required dimensions after firing. Any suitable temporary binder, for example dextrine, can be used to form the "green" shapes which are preferably fired at cone 35. An illustrative example is to wet the grain with a solution of 2% water and 1% dextrine, the percentages being on the weight of the zirconia.

At ordinary temperatures the hollow cylindrical resistor, preferably made up of the series of superimposed rings 11, is non-conductive or insufficiently so to respond to the high frequency field created by the induction coil 18 which, as above noted, is connected to any suitable source (not shown) of high frequency energy, preferably a vacuum tube type of oscillator provided as usual with any suitable form of controls for varying at will or regulating the magnitude of the energy supplied to its load and preferably provided, also, with any suitable means for changing at will and for regulating the frequency of its output. Accordingly, the resistor

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is first heated up to conducting temperature, as by a gas flame or by a temporarily inserted auxiliary electric resistance unit such as a resistor rod of bonded silicon carbide energized from an extraneous appropriate source of current, but preferably its initial or preliminary heating is effected by placing in the furnace a refractory crucible filled with graphite powder and then energizing the induction coil 18 from the high frequency source of energy. The graphite powder being conductive, responds to the rapidly alternating field created by the coil 18; being finely divided or powdered, it is, in contrast to a solid cylinder of graphite, a sufficiently high resistance and the energy dissipated therein in the form of heat is sufficient to heat the oxide resistor 11-11. When the temperature of the latter has risen to around 1400° C., the oxide has a sufficiently low resistance or a sufficiently high conductivity to absorb energy from the oscillating field of the winding 18 and the crucible can then be lifted out.

During the stage of preparatory heating, as by the inserted crucible, care should be taken, as by controlling or regulating the frequency or energy output of the oscillator, to achieve relatively slow or gradual rise in temperature of the resistor 11-11 in order to effect as uniform heating as possible throughout its mass. In this manner each transverse section of the hollow tube-like resistor 11-11, whether subdivided into rings 11 or not, has substantially the same resistance, and as heating progresses with such controlled uniformity, decreases in resistance or increases in conductivity of the several sections take place at the same rate so as to maintain uniformity throughout. Each transverse section, looped by the oscillating field of the coil 18, can then respond substantially in the same measure or degree. Likewise, the dielectric losses in each section should be the same and increase at the same rate.

Illustrative dimensions of the zirconia heater tube 11-11 are a length of 8 inches, an outside diameter of 5 inches, and an inside diameter of 3.5 inches, giving a wall thickness of 0.75 inch. Where, as is preferred, the stabilized zirconia tube 11-11 is physically subdivided into transverse sections or rings 11-11, etc., as shown in Figure 1, an illustrative number of rings for the just stated dimensions is eight, giving each an axial length of one inch. These rings rest upon one another, and preferably their upper and lower faces are nicely plane, so that successive rings make good thermal contact with each other; illustratively, these faces may be ground flat. Also, as above noted, the rings 11 need not be secured one to the other, as by cement, and preferably they simply rest in flatwise engagement with each other. Illustratively, the coil 18 may be of 3/8-inch copper tubing and may comprise about five and a half or six turns.

The dimensional relations between diameter and wall thickness of the zirconia resistor tube 11-11 are preferably predetermined according to certain features of my invention so that the wall thickness of the zirconia tube is not too thick relative to the diameter of the tube and meets the criterion that

$$\frac{ID}{Wa} \text{ is not less than } 2$$

where ID is the inside diameter of the tube and Wa is the wall thickness. This preferred aspect of my invention will presently be further amplified. It is a factor that contributes toward

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overcoming limitations and difficulties heretofore encountered and toward achieving a number of practical advantages and results heretofore impossible so far as I am aware.

In order better to understand certain features of my invention, it will be assumed, in the following preliminary discussion, that the dividing planes between rings 11, 11, 11, etc., are imaginary and that we are considering a single unitary hollow or tube-like oxide resistor. Let it be further assumed that this unitary resistor tube is energized by an alternating current (say, 60 cycles) through electrodes making uniform surface contact therewith at its upper and lower end faces whereby substantial uniformity of current flow per unit area of the cross section of the resistor tube is substantially achieved. Such a resistor tube, being a hollow cylinder, may be regarded for analytical purposes as comprising a number of individual longitudinal resistor elements arranged in a circle and in intimate side wall contact with each other and each carrying the same amount of heating current there-through, and if the resistor tubes are dimensionally within the above criterion and certain preferred controls effected, it is possible to achieve operation of such a resistor and of the furnace without materially disturbing the just described uniformity of current flow through these imaginary longitudinal subdivisions or elements of the hollow cylinder.

If a constant potential is applied to the opposite ends of such a tubular resistor and it is heated by some suitable means until the resistor becomes conducting, the conditions are in general unstable and, without more, the temperature will increase until the element is destroyed. On the other hand, if the applied voltage is so controlled that the temperature does not run away, the likelihood is that one side of the tube will become warmer than the other parts, thus becoming a better conductor with increase in current therethrough, which in turn leads to still higher temperature until virtually all of the current is channeling down one side of the tube, which usually results in breakage. It is this sort of thing that has been one of a number of major factors heretofore limiting the uses of conductive oxides and preventing employment in heating elements of large surface area.

According to certain features of my invention, these obstacles are overcome. I have investigated the factors involved therein and as of aid in describing how I overcome the above obstacles, let it first be assumed that an elongated oxide resistor element, sufficiently small in diameter to heat uniformly throughout the cross section (say, on the order of 2 millimeters) is enclosed in a furnace maintained at a constant temperature T_0 . If a small current is passed through the element, heating it to some temperature T above that of the furnace, it will lose heat to the furnace through convection and radiation. At least, as a first approximation, one can reasonably represent the heat loss by the equation

$$H = k(T - T_0) + k'(T^4 - T_0^4) \quad (1)$$

in which H represents the heat lost per square centimeter in watts, k is the heat transfer coefficient through convection, and k' is the heat transfer coefficient through radiation. Temperatures are on the Kelvin scale. As a first approximation, I have taken the values of k and k' as 0.002 and 1.75 times 10^{-12} watts. For practical purposes, at temperatures of interest in this

art, the first term in the equation can be neglected. In calculating k' it was assumed that the emissivity of zirconia is 30% of black body. This figure is based upon measurements made in a laboratory.

Accordingly, the heat lost from the heating element at any temperature above the furnace temperature can now be calculated. Knowing the resistance of the oxide at any temperature, the E. M. F. required to supply the heat lost can be calculated. Such calculations have been made for a stabilized zirconia tube of large bore with a wall thickness of 2 millimeters (in effect representing a series of small-cross-sectioned elements arranged in a circle), and the results are plotted in Figure 4 for two furnace temperatures, 1000° K. (abscissae at the top) and 1600° K. (abscissae at the bottom). It is assumed, for the moment and for purposes of this analysis, that this very thin-walled tube remains at uniform temperature throughout its cross section.

The specific resistance of lime-stabilized zirconia has been measured over a wide temperature range, and while there are variations due to impurities, porosity, and grain size distribution, it can be represented reasonably well by the equation

$$\log_{10} R = \frac{5960}{T} - 2.82 \quad (2)$$

Both curves of Figure 4 go through a definite maximum, although the one for $T_0=1000^\circ$ K. rises much more steeply and attains its maximum much sooner than the other. At any temperature and constant voltage to the left of the maximum point the element will be stable, any fluctuation causing a higher temperature resulting in more energy being radiated than is generated, and the temperature will fall back to the equilibrium position. On the other hand, any potential and temperature to the right of the maximum point will lead to eventual run-away conditions, since any accidental displacement of the temperature upwards will cause a greater generation of heat than can be radiated and the temperature will rise at a progressively faster rate until fusion occurs.

Furthermore, the element is permanently unstable at any voltage above the maximum point. In this connection it should be pointed out that the voltage at the maximum point decreases as T_0 is increased, so that a potential that is safe at a low furnace temperature may become excessive as the furnace heats up.

The relation between the critical temperature (i. e., the temperature at maximum voltage) and the furnace temperature is given in Figure 5 and the following equation

$$T^4 - \frac{4}{B} T^5 = T_0^5 \quad (3)$$

In this equation, B comes from the variant of Equation 2,

$$R = Ae^{B/T} \quad (4)$$

in which, for stabilized zirconia, $A=0.00152$, and $B=13,700$. Note that A, which contains such factors as porosity, grain size, shape of cross section of the element, and magnitude of the specific resistance, does not appear in Equation 3. It is inconsequential, therefore, from a stability standpoint, how the heating element is formed as long as the activation energy of the conduction process is not affected.

Figure 5 shows that at low temperature the

critical temperature is very little above the ambient temperature, thus providing only a narrow region of stability, while at high furnace temperatures the stability limits are very wide. At furnace temperatures above 1800° K. instability is no longer possible with a voltage below that necessary to melt the zirconia element.

In Figure 6 is plotted the heat radiated from a square centimeter of zirconia at the critical temperature as a function of ambient temperature. It shows more strikingly than does Figure 5 that at low furnace temperatures the safe radiation from a heater is very low, while with high temperatures the performance per square centimeter can be large. This indicates that a large radiating surface per unit of heat output is very desirable.

Thus critical temperature and safe radiation desiderata are determinable for the oxide resistor whose wall thickness should not be great enough to permit detrimental or excessive radial temperature gradients, and in illustrating this aspect of my invention, specific criteria are above illustratively set forth for a stabilized zirconia element. No such radial gradients are present when, as has been assumed above for purposes of analysis, the assumed heating element is a solid cylindrical element so small in diameter and hence so small in cross section that its temperature is uniform throughout its cross section. Nor are they present in the large-bore thin-walled tube used in some of the above calculations. The latter, a large-bore thin-walled tubular heating element, is in effect an assembly of small-cross-sectioned parallel elements equally and uniformly energized electrically, and the conditions for stability within that assembly so energized are the same as those described above. Moreover, the thin-walled tube used in these calculations also meets the criterion for wall thickness earlier above set forth; the wall thickness is not great enough to permit excessive radial temperature gradients. The conditions for stability apply equally well to the stability of a multiplicity of identical heating elements connected in parallel in a furnace. It has been amply confirmed in experimental furnaces.

The stacked-ring zirconia heater tube 11-11 above described meets the criterion of wall thickness above set forth, and were the current to flow into and out of its ends at uniform current density throughout its end faces or surfaces, after preliminary heating has made the heater tube sufficiently conductive, the flow of current from one end to the other would take place at substantially uniform density throughout any cross section taken between the ends of the heater tube. It functions in effect like a set of small-cross-sectioned individual elements arranged integrally in a circle, and because the above relationship of wall thickness to inside diameter is not departed from, if any one of these imaginary elements or lengthwise subdivisions of the zirconia tube heats up beyond the others, it can and does lose more heat by radiation than it gains, and thus the conditions that are otherwise conducive to channeling are opposed. Thus continued heating up of the heater tube is facilitated, as is also subsequent operation of the furnace at the desired ultimate furnace temperature.

While the above mathematical derivations of the conditions for stability apply to a resistor radiating to furnace walls, the same conclusions can be reached where the outside of the tubular

resistor is insulated and radiation is across the space in the interior.

This action of continued heating up after the tube becomes conducting will thus also be seen to contribute toward maintaining uniform current density in a tube so energized, and thus uniform heating up is more reliably and more quickly attained. The action just above described might be said to achieve, under otherwise stable conditions, substantially automatic maintenance of temperature equilibrium throughout the mass of the heater, and a similar substantially automatic action takes place during the run of the furnace at its ultimate furnace temperature at which treatment of articles or materials is desired to take place.

It is preferred to supply energy to the hollow cylindrical element of the furnace under conditions of constant current control, and where the energy is supplied to its ends by suitable electrodes, this may be done as in my copending applications, Serial No. 184,926 and Serial No. 184,927, filed of even date herewith, and to which reference may be made, where I described a suitable current regulator of the supply system to the desired current value, the regulator being manually set to function at the selected standard or value of current to be kept constant. As there described, it is possible, once the heater has been heated to become sufficiently conductive, to set the regulator at a current value that will ultimately give the desired operating furnace temperature upon completion of the heating up by the current itself, for the above-described dimensional criterion or characteristic of the zirconia tubular heater and the limitation of current or amperage effected by the current regulator coact to achieve prevention of conditions of instability such as those described above in connection with Figure 4. Because of such coactions and by setting the current regulator to successively different standards of operation, it is also possible to supply current to the heater tube at a different value during the heating-up period than is supplied during the continued operation of the furnace at its desired temperature, so long as the change in value is effected with due regard to the conditions of stability and of instability that exist, respectively, to the left and to the right of the maximum points of the graphs, such as those of Figure 4, for the heater element. Because of the wide range of stability that exists to the left of the knee in the graphs, preciseness and closeness of control can be departed from and energization, throughout that range of stability, could even be effected at higher current values or at varying (e. g., increasing) current values, and in this latter connection the energy could be applied in successive stages at successively higher values so long as the relatively high critical voltages (to the left of the maximum point in the graphs) are not reached or exceeded for any current value employed, and thus channeling is opposed further during the heating-up period. But substantial precision and closeness of control of constancy of current should be instituted just before or when the critical temperature is reached, for thereafter, as above explained and demonstrated, conditions of instability can be brought about at potentials and temperatures to the right of the maximum point in the corresponding graph like that of Figure 4. In the latter range (to the right), because the resistance of the oxide element continues to decrease, a given constant current flow

is accompanied by continual decrease in voltage, and the standard of current regulation can be raised to achieve higher temperatures in the furnace, but always within the just described voltage and temperature limits.

It is according to the principles and within the methods of energization just described that the furnace structure of Figure 1 is operated, and by manipulating or setting the various regulating controls of the high-frequency oscillator, continued heating up of the zirconia tube element 11-11 is effected within the limits of the factors of stability to the left of the maximum point, in effect maintaining the effective induced voltage below the critical limit; as earlier pointed out, the heating-up process should also be effected slowly in order thereby, also, to maintain uniform rise in temperature throughout the mass of the oxide resistor element. In this manner channeling during heating up can be better guarded against. In assembling the induction coil 13 relative to the oxide heater tube 11-11, both being of circular cross section, they are positioned (the coil 13 being supported by any suitable means, not shown) so that they are coaxial and so that the one is substantially uniformly distributed lengthwise relative to the other, at least throughout the effective length of the interior furnace space, and the winding positioned relatively close to the heater tube (about in the relationship shown in Figure 1 for the above given dimensions of the heater tube), so as to provide an appropriate coupling between the two to transfer energy from the coil to the conductive resistor element, having due regard for the need of heat insulation between the two as is provided by the parts 16, 15, and 17 of Figure 1.

The operation of this furnace has been based upon the assumption that uniform current flows axially through the walls of the heating cylinder, the same conclusions can be reached when, as in this case, the current flows tangentially around the cylinder.

Nevertheless, during the heating-up process there may be a tendency for one transverse section of the tubular oxide element to heat up more, or more rapidly, than another. There are some differences in the inductive effects on the different rings, differences in heating loss, viz., the end rings lose heat more rapidly than the center, and it is at times difficult during the early heating-up period to apply the alternating magnetic field to such intensity as to raise the temperature but still not to exceed the critical conditions for any of the rings. On account of these causes and possibly some variations in resistance from ring to ring, heating during the early period may be non-uniform. Whatever the cause, I have found that the effect is to break the oxide tubular element were it to be made of a single piece throughout its length, fracture occurring usually in the general direction lengthwise of the tube, apparently because one transverse portion expands more rapidly than the other; breakdown of furnace operation may result.

But I have also found that by physically and actually sectionalizing the oxide heater tube 11-11 into transverse rings or sections 11, 11, 11, etc., I am enabled to achieve efficient continued heating up and subsequent operation of the furnace at the desired ultimate furnace temperature. With such a succession of rings yieldably held in face-to-face and end-to-end contact, as by stacking one upon the other, each is free to expand individually of the other and

the operational integrity of the physically subdivided oxide heater tube is maintained. I have found, as a result, that as the temperature rises during the completion of heating up, any uneven heating of the above-mentioned kind becomes less and less evident, thus showing that the action of the physical subdivision into rings progressively counteracts more and more the causes that give rise to such uneven heating, and by the time the selected furnace operating temperature is reached, which illustratively may be 2000° C. or even up to 2600° C., the tubular wall structure shows a remarkable uniformity of temperature throughout. And it so continues during the continued furnace run.

Moreover, I have found that these same beneficial advantages and results take place even if, during the heating-up process, one or more of the rings 11 become cracked. Not only does the laminated or built-up oxide heater tube remain physically intact and serves, as in the illustrative embodiment of Figure 1, also as the furnace chamber to receive, on the hearth block 20, products to be treated, but also no detrimental heating action is perceptible with respect to any cracked ring or rings. This probably is because, even if circulatory currents were to be lessened or halted by the crack through the ring, eddy currents and some dielectric heat losses would still continue to be effective throughout the mass of the ring, or perhaps also by the fact that the circuit of the cracked ring is maintained closed by the adjacent face-to-face contacting ring or rings. Moreover, it appears clear, from tests, that a crack or cracks in any ring do not interrupt the path of flow of current around and within the ring, because, at the high temperatures involved, there is a heavy electron emission from the oxide and any gap that results from the crack is highly conductive. Moreover, also, any such crack is usually very small and, hence, the gap very narrow.

By the way of illustration, with the above-described furnace structure, a temperature of 2170° C. was attained with an energy of about 5 kw. input from the above-described 15 kw. 10 megacycle oscillator. In the range of such high temperatures, operation is very smooth and there is no sign of instability.

The above temperature of 2170° C., attained with an input of approximately 5 kw., was at a frequency of 10 megacycles and was achieved with the existing coupling coefficient between the above-described and dimensioned furnace structure of Figure 1. Higher power inputs and hence higher temperatures are achievable by improving the coupling coefficient of above or by balancing of the circuit with respect to the load. The optimum frequency at the just-mentioned temperature is much below 10 megacycles and is about 3 megacycles, and I have found that the applied frequency can be rather widely removed from the optimum and effective functioning of the furnace still achieved. I have found that the type and character of coupling effected as above described in the structure of Figure 1, apparently cause the coupling to act in the high-temperature or furnace operating range to decrease energy transfer from the induction coil 18 as the temperature and conductivity of the zirconia resistor element increase, and because the induced current increases with reduced resistance, the inductive reaction upon the induction coil 18, in effect loading it, serves to diminish voltage as the current increases and thus main-

tain the operation well within the temperature and voltage limits of stability as explained above with respect to the region to the right of the maximum point in the graphs of Figure 4.

Thus it will be seen that, by my invention, many thoroughly practical advantages are successfully achieved. Various risks, damage, losses, and limitations imposed or caused by channeling can be successfully lessened and controlled stability achieved according to the principles of my invention. While I have described my invention in connection with the use of zirconia resistor elements, and more particularly stabilized zirconia heater elements, I have done so because of the over-all superiority and many novel advantages that I am enabled thereby to achieve, but I do not wish to be limited thereto except as such limitation may be expressed in one or more of the claims. Many of the advantages and various of the results of my invention may be achieved by utilizing other known refractory oxides that are conducting at high enough temperatures. Of course, elements of expense or cost of some of these will enter as a consideration in their practical application. Also, the particular characteristics of any such other refractory oxide might make it more suitable for some particular purpose; for example, for very high temperatures, thoria may be employed in preference to zirconia because, for example, it has a higher melting point. Whatever the selected refractory oxide, stability of operation may be achieved according to the principles fully explained and illustrated above in connection with the use of stabilized zirconia, as, for example, by shaping it in the form of a tube in which the relation between the inside diameter and wall thickness is such that detrimental or excessive radial temperature gradients are not produced, and supplying electrical energy thereto so controlled that ambient temperature and resistor temperature are maintained within those ratios that mean stability, as is illustratively explained above in connection with stabilized zirconia tubular resistors.

It will also be seen that some known disadvantages or limitations met with heretofore are overcome, according to my invention, by the use of zirconia tubes instead of solid rods, others by the use of stabilized zirconia, others by the use of laminated or sectionalized oxide tubes (like the rings 11, 11, etc.), still others by an interrelated ring sections and induction heater coil (like coil 18), and still others by constant-current supply or current-limiting regulation, all as illustratively above described.

It will thus be seen that there has been provided by this invention a high-temperature resistor in which the various objects hereinabove set forth, together with many thoroughly practical advantages, are successfully achieved. As many possible embodiments may be made of the invention and as many changes might be made in the embodiment above set forth, it is to be understood that all matter hereinbefore set forth or shown in the accompanying drawings is to be interpreted as illustrative and not in a limiting sense.

I claim:

1. A high temperature electric furnace comprising a refractory enclosure, an induction coil adapted to be energized from a source of high-frequency alternating current, and a substantially non-channeling refractory oxide secondary for said induction coil comprising a plurality of coaxial individually unitary and continuous ring-

shaped resistor elements within said enclosure and substantially coaxial with said induction coil and made of a refractory oxide that is selected from the group consisting of zirconia and thoria, stabilized, containing from 3% to 6% of alkaline oxide selected from the group consisting of lime and magnesia and that has to be heated to become significantly conductive and that has a negative temperature coefficient of resistance, said plurality of ring-shaped resistor elements as a whole forming a hollow cylinder that has a ratio of surface area to cross-sectional area greater than that at which, for a given uniform temperature at which it is conductive, heat is generated internally thereof, in response to induced current flow therein, faster than the cylinder can lose heat through its surface, and means for raising the temperature of said ring-shaped resistor elements to become inductively affected by the field produced by said induction coil, said induction coil being adapted to induce substantially constant value of current in said refractory oxide secondary at relatively low voltage within the voltage factor of stability of the refractory oxide for the temperature of continued furnace operation.

2. A high temperature electric furnace comprising an induction coil adapted to be energized from a source of high-frequency alternating current, and a substantially non-channeling refractory oxide multi-turn secondary for said coil in the form of a plurality of individually unitary and continuous contacting ring-shaped pieces of a refractory oxide having a negative temperature coefficient and having contacting end surfaces each of relatively large area compared to the radial cross-sectional area of the ring-shaped piece, each being of the same diameter, inside and outside, and the ratio of the inside diameter of said pieces to the wall thickness thereof in a radial direction being not less than two, said ring-shaped pieces being arranged coaxially and surrounded by said induction coil and with end surfaces of adjacent pieces in conductive contact whereby, upon radial fracture of any one ring-shaped piece, its adjacent conductively-contacting ring-shaped piece maintains continuity of conductivity of the fractured piece in circumferential direction.

3. A high temperature electric furnace comprising an induction coil adapted to be energized from a source of high-frequency alternating current, and a substantially non-channeling refractory oxide multi-turn secondary for said coil in the form of a plurality of individually unitary and continuous contacting ring-shaped elements made of a refractory oxide selected from the group consisting of zirconia and thoria, stabilized, containing from 3% to 6% of alkaline oxide selected from the group consisting of lime and magnesia, said ring-shaped elements having end surfaces of a shape adapted to engage with the end surface of an adjacent ring-shaped element for conductive contact therewith, said ring-shaped elements being of the same diameter, inside and outside, and each having a ratio of surface area to cross-sectional area greater than that at which, for a given uniform temperature at which they are conductive, heat is generated therein, in response to electric current flow, faster than heat can be lost through said surface area.

4. A substantially non-channeling multi-turn refractory oxide secondary for an induction coil high temperature electric furnace, said secondary consisting of a plurality of individually unitary

and continuous ring-shaped elements made of a refractory oxide selected from the group consisting of zirconia and thoria, stabilized, containing from 3% to 6% of alkaline oxide selected from the group consisting of lime and magnesia, said ring-shaped elements having end surfaces of a shape adapted to engage with the end surface of an adjacent ring-shaped element for conductive contact therewith, said ring-shaped elements being of the same diameter, inside and outside, and each having a ratio of surface area to cross-sectional area greater than that at which, for a given uniform temperature at which they are conductive, heat is generated therein, in response to electric current flow, faster than heat can be lost through said surface area.

5. A resistor for a high temperature electric furnace comprising a plurality of individually unitary and continuous ring-shaped resistor elements each made of a refractory oxide that comprises principally the reaction product under heat of zirconia with lime of a quantity on the order of from 3% to 6% of the amount of the zirconia, and that has to be heated to become significantly conductive and each having annular end faces for making surface contact with each other when arranged coaxially, said resistor elements having a ratio of surface area to cross sectional area greater than that at which, for a given uniform temperature at which they are conductive, heat is generated therein, in response to electric current flow, faster than heat can be lost through said surface area.

6. A resistor for a high temperature electric furnace comprising a plurality of individually unitary and continuous ring-shaped resistor elements each made of a refractory oxide that is selected from the group consisting of zirconia and thoria, stabilized, containing from 3% to 6% of alkaline oxide selected from the group consisting of lime and magnesia, and that has to be heated to become significantly conductive and each having annular end faces for making surface contact with each other when arranged coaxially, said resistor elements having a ratio of surface area to cross sectional area greater than that at which, for a given uniform temperature at which they are conductive, heat is generated therein, in response to electric current flow, faster than heat can be lost through said surface area.

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