Feb. 19, 1957 A. D. EVANS 2,782,246

TEMPERATURE CONTROL

Filed March 30, 1955 3 Sheets-Sheet 1

FIG. 1

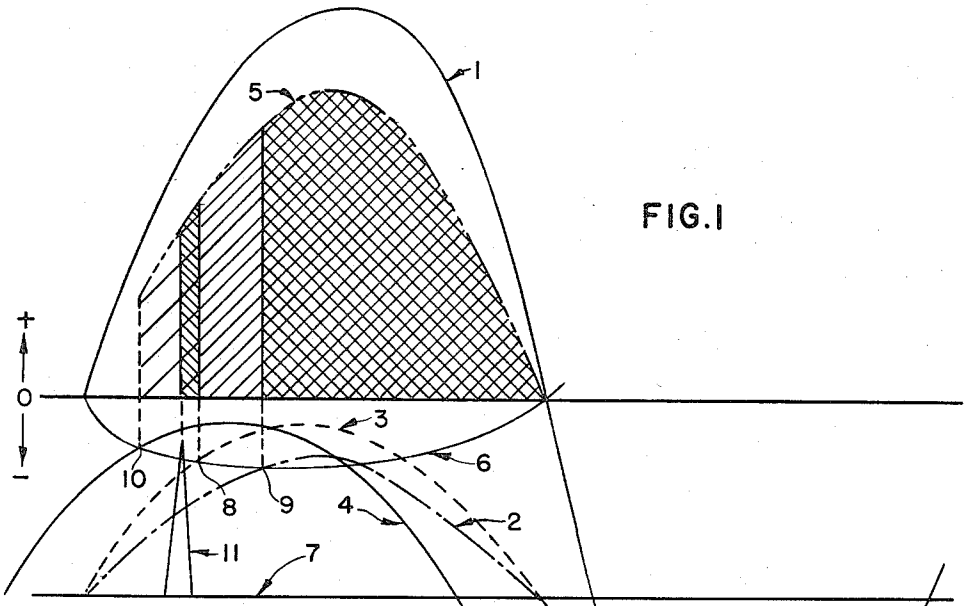
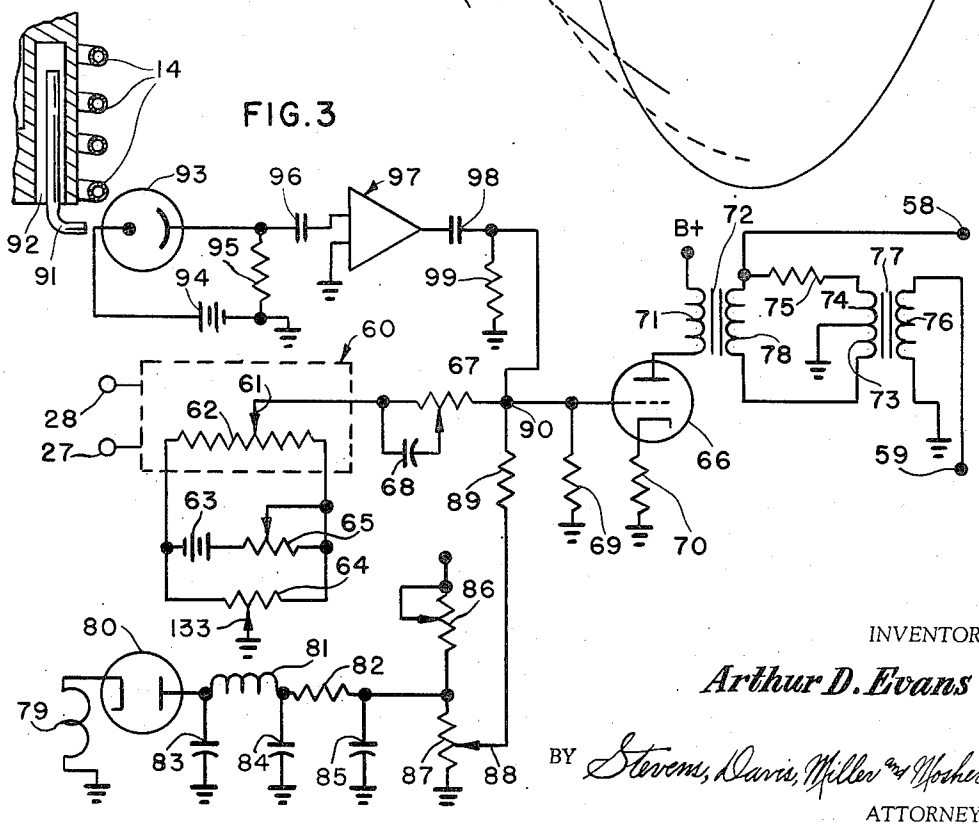


FIG. 3



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TEMPERATURE CONTROL

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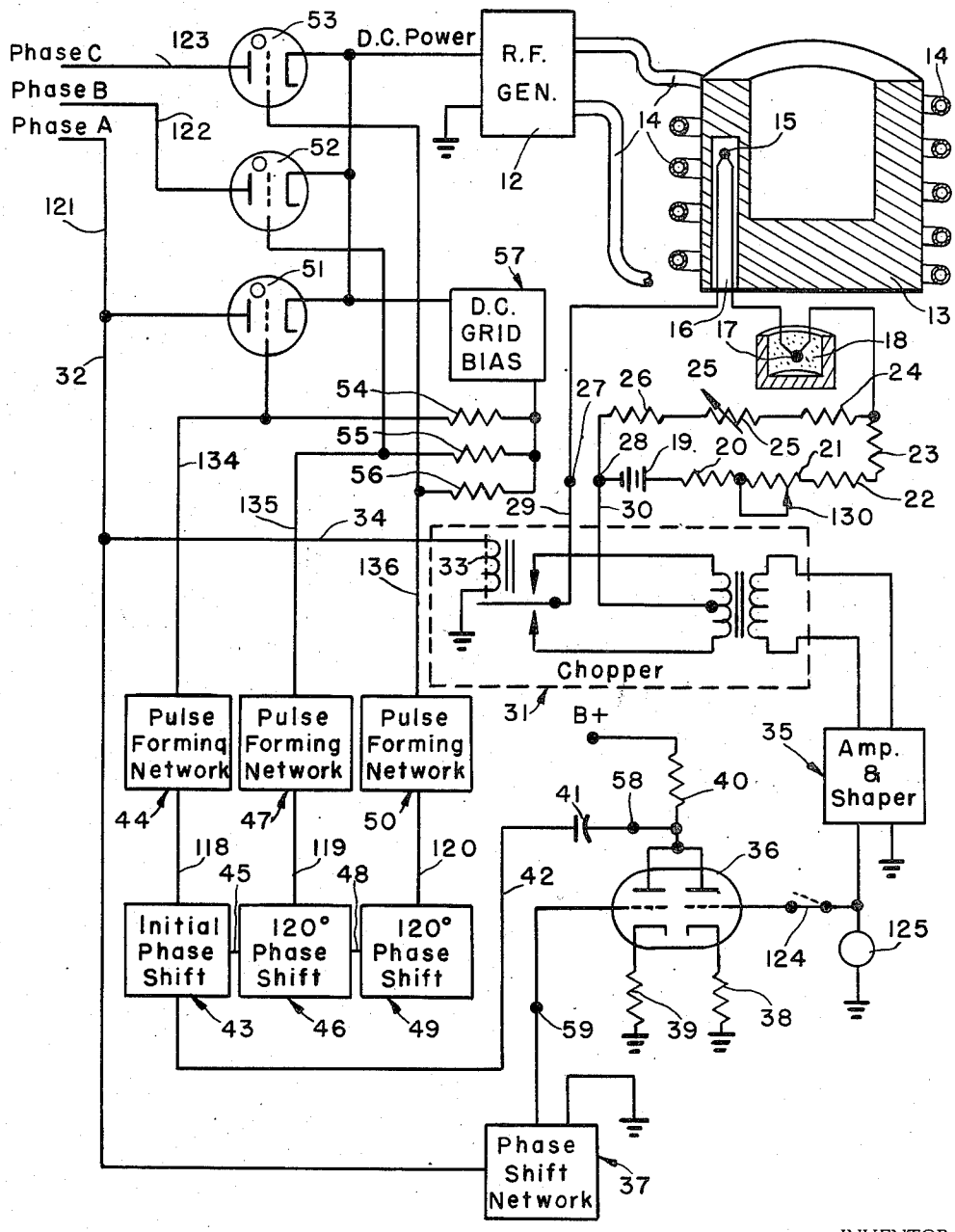


FIG. 2

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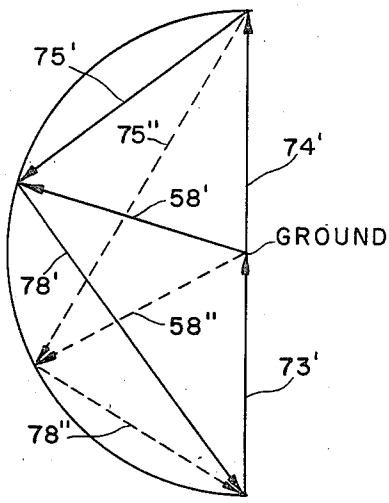
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TEMPERATURE CONTROL

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FIG.4



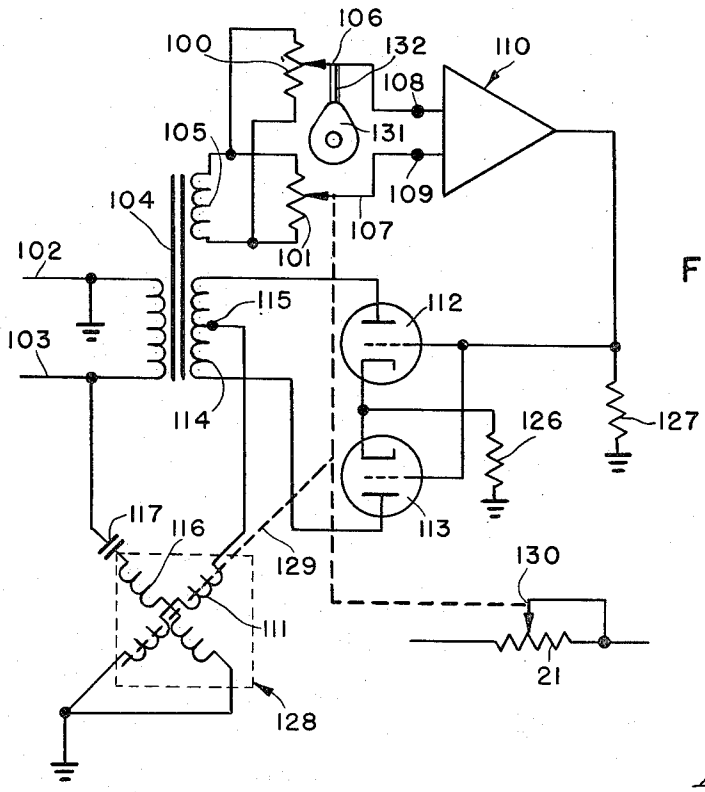


FIG.5

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2,782,246

TEMPERATURE CONTROL

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Application March 30, 1955, Serial No. 497,858

24 Claims. (Cl. 13—24)

This invention relates to temperature control systems and more particularly to a servo-system to precisely control the temperature of an electric furnace.

An early stage in the manufacture of semiconductor devices, such as transistors and crystal diodes, is the preparation of a monocrystalline ingot of semiconductor material. From this ingot or crystal are cut the small bars or wafers used to form the transistor and diode elements. The electrical characteristics of semiconductor devices are determined almost entirely by the impurity content, impurity distribution and crystal structure of the semiconductor material used in their manufacture. Most of the electrical characteristics of the finished devices are therefore fixed at the stage of manufacture in which the ingot is formed, and, for best electrical characteristics, the ingot must be a single crystal structure which is entirely free of impurities and lattice defects except at the exact points where they are desired.

One of the most widely used processes for obtaining such a semiconductor crystal involves melting a quantity of extremely pure semiconductor material in an inert atmosphere or in a vacuum. A small piece of a crystal of the desired lattice structure, called a seed, is then placed in contact with the melt. Through careful control of the temperature of the melt and the speed of withdrawal of the seed, a crystal of crystallographic orientation identical to that of the seed may be developed between the seed and the surface of the melt. By precision control of slight changes in temperature and withdrawal rate, a crystal of the desired size and shape can be obtained.

Because of the degree of purity which must be maintained in the semiconductor material throughout the growing process, the most practical heating method has been found to be a radio-frequency induction furnace in which the induction coils surround the lower portion of a sealed, transparent container of high temperature material such as glass or quartz. The charge of semiconductor material to be melted is placed in a graphite crucible within the container in such a position that it is surrounded by the induction coils. Such an arrangement has the advantage of allowing for continuous inspection of the semiconductor crystal during the growing process, concentration of the heating energy in the crucible and charge, and introduction of an inert atmosphere into the container to avoid contamination of the semiconductor material by gas or particles in the air which might react with the charge, as well as preventing the charge from becoming contaminated by heater electrodes or other materials which would necessarily come in contact with the charge in other types of furnaces.

By far the greatest problem in the crystal growing process described above is the precise control of the temperature. The melting point of semiconductor materials is relatively high; germanium melts at approximately 958.5° C. and silicon at approximately 1420° C. At certain times during the growing process it is desirable to bring the temperature of the molten charge very near

the melting-solidifying temperature. For this reason, it has been found necessary to control the temperature to within 0.2° C. at from approximately 900° to 1000° C. for germanium and 0.2° C. from approximately 1400° to 1600° C. for silicon.

The usual type of temperature control for an electric furnace is of the "on-off" cycling type in which the heating elements are turned on at a certain minimum temperature and then turned off at a certain maximum temperature. Because of the lack of control of the temperature between the minimum and maximum limits, even though these limits are relatively close together, the on-off type of control is entirely unsatisfactory for the process above described. The present invention controls temperatures through continuous incremental variations in the electrical power input to the furnace. This continuous power variation control has been accomplished by adapting to precise automatic electronic control the well-known manual method of setting the output power of radio-frequency generators. In this manual method of setting generator power output, either the phase or the amplitude of the grid voltages to the Thyratron rectifier tubes of the D.-C. voltage supply for the generator is adjusted to the setting at which the duty-cycle of each Thyratron is of such length that the average D.-C. power supplied to the generator by all the Thyratron tubes will be just sufficient to produce the desired radio-frequency power output. A "Thyratron" is a trademarked product descriptive of grid controlled, gas-filled, thermionic emission devices. In the temperature control system of the present invention, the phase of the Thyratron grid voltages, after the initial manual setting, is electronically varied in response to an electrical signal generated by a temperature measuring device within the furnace. Thus, the input power to the furnace is precisely and automatically adjusted to compensate for any variations in the furnace temperature from the desired operating temperature.

It is one object, then, of the present invention to provide a precise and accurate temperature control system for radio-frequency induction furnaces and other types of electric furnaces.

It is another object of the present invention to provide an induction furnace which is suitable for manufacturing the monocrystalline ingots of semiconductor material used in the fabrication of bars and wafer segments for transistors and diodes.

It is still another object of the present invention to provide a means for controlling the temperature of the charge of an electric furnace to within 0.2° C. at temperatures from approximately 900° C. to approximately 1600° C.

It is still another object of the present invention to provide a means for controlling, to a high degree of accuracy, variations in the firing time and duty-cycle of gas-filled, grid controlled, thermionic emission devices in such a manner that their average power output is precisely controlled.

It is a still further object of the present invention to provide a means for accurately controlling the changes in temperature of a charge in an induction or other type of electric furnace according to a predetermined program of temperature changes.

The above objects together with other objects and details of the present invention will become apparent from the following description when taken in conjunction with the accompanying drawings in which:

Figure 1 is a plot of amplitude against time for the various voltages and currents of a typical negative grid Thyratron tube of the type used in the temperature control system of the present invention;

Figure 2 is a schematic-diagrammatic illustration of

one embodiment of the temperature control system of the present invention;

Figure 3 is a schematic diagram of the electrical circuit of a second embodiment of the temperature control system of the present invention including two additional temperature measuring methods;

Figure 4 is a vector diagram illustrating the various voltages of the phase shifting network portion of the circuit illustrated in Figure 3; and

Figure 5 is a schematic representation of a temperature changing mechanism which may be used with the temperature control system of the present invention.

With reference now to Figure 1, the input power control method of the present invention will be explained. The control function is achieved through an electrical signal which controls the conducting period of the one or more Thyratron rectifier tubes providing primary D.-C. power to the furnace heating means. The Thyratron is a type of tube well-known in the electronic art. It has three elements, namely a grid, plate, and cathode, and is filled with an inert gas. One of its characteristics is that with a voltage applied between its plate and cathode elements, the tube will not conduct current until the grid voltage is made sufficiently positive for the tube to "fire," which voltage is known as the critical grid voltage. Referring to Figure 1, there is illustrated a plot of a typical critical grid characteristic **6** for a type of negative grid Thyratron suitable for use in the present invention. It can be seen that this critical grid voltage is dependent to some extent on the plate voltage (curve **1**) applied to the tube in that, as the plate voltage increases, the critical grid voltage becomes more negative.

Another Thyratron characteristic is that, after the tube fires, the grid no longer controls the amount of current flowing through the tube and the tube continues to conduct even after the grid voltage has fallen below the critical grid voltage. Once the tube begins to conduct, the amount of current flow through the tube depends only on the magnitude of the plate voltage and the tube continues to conduct until the plate voltage drops to a value equal to the inherent voltage drop across the tube, approximately five to ten volts. Thus, it can be seen that the average D.-C. power output of a Thyratron rectifier can be controlled by controlling through grid voltage variations the time at which the tube fires during each positive half-cycle of the A.-C. plate voltage. Figure 1 illustrates that these grid voltage changes may be either in phase or in amplitude to effect a change in firing time. Shown in the drawing are the curves of the A.-C. voltage **1**, a negative D.-C. grid bias voltage **7** to hold the grid below the firing point, the A.-C. grid voltage signals **2**, **3**, and **4**, and the plate current curve **5** for a negative grid Thyratron. The grid voltage curves **2** and **3** illustrate the effect of a change in grid voltage amplitude. Both of these grid voltages are in phase with the plate voltage **1** but the voltage of curve **3** is greater in amplitude than the voltage of curve **2**. With the voltage of curve **3** on its grid, the Thyratron will fire at the time indicated by the point at which this curve **3** crosses the critical grid voltage curve **6**. This point is designated as **8**. When the tube fires, the plate current flow rises immediately to the value indicated by the current curve **5** and continues to follow curve **5** until the tube is extinguished by the removal of the positive plate voltage. If a grid voltage of smaller amplitude, curve **2**, is impressed on the grid, the tube will not fire until a later time designated by the cross-over point **9**. It can easily be seen that different total amounts of plate current will flow during the plate voltage cycle according to the amplitude of the grid voltage of the Thyratron.

The grid voltage curve **4** illustrates how the same plate current control can be exercised by shifting the phase of the grid voltage. The voltage of curve **4** is of the same amplitude as the voltage of curve **3**, but it causes the Thyratron to fire earlier in the plate voltage cycle and to conduct more current during the cycle because the voltage of curve **4** is leading the voltage of curve **3** in phase and so reaches the critical grid voltage **6** at an earlier time designated as point **10**. Thus, by controlling either the phase or the amplitude of the grid voltage, the total amount of plate current flow during each plate voltage cycle and therefore the average D.-C. power output of the tube over a number of plate voltage cycles can be controlled. It is to be understood that a sharp spike of voltage such as **11** will fire the tube just as well as the sine wave voltages of the other grid voltage curves **2**, **3**, and **4**.

Turning now to Figure 2, a schematic-diagrammatic representation of one embodiment of the temperature control circuit of the present invention is shown in which the furnace controlled is of the induction type for purposes of illustrating the circuit. A radio-frequency generator **12** whose input power is controlled by Thyratron tubes **51**, **52**, and **53** as described above is used to heat the crucible **13** and charge (not shown) by means of the output coils **14**.

The temperature of the crucible and the charge is measured by means of a thermocouple **15** which is placed in a cavity **16** of the crucible **13**. In series connection with this hot junction thermocouple is a cold junction thermocouple **17** immersed in an ice-water bath **18**. Because the temperature of melting ice is constant, this cold junction thermocouple **17** provides the necessary constant temperature reference for the system. As is well-known, a thermocouple arrangement such as this produces an E. M. F. proportional to and varying directly with the temperature of the hot junction. A thermocouple wherein one element is platinum and the other element is an alloy comprised of 90% platinum and 10% rhodium, provides a sensitivity in the order of ten microvolts E. M. F. change per degree centigrade change in temperature over the range of about 900° C. to 1400° C. and has been found quite satisfactory for use in the present invention.

As a means to detect temperature changes in the order of 0.2° C., i. e., a thermocouple voltage change of two microvolts, an extremely sensitive bucking voltage system is used consisting of the battery **19** and the voltage divider resistors **20** through **26** inclusive. By varying the resistance of an element, say **25**, of the voltage divider network, the bucking voltage provided by the network, i. e., the voltage drop across the resistors **24**, **25**, and **26**, can be controlled and made to cancel exactly the thermocouple E. M. F. at the desired temperature. Thereafter, any change in the thermocouple voltage output due to a temperature change in the crucible will be indicated as a D.-C. error voltage at the terminals **27** and **28** and its polarity will depend on whether the temperature change is an increase or a decrease. Since it is much easier to detect changes of from one to twenty microvolts from a zero potential level than to detect a change of this same order of magnitude from a 10,000 microvolt level, the bucking voltage network allows accurate detection of extremely small temperature changes.

This D.-C. microvolt indication of temperature change is then fed through lines **29** and **30** to a chopper circuit **31** of the non-rectifying vibrator type well-known in the art (see Radiotron Designer's Handbook, Lanford-Smith, fourth edition, 1953, at page 1203), which has its vibration frequency controlled by the external excitation of its coil from an A.-C. voltage. The chopper **31** is synchronized at the power line frequency by the A.-C. voltage from the phase A power line **32** fed to the chopper excitation coil **33** through line **34**. The phase of the chopper output depends on the polarity of the D.-C. signal fed into it and, therefore, the chopper output voltage will be an A.-C. voltage either in phase with the voltage of the chopper excitation coil **33** (phase A voltage) or 180° out of phase with the chopper ex-

citation coil voltage as determined by the polarity of the input signal. This A.-C. voltage is then fed from the chopper to an amplifier shaper circuit **35** where it is amplified and formed into a sine wave of the same phase as the chopper output voltage and of an amplitude which is proportional to the amplitude of the D.-C. signal appearing at terminals **27** and **28**. This sine wave signal is next fed to the grid of one-half of the dual triode mixer tube **36**. The other grid of tube **36** has impressed on it a sine wave signal derived from the phase A power line **32** but shifted in phase by a phase shifting network **37** so that the signals of the two grids are exactly 90° out of phase. The two cathodes of tube **36** are each connected to ground through their respective cathode resistors **38** and **39**. The two plates of the tube **36** are tied together and connected to B+ through the load resistor **40**. The output voltage from the plates through condenser **41** and line **42** is, then, a voltage which is proportional to the vector sum of the two input grid signals. This output is also a sine wave signal but its phase depends on the amplitude and phase of the grid signal from the chopper amplifier circuits **31** and **35**. In this manner, there has been produced a sine wave signal whose phase changes with any crucible temperature change.

The variable phase sine wave voltage appearing on line **42** is next fed to the initial power control phase shift network **43** where its phase can be set as desired. (The proper setting of the phase of the output voltage from the phase shift network **43** will be discussed later.) Two sine wave voltage outputs are taken from the initial power control phase shift network **43**. One of these output voltages, on line **118**, is fed to the pulse forming network **44** whose output is a sharp "spike" pulse of voltage. The second output, on line **45**, is fed to the constant phase shift network **46** which also produces two output voltages. Both of these output voltages lag the input voltage to the network **46** in phase by exactly 120°. One of these outputs is fed through line **119** to another pulse forming network **47** which produces a spike pulse of voltage at its output. This pulse lags the output pulse of the network **44** by exactly 120° because of the phase shift introduced by the network **46**. The second output of network **46** on line **48** is used as the input signal for still another 120° constant phase shift network **49**. The single output signal from the network **49** on line **120** when impressed on the input terminals of the pulse forming network **50** produces at the output terminals of the network **50** a third spike pulse of voltage which lags the pulse from network **44** by exactly 240° and lags the pulse from the network **47** by 120°. In this way there have been produced three sharp pulses of voltage whose phase relationship corresponds to the phase relationship of the voltages of the three power lines **121**, **122**, and **123** supplying plate voltage to the three Thyratron tubes **51**, **52**, and **53**. These sharp pulses of voltage are impressed on the grids of the Thyratrons **51**, **52**, and **53** through the lines **134**, **135**, and **136** respectively to control the firing times of the tubes.

The grids of all three Thyratrons **51**, **52**, and **53** are biased below the critical grid voltage by their connection through the resistors **54**, **55**, and **56** to a negative grid bias supply **57**. Thus, the firing time of each Thyratron and, consequently, the average D.-C. power to the radio-frequency generator depends on the time of arrival, i. e. the phase with respect to the A.-C. power line voltage, of the spiked grid pulses which fire the tubes by causing their grids to become more positive than the critical grid voltage. Since the phasing of these grid pulses is a function of the thermocouple **15** voltage, there has been established a control system capable of regulating the furnace temperature through continuous control of the input power to the furnace. The control is to such a fine degree that changes can be produced from one cycle of input power to the next.

Although three Thyratron tubes connected as half-wave rectifiers are illustrated, the present invention is not to be construed as limited only to the use of such a rectifier circuit, for, by incorporating a lesser or greater number of pulse forming networks together with associated phase shift networks to produce the proper phase shifts for the several grid control voltages, the present temperature control system may be adapted to be used with either full-wave or half-wave rectifier circuits supplied from either single-phase or poly-phase power voltages.

The proper setting of the initial power phase shift network **43** mentioned above will now be discussed. The phase shift provided by the network **43** has been made manually variable in order that the temperature control system may be operated at its most sensitive point. The point of greatest system sensitivity occurs when the initial power phase shift network **43** is adjusted so that no error signal occurs at the terminals **27** and **28** when the temperature of the crucible **13** is at or near the mid-point of the temperature range to be used in growing the crystal. These mid-point temperatures are approximately 960° C. for germanium and approximately 1420° for silicon.

To accomplish the setting referred to above, the control of the bucking voltage network is set to indicate the desired operating temperature on the control dial and the switch **124** is opened to interrupt the error signal feed-back loop and prevent any automatic adjustment of the initial power phase shift network **43** due to the error signal. With power now applied to the radio-frequency generator **12**, the initial power phase shift network **43** is manually adjusted until the error signal of the feed-back loop is zero as indicated by the meter **125**. At this point, the temperature of the crucible **13** is the temperature indicated by the control dial of the buckling voltage network. The switch **124** is again closed and thereafter any change of crucible temperature will automatically be compensated for by the error signal to the initial power phase shift network **43**. This adjustment places the system at its most sensitive operating point, as noted above, and, in addition, eliminates the danger of loss of control of the temperature over the range desired should the error signal from the chopper circuit **31** become so great that it overdrives the shaper amplifier **35**.

A second embodiment of the temperature control of the present invention wherein a different means is used to control the phasing of the Thyratron firing pulses from the thermocouple voltage is illustrated in Figure 3. When the circuitry schematically diagrammed in Figure 3 is substituted for the chopper, amplifying and phasing portions of the circuit of Figure 2 between the terminals **27**, **28**, **58**, and **59**, the second embodiment is produced.

In this second embodiment, the variable amplitude and polarity D. C. voltage appearing at the terminals **27** and **28** of Figure 2 is fed to a self-balancing potentiometer-recorder designated as **60** in Figure 3. Self-balancing potentiometer-recorders are devices well-known in the electrical art. (See M. B. Stout, Basic Electrical Measurements, New York: Prentice-Hall, Inc., 1950, pages 174–178.) Briefly a self-balancing potentiometer-recorder is a type of instrument servo-mechanism wherein the input signal unbalances a resistance bridge network thereby creating an error signal which will then drive a small motor coupled to the moving contact of a potentiometer forming one element of the bridge circuit. When the error signal is produced, the sliding contact is moved along the potentiometer by the motor until the bridge is again in balance. The position of the potentiometer slider then indicates the magnitude and polarity of the input signal.

For use in the present invention, the motor of the self-balancing potentiometer-recorder **60** has coupled to it the slider contact **61** of an additional potentiometer **62**. The

potentiometer 62 is an element of a variable D. C. grid bias supply comprised of the battery 63 and the variable resistors 64 and 65. By this arrangement, the sliding contact 61 provides a grid bias potential which is proportional to the output voltage of the thermocouple 15. The condenser 68 serves the purpose of providing greater sensitivity to sudden changes. The tube 66 is connected as an ordinary D. C. amplifier with a resistor 69 from the grid to ground and a resistor 70 from the cathode to ground. The plate is connected to B+ voltage through the D. C. coil 71 of the saturable reactor 72. The saturable reactor 72, together with the transformer 77 secondary coils 73 and 74, and the resistor 75 forms a continuously variable phase shifting circuit. Through this circuit, the phase of an applied A. C. voltage can be controlled by the amplitude of the D. C. voltage in the coil 71 of the saturable reactor 72. A properly phased A. C. voltage from the terminal 59 is impressed on the primary coil 76 of the transformer 77. The secondary coils 73 and 74 of the transformer 77 produce a voltage similar to the voltage at terminal 59 across the series network comprised of secondary coil 78 of the saturable reactor 72 and the resistor 75. The phase of the output voltage between the terminal 58 and ground depends on the reactance of the coil 78 which is controlled by the D. C. current of the coil 71. (See R. R. Benedict, Introduction to Industrial Electronics, New York: Prentice-Hall 1951, pages 353 and 354, for an explanation of the change in reactance of the A. C. coil of a saturable reactor by a change in current in the D. C. coil.) The phase shifting action of this network can best be explained by reference to the vector diagram of Figure 4.

In Figure 4, the voltages induced in the coils 73 and 74 of the transformer 77 are represented by the vectors 73′ and 74′ respectively. The sum of the voltage drops across A. C. coil 78 of the reactor 72 and the resistor 75 must be equal to the voltage drop across the transformer coils 73 and 74, and the voltage across the resistor 75 will always be 90° out of phase with the voltage across the reactor coil 78. These two voltages are then represented by the vector 75′, for the drop across the resistor 75, and 78′ for the voltage drop across the reactor coil 78. The voltage at the output terminal 58 will be the voltage between ground and the junction point of coil 78 and the resistor 75 and is therefore represented by the vector 58′ from the junction point of the vectors 73′ and 74′ (ground) and the junction of vectors 75′ and 78′. Now, if the reactance of coil 78 is reduced, the voltage drop across this coil will become smaller as represented by the vector 78.″ Since the sum of the vector voltages acrosss the coil 78 and the resistor 75 must be equal to the sum of the vector voltages across the coils 73 and 74, and since the voltage across the resistor 75 must be at 90° with the voltage across the coil 78, the vector 75″ represents the voltage across the resistor 75. The vector 58″ now represents the output voltage which has been changed in phase. Thus, it can be seen that the magnitude of the D. C. current determines the phase of the output voltage at terminal 58.

Because of the time lag introduced into the system by the self-balancing potentiometer-recorder when using the embodiment of Figure 3, an additional radio-frequency feedback loop is provided to reduce any tendency of the system to oscillate. This additional feed-back circuit is shown in Figure 3. The circuit measures the actual radio-frequency output of the generator 12 and by its action limits the radio-frequency power change to approximately the amount needed to effect the desired temperature change thus eliminating over-correction and oscillation in the system.

The radio-frequency output level is detected by a single turn pickup coil 79 placed near the generator output coils 14. The radio-frequency energy induced in the pickup loop 79 is rectified by the diode tube 80, filtered in the network composed of the radio-frequency choke 81, resistor 82, and capacitors 83, 84, and 85 and fed to the voltage divider network consisting of resistors 86 and 87 connected between B+ voltage and ground. Any change in the D. C. voltage produced from the rectified and filtered radio-frequency signal changes the current flow through the resistor 87 and thus the potential at the slider arm 88 of the potentiometer 87 which is used to set the feed-back level. The voltage from the slider arm 88 is fed through the resistor 89 to produce another control bias at the terminal 90 which may be impressed on the grid of tube 66 in Figure 3 to control the Thyratron grid voltage phasing.

Still a third feed-back system may be incorporated into the temperature control system of the present invention. This third feed-back circuit, which measures the temperature of the crucible by the color of the crucible, is illustrated as part of Figure 3. A quartz rod 91 is placed in another cavity 92 of the crucible 13 to direct infra-red radiation from the hot crucible to a photocell 93 which is sensitive to such radiation. The circuit comprised of the battery 94, the phototube 93, and the resistor 95 forms a voltage divider circuit wherein the voltage drop across the phototube is governed by the amount of infra-red radiation incident upon the tube which is in turn governed by the temperature of the crucible. Any change in the voltage drop across the phototube 93 due to a change in the crucible temperature causes a change in the voltage across the resistor 95 and thus a change in the output signal through the capacitor 96 to the amplifier 97. The output signal of the amplifier is differentiated by the capacitor 98-resistor 99 network and then fed into the control system of Figure 3 at terminal 90. This feed-back system, because of the differentiation of its output signal, provides correction proportional to the rate of change of crucible temperature. This feed-back signal also tends to compensate for the time lag introduced into the thermocouple feed-back loop by the potentiometer-recorder 60.

As stated before, it is often desirable to vary the temperature of the furnace according to a predetermined program of temperature changes. The programming device schematically illustrated in Figure 5 provides the means for producing controlled temperature changes. This programmer produces changes in the crucible temperature in the following manner.

The two precision potentiometers 100 and 101 have impressed across their terminals an A.-C. voltage from the power lines 102 and 103 through the transformer 104. Because these two potentiometers are connected in parallel across the secondary coil 105 of the transformer 104, their voltages are of exactly the same phase. Therefore, if the sliders 106 and 107 of the potentiometers 100 and 101 contact their respective potentiometers at the same relative point, no voltage will be supplied to the input terminals 108 and 109 of the amplifier 110 since the sliders to which these terminals are connected will be at the same potential. However, if one of these sliders 106 is displaced, a voltage is developed between the terminals 108 and 109. The phase of this voltage will be determined by the direction of displacement of slider 106 and its amplitude will be determined by the amount of displacement. For example, if slider 106 is displaced toward the top of the drawing, the signal across the terminals 108 and 109 will be in phase with the signal across the secondary coil 105 of the transformer 104. However, if slider 106 is displaced toward the bottom of the drawing, the phase of the voltage to the terminals 108 and 109 will be reversed and it will be 180° out of phase with the voltage of the coil 105.

Any signal voltage at the terminals 108 and 109 is amplified by the amplifier 110 and fed to the grids of two triode tubes 112 and 113. The tubes 112 and 113 have their cathodes connected together and to ground through the common cathode resistor 126. The grids likewise are connected together and to ground through a

common grid resistor **127**. The plates of the two tubes are connected to opposite ends of another secondary coil **114** of the same transformer **104** which supplies voltage to the two precision potentiometers **100** and **101**. The center tap **115** of the secondary coil **114** is connected to ground through the rotor coil **111** of a balancing motor designated generally as **128**, so that the plate voltages of the two tubes **112** and **113** are 180° out of phase. Because the grid signal voltage is derived from the same transformer **104** as the plate voltage, the grid voltage on the tubes **112** and **113** will always be in phase with the plate of one of the tubes and 180° with the other, and only the tube in which the grid voltage and plate voltage are in phase will conduct current. The direction of displacement of the slider **106** determines the phase of the grid voltage to the tubes **112** and **113** and, therefore, the direction of displacement of the slider **106** determines which of the tubes, **112** or **113**, conducts.

By referring to the diagram of Figure 5, it can easily be seen that any current which flows in the rotor coil **111** of the balance motor **128** must also flow through either the upper or lower half of the transformer secondary coil **114**. Thus, the current of the rotor coil **111** must be of one of two phases each 180° different from the other and the phase of this current depends on whether it is the upper or lower half of coil **114** through which current flows or which tube, **112** or **113**, is conducting. In other words, the phase of the current in the rotor coil **111** of the balance motor **128** is determined by the direction of displacement of the slider **106**. As shown in Figure 5, slider **106** is displaced by means of the cam **131** and follower mechanism **132**, but any of several means may be used for this purpose.

The voltage of the stator coil **116** of the balance motor **128** is produced from the power supply lines **102** and **103** and, were it not for the condenser **117** inserted in the line to the stator coil **116**, the voltage would be either in phase or 180° out of phase with the rotor coil **111** voltage. However, the condenser **117** shifts the stator coil **116** voltage in phase by 90°°. Since any currents which flow in the rotor and stator coils **111** and **116** of the balance motor **128** will always be 90° out of phase with each other, the rotor of the balance motor **128** will turn when current flows in the rotor coil **111** and its direction of rotation will be determined by whether the current in the rotor coil **111** is lagging or leading the current in the stator coil **116**.

Coupled to the rotor shaft **129** of the balance motor **128** are the slider **130** of the resistor **21** in the bucking voltage network of Figure 2 and the slider **107** of the "follow-up" potentiometer **101**. The coupling of sliders **130** and **107** to the shaft **129** may be either direct or by means such as gearing depending on the construction of the potentiometers **21** and **101**. When current flows in the rotor coil **111** as the result of a displacement of the slider **106**, the rotor shaft **129** turns and there is produced a change in the error signal appearing at the terminals **29** and **30** in Figure 2 due to a movement of the slider **130** which produces a change in the bucking voltage of the bucking voltage network of Figure 2. The rotor shaft **129** will continue to turn and the temperature error signal in the system will continue to change until the slider **107** coupled to the rotor shaft **129** is displaced from its original contact point on the potentiometer **101** to a contact point at which its potential is exactly the same as the potential of the slider **106**. At this point, no further signal is developed between the terminals **108** and **109**, and thus no grid voltage signal is fed to the tubes **112** and **113**. Without a grid voltage, no current will pass through either of the tubes and, consequently, no current will flow in the rotor coil **111**. Of course, when current no longer flows in the rotor coil **111**, the rotor **129** no longer turns and the temperature error signal of the temperature control system ceases to change.

In the embodiment of the temperature control system of the present invention illustrated in Figure 3 wherein a self-balancing recording potentiometer **60** is used in the error signal feed-back loop, automatic control of the temperature may be incorporated by coupling the rotor shaft **129** of the balance motor **128** to the slider **133** of the potentiometer **64** instead of to the slider **130** of the potentiometer **21** as illustrated in Figure 5.

By means such as the cam **131** and follower **132** mechanisms coupled to slider **106** wherein variations in radius along the circumference of cam **132** are proportional to the temperature changes to be produced, the signals for a predetermined program of temperature changes can be introduced into the system. Through use of a similar cam and follower to produce signals for pull-rate changes in the pull-rate control system of the crystal pulling machine and use of a small motor to drive both cams at the same speed, the crystal pulling procedure becomes an almost completely automatic process.

It is to be understood that the phase shifting, pulse forming, amplifier and shaper circuits referred to in the above description and illustrated in the various figures of the drawings merely in block form need not be of any specific type, but may be any of the many types well-known in the art.

Thus, there have been disclosed several specific embodiments of the present invention for holding the temperature of an electric furnace to within ±0.2° C. of any desired temperature and a specific method of varying this controlled temperature according to a predetermined program of changes. These specific embodiments of the present invention have been described using a radio-frequency induction furnace, specific phasing and feed-back circuitry and a specific method for introducing a program of temperature changes; however, many changes, alterations and substitutions still within the scope and spirit of the present invention will be apparent to those skilled in the art. Therefore, it is not intended that the present invention be limited to the specific embodiments illustrated herein but that it be limited only as set forth in the appended claims.

What is claimed is:

1. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, an A.-C. control voltage applied to said at least one thermionic emission device, and means for phase modulating said A.-C. control voltage by said D.-C. error voltage thereby continuously controlling the electrical power to said furnace.

2. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, an A.-C. control voltage applied to said at least one thermionic emission device, and means for phase modulating said A.-C. control voltage by said D.-C. error voltage whereby the electrical power to said furnace is controlled during each cycle of the power voltage frequency.

3. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, means con-

tinuously changing said D.-C. voltage to a first A.-C. voltage, a second A.-C. voltage, means combining said first and second A.-C. voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first A.-C. voltage, and A.-C. power voltage applied to said at least one thermionic emission device, and means forming said combined voltages into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

4. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, means continuously changing said D.-C. voltage to a first A.-C. voltage, a second A.-C. voltage, means combining said first and second A.-C. voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first A.-C. voltage, and A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said combined voltages into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

5. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through a plurality of grid controlled, gas-filled thermionic emission devices, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, means continuously changing said D.-C. voltage to a first A.-C. voltage, a second A.-C. voltage, means combining said first and second A.-C. voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first A.-C. voltage, and A.-C. power voltage applied to each of said plurality of thermionic emission devices, and a plurality of means for phase shifting and forming said combined voltages into a plurality of time spaced pulses which, on being applied to the grids of said plurality of thermionic emission devices, control the conductive period of each of said devices during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

6. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through a plurality of grid controlled, gas-filled thermionic emission devices and a radio-frequency generator, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, means continuously changing said D.-C. voltage to a first A.-C. voltage, a second A.-C. voltage, means combining said first and second A.-C. voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first A.-C. voltage, an A.-C. power voltage applied to each of said plurality of thermionic emission devices, and a plurality of means for phase shifting and forming said combined voltages into a plurality of time spaced pulses which, on being applied to the grids of said plurality of thermionic emission devices, control the conductive period of each of said devices during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

7. A system for controlling the temperature of electric furnaces as defined in claim 4 which includes a servo-mechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

8. A system for controlling the temperature of electric furnaces as defined in claim 5 which includes a servo-mechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

9. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, means amplifying said second D.-C. voltage, an A.-C. control voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second D.-C. voltage, an A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said phase controlled A.-C. voltage into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

10. A system for controlling the temperature of electric furnaces as defined in claim 9 which includes a servo-mechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

11. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through a plurality of grid controlled, gas-filled thermionic emission devices, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, means amplifying said second D.-C. voltage, an A.-C. control voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second D.-C. voltage, an A.-C. power voltage applied to each of said plurality of thermionic emission devices, and a plurality of means for phase shifting and forming said phase controlled A.-C. control voltage into a plurality of time spaced pulses which, on being applied to the grids of said plurality of thermionic emission devices, control the conductive period of each of said devices during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

12. A system for controlling the temperature of electric furnaces as defined in claim 11 which includes a servo-mechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

13. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balanc-

ing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, infra-red sensing means associated with said furnace, radiation sensitive means producing a voltage varying with the amount of said radiation, means amplifying said varying voltage, differentiating means producing a pulse proportional to the rate of change of said radiation, means amplifying said second D.-C. voltage and said pulse, an A.-C. control voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second D.-C. voltage and said pulse, an A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said phase controlled A.-C. control voltage into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

14. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device and a radio-frequency generator, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, means amplifying said second D.-C. voltage, an A.-C. controlled voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second D.-C. voltage, an A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said phase controlled A.-C. control voltage into pulses, which on being applied to the grid of said at least one thermionic emission device control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

15. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device and a radio-frequency generator and generator output coils associated therewith, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, radio-frequency power detection means in close proximity wtih said generator output coils, means rectifying the voltage induced in said detection means, means producing a third D.-C. voltage proportional to said rectified voltage, means amplifying said second and third D.-C. voltages, an A.-C. control voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second and third D.-C. voltages, an A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said phase controlled A.-C. control voltage into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

16. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device and a radio-frequency generator and generator output coils associated therewith, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, self-balancing potentiometer means producing a second D.-C. voltage proportional to said D.-C. error voltage, radio-frequency power detection means in close proximity with said generator output coils, means rectifying the voltage induced in said detection means, means producing a third D.-C. voltage proportional to said rectified voltage, infra-red radiation sensing means associated with said furnace, radiation sensitive means producing a voltage varying with the amount of said radiation, means amplifying said varying voltage, differentiating means producing a pulse proportional to the rate of change of said radiation, means amplifying said second D.-C. voltage, said third D.-C. voltage, and said rate of change pulse, an A.-C. control voltage, means whereby the phase of said A.-C. control voltage is controlled by the amplitude of said amplified second D.-C. voltage, said third D.-C. voltage, and said rate of change pulse, an A.-C. power voltage applied to said at least one thermionic emission device, and means phase shifting and forming said phase controlled A.-C. control voltage into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

17. A system for controlling the temperature of electric furnaces as defined in claim 16 which includes a servomechanism and means for programming temperature changes in said furnace, said system thereafter accurately controlling the temperature of said furnace at the changed temperature.

18. A method of controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprising the steps of producing a D.-C. voltage indicatvie of furnace temperature, cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, applying an A.-C. control voltage to said at least one thermionic emission device, and phase modulating said A.-C. control voltage by said D.-C. error voltage thereby continuously controlling the electrical power to said furnace.

19. A method of controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprising the steps of producing a D.-C. voltage indicative of furnace temperature, cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, changing said D.-C. voltage to a first A.-C. voltage, providing a second A.-C. voltage, combining said first and second A.-C. voltages whereby the phase of the combined voltages depends on the amplitude and phase of said first A.-C. voltage, applying an A.-C. power voltage to said at least one thermionic emission device, and forming said combined voltages into pulses, which on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

20. A method of controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprising the steps of producing a D.-C. voltage indicative of furnace temperature, cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, producing another D.-C. voltage proportional to said D.-C. error voltage, amplifying said another D.-C. voltage, providing an A.-C. control voltage, controlling the phase of said A.-C. con-

trol voltage by the amplitude of said amplified another D.-C. voltage, applying an A.-C. power voltage to said at least one thermionic emission device, and forming said phase controlled A.-C. control voltage into pulses which, on being applied to the grid of said at least one thermionic emission device, control the conductive period of said at least one device during each cycle of said A.-C. power voltage thereby controlling the electrical power to said furnace.

21. A method of controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprising the steps of cyclically supplying power to said furnace through said at least one device, producing a voltage which is a function of the difference between actual furnace temperature and a reference temperature, and controlling the conductive period of said at least one device during each cycle by said voltage whereby the electrical power to said furnace is continuously controlled.

22. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means cyclically supplying power to said furnace through said at least one thermionic emission device, means producing a voltage which is a function of the difference between actual furnace temperature and a reference temperature, and means applying said voltages to said at least one thermionic emission device to control the conductive period thereof during each cycle, whereby the electrical power to said furnace is continuously controlled.

23. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means producing therefrom a D.-C. error voltage with variations in the furnace temperature from a preset temperature, an A.-C. control voltage applied to said at least one thermionic emission device, and means for modulating said A.-C. control voltage by said D.-C. error voltage thereby continuously controlling the electrical power to said furnace.

24. A system for controlling the temperature of electric furnaces in which the electrical power to said furnace is supplied through at least one grid controlled, gas-filled thermionic emission device, comprised of means producing a D.-C. voltage indicative of furnace temperature, means cancelling said D.-C. voltage at a preset temperature and producing a D.-C. error voltage with variations in temperature from said preset temperature, an A.-C. control voltage applied to said at least one thermionic emission device, and means for modulating said A.-C. control voltage by said D.-C. error voltage thereby continuously controlling the electrical power to said furnace.

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