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(54) GLOW DISCHARGE HEATING APPARATUS

(71) We, MITSUBISHI DENKI KABUSHIKI KAISHA, a Japanese body corporate, of 2—3 Marunouchi 2-chome, Chiyodaku, Tokyo, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a glow discharge heating apparatus for heating a liquid through the utilization of a glow discharge established between a pair of electrodes involved.

Japanese laid-open patent application No. 6252/1976 describes and claims a glow discharge heating apparatus for heating a liquid by utilizing a phenomenon that a glow discharge occurring between a pair of cathode and anode electrodes heats the cathode electrode to an elevated temperature. The glow discharge heating apparatus disclosed in the cited patent application comprises a hollow cylindrical enclosure, a tubular cathode electrode coaxially extended and sealed through the enclosure, and having both ends open, a hollow cylindrical anode electrode disposed in the enclosure to surround the cathode electrode substantially throughout the length thereof to form an annular discharge gap therebetween, a source of DC voltage connected across the cathode and anode electrodes to cause a glow discharge therebetween. The cathode electrode is heated with the glow discharge to directly heat a liquid flowing therethrough.

Heating apparatus of this type referred to have instantaneously heated the liquid with the simple construction and still with the high efficiency. However, where high currents are required to establish the glow discharge between the electrodes, it has been difficult to sustain the stabilized glow discharge therebetween. There have been a danger that the glow discharge will change to an arc discharge. Also the electrodes may be axially expanded by heating. This might result in the apparatus being broken.

Further it has been difficult to reliably control the glow discharge because of the absence of a control circuit for starting and extinguishing the glow discharge.

Accordingly it is an object of the present invention to mitigate at least some of the disadvantages of the prior art practice as above described by the provision of a new and improved glow discharge heating apparatus capable of always sustaining a stabilized glow discharge.

According to one aspect of the present invention there is provided a glow discharge heating apparatus comprising at least one pair of discharge electrodes disposed in opposite relationship to form a predetermined gap therebetween, means for applying a voltage across said discharge electrodes to cause a glow discharge therebetween, said glow discharge supplying thermal energy to the discharge electrode acting as a cathode during said glow discharge, the discharge electrode acting as said cathode being so constructed that a liquid to be heated with said thermal energy can flow therethrough wherein the effective area of the discharge electrode acting as an anode is smaller than the entire area of said discharge electrode acting as a cathode upon which a glow discharge may be caused thereby to impart a positive resistance characteristic to the current-to-voltage characteristic of said glow discharge.

According to a second aspect of the present invention a polyphase AC glow discharge heating apparatus comprising *m* main electrodes disposed oppositely to one another to form predetermined gaps therebetween, where *m* has a value not less than three (3), AC source means for applying an *m*-phase AC voltage to said main electrodes to cause glow discharges between successive pairs of main electrodes each of said glow discharges supplying thermal energy to the main electrode acting as a cathode during the associated glow discharge, said main electrodes being so constructed that a liquid to be heated with said thermal energy can flow therethrough wherein the effective area of the discharge electrode of each pair acting as an anode is smaller than the entire area of the discharge electrode of said pair acting as a cathode upon which a glow discharge may be caused thereby to impart a positive resistance characteristic to the current-to-voltage characteristic of said glow discharge.

In a preferred embodiment of the present invention the source of voltage may comprise a source of DC voltage and a hollow anode electrode surrounds the middle portion of a hollow cathode electrode to form the predetermined discharge gap therebetween, the cathode electrode forming a flow path for the heated liquid.

In order to ensure that the glow discharge is prevented from transmitting to an arc discharge, the flow discharge heating apparatus may advantageously include an auxiliary source of voltage for applying across the electrodes a high voltage in excess of a discharge breakdown voltage across the electrodes upon a discharge voltage across the electrodes approaching a glow discharge-hold minimum voltage, to cause a pilot glow discharge therebetween to induce the principal glow discharge.

The present invention will become more readily apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

Figure 1 is a longitudinal sectional view of a glow discharge heating apparatus constructed in accordance with the principles of the prior art;

Figure 2A is a schematic sectional view of a pair of opposite electrode useful in explaining the glow discharge;

Figure 2B is a graph illustrating a spatial voltage profile exhibited by the arrangement shown in Figure 2A;

Figure 3 is a fragmental schematic plan view illustrating how a quantity of input heat to a cathode electrode during a glow discharge is measured;

Figure 4 is a graph illustrating the results of the measurement shown in Figure 3 with the results of a corresponding theoretical calculation;

Figure 5 is a graph illustrating the relationship between a glow discharge voltage and a gap length through which a glow discharge is caused;

Figure 6 is a graph illustrating the relationship between a voltage and a current for the glow discharge;

Figure 7 is a perspective view of a modeled ion flux useful in explaining the quantity of input heat to a cathode electrode resulting from a glow discharge;

Figure 8 is a graph illustrating the current-to-voltage characteristics of the glow discharge;

Figures 9A and 9B are fragmental schematic plan views of a pair of opposite electrodes useful in explaining the principles of the present invention;

Figure 10A, 10B and 10C are views similar to Figure 9A or 9B but illustrating typically electrode configurations embodying the principles of the present invention;

Figure 11 is a longitudinal sectional view of one embodiment according to the glow discharge heating apparatus of the present invention;

Figure 12 is a current-to-voltage characteristic curve for a glow discharge caused by the arrangement shown in Figure 11;

Figures 13 and 14 are graphs useful in explaining the principles of the present invention;

Figure 15 is a longitudinal sectional view of a modification of the arrangement shown in Figure 11;

Figures 16 and 17 are graphs illustrating the characteristics of the arrangement shown in Figure 15;

Figure 18 is a longitudinal sectional view of another modification of the present invention;

Figure 19 is a graph illustrating the characteristic of the arrangement shown in Figure 18;

Figure 20 shows a modification of the arrangement shown in Figure 18 wherein Figure 20A is a cross sectional view and Figures 20B and 20C are side elevational views of the lefthand and righthand sides respectively;

Figure 21 is a view similar to Figure 18 but illustrating still another modification of the present invention;

Figure 22 is a view similar to Figure 18 but illustrating a modification of the arrangement shown in Figure 21;

Figure 23 is a view similar to Figure 18 but illustrating another modification of the arrangement shown in Figure 21;

Figure 24 is a view similar to Figure 18 but illustrating still another modification of the arrangement shown in Figure 21;

Figure 25 is a graph illustrating a leakage current calculated with the arrangement shown in Figure 24;

Figure 26 is a graphical representation of voltage and current waveforms developed in the arrangement of Figure 24 filled with a mixture of helium and hydrogen;

Figure 27 is a graph illustrating the current-to-voltage characteristics of glow discharges occurring in the arrangement of Figure 24 filled with mixtures of helium and hydrogen in different proportions;

Figure 28 is a graph illustrating the theoretical relationship between a glow hold minimum voltage and quantity of input heat to an associated electrode resulting from the glow discharge;

Figure 29 is a graph illustrating the relationship between an overlapping area for both electrodes and a pressure of a filling gas;

Figures 30, 31 and 32 are graphs illustrating how the glow hold minimum voltage is changed with a proportion of mixed gases and a discharge gap-length;

Figure 33 is a graph illustrating the relationship between the glow hold minimum voltage and a peak discharge current;

Figure 34 is a longitudinal sectional view of a different modification of the present invention including an auxiliary electrode;

Figures 35, 36 and 37 are fragmental perspective views of different modifications of one of the electrodes shown in Figure 34;

Figure 38 is a longitudinal sectional view of a modification of Figure 34 along with an associated electric circuit;

Figure 39 is a longitudinal sectional view of another modification of the arrangement shown in Figure 34;

Figure 40 is a view similar to Figure 38 but illustrating still another modification of the arrangement shown in Figure 34;

Figure 41 is view similar to Figure 39 but illustrating a different modification of the arrangement shown in Figure 34;

Figure 42 is a view similar to Figure 39 but illustrating a modification of the arrangement shown in Figure 41;

Figure 43 is a view similar to Figure 39 but illustrating a modification of the arrangement shown in Figure 40;

Figure 44 is a view similar to Figure 39 but illustrating another modification of the arrangement shown in Figure 34;

Figure 45 is a view similar to Figure 39 but illustrating a modification of the arrangement shown in Figure 44;

Figure 46 is a diagram of the fundamental control circuit used with the present invention;

Figure 47 is a graph illustrating a voltage and a current waveform developed in the arrangement shown in Figure 46;

Figure 48 is a diagram of a control circuit constructed in accordance with the principles of the present invention for driving the glow discharge heating apparatus thereof;

Figure 49 is a graph illustrating a voltage and a current waveform developed in the arrangement shown in Figure 48;

Figure 50 is a diagram similar to Figure 48 but illustrating a modification of the arrangement shown in Figure 48;

Figure 51 is a graph similar to Figure 49 but illustrating the arrangement shown in Figure 50;

Figure 52 is a diagram of another control circuit constructed in accordance with the principles of the present invention and suitable for use with an electrode structure including an auxiliary electrode;

Figure 53 is a circuit diagram similar to Figure 52 but illustrating a modification of the arrangement shown in Figure 52;

Figure 54 is a graph illustrating voltage waveforms developed at various points in the arrangement shown in Figure 52;

Figures 55 through 58 are circuit diagrams similar to Figure 52 but illustrating different modifications of the arrangement shown in Figure 52;

Figure 59 is a diagram of still another control circuit constructed in accordance with the principles of the present invention;

Figure 60 is a graph illustrating voltage waveforms developed in the arrangement shown in Figure 59;

Figure 61 is a graphical representation of a Laue plot;

Figure 62 is a circuit diagram similar to Figure 59 but illustrating a modification of the arrangement shown in Figure 59;

Figure 63 is a graph similar to Figure 60 but illustrating the arrangement shown in Figure 62;

Figure 64 is a sectional view of an embodiment according to the three-phase glow discharge heating apparatus of the present invention and a diagram of a control circuit therefor;

Figure 65 is a graph illustrating various waveforms developed in the arrangement shown in Figure 64;

Figure 66 is a diagram of the details of the control circuit shown in Figure 64;

Figure 67 is a wiring diagram of a modification of the arrangement shown in Figure 66;

Figure 68 is a graph similar to Figure 65 but illustrating the arrangement shown in Figure 67;

Figure 69 is a longitudinal sectional view of a modification of the arrangement shown in Figure 44 and a diagram of a control circuit therefor;

Figure 70 is a longitudinal sectional view of a modification of the arrangement shown in Figure 69;

Figure 71 is a view similar to Figure 64 but illustrating a modification of the arrangement shown in Figure 64;

Figure 72 is a view similar to Figure 70 but illustrating a modification of the arrangement shown in Figure 69; and

Figure 73 is a longitudinal sectional view of another modification of the arrangement shown in Figure 69.

Throughout the Figures like reference numerals designate the identical or corresponding components.

Referring now to Figure 1 of the drawings, there is illustrated a conventional glow discharge-heating apparatus. The arrangement illustrated comprises a hollow cylindrical cathode electrode 1, a hollow cylindrical anode electrode 2 surrounding coaxially the cathode electrode 1 to form an annular discharge gap 8 therebetween with the aid of two electrically insulating spacers 7 in the form of annuli fixedly disposed between both electrodes 1 and 2 adjacent both end portions of the anode electrode 2, and a cylindrical enclosure 9 formed of any suitable electrically insulating material such as glass and coaxially housing the electrodes 1 and 2 with the cathode electrode 1 hermetically extending through both ends thereof. A seal fitting 10 is sealed at the outer periphery to one end, in this case, the lefthand end as viewed in Figure 1 of the enclosure 9 and at the inner periphery to the adjacent portion of the cathode electrode 1 while a corrugated seal fitting 11 is sealed at the outer periphery to the other end of the envelope 9 and at the inner periphery to the adjacent portion of the cathode electrode 1. The corrugated seal fitting 11 may contract and expand sufficiently to prevent damage due to axial thermal strains. Thus the envelope 9 and the seal fittings 10 and 11 maintain the hermetic sealing of the discharge gap 8.

As shown in Figure 1, the anode electrode 2 includes flared end portions 2g in order to prevent an electric discharge from concentrating on the end portions of the anode electrode 2.

A positive terminal 5 connected to the central portion of the anode electrode 2 extends through and is sealed relative to the central portion of the cylindrical peripheral wall of the enclosure 9 and is connected to a positive side of a source of DC voltage 3 having a negative side connected through a stabilizing resistor 4 to a negative terminal 6 that is, in turn, connected to one end portion, in this case, the righthand end portion as viewed in Figure 1 of the cathode electrode 1.

In the arrangement of Figure 1, a DC voltage is applied across the anode and cathode electrodes 1 and 2 respectively to establish a glow discharge across the discharge gap 8 thereby to heat the cathode electrode 1. Under these circumstances, a liquid to be heated, for example water, is caused to flow through the interior of the cathode electrode 1 to be directly heated by the heated cathode electrode 1.

Conventional glow discharge heating apparatus such as shown in Figure 1 is capable of instantaneously heating liquids to be heated, for example water, resulting in heating apparatus simple in construction and still high in efficiency. However, since the apparatus requires high current, it has been extremely difficult to sustain the glow discharge across the anode and cathode electrodes in a stable manner. According to circumstances, there has been a danger of the glow discharge changing to an arc discharge. Further there is a danger that, as a result of heating, the electrodes are axially expanded leading to the destruction of the heating apparatus. In addition, conventional glow discharge heating apparatuses have not been provided with suitable control circuit means for starting and terminating the glow discharge with the result that it has been difficult to control the glow discharge reliably.

The present invention proposes reducing the disadvantages of and objections to the prior art practice as above described by providing means for imparting a positive resistance to the current-to-voltage characteristic of the glow discharge. It has been found that such a characteristic is effective for preventing the transit of the glow discharge to an arc discharge.

For a better understanding of the principles of the present invention, the description will now be made with reference to the principle that a glow discharge heats an associated cathode electrode and with reference the current-to-voltage characteristic of the glow discharge.

Figure 2A shows a pair of cathode and anode electrodes 1 and 2 respectively disposed in spaced opposite relationship and a source of DC voltage 3 including a negative side connected to the cathode electrode 1 and a positive side connected to the anode electrode 2 through a stabilizing resistor 4 whereby a glow discharge occurs within a discharge space formed between both electrodes 1 and 2. It is well known that a discharge space having a glow discharge established therein is divided into a region of cathode fall *a* in which positive ions are enriched, a region of negative glow *b* forming a thin luminescent layer, a Faraday dark space *c* in which no light is emitted, and a positive column d_0 consisting of a plasma including electrons and ions, the region *a* being closest to the cathode electrode 1.

Figure 2B shows a spatial voltage profile in the discharge space with the glow discharge established therein. In Figure 2B, voltage V is plotted against distance *d* measured from the cathode electrode 1. From Figure 2B it is seen that the region of cathode fall *a* has a very large potential-gradient because the presence of a space charge until a cathode fall of potential V_c is reached at the end of the region *a* spaced from the surface of the cathode electrode 1 by a distance of *dc*. The voltage reaches a glow voltage V_g on the surface of the anode electrode 2.

By visually observing the glow discharge, it is seen that the boundary between the region of cathode fall *a* and the region of negative glow *b* is very distinct but the boundaries between the region of negative glow *b* and the Faraday dark space *c* and between the Faraday dark space *c* and the positive column d_0 are not so distinct.

Also the Faraday dark space *c* and the positive column d_0 are in the so-called plasma state and relatively small in potential gradient. On the other hand, the region of cathode fall *a* includes positive ions in the form of a beam. As far as the discharge current is concerned, it consists essentially of an electron current in each of the Faraday dark space *c* and positive column d_0 which are in the plasma state and of an ion-current in the region of cathode fall *a*. The region of negative glow *b* forms a region of the transition from one current to the other.

Two phenomena developed in the region of cathode fall *a*, that is, (1) the mechanism by which the glow discharge is sustained and (2) the heating of the cathode electrode by the glow discharge, as well as (3) the current-to-voltage characteristic of the glow discharge, are pertinent to the principles of the present invention and therefore will now be described.

(1) Mechanism of Sustaining Glow Discharge

Positive ions present in the region of cathode fall *a* collide with the surface of the cathode electrode whereupon the cathode electrode 1 emits electrons by means of the action of emitting secondary electrons called the γ_1 action. The electrons emitted from the cathode electrode (1) collide with neutral atoms or molecules during their movement toward the anode electrode which is accompanied by an ionizing action, called the α action, with some probability. Electrons and positive ions caused by the ionization and collision are accelerated toward the anode and cathode electrodes respectively by means of the action of an electric field involved. It is noted that the positive ions accelerated by the electric field contributes to the γ_1 action.

Here the sustainment of the glow discharge will be somewhat quantitatively described. For example, assuming the cathode electrode 1 is formed of nickel, the γ_1 is approximately equal to 0.01 for slow helium ions having an energy of 1 Kev or less. That is, about 100 ions collide with the cathode electrode 1 to emit a single electron therefrom.

Also the degree of ionization α is a function of the type and pressure of a gas confined in the discharge space and a potential gradient developed therein. Electron-ion pairs formed at a distance x from the cathode electrode 1 are proportional to $e^{\alpha x}$ where e designates the base of Napierian logarithms and therefore increase exponentially with the distance x. Accordingly, the glow discharge is sustained with a distance and a voltage required for about 100 electron-ion pairs to be formed in the course of movement of a single electron toward the anode electrode 2. This distance is designated by the distance *dc* shown in Figure 2B and this voltage substantially corresponds to the voltage V_c. In other words, the glow discharge can be sustained even when the anode electrode 2 has been displaced to its position substantially shown by do in Figure 2A.

This is substantially applicable to electrodes formed of nickel, copper, iron, stainless steel or the like and operatively associated with a gas selected from helium, neon, argon, hydrogen, nitrogen inter alia.

A more detailed analysis of the phenomena developed in the vicinity of the cathode electrode 1 reveals that the current density J on the surface of the cathode electrode 1 is expressed by

$$J = j_+ + j_- = j_+ = K_1P^2 \qquad (1)$$

where j_+ and j_- designate densities of positive ions and electrons respectively, P the pressure of the discharge gas, and K_1 designates a constant determined by both the type of a cathode material and that of the discharge gas.

Also the region of cathode fall *a* has a thickness *dc* as defined by

$$dcP = K_2 \qquad (2)$$

where K_2 designates a constant dependent upon both the type of the cathode material and that of the discharge gas. Within the region of normal glow, the cathode fall of potential V_c is determined by both the type of the cathode material and that of the discharge gas but scarcely depends upon the discharge current and the pressure of the discharge gas.

The following Table I lists values of the constants K_1 and K_2 and the cathode fall of potential V_c measured within the region of normal glow with different combinations of cathode materials and discharge gases with a glow current not higher than 1 ampere and with the discharge gases maintained at a pressure of 50 Torrs or more. The measured K_1 and K_2 values are expressed in 10^{-6} ampere per cm^2Torr^2 and in cm·Torr and the voltage V_c is expressed in volts. Also the current density on the surface of the cathode electrode has been determined by measuring an area of a negative glow *b*. Probably, the negative glow is very thin so that it is observed as a luminescent film attached to the cathode electrode.

TABLE I

MEASURED VALUES OF K_1, K_2 and V_C

Cathode \ Gas		He	Ne	Ar	H_2
Cu	K_1	6.0	8.3	27	24
	K_2	3.0	3.0	0.8	2.0
	V_C	150	150	180	290
Ni	K_1	8.0	20	32	32
	K_2	3.0	4.0	1.5	3.0
	V_C	101	140	185	254
Mo	K_1	4.4	4.7	17	30
	K_2	4.0	3.0	0.8	3.0
	V_C	180	175	190	290
SUS	K_1	7.6	8.0	22	30
	K_2	5~7	2.5	0.8	1.5
	V_C	119	150	180	232

(2) Heating of Cathode Electrode

As above described, positive ions present in the region of cathode fall *a* collide with the cathode electrode to cause the γ_i action. At that time, the positive ions have surplus kinetic energy that is, in turn spent to heat the cathode electrode 1. Regarding quantities of input and output heat of the cathode electrodes, there are, in addition to collision with the positive ions, heat conduction from the plasma portions, exothermic and endothermic effects caused from chemical reactions effected on the surface of the cathode electrode 1 due to the glow discharge, cooling effects caused from the sputtering on the cathode electrode and the evaporation of the cathode material etc. However, the extent to which a quantity of heat enters the cathode has not been elucidated until the present.

In order to determine the quantity of input heat to the cathode electrode due to the glow discharge formed between that electrode and an anode electrode, experiments were conducted with a test device schematically shown in Figure 3. As shown in Figure 3, a cathode electrode in the form of a very long circular rod having a radius r of 1.8 mm was thermally isolated from the surroundings and disposed opposite to a similar anode electrode 2 to form therebetween a gap having a length *d* of 4 mm. Both electrodes were formed of copper and connected across a DC source 3 through a stabilizing resistor 4. Thus a glow discharge *g* was established across both electrodes 1 and 2 in the atmosphere. Under these circumstance, a radiation thermometer M was used to continuously measure the temperature at a point on the outer surface of the cathode electrode 1 spaced way from the discharge surface thereof by a distance Z_0 of 3 mm.

The results of the experiments are shown in Figure 4 wherein the temperature in Centigrade is plotted against time in seconds with the glow current taken as the parameter. In Figure 4, each vertical segment designates a range in which measured values of the temperatures are dispersed and solid curve describes calculated values of the temperature as will be described hereinafter. The reference numerals 111, 112, 113 and 114 mean the temperatures measured and calculated with glow currents of 400, 250, 200 and 150 milliamperes respectively.

From Figure 4 it has been confirmed that the glow discharge changes to an arc discharge upon the measured temperature approaching 1000°C. This will be because an oxide film is formed on the surface of the cathode electrode at such a temperature.

It is now assumed that in Figure 3, the cathode electrode 1 with radius r has the longitudinal axis lying on the z axis and the discharge surface passing through the origin for the z axis and that the quantity of input heat to the cathode electrode 1 is constant per unit area and per unit time. Under the assumed condition, a partial differential equation for conduction of heat referred to the z axis alone, and taking account of radiation loss, may be expressed by

$$\frac{\partial T}{\partial t} = \kappa^2 \frac{\partial^2 T}{\partial Z^2} - \alpha(T - T_o) \qquad (3)$$

where κ designates the thermal diffusibility defined by the square root of the quotient of the thermal conductivity k of the cathode electrode divided by the product of the density ρ and the heat capacity thereof and α is a constant on the assumption that the radiation loss is a linear function of the temperature T. By solving partial equation under the boundary conditions

$$\left.\frac{\partial T}{\partial Z}\right|_{Z=0} = -\xi \frac{IV_c}{\pi r^2 k} = -\xi \frac{jV_c}{k} \qquad (4)$$

and

$$\left.\frac{\partial T}{\partial Z}\right|_{Z=\infty} = 0 \qquad (5)$$

where ξ designates a coefficient of heat input and the initial condition

$$T(z,o) = T_o$$

where T_o designates room temperature, a solution results in

$$T(z,t) = T_0 + \frac{\xi IV_c}{\pi r^2 k} \frac{\kappa}{\sqrt{\alpha}} \left(e^{-\frac{\sqrt{\alpha}}{\kappa} z} (1 - F(\gamma_1)) - e^{\frac{\sqrt{\alpha}}{\kappa} z} F(\gamma_2) \right) \qquad (6)$$

where I = glow current.

In the expression (6) $F(\gamma_1)$ and $F(\gamma_2)$ are error functions expressed by

$$F(\gamma_1) = \frac{1}{\sqrt{2\pi}} \int_{\gamma_1}^{\infty} e^{-\frac{\gamma^2}{2}} d\gamma$$

and (7)

$$F(\gamma_2) = \frac{1}{\sqrt{2\pi}} \int_{\gamma_2}^{\infty} e^{-\frac{\gamma^2}{2}} d\gamma$$

respectively where γ_1 and γ_2 are expressed by

$$\gamma_1 = \frac{2\kappa\sqrt{\alpha}t - z}{\kappa\sqrt{2t}} \text{ and } \gamma_2 = \frac{2\kappa\sqrt{\alpha}t + z}{\kappa\sqrt{2t}} \qquad (8)$$

respectively. Also α is defined by

$$\alpha = \frac{2\varepsilon\sigma(Ta^3+ToTa^2+To^2Ta+To^3)}{\rho ca} \quad (9)$$

where ε designates the emissivity, σ the Stefan-Boltzmann constant and Ta designates the average value of room temperature and cathode electrode temperature.

The expression (3) was used to calculate the time dependency of the temperature rise on the measured point as shown in Figure 3. The results of the calculations are indicated by the solid curves shown in Figure 4.

From Figure 4 it is seen that the measured values of the temperature fairly well coincide with the calculated values thereof.

Figure 5 illustrates the glow discharge voltage V in volts plotted against the length of the discharge gap in millimeters. The voltage V was measured with the electrodes formed of copper and disposed in the atmosphere. Curves labelled 115, 116, 117 and 118 depict glow currents of 10, 50, 100 and 400 milliamperes respectively.

In Figure 4 it is to be noted that the curves have been drawn with the cathode potential drop Vc equal to 285 volts estimated with zero gap length as with the curves shown in Figure 5.

Also the coefficient of heat input ξ has been determined to cause the calculated values of the temperature to coincide with the measured values thereof shown in Figure 4. The coefficient ξ has been of 1.4.

Further it is considered that the quantity of heat corresponding to 0.4 jV_c per unit area per unit time will result from one portion of heat generated in that portion of the glow discharge formed of both the Faraday dark space *c* and the positive column *d* except for the region of cathode fall *a* having a thickness *dc* approximately equal to 2×10^{-3} centimeter.

Figure 6 illustrates the glow voltage V_g in volts plotted against the glow current I in milliamperes. Curve 119 describes the glow current-to-voltage characteristic exhibited by the arrangement of Figure 2. Dotted curve 120 shows the total power consumed by the glow discharge and expressed by IV_g while broken curve 121 illustrates the electric power entering the cathode electrode and calculated as 1.4 IV_g. The glow voltage and powers in watts are plotted against the same glow current.

From Figure 6 it is seen that at least 80% of the total consumed power enters the cathode electrode and that the higher the glow current I the greater the proportion of the power entering the cathode electrode to the total consumed power will be.

Also it is seen that the quantity of input heat *q* to the cathode electrode 1 per unit area per unit time is given by

$$q = jV_c = jV_g$$

provided that the spacing *d* between the cathode and anode electrodes 1 and 2 respectively substantially approximates to the thickness of the region of cathode fall *a* (see Figure 2), that is to say, the glow discharge includes no plasma portion. From this it is seen that the smaller the spacing *d* between the cathode and anode electrodes the larger the proportion of the power entering the cathode electrode to the total consumed power will be.

Figure 7 shows a model for a positive ion flux striking against a unit area of the surface of the cathode electrode per unit time. In Figure 7, a square prism has a square bottom of side 1 centimeter and contacting the surface of the cathode electrode 1 and a height corresponding to the velocity V_i cm/sec of ions multiplied by one second. Within the prism, positive ions designated by the symbol "cross in circle" move as shown by the arrows to collide with the cathode electrode 1. Thus the square prism designates a positive ion flux colliding against the cathode electrode per unit area per unit time and electrical energy of the ion flux results in the quantity of input heat *q* to the cathode electrode. Since the number of the positive ions is expressed by j/e where e designates the elementary electric charge and since each ion has electrical energy of eV_c, the quantity of input heat *q* is expressed by

$$q = eV_c \frac{j}{e} = jV_c \text{ in watts/cm}^2.$$

Thus the model for the positive ion flux also explains that the quantity of input heat to the cathode electrode is expressed by jV_c per unit area per unit time.

From the foregoing it will be understood that the glow discharge established across the cathode and anode electrodes causes the quantity of heat expressed by ξjV_c to enter the cathode electrode per unit area per unit time. Also by decreasing the spacing between both electrodes to increase the glow current through the spacing, the quantity of input heat to the cathode electrode per unit area per unit time can approximate to the product of the current density on the surface of the cathode electrode multiplied by the glow voltage or $J{\cdot}V_c$.

Therefore the glow discharge without the positive column can be utilized as a heat source having a high efficiency because almost all heat due to the glow discharge enters the cathode electrode and also as a heat source having a power density variable at will by changing the gas pressure within the spacing between both electrodes because the current density on the surface of the cathode electrode is proportional to the square of the gas pressure.

(3) Current-to-Voltage Characteristic of Glow Discharge

The current-to-voltage characteristic of the glow discharge will now be described and then the principles of the present invention will be described in detail.

Figure 8 shows the relationship between a current and a voltage for the glow discharge. In Figure 8 the abscissa represents current and the ordinate represents voltage.

A DC voltage is applied across a cathode and an anode electrode 1 and 2 respectively (see Figure 9A) to render the anode electrode 2 positive with respect to the cathode electrode 1. This causes a glow discharge across the electrodes. When the current flowing through both electrodes is increased, a negative glow region *b* included in the glow discharge spreads in area on the surface of the cathode electrode 1 (see Figures 9A and 9B). This results in a change in current-to-voltage characteristic as shown at solid line N in Figure 8.

However, when the current is quite low, the current-to-voltage characteristic droops as shown by a characteristic portion N_1 in Figure 8. The region in which the drooping characteristic N_1 appears is called a region of subnormal glow *e*.

In the region following the region of subnormal glow *e* an increase in current causes the voltage to be kept substantially constant as shown by a characteristic portion N_2 in Figure 8 as long as the surface of the cathode electrode 1 having the negative glow *b* caused thereon is smaller in area than the entire surface thereof opposite to the anode electrode 2 as shown in Figure 9A. The region in which the characteristic portion N_2 is developed is called a region of normal glow *f*.

A further increase in current causes an increase in voltage because the negative glow *b* has covered the entire area of the surface of the cathode electrode 1 opposite to the anode electrode 2 as shown in Figure 9B whereby the negative glow increases in current density. The resulting I—V characteristic is upturned with an increase in current as shown by a characteristic portion N_3 in Figure 8. The characteristic portion N_3 is called a positive resistance characteristic and the region in which the positive resistance characteristic N_3 appears is called a region of abnormal glow. In that region of abnormal glow *g* the entire area of the surface of the cathode electrode 1 is covered with the negative glow *b* (see Figure 9B) with the result that the current is apt is concentrate at the edge portion or the like of the cathode electrode 1 and therefore the glow discharge is easily changed to an arc discharge. As a result, it is difficult to maintain the glow discharge in its stable state. The arc discharge appears in a region *h* as shown in Figure 8.

With no impedance connected between the cathode and anode electrode 1 and 2 respectively and an electric source for supplying an electric power across both electrodes, the source side has the current-to-voltage characteristic of the constant voltage type such as shown at horizontal broken line P in Figure 8. This is because even an increase in current does not cause a voltage drop across an impedance.

Under these circumstances, the glow discharge has its operating point coinciding with a point P_1 where the characteristic P of the source side intersects the characteristic N of the glow discharge. However, this operating point P_1 is located in the region of abnormal glow *g*, which is apt to change to a region of arc discharge *h*, as above described. Accordingly it is difficult to maintain the glow discharge stable in the region of abnormal glow *g*.

Further it is to be noted that the flat characteristic P of the source side cannot stably cross the flat characteristic portion N_2 of the glow discharge in the region of normal glow f.

On the other hand, with a resistance R as the impedance connected to the source, an increase in current I causes an increase in voltage drop IR across the resistance. Thus the source side has the current-to-voltage characteristic such as shown at dotted straight line Q in Figure 8 and the glow discharge has its operating point designated by an intersection Q_1 of the characteristics Q and N. This operating point is located in the region of normal glow *f* resulting in a stable glow discharge.

Where electrical energy participating in the glow discharge is converted to thermal energy with a very high efficiency, the connection of an impedance to the source as above described forms one of the factors decreasing the efficient utilization of electrical energy. For example, the use of a resistor causes a Joule's loss and the use of reactor causes a Joule's loss of a winding involved and an eddy current loss and a hysteresis loss of the iron core involved. Since such energy losses scatter as thermal energy, it is difficult to recover the thermal energy. This, of course, deprives the resulting heating device of its convenience and compactness.

From the foregoing it is seen that whether or not an impedance is connected to an electric source the abovementioned disadvantages remain as long as the glow discharge has the current-to-voltage characteristic in the form of a curve such as shown at N in Figure 8.

In order that the glow discharge can be maintained stable even with the flat current-to-voltage characteristic of an associated source side such as shown by straight line P in Figure 8 and without an impedance connected to the source, the present invention proposes means for imparting a positive resistance to the current-to-voltage characteristic of the glow discharge in a different manner as compared with conventional abnormal glows.

First it is seen in Figure 10A that the surface of a cathode electrode 1 opposite to an anode electrode 2 has an area made sufficiently larger than that of the anode electrode 2 so as not to impede the spread of a negative glow *b*. In other words, the opposite surface area of the anode electrode 2 is made small with respect to the area of the cathode electrode. Thus the distance of a peripheral edge root b_1 of the negative glow *b* lying on the surface of the cathode electrode 1 to the anode electrode 2 is gradually increased as the negative glow *b* spreads due to an increase in glow discharge current and therefore the voltage across both electrodes 1 and 2 is gradually raised. Under these circumstances, the glow discharge has a current-to-voltage characteristic such that the voltage increases with the current as shown at broken curve T in Figure 8. That is, the characteristic is of the positive resistance type.

In this connection, it is to be noted that the positive resistance characteristic developed in the region of abnormal glow *g* in the prior art practice as shown at curve N_3 in Figure 8 is caused by the fact that the negative glow *b* has spread over the surface of the cathode electrode and can not spread any more (see Figure 9B). Accordingly, such a positive resistance characteristic is quite different from that according to the principles of the present invention. As above described, the negative glow of the present invention is permitted to spread with an increase in current because the active surface area of the cathode electrode 1 opposite the anode electrode 2 is sufficiently larger than that of the anode electrode with the result that there is no problem that the glow discharge may change to an arc discharge due to the impossibility of spreading the negative glow.

From the foregoing it is seen that the characteristic T of the present invention as shown in Figure 8 is developed in the region of normal glow and not in the region of abnormal glow even though it has a positive resistance. That is, even the regions *q* and *h* are regions of normal glow for the characteristic T.

In the present invention, even with an associated electric source having no impedance connected thereto, the characteristic T intersects the characteristic of an associated source side at a point T_1 (see Figure 8) where the glow discharge is stable. It is to be noted that the point T_1 lies in the region of the normal glow unlike the characteristic N_3 of the prior art practice so that the present invention does not encounter the problems that the glow discharge may change to an arc discharge and so on.

In order to impart a positive resistance to the current-to-voltage characteristic of the glow discharge by further increasing the distance between the peripheral edge b_1 of the negative glow b on a cathode electrode 1 and an associated anode electrode 2, the cathode electrode 1 can be made cylindrical and opposite to the anode electrode 2 as shown in Figure 10B. In the arrangement of Figure 10B, the peripheral glow edge b_1 is located on the peripheral wall surface of the cylindrical cathode electrode 1 at some distance from the end surface thereof. Thus, the glow edge b_1 is further away from the anode electrode 2 as compared with the arrangement of Figure 10A, resulting in a satisfactory positive resistance characteristic.

When an AC voltage is applied across the cathode and anode electrodes, each of the electrodes becomes alternately a positive electrode so that a glow discharge is caused on the opposite surfaces of both electrodes. With an AC voltage used, it is desirable that the cathode and anode electrodes should be in the form of identical cylinders and oppose each other as shown in Figure 10C. From Figure 10C it is seen that the peripheral edge b_1 of the negative glow b on either electrode 1 or 2 is far spaced away from the mating electrode 2 or 1 as in the arrangement of Figure 10B.

Referring now to Figure 11, there is illustrated a glow discharge heating apparatus embodying the principles of the present invention as above described. The arrangement illustrated comprises an electrically insulating enclosure 9 in the form of a hollow cylinder formed of glass, a cathode electrode 1 in the form of a hollow cylinder with both open ends coaxially extending through the enclosure 9 and an anode electrode 2 in the form of a hollow cylinder with two open flare ends disposed coaxially with the cathode electrode 1 within the enclosure 9 to form an annular glow discharge gap 8 therebetween. The cathode electrode 1 is extended and sealed through the ends of the enclosure 9 by means of seal fittings 10 and 11 respectively. Thus the enclosure 9 along with the cathode electrode 1 defines an annular space 81 which includes the glow discharge gap 8 and is filled with an electrically dischargeable gas for example an inert gas such as helium, a mixture of inert gases, for example, a mixture of neon and argon or a mixture of helium and hydrogen.

An annular anode terminal 5 is fixedly secured at the inner periphery to the central portion of the outer cylindrical surface of the anode electrode 2 and has a protrusion extended through and sealed relative to the enclosure 9 by having the outer periphery fixed to a seal fitting sealed to adjacent ends of two similar enclosure portions forming the enclosure 9. The anode terminal 5 is connected to a positive side of a source of DC voltage 3 having a negative side connected by a stabilizer 4 to a cathode terminal 6 which is connected to that portion of the cathode electrode 1 disposed outside of the enclosure 9, in this case, adjacent the seal fitting 11. The stabilizer 4 may be a small capacity reactor or a resistor. If desired, the stabilizer may be omitted.

In order to facilitate the description of the present invention, the symbol "S−" designates the entire area of that portion of the cathode electrode 1 on which a glow discharge can be caused while the symbol "S+" designates the area of that portion of the anode electrode 2 opposing to the cathode electrode 1 and actually used for the glow discharge. Therefore the area labelled S+ is called an "anode area effective for discharge" or an "effective anode area".

The operation of the arrangement as shown in Figure 11 will now be described. A DC voltage from the source 3 is applied across the anode and cathode electrodes 2 and 1 respectively through the stabilizer 4 to establish a stable glow discharge in the annular discharge gas 8 thereby to heat the cathode electrode 1. Under these circumstances, a fluid to be heated, for example water, flows into the interior of the cathode electrode 1 as shown at the arrow A in Figure 11 to absorb heat from the cathode electrode 1 to be heated. Then the heated fluid flows out from the cathode electrode 1 as shown at the arrow B in Figure 1.

During the glow discharge, the current and the voltage thereof is illustrated by a characteristic curve shown in Figure 12 wherein the glow discharge current I_g in amperes is plotted against the glow discharge voltage V_g in volts. The glow discharge voltage V_g may be approximately expressed by

$$V_g = V_o + I_gR$$

where V_o designates the glow discharge-hold minimum voltage as will be described hereinafter and R designates the slope of the characteristic curve. The slope of the characteristic curve as shown in Figure 12 is called the "positive resistance R".

Referring back to Figure 11, L designates the axial length of the anode electrode 12 and has been differently changed to vary the effective anode area S+ thereby to obtain the relationship between a ratio of the effective anode area S+ to the cathode discharge area S– and the positive resistance R as shown in Figure 13.

In Figure 13, the positive resistance R in ohms is plotted against the ratio between the areas S+/S–. Curves labelled 122, 123 and 124 have been plotted with data measured by filling the interior of the enclosure 9 or the annular space 81 with a gaseous mixture including 70% by volume of helium and 30% by volume of hydrogen under pressures of 100, 150 and 200 Torrs respectively. The gap between the electrodes 1 and 2 has been maintained at a magnitude of 1 mm. Also the vertical segment has the same meaning as that shown in Figure 4.

From Figure 13 it is seen that the positive resistance R when the ratio of S+/S– is 0.2 is some four times as great as the resistance when the ratio is 1.

The tendency of the positive resistance characteristic as shown in Figure 13 can be observed with the spacing of 5 mm between the both electrodes 1 and 2 filled with the dischargeable gas including neon, helium, a mixture of neon and argon, or a mixture of helium and at most 30% by volume of hydrogen under a pressure of 200 Torrs or less.

Also experiments have been conducted with the DC source 3 having varied regulations of the source voltage.

The results of the experiments are shown in Figure 14 wherein the ordinate axis represents the regulation of the source voltage in percent and the abscissa represents the ratio of the actual discharge current I to the rated discharge current I_0 in percent. Straight lines labelled 125 and 126 describe the regulations of source voltage with the positive resistance R having values of 3 and 1 ohms respectively.

From Figure 14 it is seen that a variation of 15% in source voltage gives a current regulation or a ratio of the actual current I to the rated discharge current I_0 muiltiplied by one hundred in percent ±42% and ±14% with positive resistance R of 1 and 3 ohms respectively. Thus the positive resistance of 3 ohms renders the glow discharge relatively stable.

Further, by making the positive value R higher, it is possible to control the maximum current for supplying a predetermined electric power to a small magnitude which is, in turn, advantageous in that the glow discharge apparatus is made compact.

The measure as above described is also applied to constructions in which an AC voltage is applied across the electrodes 1 and 2 to cause the glow discharge thereacross only when the electrode 1 acts as a cathode electrode.

From the foregoing it is seen that the arrangement of Figure 11 eliminates the disadvantages of conventional glow discharge heating apparatus in which the positive resistance for the glow discharge is low, the glow discharge moves about on the electrode, the discharge current changes substantially with variation in source voltage resulting in the necessity of connecting a stabilizer or the like to the source and so on. Those disadvantages have been caused by the cathode area being substantially equal to the anode area.

Figure 15 shows a modification of the present invention operatively associated with an AC source. The arrangement illustrated comprises an inner electrode 1 in the form of a hollow cylinder having one end closed, an outer electrode 2 in the form of a hollow cylinder having one end open and disposed coaxially with the inner electrode 1 so that the closed end portion of the inner electrode 1 is inserted into the opened end portion of the outer electrode 2 to form an annular discharge gap 8 therebetween.

The inner electrode 1 is coaxially disposed within a tubular glass enclosure 9 to extend beyond both open ends thereof and the open end portion of the electrode 1 is rigidly fitted into an annular supporting disc 13 of any suitable metallic material including an outer periphery connected to the adjacent end of the enclosure 9 through the seal fitting 11. The outer electrode 2 has an open end portion extending into the enclosure 9 and supported by another annular supporting disc 14 of the same material as the disc 13 similarly connected to the other end of the enclosure 9 through another seal fitting 10. In this way the enclosure 9 defines a closed space 81 with the supporting discs 13 and 14, the seal fittings 10 and 11, the inner electrode 1 and the outer electrode 2 having the other end closed.

Then a pair of terminals 5 and 6 is attached to the supporting discs 13 and 14 to connect both electrodes 1 and 2 to an AC source 31 therethrough.

An inflow tube 15 is coaxially disposed within the inner hollow electrode 1 to form an annular passageway therebetween. The tube 15 is maintained in place through a closing member 16 rigidly fitted into the open end of the inner electrode 1 and having the tube 15 extending therethrough. The inner electrode 1 is provided on the open end portion with an outlet duct 17.

On the other hand, the outer electrode 2 is double walled and provided on the closed end portion of the outer wall with an inlet duct 18 and that portion thereof adjacent to the supporting disc 14 with an outlet duct 19 communicating with the inlet duct 18 through an annular space defined by the inner and outer walls of the electrode 2. A liquid to be heated, for example water, enters the inlet duct 18 as shown at the arrow A in Figure 15 and thence to the annular space due to the double-walled structure of the outer electrode 2 after which it leave the outlet duct 19. Also water enters the inflow tube 15 as shown at the arrow C in Figure 15 and flows into the annular space between the inflow tube 15 and the inner electrode 1. Then the water flows out from the outlet duct 17 as shown at the arrow D in Figure 15.

It will readily be understood that the space 81 is filled with an easy dischargeable gas as above described in conjunction with Figure 11.

In operation an AC voltage across the source 31 is applied across both electrodes 1 and 2 to cause a glow discharge mainly in the annular discharge gap 8.

As above described, the inner electrode 1 is inserted into the outer electrode 2 to overlap the latter. This ensures that the area of that portion of one of the electrodes opposite to the other electrode is smaller than an electrode area over which a glow discharge can occur between the electrodes 1 and 2. This means that the anode area on the side of that electrode acting as an anode for the glow discharge is always limited. For example, with the dischargeable gas maintained under a pressure of about 200 Torrs and with the gap between both electrodes having a length not exceeding 5 millimeters, the limitation of the anode area results in an indirect limitation of an associated negative glow region and therefore an increase in positive resistance for the glow discharge. That is, the current-to-voltage characteristic of the glow discharge such as shown at point T_1 in Figure 8 has a larger slope whereby the AC glow discharge can be maintained stable. Accordingly, a stable glow discharge can be sustained even with a high current under a high pressure without the glow discharge changing to an arc discharge.

Under these circumstances, either of the inner and outer electrodes 1 and 2 respectively is heated when it acts as the cathode electrode resulting in heating of both electrodes. Thus the fluid such as water flowing in contact with the electrodes is instantaneously heated and the heated fluid leaves the outlet ducts 17 and 19.

Figure 16 is a characteristic curve illustrating the relationship between the area of one of the electrodes overlapping the other electrode and the positive resistance exhibited by the glow discharge. In Figure 16 the positive resistance R in ohms is plotted against the ratio of the overlapping area to the entire area of the electrode acting as the cathode. Curves labelled 127, 128 and 129 have been plotted with the discharge gap 8 having a length not exceeding 5 mm and filled with a mixture of helium and hydrogen under pressures of 100, 150 and 200 Torrs respectively. The vertical segment has the same meaning as that shown in Figure 4.

From Figure 16 it is seen that the smaller the overlapping area for both electrodes 1 and 2 the higher the positive resistance will be.

In the arrangement of Figure 15, the inner and outer electrodes 1 and 2 respectively are disposed in coaxial relationship but different in shape from each other. Therefore the current-to-voltage characteristic of the glow discharge is different between the half-cycle of the source 31 having the inner electrode 1 acting as a cathode and that having the outer electrode acting as an anode as shown in Figure 17. In Figure 17, the ordinate axis represents a discharge voltage V and the axis of abscissa represents the discharge current I. When the inner electrode 1 acts as the cathode, the discharge current I is forwardly and rearwardly changed along a straight line 130 shown in Figure 17 and has a maximum value of I_1. In the next succeeding half-cycle the outer electrode 2 takes over the cathode and the current is forwardly and rearwardly changed along a straight line 131 shown in Figure 17. In the latter case, the current has the absolute maximum value I_2 different from that of the current I_2 flowing in the just preceding half cycle of the source 31. Both straight lines have the same absolute values of a voltage V_o at zero current. Thus the resulting characteristic becomes asymmetric to permit a zero-phase sequence component of a current to flow through the AC source 31. This is objectionable to the source 31. Further the inner electrode 1 is free at one end but the outer electrode 2 has no free end. This results in the occurrence of thermal strains in the outer electrode 2 during the glow discharge.

These objections can be eliminated by still another modification of the present invention shown in Figure 18. In the arrangement illustrated, a first cathode 1 in the form of a hollow cylinder having one end closed with a flat disc opposes a second electrode 2 identical to the first electrode to form a discharge gap 8 having a predetermined spacing or gap width of *d* between the opposite closed end surfaces.

A flow confining tube 20 or 21 of the double wall type inserted into the second or first electrode 2 or 1 respectively includes a central tubular portion extending on the longitudinal axis of the mating electrode, a radially extended end wall to form a predetermined gap between the same and the internal closed end surface of the electrode and a peripheral wall extending parallel to the internal peripheral surface of the latter to form also a predetermined annular gap therebetween. Each electrode 1 or 2 is provided on the open end portion with an outlet duct 17 or 18 communicating with the flow path formed therein while annular blind cover disc 23 or 22 is rigidly inserted into the annular gap between the peripheral surface of the electrode 1 or 2 and the outer wall of the tube 21 or 20 at the open end. The purpose of the flow confining tubes 20 or 21 is to cause a fluid to be heated to enter first the central tubular portion as shown at the arrow A or C in Figure 18 and flow along the internal surface of the mating electrodes at an increased speed to enhance the heat transfer between the fluid and the electrode and also to enable the fluid to be instantaneously heated. The heated fluid then flows out from the outlet duct 17 or 18 as shown at the arrow B or D in Figure 18.

Then the first and second electrodes 1 and 2 respectively are snugly fitted into individual supporting rings 14 and 13 which are hermetically connected to both ends of circular enclosure 9 through annular seal fittings 10 and 11. In this way both electrodes 1 and 2 are supported in cantilever manner to the supporting members 14 and 13 and the substantial portions thereof are coaxially disposed within the enclosure 9 to form the space 81 that is then filled with a dischargeable gas such as previously described.

As in the arrangement shown in Figure 11 or 15, the AC source 31 is connected across the electrodes 1 and 2 through the terminals 6 and 5 connected thereto respectively.

In the arrangement of Figure 18 it is noted that those portions of both electrodes 1 and 2 superposing each other as designated by the reference character *l* is made smaller in area than that portion of each electrode on which the glow discharge occurs. In the example illustrated the glow discharge occurs on each of the electrodes 1 and 2 throughout the surface.

In the arrangement of Figure 18 the electrodes 1 and 2 are formed to be symmetric about the predetermined gap 8 formed between them. This results in the symmetric glow discharge characteristic as shown in Figure 19. In Figure 19 similar to Figure 17, the characteristics 132 and 133 are substantially symmetric and have respective discharge currents I_1 and I_2 which have the same absolute value.

Also, as the electrodes 1 and 2 are supported in cantilever manner to the annular supporting discs 14 and 13 respectively, the electrodes are prevented from breaking due to thermal stains.

It will readily be understood that the gap 8 between electrodes 1 and 2 should be dimensioned so that the electrodes are prevented from contacting each other due to thermal expansions during operation.

As in the arrangement of Figure 15, an AC voltage across the source 31 is applied across the electrodes 1 and 2 to cause a glow discharge between the opposite surfaces thereof while a fluid to be heated enters the interiors of the electrodes 1 and 2 as shown at the arrows A and C in Figure 18. Then the fluid flows through spacing formed between each electrode and the flow confining tube 20 or 21 to be heated with heat generated on the electrode 1 or 2 due to the glow discharge. Thereafter the heated fluid flows out from each outlet duct 19 or 17.

Figure 20 illustrates a modification of the arrangement shown in Figure 18. As shown in vertical section in Figure 20B, the electrodes 1 and 2 of the identical structure are opposed to and somewhat offset from each other to form a predetermined discharge gap 8 between them. As seen in side elevational views of Figures 20A and 20C, the electrodes 1 and 2 are in the form of rectangular boxes and therefore their discharge surfaces are rectangular and flat. Then each electrode is provided on the rear surface with a pair of inlet and outlet tubes.

In other respects, the arrangement is substantially identical to that shown in

Figure 18. The electrodes 1 and 2 have discharge surfaces identical in shape to each other and are of the cantilever type so that the arrangement exhibits the same results as that shown in Figure 18.

In the arrangements of the present invention shown in Figures 15, 18 and 20 the electrode material and impurities such as metallic oxides included in the electrode might be scattered in the discharge gap during the glow discharge and adhered to that surface portion of the enclosure 9 facing the electrodes 1 and 2. This sticking of such metallic materials to the enclosure might lead not only to the danger of the seal fitting 10 and 11 short-circuiting with each other through the adhered materials but also to a fear that, if the scattered impurities again adhere to the electrodes, the glow discharge will change to an arc discharge.

The present invention also seeks to mitigate the danger and fear as above described, by the provision of the arrangement shown in Figure 21. The arrangement illustrated is different from that shown in Figure 18 only in that in Figure 21 two annular shields 24 and 25 one for each electrode are disposed to surround the mating electrodes and face at least the internal surface portions of the enclosure 9 by having flare ends fixedly secured to the internal surface portions of the enclosure 9. Each shield 24 or 25 has a substantial portion parallel to the associated electrode and ending short of the adjacent annular supporting disc 13 or 14. The shields 24 and 25 may be of an electrically insulating or conductive material.

In operation when the electrode material and the impurities are emitted from the electrode 1 or 2 and scattered in the discharge gap, they are adhered to that surface of each shield 24 or 25 facing the associated electrode and prevented from adhering to that inner surface portion of the enclosure 9 covered with the shield 24 or 25. Also the shield is effective for preventing the scattered electrode material and impurities from again adhering to the associated electrode.

The arrangement illustrated in Figure 22 is different from that shown in Figure 21 only in that in Figure 22 a pair of annular electrodes 26 and 27 are respectively buried in annular shields 24 and 25 formed of an electrically insulating material. Then a suitable voltage is applied to the annular electrode 26 and 27 whereby the scattered metallic materials are apt to adhere to the shields 24 and 25.

Figure 23 shows another modification of the arrangement illustrated in Figure 21. In Figure 23 the electrodes 1 and 2 are in the form of hollow flat discs and disposed in opposite relationship to form the discharge gap 8 having a predetermined gap width of *d* therebetween.

The seal fitting 10 in the form of a short hollow cylinder has one end fixedly secured to the peripheral portion of that surface of the electrode 1 remote from the electrode 2 and the other end in the form of a flange to an enclosure portion 91 in the form of an annulus. Then an annular shield disc 28 of electrically insulating material is located between the annular enclosure portion 91 and the peripheral portion of the electrode 1 by having a fitting perpendicular to the same and connected to the outer peripheral surface of the seal fitting 10. The sealing fitting 11, an enclosure portion 92 and a shield 29 identical to the components 10, 91 and 28 respectively are operatively coupled in the same manner to the electrode 2.

A toroidal metallic enclosure portion 93 of double L-shaped cross section is hermetically connected to the annular enclosure portions 91 and 92 to form a hermetically closed space 81 in the form of a toroid.

As shown in Figure 23, a feed water tube 18 and a drain tube 19 project in spaced relationship from that surface of the electrode 1 remote from the electrode 2 and a pair of deflector or baffle plates 30 and 32 are disposed in the interior of the electrode 1 so as to direct a liquid to be heated toward the peripheral portion thereof and enter the fluid into the drain tube 19 after it has flowed along the heated surface of the electrode 1 to be heated. Also a feed water tube 18′ and a drain tube 17 similarly project from the electrode 2 and a pair of baffle plates 33 and 34 are similarly disposed within the hollow electrode 2.

If desired, the shield 28 and 29 may be formed of any suitable metallic material. In the latter case, the shields 28 and 29 should be suitably insulated from the associated electrodes 1 and 2 respectively.

Further the present invention contemplates to prevent the occurrence of electric shock-accidents through the heated liquid such as water.

The arrangement illustrated in Figure 24 is substantially similar to that shown in Figure 22 except for the provision of means for preventing the user from receiving electric shocks. As shown in Figure 24, the control tubular portion of the flow confining tube 20 or 21 is connected to an electrically insulating tube 37 or 38 that is, in turn connected to metallic inflow tube 41 or 42.

The outlet of the flow confining tube 20 or 21 is connected to connecting tube 35 or 36 subsequently connected to an electrically insulating tube 39 or 40 that is, in turn, connected to a metallic outflow tube 43 or 44.

The metallic tubes 41 and 43 are electrically connected together to ground as are the metallic tubes 42 and 44.

It has been found that an end-to-end distance l_p between the central tubular portion of the flow confining tube and the inflow tube or between the connecting tube and the outflow tube, that is to say, a length of the insulating portion should be equal to or less than a predetermined magnitude dependent upon a voltage applied across the electrodes, the resistivity of the particular liquid to be heated, the cross sectional area of the tube etc.

The arrangement of Figure 24 is operated as follows: A switch 45 is closed to apply an AC voltage from the source 31 across the electrodes 1 and 2. This causes the flow confining tubes 20 and 21, and the connecting tubes 35 and 36 to be put at a certain potential relative to the ground potential. For example, in glow discharge heating apparatus having a discharge input of about 8 kilowatts, the AC source 31 is required to supply to the heating apparatus an AC voltage having the effective value of 200 volts so that the tubes 20, 21, 35 and 36 are put at a voltage having the effective value of 200 volts.

On the other hand, the metallic inflow tubes 41 and 42 and the metallic outflow tubes 43 and 44 are connected to ground so that the particular liquid flowing into or out from the extremities thereof is put at zero potential. This ensures that electric shock accidents are prevented from occurring through the liquid.

More specifically, the source voltage is applied across the electrodes 1 and 2 to cause a glow discharge therebetween. Heat generated during the glow discharge heats the liquid. When the heated liquid flow within the apparatus, it reaches any of the tubes 41, 42, 43 and 44 where it is put at the ground potential. This ensures that the user is kept safe.

Under these circumstances the electrodes 1 and 2 rapidly transfer heat to the liquid flowing within their interiors to prevent the electrodes 1 and 2 from effecting an abnormal temperature rise whereby the stable glow discharge is sustained.

However, as a potential difference having the effective value of 200 volts occurs between the inflow and outflow tubes 41, 42 and 43, 44 and the confining and connecting tubes 20, 21 and 35, 36, the insulating tubes 37, 38, 39 and 40 must have a dielectric strength withstanding a voltage having the effective value of 200 volts. In this connection, it is required to consider a leakage current flowing to ground through the liquid, in addition to the surface status of the insulating tubes.

In the arrangement of Figure 24 applied to a water warmer operated with the source voltage of 200 volts, a leakage breaker must be provided. Leakage breakers are responsive to the leakage current in excess of the predetermined magnitude flowing through the inflow and outflow tubes 41, 42 and 43, 44 to ground to be continuously operated to prevent the source voltage from being applied across the electrodes 1 and 2. Accordingly, it is required to impart to the length l_p of the insulating portion a value sufficient to limit the leakage current to a certain value or less.

Assuming that each of the insulating tubes 37, 38, 39 and 40 has a cross sectional area of flow path designated by S and a liquid to be heated such as water has a resistivity designated by ρ, the insulating portion presents a resistance R_l before the liquid expressed by

$$R_l = \rho \frac{l_p}{S} \qquad (10)$$

Also assuming that each of the insulating tubes 37, 38, 39 and 40 has a surface resistance sufficiently large as compared with the resistance of the liquid, the leakage current I_l may be expressed by

$$I_l = \frac{V_l}{R_l} = V_l \frac{S}{\rho l_p} = \frac{V_l S}{\rho} \frac{1}{l_p} \qquad (11)$$

where V_l designates the voltage across the liquid located in the insulating portion having the length of l_p. Accordingly, the leakage current I_l is inversely proportional to the length l_p with the voltage V_l, the cross sectional area S and the resistivity ρ remaining unchanged.

Figure 25 is a graph illustrating the relationship between the length l_p of the insulating portion and the leakage current I_l on the basis of the above two expressions (4) and (5) and with $V_l = 200$ volts, $S = 0.636$ square centimeters (which results from the insulating tubes 37, 38, 39 and 40 having an inside diameter of 9 millimeters) and $\rho = 1300$ ohms/centimeter. The resistivity of 1300 ohms/centimeter is a minimum value of a resistivity of usable water as determined by the IEC standards. In Figure 25 the leakage current I_l in milliamperes is plotted against the length l_p of the insulating portion in centimeters.

Assuming that the particular water warmer is provided with a highly sensitive leakage breaker having a rated sensible current of 15 milliamperes, the breaker has a rated inoperative current of 7.5 milliamperes. In order to prevent this leakage breaker from being continuously operated due to a leakage current flowing through the insulating portion, the length l_p of the latter is necessarily at least 13 centimeters with used water having a resistivity of 1,300 ohms/centimeter as will be seen from the curve of Figure 25. The expression (11) indicates that the length l_p changes with the leakage current, voltage, the cross sectional area of the flow path and resistivity of the liquid. However, the length of the particular insulating portion can be estimated as above described and in accordance with the rating of a given leakage breaker, the source voltage, the resistivity of the particular liquid and the cross sectional area of the flow path.

In the arrangement of Figure 24, the flow path of the heated liquid has been provided with insulating tubes having the required length while each of the insulating tubes has been connected at the extremity to the metallic inflow or outflow tube that is connected to ground. Accordingly, it is ensured that any electric shock accident can be prevented from occurring through a liquid involved and still one can eliminate the insulating treatment that electrode components are coated with an electrically insulating material. This results in simplified inexpensive apparatus and also results in rapid heat transfer from the electrode components to the liquid. Therefore the arrangement of Figure 24 is extremely advantageous in both the heat efficiency and the stability of operation.

Also glow discharge heating apparatus such as shown in Figure 24 can be utilized to instantaneously heat a liquid, for example water, by feeding the water at a flow rate of from 1 to 10 litres per minute through the interior of the electrodes thereby to transfer thermal energy injected into the electrodes to the water. Under these circumstances, water at room temperature must be heated to a temperature of about 80°C. This results in the necessity of injecting thermal energy of at least 5 kilowatts into the electrodes. This means that, with a power source of AC 200 volts used, an effective current of at least 25 amperes must flow through the electrodes. If the discharge current becomes high and also if the discharge gap is filled with a gas under an increasing pressure then it is difficult to sustain the flow discharge. For example, the glow discharge changes to an arc discharge.

It has been found that the stable maintenance of the glow discharge is affected by the type of gas filling the discharge space. Also it has been experimentally confirmed that, by filling the discharge space with a mixture of at least helium and hydrogen, the glow discharge can be sustained without the change to an arc discharge, even with an electric power required for heating the particular liquid, that is to say, a discharge current as high as possible.

This will now be described in conjunction with Figure 24. Various experiments were conducted with the discharge space 81 filled with an inert gas heavier than argon under a pressure ranging from 50 to 200 Torrs. The result of experiments indicates that the glow discharge is difficult to spread and that an increase in glow current causes a contraction of the positive column included in the glow discharge to move the glow discharge about on the electrodes 1 and 2. Thus the glow discharge is put in its unstable state so that it is apt to change an arc discharge. The mean value of the glow current in excess of 5 amperes has caused the glow discharge to change to an arc discharge.

With neon used, relatively stable glow discharge has occurred under a gas pressure not higher than 70 Torrs. Under a gas pressure of 100 Torrs, however, the glow discharge has been relatively stable at effective currents up to about 20 amperes. Upon the effective current exceeding 20 ampere, the positive column has been contracted. This might cause the glow discharge to change to an arc discharge.

Further, when an inert gas used has been heavier than neon, the scatter from the electrodes 1 and 2 has increased in amount with the result that the electrodes 1 and 2 are violently consumed while insulating materials such as glass forming the enclosure 9 is sharply deteriorated in electrical insulation because metallic materials scattered from the electrodes 1 and 2 stick to the glass. As a result, the useful life of the glow discharge heating apparatus has been much reduced.

From the foregoing it is summarised that, with the arrangement of Figure 24 used as a heating apparatus for instantaneously heating water, it is required to sustain stably the glow discharge under a relatively high pressure of 50 Torrs or more and still at a high current exceeding 25 amperes at an AC voltage of 200 volts.

Also from the foregoing it has been found that it is desirable to fill the discharge space 81 with a chemically stable, light, inert gas such as helium or hydrogen.

In the arrangement of Figure 24, however, it has been seen that, with helium filling the discharge space 81, the flow discharge spreads throughout the surface of the electrodes 1 and 2 at low current because of a small current density and that electrical energy of the glow discharge entering the electrodes 1 and 2 amounts to only about 2 Killowatts. Also in a glow discharge caused in an atmosphere of helium, its positive column has been contracted upon a pressure of helium increasing to 150 Torrs to increase a current density for the glow dicharge. Thus the glow discharge has been moved about on the electrodes and become unstable. The glow discharge tends to change to an arc discharge.

On the other hand, a glow discharge in an atmosphere of hydrogen has made a discharge hold minimum voltage Vo equal to at least 240 volts as shown in Figures 30, 31 and 32 which will be described hereinafter. Therefore, it has been difficult to cause a glow discharge having an electric power of 5 kilowatts or more by using an AC source with 200 volts.

It has been found that, in order to manufacture glow discharge heating apparatus requiring at least 5 kilowatts with an AC voltage of 200 volts, it is optimum to employ a mixture of helium (He) and hydrogen (H_2) as a filling gas.

When the arrangement of Figure 24 is filled with a mixture of helium and hydrogen under a pressure of 100 Torrs, and applied with an AC voltage of 60 hertz having a waveform E shown in Figure 26, a glow current flowing therethrough is changed in accordance with the proportion of hydrogen to helium as shown at current waveforms F, G, H and I in Figure 26. Figure 26 shows the voltage and current waveforms in one cycle of the source voltage. The current waveforms F, G, H and I have been plotted with gaseous mixtures having 5, 10, 30 and 50% by volume of hydrogen respectively, the balance being helium.

Also the glow discharge exhibits the current-to-voltage characteristic dependent upon the proportion of the hydrogen to the helium as shown in Figure 27 wherein voltage in volts is plotted against current I in amperes and like reference characters have been employed to identify the helium-hydrogen mixtures identical to those designated in Figure 26. As shown in Figure 27, each of the current-to-voltage characteristics is substantially rectilinear. By calculating both values of glow voltages S, T, U and W through the extrapolation and slopes of respective characteristic curves, the glow voltage Vg may be approximately expressed by

$$Vg = V_o + RI$$

where V_o designates a glow discharge hold minimum voltage designated by S, T, U or W, and R designates the slope of the characteristic called the positive characteristic R. As well known, the voltage V_o is expressed by $V_o = Em \sin \omega t$ where Em designates the peak value thereof and ω designates an angular frequency of the source voltage. To calculate a discharge power P from the above expression for V_o, referring to Figure 26 gives

$$P = \frac{2}{TR} \int_{t}^{\frac{T}{2}-t} (Em \sin wt - Vo)\, Em \sin wt\, dt$$

$$= \frac{2Em}{TR} \left\{ \frac{1}{4} TEm - \frac{Em}{w} \sin^{-1} \frac{Vo}{Em} - \frac{Vo}{w} \cos\left(\sin^{-1} \frac{Vo}{Em}\right) \right\} \quad (12)$$

where T designates a period of the source voltage. The discharge voltage is thermal energy entering the electrodes 1 and 2 due to the glow discharge.

Assuming that the source voltage has its frequency of 60 hertz and 200 volts or the peak value of $Em = \sqrt{2}\, 200 \simeq 280$ volts, its period is of 16.67 milliseconds and its angular frequency is of 377 radians per second. By using those figures in the expression for the discharge power, the glow discharge hold minimum voltage V_o relates to the positive characteristic R as shown in Figure 28 wherein the positive resistance R in ohms is plotted against the glow hold minimum voltage V_o in volts with the parameter being the discharge power or thermal energy P.

From the Figure 28 it is seen that, in order to provide a thermal energy of not less than 5 kilowatts, the V_o and R may lie in a hatched region as shown in Figure 28 defined by a line for the power of 5 kilowatts, and both coordinate axes.

Also the glow hold minimum voltage V_o is determined by the pressure of a filling gas and the gap length *d* between the electrodes 1 and 2 while the positive characteristic R is determined by the configuration of the electrodes, the overlapping area S_o for both electrodes 1 and 2 and the pressure of the filling gas.

By changing the relative diameter M of one to the other of the electrodes 1 and 2 to vary the overlapping area S_o and also by changing the pressure of the filling gas, the positive characteristic R is varied as shown in Figure 29 wherein the overlapping area S_o in square centimeters is plotted against the pressure of the filling gas in Torrs with the positive characteristic R variously changed. In Figure 29 solid lines indicate measured values and dotted lines indicate values estimated from the associated measured values.

From Figure 29 it is seen that, under a gas pressure less than 50 Torrs, a current density for the glow discharge is low and the supply of discharge power or heat input in excess of 5 kilowatts to the electrodes requires an increase in overlapping area S. This raises a problem in portability because the electrode area must be increased.

On the other hand, a gas pressure in excess of 150 Torrs causes the discharge input to the electrodes to increase to at least 5 kilowatts, resulting in a glow current of at least 25 amperes. Under these circumstances a positive column involved is contracted and the particular glow discharge is moved about on the electrodes. This might sometimes cause the glow discharge to change to an arc discharge.

With the gas pressure further increased to 200 Torrs or higher, a positive column involved is contracted at a glow current of at least 5 amperes until the change to an arc discharge occurs.

As an example, it is assumed that the glow hold minimum voltage V_o cannot be decreased to 176 volts or less. Under the assumed condition, it is seen from Figure 28 that, in order to manufacture glow discharge heating apparatus having a discharge input of at least 5 kilowatts, the pressure of the particular filling gas, the overlapping area S_o and the positive characteristic R must lie in the hatched portion shown in Figure 29 as being defined by a pair of vertical broken lines passing through the abscissas of 50 and 150 Torrs respectively and curve labelled $R = 2\Omega$.

In addition, by changing both the proportion of hydrogen to helium and the gap length *d* between the electrodes 1 and 2, the glow hold minimum voltage V_o is varied as shown in Figures 30, 31 and 32 wherein the ordinate axis represents the proportion of hydrogen to helium in percent and the axis of abscissa represents the gap length d in millimetres. The helium-hydrogen mixture is maintained under pressures of 50, 100 and 150 Torrs in Figures 30, 31 and 32 respectively. In these Figures curves are labelled measured values of the glow hold minimum voltage V_0 and for pure hydrogen the measured voltages V_0 are denoted beside corresponding dots.

Also a gap length d of less than about 0.5 millimeters between both electrodes 1 and (2) has resulted in the danger of both electrodes contacting and shortcircuiting each other due to a pressure difference between the pressure of the particular heated liquid within either of the electrodes and that of a filling gas involved. On the other hand, an excessively large gap length d between both electrodes cause a positive column to contract and to move the resulting discharge about on the electrodes until the discharge sometimes changes to an arc discharge. This might result in damage to the electrodes 1 and 2. It has been seen that the contraction of the positive column occurs with the gap length d of at least 9, 6 and 3 millimeters under the gas pressures of 50, 100 and 150 Torrs respectively.

With the proportion of hydrogen to helium decreased to 2.5% or less, the resulting glow discharge resembles that occurring in an atmosphere of pure helium. This has made it difficult to increase the discharge input to at least 5 kilowatts. Also as Figure 29 describes that it is difficult to decrease the positive characteristic R to at most 1, 0.5 and 0.3 ohms under gas pressures of 50, 100 and 150 Torrs respectively, it has been difficult to increase the discharge input to at least 5 kilowatts at the glow hold minimum voltages V_0 of at least 210, 230 and 240 volts under the gas pressures of 50, 100 and 150 Torrs respectively as will readily be understood from the graph shown in Figure 28. Further an increase in glow hold minimum voltage V_0 causes an increase in peak value of the glow current as shown in Figure 33 wherein the peak current for the glow discharge in amperes is plotted against the glow hold minimum voltage V_0 in volts. This has resulted in the disadvantage that the resulting apparatus should be made larger.

From the foregoing it will readily be understood that the proportion of hydrogen to helium and gap length d between the electrodes 1 and 2 are desirably located in dotted closed areas shown in Figures 30, 31 and 32. More specifically, the proportion of hydrogen is not less than 2.5% and the gap length d is not less than 0.5 millimeter while the voltage V_0 has values of 210, 230 and 240 volts dependent upon the pressure of the filling gas.

While the present invention has been described in conjunction with an AC source having a voltage of 200 volts it is to be understood that it is equally applicable to AC sources having a voltage higher than that of 200 volts, for example, a voltage of 400 volts. In the latter case, the glow current may be made low by using a helium-hydrogen mixture including not less than 50% by volume of hydrogen which is effective for increasing the glow hold minimum voltage V_0 shown at any of the points S, T, U and W illustrated in Figure 27. This provides a stable glow discharge while being able to decrease the surface area of the electrodes 1 and 2. In addition, wiring leads may be fine. Therefore the resulting apparatus can be made compact.

Examples of the electrode material are copper, aluminum, nickel, pure ion, molybdenum, stainless steel and Kovar (Trade mark) used with vacuum tubes or voltage regulator tubes. However, copper is not suitable for use in the present invention because the copper has a high current density for the glow discharge to enhance the sputtering thereby to deteriorate severely the insulation of associated insulators. Also aluminum is not suitable for use in the present invention because a glow discharge involved changes to an arc discharge with a current as low as one ampere. Therefore suitable examples of the electrode material are nickel, pure iron, molybdenum, stainless steel and Kovar (Trade mark). The electrode used with the present invention has been formed of sheet nickel or stainless steel one millimeter thick.

From the foregoing it is seen that the filling of the discharge space 8 with a mixture including at least helium and hydrogen can eliminate the change of the glow to an arc discharge and the sputtering with a high discharge current. This gives the result that a stable glow discharge can be sustained. The reason why the glow discharge can be prevented from changing to an arc discharge is that oxides on the surface of the electrodes are removed by the hydrogen included in the filling gaseous mixture.

The use of the helium-hydrogen mixture is also advantageous in that, only by changing the proportion of the hydrogen to the helium, the glow hold minimum voltage can be selected at will to control the discharge input to both electrodes involved as desired.

Figure 34 shows still another modification of the present invention. The arrangement illustrated is different from that shown in Figure 24 only in that in Figure 34 the opposite surfaces of the electrodes 1 and 2 are corrugated to increase the surface areas of the electrodes and an auxiliary electrode 46 is operatively associated with the gap 8 formed between the electrodes 1 and 2 as will be subsequently described.

In glow discharge heating apparatus having the discharge input of 5 kilowatts, for example, the diameter M of the electrodes 1 and 2 is required to be at least 80 millimeters and also that of the insulating enclosure 9 is necessarily at least 100 millimeters. In other words, the larger the diameter of the electrodes the larger the enclosure 9, and therefore the seal fittings 10 and 11, will be. This is attended with the disadvantages that the components become excessively expensive and also manufacturing cost is increased.

In addition, the opposite surfaces of the electrodes 1 and 2 can be forced toward each other to be crowned in response to a difference between the pressure within discharge space 81 and the pressure of a heated liquid within each electrode so that the bending of the electrodes increases to be proportional to the fourth power of the radius M/2. Accordingly, an increase in diameter of the electrodes may causes the electrodes 1 and 2 to contact and short circuit each other due to crowning.

To avoid this objection, the opposite surfaces of the electrodes 1 and 2 have a diametric section of corrugated shape to increase areas of the opposite electrode surfaces with the diameter of the electrodes remaining unchanged. In the arrangement of Figure 34 each electrode 1 or 2 has the diameter M of 52 millimeters and the area of 80 square centimeters of that surface thereof opposite to the other electrode 2 or 1.

As shown in Figure 34, the auxiliary electrode 46 is extended and sealed through the insulating enclosure 9 so as to centre the gap 8 formed between the opposite corrugated surfaces of the electrodes 1 and 2 and to be substantially contacted at the free end by the adjacent portion of the edge of the gap 8.

Then the AC source 31 is connected at one end to the electrode terminal 5 through a normally open switch 45 and at the other end directly to the electrode terminal 6. The auxiliary electrode 46 is connected to the electrode terminals 6 and 5 through respective resistors 47 and 48 and also by a resistor 49 to one output of an auxiliary source circuit 50. The auxiliary source circuit 50 includes the other output connected to the electrode terminal 5 and therefore the switch 45 and is also connected to the switch 45 through another normally open switch 51 and to the other end of the AC source 31. The operation of the abovementioned circuit configuration will be described hereinafter.

With the auxiliary electrode 46 operatively associated with the discharge gap 8 as in the arrangement of Figure 34, the electrodes 1 and 2 are called hereinafter the "main electrodes" to be distinguished from the auxiliary electrode 46.

In the arrangement of Figure 34 a glow discharge is fired between the main electrodes 1 and 2 after which the glow discharge is smoothly spread on the corrugated surfaces 1*a* and 2*a* respectively of the main electrodes 1 and 2. Under these circumstances, a high current can enter the opposite corrugated surfaces of the main electrodes 1 and 2 as compared with pairs of discharge electrodes having opposite flat surfaces. Therefore, the discharge input to the electrodes increased while the voltage across the main electrodes remains unchanged.

As a result, the corrugated surface of the main electrodes permits a decrease in diameter thereof attended with a reduction in diameter of each of the insulating enclosure 9 and the seal fittings 10 and 11. Accordingly manufacturing cost can be decreased. Also the corrugated surface of the main electrodes is effective for preventing the crowning of the opposite surfaces thereof.

The opposite surface 1*a* of the main electrode 1 shown in Figure 35 includes a plurality of grooves of rectangular cross section concentrically disposed at substantially equal intervals thereon.

Figure 36 shows a plurality of parallel grooves disposed at predetermined intervals on the discharge surface 1*a* of the main electrode 1.

The discharge surface 1*a* of the main electrode 1 shown in Figure 37 includes a plurality of cylindrical depressions disposed in a predetermined pattern thereon.

In the arrangement shown in Figure 38, a pair of flow confining blocks generally designated by the reference numeral 200 and 210 respectively are of the same construction and disposed in place within the main electrodes 2 and 1 to form heating spaces or flow paths 2A and 1A for a heated liquid therein respectively. The flow confining block 200 is formed of an electrically insulating material such as a synthetic resinous material and includes a feed water tube 201 and a drain tube 202 formed in parallel relationship on the exposed end surface thereof to be integral therewith and through openings 201*a* and 202*a* connected to the tubes 201 and 202 respectively. Then openings 201*a* and 202*a* open on that end surface thereof facing the inside of the gap forming surface of the main electrode 2 and a peripheral surface thereof respectively. The tube 201 and the opening 201*a* interconnected serves as a feed water tube opening in the flow path 2A while the tube 202 and the opening 202*a* interconnected serves as a drain tube also opening in the flow path 2A.

The flow confining block 210 includes a feed water and a drain tube identical to those as above described in conjunction with the flow confining block 200 and designated by like reference numerals identifying the corresponding components of the confining block 200 numbered from 210. For example, the reference numeral 211 designates a feed water tube.

The flow confining blocks 200 and 210 have the exposed end portions screw threaded through the blind cover plate 22 and 23 fixed to the open end portions of the main electrodes 2 and 1 to be flush with the open ends thereof respectively.

In other respects, the arrangement is substantially identical to that shown in Figure 34 except for the omission of the insulating tubes 37, 38, 39 and 40 shown in Figure 34.

In the arrangement of Figure 38, the flow confining blocks 200 and 210 can be removed from the blind cover plates 22 and 23 respectively for the purpose of inspecting or cleaning the internal surfaces of the main electrodes 2 and 1. Therefore the heating efficiency can be always maintained high.

Figure 39 shows modification of the arrangement shown in Figure 15 wherein the user has access to the heat transfer surfaces of the main electrodes as in the arrangement of Figure 38 and an auxiliary electrode 46 is operatively associated with the discharge gap 8. As shown in Figure 39 a flow confining tube 200 in the form of a hollow cylinder having both ends open is coaxially disposed within the main electrode 1 to form a flow path for a heated liquid therethrough. The cylindrical tube 200 is screw threaded through a screw member 200*a* rigidly fitted into the open end of the main electrode 1.

Similarly another flow confining tube 210 in the form of a hollow cylinder having one end closed is detachably connected to the main electrode 2 at the outwardly folded end through a screw member 210*a* formed internally with the tube 210 to form an annular flow path for the heated liquid.

The flow confining tubes 200 and 210 are of an electrically insulating material such as a synthetic resinous material.

As in the arrangement of Figure 38, the flow confining blocks 200 and 210 can readily be removed from the main electrodes 1 and 2 respectively for purposes of inspection and cleaning.

In other respects, the arrangement is substantially similar to that shown in Figure 15 excepting that electric shock preventing means such as above described in conjunction with Figure 24 are provided on the feed water and drain tubes 41, 42 and 43, 44 and the auxiliary electrode 46 is operatively coupled to the gap 8 formed between the main opposite electrodes 1 and 2.

Figure 40 shows a different modification of the present invention enabled to decrease the dimension of the electrically insulating enclosure and still increase the diameter of the main electrodes. In the arrangement illustrated a pair of main electrodes 1 and 2 identical to each other are horizontally disposed in opposite relationship to form a discharge gap 8 therebetween. Each of the main electrodes 1 or 2 is in the form of a hollow cylinder having one end closed and the other end portion 1B or 2B reduced in diameter. The closed flat ends of both main electrodes 1 and 2 form therebetween the gap 8 having a width *d* and a diameter M.

Each electrode 1 or 2 includes a shoulder connected to an electrically insulating enclosure 9*a* or 9*b* in the form of a narrow annulus through a first annular seal fitting 10*a* or 11*a*. Thus the enclosures 9*a* or 9*b* encircles the reduced diameter end portion 1B or 2B of the main electrode 1 or 2. Then a cylindrical metallic shell 9*c* or 9*d* encircles in spaced relationship the adjacent main electrode 1 or 2 and includes a radially inward directed flange connected at one end to the enclosure 9*a* or 9*b* through a second annular seal fitting 10*b* or 11*b*. Both shells 9*c* and 9*d* have the other ends abutting against and fixed together as by welding. Thus the shells 9*c* and 9*d* and the main electrodes 1 and 2 form therebetween an annular discharge space 81 including the gap 8 with the enclosures 9*a* and 9*b*, the seal fittings 10*a*, 10*b*, 11*a* and 11*b*.

The blind cover plate 22 or 23 is rigidly fitted into the open end of the main electrode 1 or 2. A feed water tube 41 or 42 is extended and sealed through the blind cover plate 22 or 23 and has an outlet opening substantially flush with the internal surface of the cover plate 22 or 23. Also a drain tube 43 or 44 is extended and sealed through the blind cover plate 22 or 23 and has an end portion bent into an L in order to fill a heating space 1A or 2A formed of the interior of the main electrode 1 or 2 with a liquid to be heated. The end of the L-shape tube 43 or 44 faces the uppermost portion of the internal surface of the main electrode 1 or 2 with a distance l_0 maintained therebetween.

Further, the auxiliary electrode 46 and an associated electric circuit are provided in the same manner as above described in conjunction with Figure 34.

The main electrodes 1 and 2 may be of any desired shape other than the cylindrical shape as above described.

As the main electrodes 1 and 2 are of the same structure, the operation will now be described in conjunction of one of the electrodes, for example, the electrode 1.

A liquid to be heated enters the heating space 1A through the feed water tube 42 as shown at the arrow A in Figure 40 until its liquid surface reaches a level at which the drain tube 44 opens while the liquid is heated by the main electrode 1. Thereafter the heated liquid is exhausted from the space 1A through the drain tube 44 as shown at the arrow B in Figure 40. The outflow of the liquid causes a pressure loss across the drain tube 44 permitting the heated liquid charge in the heating space 1A to have a pressure higher than the atmospheric pressure. In keeping with this increase in pressure, the surface of the liquid within the heating space 1A is forced to be gradually raised beyond the open end of the drain tube 44 resulting a decrease in volume of a cavity existing in the heating space 1A.

In this case, a decrease in the diameter of the drain tube 44 will be accompanied by an increase in speed of the liquid flowing through the drain tube 44. As a result, the open end of the drain tube 44 is less in pressure than the cavity within the heating space 1A. This causes an increase in rate at which the drain tube 44 sucks up air left within the heating space 1A.

It has been experimentally proved that the distance l_0 exceeding 10 millimeters causes the air phase in the heating space 1A to be too far spaced from that portion of the liquid just flowing through the open end of the drain tube 44. Therefore the heating space 1A has been difficult to be sufficiently deaerated. This means that the distance l_0 is preferably at most 10 millimeters.

In other words, the distance l_0 is so dimensioned that, even though steam bubbles would be evolved from the liquid being heated within either of the heating spaces 1A and 2A and reach the uppermost portion thereof, they can be rapidly exhausted through the drain tube 43 or 44.

After the air has been fully removed from either of the heating spaces 1A and 2A as above described, both spaces are entirely filled with the heated liquid without the steam bubbles accumulated to form a cavity therein. Otherwise a cavity not filled with the heated liquid is formed within either of the main electrodes 1 and 2 and therefore that portion thereof contacted by and located adjacent to the cavity excessively rises in temperature resulting in its failure.

The arrangement of Figure 40 is further advantageous in that the insulating enclosures decrease in diameter and therefore are easily manufactured with low cost and are mechanically strong because the enclosures surround the reduced diameter portions of the main electrodes which are encircled by the metallic shells interconnected into a unitary structure to permit the region occupied by the insulating enclosures to be considerably decreased. Further the main electrodes are insulated from the shells through the insulating enclosures respectively. Accordingly, the resulting apparatus is easy to be manufactured, inexpensive and robust while having a long useful life.

In the arrangement shown in Figure 41, the insulating enclosure 9 in the form of a hollow cylinder having both ends open includes a pair of upper and lower apertured cover plates 13 and 14 respectively connected to both open ends thereof through annular seal fittings 10 and 11 respectively. A pair of hollow main electrodes 1 and 2 having one end open are vertically disposed in opposite parallel relationship within the enclosure 9 to be staggered longitudinally of the enclosure and form a discharge gap 8 in a discharge space 81 defined by the enclosure 9, the seal fittings 10, 11 and the cover plates 13 and 14. The main electrodes 1 and 2 have the other open ends fixedly fitted into apertures on the upper and lower cover plates 13 and 14 to be flush with the outer surfaces thereof respectively.

The main electrodes 1 and 2 have the open ends closed with blind cover plates 23 and 22 having central openings respectively. Then a L-shaped tube 44 or 41 has one leg connected to the central opening on the blind cover plate 23 or 22 and the other leg horizontally extended to form an outflow or an inflow tube.

A feed water tube 42 extends in sealing relationship through the one leg of the outflow tube 44 and into a heating space 1A within the main electrode 1 from above the upper plate 13. Similarly, the drain tube 43 extends through the inflow tube 14 and into a heating space 2A within the main electrode 2 from below the lower plate 14.

As in the arrangement of Figure 40, the drain tube 43 has its open end facing the inside of the closed end of the main electrode 2 through a spacing l_0 not greater than 10 millimeters.

In Figure 41, the inflow tube 41 has the end opening in the heating space 2A below the inlet of the drain tube 43 while the feed liquid tube 42 has the end opening in the heating space 1A below the inlet of the drain tube 44. Therefore the heating spaces 1A and 2A can be entirely filled with the heated liquid as in the arrangement of Figure 40.

Further an auxiliary electrode 46 is operatively associated with the discharge gap 8 formed between the main opposite electrodes 1 and 2. If desired, both main electrodes may be concentrically disposed.

In the arrangement shown in Figure 42, a seamless metallic tube is closely wound into a helix 41*a* or 42*a* having the outside diameter substantially equal to the inside diameter of the main electrode 2 or 1. The helix 41*a* or 42*a* includes one end portion 43 or 42 extending through the central hollow portion thereof and the other end portion 41 or 44 bent into an L-shape. Both helices 41*a* and 42*a* are inserted into the main electrodes 2 and 1 to be brazed or welded to the internal surfaces thereof respectively for the purpose of improving the heat transfer from the mating main electrodes thereto. A liquid to be heated enters the helix 41a or 42a through the end portion 41 or 42 and leaves the end portion 43 or 44.

In other respects, the arrangement is identical to that shown in Figure 41.

Each of the main electrodes 1 or 2 can be prevented from corroding starting with those portions thereof brazed or welded to the helix 42*a* or 41*a* because the brazed or welded portions are not directly contacted by the heated liquid flowing through the helix. Since the heated liquid flows at a high speed through the helix 41*a* or 42*a*, nuclear ebullition can be prevented and also pressure loss in the helix is increased to prevent steam bubbles from staying in the helix. This results in the smooth heat transfer from the main electrode to the heated liquid flowing through the mating helix. Thus the main electrodes are prevented from excessively rising in surface temperature thereby to sustain stably the glow discharge.

The arrangement shown in Figure 43 is substantially similar to that illustrated in Figure 40 excepting that, in addition to disposing the main electrodes 1 and 2 vertically, they are in the form of square hollow prisms and a tube is closely wound in a helix complementary in shape to the interior of the associated main electrode and fixed thereto.

Each of the arrangements shown in Figures 42 and 43 is characterized in that the tube means formed of a good thermally conductive material contacts the internal surface of the mating main electrode to be thermally integral therewith and the heated liquid flows through the tube means. This results in the alleviation of limitations as to the configuration of the main electrode while facilitating the manufacturing of the apparatus and prolonging the useful life.

In the arrangement shown in Figure 44 either of the blind cover plates 22 and 23 is provided on that portion diametrically opposite to the normal outlet with an exhaust port that is, in turn, closed with a plug 221 or 231 for example through a screw mechanism. Further an auxiliary electrode 46 is operatively coupled to the gap formed between the main opposite electrodes 1 and 2 as above described in conjunction with Figure 34.

In other respects, the arrangement is substantially identical to that shown in Figure 24.

The arrangement shown in Figure 45 includes the U-shaped flow path or heating space 1A or 2A within the main electrode 1 or 2 and a connecting tube 361 or 351 connected to the heating space 1A or 1B on the inlet side. Then the connecting tube 361 or 351 is provided with an exhaust port closed with a detachable plug 231 or 221.

In other respects the arrangement is substantially identical to that shown in Figure 44.

When each of the arrangements shown in Figures 44 and 45 is desired to be out of service for a long time, the plugs 221 and 231 can be removed from the associated exhaust ports to drain the liquid out from interior of the main electrodes for the purpose of preventing the liquid within the main electrode from spoiling or freezing. Also the useful life can be prolonged.

While the main electrodes have been described as being in the form of hollow cylinders having the same shape and disposed in opposite relationship it is to be understood that the main electrode may be of any other desired shape. For example, the main electrodes may be in the form of hollow cylinders disposed in coaxial relationship. It is essential that, in order to empty the interior of the main electrodes, the exhaust port must be provided on the lower portions thereof.

While some of the abovementioned Figures, for example, Figure 34 illustrate the control circuit for controlling the glow discharges Figure 46 shows the fundamental circuit configuration of a control circuit for controlling any of the arrangements as above described including no auxiliary electrode. In Figure 46, the arrangement generally designated by the reference numeral 100 comprises a pair of first and second electrodes 1 and 2 respectively disposed in opposite relationship to form therebetween a gap having a gap width d and each including an inflow and an outflow tube. Water enters the interior of either of the electrodes 1 and 2 through the inflow tube to be heated and heated water leaves it through the outflow tube.

The source of AC voltage 31 is connected across the electrodes 1 and 2 through a bidirectional triode thyristor 60 with the first electrode 1 connected to ground. The bidirectional triode thyristor is called hereinafter a "Triac" (trade mark). The source 31 is also connected across a gate circuit 61 through a normally open switch 62. Then the gate circuit is connected across one electrode and a gate electrode of the Triac 60. The switch 62 is closed to fire a glow discharge between the electrodes 1 and 2 thereby to heat a liquid, for example, water flowing through the interior of each electrode.

The operation of the control circuit shown in Figure 46 will now be described with reference to Figure 47 wherein there are illustrated a voltage waveform V supplied from the source 31 and having a peak value E_m and a current waveform V of the glow discharge. As shown in Figure 47, the voltage waveform V in the positive half-cycle of the source gradually increases from its zero point until time point t_1 is reached. At that time voltage reaches a value of a discharge breakdown voltage V_5 to fire a glow discharge between the electrodes 1 and 2. At that time point t_1 a glow current I abruptly flows through the electrodes 1 and 2. The glow current I corresponds to a voltage drop expressed by $V_f - V_0$ where V_0 designates a glow hold minimum voltage and may be expressed by $I = (V_f - V_0)/R$ where R designates a discharge resistance corresponding to a slope of a current-to-voltage characteristic curve for a glow discharge as above described in conjunction with Figure 8.

Then at time point t_2 the voltage V is equal to the glow hold minimum voltage V_0 after which the glow discharge is extinguished because the voltage is less than the voltage V_0.

Thereafter the source 31 enters the next succeeding negative half-cycle in which the process as above described is repeated to cause a glow discharge between the electrodes 1 and 2. In the arrangement shown in Figure 46 the application of the AC voltage causes the electrodes 1 and 2 to act alternately as a cathode and an anode electrode respectively to be heated because the glow discharge heats that electrode acting as the cathode as above described.

From the foregoing it will be seen that the firing of the glow discharge at time point t_1 causes an instantaneous increase in glow current so that the glow discharge can not spread following this increase in glow current. This results in the tendency to locally concentrate the glow current on the electrode to change the glow discharge to an arc discharge. The arc charge has a chance of melting the electrode which, in turn, reduces the useful life of the heating apparatus.

Also the glow current is initiated to flow through the electrodes 1 and 2 only upon the source voltage across both electrodes reaching the discharge breakdown voltage V_f while $V_f > V_0$ holds. Therefore it is impossible to utilize the time interval during which the source voltage is not less than the glow hold minimum voltages V_0

as a conduction time resulting in a poor efficiency of utilization of the source voltage.

Figure 48 shows a control circuit for controlling the glow discharge heating apparatus of the present invention constructed in accordance with the principles thereof. The arrangement illustrated comprises an auxiliary source circuit *61* connected across the source of AC voltage 31 that supplies AC voltage of 200 volts at the commercial frequency. The circuit 61 includes a normally open switch 62, a step-up transformer 63 having a primary winding connected across the source 31 through the switch 62 and a secondary winding having one end connected to the electrode 2 through a current limiting resistor 64 and the other end connected to the electrode 1 and also to ground.

As in the arrangement of Figure 46, the source 31 is connected to the electrode 2 through the Triac 60. The resistor 64 is connected across a primary winding of an electrically insulating transformer 65 including a secondary winding connected across a pair of AC inputs of a rectifier bridge 66. The rectifier bridge 66 includes a pair of DC outputs one of which is connected to the junction of the source 31 and the Triac 60 through a resistor 67 and the other of which is connected to the remaining terminal or a gate terminal of the Triac 60.

The step-up transformer 63 is designed and constructed so that the discharge breakdown voltage V_f is applied across the electrodes 1 and 2 before the time point where an instantaneous voltage from the source 31 reaches the glow discharge minimum voltage V_0.

The operation of the arrangement shown in Figure 48 will now be described with reference to Figure 49 similar to Figure 47. In Figure 49 wherein like reference characters designate the components corresponding to those shown in Figure 47, the switch 62 is closed at time point A to permit the source to apply the source voltage across the primary winding of the transformer 63. At a point B, a secondary or an output voltage from the transformer 63 reaches the discharge breakdown voltage V_f whereupon the gap between the electrodes 1 and 2 is broken down to start an electric discharge therebetween. At that time the output voltage drops to the glow hold minimum voltage V_0 (see point C, Figure 49) for a glow discharge by means of the current limiting resistor 64. This causes a current *i* of the order of 0.1 ampere to flow through the electrodes 1 and 2 resulting in a glow discharge occurring across the electrodes 1 and 2. That glow discharge is called a "pilot glow discharge".

The current for the pilot glow discharge causes a voltage drop across the current limiting resistor 64 that, in turn, induces a secondary voltage across the transformer 65. The secondary voltage from the transformer 65 is applied to the gate electrode of the Triac 60 after having been fullwave rectified by the rectifier bridge 67 to put the Triac 60 in its conducting state. Therefore the source voltage is applied across the electrodes 1 and 2. Under these circumstance, if the pilot glow discharge has not occurred across the electrodes 1 and 2 then the pilot glow current *i* does not flow through the electrodes 1 and 2 and no voltage is induced across the insulating transformer 65 with the result that the Triac 60 is maintained non-conducting. This ensures that the application of the high AC voltage across the electrodes 1 and 2 does not result in the occurrence of an arc discharge therebetween unless the preliminary pilot glow discharge occurs across the electrodes 1 and 2.

When the source voltage is applied across the electrodes 1 and 2 through the now conducting Triac 60 and reaches the glow hold minimum voltage V_0, the principal glow discharge is fired across the electrodes 1 and 2. That is, a current I for the principal glow discharge flows through the electrodes 1 and 2. That principal glow discharge current I is extinguished after the source voltage V has again reached the glow hold minimum voltage V_0 at point E or time point t_2 and therefore the principal glow discharge is extinguished. However it is noted that at point E the voltage V_0 from the step-up transformer 63 is applied across the electrodes 1 and 2 through the resistor 64 with the result that the pilot glow discharge is still established.

Then at point F, the output voltage from the step-up transformer 63 becomes also less than the voltage V_0 and the pilot glow discharge ceases.

Then the source 31 enters the next succeeding negative half-cycle in which the process as above described is repeated.

The concept of the embodiment of the present invention as shown in Figure 48 is to apply preliminarily a high voltage across the electrodes by means of the auxiliary source circuit to cause the preliminary or pilot glow discharge thereacross and to smoothly derive the principal glow discharge from the pilot glow discharge. Therefore the arrangement of Figure 48 is effective for preventing the principal glow discharge current from abruptly increasing resulting in an arc discharge as in the arrangement of Figure 46. Further the efficiency of utilization of the source is increased.

The arrangement shown in Figure 50 comprises a reactor 68 connected between the source 31 and the electrode 2, and an AC pulse generator 69 connected across the source 31 through the normally open switch 62. The pulse generator 69 includes one output connected by the current limiting resistor 64 to the junction of the reactor 68 and the electrode 2 and the other output connected to the electrode 1 and therefore to ground.

The gap formed between the electrodes 1 and 2 is so dimensioned that the peak voltage E_m from the source 31 is prevented from effecting the discharge breakdown of the gap.

As shown in Figure 51 wherein a voltage and a current waveform V and I respectively and a pulse waveform P are illustrated, the AC pulse generator 69 generates an AC pulse voltage P sufficient to reach the discharge breakdown voltage V_f at time point t_1 where the voltage from the source 31 approximately reaches the glow hold minimum voltage V_o. The pulse voltage P first effects the discharge breakdown of the gap between the electrodes 1 and 2 followed by a flow of the principal glow current I through the electrodes.

As in the arrangement of Figure 46, the current I becomes zero at time point t_2 to extinguish the glow discharge after which the process as above described is repeated in the next succeeding negative half-cycle.

It is noted that the reactor 68 is designed and constructed so that it present a high impedance to the pulse waveform P but a low impedance to the commercial frequency of the source 31.

Thus the arrangement of Figure 50 ensures that, when the source voltage V is close to the glow hold minimum voltage V_o, the principal glow discharge is initiated between the electrodes 1 and 2 and then the principal glow current I is smoothly increased without the change to an arc discharge.

Figure 52 shows a modification of the present invention wherein the pilot glow discharge occurs between the auxiliary electrode and either of the main electrodes prior to the principal glow discharge as above described, for example, in conjunction with Figure 34. In Figure 52, the main and auxiliary electrodes 1, 2 and 46 respectively are schematically shown and may have any of their structures shown in Figure 34 and Figures 38 to 45.

The arrangement illustrated comprises the AC source 31 and an auxiliary source shown as comprising a step-up transformer 70 including a primary winding connected across the source 31 through the normally open switch 51 and a center-tapped secondary winding. The dot convention is used to identify the polarity of the instantaneous voltage across the associated winding. The secondary winding includes a center tap connected to the auxiliary electrode 46 through a current limiting resistor 71 and a normally open switch 72, and a pair of end terminals connected to the main electrodes 1 and 2 through individual semiconductor rectifier diodes 73 and 74 with anode electrodes thereof connected to the respective main electrodes. The gap formed between the electrodes 1 and 2 has a gap width d satisfying $V_f > E_m > V_o$, where V_f, E_m and V_o have been previously defined.

The switch 51 is closed to apply the AC voltage V from the AC source 31 across the electrodes 1 and 2 while the switch 72 is closed to apply a high voltage waveform from the step-up transformer 70 to the auxiliary electrode 46. Under these circumstances, when a potential at the main electrode 1 is higher than that at the main electrode 2, the diodes 73 and 74 are turned off and on respectively to cause a pilot glow discharge between the auxiliary electrode 46 acting as an anode and the main electrode 2 acting as a cathode. On the other hand, when the main electrode 2 is higher in potential than the main electrode 1, the diodes 73 and 74 are turned on and off respectively to cause a pilot glow discharge between the auxiliary electrode 46 acting as anode and the main electrode 1 as the cathode.

In addition, as the auxiliary electrode 46 has applied thereto the voltage from the center tap on the secondary transformer 70 winding, the voltage applied across the auxiliary electrode 46 and the main electrode 1 to cause the pilot glow discharge therebetween is identical to that applied across the auxiliary electrode 46 and main electrode 2 to cause the pilot discharge therebetween. Therefore, the change of the pilot glow discharge due to the auxiliary electrode to the principal glow discharge between the main electrodes 1 and 2 is equally effected between each of the positive and negative half-cycles of the source 31.

Further, the occurrence of the pilot glow discharge completes a closed circuit including the diode 73 or 74, the associated half of the secondary transformer 70 winding, the resistor 71, the closed switch 72 and the pilot glow discharge between the auxiliary electrode 46 and the main electrode 1 or 2. This prevents the current for the pilot glow discharge from entering a circuit with the source 31.

The opening of the switch 72 stops the pilot glow discharge from occurring between the auxiliary electrode 46 and either of the main electrodes 1 and 2. Thus the principal glow discharges are not fired in the next succeeding cycle of the source and the cycles following the latter with the result that the heating operation is not performed. In other words, the ON-OFF control of the principal glow discharge can be conducted by turning the pilot discharge on and off.

It is noted that the pilot glow discharge always occurs between the auxiliary electrode 46 acting as the anode and either of the main electrodes 1 and 2 acting as the cathode so that the auxiliary electrode 46 is not heated. This results in the elimination of the necessity of cooling the auxiliary electrode.

From the foregoing it is seen that the arrangement when effecting the ON-OFF control of the heating apparatus proper of Figure 52 ensures the change of the glow discharge by turning the pilot glow discharge on and off.

The arrangement illustrated in Figure 53 is different from that shown in Figure 52 only in that in Figure 53 a zero-voltage firing circuit is provided to prevent the glow current from abruptly increasing. In Figure 53 a pair of serially connected resistors 75 and 76 are connected across the AC source 31 through the normally open switch 51 to form a voltage divider, and the junction A of both resistors is connected to a resistor 77 subsequently connected to a base resistor 78 that is connected to a base source V_{BB}. The resistor 76 is connected to ground. The junction B of the resistors 77 and 78 is connected to the base electrode of an NPN transistor 79 including an emitter electrode connected to the resistor 76 and a collector electrode connected to a DC source V_{cc} through a collector resistor 80. The transistor 79 has connected across the emitter and base electrodes a semiconductor diode 81 serving to prevent a high reverse voltage from being applied across those electrodes and also connected across the collector and emitter electrodes a differentiating circuit including a capacitor 82 and a resistor 83. The junction of that collector electrode and the capacitor is designated by the reference character C and the junction of the capacitor 82 and the resistor 78 is designated by the reference character D only for purposes of illustration.

The junction D is connected to one AC input to a rectifier bridge 84 including the other AC input connected to the resistor 83. The rectifier bridge 84 includes a pair of DC outputs connected across a resistor 85 that is connected at one end to a gate electrode of a Triac 87 through a normally open switch 86 and at the other end to the primary winding of the transformer 70. The Triac 87 is connected across AC source through the primary transformer 70 winding and the switch 51 and has connected thereacross a series combination of a capacitor 88 and a resistor 89 serving as an absorber.

The components 75 through 89 as above described form a zero-voltage firing circuit generally designated by the reference numeral 90.

With the switch 51 closed, an AC voltage developed at the point A is similar to the source voltage and sinusoidal as shown at waveform A in Figure 54. The AC sinusoidal voltage passes through its zero voltage points at time points t_0, t_1 and t_2 in each cycle of the source 31. Assuming that the source V_{BB} is at zero potential, a voltage developed at the point B is sinusoidal between time points t_0 and t_1 or in the positive half-cycle of the source and remains zero between time point t_1 and t_2 or in the negative half-cycle thereof by means of the action of the diode 81 as shown at waveform B in Figure 54. Since the transistor 79 is turned on only in response to a voltage applied to the base electrode to render the latter positive with respect to the emitter electrode, the same is in its ON state between time points t_0 and t_1 and in its OFF state between time points t_1 and t_2. Accordingly, a voltage developed at the point C is zero when the transistor 79 is in its ON state and equal to a voltage across the source V_{CC} also designated by V_{CC} when it is in its OFF state as shown at waveform C in Figure 54.

The voltage at the point C is differentiated by the differentiating circuit 82, 83 to produce alternately a negative and a positive pulse at the point D as shown at waveform D in Figure 54. Those pulses are rectified by the rectifier bridge 84 to form positive pulses which appear at a point E connected to the switch 84 at time points t_0, t_1 and t_2 as shown at waveform E on Figure 54.

With the switch 86 closed, the pulses shown at waveform E in Figure 54 are successively applied to the gate electrode of the Triac 87. In other words, gate pulses are necessarily developed at the gate electrode of the Triac 87 at the zero passage points of the source voltage or at time points t_0, t_1 and t_2. Thus it is seen that, even though the switch 86 has been closed at any time point, the Triac 87 is brought into its ON state starting with the zero passage point of the source voltage. As a result, a pilot voltage from the transformer 70 is applied to the auxiliary electrode 46 starting with the zero passage point of the source voltage or time point t_0, t_1 or t_2 with the result that the principal glow current is prevented from sharply increasing. This means that a liquid flowing in heat transfer relationship along the internal surface of each electrode 1 or 2 is smoothly heated.

The arrangement of Figure 53 is advantageous in that the principal glow current is prevented from sharply rising at a firing time point and the glow discharge is prevented from changing to an arc discharge due to the local concentration of the current while efficiency of utilization of the source voltage is high.

If desired, the zero voltage firing circuit 90 may be formed of solid state relays.

In the arrangements shown in Figures 52 and 53 the auxiliary source circuit including the step-up transformer is formed of components having stray capacitances between one another and with respect to ground with the switch 72 put in its open position. This results in a fear that a potential at the auxiliary electrodes 46 would be raised due to those stray capacitances until a voltage across the auxiliary electrode 46 and either of the main electrodes 1 and 2 exceeds the discharge breakdown voltage across the associated gap. This results in the undesirable occurrence of a glow discharge between the main electrodes 1 and 2 which disables the principal glow discharge to be controlled with the pilot glow discharge.

In order to avoid this objection, the arrangement illustrated in Figure 55 includes a pair of dummy resistors 93 and 94 connected between the diode 73 and the resistor 71 and between the diode 74 and the resistor 71 respectively. The resistors 93 and 94 are effective for determining the potential at the auxiliary electrode 46 so as to prevent the voltage across the auxiliary electrodes 46 and either of the main electrodes 1 and 2 from exceeding the discharge breakdown voltage across the gap as above described.

In other respects, the arrangement is identical to that shown in Figure 53 except for the omission of the switch 72.

The auxiliary electrode 46 is normally positioned to be equidistant from both main electrodes 1 and 2 and therefore the resistors 93 and 94 are equal in magnitude of resistance to each other in order to make the voltage across the auxiliary electrode 46 and the main electrode 1 equal to that across the electrodes 46 and 2 with the switch 62 put in its open position. Even under these circumstances, it is to be understood that the gap length between the auxiliary electrode 46 and either of the main electrodes 1 and 2, and the type and pressure of a dischargeable gas should be preliminarily determined so as to prevent the occurrence of a discharge breakdown between the auxiliary electrode 46 and either of the main electrodes 1 and 2 with the switch 62 put in its open position.

The arrangement illustrated in Figures 56 is different from that shown in Figure 55 only in that in Figure 56 a Triac is substituted for the switch 62 in order to permit the ON-OFF operation to be repeatedly performed with a high frequency. As shown in Figure 56, a Triac or a bidirectional triode thyristor 95 is located in place of the switch 62 shown in Figure 55. The Triac 95 includes a gate circuit 95 connected to a gate electrode thereof to deliver trigger signals to the gate electrode to turn the Triac 95 on and off and a series combination of a capacitor 97 and a resistor 98 serving as an absorber.

If desired, the Triac 95 may be included in the zero voltage firing circuit 90.

When the pilot glow discharge has a discharge breakdown characteristic with a fairy long time delay, the pilot glow discharge may be fired at a time point where the source voltage approaches its peak value provided that the Triac 95 has flowing therethrough a current in excess of its holding current. This is attended with the occurrence of the principal glow discharge having a sharply rising current. A current for this glow discharge may sharply rise. In this case, a negative glow included in the principal discharge can not spread following an increase in current to locally concentrate the current resulting in a danger that the glow discharge changes to an arc discharge. In order to avoid this danger, it is necessary to determine magnitudes of resistances 93 and 94 and an impedance on the primary side of the step-up transformer 70 enough to prevent a flow of current through the Triac 95 in excess of its holding current.

In the arrangement illustrated in Figure 57 an electronic switch 98 such as a thyristor with a trigger circuit 99 is connected between the resistor 71 and the junction of dummy resistors 93 and 44 as shown in Figure 57. When the voltage drop across the serially connected resistors 93 and 94 decreases to some extent, and when the electronic switch 98 is put in its ON state by the trigger circuit 99, a current flowing through the electronic switch 98 may exceed its holding current even in the absence of a pilot glow discharge. Under these circumstances, if the pilot glow discharge has a discharge breakdown characteristic with a long time delay, there is a danger that the resulting glow discharge will change to an arc discharge as above described. In order to avoid this danger, the resistors 93 and 94 are required to have high resistance.

Alternatively the electronic switch 98 with its trigger circuit 99 may be connected between the junction of the dummy resistors 93 and 94 and the auxiliary electrode 46 as shown in Figure 58. In these case, the resistors 93 and 94 are not particularly subjected to limitations as to their resistances unless the voltage across the auxiliary electrode 46 and either of the main electrodes 1 and 2 is reduced.

The arrangements shown in Figures 55 through 58 ensure that the principal glow discharge is controlled with the pilot glow discharge. This is because the dummy resistors prevent the potential at the auxiliary electrode from floating by means of stray capacitances as above described in conjunction with Figures 52 and 53 and the like in the absence of the voltage applied to the auxiliary electrode.

The arrangement illustrated in Figure 59 comprises an electrically isolating transformer 141 including a primary winding connected across the AC source 31 and a secondary winding connected across a series combination of a rectifying diode 142, a current limiting resistor 143 and capacitor 144, and an NPN transistor 145 including an emitter electrode connected to one side of the capacitor 144 and a collector electrode connected to the other side of the capacitor 144 through a semiconductor diode 146 for absorbing back pulses. The transistor 145 includes a base electrode connected to a gate circuit 149 also connected to the emitter electrode thereof to turn the transistor 145 on and off.

The components 141 through 146 form a high voltage pulse generator circuit generally designated by the reference numeral 140 with a step-up pulse transformer 147 which includes a primary winding connected across the diode 146 and a secondary winding connected to a semiconductor diode 148 for shaping a pulse waveform.

As in the arrangement of Figure 57, the diode 148 is connected to the resistor 71 subsequently connected to the auxiliary electrode 46 through the thyristor 98 which is turned on and off by a trigger circuit 99. Further the serially connected dummy resistors 93 and 94 are connected across the main electrodes 1 and 2 also through the switch 51 across the AC source with the junction of both resistors connected to the auxiliary electrode 46.

The operation of the arrangement shown in Figure 59 will now be described with reference to Figure 60 wherein there are illustrated a voltage waveform V across the main electrodes 1 and 2 and a no-load voltage waveform V_N at the auxiliary electrode 46. With the main electrode 1 disposed opposite to the main electrode 2 to form therebetween a predetermined gap fulfilling the relationship that the discharge breakdown voltage V_f for the gap is higher than the peak value E_m of the source voltage under the predetermined discharge conditions, the switch 51 is closed to apply the AC voltage across both electrodes 1 and 2 from the source 31. Also the source 31 charges the capacitor 144 with the polarity illustrated through the transformer 141, the diode 142 and the resistor 143. Then gate and trigger circuits 149 and 99 respectively apply simultaneous respective gate signals to the transistor 145 and the thyristor 98 to turn them on. The turn-on of the transistor 145 causes the charged capacitor 144 to discharge through the primary winding of the pulse transformer 147 and the now conducting transistor 145. As a result, a pulse voltage stepped up by the pulse transformer 147 is supplied from the secondary winding thereof through the diode 148, the resistor 71 and the now conducting thyristor 98 to the auxiliary electrode 46. It is noted that the circuits 149 and 99 generate the respective pulses before the voltage across the main electrode 1 and 2 reaches the discharge breakdown voltage V_o. As shown in Figure 60, the circuits 149 and 99 generate the pulses at time point t_2 before time point t_0 where the source voltage reaches the discharge breakdown voltage V_o in each positive half cycle thereof and the pulse terminates shortly after time point t_0. That is, each pulse has a predetermined pulse width a little longer than a time interval between time points t_2 and t_0. Each pulse is shown at waveform V_N in Figure 60 as being superposed on that portion of the source voltage divided by the resistors 93 and 94, assuming that both resistors are equal in magnitude of resistance to each other. In the next succeeding negative cycle of the source voltage the pulse is similarly developed at time point t_3 before time point t_1 where the voltage across the main electrodes 1 and 2 reaches the negative value $-V_0$ of the discharge breakdown voltage and terminates short after time point t_1 to have the same pulse width as that appearing in the positive half-cycle of the source voltage.

In the arrangement of Figure 59 it is required to cause a pilot glow discharge before time point t_0 or t_1 by applying the pulse waveform V_N to the auxiliary electrode 46 as above described. Also it is required to select the pulse width so as to effect surely the discharge breakdown of the gap between the auxiliary electrode and either of the main electrodes 1 and 2 within the duration of the associated pulse.

In general, a time delay is caused after the voltage has been applied across discharge gaps and until the discharge breakdown is accomplished therebetween. It is well known that this time delay is equal to the sum of a time interval between the application of the voltage across the discharge gap and the appearance of a first electron resulting in the initiation of development of the electron avalanche and another time interval between the initiation of development of an electron avalanche and the completion of a stead-state discharge. The first mentioned time interval is called a statistic delay and the latter is called a formation delay. The statistic delay is overpoweringly long.

Assuming that the voltage applied across the particular discharge gap has a peak value higher than the voltage effecting the DC breakdown of the discharge gap, stepped voltages are applied across the discharge gap n_0 times. Assuming that, among them the n applications of the voltage has time delays not shorter than τ and $(n + \Delta n)$ applications thereof has time delays not shorter than $(\tau + \Delta\tau)$,

$$\Delta n = -An\Delta\tau \qquad (13)$$

holds where A designates a constant. Thus

$$n = n_0 e^{-A\tau} \qquad (14)$$

is fulfilled by the statistic delay. The above expression may be plotted into a straight line with the axes of ordinate and abscissa representing the n and τ respectively in a semilogarithmic scale. A graphic representation thus plotted is called a Laue plot.

Figure 61 shows an example of the Laue plot. In Figure 61 an extremity of an auxiliary electrode having a diameter of 3 millimeters is located at an edge of a gap of 3 millimeters formed between a pair of main opposite electrodes to form a spacing of about 1 millimeter between the extremity of the auxiliary electrode and either of the main electrodes. The gap was filled with a discharge gap formed of a mixture including 89% by volume of helium and 11% by volume of hydrogen under a pressure of 100 Torrs. In Figure 61 the reference numerals 150, 151, 152 and 153 depict the source voltages having the peak values of 600, 800, 1000 and 1200 volts respectively. From a stepped curve 152, for example, it is seen that for the peak source value of 1000 volts the time interval between the t_2 and t_0 or between the t_3 and t_1 (see Figure 60) must be of at least 250 microseconds. Also the auxiliary source for the pilot glow discharge should have a current capacity of at least about 10 milliamperes in order to change the pilot glow discharge smoothly to the principal glow discharge.

By taking account of a time delay with which the discharge gap is broken down with the pulse voltage of the voltage waveform N_N shown in Figure 60, the waveform V_N is given a pulse width or a duration defined by the time intervals ranging from time point t_2 or t_3 to time point t_0 or t_1 respectively while the current capacity of the auxiliary source is determined as required for changing the pilot glow discharge to the principal glow discharge and the pulse voltage delays rapidly at and after time point t_0 or t_1. This measure ensures that the pilot glow discharge is always caused prior to time point t_0 or t_1 and the principal discharge current surely rises at time point t_0 or t_1.

After the principal glow discharge has been caused between the main electrodes 1 and 2, discharge energy from the principal glow discharge as thermal energy alternately enters the main electrodes 1 and 2 with result that a liquid flowing in contact relationship through either of the main electrodes is instantaneously heated.

The arrangement of Figure 59 is advantageous in that the principal discharge current smoothly rises to cause the development of a negative glow involved to satisfactorily follow up a change in discharge current thereby to prevent the local concentration of the current without the glow discharge changing to an arc discharge while ensuring the efficiency of utilization of the source voltage. This is because the auxiliary electrode is adapted to be applied with a pulse voltage that rises before the time point where the voltage applied across the main electrodes reaches a glow hold minimum voltage across the main electrodes, thereby to fire always the pilot glow discharge before that time point, and rapidly falls to its zero value at and after said time point. Also the use of the pulse waveform is effective for decreasing the power capacity of the auxiliary source and therefore reducing the size and cost.

Figure 62 shows a modification of the arrangement shown in Figure 59. The arrangement illustrated comprises a pair of electrically isolating transformers 141 and 155 including a common iron core and a common primary winding connected across the AC source 31 through the normally open switch 51, the high voltage pulse generator circuit 140 as above described in conjunction with Figure 59 connected to the transformer 141, and a current supply circuit generally designated by the reference numeral 154 and connected across the transformer 155.

The current supply circuit 154 includes a center-tapped secondary winding of the transformer 155, and a pair of semiconductor diodes 156 and 157. The diode 156 is connected at the anode electrode to one side of the source 31 through the switch 51 and therefore the main electrode 1 while diode 157 is connected at the anode electrode to the other side of the source 31 and therefore the main electrode 2 that is, in turn, connected to ground. The center tap on the secondary winding of the transformer 155 is connected to the output of the pulse generator circuit 140 or the junction of the diode 148 and the current limiting resistor 71.

In other respects, the arrangement is identical to that shown in Figure 59. The dot convention is used to identify the polarity of the instantaneous voltage developed across the associated transformer winding.

The current supply circuit 155 is operative to full-wave rectify an AC voltage induced across the secondary transformer 155 winding and supply a current due to the full-wave rectified voltage to the auxilairy electrode 46 through the resistor 71 and the thyristor 98 with the pulse voltage from the pulse generator circuit 140.

In the arrangement of Figure 62, the discharge gap between the main electrodes 1 and 2 has been dimensioned as above described in conjunction with Figure 59 and the switch 51 is closed to supply the source voltage across the main electrodes 1 and 2. The source voltage is a commercial AC voltage having a frequency of 60 hertz as shown at dotted waveform V in Figure 63 wherein its cycle has a duration of 16.7 milliseconds.

The pulse generator circuit 140 generates a high voltage pulse in each of the half-cycles of the source voltage in the same manner as above described in conjunction with Figure 59. After being shaped by the diode 148, the high voltage pulse is developed on the resistor 71 and superposed on the full-wave rectified voltage from the current supply circuit 154 also applied to the resistor 71 as shown at voltage waveform V_N in Figure 62. Then pulse voltage V_N superposed on the voltage from the current supply circuit 154 is supplied to the auxiliary electrode 46 through the conducting thyristor 98.

From Figure 63 it is seen that the voltage waveform V_N includes the full-wave rectified component having a relative voltage to the main electrode 2 equal to a voltage V_{op} for the pilot glow discharge at time point t_6 in the positive half-cycle of the source voltage and also a relative voltage to the main electrode 1 equal to that voltage V_{op} at time point t_7 in the negative half-cycle thereof. Time points t_6 and t_7 are ahead of time points t_0 and t_1 respectively where the source voltage is equal to the glow hold minimum voltage V_0.

With the main electrode 1 higher in potential than the main electrode 2, the diode 156 is in its OFF state while the diode 157 is in its ON state tending to cause a pilot glow discharge between the auxiliary electrode 46 and the main electrode 2. On the contrary, with the main electrode 1 less in potential than the main electrode 2, the diodes 156 and 157 are turned on and off respectively. This tends to cause a pilot glow discharge between the auxiliary electrode 46 and the main electrode 1. In each case, the voltage across the auxiliary and main electrode 46 and 1 respectively is equal to that across the auxiliary and main electrode 46 and 2 respectively so that a current for the pilot glow discharge remain unchanged. With the auxiliary electrode 46 equidistant from the main electrodes 1 and 2, the change of the pilot glow discharge to the principal glow discharge between the main electrodes 1 and 2 is accomplished in a similar manner in both cases.

The voltage waveform V_N also includes a pulse waveform component from the pulse generator circuit 140 rising at time point t_2 or t_3 behind time point t_6 or t_7 and falling at time point t_4 or t_5 ahead of time point t_0 or t_1. The pulse waveform component results from a gate pulse P_1 from either of the gate and trigger circuits 149 and 99 rising and falling simultaneously with the rise and fall of the associated pulse component. The pulse waveform component is required to have a pulse width sufficient to effect the discharge breakdown of the gap between the auxiliary electrode 46 and either of the main electrodes 1 and 2. It is to be noted that it is not required to cause time point t_4 or t_5 to coincide with time point t_2 or t_1 respectively as in the arrangement of Figure 59 and that the pulse width may be sufficiently shorter than that required for the latter. In addition, the discharge breakdown scarcely requires a current resulting in the pulse generator circuit 140 being reduced in power capacity.

The gate pulse from each of the gate and trigger circuits 149 and 99 should have a rise time fulfilling the following requirements: The gate pulse P_1 should rise at time point t_2 or t_3 required to be behind time t_6 or t_7 respectively while the pilot glow discharge should be caused not later than time point t_0 or t_1. Otherwise the principal discharge current is too sharply raised to cause the spread of the particular negative glow to follow this rise in current resulting in a danger that the current is locally concentrated on either of the main electrode to permit the glow discharge to change to an arc discharge. Also the source voltage can be utilized only with a low efficiency. Thus time point t_4 or t_5 should be ahead of time point t_0 or t_1 respectively.

With the gate pulse P_1 generated to fulfill the requirements as above described, the pilot glow discharge is always caused ahead of time t_0 or t_1 in the positive or negative half-cycle of the source voltage and the glow discharge current through the main electrodes 1 and 2 smoothly rises at and after time point t_0 and t_1 in the positive or negative half-cycle of the source voltage. Accordingly, the principal glow discharge is established resulting in the instantaneous heating of the particular liquid contacted by either of the main electrodes 1 and 2.

Further it is required to make the peak voltage value of the sinusoidal component of the voltage waveform V_N less than the discharge breakdown voltage for the gap between the auxiliary electrode 46 and either of the main electrodes 1 and 2 thereby to prevent the pilot glow discharge from firing with the sinusoidal component. Alternatively, it is required to impart a high value to each of the resistances 93 and 94 to prevent the voltage waveform V_N from being applied to the auxiliary electrode 46 in the absence of the gate pulse P_1 and to prevent a current flowing through the thyristor 98 via the resistors 93 and 94 from exceeding the holding current thereof when the pilot glow discharge is not fired. Also the diodes 156 and 157 must have such reverse voltage withstanding characteristic that both diodes are not broken down with the high voltage pulses generated by the pulse generator circuit 140.

If desired, the pulse generator circuit may utilize a peak transformer.

The arrangement of Figure 62 is advantageous in that the pulse generator circuit can be reduced in power capacity resulting in the provision of an auxiliary source circuit easy and inexpensive to manufacture. This is because the pulse generator circuit for effecting the discharge breakdown of the pilot glow discharge gap is separated from the circuit for supplying current to the main electrodes after this discharge breakdown.

Figure 64 shows a different modification of the present invention driven by a three-phase AC source. The arrangement illustrated comprises three main electrodes 1U, 1V and 1W radially disposed by having their longitudinal axes arranged at equal angular intervals of 120 degrees. The main electrodes are in the form of hollow cylinders having one end closed into a crown shape that, in turn, faces the remaining closed ends of the same shape. The main electrodes 1U, 1V and 1W include the other end portions rigidly fitted into respective annular supporting members 14U, 14V and 14W interconnected through enclosure portions 9 formed of an electrically insulating material such as glass porcelain or the like and seal fittings 10U, 10V and 10W connected to both adjacent supporting members and the adjacent edges of the enclosure portions 9 to define a hermetic discharge space.

The other ends of each electrode 1U, 1V or 1W is closed with a blind cover plate 23U, 23V or 23W having an inflow tube 42U, 42V or 42W and an outflow tube 44U, 44V or 44W is extended and sealed therethrough.

Three auxiliary electrodes 46U, 46V and 46W are radially extended and sealed through the enclosure portions 9 respectively to be equidistant from the adjacent main electrodes and includes end portions bent toward the associated main electrodes to form very narrow gaps therebetween. For example, the auxiliary electrode 46U is radially extended and sealed through the enclosure portion 9 disposed between the main electrodes 1U and 1V and includes the end portion bent toward the main electrode 1U so as to enable a pilot glow discharge to be formed. Each of the auxiliary electrodes is coated with the same electrically insulating material as the enclosure portion 9 except for the end facing the associated main electrode and that portion externally protruding from the mating enclosure portion 9.

A three-phase source is represented by source terminals U, V and W which are connected to annular electrode terminals 6U, 6V and 6W fitted onto those portions of the main electrodes 1U, 1V and 1W disposed externally of the enclosure portions 9 respectively. Each of the auxiliary electrodes is connected to the electrode terminals disposed on the adjacent main electrodes through individual dummy resistors. For example, the auxiliary electrode 46U is connected to the electrode terminal 6U of the main cylinder 1U through the dummy resistor 47U on the one hand and to the electrode terminal 6V of the main electrode 1V through the dummy resistor 48U.

The auxiliary electrode 46U is also connected by a current limiting resistor 49U to an auxiliary source circuit 50 also connected to the electrode terminal 6U. The auxiliary source circuit 50 is further connected across the source terminals U and V through a normally open switch 51U connected to the source terminal V.

A circuit identical to that above described is provided for each of the remaining main electrodes and the auxiliary electrode operatively associated therewith and includes the components identical to those above described. Therefore the identical components are designated by like reference numerals suffixed with the reference character U, V or W identifying the mating source terminal or the phase of the three-phase source.

The operation of the arrangement shown in Figure 64 will now be described with reference to Figure 65 wherein there are illustrated voltage and current waveforms developed at various points in the arrangement of Figure 64 with a voltage V_U applied to the main electrode 1U being selected as a reference.

While a liquid to be heated is flowing through the interior of each main electrode via the associated inflow tube and leaves via the mating outflow tube a three phase voltage is applied to the main electrodes 1U, 1V and 1W through the source terminals U, V and W and all the switches 51U, 51V and 51W put in their closed position. At time point t_1 shortly before the voltage (see waveform V_V, Figure 65) applied across the main electrodes 1U and 1V reaches a glow hold minimum voltage V_0, a high voltage pulse (see waveform P_{uo}, Figure 65) from the auxiliary source circuit 50U is applied to the auxiliary electrode 46U to cause a pilot glow discharge across the narrow gap between the auxiliary electrode and main electrodes 46U and 1U respectively with the main electrode 1U acting as a cathode. This pilot glow discharge is caused with a low current, and upon time point D being reached, it instantaneously induces a glow discharge between the main electrodes 1U and 1V with the electrode 1U acting as a cathode. The latter discharge spreads through the surface of both main electrodes 1U and 1V and is sustained after time point D.

Then when a voltage (see waveform V_W, Figure 65) applied across the main electrodes 1U and 1W exceeds the glow hold minimum voltage V_0 at time point E, the glow discharge developed between the main electrodes 1U and 1V plays a role of the pilot glow discharge to cause a glow discharge between the main electrodes 1U and 1W at and after that time point with the main electrode 1U acting as a cathode.

At time point F the voltage across the main electrodes 1V and 1W is equal to the voltage V_0 but no discharge is caused between those main electrodes because of the absence of a pilot glow discharge with the main electrode 1V acting as a cathode. Therefore a high voltage pulse (see waveform P_{Vo}, Figure 65) from the auxiliary source circuit 50V is applied to the auxiliary electrode 46V at time point t_2 shortly ahead of time point F to cause a pilot glow discharge between the auxiliary and main electrodes 46V and 1V respectively. That pilot glow discharge similarly causes a glow discharge between the main electrodes 1V and 1W at and after time point F with the main electrode 1V acting as a cathode.

When time point G is reached, the voltage V_v across the main electrodes 1U and 1V is equal to the voltage V_0 and the glow discharge caused between the main electrode 1V acting as the cathode and the main electrode 1W plays the role of a pilot glow discharge. This causes a glow discharge between the main electrode IV acting as a cathode and the main electrode 1W at and after time point G.

Similarly, since the voltage V_W across the main electrodes 1W and 1U exceeds the voltage V_o at time point H, a high voltage pulse (see waveform P_{Wo}, Figure 65) from the auxiliary source circuit 50W has been preliminarily applied to the auxiliary electrode 46W at time point t_3 shortly ahead of time point H to cause a pilot glow discharge between the auxiliary electrode 46W and the main electrode acting as a cathode. The pilot glow discharge between the auxiliary and main electrode 46W and 1W respectively changes to a glow discharge caused between the main electrode 1W acting as a cathode and the main electrode 1U at and after time point H.

Then at time point I the voltage V_W across the main electrodes 1V and 1W exceeds the voltage V_0 so that the glow discharge between the main electrodes 1W and 1U serves as a pilot glow discharge to cause a glow discharge between the main electrode 1W acting as a cathode and the main electrode 1U until one cycle of the source voltage is completed.

Thereafter the process as above described is repeated to cause repeatedly glow discharge between pairs of the main electrodes. When acting as the cathode, the main electrodes successively heat the liquid therein.

From the foregoing it will readily be understood that the gate pulses are repeatedly applied to the auxiliary electrodes 46U, 46V and 46W at time points *t* defined by

$$T = t_1 + nT,\ t = t_2 + nT \text{ and } t = t_3 + nT$$

respectively where T designates a period of the three-phase source voltage and *n* indicates any positive integer including zero.

In Figure 65 solid current waveform I_U designates glow discharge currents with the main electrode 1U acting as cathode, dotted current waveform I_V those with the main electrode 1V acting as cathode and broken current waveform I_W designates the glow discharge current with the main electrode 1W acting as the cathode. The reference characters P_{Uo}, P_{Vo} and P_{Wo}d designate no-load pulse waveforms which change to the actual pulse waveforms P_U, P_V and P_W respectively after the associated pilot glow discharges have been fired.

Also it is noted that Figure 65 illustrates the waveforms developed during a time interval equal to twice the period T of the source voltage V_v applied across the main electrodes 1U and 1V and that the polarity of the current waveforms have not been considered.

From the foregoing it will readily be understood that the glow discharge has a time period equal to three times that provided by single-phase system and therefore the three-phase apparatus has triple power capacity over the single-phase apparatus.

In the arrangement of Figure 64 the auxiliary electrode is disposed between each pair of adjacent main electrodes for the purpose of controlling thermal energy entering each of the main electrodes. However it is included in the scope of the present invention to replace the auxiliary electrode by a bidirectional triode thyristor serially connected to each of the main electrode to control thermal energy entered thereinto through the ON-OFF operation of the thyristors.

The arrangement illustrated in Figure 66 is different from that shown in Figure 64 only in that in Figure 66 a combination of a pulse transformer 70U, 70V or 70W and a high voltage pulse generator circuit 140U, 140V or 140W is substituted for each auxiliary source circuit. The combination of the pulse transformer and pulse generator circuit may be identical to the pulse generator circuit 140 shown in Figure 59.

Also the main and auxiliary electrodes are schematically illustrated in Figure 66 and may be similar to those shown in Figure 64 and the resistors 48U, 48V and 48W are omitted.

Figure 67 shows another modification of the arrangement shown in Figure 66. In the arrangement illustrated, the electrically isolating transformer 70 includes a primary winding W_1 connected across the source terminals U and V through the switch 51 and a pair of secondary windings W_2 and W_3 connected respectively across a high voltage pulse generator circuit 140 such as above described in conjunction with Figure 59 and a gate circuit 161. The pulse generator circuit 140 includes one output connected to the source terminal U and the other output connected to anode electrodes of thrysistors S_U, S_V and S_W through the common current limiting resistor 49. The thryristors S_U, S_V and S_W include cathode electrodes connected to the auxiliary electrodes 46U, 46V and 46W respectively. The gate circuit 161 is connected to the thrysistors S_U, S_V and S_W to control the firing thereof.

In other respects, the arrangement is substantially identical to that shown in Figure 66.

Figure 68 illustrates voltage and current waveforms developed at various points in the arrangement shown in Figure 67. From the comparison of Figure 68 with Figure 65 it is seen that voltage and current waveforms shown on the upper portion of Figure 68 are substantially similar to those illustrated in Figure 65 and pulse waveforms Po are substituted for the pulse waveforms P_U—P_{Uo}, P_V—P_{Vo} and P_W—P_{Wo} shown in Figure 65. Thus like reference characters have been employed to identify the waveforms corresponding to those illustrated in Figure 65. Thus the arrangement is substantially identical in operation to that shown in Figure 66.

As seen in Figure 68, the gate circuit 161 applies a gate pulse (see waveform G_U) across the gate and cathode electrodes of the thyristor S_U shortly before the high voltage pulse (see waveform Po) from the pulse generator 140 is supplied to the auxiliary electrode 46U to bring it in its conducting state and then the pulse Po is supplied to the auxiliary electrode 46U through the resistor 49 and the now conducting thyristor S_U. This is true in the case of the remaining pulses P passing through the respective thyristors S_V and S_W.

Each of the gate pulses shown at waveforms G_U, G_V and G_W in Figure 68 should have a pulse width sufficient to ensure that a pilot glow discharge is fired between the associated auxiliary and main electrodes such as shown by 46U and 1U and changes to the principal glow discharge caused between the mating main electrodes such as shown by 1U and 1V. That is, the gate pulse should be at least sustained until the time point is reached where the associated source voltage, for example, the voltage V_V exceeds the glow minimum voltage V_o. If the pilot glow discharge causes a current flowing through the associated thyristor to exceed its holding current then the gate pulse may continue until the pilot glow discharge is fired.

The arrangement of Figure 67 is advantageous over that shown in Figure 66 in that the resulting circuit is simple, small-sized and inexpensive because of the provision of a single high voltage pulse generator circuit.

In the preferred embodiments of the present invention, the main electrodes and associated components, such as the flow confining tubes, the connecting tubes, the inflow and outflow tube, the blind cover plates shown, for example, in Figure 24 are formed of metallic material and put in contact with a heated liquid that is electrolytic. This may result in a fear that those metallic components are corroded with the heated liquid and reduced in useful life. Particularly the main electrodes and those tubes directly connected thereto have high probabilities of electrolytic corrosion because the source voltage is directly applied across the main electrodes while the inflow and outflow tubes are connected to ground thereby to permit currents to flow in to the main electrodes and those tubes through the heated electrolytic liquid.

The arrangement shown in Figure 69 includes corrosion preventing electrodes for preventing metallic components from corroding as above described. In the arrangement illustrated a corrosion preventing electrode 161 or 162 is electrically insulatingly extended and sealed through that wall portion of the flow confining tube 20 or 21 facing the inside of the gap forming surface of the main electrode 2 or 1, that is, each of the opposite surfaces of both main electrodes with an electrically insulating holder 163 or 164 hermetically interposed therebetween. The electrode protrudes into the flow path for the heated liquid. The anticorrosive electrode may be formed of platinum, carbon, triiron tetroxide (Fe_3O_4) or the like. The a DC source 165 or 166 is connected across the corrosion preventing electrode 161 or 162 and the electrode terminal 5 or 6 thereby to supply to the electrode 161 or 162 a voltage higher than the voltage across the main electrodes. Each of the DC source 165 or 166 includes a negative side connected to the associated electrode terminal 5 or 6.

Then the electrode terminals 5 and 6 are connected to a control circuit identical to that shown in Figure 34.

In other respects, the arrangement is identical to that shown in Figure 24 except for the provision of the auxiliary electrode 46 but the main electrode 1, in this case, made of stainless steel or the like, the flow confining tube 21, the blind cover plate 23, the connecting tube 36, the insulating tubes 38 and 40, the inflow tube 42 and the outflow tube 44 form an assembly prevented from corroding and generally designated by the reference numeral 167. Also, the similar components 2, 20, 22, 35, 37, 39, 41 and 43 form another assembly prevented from corroding and generally designated by the reference numeral 168. The main electrode 2 is also made of stainless steel.

The corrosion of the main electrodes and others is called the electrolytic corrosion resulting from a flow of current therethrough via a heated electrolytic liquid that is caused from the dissolution of materials forming the main electrode and others into an electrolyte such as water. In the arrangement of Figure 69, the DC sources 165 and 166 are adapted to apply to the respective corrosion preventing electrodes 161 and 162 voltages higher that the voltage applied across the associated main electrodes. Thus the corrosion preventing electrodes 161 and 162 provide the so-called scapegoat electrodes. That is, the material or materials forming the scapegoat electrode is or are dissolved into an electrolyte such as water thereby to prevent the materials forming the assemblies 167 and 168 from dissolving into the heated liquid.

The DC sources 165 and 166 may be omitted by forming the corrosion preventing electrode of a metallic material less in corrosion potential and more easily ionized than the material of the main electrode. For example, with the main electrodes 1 and 2 formed of stainless steel, magnesium, zinc, aluminum, etc. are optimum of forming the corrosion preventing electrode.

Also the DC source may be replaced by any suitable source for supplying a DC voltage.

Figure 70 shows corrosion preventing electrodes provided on the arrangement shown in Figure 39. In Figure 70 the corrosion preventing electrodes 161 and 162 are provided on the exposed portion of the feed water tube 20 disposed within the main electrode 2 and on the outer wall of the main electrode 1 respectively in the same manner as above described in conjunction with Figure 69.

Then the corrosion preventing electrodes 161 and 162 are connected to the terminals *d* and *e* subsequently connected, for example, to the DC sources 165 and 166 (see Figure 69) respectively. Also terminals *a* and *b* connected to the electrode terminals 5 and 6 respectively are connected across the AC source 31 shown in Figure 69 while a terminal C connected to the auxiliary electrode 46 is connected to the auxiliary source circuit 50 also shown in Figure 69.

Figure 71 shows anticorrosive electrodes provided on the arrangement illustrated in Figure 64. As shown, an anticorrosive electrode 161U, 161V or 161W is electrically insulatingly extended and sealed through the feed water tube 42U, 42V or 42W operatively coupled with each main electrode 1U, 1V or 1W with an electrically insulating holder 164U, 164V or 174W interposed therebetween.

Figure 72 shows a separate modification of the present invention wherein the temperature of a heated liquid is measured. In the arrangement illustrated, a temperature sensor 169 such as a thermistor is electrically insulatingly extended and sealed through that portion of a flow confining tube 20 facing the peripheral wall of the main electrode 2 with an electrically insulating holder 170 interposed therebetween.

The temperature sensor 169 may be entirely covered with a electrically insulating material in accordance with the particular electric field established in the vicinity thereof.

In other respects, the arrangement is substantially identical to that shown in Figure 24 except for the provision of the auxiliary electrode 46.

The electrode terminals 5 and 6 and the auxiliary electrode 46 are connected to a control circuit identical to that shown in Figure 57 except for the omission of the zero volt firing circuit 90. The temperature sensor 169 includes an output connected to the trigger circuit 99 for the thyristor 98.

In operation the temperature sensor 169 senses the temperature of the heated liquid and feeds a measured temperature signal to the trigger circuit 99. More specifically, with the temperature sensor 169 formed of a thermistor or a temperature measuring resistor, a resistance thereof is changed with a temperature so that a signal representative of a change in resistance is applied to the trigger circuit 99. Alternatively, with the temperature sensor 169 formed of a thermocouple, it responds to the temperature of the heated liquid to change in thermoelectromotive force thereof. This change in thermoelectromotive force is signalled to the trigger circuit 99.

If it is desired to control the heated liquid to a predetermined fixed temperature then the actual temperature measured by the temperature sensor 169 is compared with an output therefrom at a predetermined temperature as the reference. With the actual temperature higher than the predetermined temperature, the trigger circuit 99 applies no trigger signal to the thyristor 98. Otherwise, the trigger circuit 99 delivers the trigger signal to the thyristor 98. Then the thyristor 98 is correspondingly turned on and off to fire and extinguish a pilot glow discharge thereby to effect the ON-OFF control of a glow discharge between the main electrodes 1 and 2.

Under these circumstances, some time goes until heat from either of the main electrodes 1 and 2 acting as the heating surface is transferred to the heated liquid. This results in a time delay with which the temperature of the heated liquid is controlled. Therefore, the temperature sensor 169 has preferably a sensor end located as near to the heating surface of the associated main electrode as possible.

With the temperature of the heated liquid controlled according to a predetermined program, the function of effecting such control may be incorporated into the trigger circuit 99 and the thyristor 98 is operated in the ON-OFF control mode and in accordance with the output signal from the temperature sensor 169.

The temperature sensor 169 may be used with the control of the glow discharge effected by a control such as a thyristor connected in series to the particular glow discharge heating apparatus in a circuit with an electric source circuit for the apparatus.

The arrangement illustrated in Figure 73 is different from that shown in Figure 72 only in that in Figure 73 a bidirectional triode thyristor or a Triac is provided to control the glow discharge as in the arrangement of Figure 48. In Figure 73 a thyristor 172 is connected at the anode electrode to one of the DC output terminals of the rectifier bridge 66 and at the cathode electrode to the Triac 60. The resistor 67 is connected to the Triac 60 at the gate electrode but not to one main electrode thereof. Then the thyristor 172 has the cathode and gate electrodes connected across a trigger circuit 173 subsequently connected to the temperature sensor 172.

In other respects, the control circuit is substantially identical to that shown in Figure 48. However the dot convention is used to identify the polarity of the instantaneous voltage across the associated transformer winding.

The electrically isolating transformer 65 is operative to adapt a potential difference developed across the resistor 64 to a voltage required for the Triac 60 to be fired.

With the switch 51 put in its closed position, the step-up transformer 70 applies a high AC voltage across the electrodes 1 and 2 resulting in the discharge breakdown occurring therebetween. This causes a potential difference across the current limiting resistor 64 whereby a potential difference appears across the resistor 67 through the transformer 65 and the rectifier bridge 66. At that time, the trigger circuit 173 is actuated to put the thyristor 172 in its ON state to cause a trigger signal to be applied to the gate electrode of the Triac 60 to turn it on. Therefore the AC source across the source 31 is supplied across the main electrodes 1 and 2 through the now conducting thyristor 60 to cause a glow discharge therebetween.

Under these circumstances, the temperature sensor 169 senses a temperature of a heated liquid involved and feeds signal for the sensed temperature to the trigger circuit to control the glow discharge between the electrodes 1 and 2.

From the foregoing it is seen that in the arrangements shown in Figures 72 and 73 the temperature of the heated liquid sensed by the temperature sensor is fed to the auxiliary source circuit for controlling the glow discharge caused between the main electrodes resulting in the easy, reliable temperature control of the heated liquid.

While the present invention has been illustrated and described in conjunction with various preferred embodiments thereof it is to be understood that numerous changes and modifications may be resorted to without departing from the scope of the present invention. For example, the embodiments of the present invention illustrated and described in conjunction with the single-phase source may readily be modified to be driven by the three-phase source. Similarly, the embodiments illustrated and described in conjunction with the three-phase source may readily be suited for use with polyphase sources having *m* phases where *m* is greater than three (3). In the latter case, an *m*-phase AC voltages is applied to *m* main electrodes to cause successively glow discharges between the pairs thereof. The resulting power capacity is equal to *m* times that provided by single-phase apparatus leading to inexpensive structures.

WHAT WE CLAIM IS:—

1. A glow discharge heating apparatus comprising at least one pair of discharge electrodes disposed in opposite relationship to form a predetermined gap therebetween, means for applying a voltage across said discharge electrodes to cause a glow discharge therebetween, said glow discharge supplying thermal energy to the discharge electrode acting as a cathode during said glow discharge, the discharge electrode acting as said cathode being so constructed that a liquid to be heated with said thermal energy can flow therethrough wherein the effective area of the discharge electrode acting as an anode is smaller that the entire area of said discharge electrode acting as a cathode upon which a glow discharge may be caused thereby to impart a positive resistance characteristic to the current-to-voltage characteristic of said glow discharge.

2. A glow discharge heating apparatus as claimed in claim 1 comprising a pair of discharge electrodes in the form of hollow cylinders having one end closed, said discharge electrodes being of substantially the same shape and disposed in opposite relationship by having said closed ends opposing each other to form a predetermined gap therebetween and AC electric source means for applying an AC voltage across said discharge electrodes to cause a glow discharge therebetween.

3. A glow discharge heating apparatus as claimed in claim 1 comprising a pair of electrodes opposing each other across a predetermined gap, and means for applying an AC voltage across said pair of electrodes to cause a glow discharge across said gap wherein said pair of electrodes are disposed to oppose each other on end surfaces formed into the substantially same shape while being supported only on one portion.

4. A glow discharge heating apparatus as claimed in any preceding claim wherein there is provided an enclosure for hermetically sealing therein said discharge electrodes and said gap therebetween, thereby forming a discharge space.

5. A glow discharge heating apparatus as claimed in claim 4 wherein said discharge space is filled with a gaseous mixture of at least helium and hydrogen.

6. A glow discharge heating apparatus as claimed in claim 5 wherein the distance between said discharge electrodes lies in the range from 0.5 to 9 millimeters and said gaseous mixture has a pressure ranging 50 to 200 Torrs.

7. A glow discharge heating apparatus as claimed in claim 6 wherein a voltage applied across said discharge electrodes is either 200 or 220 volts and the proportion of said hydrogen in said gaseous mixture lies in the range from 2.5 to 50% by volume.

8. A glow discharge heating apparatus as claimed in claim 6 wherein the voltage applied across said discharge electrodes is approximately 400 volts and the proportion of hydrogen in said gaseuous mixture lies in the range from 50 to 100% by volume.

9. A glow discharge heating apparatus as claimed in claim 4 wherein said enclosure includes at least one portion made of an insulating material and a shield plate disposed between said insulating portion of said enclosure and a corresponding electrode.

10. A glow discharge heating apparatus as claimed in claim 9 wherein an electrode is buried in the interior of said shield plate.

11. A glow discharge heating apparatus as claimed in claim 9 or 10 wherein the shield plate is made of an insulating material.

12. A glow discharge heating apparatus as claimed in claim 9 or 10 wherein the shield plate is made of a metallic material.

13. A glow discharge heating apparatus as claimed in claim 11 wherein the shield plate is disposed to be integral with the insulating portion of the enclosure.

14. A glow discharge heating apparatus as claimed in any preceding claim wherein a heating space is formed within each of said discharge electrodes to cause said liquid to flow through said heating space while contacting directly the internal

surface of each of said discharge electrodes thereby to be heated by said discharge electrodes.

15. A glow discharge heating apparatus as claimed in claim 14 wherein there is provided flow confining means for confining a flow path for said liquid within said heating space thereby to facilitate the transfer of heat from said discharge electrode to said liquid.

16. A glow discharge heating apparatus as claimed in claim 15 wherein said flow confining means is detachably disposed in each of said discharge electrodes.

17. A glow discharge heating apparatus as claimed in claim 14 wherein said heating space includes an inflow port through which the liquid enters said heating space and an outflow port through which the liquid leaves said heating space, said inflow port being located below said outflow port.

18. A glow discharge heating apparatus as claimed in any preceding claim, wherein an insulating pipe is provided on each of an inflow port and an outflow port for the heated liquid on said electrode and also on the extremity portion with a metallic pipe, the metallic pipes being connected to ground.

19. A glow discharge heating apparatus as claimed in claim 15 wherein said flow confining means includes a through opening through which the liquid enters said heating space and another through opening through which the liquid leaves said heating space.

20. A glow discharge heating apparatus as claimed in claim 2 wherein said discharge electrodes are provided on portions thereof opposite to each other with concave and convex areas.

21. A glow discharge heating apparatus as claimed in claim 20 wherein said concave and convex areas are arranged into a plurality of annuli, said annuli being in the form of concentric circles.

22. A glow discharge heating apparatus as claimed in claim 20 wherein said concave and convex areas are in the form of straight lines running substantially in parallel relationship.

23. A glow discharge heating apparatus as claimed in claim 20 wherein said concave and convex areas include a plurality of depressions extending into said dicharge electrode.

24. A glow discharge heating apparatus as claimed in claim 1 wherein a tubular member is disposed in each of said discharge electrodes to abut against an internal wall surface of each of said discharge electrodes and said liquid flows through said tubular member.

25. A glow discharge heating apparatus as claimed in claim 24 wherein said tubular member comprises a seamless copper tube brazed to the internal wall surface of the associated discharge electrode.

26. A glow discharge heating apparatus as claimed in claim 14 wherein said heating space includes a normally closed exhaust port capable of being opened to permit the liquid to be exhausted in said heating space.

27. A glow discharge heating apparatus as claimed in claim 14 wherein a corrosion preventing electrode is disposed on each of said main electrodes to be electrically insulated from the associated discharge electrode and contacted by said liquid.

28. A glow discharge heating apparatus as claimed in claim 27 wherein said corrosion preventing electrode has applied thereto a voltage higher than the voltage applied across said discharge electrodes.

29. A glow discharge heating apparatus as claimed in claim 27 or 28 wherein said corrosion preventing electrode is formed of a metallic material less in corrosion potential and more easily ionized than a metallic material forming said discharge electrodes.

30. A glow discharge heating apparatus as claimed in claim 1 comprising a pair of main electrodes opposing each other across a predetermined gap and including reduced diameter portions, insulating members facing said reduced diameter portions of said main electrodes and fixed to the main electrodes, and a metallic enclosure fixed to said main electrodes through said insulating members to form a discharge space around said main electrodes.

31. A glow discharge heating apparatus as claimed in claim 30 wherein said main electrodes include heating tanks in interiors thereof.

32. A glow discharge heating apparatus as claimed in claim 30 or 31 wherein the main electrodes include the reduced diameter portions on end portions thereof opposite to the opposing end portions thereof.

33. A glow discharge heating apparatus as claimed in claim 31 wherein each

heating tank includes an inflow pipe for effecting the inflow of the heated liquid and an outflow pipe for effecting the outflow of the heated liquid, said outflow pipe being bent upwardly in the interior of the heating tank and having an opening face at its end formed to face the uppermost portion of the internal surface of the main electrode through a length *l* permitting almost all bubbles evolved in the heated liquid to be exhausted into the exterior.

34. A glow discharge heating apparatus as claimed in claim 1 wherein a first discharge electrode is in the form of a hollow cylinder having at least one end open, and a second discharge electrode is in the form of a hollow cylinder partly inserted in coaxial relationship into the hollow portion of said first discharge electrode from said open end so that said inserted portion of said second discharge electrode has an outer peripheral surface opposite to an inner peripheral surface of said first discharge electrode to form a predetermined gap therebetween.

35. A glow discharge heating apparatus as claimed in claim 1, wherein the means for applying a voltage across said discharge electrodes to cause a glow discharge therebetween comprises DC source means for applying a DC voltage across said discharge electrodes.

36. A glow discharge heating apparatus as claimed in claim 1 comprising a plurality of discharge electrodes opposing one another across predetermined gaps, main electric source means connected to said plurality of discharge electrodes to cause glow discharges between successive pairs of discharge electrodes, each of said glow discharges supplying thermal energy to the discharge electrode acting as a cathode during the associated glow discharge, auxiliary electric source means for controlling said glow discharges, a liquid to be heated flowing through said discharge electrodes to be heated with said thermal energy, and a temperature sensor operatively coupled to a selected one of said discharge electrodes to sense the temperature of said heated liquid to feed a signal representative of the measured temperature to said auxiliary electric source means to control said glow discharges thereby to control the temperature of said heated liquid.

37. A glow discharge heating apparatus as claimed in claim 1 comprising AC source means for applying across said discharge electrodes a voltage not less than a glow discharge hold minimum voltage for said gap to cause a principal glow discharge therebetween, said principal glow discharge supplying thermal energy to the discharge electrode acting as a cathode during said principal glow discharge, and wherein when said voltage across said discharge electrodes approximately reaches said glow discharge hold minimum voltage, a voltage higher than a discharge breakdown voltage for said gap is applied across said discharge electrodes to cause a pilot glow discharge therebetween, said pilot glow discharge inducing said principal glow discharge.

38. A glow discharge heating apparatus as claimed in claim 37 wherein auxiliary electric source means is connected across said pair of discharge electrodes to generate a voltage not less than the discharge breakdown voltage across said pair of discharge electrodes thereby to enable said glow discharge between said discharge electrodes to be initiated at said glow discharge hold minimum voltage from said AC source means in relation to a frequency of said AC source means.

39. A glow discharge heating apparatus as claimed in claim 38 wherein said auxiliary source means includes a current path switch consisting of a bidirectional triode thyristor connected between one of said discharge electrodes and said AC source means, a first transformer for supplying the voltage across said auxiliary source means between said pair of discharge electrodes, impedance means serially connected between an output terminal of said first transformer and said one discharge electrodes, a second transformer connected across said impedance means, and pilot glow discharge generation and detection means connected to the secondary side of said second transformer, to control said bidirectional triode thyristor.

40. A glow discharge heating apparatus as claimed in claim 38 wherein auxiliary source means includes a pulse generator circuit having an input side connected across said AC source means and an output side connected across said pair of discharge electrodes, a current limiting resistor serially connected between output side of said pulse generator circuit and one of said discharge electrode, and a reactor serially connected between said AC source means and said one discharge electrode.

41. A glow discharge heating apparatus as claimed in claim 37 wherein there is provided an auxiliary electrode for applying a high voltage of either of said

discharge electrodes to cause a pilot glow discharge between the auxiliary electrode and the discharge electrode concerned.

42. A glow discharge heating apparatus as claimed in claim 41 wherein said auxiliary electrode is in the form of a rod.

43. A glow discharge heating apparatus as claimed in claim 37 wherein said voltage applied across said discharge electrodes to cause the principal glow discharge therebetween has a maximum value set to be less than the discharge breakdown voltage across said discharge electrodes.

44. A glow discharge heating apparatus as claimed in claim 41 wherein said auxiliary electrode has applied thereto a pulse voltage rising before the time point where the voltage applied across said discharge electrodes reaches the glow discharge hold minimum voltage across said discharge electrodes and rapidly falling after said time point.

45. A glow discharge heating apparatus as claimed in claim 1, wherein there are an auxiliary electrode disposed within the gap between a pair of main electrodes, and means for causing a pilot glow discharge between either of said main electrodes and said auxiliary electrode and causing a glow discharge between said main electrodes through the induction of said pilot glow discharge thereby to heat a heated liquid with thermal energy injected into said main electrodes, and wherein said auxiliary electrode has applied thereto a pulse voltage superposed on a voltage due to the full-wave rectification of an AC voltage, said pulse voltage rising before the time point where a voltage applied across said main electrodes reaches a glow discharge hold minimum voltage across said main electrodes and also falling before said time point, said pulse voltage effecting the discharge breakdown between said main electrodes and said auxiliary electrode, said full-save rectified voltage supplying a current for said pilot glow discharge after said discharge breakdown.

46. A glow discharge heating apparatus as claimed in claim 41 wherein there is provided a zero voltage firing circuit for applying across either of said discharge electrodes and said auxiliary electrode a high voltage causing the pilot glow discharge to start substantially at a zero voltage passage point of the voltage waveform applied across said discharge electrodes.

47. A glow discharge heating apparatus as claimed in claim 46 wherein said zero voltage firing circuit includes a first switching element put in its conducting state when the voltage across said AC source means has one polarity, a differentiating circuit for differentiating a voltage developed across said first switching element, a full-wave rectifier circuit for full-wave rectifying a voltage from said differentiating circuit, and a second switching element fired with an output from said full-wave rectifier circuit and causing the voltage to be applied across either of said discharge electrodes and said auxiliary electrode.

48. A glow discharge heating apparatus as claimed in claim 41 wherein there are provided a step-up transformer having the secondary side connected to said auxiliary electrode to cause a pilot glow discharge between either of said discharge electrodes and said auxiliary electrode, said pilot glow discharge inducing a glow discharge between said discharge electrodes, switching means connected to the primary side of said step-up transformer to effect the ON-OFF control of an output from said step-up transformer, and an impedance element connected between said auxiliary electrodes to prevent the occurrence of said pilot glow discharge when said switching means is in its OFF state.

49. A glow discharge heating apparatus as claimed in claim 48 wherein said impedance element comprises a resistor.

50. A glow discharge heating apparatus as claimed in claim 48 wherein said switching means comprises an electronic switch such as a bidirectional triode thyristor.

51. A glow discharge heating apparatus as claimed in claim 50 wherein said impedance element has a magnitude sufficient to prevent a current flowing through said electronic switch from exceeding a holding current thereof when said pilot glow discharge is not fired.

52. A glow discharge heating apparatus as claimed in claim 41 wherein there are provided a step-up transformer having the secondary side connected to said auxiliary electrode to cause a pilot glow discharge between either of said discharge electrodes and said auxiliary electrode, said pilot glow discharge inducing a glow discharge between said discharge electrodes, switching means connected between the secondary side of said step-up transformer and said auxiliary electrode to effect the ON-OFF control of an output from said step-up transformer, and an impedance

element connected between said auxiliary electrode and either of said discharge electrodes to prevent the occurrence of said pilot glow discharge when said switching means is in its OFF state.

53. A glow discharge heating apparatus as claimed in claim 52 wherein said impedance element comprises a resistor.

54. A glow discharge heating apparatus as claimed in claim 52 wherein said switching means comprises an electronic switch such as a bidirectional triode thyristor.

55. A glow discharge heating apparatus as claimed in claim 54 wherein said impedance element is connected to said electronic switch on the cathode side.

56. A glow discharge heating apparatus as claimed in claim 54 wherein said impedance element is connected to said electronic switch on the anode side.

57. A glow discharge heating apparatus as claimed in claim 54 wherein said impedance element has a magnitude sufficient to prevent a current flowing through said electronic switch from exceeding a holding current thereof when said pilot glow discharge is not fired.

58. A glow discharge heating apparatus as claimed in claim 41 wherein there are provided AC source means for causing said principal glow discharge between said discharge electrodes, and auxiliary source means for causing said pilot glow discharge between either of said discharge electrodes and said auxiliary electrode, the arrangement being such that said pilot glow discharge is successively caused between said auxiliary electrodes playing a role of an anode and which of said discharge electrodes is less in potential than the other discharge electrode and that a closed circuit is formed of said auxiliary electrode, the discharge electrode put at the lower potential and said auxiliary source means for each of said pilot glow discharges.

59. A glow discharge heating apparatus as claimed in claim 58 wherein said auxiliary source means comprises a transformer including a primary winding connected across said AC source means and a center tapped secondary winding connected across said pair of discharge electrodes, said center tapped secondary winding including end terminals connected to said discharge electrodes through individual rectifier elements respectively and the center tap connected to said auxiliary electrode through a current limiting resistor.

60. A polyphase AC glow discharge heating apparatus comprising *m* main electrodes disposed oppositely to one another to form predetermined gaps therebetween, where *m* has a value not less than three (3), AC source means for applying an *m*-phase AC voltage to said main electrodes to cause glow discharges between successive pairs of main electrodes, each of said glow discharges supplying thermal energy to the main electrode acting as a cathode during the associated glow discharge, said main electrodes being so constructed that a liquid to be heated with said thermal energy can flow therethrough wherein the effective area of the discharge electrode of each pair acting as an anode is smaller than the entire area of the discharge electrode of said pair acting as a cathode upon which a glow discharge may be caused thereby to impart a positive resistance characteristic to the current-to-voltage characteristic of said glow discharge.

61. A polyphase AC glow discharge heating apparatus as claimed in claim 60 wherein said main electrodes include opposite portions disposed in an atmosphere of an electrically dischargeable gas.

62. A polyphase AC glow discharge heating apparatus as claimed in claim 60 or 61 wherein a plurality of auxiliary electrodes are operatively coupled to said gaps to cause successively pilot glow discharges between the same and associated main electrodes and to control said thermal energy entering the main electrodes.

63. A polyphase AC glow discharge heating apparatus as claimed in claim 62 wherein the number of said auxiliary electrodes is equal to that of said main electrodes and wherein each of said auxiliary electrodes is arranged to apply a high voltage across the same and the main electrode opposite thereto.

64. A polyphase AC glow discharge heating apparatus as claimed in any one of claims 60 to 63 wherein each of said main electrodes includes means for causing said liquid to circulating in heat transfer relationship through the interior thereof.

65. A polyphase AC glow discharge heating apparatus as claimed in any one of claims 60 to 64 wherein three main electrodes are radially disposed at equal angular intervals of 120 degrees to be opposite to each other, and said AC source applies a three-phase AC voltage to said main electrodes.

66. A polyphase AC glow discharge heating apparatus as claimed in any of claims 60 to 65 wherein a bidirectional triode thyristor is serially connected to each

of said main electrodes and the conduction of said thyristors is controlled to control said thermal energy entering the associated main electrodes.

67. A polyphase AC glow discharge heating apparatus as claimed in claim 60 wherein there are provided *m* auxiliary electrodes each disposed oppositely to a different one of said *m* main electrodes to form a predetermined narrow gap therebetween, a high voltage generator circuit for applying a high voltage to each of said auxiliary electrodes to cause a pilot glow discharge across said narrow gap, said pilot glow discharge inducing a glow discharge between the associated pair of opposite main electrodes, *m* thyristor connected in parallel circuit relationship to an output of said high voltage generator circuit and connected to said auxiliary electrodes respectively, each of said thyristors being operated when conducting to apply the high voltage from said high voltage generator circuit to the associated auxiliary electrode to cause said pilot glow discharge, and a trigger circuit for applying gate signals to said thyristors respectively whereby a heated liquid is heated with thermal energy entering said main electrodes due to said glow discharges.

68. A polyphase AC glow discharge heating apparatus as claimed in claim 67 wherein three main electrodes are radially disposed at equal angular intervals of 120 degrees to be opposite to each other, and said AC source applies a three-phase AC voltage to said main electrodes.

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London, WC2A 3LS.
Agents for the Applicants.

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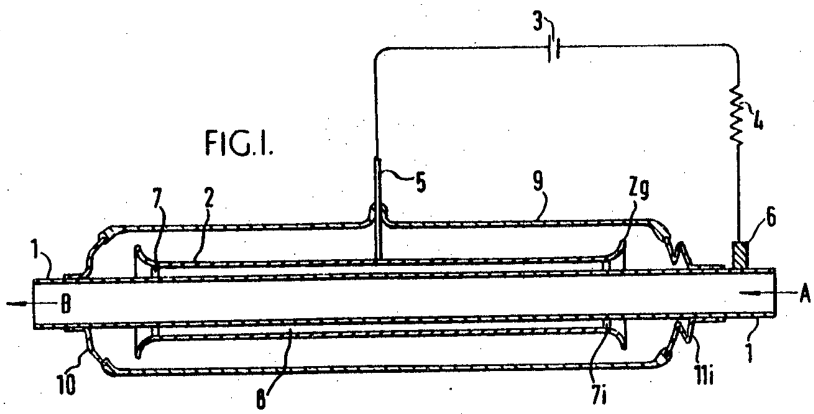
FIG.1.



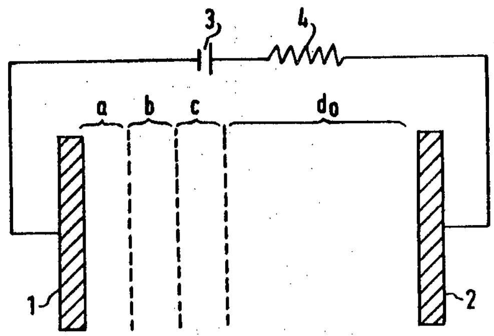


FIG.2A.

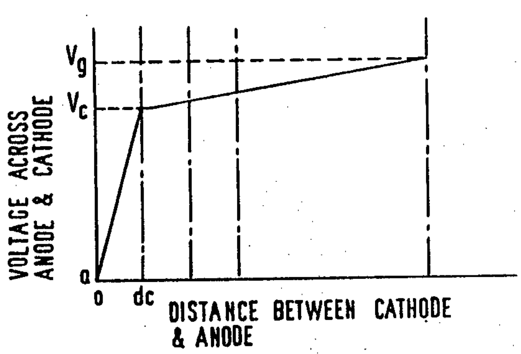


FIG.2B.

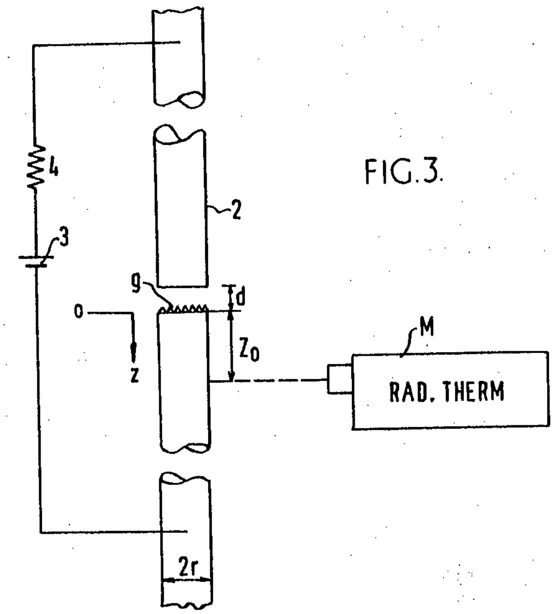
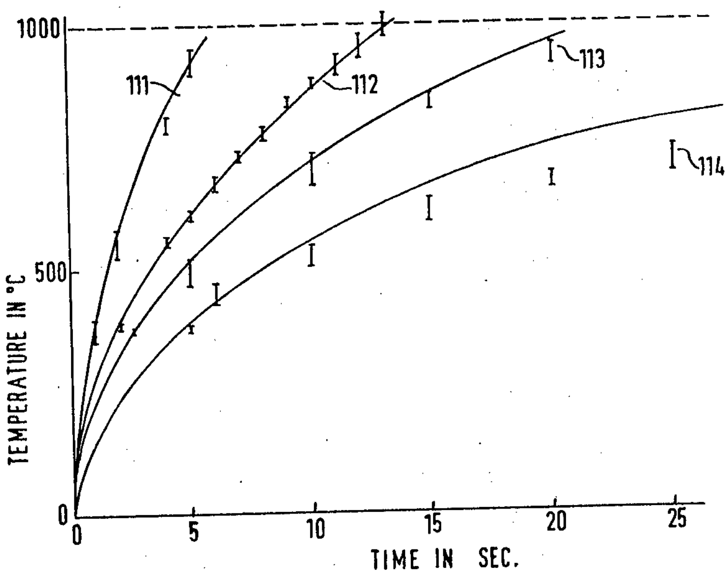

4
3
2
g
d
O
Z
Z_0
M
RAD. THERM
2r

FIG.3.

FIG.4.


1000
500
0
TEMPERATURE IN °C
111
112
113
114
0
5
10
15
20
25
TIME IN SEC.

1585017 COMPLETE SPECIFICATION

34 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

FIG.6.

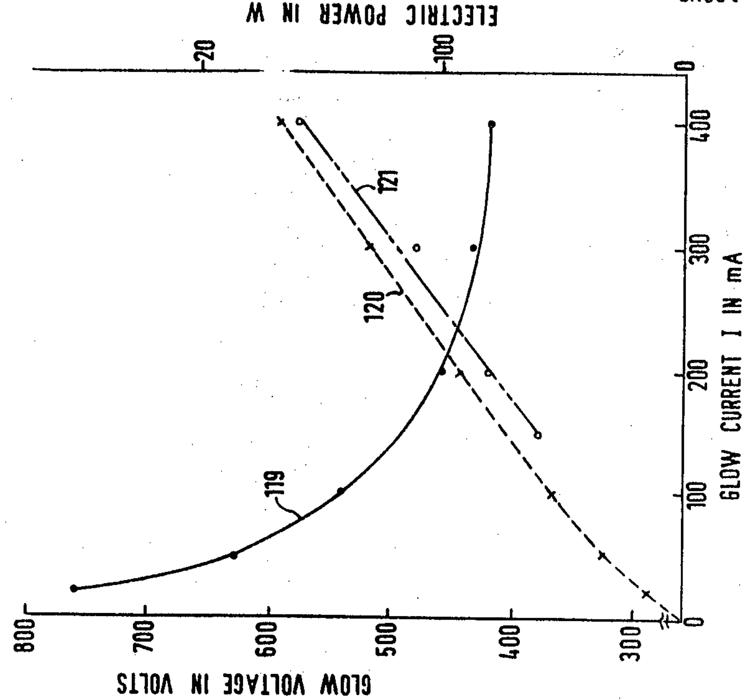
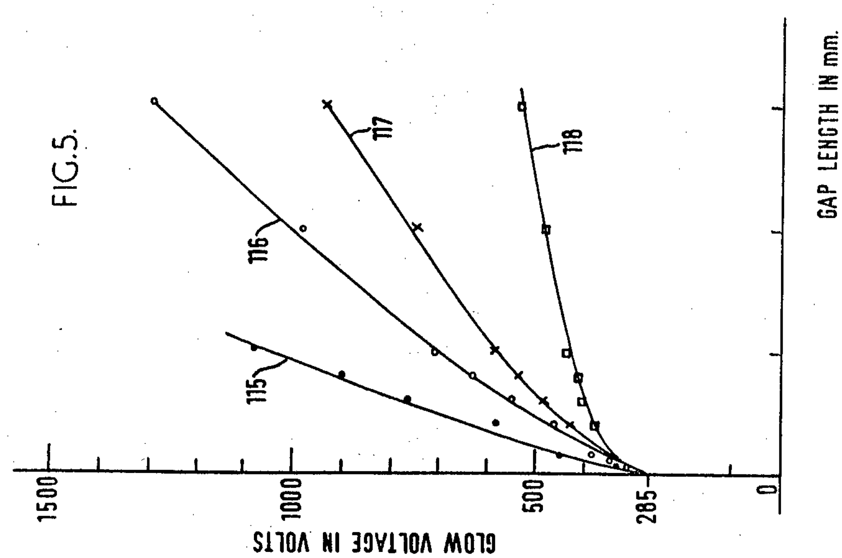


FIG.5.



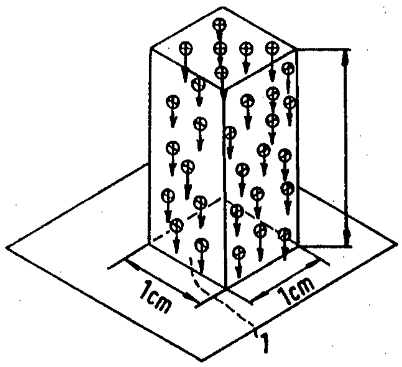


FIG.7.

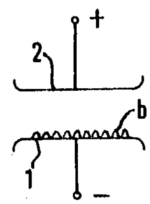


FIG.9A.

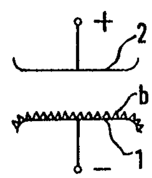
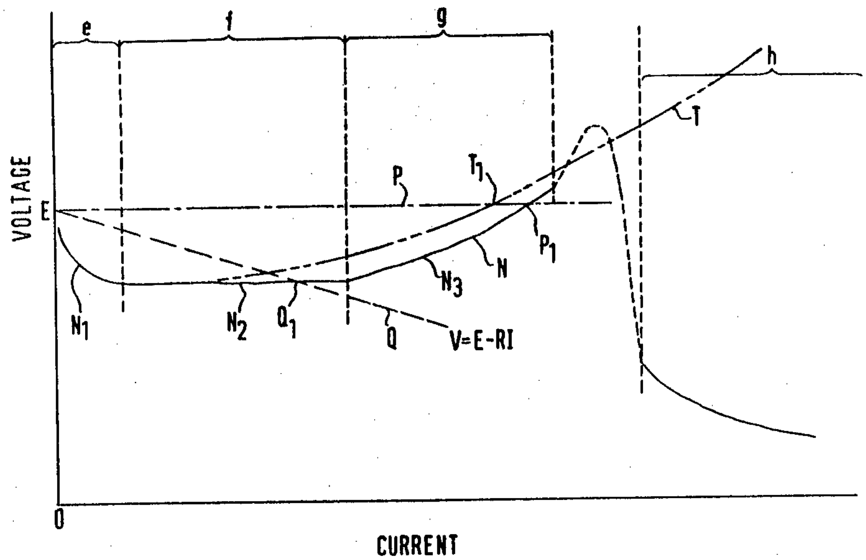


FIG.9B.

FIG.8.



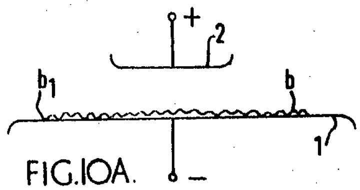


FIG.10A.

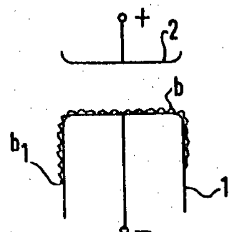


FIG.10B.

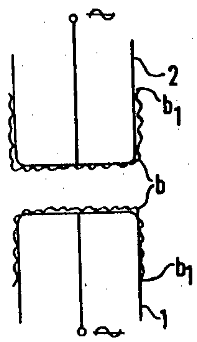


FIG.10C.

FIG.12.

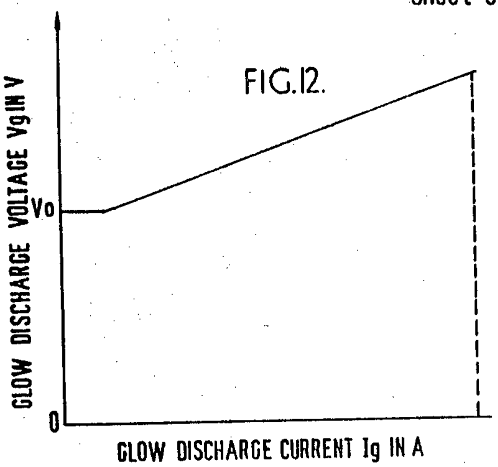


FIG.13.

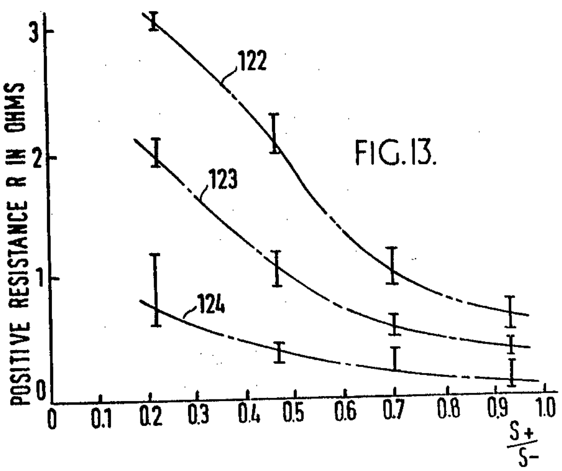


FIG.11.

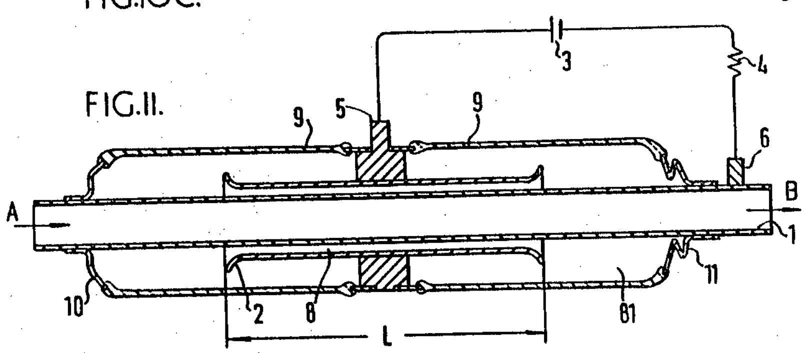
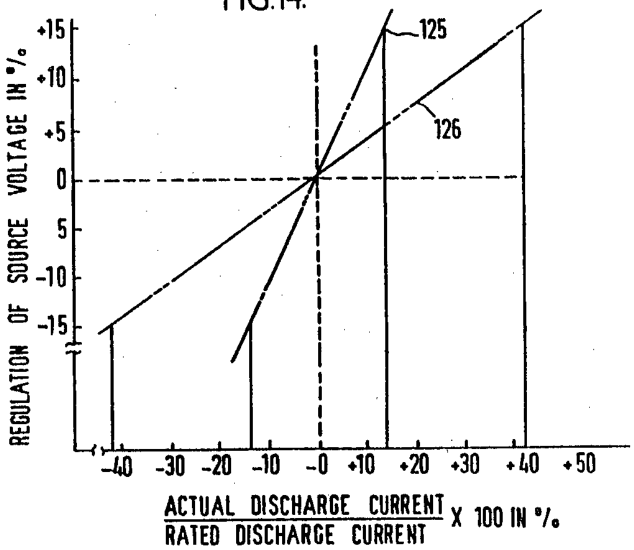


FIG.14.


+15
+10
+5
0
5
-10
-15
REGULATION OF SOURCE VOLTAGE IN %
125
126
-40
-30
-20
-10
-0
+10
+20
+30
+40
+50
ACTUAL DISCHARGE CURRENT / RATED DISCHARGE CURRENT X 100 IN %

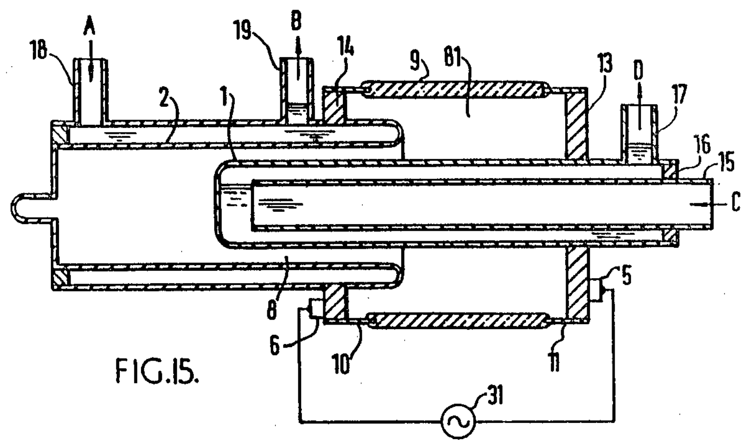

A
B
D
C
18
19
14
9
81
13
17
16
15
2
1
8
6
10
11
5
31

FIG.15.

FIG.16.

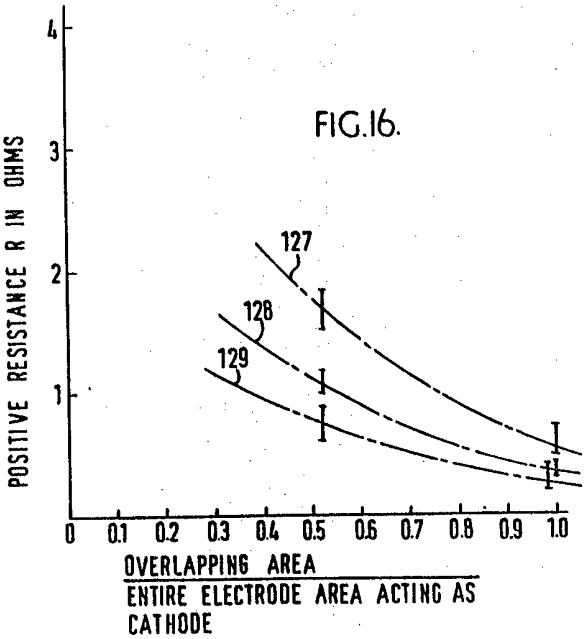
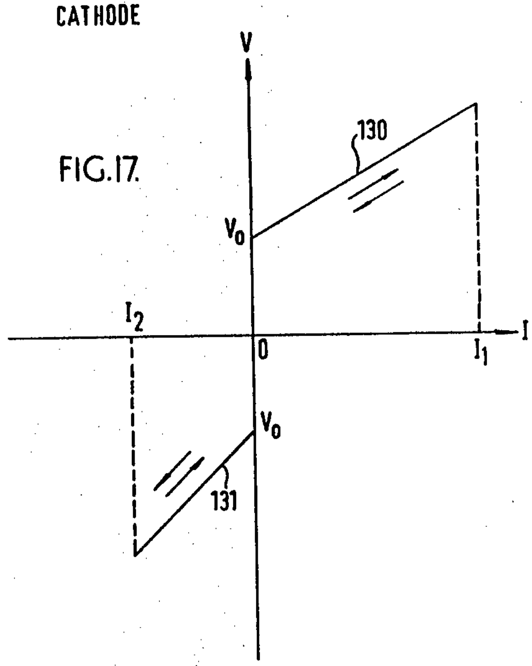

POSITIVE RESISTANCE R IN OHMS
4
3
2
1
127
128
129
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
OVERLAPPING AREA
ENTIRE ELECTRODE AREA ACTING AS CATHODE

FIG.17.


V
130
V_0
I_2
0
I_1
I
V_0
131

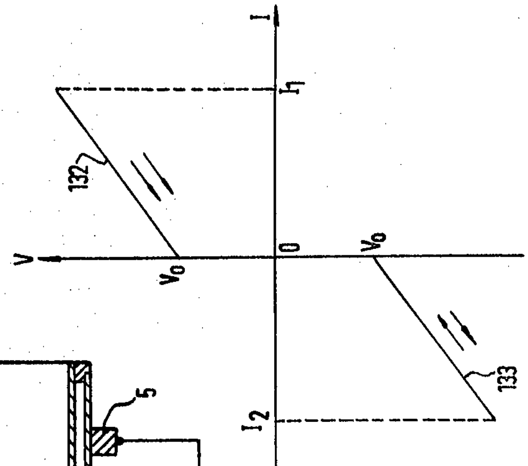

I
I_1
132
V
V_o
0
V_o
133
I_2

FIG.19.

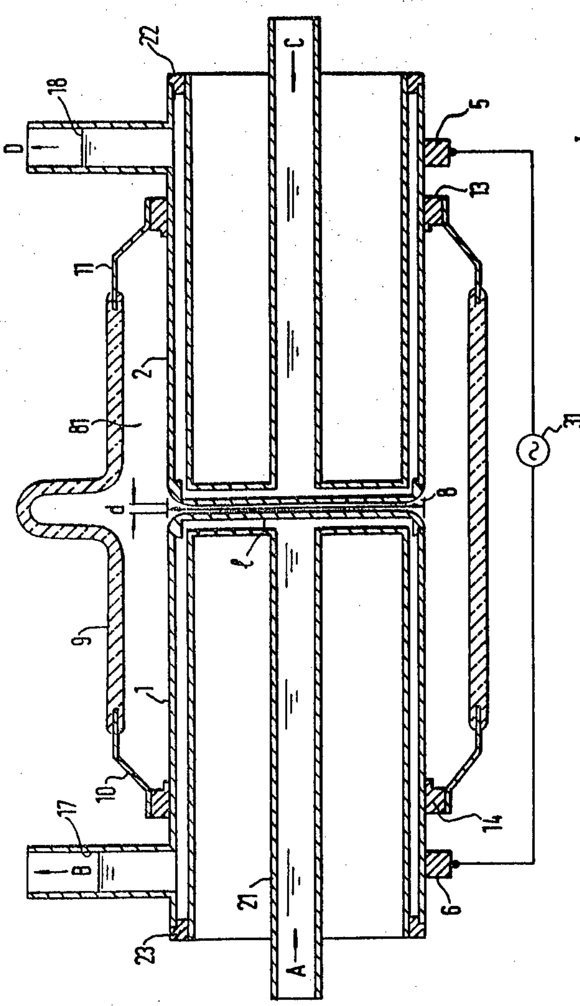

18
D
22
C
5
13
11
2
81
31
d
8
ℓ
9
1
10
17
B
14
21
6
23
A

FIG 18

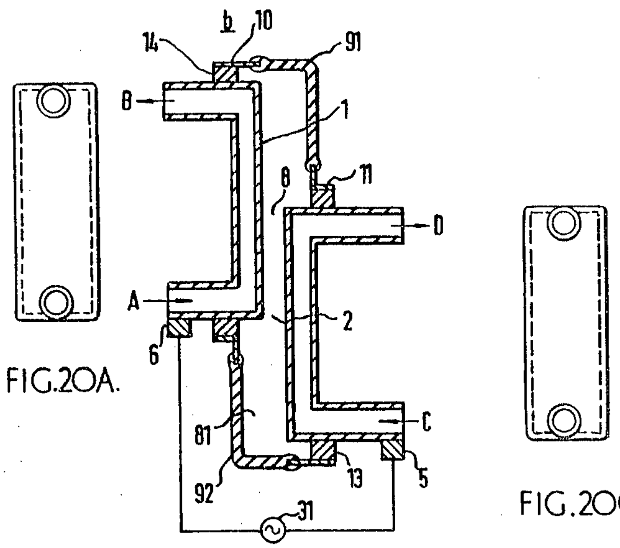


FIG.20A.

FIG.20B.

FIG.20C.

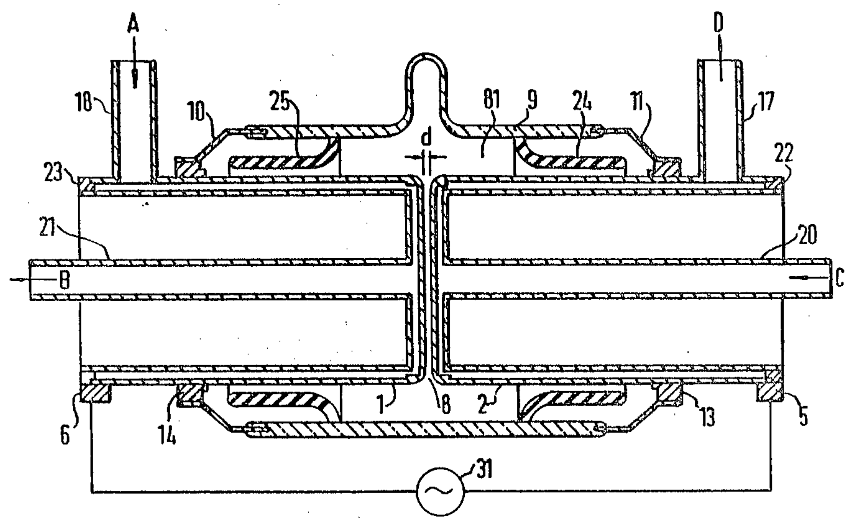


FIG.21.

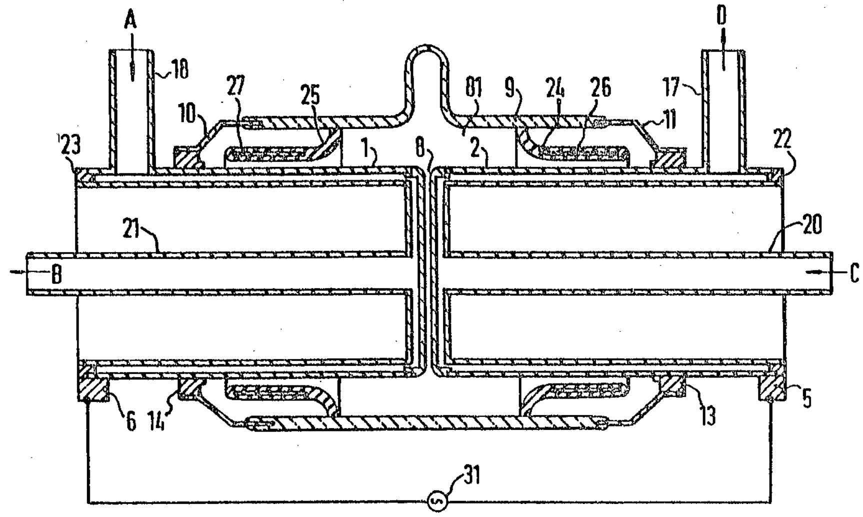

A
D
18
27
25
81
9
24
26
17
10
11
23
1
8
2
22
21
20
B
C
6
14
13
5
31

FIG. 22.

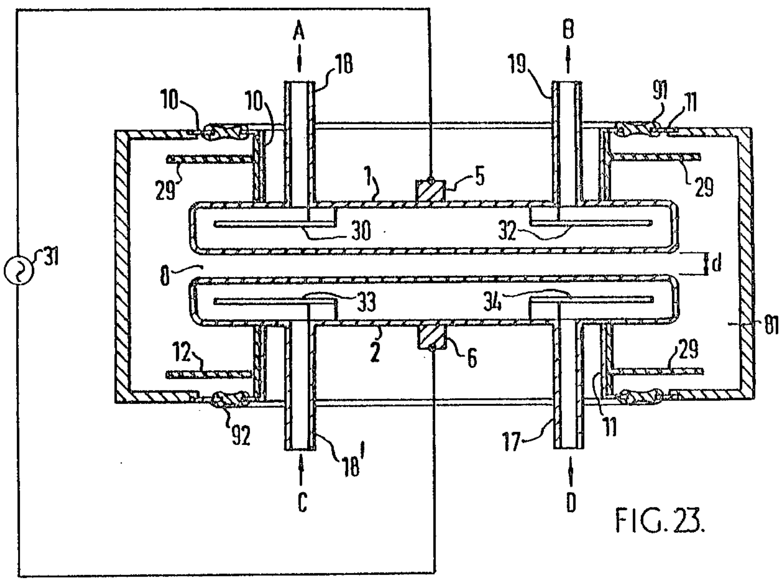

A
B
18
19
10
10
91
11
29
1
5
29
30
32
31
8
d
33
34
81
2
6
12
29
92
11
18'
17
C
D

FIG. 23.

1585017 COMPLETE SPECIFICATION

34 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 11

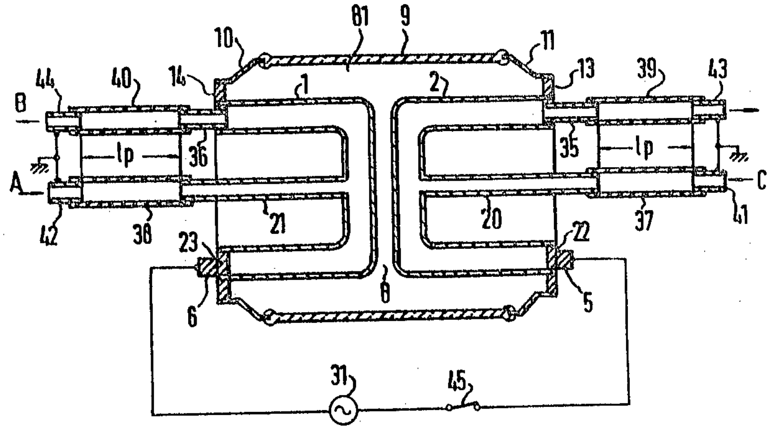


FIG. 24.

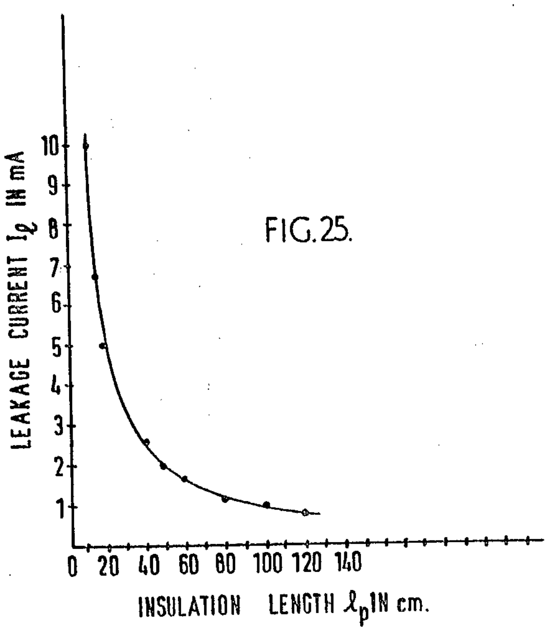


FIG. 25.

1585017 COMPLETE SPECIFICATION

34 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 12

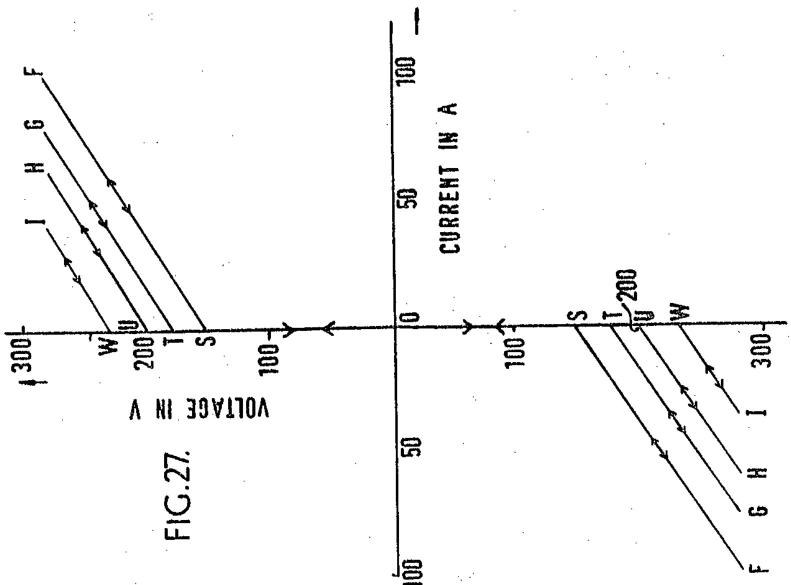


FIG.27.

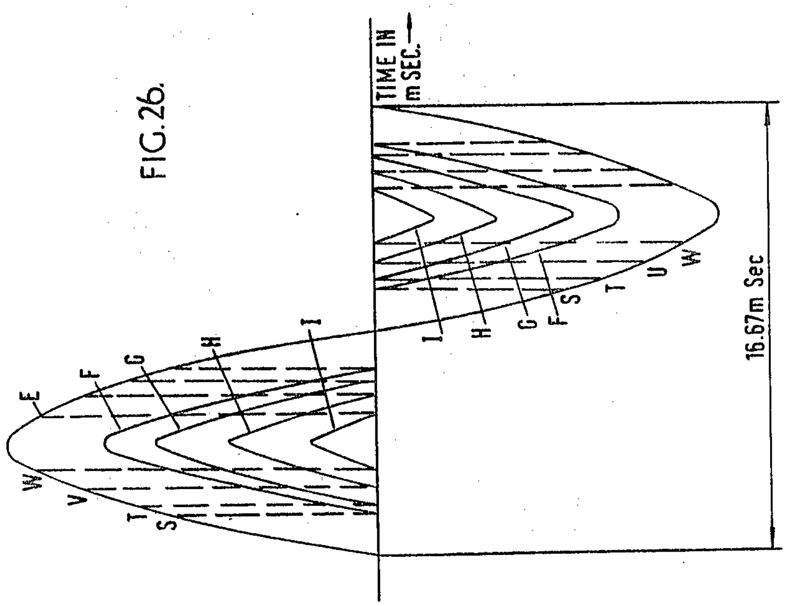


FIG.26.

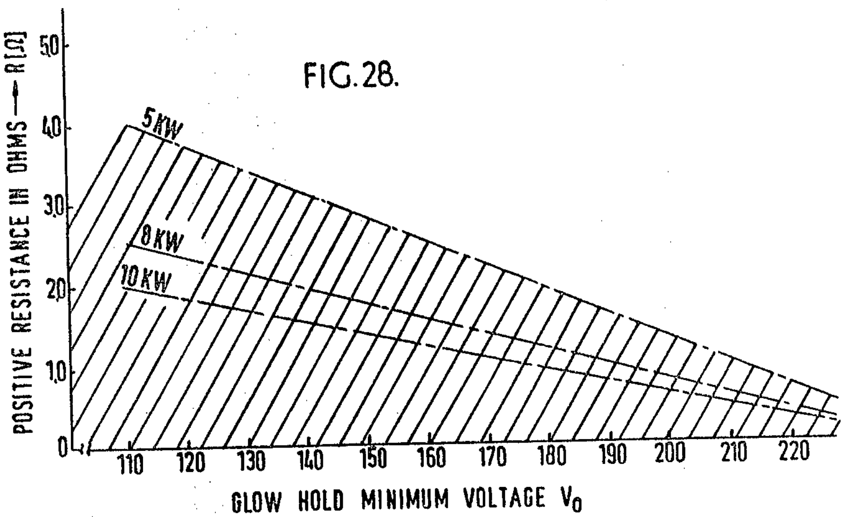

POSITIVE RESISTANCE IN OHMS ⟶ R[Ω]
50
40
30
20
10
0
5KW
8KW
10KW
110
120
130
140
150
160
170
180
190
200
210
220
GLOW HOLD MINIMUM VOLTAGE V_0

FIG. 28.

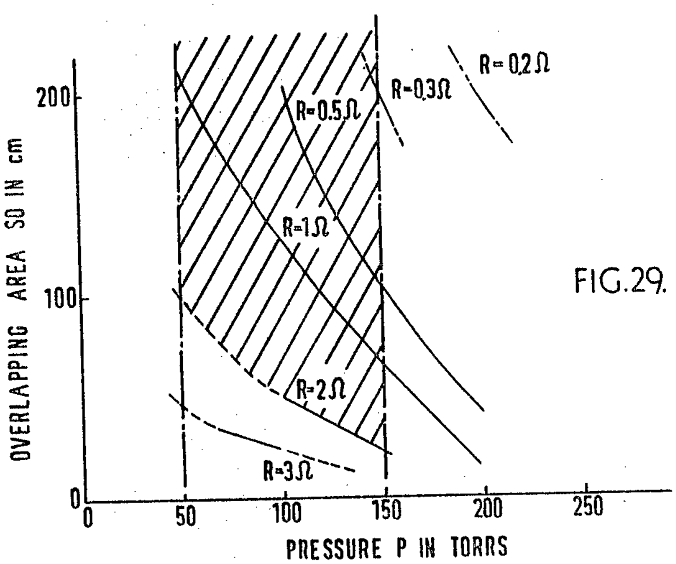

OVERLAPPING AREA SO IN cm
200
100
0
R=0.5Ω
R=0.3Ω
R=0.2Ω
R=1Ω
R=2Ω
R=3Ω
0
50
100
150
200
250
PRESSURE P IN TORRS

FIG. 29.

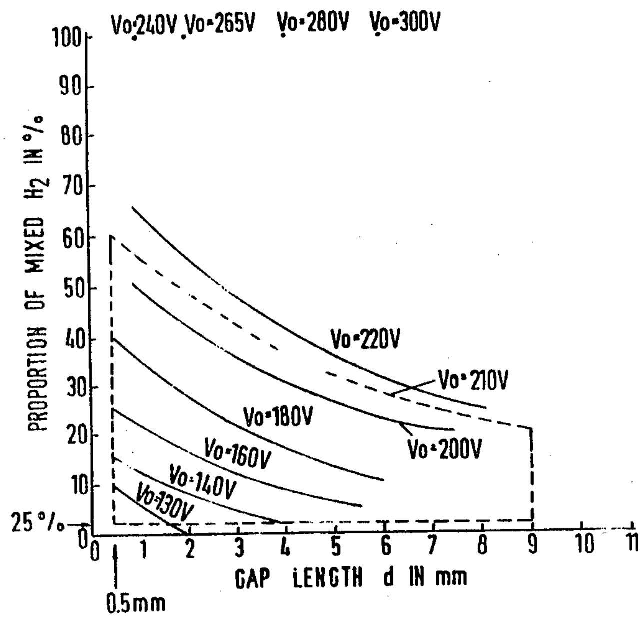

Vo=240V
Vo=265V
Vo=280V
Vo=300V
100
90
80
70
60
50
40
30
20
10
25%
0
PROPORTION OF MIXED H2 IN %
Vo=220V
Vo=210V
Vo=180V
Vo=200V
Vo=160V
Vo=140V
Vo=130V
0 1 2 3 4 5 6 7 8 9 10 11
GAP LENGTH d IN mm
0.5mm

FIG.30.

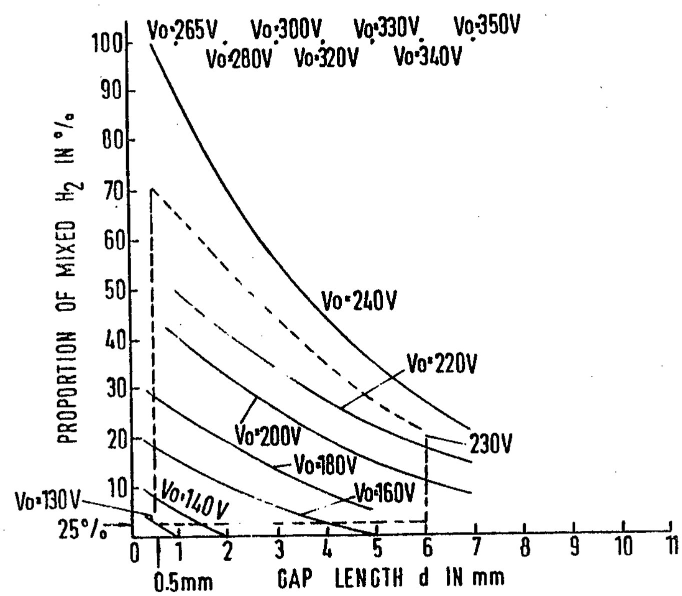

Vo=265V
Vo=300V
Vo=330V
Vo=350V
Vo=280V
Vo=320V
Vo=340V
100
90
80
70
60
50
40
30
20
10
25%
0
PROPORTION OF MIXED H2 IN %
Vo=240V
Vo=220V
230V
Vo=200V
Vo=180V
Vo=160V
Vo=140V
Vo=130V
0 1 2 3 4 5 6 7 8 9 10 11
0.5mm
GAP LENGTH d IN mm

FIG 31

FIG.33.

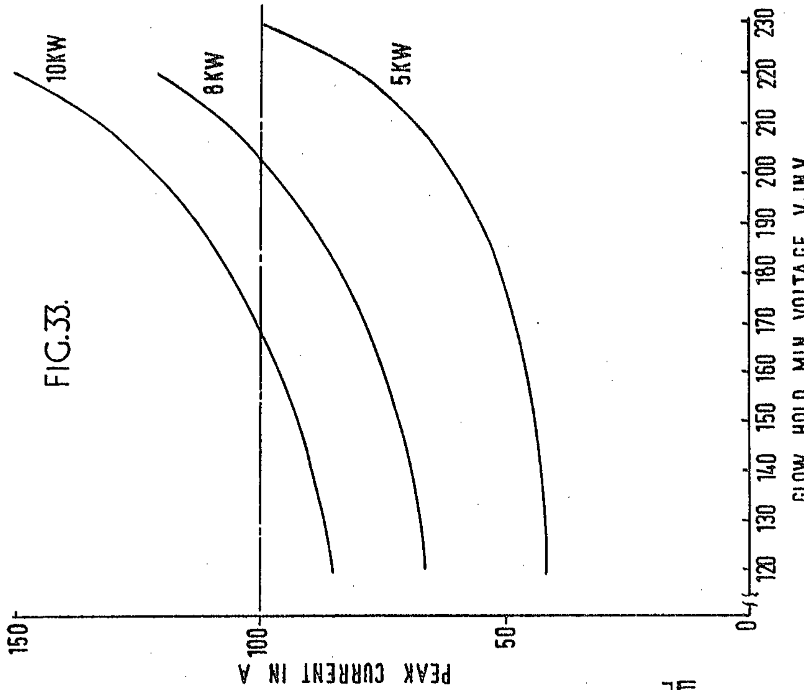
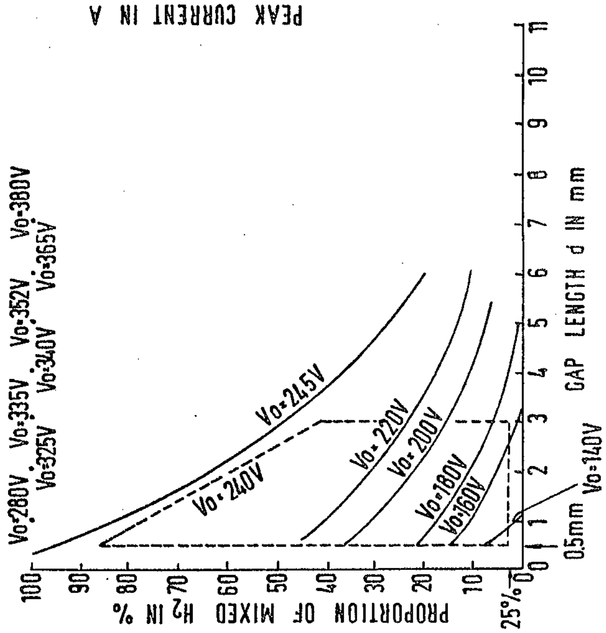

10KW
8KW
5KW
PEAK CURRENT IN A
150
100
50
0
120 130 140 150 160 170 180 190 200 210 220 230
GLOW HOLD MIN. VOLTAGE V_0 IN V

FIG.32.


Vo=280V Vo=335V Vo=352V Vo=380V
Vo=325V Vo=340V Vo=365V
Vo=245V
Vo=240V
Vo=220V
Vo=200V
Vo=180V
Vo=160V
Vo=140V
0.5mm
25%
PROPORTION OF MIXED H_2 IN %
100 90 80 70 60 50 40 30 20 10 0
0 1 2 3 4 5 6 7 8 9 10 11
GAP LENGTH d IN mm

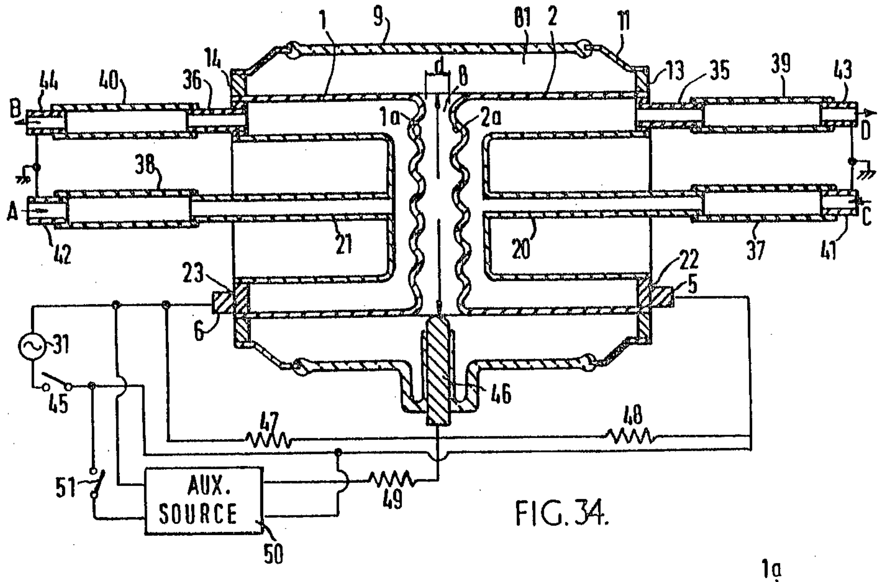


FIG. 34.

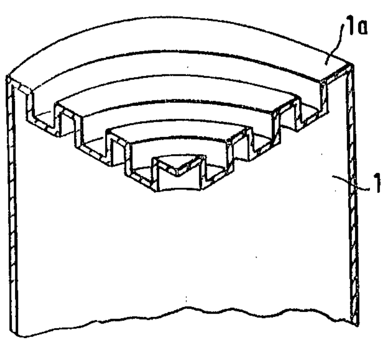


FIG. 35.

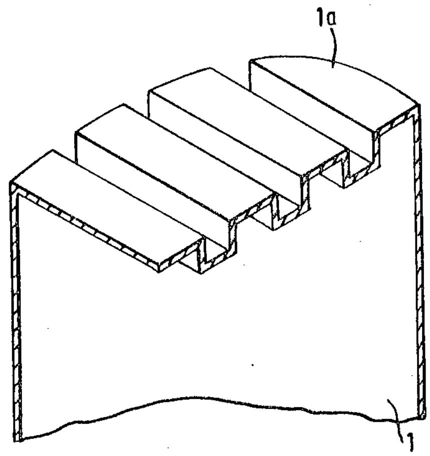


FIG. 36.

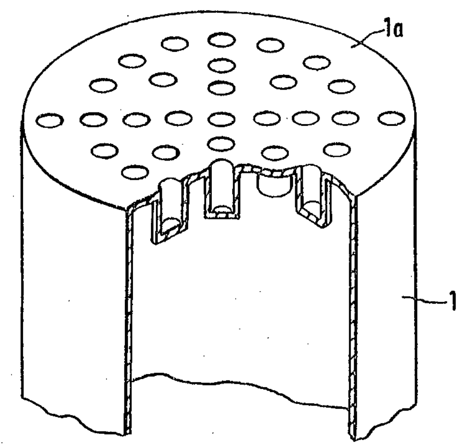

1a
1

FIG.37.

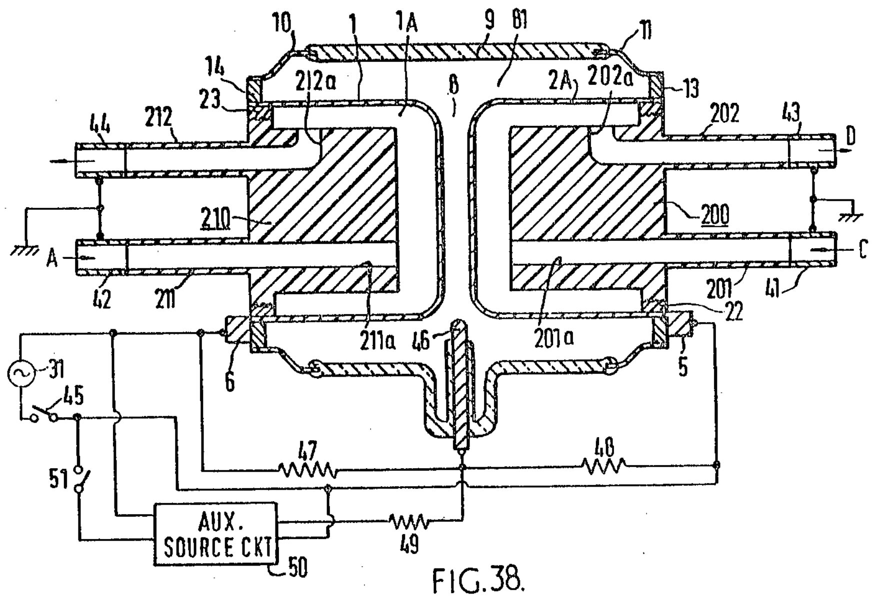

10
1
1A
9
81
11
14
23
212a
8
2A
202a
13
44
212
202
43
D
210
200
A
42
211
211a
46
201a
201
41
C
22
31
45
6
5
47
48
51
AUX. SOURCE CKT
49
50

FIG.38.

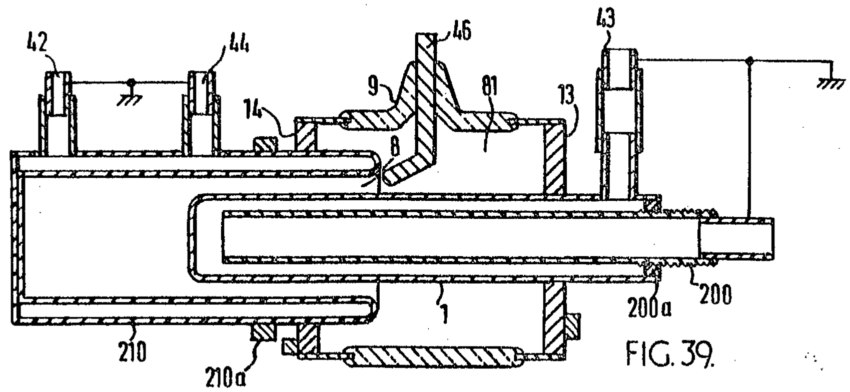

42
44
46
43
9
81
13
14
8
1
200a
200
210
210a

FIG. 39.

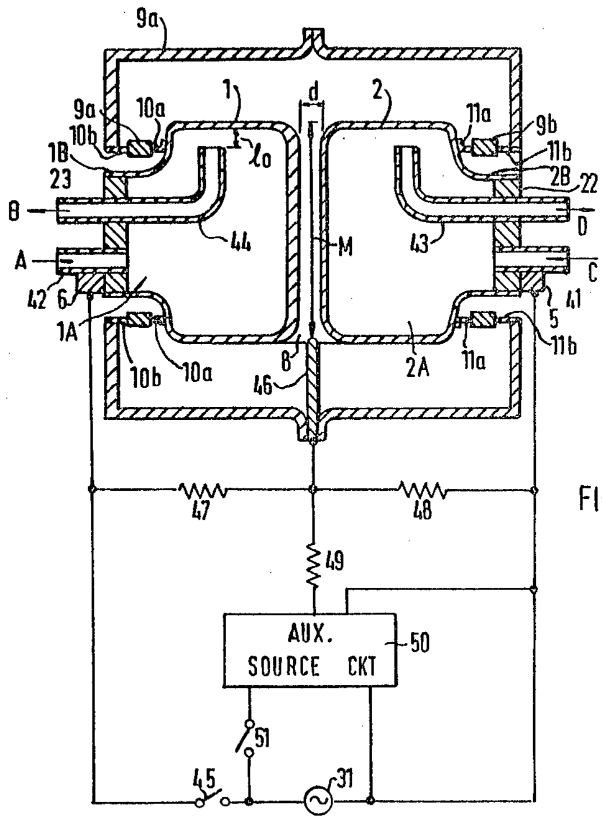
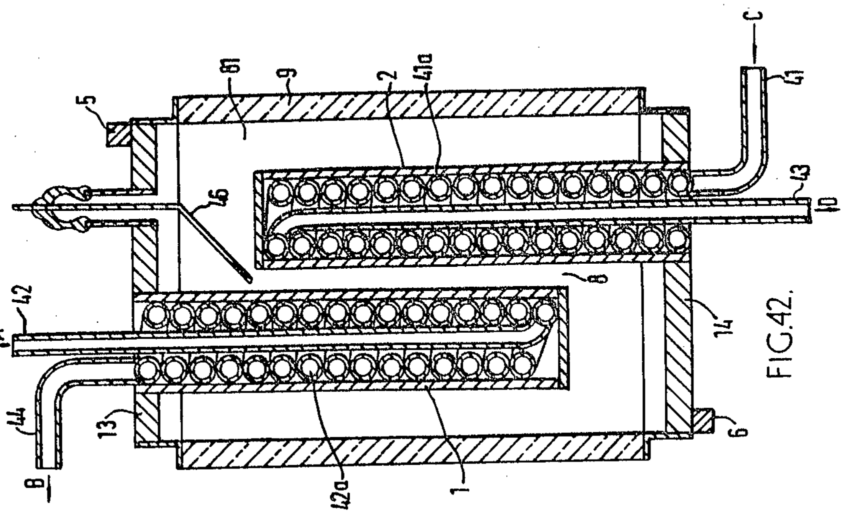
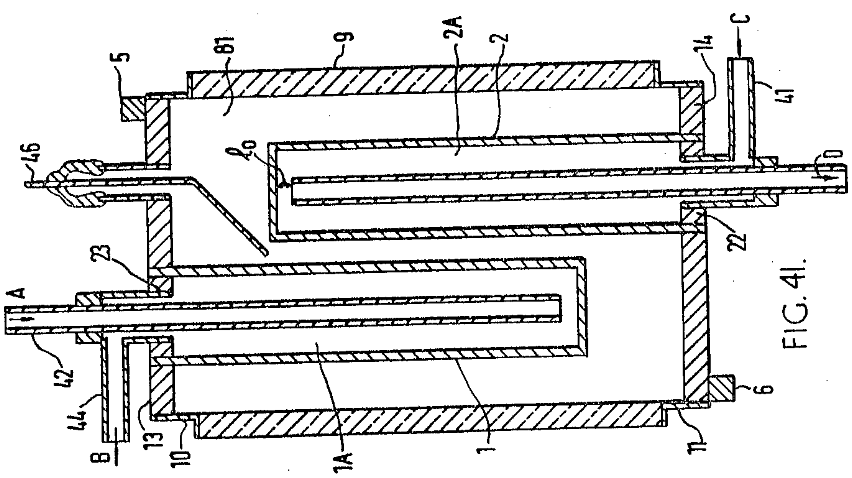

9a
9a
10a
1
d
2
11a
9b
10b
11b
1B
2B
23
22
B
D
44
M
43
A
C
42
6
41
5
1A
8
2A
11a
11b
10b
10a
46
47
48
49
AUX.
SOURCE CKT
50
51
45
31

FIG. 40.



C
41
43
D
14
6
81
9
2
41a
5
46
8
42
A
44
13
B
42a
1

FIG.42.



C
14
41
D
22
11
6
9
2A
2
81
5
46
23
A
42
44
B
13
10
1A
1

FIG. 41.

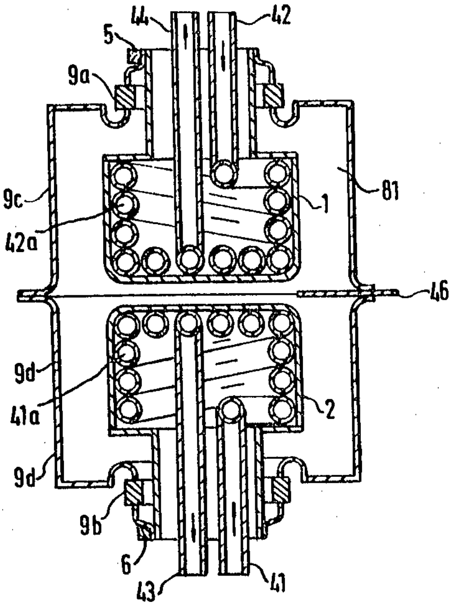

44
42
5
9a
9c
81
1
42a
46
9d
41a
2
9d
9b
6
43
41

FIG.43.

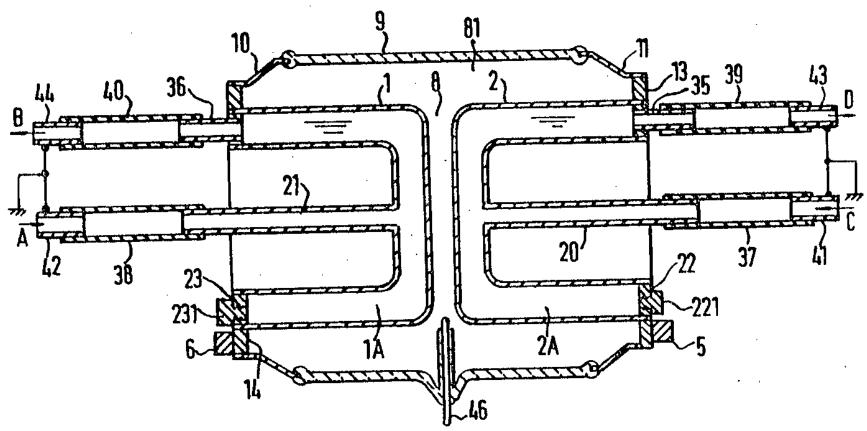

10
9
81
11
13
35
39
43
44
40
36
1
8
2
B
D
21
A
C
42
38
20
37
41
23
22
231
221
6
1A
2A
5
14
46

FIG.44.

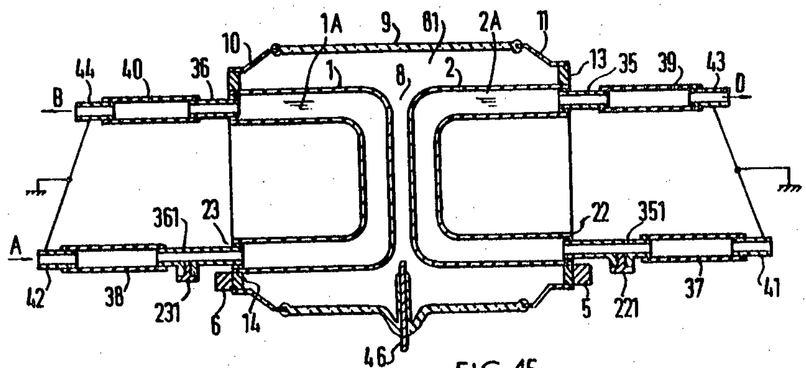


FIG.45.

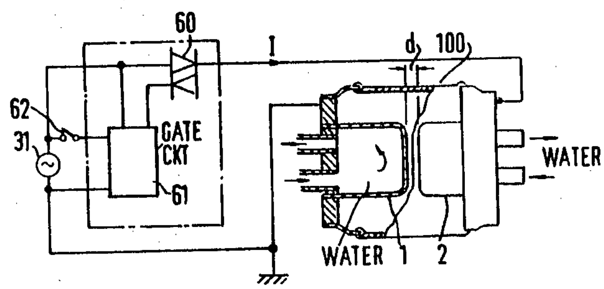


FIG 46

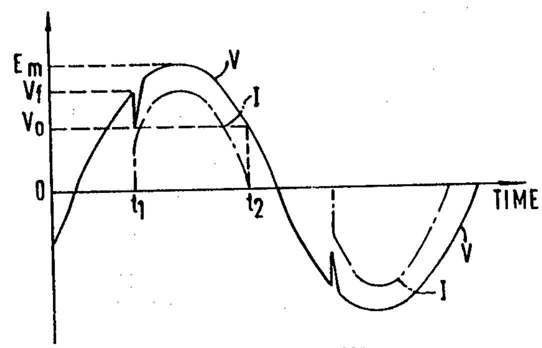


FIG. 47.

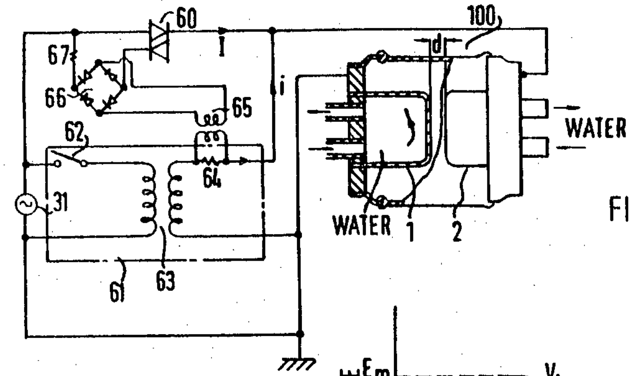


FIG.48.

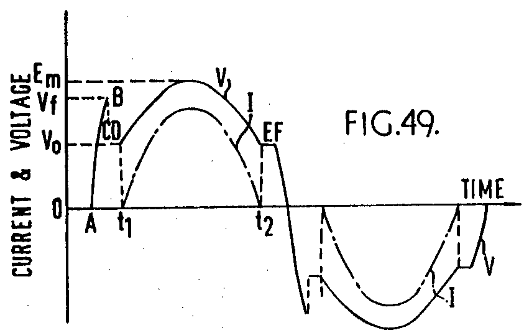


FIG.49.

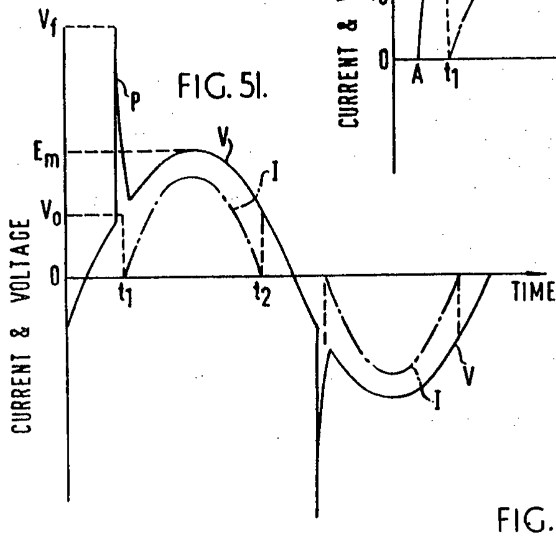
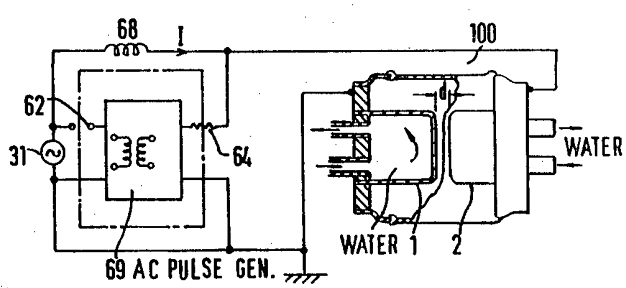


FIG. 51.

FIG.50.



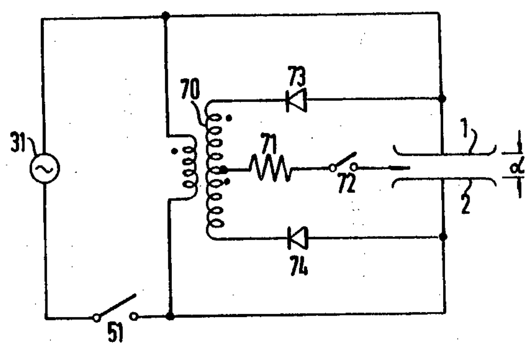

70
73
31
71
72
1
α
2
74
51

FIG. 52.

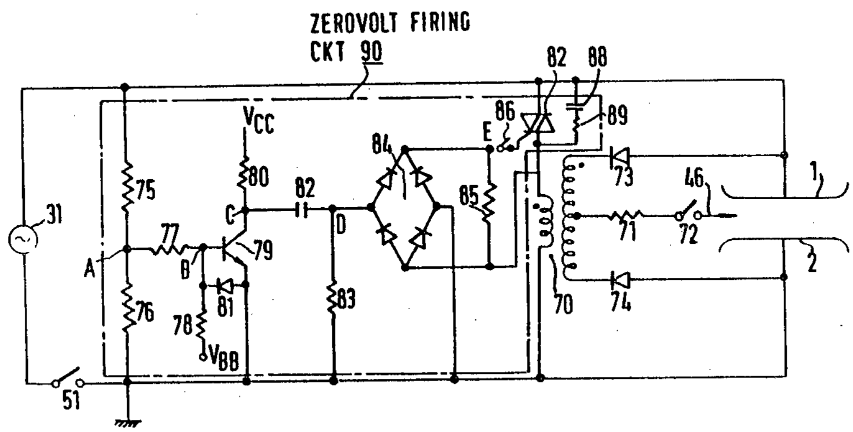

ZEROVOLT FIRING
CKT 90
82
88
86
89
VCC
84
E
80
82
85
75
C
73
46
1
31
77
79
D
71
72
A
B
2
81
83
70
74
76
78
VBB
51

FIG. 53.

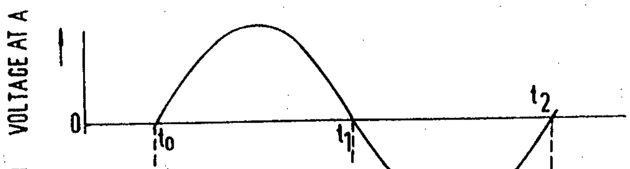


FIG.54A.

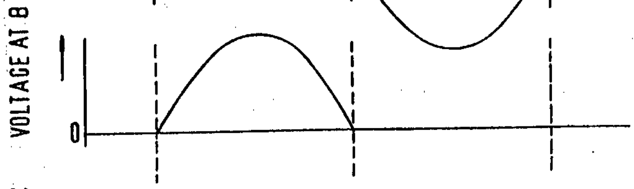


FIG.54B.

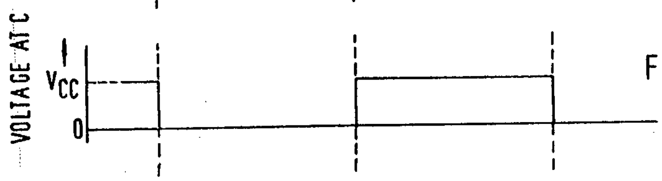


FIG. 54C.

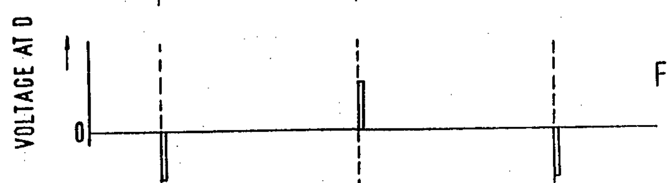


FIG.54D.

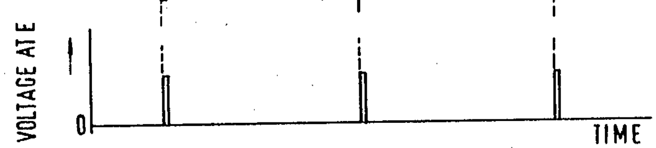


FIG.54E.

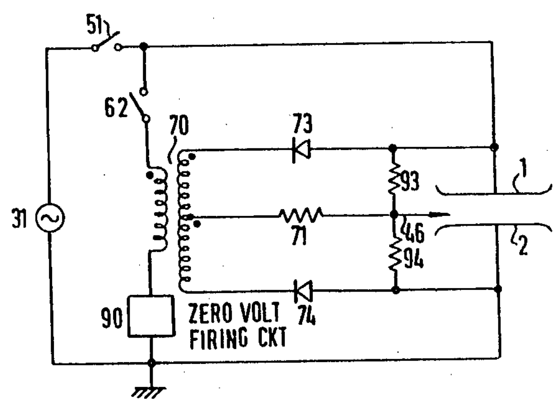


FIG. 55.

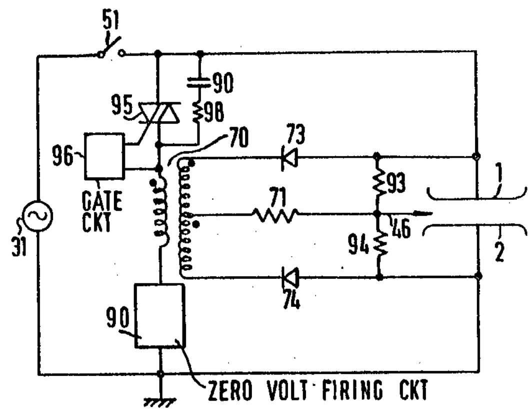

51
90
95
98
96
70
73
GATE CKT
71
93
1
31
46
94
2
74
90
ZERO VOLT FIRING CKT

FIG.56.

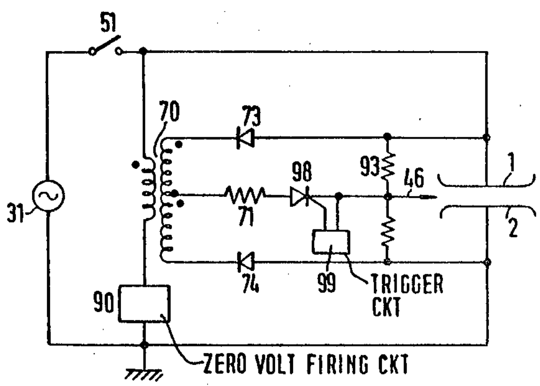

51
70
73
98
93
46
1
31
71
2
74
99
TRIGGER CKT
90
ZERO VOLT FIRING CKT

FIG.57.

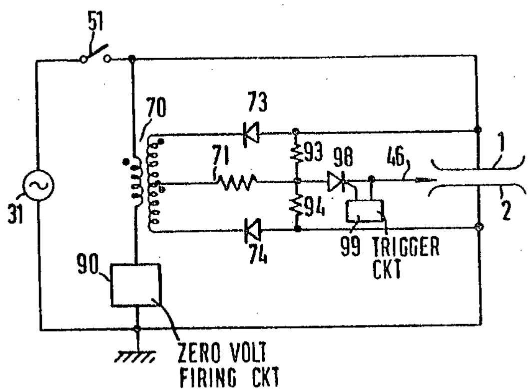

51
70
73
71
93
98
46
1
2
31
94
74
99 TRIGGER CKT
90
ZERO VOLT FIRING CKT

FIG.58.

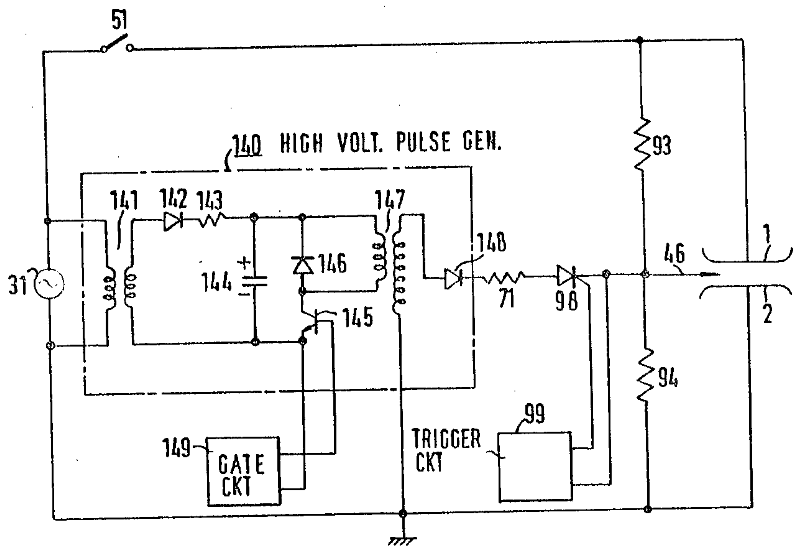
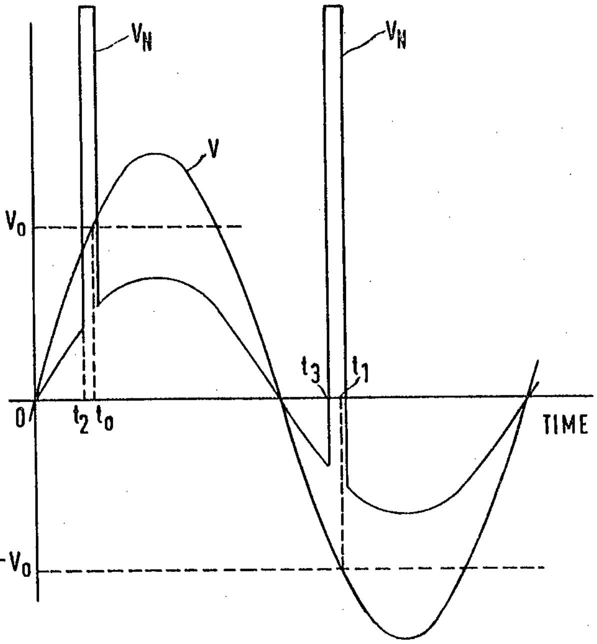

51
140 HIGH VOLT. PULSE GEN.
93
141
142
143
147
148
46
1
2
31
144
146
145
71
98
94
99
149
GATE CKT
TRIGGER CKT

FIG.59.

FIG. 60.


V_N
V_N
V
VOLTAGE
V_0
$-V_0$
0
t_2
t_0
t_3
t_1
TIME

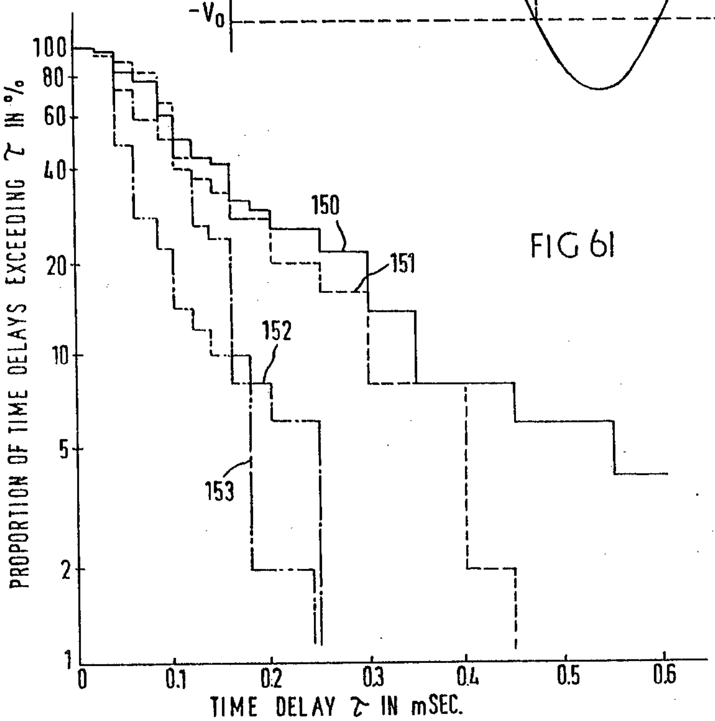

PROPORTION OF TIME DELAYS EXCEEDING τ IN %
100
80
60
40
20
10
5
2
1
150
151
152
153
0
0.1
0.2
0.3
0.4
0.5
0.6
TIME DELAY τ IN mSEC.

FIG 61

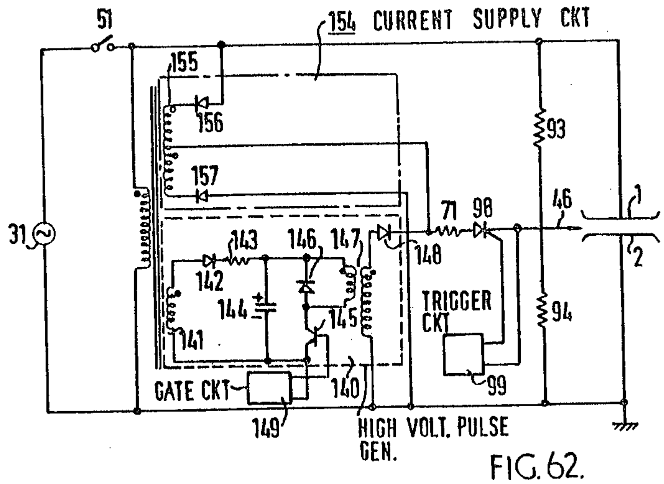

51
154 CURRENT SUPPLY CKT
155
156
157
93
71
98
46
1
2
31
143
146
147
148
142
144
145
TRIGGER CKT
94
141
GATE CKT
140
99
149
HIGH VOLT. PULSE GEN.

FIG. 62.

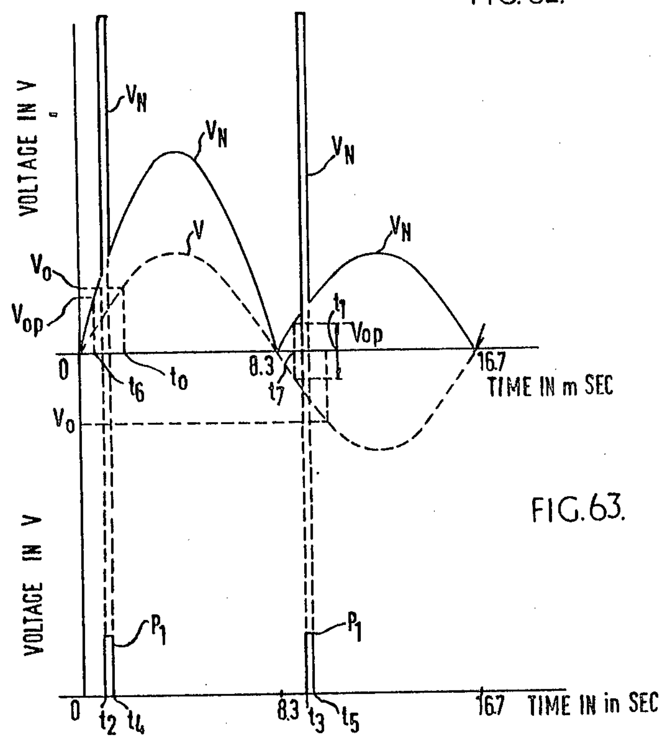

VOLTAGE IN V
VN
V
Vo
Vop
0
t6
to
8.3
t7
t1
16.7
TIME IN m SEC
VOLTAGE IN V
P1
t2
t4
t3
t5
TIME IN in SEC

FIG. 63.

1585017 COMPLETE SPECIFICATION

34 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 29

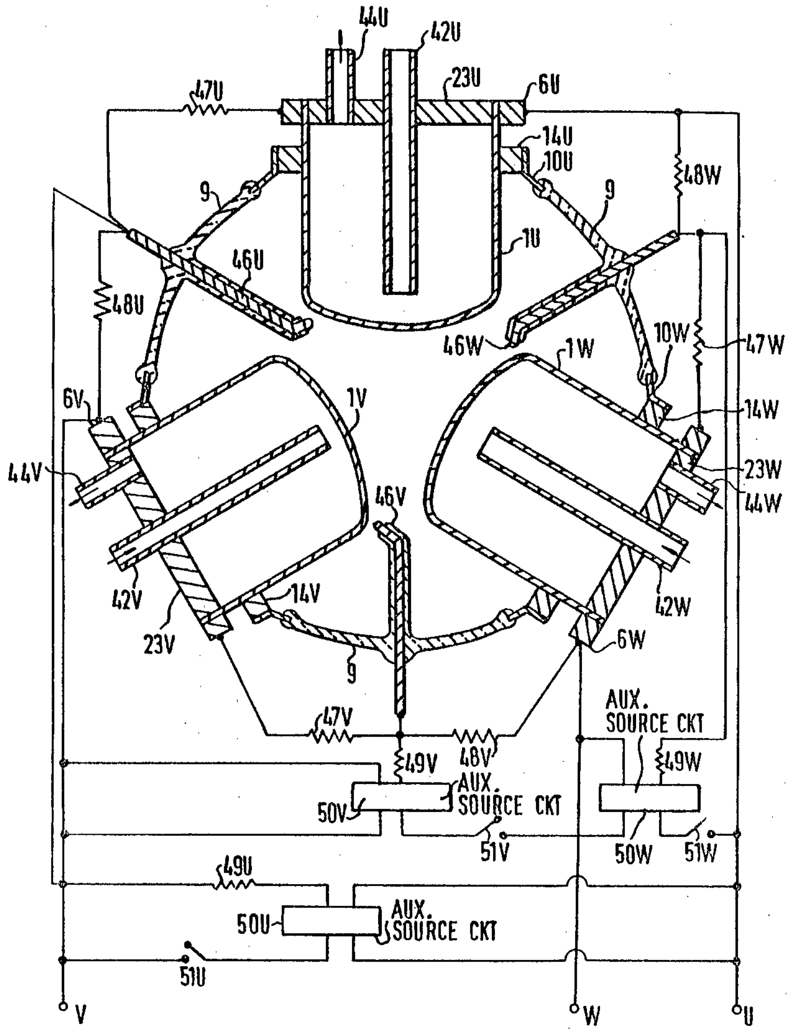


FIG 64

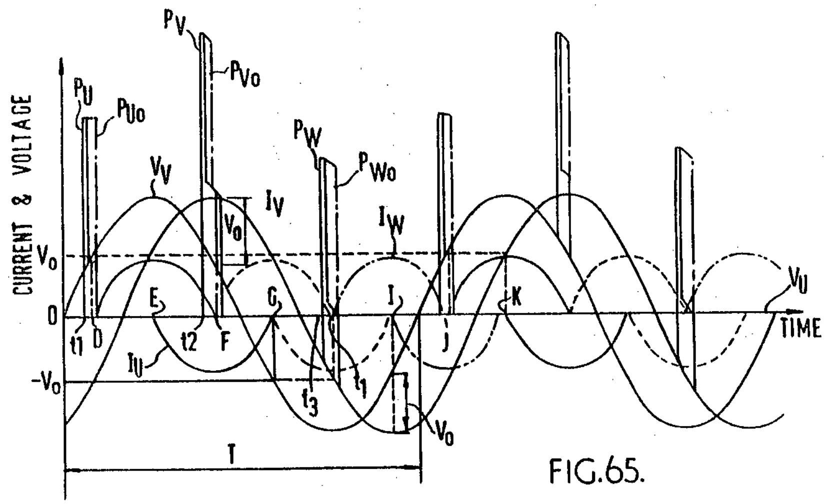

PV
PVo
PU
PUo
PW
PWo
VV
IV
Vo
IW
CURRENT & VOLTAGE
Vo
0
-Vo
E
G
I
K
VU
TIME
t1
D
t2
F
t3
t1
J
IU
Vo
T

FIG.65.

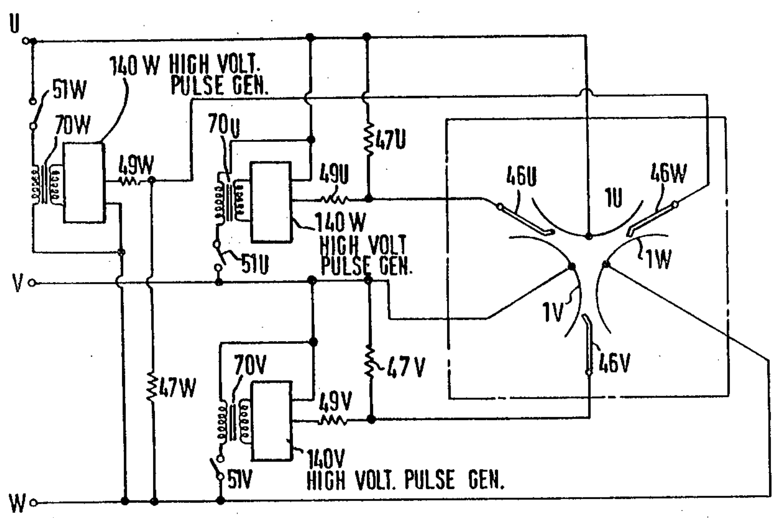

U
V
W
51W
70W
140 W HIGH VOLT. PULSE GEN.
49W
47W
70U
49U
47U
140 W
HIGH VOLT PULSE GEN.
51U
70V
49V
47 V
140V
HIGH VOLT. PULSE GEN.
51V
46U
1U
46W
1W
1V
46V

FIG.66.

1585017 COMPLETE SPECIFICATION

34 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 31

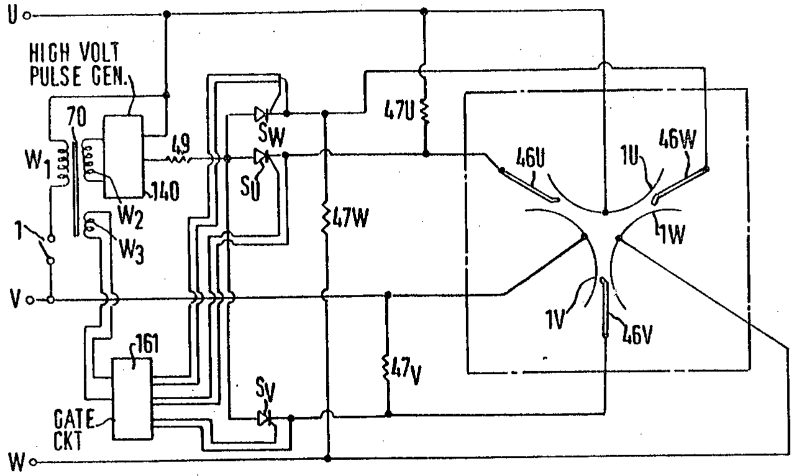


FIG. 67.

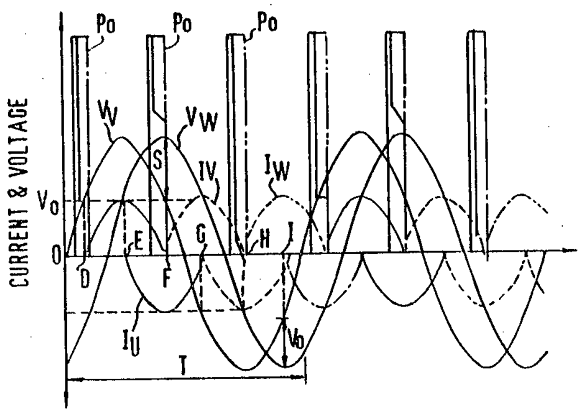


FIG 68A

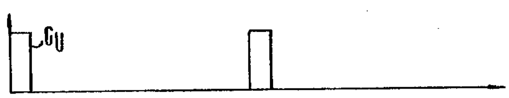


FIG. 68B.

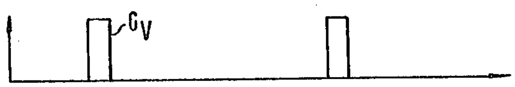


FIG. 68C.

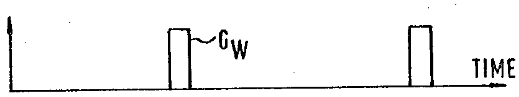


FIG. 68D.

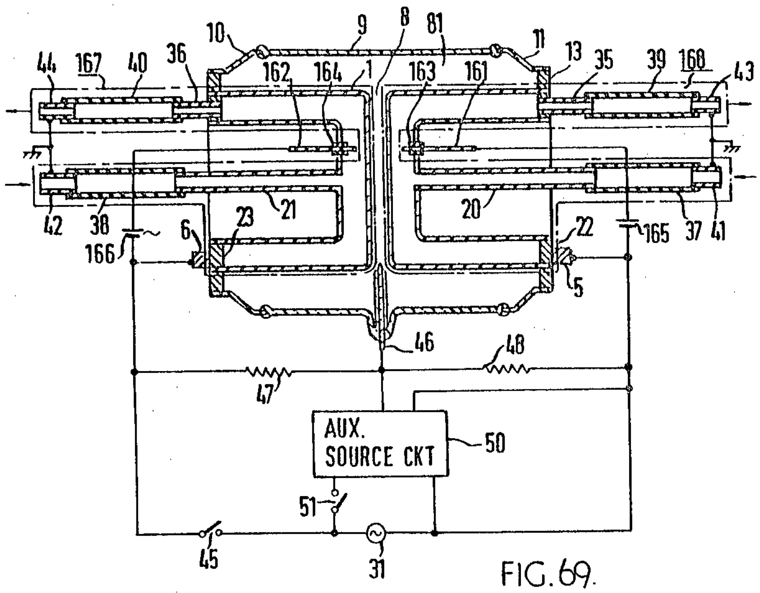


FIG. 69.

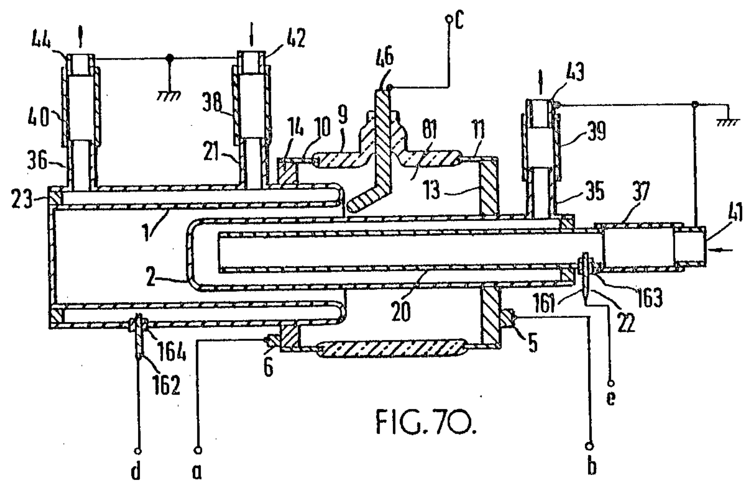


FIG. 70.

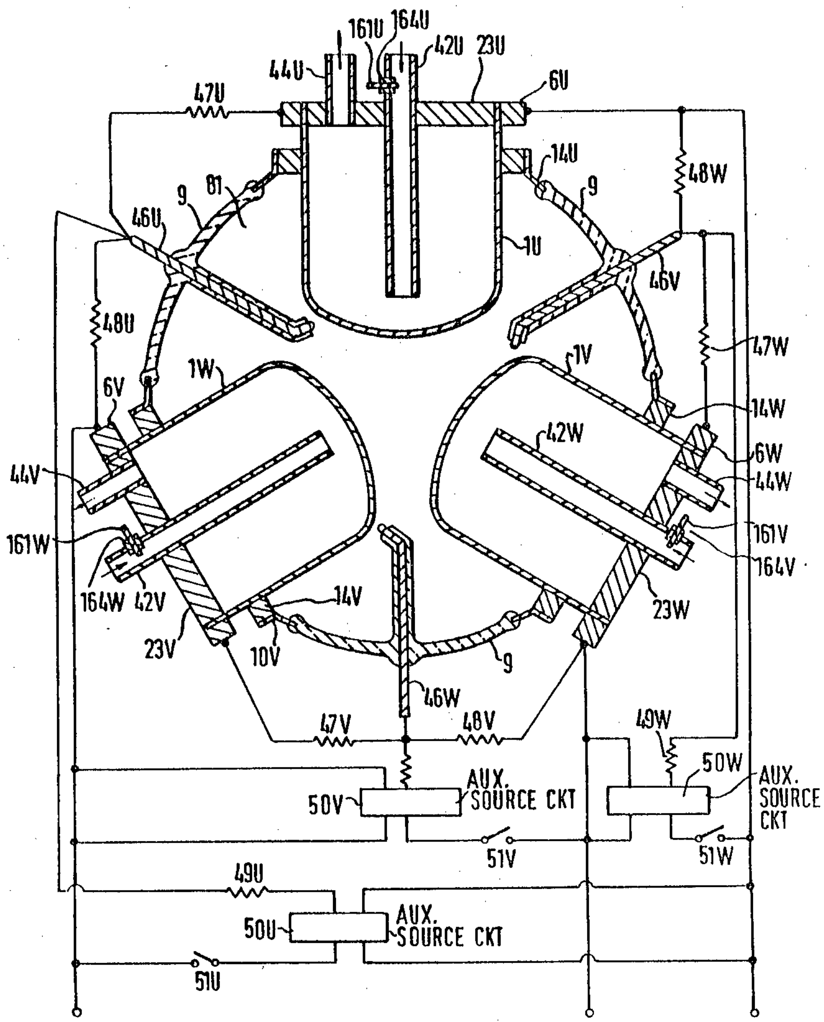

161U
164U
42U
23U
44U
6U
47U
14U
9
48W
81
46U
1U
46V
48U
47W
1W
1V
6V
14W
42W
6W
44V
44W
161W
161V
164V
164W
42V
14V
23W
23V
10V
9
46W
47V
48V
49W
50W
AUX.
SOURCE CKT
50V
AUX.
SOURCE
CKT
51V
51W
49U
50U
AUX.
SOURCE CKT
51U

FIG. 71.

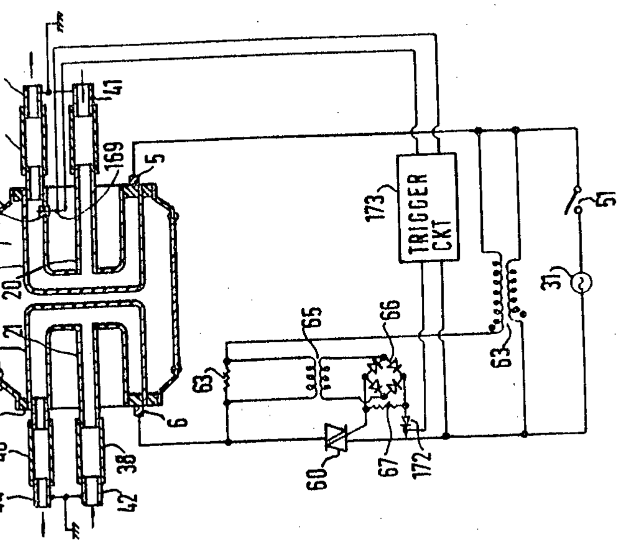


FIG.73.

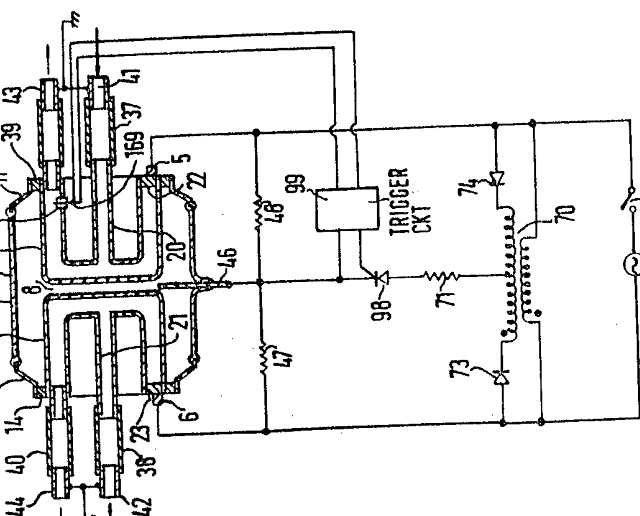


FIG.72.