Feb. 26, 1957 H. R. WARREN 2,783,348

HIGH-FREQUENCY HEATING APPLICATORS

Filed March 26, 1954 3 Sheets-Sheet 1

Fig. 1

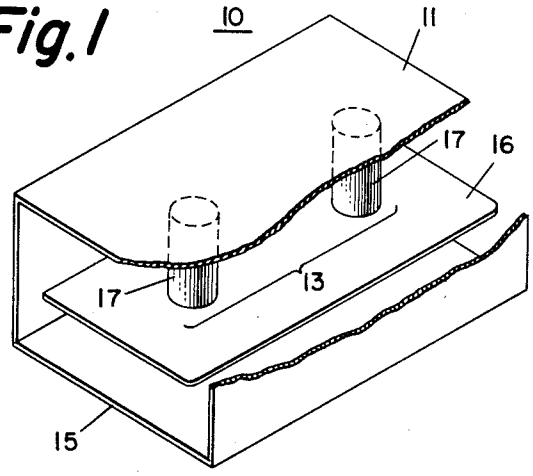


Fig. 2

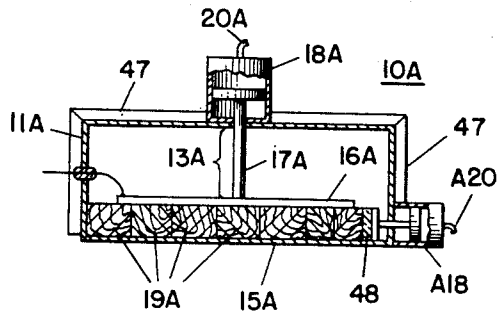
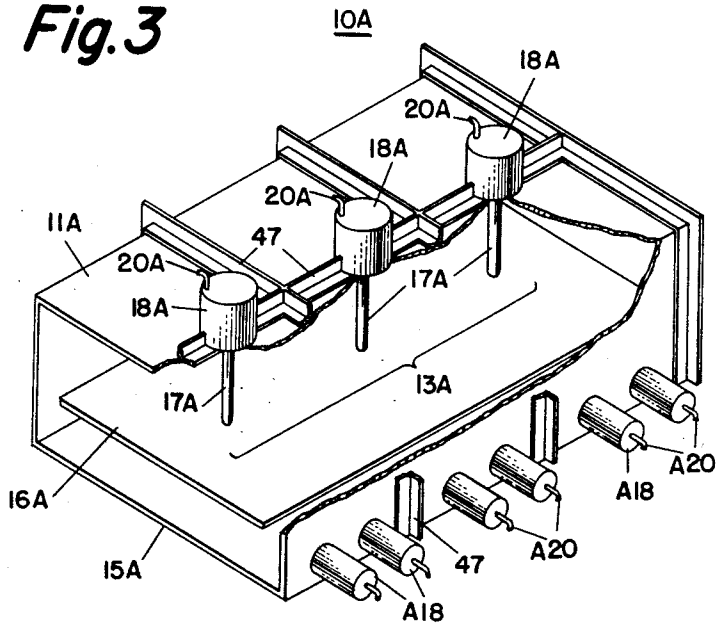


Fig. 3



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HIGH-FREQUENCY HEATING APPLICATORS

Filed March 26, 1954 3 Sheets-Sheet 2

Fig. 4

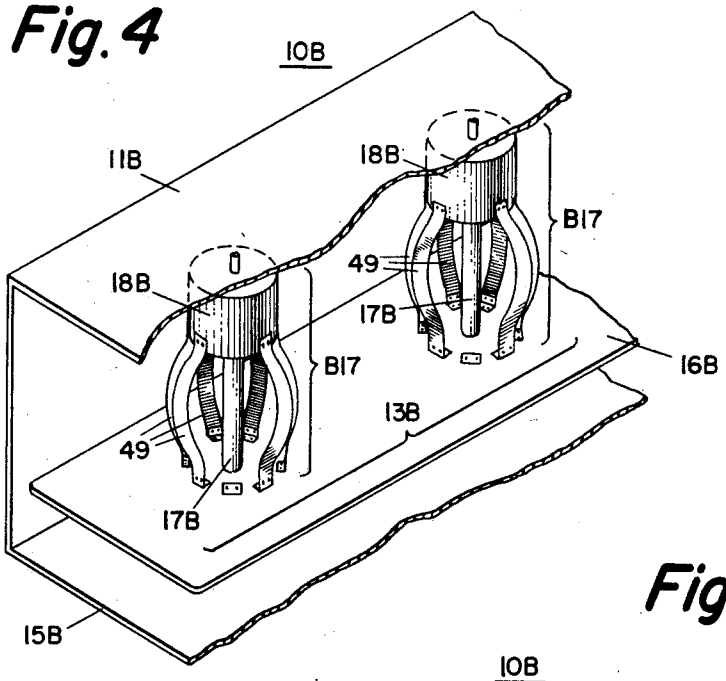


Fig. 5

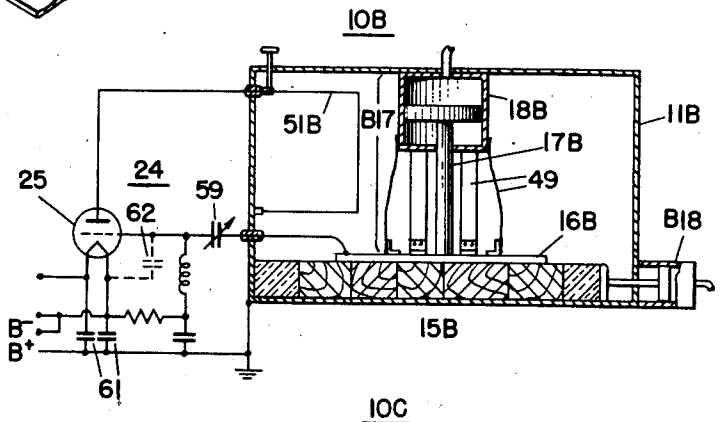
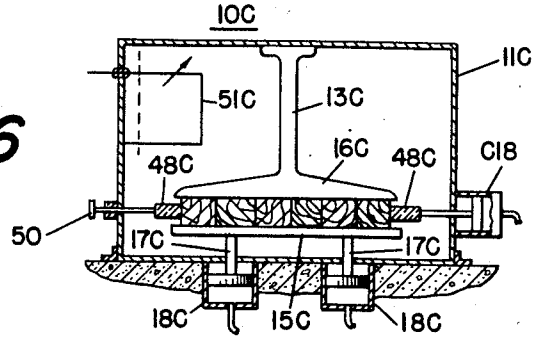


Fig. 6



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HIGH-FREQUENCY HEATING APPLICATORS

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Fig. 7

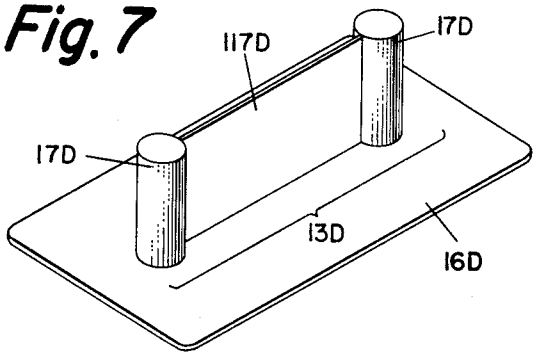


Fig. 8

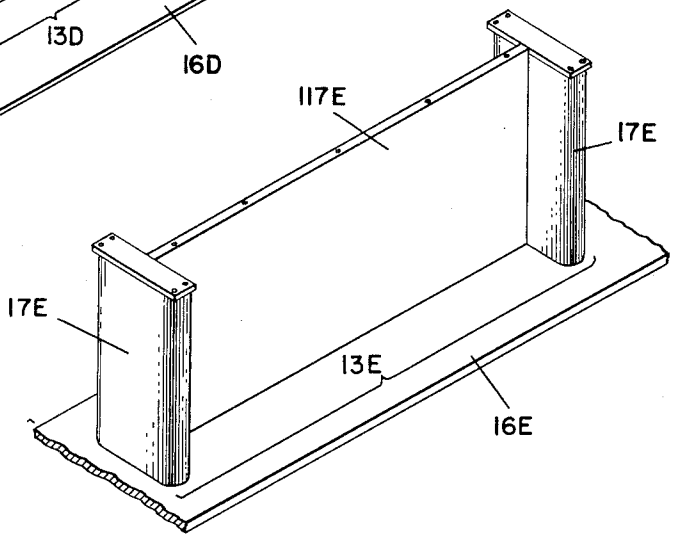
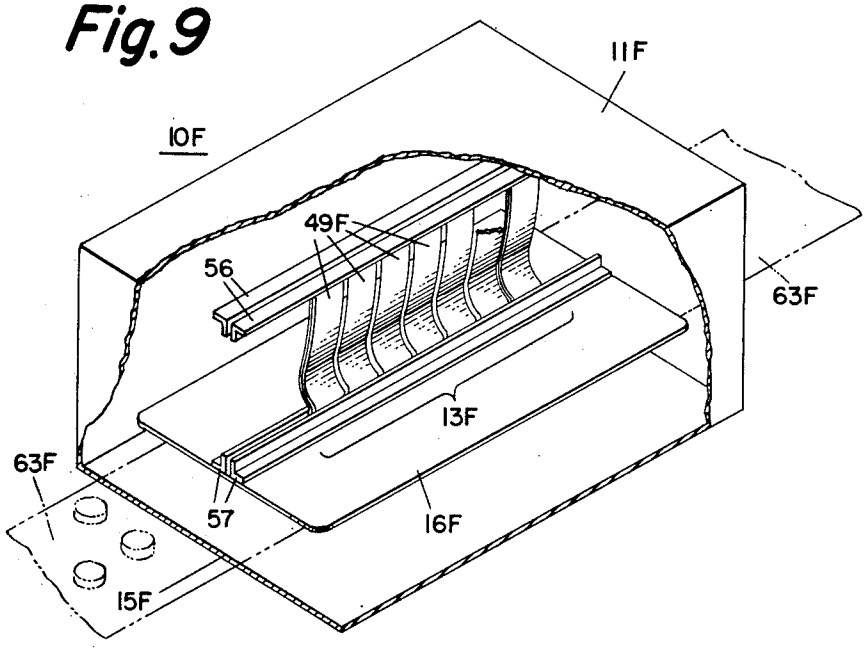


Fig. 9



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Patented Feb. 26, 1957

2,783,348

HIGH-FREQUENCY HEATING APPLICATORS

Henry R. Warren, Columbus, Ind., assignor to National Cylinder Gas Company, Chicago, Ill., a corporation of Delaware

Application March 26, 1954, Serial No. 419,071

27 Claims. (Cl. 219—10.55)

This invention relates to high-frequency heating and particularly to resonant applicators especially suited for rapid dielectric heating of large area loads, such as foam-rubber mattresses, wallboard panels, groups of sand cores or plastic preforms, and the like, and in other similar applications of high-frequency heating, wherein it frequently is required, or at least desirable, that the "hot" heating electrode be many feet long, i. e., of the order of two feet to twenty-five feet or more.

This application, a continuation-in-part of my application Serial No. 138,628, filed January 14, 1950, and now abandoned in favor of my continuation-in-part application Serial No. 419,633, filed March 26, 1954, has claims directed to subject matter divided from my parent application Serial No. 138,628. My aforesaid applications contain a more detailed discussion, included herein by this reference, of the structural and operating characteristics of resonant applicators of the kind to which the present invention is particularly directed.

In general, such applicators comprise relatively large electrode structures electrically interconnected through conductive structure which at least in part has substantial inductance cooperative with capacity-means including the capacitance between said electrode structures to form a resonant circuit device, and a power transfer coupling means, preferably a coupling loop disposed in position to be traversed by a high-frequency magnetic field encircling a part of said interconnecting conductive structure. More particularly, in the preferred form of such applicators, the interconnecting structure includes low resistance conductive walls of a shielding enclosure which completes the resonant circuit of said device and serves to confine said magnetic field and also the electric field produced between said electrode structures, at least one of the electrode structures being electrically interconnected with wall structure of the enclosure through a leg or fin-like element which projects into the enclosure and in which a substantial part of the inductance of the resonant applicator is concentrated, and the said coupling loop being arranged to be traversed by the magnetic field encircling the inwardly projecting leg or fin-like element. Such loop may serve to provide for excitation of the applicator by a self-excited oscillator having the loop in its anode circuit.

In accordance with one feature of the present invention, the electrode structures are elongated for heating applications of the kind above mentioned, and the electrode structures and electrically interconnecting conductive structure, including the inductance of the applicator as aforesaid, are arranged and dimensioned in accordance with principles hereinafter set forth so as to obtain substantial uniformity of potential gradient over the electrode area, or a desired potential rise in one or more directions, in either case without recourse to the complications of "stubbing" or to use of frequencies too low for satisfactory heating.

As will become more apparent from the ensuing description, control of voltage gradient along the heating

electrode structure in a given direction may be accomplished in large part by effectively elongating, in that direction, the part of the said interconnecting conductive structure of the applicator which connects to the heating electrode structure. Therefore, a further important feature of the present invention resides in designs and constructions for accomplishing such elongation in the most satisfactory manner for various applications.

More particularly and in some forms of the invention, such elongated part of the interconnecting structure, which may comprise the principal inductance of the applicator, may be formed by a row of two or more columns, straps, or the like in spaced apart relationship and, in the case of an elongated electrode, extending in the direction of elongation of the electrode. The elements which form the edges of the elongated structure may be of substantial peripheral area, greater than that of intervening elements. When only two elements are used, with substantial spacing between them, the intervening space may be substantially or completely bridged by a conductive web to avoid the possibility of "moding" of the applicator, to minimize excessive voltage gradients, and to facilitate coupling to an exciting loop.

The invention further resides in features of construction, combination and arrangement hereinafter described and claimed.

For a more detailed understanding of the present invention, and for illustration of specific various embodiments, reference is made to the accompanying drawings in which:

Fig. 1 is a perspective view, partly broken away, of an applicator embodying the invention in an elemental form;

Fig. 2 is a sectional view of a press-type applicator incorporating features of Fig. 1;

Fig. 3 is a perspective view, partly broken away, of the applicator of Fig. 2;

Fig. 4 is a perspective view, partly broken away, of a modification of the applicator of Figs. 2, 3;

Fig. 5 is a sectional view of the applicator of Fig. 4 together with an associated oscillator circuit;

Fig. 6 is a sectional view of another modification of the applicator of Figs. 2, 3;

Fig. 7 is a perspective view of an electrode-inductance assembly;

Fig. 8 is a perspective view of a modification of Fig. 7; and

Fig. 9 is a perspective view of an applicator, partly broken away, using a modification of the electrode-inductance assembly of Fig. 7.

The high-frequency heating applicator **10** of Fig. 1 embodies the invention herein claimed in one of its simplest elementary forms. The elongated heating electrode **16** is supported within an elongated metallic housing **11** with sufficient spacing to avoid flash-over to any wall of the housing at the high potentials developed on the electrode. The electrode **16** is connected to the top wall of the housing or tunnel by a row of conductive columns **17** which are spaced in the direction of elongation of the electrode **16** which is hereinafter called the "hot" electrode. The bottom wall **15** of the housing may serve as the "cold" or lower electrode of the applicator. Alternatively, the lower electrode may be an auxiliary conductive member, movable or stationary, conductively connected or otherwise coupled to the tunnel wall structure. In such latter case, the connection or coupling of the lower electrode to the wall structure may be effected through a second fin structure, or equivalent, as in other of the constructions hereinafter described.

The ends of the housing **11** may be open as in Fig. 1 or either or both ends may be closed by metal doors or covers to provide a complete enclosure so to minimize or eliminate radiation. Partial end closures permitting

insertion or removal of work from either end of the applicator or for continuous passage of work between the applicator electrodes may be provided. In all of these arrangements, the spaced columns **17** jointly form an inductance structure **13** constituting largely or wholly the inductance of a resonant applicator whose capacitance is largely or wholly that between the heating electrodes **15, 16.**

The resonant applicator so formed may be excited in any of the various suitable ways as more fully discussed in my aforesaid applications, to produce a high-frequency magnetic field, which encircles the row of columns **17,** and a high-frequency electric field between the heating electrodes **15, 16.**

The walls of the housing **11** in all cases provide a return path of very low resistance and of very low reactance for the high-frequency circulating current from the lower heating electrode to the top of the inductance structure **13** provided by the spaced columns **17.** In addition, the high-frequency resistance of the inductance structure **13** formed by columns **17** is very low because of their substantial peripheral area and because at least their surface is of copper, aluminum or other metal of high conductivity. The high-frequency resistance of the capacitance structure of the applicator is also very low because of the large electrode areas and the high conductivity of the aluminum or other metal of which they are usually made or surfaced. Thus the Q of the unloaded applicator is very high (Q's well in excess of 1000 are obtainable) despite its high ratio of capacitance to inductance.

Because of their high-frequency, the circulating currents (which may attain the magnitude of thousands of amperes) are practically confined to the inner surfaces of the applicator housing. Consequently all external surfaces of the housing are "cold" and serve as a radio-frequency shield for the high-frequency magnetic field encircling the row of columns **13** and for the high-frequency electric field between the heating electrodes. The radiation losses are therefore very low or negligible which minimizes radio interference and further contributes to the high Q of the unloaded applicator. Because of its high Q, the applicator is uniquely suited for efficient dielectric heating of load materials having very low power-factor, such as foam rubber, rubber hose, rubber gaskets and the like, as well as those having substantially higher power-factor such as wood.

The row of columns **17** provides an inductance structure or fin **13** which is effectively elongated transversely of the direction of current flow through it and is elongated in the direction of elongation of the heating electrode **16.** Consequently, despite the great length of the electrode the potential gradient from the ends of the electrode to its connection to the lower end of the inductance can be made suitably small by so spacing the columns that the distance from each to the adjacent end of the electrode is substantially less than a quarter-wavelength, and usually less than an eighth-wavelength at the resonant frequency of the applicator. For very long electrodes, such as those having a length which is large relative to a wavelength at such frequency, and when only two columns are in the row, this may require such excessive column spacing that the magnetic flux path instead of encircling the row of columns tends to break into two paths encircling the respective columns. This may give rise to undesirably high voltage gradient along the electrode, to difficulty in coupling of the applicator to an exciting source, or to "moding" of the applicator. When any one or more of these are encountered, they can be overcome by inclusion of additional columns in the intervening space between end columns **17, 17** or as otherwise herein later described.

The dielectric heating press applicator **10A** shown in Figs. 2 and 3 incorporates all of the features above described. It is particularly suited for production of large laminated plywood sheets, for production of large panels by edge-bonding of wooden strips and for like purposes requiring large, elongated electrodes and dissipation of many kilowatts in the dielectric load.

The press frame is in the form of an elongated metal tunnel or housing **11A.** A plurality of pressure-applying devices, exemplified by cylinders **18A,** are spaced lengthwise of the tunnel **11A** with their plungers or rams **17A** attached, without interposition of insulation, to correspondingly spaced regions of the elongated, movable electrode or platen **16A.** The plungers or rams **17A,** like the columns **17** of Fig. 1, define an inductance structure which connects the hot electrode **16A** to a wall of the housing and which is elongated in the direction of elongation of the electrode to reduce the voltage gradient along the electrode.

For applying lateral pressure to a load, as in edge-bonding of wooden strips, such as indicated at **19A** (Fig. 2) the press frame or housing **11A** may be provided with a second series of pressure-applying devices, exemplified by cylinders **A18,** having plungers or rams for applying side pressure to the work strips **19A** either directly or through an interposed filler block **43.** These cylinders as well as cylinders **18A** are supplied from associated pressure lines **20** in the usual manner.

The tunnel walls may be of relatively thin sheet metal reinforced, as suggested by frame members **47,** to provide the strength and rigidity necessary to resist deformation by the pressure. The dimensions and disposition of the reinforcing members will vary widely to suit the pressure-resisting requirements of different installations and, being external, have no effect upon the high-frequency or electrical characteristics of the resonant press applicator.

In this modification, as in that of Fig. 1 and others herein described, the bottom wall **15A** of the tunnel may itself serve as the lower or "cold" electrode. With this resonant tunnel-press applicator, all, or practically all, of the inductance is concentrated in the central vertical conductive structure **13A** afforded in this modification by those portions of spaced plungers **17A** between their electrical connection to electrode **16A** and their electrical connection to the metal wall structure of the tunnel. All, or practically all, of the capacitance of the applicator is that between the heating electrodes **15A, 16A.**

Except in the regions immediately adjacent the upper ends of plungers **17A,** the density of the circulating current in the wall structure of the applicator housing **11A** is low. Inasmuch as this structure is of high conductivity and large area, it serves as a path of very low resistance and of very low reactance for the circulating current between the lower heating electrode **15A** and the upper portions of plungers **17A** within the housing. In addition, the resistance of the inductance **13A** provided by columns **17A** and of the electrodes **16A** and **15A** is very low. As above stated, the resistance of the remainder of the current path afforded by the housing wall structure is also very low so that as in all applicators herein described, the Q is very high.

In the modified form of press applicator **10B** shown in Figs. 4 and 5, the construction is similar to that of Figs. 2 and 3 except that the vertical pressure cylinders **18B** are within housing **11B** and serve as a substantial part of the inductance formed by the row of columns **B17.** The remainder of such inductance may be essentially that afforded by the projecting portions of the rams **17B** if unshunted as in Figs. 2 and 3. Preferably, however, as in Figs. 4 and 5 each of the rams is effectively electrically shunted by strap members **49** attached to the movable heating electrode or platen **16B** and slidably or fixedly engaging the outer face of the corresponding cylinder **18B.** In this case, the upper part of each column **B17** is formed by a cylinder **18B** and the lower part thereof is formed by the circular array of straps **49.** The row of columns **B17** jointly form the elongated inductive structure **13B**

spaced along electrode 16B in the direction of its elongation.

The straps 49, preferably of springy metal of high conductivity such as beryllium-copper or some other springly metal coated with copper or other metal of high conductivity, are arranged peripherally about each cylinder 18B to afford a low resistance path for the heavy circulating currents between the upper wall of the applicator housing 11B and the hot electrode 16B. With such arrangement of straps, no appreciable amount of current flows along the plungers 17B and the straps, instead of the plungers, serve as part of the applicator inductance.

In résumé, each cylinder 18B with its associated straps serves as one of the columns of Fig. 1 and the row of cylinders with straps corresponds with the row of columns of Fig. 1 to afford a fin inductor which is elongated in the direction of elongation of the hot electrode connected thereto and held thereby in spaced relation to all walls of the applicator.

As in all applicators herein described, the resonant applicator of Figs. 4 and 5 may be, and preferably is, the tank circuit or frequency-determining circuit of a self-excited oscillator. The oscillator system 24 shown in Fig. 5 is of the preferred type more fully described and claimed in my aforesaid applications.

As shown in Fig. 5, the resonant applicator is coupled to the anode circuit of oscillator tube 25 by loop 51B which is disposed within the applicator housing or tunnel 11B and is threaded by the high-frequency magnetic flux which encircles the row of conductive columns above the hot electrode 16B. The loop 51B is adjustable, as about a vertical or horizontal axis, to vary its area normal to the lines of the magnetic field so to permit smooth variation of the mutual inductance of the circuits coupled by it. The mutual inductance of the applicator and anode circuits may, however, be varied in many other ways including those disclosed in my aforesaid application. For reasons therein fully discussed, the range of adjustment of mutual inductance is preferably entirely in the supraoptimum range. It suffices here to say that in such range, the change in magnitude of the high-frequency potential of the "hot" electrode with change in the loaded power-factor of the tunnel (as effected for example by changes in the power-factor of the work during its heating or by the varying number of load objects in conveyor-fed applicators) is materially reduced.

In the illustration of Fig. 5, the grid of tube 25 is connected to the "hot" electrode 16B by a capacitor 59 having high reactance at the operating frequency of the oscillator in those cases where high heating electrode voltage is desired. The cathode of tube 25, so far as the operating frequency of the oscillator is concerned, is grounded through by-pass condensers 61. The radio-frequency potential difference between the heating electrodes 15B, 16B may be adjusted to any desired value within a wide range by adjustment of the mutual inductance between the loop 51B and the resonant applicator. Since the grid-excitation is derived from the heating electrode 16B, such potential-difference must have a minimum value sufficient for proper grid-excitation. As the mutual inductance is varied in direction to increase such potential-difference, the capacitor 59 is varied in sense to prevent excessive grid-excitation. The radio-frequency potential of heating electrode 16B may be, and usually is, many times the grid-potential when the capacity of capacitor 59 is of magnitude much less than the effective input capacity 62 of tube 25, these two capacities forming a potential-divider, all as more fully described and claimed in my aforesaid applications.

The radio-frequency potential of the grid of oscillator tube 25 is thus always a fraction of the radio-frequency potential-difference between the applicator electrodes 15B, 16B and is inversely proportional to the ratio of the total reactance of the series-connected capacitors 59, 62 to the reactance of the effective input capacity of tube 25

represented by capacitor 62 (alone or additive to the capacity of an external shunt condenser): for example, with low power-factor loads, the radio-frequency potential of the grid may be one-twentieth of the potential of the "hot" electrode.

With the mutual inductance adjusted, as by loop 51B, to provide the desired radio-frequency voltage of electrode 16B, or equivalent, and with capacitor 59 pre-adjusted or preset for proper grid-excitation, the capacity 62 has an effective value which, as fully explained in my aforesaid applications, inherently varies with the applicator load so that the ratio of the two reactances of the capacitor voltage-divider 59, 62 varies automatically with load and in proper sense to stabilize the grid-excitation.

In the modified form of press applicator 10C shown in Fig. 6, the positions of the stationary and movable electrodes or platens are interchanged so that the cylinders 18C, or equivalent devices, for applying pressure in direction normal to the faces of the heating electrodes or platens, may be disposed below the applicator housing 11C in the press foundations. It will be understood from preceding figures that the electrodes 15C, 16C are elongated in direction normal to the plane of Fig. 6 and that each of plungers 17C of Fig. 6 is one of a row extending in the direction of elongation of the electrodes.

As in Figs. 2 to 5, the cylinders C18 for applying lateral pressure to the heating load extend externally of the applicator housing 11C from one of its side walls. In any of these modifications, the stroke of the side rams may be small and the applicator adapted for a wide range of load widths by provision of manually adjustable pressure screws 50 along the opposite side wall as shown in Fig. 6.

The stationary "hot" electrode 16C (Fig. 6) is formed by the lower wide and elongated face of an elongated beam attached along its upper end to the inner face of the upper wall of the applicator housing 11C. The movable electrode 15C of corresponding length and width is supported by or upon the upper ends of the vertical plungers or rams 17C spaced longitudinally and transversely of electrode 15C.

As in preceding modifications, the resonant load-heating circuit is predominantly formed by the inductance and capacity of the pressure structure itself. Specifically, the capacitance of the load circuit is internally of the applicator housing and is chiefly that between the opposed faces of electrodes 15C, 16C; the inductance of the load circuit is internally of the applicator housing and is predominantly that of the conductive press structure within the housing. The conductive press structure is connected to the electrode structure between the upper and lower walls of the housing. More particularly, the web or central fin 13C of the stationary internal frame member is a significant portion of the total inductance and substantially all of the remainder consists of the inductance of the portions of plungers 17C within the tunnel or of flexible straps (not shown) shunting them in manner generally corresponding to straps 49 of Figs. 4 and 5 and extending from movable electrode 15C to the bottom wall of the tunnel or to its side walls below the uppermost position of the movable electrode.

The applicator 10C of Fig. 6 may be excited by an oscillator system, such as system 24 of Fig. 5, to which the applicator may be coupled by a loop, such as indicated by 51C.

In the applicators of Figs. 2 to 6 and as shown in Fig. 3, the row of inductance columns spaced along an elongated heating electrode may include a column in addition to the end columns. When necessary to avoid difficulties hereinbefore discussed, a greater number of intervening columns may be used. Alternatively, as shown in Fig. 7, the space between the edge-forming columns 17D may be bridged by a conductive web member 117D whose main purpose is to force the high-frequency magnetic

flux to flow in a single path encircling the row of columns 17D. With the web 117D connected at its upper and lower ends respectively to the applicator wall, as in preceding figures, and to the electrode 16D, the web 117D also serves as part of the total fin inductance. Also with the web so connected, the current paths in the upper wall of the tunnel have decreased tendency to converge toward the free edges of the fin, as represented by 17D, 17D.

In the modification of Fig. 7 shown in Fig. 8, the elongated fin inductor may be fabricated from a framework covered with sheet metal, for example, aluminum, to provide the flattened columns 17E, 17E connected by an intervening web member 117E. The lower end of the fin is connected to the elongated "hot" electrode 16E in the direction of its elongation. The upper end of the fin may be connected by a series of flexible strap conductors (not shown) to the upper wall of an applicator housing.

In a particular embodiment of Fig. 8, the fin inductance was approximately 6 feet long and attached to an electrode 16E, 14.5 feet long. The applicator was used for supplying about 20 kilowatts at frequencies in about the range of 19 to 26 megacycles.

In the modification of Fig. 7 shown in Fig. 9, the elongated fin or inductance structure 13F of the applicator 10F is formed by a row of wide straps 49F, said row extending in the direction of elongation of electrode 16F and said straps being connected at their upper ends to a supporting bar or frame members 56 attached, as by welding, to the upper wall of the applicator. The lower ends of the straps may be similarly attached to the conductive members 57 of the electrode 16F. The edge-forming straps of the row may be of soft copper and the intermediate straps of beryllium-copper. Increased conductance of the end straps is also obtained by providing that they shall be of greater cross-section as obtained by using several straps face-to-face. Thus, generally as in Figs. 7 and 8, the elongated fin inductance structure comprises enlarged or columnar edge elements with intervening web structure, in this case spaced straps, which forces at least most of the magnetic field to encircle the elongated inductance structure in avoidance of the difficulties hereinbefore mentioned and which web structure also carries part of the circulating current of the resonant applicator.

Here, as in all of the other modifications, and due to the effect of the encircling high-frequency magnetic field, the high-frequency fin current strongly tends to be concentrated at the opposite free edges of the elongated fin. However, the provision of enlarged edge elements suitably reduces the current density at the free edges of the fin in avoidance of excessive localized heating which would cause increased losses and reduction in Q of the applicator.

The edge elements of the inductance structure are so shaped, or so spaced from the partially closed end walls of the applicator housing as to leave an unobstructed path about the elongated fin for its high-frequency magnetic field. This relation should exist in all of the applicators when the ends are partially or completely closed.

The inductance of the resonant applicator 10F, Fig. 9, may be adjusted by removal, addition of, or variation in spacing between straps 49F, and when it is desired to minimize voltage gradients along the elongated electrode, the straps should be disposed in substantially equally spaced relationship along the major portion of the length of the electrode. If, on the other hand, a voltage rise toward one end of the electrode is desired, the row of straps may be shifted toward the other end of the electrodes. The relative shifting of the row of straps 49F relative to electrode 16F displaces the projecting end of the inductance structure to an unsymmetrical position on the electrode 16F.

The flexibility of straps 49F permits the electrode 16F to be raised or lowered to accommodate work loads of different physical or electrical characteristics or, when the electrode is spaced from the load, to adjust the potential gradient through the work. Suitable raising and lowering mechanism is shown in my aforesaid applications: also suitable structure, not shown in Fig. 9, may be provided to hold the "hot" electrode 16F in adjusted position at desired height above the bottom wall or equivalent "cold" electrode.

For batch operation, one or both ends of the applicator 10F may be provided with doors or removable panels for insertion and withdrawal of work and for minimizing radiation from the applicator during a heating run. The ends of the applicator may be left open, at least part way up from the bottom wall for insertion, removal or passage through the tunnel of the objects or material to be heated. For the last named, a conveyor, such as indicated at 63F, may pass through the tunnel below the "hot" electrode 16F. If the conveyor is a belt of insulating material, the bottom wall of the applicator may support it and serve as the "cold" electrode; or such conveyor belt may be supported by a metal sheet or structure which may be electrically connected to the bottom or side wall structure to serve as the "cold" electrode. If the conveyor belt be metallic, it may be electrically connected to the actual bottom wall or to the side walls to serve as the "cold" electrode.

In batch operation, it usually is desirable to maintain substantial uniformity of voltage gradient throughout the heating electrode area. However, in applicators employing conveyors for continuous feeding of material, it frequently is not so important to maintain uniformity of voltage gradient along the electrode structures in the direction of conveyor travel. Thus the electrode structures may be made quite long in such direction of conveyor travel but, as will be explained more in detail hereinafter, the dimension of the electrode structure at right angles to the direction of conveyor travel usually should be maintained small relative to a wavelength at the resonant frequency of operation of the applicator.

An applicator similar in construction to Fig. 9 employing a housing having height, length and width approximately of 3, 12 and 8 feet respectively with an electrode having length and width respectively of 10 and 5 feet has been operated at frequencies of from about 12 to 16 megacycles for dielectric heating of pulp wallboard panels requiring dissipation in the load of radio-frequency power of the order of 125 kilowatts and radio-frequency potential between the heating electrodes of the order of 25,000 volts.

Among the important and singular advantages of resonant tunnel applicators such as herein described is that they have made possible, on commercial scale, the efficient uniform heating of large sheets or masses of dielectric material of very low power-factor, i. e., of 1% and less, so permitting the application of dielectric heating equipment for such purposes as heating or drying of pulp wallboard, foam rubber, pure gum rubber and the like. With conventional coil circuits or applicators, the percentage of power dissipated as circuit losses is excessively high for power factors lower than 1%. Furthermore, with conventional coil circuits or applicators, operation at higher frequencies to obtain efficient heating at voltages low enough to prevent arcing and with elongated electrodes to accommodate large sheets, panels and the like require "stubbing" which, aside from difficulties of adjustment, is cumbersome and so reduces the unloaded Q of the heating circuit or applicator that heating of low power-factor loads is impractical.

The use of microwave or very high-frequency generators using waveguides, concentric lines, and conventional resonant cavities requiring complete enclosure and axial symmetry as applicators is unsatisfactory for applications of dielectric heating involving work of large rectangular area and substantial thickness because of non-uniform

heating due to standing waves, localizing of heat at or near the surface of the work and the low-power, low-voltage limitations of such equipment. In contrast thereto, resonant applicators of the kind herein described may be designed and dimensioned in accordance with principles herein set forth so as to provide, when desired, elongated heating electrodes between which the electric field may be made substantially uniform, without "stubbing," by elongation of the associated inductance structure, and so that operation of the applicators without "stubbing" may be carried on at frequencies which are suitably high for safe, satisfactory heating despite the high electrode capacity required for dielectric loads of great length and area.

With resonant tunnel applicators, such as herein disclosed, it has been proved possible to obtain efficient uniform heating of very low power-factor loads requiring high-frequency energy at high power levels, even in excess of 100 kilowatts (in some cases 250 kilowatts). Satisfactory heating has been accomplished, with commercially available tubes, efficiently in the range of about 5 to 50 megacycles, for which frequencies the elongated fin permits long heating electrodes to be used without need for "stubbing." In contrast with the resonant load circuits heretofore used for heating at these frequencies, the resonant tunnel applicator has an exceptionally high unloaded "Q" (Q's of over 5000 are obtainable), affording unusually high available electrode voltage without attendant excessive circuit losses. Even with dielectric loads having a power-factor much less than 1%, the percentage of the high-frequency power delivered to the applicator which is utilized in useful heating of the dielectric load is of the order of 90%. By way of specific example, a resonant tunnel applicator (Fig. 9) having an unloaded "Q" of 2750, a 5 by 10 foot electrode of 370 micromicrofarad capacity and operating at a frequency of 14 megacycles with a peak electrode voltage of 32,000 volts delivered 148 kilowatts in heating a load having a power-factor of 0.9% with a power loss of only 6 kilowatts in the applicator. A generator using a conventional load circuit having an unloaded Q of 200 and delivering the same power (148 kilowatts) to an identical load would be forced to supply 83 kilowatts of wasted power to the load circuit. Although uniquely suited therefor, the resonant tunnel applicators herein disclosed are not limited to dielectric heating of very low power-factor loads; they can and have been used for heating of materials having higher power-factor which can be heated, though at lower efficiencies, by conventional applicators.

In the examples given, and as usually is desirable in resonant applicators such as herein described, the length of the fin inductance in the direction of current flow is very substantially less than a quarter-wavelength at the operating frequency, ordinarily being even less than an eighth-wavelength, and also is less than the long dimension of the electrode.

Moreover, when it is desirable to secure substantial uniformity of voltage gradient over the whole of the heating electrode area, this can be accomplished by making at least one face dimension of the electrode structure very much smaller than a wavelength at the operating frequency, and, when an elongated electrode is used, as with the conveyor, by elongating the inductive fin structure in the direction of elongation of the electrode so that the length of the fin is very close to, or equal to, the length of the electrode. Still more particularly, in the case of an elongated electrode, its projection, if any, beyond the elongated fin should be substantially less than an eighth-wavelength in the direction of elongation. When a conveyor is used, the direction of such elongation will generally be along its path of travel. Also, the amount of projection, if any, of the electrode beyond the fin inductance in the direction at right angles to the direction of elongation of the fin inductance, should be substantially less than a quarter-wavelength and usually even less than an eighth-wavelength. For satisfactory commercial operation, it usually is desirable that the half-width of the electrode, taken normal to the direction of elongation of the fin inductance, be substantially less than an eighth-wavelength.

Contrary to the experience with other types of applicators, it was found that the electrode voltage was higher the higher the electrode capacitance. Accordingly, the "hot" heating electrode may be provided, as disclosed and claimed in my aforesaid applications with supplemental capacity areas, not used for heating, to further increase the electrode voltage. Such areas, when provided, for example, by plates extending vertically upwardly from the ends of the "hot" electrode, still further effectively elongate it. By elongation of the fin inductance in the direction of such elongation of the electrode, excessive voltage rise along the supplemental areas of the electrode is avoided.

What is claimed is:

1. A resonant applicator for high-frequency electric heating of dielectric materials comprising means providing a pair of electrodes having substantial length and breadth and supported in spaced relationship to accommodate therebetween the material to be heated, and conductive structure forming part of the resonant applicator and electrically interconnecting said electrodes, which structure has substantial inductance cooperative with the capacity between said electrodes to form a resonant circuit, at least a part of which conductive structure is elongated in a direction transverse to the direction of current flow through said part of said structure and is electrically connected along one of its elongated ends to one of said electrodes, the aforesaid elongation of the conductive structure and its aforesaid connection controlling the voltage gradient along the electrode in said direction of elongation, the longer dimension of said part of said conductive structure comprising a major portion of the dimension of said one electrode in said direction of elongation.

2. A resonant applicator as in claim 1, wherein the elongated part of said conductive structure is substantially a lumped inductance and constitutes a predominant portion of the inductance of the applicator.

3. A resonant applicator as in claim 2, wherein the length of said elongated part in the direction of current flow through said part is less than one-quarter wavelength at the resonant frequency of the applicator.

4. A resonant applicator as in claim 3, wherein the said length of the elongated part is less than one-eighth wavelength at said resonant frequency.

5. A resonant applicator as in claim 1, wherein the said elongated part of the conductive structure and the said one electrode to which it is connected both are elongated in the same direction and the long dimension of said part is less than the long dimension of said one electrode but the difference between said long dimensions at each end of said elongated part is less than one-quarter wavelength at the resonant frequency of the applicator.

6. A resonant applicator as in claim 5, wherein the said difference between said long dimensions of said part and said one electrode is less than one-eighth wavelength at said frequency.

7. A resonant applicator as in claim 1, wherein the said elongated part of the said conductive structure, which part is connected along one of its elongated ends to said one electrode, has relatively enlarged portions respectively at its opposite free edges and intervening conductive structure between the edge-forming portions, a substantial part of which intervening structure is of less thickness than said edge-forming portions in a direction normal to the direction of elongation of said elongated part.

8. A resonant applicator as in claim 1, wherein the said elongated part of the said conductive structure comprises at least two conductive elements disposed in spaced apart relationship and in substantial alignment in the

direction of elongation of said part, each of said elements having substantial peripheral area and each being electrically connected at one end to said one electrode.

9. A resonant applicator as in claim 8, wherein each of said spaced elements is of generally columnar form.

10. A resonant applicator as in claim 8, wherein each of said spaced elements has associated therewith means operative to effect movement of said one electrode and to impose pressure on material between the said pair of electrodes.

11. A resonant applicator as in claim 8, wherein two such conductive elements of substantial peripheral area respectively form the opposite edges of the said elongated part of said conductive structure and said part includes at least one intervening conductive element disposed between said edge-forming elements and connected at one end to said one electrode.

12. A resonant applicator as in claim 8, wherein there is an intervening conductive element disposed between two spaced conductive elements of substantial peripheral area and the intervening element comprises a member extending between and connected at its opposite edges respectively to said two spaced elements and connected along one end to said one electrode, said member having substantially less thickness than said spaced elements in a direction normal to the direction of elongation of the said elongated part.

13. A resonant applicator as in claim 8, wherein a plurality of conductive straps are disposed in spaced relationship in a row between said two conductive elements of substantial peripheral area, each of which straps is electrically connected at one end to said one electrode.

14. A resonant applicator for high-frequency electric heating of dielectric materials comprising means providing a pair of electrodes having substantial length and breadth and supported in spaced relationship to accommodate therebetween the material to be heated, and conductive structure forming part of the resonant applicator and electrically interconnecting said electrodes, which structure has substantial inductance cooperative with the capacity between said electrodes to form a resonant circuit, at least a part of which conductive structure is elongated in a direction transverse to the direction of current flow through said part of said structure and is electrically connected along one of its elongated ends to one of said electrodes, said electrode-connected end of said elongated part of said conductive structure on the electrode to which it is connected being displaced from one edge toward the opposite edge thereof so that said end of said part is unsymmetrically located between said opposite edges for producing a voltage rise along said electrode toward said one edge of said electrode.

15. A high-frequency heating applicator comprising a pair of elongated electrodes, supported in spaced relation one from the other, conductive structure electrically connected at one end to one of said electrodes and extending away from said one electrode, said structure being elongated in a direction parallel to a face of said electrode to control the voltage gradient along said electrode in said direction, a housing enclosing said structure and the space between said electrodes, and means including wall structure of said housing electrically interconnecting the other end of said structure with the other of said electrodes.

16. A resonant applicator for high-frequency electric heating of dielectric materials comprising spaced cooperative electrodes of substantial length and breadth for receiving therebetween the material to be heated, means for minimizing the voltage gradient along said electrodes, said means comprising an electrically conductive inductance structure which is elongated in a direction transverse to the direction of current flow through said structure and which is connected along one of its elongated ends to one of said electrodes, and an electrically conductive housing enclosing said structure and the space between said electrodes, said housing having walls in spaced relation to said one electrode, the other end of said inductance structure being electrically connected to wall structure of said housing, said applicator being resonant at an operating frequency predominantly determined by the inductance of said inductance structure and the capacity between said electrodes, and the longer dimension of said inductance structure comprising a major portion of the dimension of said one electrode in said direction of elongation of said inductance structure.

17. A self-shielding high-frequency heating applicator comprising conductive walls defining an enclosure having therein elongated spaced electrodes, an inductance structure electrically connected to and extending away from wall structure of said enclosure to one of said electrodes and elongated in the direction of elongation of said one electrode to control the voltage gradient along said electrode in said direction, the other of said electrodes being similarly electrically connected to or formed by other wall structure of the enclosure, said applicator being resonant at an operating frequency predominantly determined by the inductance of said inductance structure and the capacity between said elongated electrodes, said conductive walls completing a low-reactance, low-resistance path for high-frequency current circulating between said inductance and capacity and serving as a shield for the high-frequency magnetic and electric fields thereof.

18. A high-frequency heating applicator as in claim 17, wherein the said one electrode is rectangular, the length of said inductance structure from said one electrode to the first-mentioned wall structure is less than one-eighth wavelength at the resonant frequency of said applicator, and said one electrode at each end extends beyond said inductance structure a distance which is less than one-eighth wavelength at said frequency.

19. A self-shielding high-frequency heating applicator as in claim 17 in which the dimension of said inductance structure in the direction of high-frequency current flow therethrough is less than the maximum dimension of said one electrode.

20. A resonant applicator for high-frequency electric heating of dielectric material comprising means providing a pair of electrodes having substantial length and breadth and supported in spaced relationship to accommodate therebetween the material to be heated, and conductive structure forming part of the resonant applicator and electrically interconnecting said electrodes, which structure has substantial inductance cooperative with the capacity between said electrodes to form a resonant circuit, at least a part of which conductive structure is elongated in a direction transverse to the direction of current flow through said part of said structure and is connected along one of its elongated ends to one of said electrodes, the aforesaid elongation of the conductive structure and its aforesaid connection controlling the voltage gradient along the electrode in said direction of elongation, the longer dimension of said part of said conductive structure comprising a major portion of the dimension of said one electrode in said direction of elongation and the electrode-connected end of said elongated part of said conductive structure being displaced toward an edge of the electrode.

21. A resonant applicator comprising electrodes spaced to receive work to be heated, at least one of said electrodes being elongated in one direction and having a half-width transverse dimension less than one-eighth wavelength at the resonant operating frequency of said applicator, and conductive structure forming part of said resonator and electrically interconnecting said electrodes, which structure has substantial inductance cooperative with the capacity between said electrodes in determining said resonant frequency, at least a part of which conductive structure is elongated and connected along said one of said electrodes, the aforesaid elongation of the conductive structure and its aforesaid connection to said one of said electrodes controlling the voltage gradient along the electrode in said direction of elongation, the elongated dimen-

sion of said conductive structure being at least a major portion of the dimension of said one electrode in said direction of elongation thereof.

22. A resonant applicator as in claim 21 in which conveying means transports the work through the space between said electrodes in the direction of elongation of said one of said electrodes.

23. A resonant high-frequency heating applicator comprising a housing having electrically conductive walls, a first heating electrode within said housing in spaced relation to walls thereof, a second heating electrode spaced from said first heating electrode, conveyor means for transporting work along a path extending between said spaced electrodes, and inductance structure extending from said first heating electrode toward wall structure of said housing and electrically to interconnecting said wall structure and said first heating electrode, the dimension of said inductance structure transversely of said path of the work being so related to the corresponding transverse dimension of said first heating electrode that the distance said first electrode projects outwardly from said inductance structure is substantially less than one-eighth wavelength at the resonant frequency of the applicator.

24. A resonant applicator comprising heating electrodes spaced to receive work to be heated, which electrodes in at least one direction have a dimension not less than one-eighth wavelength at the resonant frequency of the applicator, and means including inductance structure electrically interconnecting said electrodes, one of said electrodes being located at a projecting end of said inductance structure and extending outwardly therefrom, said inductance structure in said one direction being so dimensioned that the projection in said one direction of said one electrode outwardly of said inductance structure is substantially less than one-eighth wavelength to obtain between said electrodes substantial uniformity of the voltage gradient in said one direction.

25. A resonant applicator for high-frequency electric heating of dielectric material comprising means providing a pair of electrodes having substantial length and breadth and supported in spaced relationship to accommodate therebetween the material to be heated, conductive structure forming part of the resonant applicator and electrically interconnecting said electrodes, which structure has substantial inductance cooperative with the capacity between said electrodes to form a resonant circuit, and means for controlling the voltage gradient along the length of said electrodes, said means comprising at least a part of said conductive structure having an end elongated in a direction transverse to the direction of current flow through said structure and connected along the elongated end to one of said electrodes, the extent of elongation of said conductive structure along said one electrode in said direction of elongation predetermining the voltage gradient along said electrode.

26. A resonant applicator for high-frequency electric heating of dielectric materials comprising spaced cooperative electrodes of substantial length and breadth for receiving therebetween the material to be heated, means for controlling voltage gradients along said electrodes, said means comprising an electrically conductive inductance structure at least part of which is elongated in a direction transverse to the direction of current flow through said structure and which is connected along one of its elongated ends to one of said electrodes, and an electrically conductive housing enclosing said structure and the space between said electrodes, said housing having walls in spaced relation to said one electrode, the other end of said inductance structure being electrically connected to said other electrode through structure including wall structure of said housing, the longer dimension of said inductance structure comprising a major portion of the dimension of said one electrode taken in said direction of elongation of said inductance structure, said applicator being resonant at an operating frequency predominantly determined by lumped parameters including the inductance of said inductance structure and the capacity between said electrodes.

27. A resonant high-frequency heating applicator comprising an elongated housing having electrically conductive walls, a large heating electrode within said housing in spaced relation to the walls thereof and elongated in the direction of elongation of said housing, an inductance structure electrically connected at its opposite ends respectively to said electrode and to wall structure of said housing and having a cross-sectional area substantially less than the area of said electrode, and a second electrode cooperative with said first-mentioned electrode to provide a space therebetween for dielectric material to be heated, said inductance structure having a length, in the direction of current flow therethrough, substantially less than an eighth-wavelength at the resonant frequency of the applicator and having a perimeter so dimensioned and shaped that throughout said perimeter the distance therefrom to the edge of said first-mentioned electrode is substantially less than an eight-wavelength to obtain substantial uniformity of the potential-difference between said electrodes.

References Cited in the file of this patent

UNITED STATES PATENTS

2,107,387	Potter	Feb. 8, 1938
2,177,272	Zottu	Oct. 24, 1939
2,504,109	Dakin et al.	Apr. 18, 1950
2,607,850	Fox	Aug. 19, 1952
2,623,981	Anderson et al.	Dec. 30, 1952
2,629,812	Hagopian	Feb. 24, 1953
2,708,703	Cunningham et al.	May 17, 1955