

106/84

Substitute For Missing Copy

June 18, 1957

C. V. BOCCIARELLI

2,796,505

PRECISION VOLTAGE REGULATING ELEMENT

Original Filed June 2, 1950

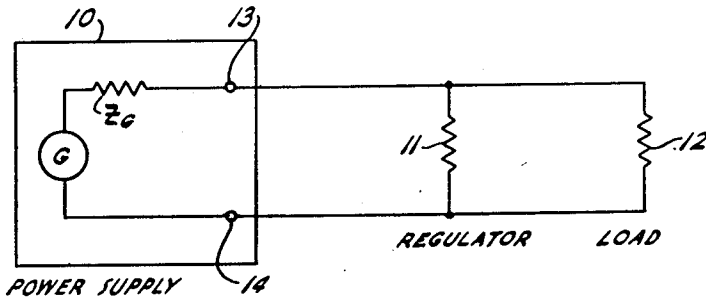


FIG. 1.

FIG. 2.

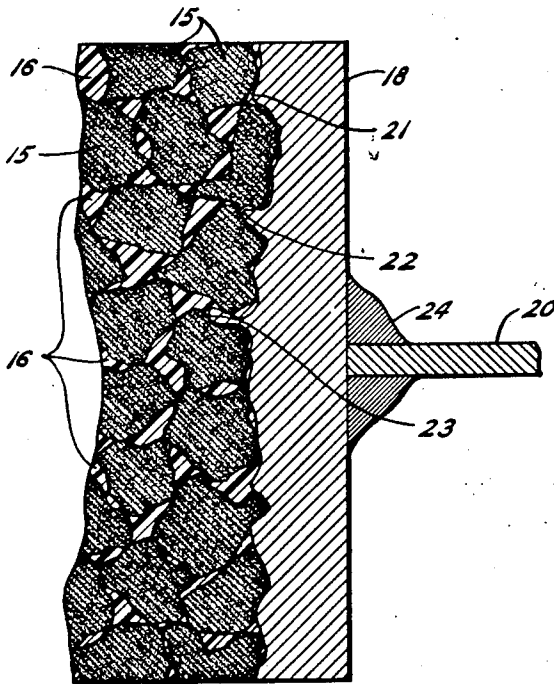
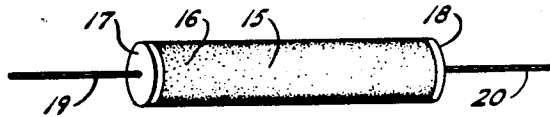
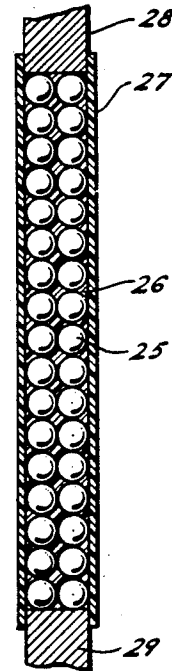


FIG. 3.

FIG. 4.



INVENTOR.
CARLO V. BOCCIARELLI
BY *Allen V. Haynes*
ATTORNEY

1

2,796,505

PRECISION VOLTAGE REGULATING ELEMENT

Carlo V. Bocciarelli, Feasterville, Pa., assignor to Philco Corporation, Philadelphia, Pa., a corporation of Pennsylvania

Continuation of abandoned application Serial No. 165,846, June 2, 1950. This application December 22, 1952, Serial No. 327,257

10 Claims. (Cl. 201-66)

The present invention relates to non-linear electrical circuit elements, the instant disclosure being a continuation of my copending application, Serial No. 165,846, now abandoned, filed June 2, 1950. More particularly, the invention relates to non-linear circuit elements which are particularly adapted for use as precision voltage regulators.

It is well known that, in electrical systems which comprise a generator or power supply and a load suitably coupled thereto, it is often essential to maintain a constant voltage across the load in the face of varying values of power supply output voltage and load current.

The relation between the load voltage under these varying conditions and the load voltage under predetermined normal conditions is termed "regulation," the regulation being said to be "good" when changing conditions produce little or no change in load voltage and "poor" when the opposite is true. It is in this sense that the above terms are used in the subsequent discussion.

When the inherent regulation of an electrical system of the type hereinbefore described is poor, recourse is often had to some type of voltage regulating device which is ordinarily connected intermediate the power supply and the load, for the purpose of improving this regulation.

Such a device may be a so-called non-linear resistor which is characterized in that, over a certain range of values of current flowing therethrough, the voltage across its terminals remains substantially constant. The manner in which such a resistor maintains the load voltage constant is described in more detail hereinafter.

Non-linear resistors have been known, in the past, whose characteristics approximated to some extent the desired condition of constant terminal voltage in response to varying current flow. Such resistors have usually consisted of silicon carbide particles fixed in a binder material and provided with a pair of terminal connections which adapted them for connection into the network to be regulated. These prior art silicon carbide resistors were satisfactory for use as lightning arrestors, overload protectors and for similar applications in which they served to protect the load from the full effects of a sudden voltage surge, while nevertheless permitting an appreciable increase in load voltage to take place. However, since these prior art resistors were entirely incapable of providing precision voltage regulation, i. e. substantially constant load voltage with increasing supply voltage, they were unsuitable for many recent applications to delicate and highly accurate apparatus.

It is, accordingly, a primary object of my invention to provide an improved non-linear electrical circuit element.

It is another object of my invention to provide an improved non-linear electrical circuit element which is particularly adapted for use as a precision voltage regulator.

It is a further object of my invention to provide a voltage regulating resistor which maintains its terminal voltage constant to any desired approximation over the operating range for which it is designed.

2

A still further object of my invention resides in the provision of a voltage regulator which is of extremely simple, sturdy and easily reproducible construction.

Briefly, my improved non-linear circuit element is comprised of a column of particles having highly conductive interiors and substantially non-conductive surface layers of metallic oxide. Substances having this general composition are commonly said to be "semi-conductive" and the term is used in this sense hereinafter. My novel circuit element further comprises an inorganic binder material substantially completely filling the interstices between particles to provide cohesion between them. The particular binder material which is incorporated in my improved non-linear circuit element constitutes the principal feature of my invention and from its selection in accordance with my inventive concept flow the principal advantages of my improved non-linear circuit element. This inventive concept demands that the binder material have, in addition to certain ancillary characteristics, a coefficient of thermal expansion which is not greater than, and which is preferably lower than that of the semi-conductive particles embedded therein. This particular relation between expansion coefficients causes increased inter-particle pressure when current flow raises the temperature of the element. This increased pressure is principally responsible for the desired non-linear characteristics of the element. Furthermore, proper choice of this binder material determines important ancillary characteristics of the construction and operation of my element.

A complete understanding of these and other objects and features of my invention will be obtained from a consideration of the following discussion in conjunction with the accompanying drawings wherein:

Figure 1 is a schematic representation of an electrical system which comprises a voltage regulator and which will be used to illustrate some of the general properties pertaining thereto;

Figure 2 is a perspective view of the over-all construction of a non-linear voltage regulating resistor embodying my invention;

Figure 3 is a greatly enlarged, fragmentary cross-sectional view of the improved voltage regulating resistor shown in Figure 2 and will be useful in explaining the detailed construction and operation thereof; and

Figure 4 is a cross-sectional view of another embodiment of a non-linear resistor constructed in accordance with my invention.

Although my novel non-linear circuit element is not limited, in its applicability, to use as a voltage regulator, it is particularly useful for this purpose. Accordingly, the detailed description of my novel non-linear circuit element is prefaced by a brief explanation of the overall characteristics of a voltage regulator.

As has been pointed out in the preceding discussion, voltage regulators are usually inserted intermediate a power supply and its load. This is schematically illustrated in Figure 1, to which more detailed reference will now be had. In this figure, there is shown a power supply 10 interconnected with a voltage regulator 11, of the non-linear resistive type here under discussion, and a load 12. Power supply 10 is schematically represented as comprising a voltage generator G in series with an internal impedance Z_g , the output voltage thereof being developed across terminals 13 and 14 and being equal to the voltage generated by generator G less the voltage drop across internal impedance Z_g due to the current flowing therethrough. Load 12 is represented schematically by an impedance connected to the output terminals of the power supply. The regulator 11 is represented as

an impedance connected in shunt with the load impedance. The operation of such a system is so well known that a brief recapitulation here will suffice. The load voltage, which it is desired to maintain constant, will be equal to the voltage across terminals 13 and 14 and thus equal to the voltage generated by generator G less the voltage drop due to current flowing through internal impedance Z_4 . The regulator, being in parallel with the load, will, of course, have the same voltage applied to its terminals. Current will flow through the load and through the regulating resistor, the ratio of the currents in the two paths being equal to the reciprocal of their respective impedances. An increase in generated voltage above its desired value, due to any cause, will result in an increase in the terminal voltage of the power supply which is applied across the load and regulator impedances 11 and 12. If the voltage regulator 11 is operating properly, its effective impedance will tend to decrease in response to the increasing voltage thereacross, thereby drawing increased current from the power supply. This in turn increases the voltage drop across the internal impedance Z_4 of the supply, thus lowering its terminal voltage until the desired condition of supply and load voltage has been re-established. Of course, the converse phenomenon takes place if the generated voltage should decrease.

On the other hand, should the load current increase due to a decrease in the value of the load impedance, this would cause increased current drain from the power supply, with attendant increased drop across its internal impedance and lowering of the terminal and load voltage. This lowering of voltage would also be sensed by the regulator which would again react by increasing its effective impedance, thereby reducing its own current drain on the power supply and compensating for the increased current drain due to the load until the terminal voltage of the supply is restored to substantially its desired value. Here again a similar reasoning process will explain the converse behavior.

Summarizing then, changes in voltage across a regulator of the type under discussion produce non-linearly related changes of current therethrough in the region in which it provides regulation. In fact, in that region, at any rate, a small increase in voltage produced a relatively large increase in current, while a small decrease in voltage produces a disproportionately large decrease in current. This characteristic is used to impart voltage regulation to an electrical system in the manner hereinbefore outlined.

A non-linear circuit element according to the invention, which operates in the manner hereinbefore described, is illustrated in Figure 2 where it may be seen to comprise a column of silicon carbide particles, collectively designated by reference numeral 15, retained in place by an inorganic binder material 16 distributed throughout the interstices between the particles 15. In its preferred form, this column is cylindrical in shape and is terminated, at each end, by contacting plates, respectively designated by reference numerals 17 and 18 and made of highly conductive material, such as silver. Connecting leads 19 and 20 may, respectively, be soldered or otherwise conductively affixed to terminal plates 17 and 18 so as to adapt the resistor for connection in the network to be regulated.

Since this macroscopic representation of my non-linear voltage-regulating resistor does not show in sufficient detail the arrangement of the minute silicon carbide particles which constitute the main body of the resistor, reference may now be had to Figure 3, which represents a greatly enlarged longitudinal section of one end of the resistor whose over-all construction is shown in Figure 2. Similar portions of the two figures have been designated by similar reference numerals. Thus, silicon carbide particles 15 are seen to occupy the major portion of the

space within the confines of the outer edges of the resistor. These silicon carbide particles are seen to be highly irregular in shape, although preferably of approximately the same size. By virtue of their irregular external configurations, these particles 15 will ordinarily be point-contiguous—that is, they will contact each other only at discrete points—e. g. where a corner of one abuts the face of another. For reasons which will appear hereinafter, binder material 16 which fills the interstices between the silicon carbide particles is chosen so as to have low electrical conductivity while simultaneously having high thermal conductivity. Although many inorganic materials are available which combine the aforesaid characteristics required of the binder material, a binder used in a successful embodiment of my voltage-regulating resistor was made using magnesium aluminum silicate, which has the chemical formula $2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$. Other materials which are suitable for use as the binder material for this embodiment of my resistor are ceramics such as quartz, beryllium aluminum silicate, lithium aluminum silicate and zinc orthosilicate.

Figure 3 further shows the detailed appearance of end contact 18 which is made, as stated, of a highly conductive material such as silver and preferably placed in the most intimate contact practicable with the silicon carbide particles in the end layer of the resistor. Such end contacts may be affixed to the resistor by any suitable process such as spraying, painting, baking or others. In most of these processes, portions of the end contact material may extend into the interstices between the silicon carbide particles of the end layer. This condition is illustrated in Figure 3 by protuberances 21, 22 and 23 which are seen extending into the body of the resistor. Such penetration into the body of the resistor is desirable rather than harmful since it increases the intimacy of contact between the resistor and its end contacts, thereby reducing contact losses which might otherwise occur at their junction. In Figure 3, terminal lead 20 is shown affixed to end contact 18 by solder fillet 24. Connection of this lead wire to the end contact may, of course, be made, alternatively, in any other equivalent conventional manner.

Although the properties of electrical and thermal conductivity of the binder material hereinbefore specified are important considerations in constructing a resistor in accordance with my invention, the property which is most critical in determining its characteristics is the coefficient of thermal expansion. Specifically, this coefficient of thermal expansion of the binder material must, under no circumstances, be greater than that of the silicon carbide particles. As will be seen from the following detailed description of the operation of my voltage-regulating resistor, the successful operation of this resistor is predicated upon the aforesaid relation between the coefficients of thermal expansion of the binder material and the silicon carbide particles.

Although the theoretical bases underlying the operation of a non-linear resistor constructed in accordance with my invention are still somewhat uncertain, nevertheless the following conclusions may be drawn from observations of its behavior. It is known that silicon carbide particles, upon exposure to air, even at room temperature, very quickly acquire a thin surface film of silicon dioxide, commonly known as quartz, as a result of oxidation of the silicon carbide by the oxygen of the air. Thus, the semi-conductive characteristics hereinbefore attributed to a non-linear circuit element according to my invention are inherent in silicon carbide particles, in that they naturally possess a conductive silicon carbide interior and a substantially non-conductive surface layer of metallic oxide, in this case silicon dioxide.

Tests have shown that conduction of current between adjacent silicon carbide particles through point contacts between their respective silicon dioxide films is responsible for the non-linear behavior exhibited by these particles.

5

I have further found that this non-linear behavior may be greatly accentuated by increasing the pressure between these point contacts, and that such increased pressure between contacts is particularly important when the resistor has to conduct relatively high currents. To maintain this pressure between point contacts of the silicon carbide particles and to increase this pressure with increasing values of current passing through the resistor, a binder material having the aforesaid thermal expansion characteristics is provided in accordance with my invention. As current flows through the resistor, following a plurality of paths through the various silicon carbide particles and the contacts therebetween, these particles are heated by the passage of current so that they expand and exert increased pressure at the contact points. By selecting the binder material in the stated manner, namely to have a coefficient of thermal expansion which is no greater than that of the silicon carbide, and which is preferably less than that of the silicon carbide, the binder material will expand less due to heating effected by current flow through the resistor than will the silicon carbide particles, with the result that the expansion of the binder material will not counteract, to any noticeable degree, the tendency of the expansion of the silicon carbide particles to increase the contact pressure therebetween.

It will be understood from the preceding discussion, that other characteristics of the binder material used in a resistor constructed in accordance with my invention, such as ease of manufacture, malleability, etc., are subordinate to the requirements relating to the coefficient of thermal expansion as well as to the electrical and thermal conductivity requirements of the material. In this connection, it is of interest to note that, by varying the coefficient of thermal expansion of the binder material relative to that of the silicon carbide particles, different voltage-current relationships may be obtained in the resistor. In general, it may be said that, if the coefficient of thermal expansion of the binder material is not much lower than that of the silicon carbide, then there will be substantially no change in voltage across the resistor, for a given increase in current flow through the resistor. In other words, a precision voltage regulator will be obtained. On the other hand, by sufficiently increasing the discrepancy between the coefficients of thermal expansion of the binder and the silicon carbide, a resistor may be made having a voltage-current characteristic such that, within a given range of current values an increase in current flow through the resistor may actually produce a decrease in its terminal voltage. A resistor having a voltage-current characteristic with this negative slope is commonly said to have negative resistance. While this negative slope of the voltage-current characteristic may in itself be desirable for some applications, it will ordinarily be preferable to restore a regulator having such a characteristic to its desired constant voltage-current characteristic by simply connecting in series therewith a resistor of sufficient magnitude to counteract the negative resistance characteristic of the regulator.

The characteristics of high thermal conductivity and low electrical conductivity of the binder material used in my novel voltage-regulating resistor are also intimately related to my inventive concept and, consequently, merit further explanation. To begin with, the binder material should have low electrical conductivity because the non-linear conduction characteristics of my resistor are predicated, to a large extent, upon having conduction between adjacent silicon carbide particles only through the point contacts therebetween. If the binder material did not have low electrical conductivity, as specified, portions of the current flowing through the resistor would bypass the intended paths established by the point contacts between silicon carbide particles and flow through the binder material instead. This, in turn would deleteriously affect the non-linear characteristic of the resistor and, with it, its voltage regulation.

The requirement that the binder material have high

6

thermal conductivity is also predicated upon the desired limitation of current flow to the paths established by the point contacts between adjacent silicon carbide particles. Since the current is confined to these narrow paths, high current densities will result in the point contacts and this, in turn, may produce excessive heating of the contacts with resultant breakdown of the resistor. To enable a given size of resistor, having a limited number of point contacts, to carry a larger amount of current, it is necessary that the heat generated by current flow through the point contacts be removed from the resistor as efficiently as possible. This is, of course, accomplished most readily by the presence of a binder material having high thermal conductivity. In appropriate cases, the current carrying capacity of the resistor may be additionally enhanced by the provision of suitable cooling fins or even forced ventilation about the outside of the resistor.

The aforementioned heating of the particle contacts also compels the use of an inorganic material for the binder, since organic materials would carbonize at the temperatures which are encountered in operation and would lose their cohesive properties.

It has further been found that, in non-linear circuit elements of the sort above-described, the voltage across the element is proportional to the number of particles per unit length of the element. Accordingly, when such elements are to be used as voltage regulators, this relationship of direct proportionality should exist between the number of particles per unit length of the element and the magnitude of the voltage to be regulated. Thus, the larger the voltage to be regulated, the greater should be the number of particles per unit length. Conversely it may be said that the size of the particles should be inversely proportional to the magnitude of the voltage to be regulated. It would then appear that decreasing the particle size would result in increasing this voltage, provided the column length is held constant, and this is borne out by experiment.

The current through the voltage regulator, on the other hand, is roughly proportional to the number of particles per unit of cross-sectional area. Thus the conductivity of the regulator decreases approximately with the square of the diameter of the particles. From the above, it is clear that it is a simple matter to design a voltage regulator in accordance with my invention for any specific application.

Finally, mention should be made of a feature which has not been previously treated because it is inherent in the operation of my novel type of voltage regulator as described in connection with Figure 3. Reference is had to the fact that some current continuously flows through the regulator regardless of whether the load is open circuited or has some finite value of impedance. This current, sometimes termed "standby" current, may constitute a substantial fraction of the total current drawn from the power supply, and it inevitably increases, sometimes even prohibitively, the current capacity requirements of such a supply. It is, therefore, highly desirable to maintain this standby current at its minimum permissible value for any given value of desired regulated voltage. Fortunately, this is inherently achieved in the preferred embodiment of my invention. Specifically, it is the appropriate application of pressure to the point contacts between adjacent silicon carbide particles, as hereinbefore described, which, simultaneously with its other effects, results in keeping the value of the standby current at a virtual minimum for any particular set of operating conditions.

While, as has been seen, certain materials such as silicon carbide naturally exhibit the semi-conductive characteristics required of the particles which form the main body of my non-linear circuit element, there are other substances which may be given those characteristics by suitable preparation.

One form which such an artificially prepared semi-conductive material may take is illustrated in Figure 4 of the drawings where there is shown an alternative em-

bodiment of my non-linear circuit element. This embodiment is seen to comprise a column of small conductive spherical particles 25, such as ball bearings, whose outer surfaces have previously been oxidized to form a metallic oxide surface layer surrounding each particle and turning it into a semi-conductive particle in accordance with the foregoing definition. The spherical shape of the particles insures that the desired point-contiguity between adjacent particles of the column is attained. The interstices between the oxidized steel particles are filled with a binder material which conforms, in every respect, to the criteria hereinbefore set up for binder materials suitable for use in my novel non-linear circuit element. That is, the binder material 26 has sufficiently low electrical conductivity to confine the path of currents flowing through the column to the point contacts between adjoining steel particles, it has high heat transmissivity so as to provide good dissipation of the heat generated by such current flow, and, most importantly, its coefficient of thermal expansion is not greater than that of the steel particles. A particular binder which was successfully used in this embodiment and which conformed to the above-mentioned requirements was sodium silicate. In addition, a cylindrical glass envelope 27 may be provided for the column of steel particles in order to give it greater mechanical rigidity. Contact is made with each end layer of steel particles by means of plungers 28 and 29, respectively. Operation of the embodiment of the invention shown in Figure 4 is fully in accordance with the non-linear conduction principles hereinbefore set forth, the degree of its non-linear behavior depending again upon the differential between the coefficients of thermal expansion of the oxidized steel particles and of the binder material.

It is to be noted that, while sodium silicate is suitable as a binder for oxidized steel particles because it has a coefficient of thermal expansion which is lower than that of steel, it is not suitable for use with silicon carbide particles because its coefficient of thermal expansion exceeds that of silicon carbide. For this reason, sodium silicate is not included in the foregoing list of representative binder materials for silicon carbide.

Although the invention has been described with reference to two specific embodiments, its principles have been set forth in sufficient detail to enable those skilled in the art to design and construct other useful apparatus embodying these principles and adapt it for other particular applications.

I claim:

1. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous silicon carbide particles, an electrically insulating, thermally conductive, cohesive binder of inorganic material substantially completely filling the interstices between said particles, said binder having a coefficient of thermal expansion not exceeding the coefficient of thermal expansion of silicon carbide, and a pair of electrical contacts located at spaced points on the boundary surface of said aggregate, each of said contacts being in electrical contact with at least some of said particles.

2. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous semi-conductive particles, each of said particles comprising a conductive core and a non-conductive boundary surface, an electrically insulating, thermally conductive, cohesive binder of inorganic material substantially completely filling the interstices between said particles, said binder having a coefficient of thermal expansion not exceeding the coefficient of thermal expansion of said particles, and a pair of electrical contacts located at spaced points on the boundary surface of said aggregate, each of said contacts being in electrical contact with at least some of said particles.

3. A non-linear electrical circuit element according to claim 2 and further characterized in that the particles comprising said aggregate comprise conductive particles whose boundary surfaces are coated with a metallic oxide.

4. A non-linear electrical circuit element according to claim 2 and further characterized in that said binder is a ceramic.

5. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous semi-conductive particles, each of said particles comprising a conductive core and a non-conductive boundary surface, an electrically insulating, thermally conductive, cohesive binder of inorganic material substantially completely filling the interstices between said particles, said binder having a coefficient of thermal expansion less than the coefficient of thermal expansion of said particles, and a pair of electrical contacts located at spaced points on the boundary surface of said aggregate, each of said contacts being in electrical contact with at least some of said particles.

6. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous semi-conductive particles, each of said particles comprising a conductive core and a non-conductive boundary surface and having a coefficient of thermal expansion not less than that of silicon carbide, and a thermally conductive, cohesive binder substantially completely filling the interstices between said particles, said binder being selected from the group of materials comprising quartz, magnesium aluminum silicate, beryllium aluminum silicate, lithium aluminum silicate and zinc orthosilicate.

7. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous silicon carbide particles, and a thermally conductive, cohesive binder substantially completely filling the interstices between said particles, said binder being selected from the group of materials comprising quartz, magnesium aluminum silicate, beryllium aluminum silicate, lithium aluminum silicate and zinc orthosilicate.

8. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous steel particles, each of said steel particles having an oxidized boundary surface, a binder of sodium silicate substantially completely filling the interstices between said particles, and a pair of electrical contacts located at spaced points on the boundary surface of said aggregate, each of said contacts being in electrical contact with at least some of said particles.

9. A non-linear electrical circuit element suitable for use as a precision voltage regulator comprising an aggregate of point-contiguous silicon carbide particles, and an electrically insulating, thermally conductive, cohesive binder of inorganic material substantially completely filling the interstices between said particles, said binder having a coefficient of thermal expansion less than the coefficient of thermal expansion of silicon carbide.

10. A material suitable for use in a precision voltage regulator, said material comprising an aggregate of point-contiguous semi-conductive particles, each of said particles comprising a conductive core and a non-conductive boundary surface, and an electrically insulating, thermally conductive, cohesive binder of inorganic material substantially completely filling the interstices between said particles, said binder having a coefficient of thermal expansion less than the coefficient of thermal expansion of said particles.

References Cited in the file of this patent

UNITED STATES PATENTS

2,253,360 Berkey Aug. 19, 1941
2,529,144 Evans et al. Nov. 7, 1950

FOREIGN PATENTS

75 539,728 Great Britain Sept. 22, 1941