Properties and Uses of Thermistors—Thermally Sensitive Resistors*

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A new circuit element and control device, the thermistor or thermally sensitive resistor, is made of solid semiconducting materials whose resistance decreases about four per cent per centigrade degree. The thermistor presents interesting opportunities to the designer and engineer in many fields of technology for accomplishing tasks more simply, economically and better than with available devices. Part I discusses the conduction mechanism in semiconductors and the criteria for usefulness of circuit elements made from them. The fundamental physical properties of thermistors, their construction, their static and dynamic characteristics and general principles of operation are treated.

Part II of this paper deals with the applications of thermistors. These include: sensitive thermometers and temperature control elements, simple temperature compensators, ultrahigh frequency power meters, automatic gain controls for transmission systems such as the Types K2 and L1 carrier telephone systems, voltage regulators, speech volume limiters, compressors and expandors, gas pressure gauges and flowmeters, meters for thermal conductivity determination of liquids, and contactless time delay devices. Thermistors with short time constants have been used as sensitive bolometers and show promise as simple compact audio-frequency oscillators, modulators and amplifiers.

PART I—PROPERTIES OF THERMISTORS

Introduction

THERMISTORS, or *therm*ally sensitive res*istors*, are devices made of solids whose electrical resistance varies rapidly with temperature. Even though they are only about 15 years old they have already found important and large scale uses in the telephone plant and in military equipments. Some of these uses are as time delay devices, protective devices, voltage regulators, regulators in carrier systems, speech volume limiters, test equipment for ultra-high-frequency power, and detecting elements for very small radiant power. In all these applications thermistors were chosen because they are simple, small, rugged, have a long life, and require little maintenance. Because of these and other desirable properties, thermistors promise to become new circuit elements which will be used extensively in the fields of communications, radio, electrical and thermal instrumentation, research in physics, chemistry and biology, and war technology. Specific types of uses which will be discussed in the second part of this paper include: 1) simple, sensitive and fast responding thermometers,

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temperature compensators and temperature control devices; 2) special switching devices without moving contacts; 3) regulators or volume limiters; 4) pressure gauges, flowmeters, and simple meters for measuring thermal conductivity in liquids and gases; 5) time delay and surge suppressors; 6) special oscillators, modulators and amplifiers for relatively low frequencies. Before these uses are discussed in detail it is desirable to present the physical principles which determine the properties of thermistors.

The question naturally arises "why have devices of this kind come into use only recently?" The answer is that thermistors are made of semiconductors and that the resistance of these can vary by factors up to a thousand or a million with surprisingly small amounts of certain impurities, with heat treatment, methods of making contact and with the treatment during life or use. Consequently the potential application of semiconductors was discouraged by experiences such as the following: two or more units made by what appeared to be the same process would show large variations in their properties. Even the same unit might change its resistance by factors of two to ten by exposure to moderate temperatures or to the passage of current. Before semiconductors could seriously be considered in industrial applications, it was necessary to devote a large amount of research and development effort to a study of the nature of the conductivity in semiconductors, and of the effect of impurities and heat treatment on this conductivity, and to methods of making reliable and permanent contacts to semiconductors. Even though Faraday discovered that the resistance of silver sulphide changed rapidly with temperature, and even though thousands of other semiconductors have been found to have large negative temperature coefficients of resistance, it has taken about a century of effort in physics and chemistry to give the engineering profession this new tool which may have an influence similar to that of the vacuum tube and may replace vacuum tubes in many instances.

If thermistors are to be generally useful in industry:

1) it should be possible to reproduce units having the same characteristics;
2) it should be possible to maintain constant characteristics during use; the contact should be permanent and the unit should be chemically inert;
3) the units should be mechanically rugged;
4) the technique should be such that the material can be formed into various shapes and sizes;
5) it should be possible to cover a wide range of resistance, temperature coefficient and power dissipation.

Thermistors might be made by any method by which a semiconductor could be shaped to definite dimensions and contacts applied. These methods include: 1) melting the semiconductor, cooling and solidifying, cutting to size and shape; 2) evaporation; 3) heating compressed powders of semiconductors to a temperature at which they sinter into a strong compact mass and firing on metal powder contacts. While all three processes have been used, the third method has been found to be most generally useful for mass production. This method is similar to that employed in ceramics or in powder metallurgy. At the sintering temperatures the powders recrystallize and the dimensions shrink by controlled amounts. The powder process makes it possible to mix two or more semiconducting oxides in varying proportions and obtain a homogeneous and uniform solid. It is thus possible to cover a considerable range of specific resistance and temperature coefficient of resistance with the same system of oxides. By means of the powder process it is possible to make thermistors of a great variety of shapes and sizes to cover a large range of resistances and power handling capacities.

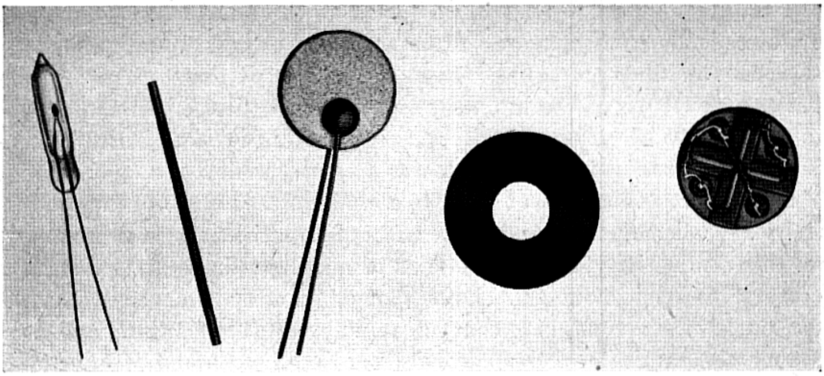

Fig. 1.—Thermistors made in the form of a bead, rod, disc, washer and flakes.

Figure 1 is a photograph of thermistors made in the form of beads, rods, discs, washers and flakes. Beads are made by stringing two platinum alloy wires parallel to each other with a spacing of five to ten times the wire diameter. A mass of a slurry of mixed oxides is applied to the wires. Surface tension draws this mass into the form of a bead. From 10 to 20 such beads are evenly spaced along the wires. The beads are allowed to dry and are heated slightly until they have sufficient strength so that the string can be handled. They then are passed through the sintering furnace. The oxides shrink onto the platinum alloy wires and make an intimate and permanent electrical contact. The wires then are cut to separate the individual beads.

The diameters of the beads range from 0.015 to 0.15 centimeters with wire diameters ranging from 0.0025 to 0.015 centimeters.

Rod thermistors are made by mixing the oxides with an organic binder and solvent, extruding the mixture through a die, drying, cutting to length, heating to drive out the binder, and sintering at a high temperature. Contacts are applied by coating the ends with silver, gold, or platinum paste as used in the ceramic art, and heating or curing the paste at a suitable temperature. The diameter of the rods can ordinarily be varied from 0.080 to 0.64 centimeter. The length can vary from 0.15 to 5 centimeters.

Discs and washers are made in a similar way by pressing the bonded powders in a die. Possible disc diameters are 0.15 to 3 or 5 centimeters; thicknesses from 0.080 to 0.64 centimeter.

Flakes are made by mixing the oxides with a suitable binder and solvent to a creamy consistency, spreading a film on a smooth glass surface, allowing the film to dry, removing the film, cutting it into flakes of the desired size and shape, and firing the flakes at the sintering temperatures on smooth ceramic surfaces. Contacts are applied as described above. Possible dimensions are: thickness, 0.001 to 0.004 centimeter; length, 0.1 to 1.0 centimeter; width, 0.02 to 0.1 centimeter.

In any of these forms lead wires can be attached to the contacts by soldering or by firing heavy metal pastes. The dimensional limits given above are those which have been found to be readily attainable.

In the design of a thermistor for a specific application, the following characteristics should be considered: 1) Mechanical dimensions including those of the supports. 2) The material from which it is made and its properties. These include the specific resistance and how it varies with temperature, the specific heat, density, and expansion coefficient. 3) The dissipation constant and power sensitivity. The dissipation constant is the watts that are dissipated in the thermistor divided by its temperature rise in centigrade degrees above its surroundings. The power sensitivity is the watts dissipated to reduce the resistance by one per cent. These constants are determined by the area and nature of the surface, the surrounding medium, and the thermal conductivity of the supports. 4) The heat capacity which is determined by specific heat, dimensions, and density. 5) The time constant. This determines how rapidly the thermistor will heat or cool. If a thermistor is heated above its surroundings and then allowed to cool, its temperature will decrease rapidly at first and then more slowly until it finally reaches ambient temperature. The time constant is the time required for the temperature to fall 63 per cent of the way toward ambient temperature. The time constant in seconds is equal to the heat capacity in joules per centigrade degree divided by the dissipation constant in watts per centigrade degree. 6) The maximum permissible power that can be dissipated consistent with good stability and long life, for continuous operation, and for surges. This can be computed from the dissipation constant and the maximum permissible temperature rise. This and the resistance-temperature relation determine the maximum decrease in resistance.

Properties of Semiconductors

As most thermistors are made of semiconductors it is important to discuss the properties of the latter. A semiconductor may be defined as a substance

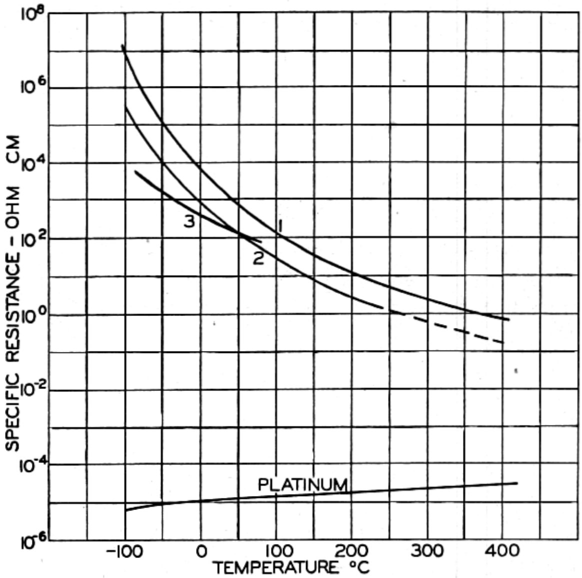

Fig. 2.—Logarithm of specific resistance versus temperature for three thermistor materials as compared with platinum.

whose electrical conductivity at or near room temperature is much less than that of typical metals but much greater than that of typical insulators. While no sharp boundaries exist between these classes of conductors, one might say that semiconductors have specific resistances at room temperature from 0.1 to 10^9 ohm centimeters. Semiconductors usually have high negative temperature coefficients of resistance. As the temperature is increased from 0°C. to 300°C., the resistance may decrease by a factor of a thousand. Over this same temperature range the resistance of a typical metal such as platinum will increase by a factor of two. Figure 2 shows how the logarithm of the specific resistance, ρ, varies with temperature, T, in degrees centigrade for three typical semiconductors and for platinum.

Curves 1 and 2 are for Materials No. 1 and No. 2 which have been extensively used to date. Material No. 1 is composed of manganese and nickel oxides. Material No. 2 is composed of oxides of manganese, nickel and cobalt. The dashed part of Curve 2 covers a region in which the resistance-temperature relation is not known as accurately as it is at lower temperatures. Curve 3 is an experimental curve for a mixture of iron and zinc

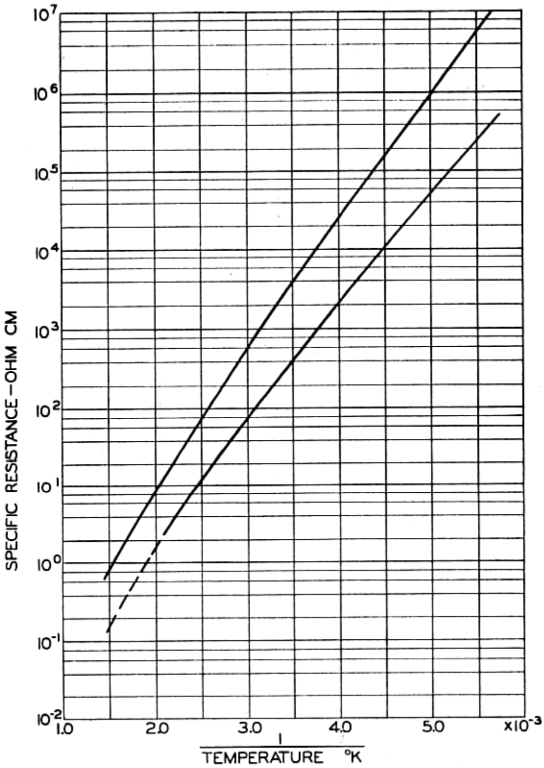

Fig. 3.—Logarithm of the specific resistance of two thermistor materials as a function of inverse absolute temperature. See equation (1).

oxides in the proportions to form zinc ferrite. From Fig. 2 it is obvious that neither the resistance R nor log R varies linearly with T.

Figure 3 shows plots of log ρ versus $1/T$ for Materials No. 1 and No. 2. These do form approximate straight lines. Hence

$$\rho = \rho_\infty \epsilon^{B/T} \text{ or } \rho = \rho_0 \epsilon^{(B/T)-(B/T_0)} \quad (1)$$

where T = temperature in degrees Kelvin; $\rho_\infty = \rho$ when $T = \infty$ or $1/T = 0$; $\rho_0 = \rho$ when $T = T_0$; ϵ = Naperian base = 2.718 and B is a constant equal to 2.303 times the slope of the straight lines in Fig. 3. The dimensions of B

are Kelvin degrees or centigrade degrees; it plays the same role in equation (1) as does the work function in Richardson's equation for thermionic emission. For Material No. 1, $B = 3920C°$. This corresponds to an electron energy equivalent to 3920/11600 or 0.34 volt.

While the curves in Fig. 3 are approximately straight, a more careful investigation shows that the slope increases linearly as the temperature increases. From this it follows that a more precise expression for ρ is:

$$\rho = AT^{-c}\,\epsilon^{D/T} \qquad \text{or}$$

$$\log \rho = \log A - c \log T + D/2.303T \qquad (2)$$

The constant c is a small positive or negative number or zero. For Material No. 1, $\log A = 5.563$, $c = 2.73$ and $D = 3100$. For a particular form of Material No. 2 $\log A = 11.514$, $c = 4.83$ and $D = 2064$.

If we define temperature coefficient of resistance, α, by the equation

$$\alpha = (1/R)\,(dR/dT) \qquad (3)$$

it follows from equation (1) that

$$\alpha = -B/T^2. \qquad (4)$$

For Material No. 1 and $T = 300°K$, $\alpha = -3920/90{,}000 = -0.044$. For platinum, $\alpha = +0.0037$ or roughly ten times smaller than for semiconductors and of the opposite sign. From equation (2) it follows that

$$\alpha = -(D/T^2) - (c/T). \qquad (5)$$

From equation (3) it follows that

$$\alpha = (1/2.303)\,(d \log R/dT). \qquad (6)$$

For a discussion of the nature of the conductivity in semiconductors, it is simpler and more convenient to consider the conductivity, σ, rather than the resistivity, ρ.

$$\sigma = 1/\rho \qquad \text{and} \qquad \log \sigma = -\log \rho. \qquad (7)$$

The characteristics of semiconductors are brought out more clearly if the conductivity or its logarithm are plotted as a function of $1/T$ over a wide temperature range. Figure 4 is such a plot for a number of silicon samples containing increasing amounts of impurity. At high temperatures all the samples have nearly the same conductivity. This is called the intrinsic conductivity since it seems to be an intrinsic property of silicon. At low temperatures the conductivity of different samples varies by large factors. In this region silicon is said to be an impurity semiconductor. For extremely pure silicon only intrinsic conductivity is present and the resistivity obeys equation (1). As the concentration of a particular impurity increases, the conductivity increases and the impurity conductivity predominates to higher temperatures. Some impurities are much more effective in increasing the conductivity than others. One hundred parts per million of some impurities may increase the conductivity of pure silicon at room temperature by a factor of 10^7. Other impurities may be present

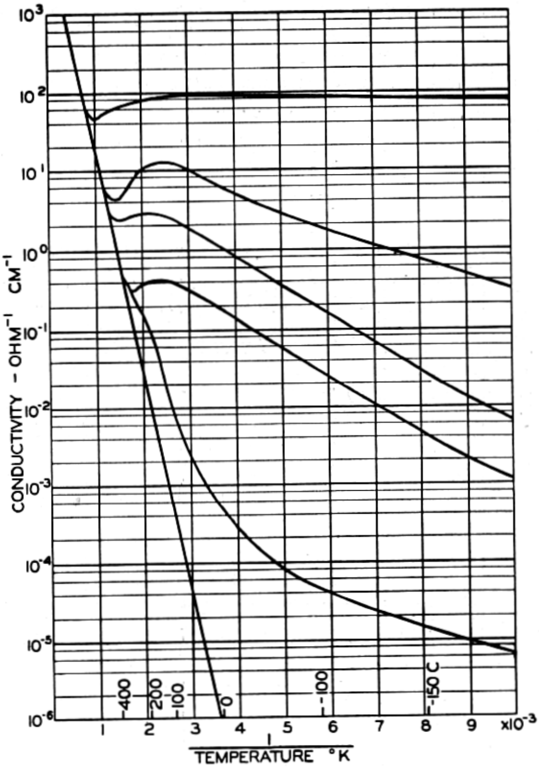

Fig. 4.—Logarithm of the conductivity of various specimens of silicon as a function of inverse absolute temperature. The conductivity increases with the amount of impurity.

in 10,000 parts per million and have a small effect on the conductivity. Two samples may contain the same concentration of an impurity and still differ greatly in their low temperature conductivity; if the impurity is in solid solution, i.e., atomically dispersed, the effect is great; if the impurity is segregated in atomically large particles, the effect is small. Since heat treatments affect the dispersion of impurities in solids, the conductivity of semiconductors may frequently be altered radically by heat treatment. Some other semiconductors are not greatly affected by heat treatment.

The impurity need not even be a foreign element; in the case of oxides or sulphides, it can be an excess or a deficiency of oxygen or sulphur from the exact stoichiometric relation. This excess or deficiency can be brought about by heat treatment. Figure 5 shows how the conductivity depends on temperature for a number of samples of cuprous oxide, Cu_2O, heat

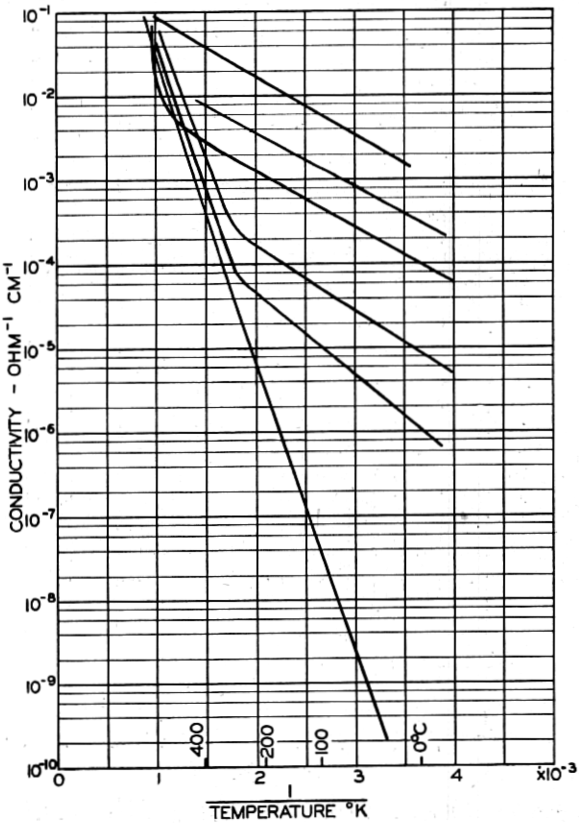

Fig. 5.—Logarithm of the conductivity of various specimens of cuprous oxide as a function of inverse absolute temperature. The conductivity increases with the amount of excess oxygen above the stoichiometric value in Cu_2O. Data from reference 1.

treated in such a way as to result in varying amounts of excess oxygen from zero to about one per cent.[1] The greater the amount of excess oxygen the greater is the conductivity in the low temperature range. At high temperatures, all samples have about the same conductivity.

Semiconductors can be classified on the basis of the carriers of the current into ionic, electronic, and mixed conductors. Chlorides such as NaCl and some sulphides are ionic semiconductors; other sulphides and a few oxides such as uranium oxide are mixed semiconductors; electronic semiconductors include most oxides such as Mn_2O_3, Fe_2O_3, NiO, carbides such as silicon carbide, and elements such as boron, silicon, germanium and tellurium. In ionic and mixed conductors, ions are transported through the solid. This changes the density of carriers in various regions, and thus changes the conductivity. Because this is undesirable, they are rarely used in making thermistors, and hence we will concentrate our interest on electronic semiconductors.

The theoretical and experimental physicists have established that there are two types of electronic semiconductors which can be called *N* and *P* type, depending upon whether the carriers are negative electrons or are equivalent to positive "holes" in the filled energy band. In *N* type, the

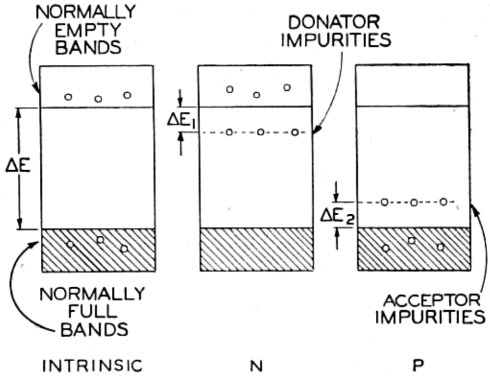

Fig. 6.—Schematic energy level diagrams illustrating intrinsic, *N* and *P* types of semiconductors.

carriers are deflected by a magnetic field as negatively charged particles would be and conversely for *P* type. The direction of deflections is ascertained by measurement of the sign of the Hall effect. The direction of the thermoelectric effect also fixes the sign of the carriers. By determining the resistivity, Hall coefficient and thermoelectric power of a particular specimen at a particular temperature it is possible to determine the density of carriers, whether they are negative or positive, and their mobility or mean free path. The mobility is the mean drift velocity in a field of one volt per centimeter.

The existence of these classifications is explained by the theoretical physicist[2,3,4] in terms of the diagrams in Fig. 6. In an intrinsic semiconductor at low temperatures the valence electrons completely fill all the allowable energy states. According to the exclusion principle only one electron can occupy a particular energy state in any system. In semiconductors and insulators there exists a region of energy values, just above the allowed band, which are not allowed. The height of this unallowed band is expressed in equivalent electron volts, ΔE. Above this unallowed band there exists an allowed band; but at low temperatures there are no electrons in this band. When a field is applied across such a semiconductor, no electron can be accelerated, because if it were accelerated its energy would be increased to an energy state which is either filled or unallowed. As the temperature is raised some electrons acquire sufficient energy to be raised across the unallowed band into the upper allowed band. These electrons can be accelerated into a slightly higher energy state by the applied field and thus can carry current. For every electron that is put into an "activated" state there is left behind a "hole" in the normally filled band. Other electrons having slightly lower energies can be accelerated into these holes by the applied field. The physicist has shown that these holes act toward the applied field as if they were particles having a charge equal to that of an electron but of opposite sign and a mass equal to or somewhat larger than the electronic mass. In an intrinsic semiconductor about half the conductivity is due to electrons and half due to holes.

The quantity ΔE is related to B in equation (1) by:

$$2B = (\Delta E)\, e/k \qquad (8)$$

in which B is in centigrade degrees, ΔE is in volts, e is the electronic charge in coulombs, k is Boltzmann's constant in joules per centigrade degree. The value of e/k is 11,600 so that

$$\Delta E = B/5800. \qquad (8a)$$

The difference between metals, semiconductors, and insulators results from the value of ΔE. For metals ΔE is zero or very small. For semiconductors ΔE is greater than about 0.1 volt but less than about 1.5 volts. For insulators ΔE is greater than about 1.5 volts.

Some impurities with positive valencies which may be present in the semiconductor may have energy states such that ΔE_1 volts equivalent energy can raise the valence electron of the impurity atom into the allowed conduction band. See Figure 6. The electron now can take part in conduction; the donator impurity is a positive ion which is usually bound to a particular location and can take no part in the conductivity. These are excess or N type conductors. The conductivity depends on the density of donotors, ΔE_1, and T.

Similarly some other impurity with negative valencies may have an energy state ΔE_2 volts above the top of the filled band. At room temperature or higher, an electron in the filled band may be raised in energy and accepted by the impurity which then becomes a negative ion and usually is immobile. However, the resulting hole can take part in the conductivity.

In all cases represented in Fig. 6 an electron occupying a higher energy level than a positive ion or a hole has a certain probability that in any short interval of time it will drop into a lower energy state. However, during this same time interval there will be electrons which will be raised to a higher energy level by thermal agitation. When the number of electrons per second which are being elevated is equal to the number which are descending in energy, equilibrium prevails. The conductivity, σ, is then

$$\sigma = N e v_1 + P e v_2 \tag{9}$$

where N and P are the concentrations of electrons and holes respectively, e is the charge on the electron, v_1 and v_2 are the mobilities of electrons and holes respectively.

The above picture explains the following experimental facts which otherwise are difficult to interpret. 1) N type oxides, such as ZnO, when heated in a neutral or slightly reducing atmosphere become good conductors, presumably because they contain excess zinc which can donate electrons. If they then are heated in atmospheres which are increasingly more oxidizing their conductivity decreases until eventually they are intrinsic semiconductors or insulators. 2) P type oxides, such as NiO, when heat treated in strongly oxidizing atmospheres are good conductors. Very likely they contain oxygen in excess of the stoichiometric relation and this oxygen accepts additional electrons. When these are heated in less oxidizing or neutral atmospheres they become poorer conductors, semiconductors, or insulators. 3) When a P type oxide is sintered with another P type oxide, the conductivity increases. Similarly for two N type oxides. But when a P type is added to an N type the conductivity decreases. 4) If a metal forms several oxides the one in which the metal exerts its highest valence is N type, while the one in which it exerts its lowest valence will be P type.[5]

For several reasons it is desirable to survey the whole field of semiconductors for resistivity and temperature coefficient. One way in which this might be done is to draw a line in Figure 3 for each specimen. Before long such a figure would consist of such a maze of intersecting lines that it would be difficult to single out and follow any one line. The information can be condensed by plotting log ρ_0 versus B in equation (1) for each specimen.[6] The most important characteristics of a specimen thus are represented by a single point and many more specimens can be surveyed in a single diagram. Figure 7 shows such a plot for a large number of semiconductors investigated at these Laboratories or reported in the literature. Values for ρ_0 and B are given for T = 25 degrees centigrade. The points form a sort of milky way. Semiconductors having a high ρ_0 are likely to have a high value of B and vice versa. If a series of semiconductors have points in Fig. 7 which fall on a straight line with a slope of $1/2.3T_0$, they have a common intercept in Fig. 3 for $(1/T) = 0$.

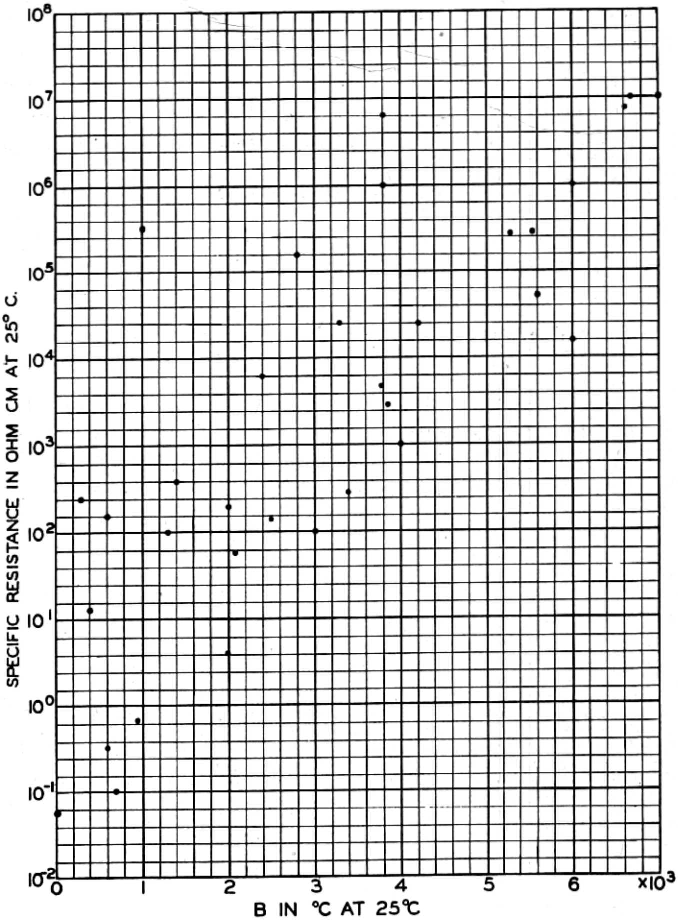

Fig. 7.—Logarithm of the resistivity of various semiconducting materials as a function of B in equation (1). The quantity, B, is proportional to the temperature coefficient of resistance as given in equation (4).

Physical Properties of Thermistors

One of the most interesting and useful properties of a thermistor is the way in which the voltage, V, across it changes as the current, I, through it increases. Figure 8 shows this relationship for a 0.061 centimeter diameter bead of Material No. 1 suspended in air. Each time the current is changed, sufficient time is allowed for the voltage to attain a new steady value. Hence this curve is called the steady state curve. For sufficiently small currents, the power dissipated is too small to heat the thermistor appreciably, and Ohm's law is followed. However, as the current assumes larger values, the power dissipated increases, the temperature rises above ambient temperature, the resistance decreases, and hence the voltage is less than it would have been had the resistance remained constant. At some current, I_m, the voltage attains a maximum or peak value, V_m. Beyond

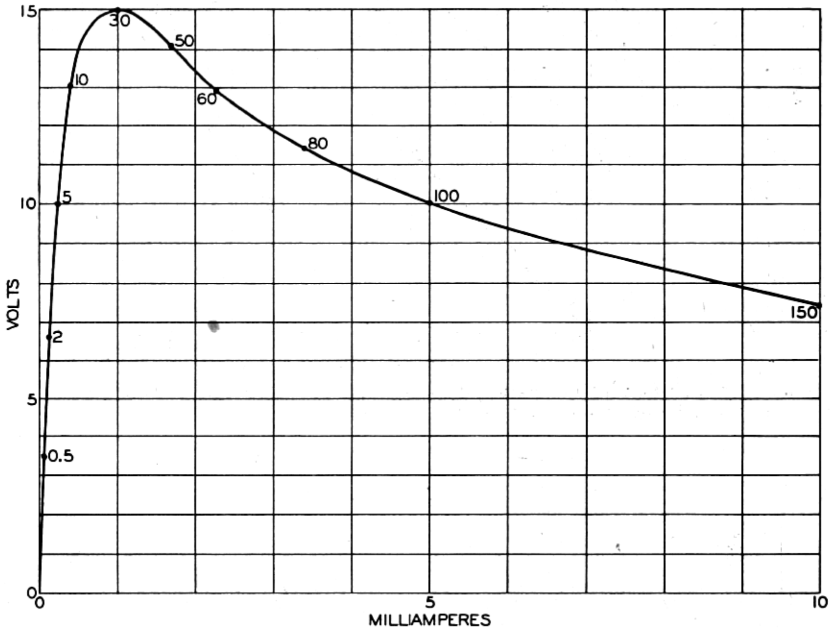

Fig. 8.—Static voltage-current curve for a typical thermistor. The numbers on the curve are the centigrade degrees rise in temperature above ambient.

this point as the current increases the voltage decreases and the thermistor is said to have a negative resistance whose value is dV/dI. The numbers on the curve give the rise in temperature above ambient temperature in centigrade degrees.

Because currents and voltages for different thermistors cover such a large range of values it has been found convenient to plot log V versus log I. Figure 9 shows such a plot for the same data as in Fig. 8. For various points on the curve, the temperature rise above ambient temperature is given. In a log plot, a line with a slope of 45 degrees represents a constant resistance; a line with a slope of -45 degrees represents constant power.

For a particular thermistor, the position of the log V versus log I plot is shifted, as shown in Fig. 10, by changing the dissipation constant C. This

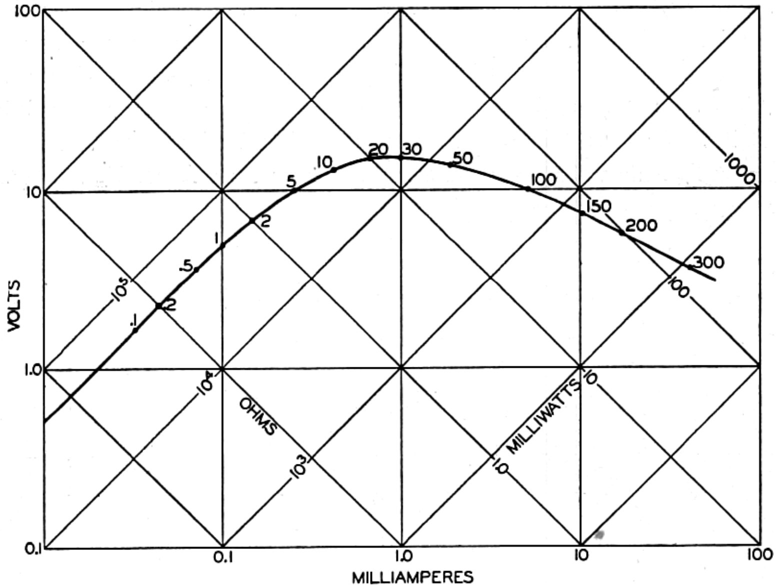

Fig. 9.—Logarithmic plot of static voltage-current curve for the same data as in Figure 8. The diagonal lines give the values of resistance and power.

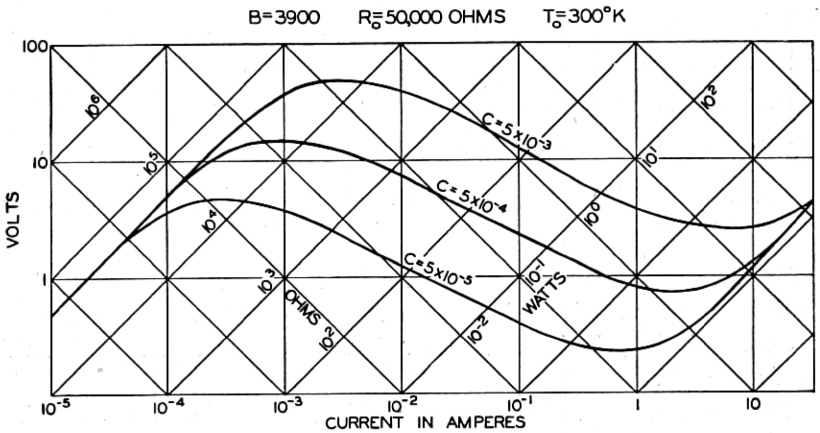

Fig. 10.—Logarithmic plots of voltage versus current for three values of the dissipation constant C. These curves are calculated for the constants given in the upper part of the figure.

can be done by changing the air pressure surrounding the bead, changing the medium, or changing the degree of thermal coupling between the thermistor and its surroundings. The value of C for a particular thermistor in given surroundings can readily be determined from the V versus I curve in either Figs. 8 or 9. For each point, V/I is the resistance while V times I is W, the watts dissipated. The resistance data are converted to temperature from R versus T given by equation (2). A plot is then made of W versus T. For thermistors in which most of the heat is conducted away, W will increase linearly with T, so that C is constant. For thermistors suspended by fine wires in a vacuum, W will increase more rapidly than proportional to T, and C will increase with T. For thermistors of ordinary size and shape, in still air, $C/\text{Area} = 1$ to 40 milliwatts per centigrade degree per square centimeter depending upon the size and shape factor.

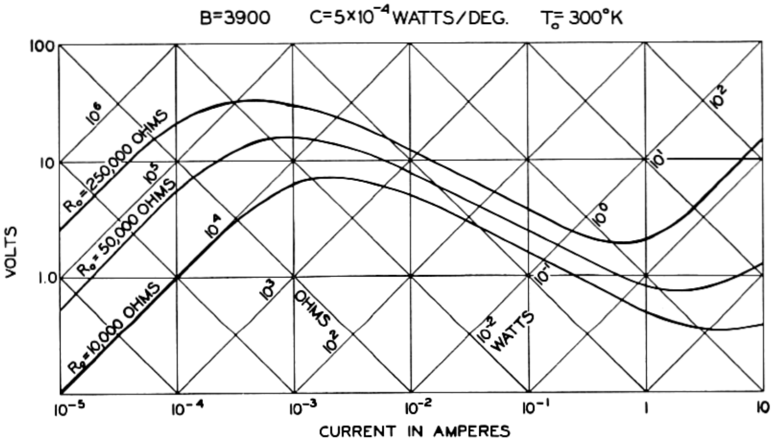

Fig. 11.—Logarithmic plots of voltage versus current for three values of the resistance, R_0, at ambient temperature. These curves are calculated for the constants given in the upper part of the figure.

The user of a thermistor may want to know how many watts can be dissipated before the resistance decreases by one per cent. This may be called the power sensitivity. It is equal to $C/(\alpha \times 100)$, and amounts to about one to ten milliwatts per square centimeter of area in still air. Both C and the power sensitivity increase with air velocity. The dependence of C on gas pressure and velocity is the basis of the use of thermistors as manometers and as anemometers or flowmeters. Note that in Fig. 10 one curve can be superposed on any other by a shift along a constant resistance line.

Figure 11 shows a family of log V versus log I curves for various values on R_0 while B, C, and T_0 are kept constant. This can be brought about by changing the length, width and thickness to vary R_0 while the surface area is kept constant. If the resistance had been changed by changing the ambient temperature, T_0, the resulting curves would not appear very different from those shown. Note that one curve can be superposed on any other curve by a shift along a constant power line.

Figure 12 shows a family of log V versus log I curves for eight different values of B while C, R_0, and T_0 are kept constant. In contrast to the curves in Figs. 10 and 11 in which any curve could be obtained from any other curve by a shift along an appropriate axis, the curves in Fig. 12 are each distinct. For each curve there exists a limiting ohmic resistance for

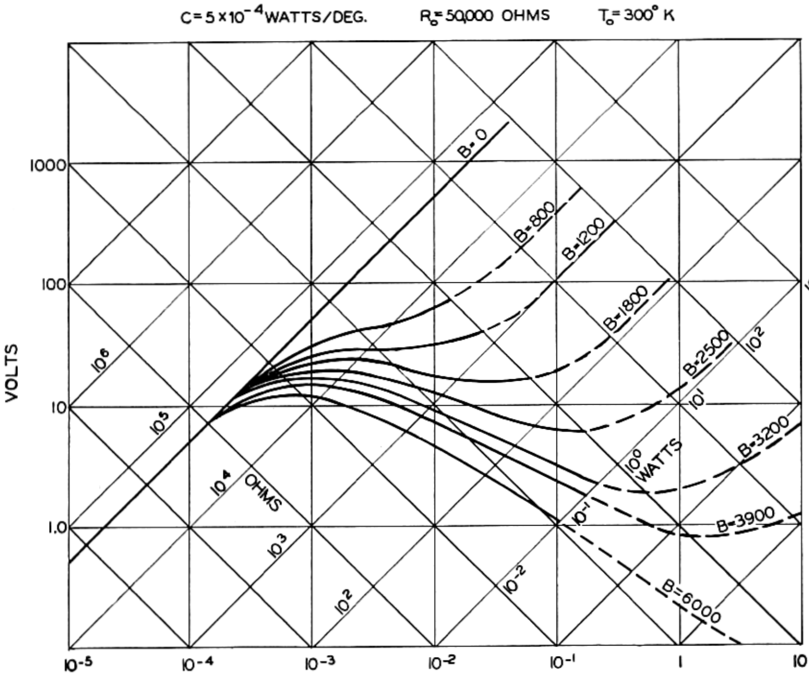

Fig. 12.—Logarithmic plots of voltage versus current for eight values of B in equation (1). These curves are calculated for the constants given in the upper part of the figure.

currents and another for high currents. For $B = 0$ these two are identical. As B becomes larger the log of the ratio of the two limiting resistances increases proportional to B. Note also that for $B > 1200\ K°$, the curves have a maximum. For large B values this maximum occurs at low powers and hence at low values of $T - T_0$. This follows since $W = C(T - T_0)$. As B decreases, V_m occurs at increasingly higher powers or temperatures. For $B < 1200\ K°$, no maximum exists.

The curves in Figs. 10 to 12 have been drawn for the ideal case in which the resistance in series with the thermistor is zero and in which no temperature limitations have been considered. In any actual case there is always some unavoidable small resistance, such as that of the leads, in series with the thermistor and hence the parts of the curves corresponding to low resistances may not be observable. Also at high powers the temperature may attain such values that something in the thermistor structure will go to pieces thus limiting the range of observation. These unobservable ranges have been indicated by dashed lines in Fig. 12. The exact location of the dashed portions will of course depend on how a completed thermistor is constructed. In setting these limits consideration is given to temperature limitations beyond which aging effects might become too great.

The curves in Figs. 9 to 12 have been computed on the basis of the following equations:

$$R = R_0\, \epsilon^{(B/T)-(B/T_0)} = V/I \tag{10}$$

$$W = C(T - T_0) = VI \tag{11}$$

For these curves the constants R_0, T_0, B, and C are specified. The values of temperature, T_m, power, W_m, resistance, R_m, voltage, V_m, and current, I_m, that prevail at the maximum in the voltage current curve are given by the following equations in which T_m is chosen as the independent parameter. By differentiating equations (10) and (11) with respect to I, putting the derivatives equal to zero, one obtains

$$T_m^2 = B(T_m - T_0) \tag{12}$$

whose solution is

$$T_m = (B/2)\,(1 \mp \sqrt{1 - 4T_0/B}). \tag{13}$$

The minus sign pertains to the maximum in Figs. 10 to 12 while the plus sign pertains to the minimum. Note that T_m depends only on B and T_0, and not on R, R_0 or C. From equations (4), (10) and (11) it follows that:

$$-\,\alpha_m\,(T_m - T_0) = 1 \tag{14}$$

$$W_m = C(T_m - T_0) \tag{15}$$

$$R_m = R_0\,\epsilon^{-T_m/T_0} \doteq R_0\,\epsilon^{-1}[1 - (T_m - T_0)/T_0 + (1/2)\{(T_m - T_0)/T_0\}^2 - \cdots] \tag{16}$$

$$V_m = [C\,R_0\,(T_m - T_0)\,(\epsilon^{-T_m/T_0})]^{1/2} = \{\{C\,R_0\,(T_m - T_0)\,\epsilon^{-1}\,[1 - (T_m - T_0)/T_0 + (1/2)\,\{(T_m - T_0)/T_0\}^2 - \cdots]\}\}^{1/2} \tag{17}$$

$$I_m = [(C/R_0)\,(T_m - T_0)\,\epsilon^{T_m/T_0}]^{1/2} = \{\{(C/R_0)\,(T_m - T_0)\,\epsilon[1 + (T_m - T_0)/T_0 + (1/2)\{(T_m - T_0)/T_0\}^2 + \cdots]\}\}^{1/2} \tag{18}$$

Thus far the presentation has been limited to steady state conditions, in which the power supplied to the thermistor is equal to the power dissipated by it, and the temperature remains constant. In many cases, however, it is important to consider transient conditions when the temperature, and any quantities which are functions of temperature, vary with time. A simple case which will illustrate the concepts and constants involved in such problems is as follows: A massive thermistor is heated to about 150 to 200 degrees centigrade by operating it well beyond the peak of its voltage

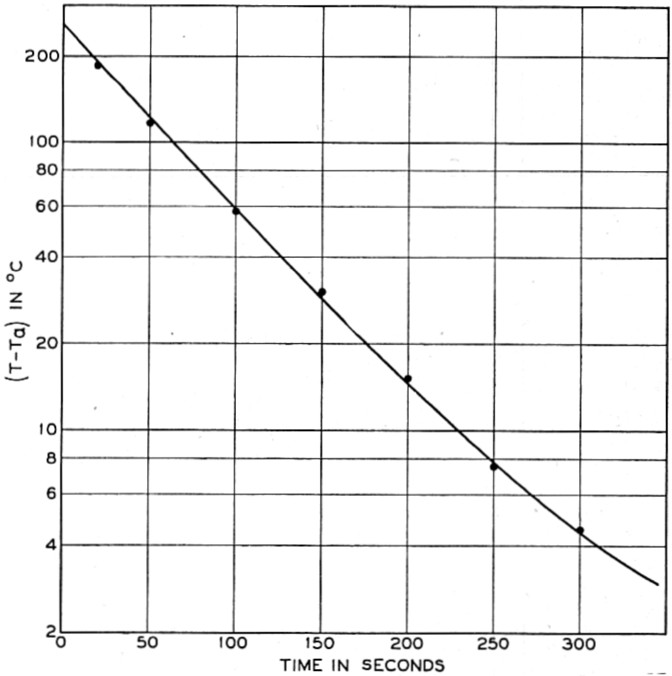

Fig. 13.—Cooling characteristic of a massive thermistor: log of temperature above ambient versus time.

current characteristic. At time $t = 0$, the circuit is switched over to a constant current having a value so small that I^2R is always negligibly small. The voltage across the thermistor is then followed as a function of time. From this, the resistance and temperature are computed. Figure 13 shows a plot of log $(T - T_a)$ versus t for a rod thermistor of Material No. 1 about 1.2 centimeters long, 0.30 centimeter in diameter and weighing 0.380 gram. In any time interval Δt, there are $C(T - T_a)\, \Delta t$ joules being dissipated. As a result the temperature will decrease by ΔT given by

$$-H\Delta T = C(T - T_a)\, \Delta t \text{ or } (T - T_a) = -(H/C)\, (\Delta T/\Delta t) \quad (19)$$

where H = heat capacity in joules per centigrade degree. The solution of this equation is

$$(T - T_a) = (T_0 - T_a)\,\epsilon^{-t/\tau} \tag{20}$$

in which $T_0 = T$ when $t = 0$ and

$$\tau = H/C, \tag{21}$$

where τ is in seconds. It is commonly called the time constant. From equation (20) it follows that a plot of log $(T - T_a)$ versus t should yield a straight line whose slope $= -1/2.303\tau$. If H and C vary slightly with temperature then τ will vary slightly with T and t. The line will not be perfectly straight but its slope at any t or $(T - T_a)$ will yield the appro-

TABLE I.—VALUES OF C, τ, H AS FUNCTIONS OF T FOR A THERMISTOR OF MATERIAL NO. 1 ABOUT 1.2 CENTIMETERS LONG, 0.30 CENTIMETERS IN DIAMETER AND WEIGHING 0.380 GRAM

T_a = 24 degrees centigrade

T Degrees Centigrade	C Watts per C. degree	τ Seconds	H Joules per C. degree	h Joules per gram per C. degree
44	0.0037	76	0.28	0.75
64	0.0037	74	0.27	0.72
84	0.0038	71	0.27	0.71
104	0.0037	69	0.26	0.68
124	0.0038	68	0.26	0.67
144	0.0038	67	0.26	0.67
164	0.0039	67	0.26	0.69
184	0.0041	66	0.27	0.71
204	0.0042	66	0.28	0.73

priate τ or H/C for that T. As previously described, C can be determined from a plot of watts dissipated versus T. For this thermistor this curve became steeper at the higher temperatures so that C increased for higher temperatures. Table I summarizes the values of C, τ, and H at various T for the unit in air.

When a thermistor is heated by passing current through it, conditions are somewhat more involved since the I^2R power will be a function of time. At any time in the heating cycle the heat power liberated will be equal to the watts dissipated or $C(T - T_a)$ plus watts required to raise the temperature or HdT/dt. The heat power liberated will depend on the circuit conditions. In a circuit like that shown in the upper corner of Figure 14, the current varies with time as shown by the six curves for six values of the battery voltage E. If a relay in the circuit operates when the current reaches a definite value, a considerable range of time delays can be achieved.

This family of curves will be modified by changes in ambient temperature and where rather precise time delays are required, the ambient temperature must be controlled or compensated.

Since thermistors cover a wide range in size, shape, and heat conductivity of surrounding media, large variations in H, C, and τ can be produced. The time constant can be varied from about one millisecond to about ten minutes or a millionfold.

One very important property of a thermistor is its aging characteristic or how constant the resistance at a given temperature stays with use. To obtain a stable thermistor it is necessary to: 1) select only semiconductors which are pure electronic conductors; 2) select those which do not change chemically when exposed to the atmosphere at elevated temperatures;

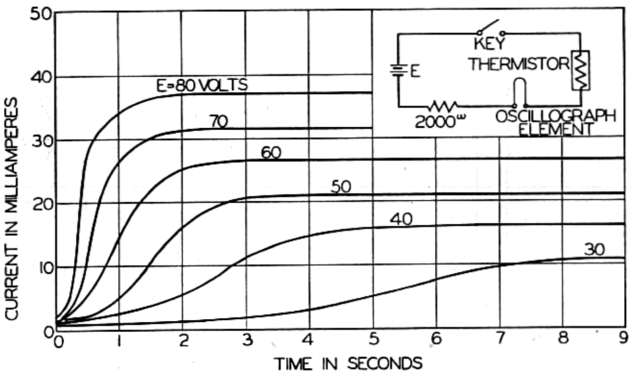

Fig. 14.—Current versus time curves for six values of the battery voltage in the circuit shown in the insert.

3) select one which is not sensitive to impurities likely to be encountered in manufacture or in use; 4) treat it so that the degree of dispersion of the critical impurities is in equilibrium or else that the approach to equilibrium is very slow at operating temperatures; 5) make a contact which is intimate, sticks tenaciously, has an expansion coefficient compatible with the semiconductor, and is durable in the atmospheres to which it will be exposed; 6) in some cases, enclose the thermistor in a thin coat of glass or material impervious to gases and liquids, the coat having a suitable expansion coefficient; 7) preage the unit for several days or weeks at a temperature somewhat higher than that to which it will be subjected. By taking these precautions remarkably good stabilities can be attained.

Figure 15 shows aging data taken on three-quarter inch diameter discs of Materials No. 1 and No. 2 with silver contacts and soldered leads. These discs were measured soon after production, were aged in an oven at 105 degrees centigrade and were periodically tested at 24 degrees centigrade.

The percentage change in resistance over its initial value is plotted versus the logarithm of the time in the aging oven. It is to be noted that most of the aging takes place in the first day or week. If these discs were preaged for a week or a month and the subsequent change in resistance referred to the resistance after preaging, they would age only about 0.2 per cent in one year. In a thermistor thermometer, this change in resistance would correspond to a temperature change of 0.05 centigrade degree. Thermistors mounted in an evacuated tube or coated with a thin layer of glass age even less than those shown in the figure. For some applications such high stability is not essential and it is not necessary to give the thermistors special treatment.

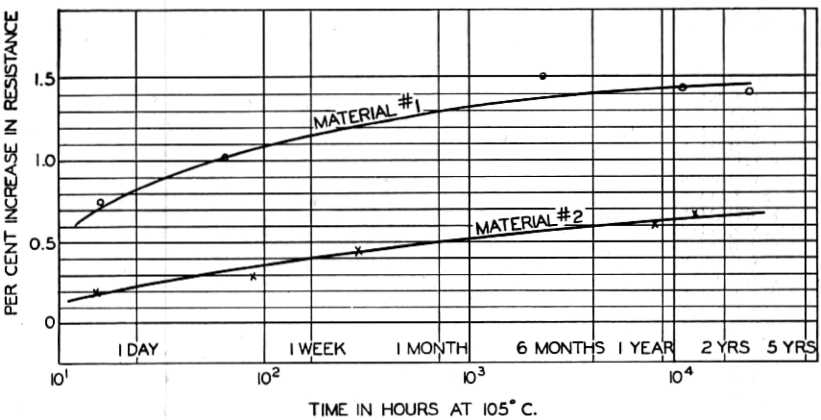

Fig. 15.—Aging characteristics of thermistors made of Materials No. 1 and No. 2 aged in an oven at 105°C. Per cent increase in resistance over its initial value versus time on a logarithmic scale.

Thermistors have been used at higher temperatures with satisfactory aging characteristics. Extruded rods of Material No. 1 have been tested for stability by treating them for two months at a temperature of 300 degrees centigrade. Typical units aged from 0.5 to 1.5 per cent of their initial resistance. Similar thermistors have been exposed alternately to temperatures of 300 degrees centigrade and −75 degrees centigrade for a total of 700 temperature cycles, each lasting one-half hour. The resistance of typical units changed by less than one per cent.

In some applications of thermistors very small changes in temperature produce small changes in potential across the thermistor which then are amplified in high gain amplifiers. If at the same time the resistance is fluctuating randomly by as little as one part in a million, the potential across the thermistor will also fluctuate by a magnitude which will be directly proportional to the current. This fluctuating potential is called noise and since it depends on the current it is called current noise. In order to obtain the best signal to noise ratio, it is necessary that the current noise at operating conditions be less than Johnson or thermal noise.[7,8] To make noise-free units it is necessary to pay particular attention to the raw materials, the degree of sintering, the grain size, the method of making contact and any steps in the process which might result in minute surface cracks or fissures.

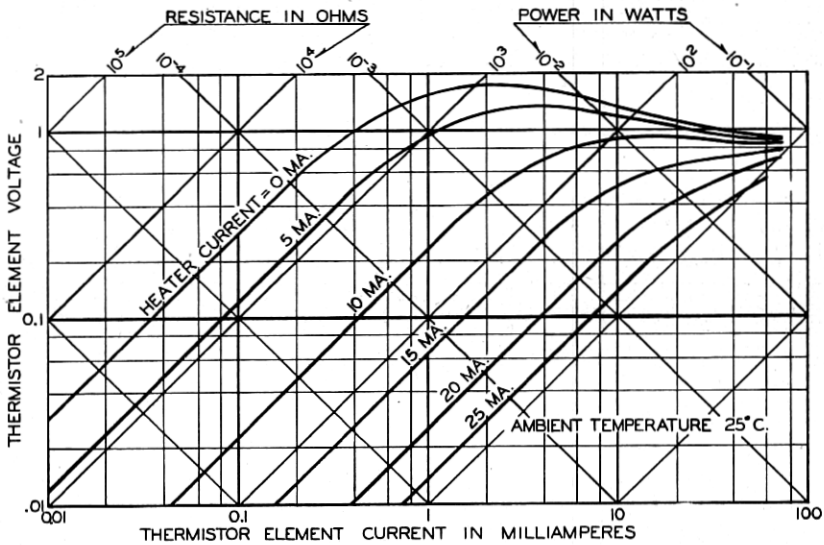

Fig. 16.—Logarithmic plots of voltage versus current for six values of heater curren in an indirectly heated thermistor. Resistance and power scales are given on the diag onal lines.

All the thermistors discussed thus far were either directly heated by the current passing through them or by changes in ambient temperature. In indirectly heated thermistors, the temperature and resistance of the thermistor are controlled primarily by the power fed into a heater thermally coupled to it. One such form might consist of a 0.038 centimeter diameter bead of Material No. 2 embedded in a small cylinder of glass about 0.38 centimeter long and 0.076 centimeter in diameter. A small nichrome heater coil having a resistance of 100 ohms is wound on the glass and is fused onto it with more glass. Figure 16 shows a plot of log V versus log I for the bead element at various currents through the heater. In this way the bead resistance can be changed from 3000 ohms to about 10 ohms. Indirectly heated thermistors are ordinarily used where the controlled circuit must be isolated electrically from the actuating circuit, and where the power from the latter must be fed into a constant resistance heater.

PART II—USES OF THERMISTORS

The thermistor, or thermally sensitive resistor, has probably excited more interest as a major electric circuit element than any other except the vacuum tube in the last decade. Its extreme versatility, small size and ruggedness were responsible for its introduction in great numbers into communications circuits within five years after its first application in this field. The next five year period spanned the war, and saw thermistors widely used in additional important applications. The more important of these uses ranged from time delays and temperature controls to feed-back amplifier automatic gain controls, speech volume limiters and superhigh frequency power meters. It is surprising that such versatility can result from a temperature dependent resistance characteristic alone. However, this effect produces a very useful nonlinear volt-ampere relationship. This, together with the ability to produce the sensitive element in a wide variety of shapes and sizes results in applications in diverse fields. The variables of design are many and interrelated, including electrical, thermal and mechanical dimensions.

The more important uses of thermistors as indication, control and circuit elements will be discussed, grouping the uses as they fall under the primary characteristics: resistance-temperature, volt-ampere, and current-time or dynamic relations.

Resistance-Temperature Relations

It has been pointed out in Part I that the temperature coefficient of electrical resistance of thermistors is negative and several times that of the ordinary metals at room temperature. In Thermistor Material No. 1, which is commonly used, the coefficient at 25 degrees centigrade is -4.4 per cent per centigrade degree, or over ten times that of copper, which is $+0.39$ per cent per centigrade degree at the same temperature. A circuit element made of this thermistor material has a resistance at zero degrees centigrade which is nine times the resistance of the same element at 50 degrees centigrade. For comparison, the resistance of a copper wire at 50 degrees centigrade is 1.21 times its value at zero degrees centigrade.

The resistance-temperature characteristics of thermistors suggest their use as sensitive thermometers, as temperature actuated controls and as compensators for the effects of varying ambient temperature on other elements in electric circuits.

Thermometry

The application of thermistors to temperature measurement follows the usual principles of resistance thermometry. However, the large value of temperature coefficient of thermistors permits a new order of sensitivity to be obtained. This and the small size, simplicity and ruggedness of thermistors adapt them to a wide variety of temperature measuring applications. When designed for this service, thermistor thermometers have long-time stability which is good for temperatures up to 300 degrees centigrade and excellent for more moderate temperatures. A well aged thermistor used in precision temperature measurements was found to be within 0.01 centigrade degree of its calibration after two months use at various temperatures up to 100 degrees centigrade. As development proceeds, the stability of thermistor thermometers may be expected to approach that of precision platinum thermometers. Conventional bridge or other resistance measuring circuits are commonly employed with thermistors. As with any resistance thermometer, consideration must be given to keeping the measuring current sufficiently small so that it produces no appreciable heating in order that the

TABLE II.—TEMPERATURE-RESISTANCE CHARACTERISTIC OF A TYPICAL THERMISTOR THERMOMETER

Temperature	Resistance	Temperature Coefficients	
		B	α
−25°C.	580,000 ohms	3780 C. deg.	−6.1%/ C. deg.
0	145,000	3850	−5.2
25	46,000	3920	−4.4
50	16,400	3980	−3.8
75	6,700	4050	−3.3
100	3,200	4120	−3.0
150	830	4260	−2.4
200	305	4410	−2.0
275	100	4600	−1.5

Dissipation constant in still air, approx. . . . . 4 milliwatts/C. deg.
Thermal time constant in still air, approx. . . . . 70 seconds
Dimensions of thermistor, diameter approx. 0.11 inch
length approx. . . . . 0.54 inch

thermistor resistance shall be dependent upon the ambient temperature alone.

Since thermistors are readily designed for higher resistance values than metallic resistance thermometers or thermocouples, lead resistances are not ordinarily bothersome. Hence the temperature sensitive element can be located remotely from its associated measuring circuit. This permits great flexibility in application, such as for instance wire line transmission of temperature indications to control points.

Table II gives the characteristics of a typical thermistor thermometer. The dissipation constant is the ratio of the power input in watts dissipated in the thermistor to the resultant temperature rise in centigrade degrees. The time constant is the time required for the temperature of the thermistor to change 63 per cent of the difference between its initial value and that of the surroundings. As a sensitive thermometer, this thermistor with a simple Wheatstone bridge and a galvanometer whose sensitivity is 2 ×

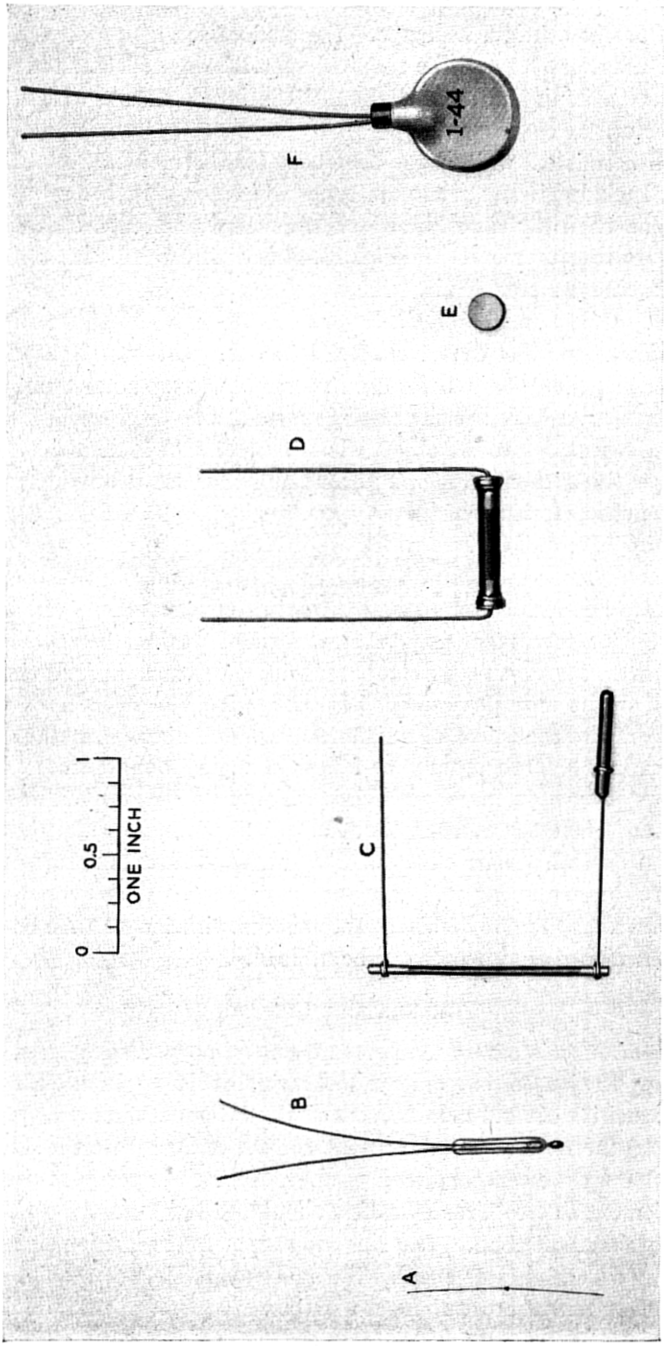

Fig. 17.—Some forms of thermistors which have been used as resistance thermometers.

10^{-10} amperes per millimeter per meter will readily indicate a temperature change of 0.0005 centigrade degree. For comparison a precision platinum resistance thermometer and the required special bridge such as the Mueller will indicate a minimum change of 0.003 centigrade degree with a similar galvanometer.

Several thermistors which have been used for thermometry are shown in Fig. 17. Included in the group are types which are suited to such diverse applications as intravenous blood thermometry and supercharger rotor temperature measurement. In Fig. 17, A is a tiny bead with a response time of less than a second in air. B is a probe type unit for use in air streams or liquids. C is a meteorological thermometer used in automatic radio transmission of weather data from free balloons. D is a rod shaped unit. E is a disc or pellet, adapted for use in a metal thermometer bulb. Discs like the one shown have been sweated to metal plates to give a low thermal impedance connection to the object whose temperature is to be determined. F is a large disc with an enveloping paint finish for use in humid surroundings. The characteristics of these types are given in Table III.

The temperature of objects which are inaccessible, in motion, or too hot for contact thermometry can be determined by permitting radiation from the object to be focussed on a suitable thermistor by means of an elliptical mirror. Such a thermistor may take the form of a thin flake attached to a solid support. Its advantages compared with the thermopile and resistance bolometer are its more favorable resistance value, its ruggedness, and its high temperature coefficient of resistance. It can be made small to reduce its heat capacity so as rapidly to follow changing temperatures. Flake thermistors have been made with time constants from one millisecond to one second. Since the amount of radiant power falling on the thermistor may be quite small, sensitive meters or vacuum tube amplifiers are required to measure the small changes in the flake resistance. Where rapidly varying temperatures are not involved, thermistors with longer time constants and simpler circuit equipments can be utilized.

Temperature Control

The use of thermistors for temperature control purposes is related closely to their application as temperature measuring devices. In the ideal temperature sensitive control element, sensitivity to temperature change should be high and the resistance value at the control temperature should be the proper value for the control circuit used. Also the temperature rise of the control element due to circuit heating should be low, and the stability of calibration should be good. The size and shape of the sensitive element are dictated by several factors such as the space available, the required speed of response to temperature changes and the amount of power which must be dissipated in the element by the control circuit to permit the arrangement to operate relays, motors or valves.

Because of their high temperature sensitivity, thermistors have shown much promise as control elements. Their adaptability and their stability at relatively high temperatures led, for instance, to an aircraft engine control system using a rod-shaped thermistor as the control element.[9] The

TABLE III.—THERMISTOR THERMOMETERS

	A	B	C	D	E	F
Nominal Resistance, Ohms at						
−25°C.	—	—	87,500	610,000	—	13,000
0.	5,000	325,000	37,500	153,000	490	3,200
25.	2,000	100,000	18,000	48,500	175	950
50.	900	33,000	9,700	17,300	71	340
75.	460	13,000	5,500	7,100	32	145
100.	250	6,000	3,700	3,400	16	70
150.	95	1,600	—	870	4.5	—
200.	—	500	—	—	1.6	—
300.	—	80	—	—	—	—
Temp. Coeff. α, %/C. deg. at 25°C.	−3.4	−4.4	−2.8	−4.4	−3.8	−4.4
Max. Permissible Temp., °C.	150	300	100	150	200	100
Dissipation Constant, C, *mw*/C. deg.						
Still air.	0.1	1	7	7	—	20
Still water.	—	7	—	—	—	—
Thermal Time Constant, Seconds						
Still air.	1	30	25	60	—	—
Still water.	—	4	—	—	—	—
Shape.	Bead	Probe	Rod	Rod	Disc	Disc
Dimensions, Inches						
Diameter or Width.	0.015	0.1	0.05	0.15	0.2	0.56
Length or Thickness (less leads).	0.02	0.6	1.2	0.7	0.1	0.31

thermistor, mounted in a standard one-quarter inch diameter temperature bulb assembly, operated at approximately 275 degrees centigrade. It was associated with a differential relay and control motor on the aircraft 28 volt d-c system. The power dissipation in the thermistor was two watts. The resistance of a typical thermistor under these high temperature conditions remained within ± 1.5 per cent over a period of months. This corresponds to about ± one centigrade degree variation in calibration. Several other related designs were developed using the same control system with other thermistors designed for both higher and lower temperature operation. In the lower temperature applications, typical thermistors maintained their calibrations within a few tenths of a centigrade degree.

In general, electron tube control circuits dissipate less power in the thermistor than relay circuits do. This results in less temperature rise in the thermistor and leads to a more accurate control. While the average value of this temperature rise can be allowed for in the design, the variations in different installations require individual calibration to correct the errors if they are large. The corrections may be different as a result of variations of the thermal conductivity of the surrounding media from time to time or from one installation to another. The greater the power dissipated in the thermistor the greater the absolute error in the control temperature for a given change in thermal conductivity. This follows from the relation

$$\Delta T = W/C \tag{22}$$

where ΔT is the temperature rise, W is the power dissipated and C is the dissipation constant which depends on thermal coupling to the surroundings. For the same reason, the temperature indicated by a resistance thermometer immersed in an agitated medium will depend on the rate of flow if the temperature sensitive element is operated several degrees hotter than its surroundings.

The design of a thermistor for a ventilating duct thermostat might proceed as follows as far as temperature rise is concerned:

1. Determine the power dissipation. This depends upon the circuit selected and the required overall sensitivity.

2. Estimate the permissible temperature rise of the thermistor, set by the expected variation in air speed and the required temperature control accuracy.

3. Solve Equation (22) for the dissipation constant and select a thermistor of appropriate design and size for this constant in the nominal air speed. Where more than one style of thermistor is available, the required time constant will determine the choice.

Compensators

It is a natural and obvious application of thermistors to use them to compensate for changes in resistance of electrical circuits caused by ambient temperature variations. A simple example is the compensation of a copper wire line, the resistance of which increases approximately 0.4 per cent per centigrade degree. A thermistor having approximately one-tenth the resistance of the copper, with a temperature coefficient of -4 per cent per centigrade degree placed in series with the line and subjected to the same ambient temperature, would serve to compensate it over a narrow temperature range. In practice however, the compensating thermistor is associated with parallel and sometimes series resistance, so that the combination gives a change in resistance closely equal and opposite to that of the circuit to be compensated over a wide range of temperatures. See Fig. 18.

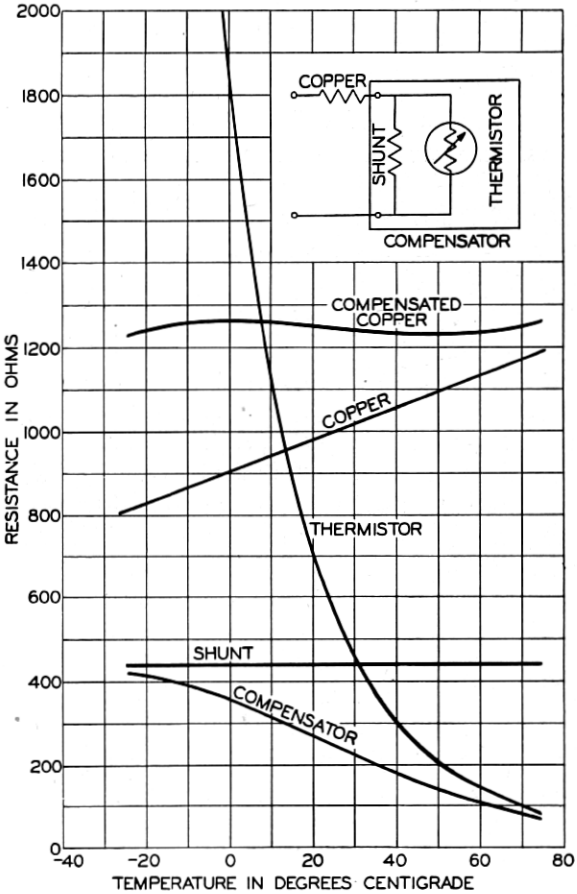

Fig. 18.—Temperature compensation of a copper conductor by means of a thermistor network.

A copper winding having a resistance of 1000 ohms at 25 degrees centigrade can be compensated by means of a thermistor of 566 ohms at 25 degrees centigrade in parallel with an ohmic resistance of 445 ohms as shown in Fig. 18. The winding with compensator has a resistance of 1250 ohms constant to $\pm$ 1.6 per cent over the temperature range -25 degrees centigrade to $+75$ degrees centigrade. Over this range the copper alone varies from 807.5 ohms to 1192.5 ohms, or $\pm$ 19 per cent about the mean. The total resistance of the circuit has been increased only 6.1 per cent at the upper temperature limit by the addition of a compensator. This increase is small because of the high temperature coefficient of the compensating thermistor. The characteristics of such a thermistor are so stable that the resistance would remain constant within less than one per cent for ten years if maintained at any temperature up to about 100 degrees centigrade. Figure 15 shows aging characteristics for typical thermistors suitable for use in compensators. These curves include the change which occurs during the seasoning period of several days at the factory, so that the aging in use is a fraction of the total shown.

In many circuits which need to function to close tolerances under wide ambient temperature variation, the values of one or more circuit elements may vary undesirably with temperature. Frequently the resultant overall variation with temperature can be reduced by the insertion of a simple thermistor placed at an appropriate point in the circuit. This is particularly true if the circuit contains vacuum tube amplifiers. In this manner frequency and gain shifts in communications circuits have been cancelled and temperature errors prevented in the operation of devices such as electric meters. The change in inductance of a coil due to the variation of magnetic characteristics of the core material with temperature has been prevented by partially saturating the coil with direct current, the magnitude of which is directly controlled by the resistance of a thermistor imbedded in the core. In this way the amount of d-c magnetic flux is adjusted by the thermistor so that the inductance of the coil is independent of temperature.

In designing a compensator, care must be taken to ensure exposure of the thermistor to the temperature affecting the element to be compensated. Power dissipation in the thermistor must be considered and either limited to a value which will not produce a significant rise in temperature above ambient, or offset in the design.

Volt-Ampere Characteristics

The nonlinear shape of the static characteristic relating voltage, current, resistance and power for a typical thermistor was illustrated by Fig. 9. The part of the curve to the right of the voltage maximum has a negative slope, applicable in a large number of ways in electric circuits. The particular characteristic shown begins with a resistance of approximately 50,000 ohms at low power. Additional power dissipation raises the temperature of the thermistor element and decreases its resistance. At the voltage maximum the resistance is reduced to about one-third its cold value, or 17,000 ohms, and the dissipation is 13 milliwatts. The resistance becomes approximately 300 ohms when the dissipation is 100 milliwatts. Such resistance-power characteristics have resulted in the use of thermistors as sensitive power measuring devices, and as automatically variable resistances for such applications as output amplitude controls for oscillators and amplifiers. Their nonlinear characteristics also fit thermistors for use as voltage regulators, volume controls, expandors, contactless switches and remote control devices. To permit their use in these applications for d-c as well as a-c circuits, nonpolarizing semiconductors alone are employed in thermistors with the exception of two early types.

Power Meter

Thermistors have been used very extensively in the ultra and superhigh frequency ranges in test sets as power measuring elements. The particular advantages of thermistors for this use are that they can be made small in size, have a small electrical capacity, can be severely overloaded without

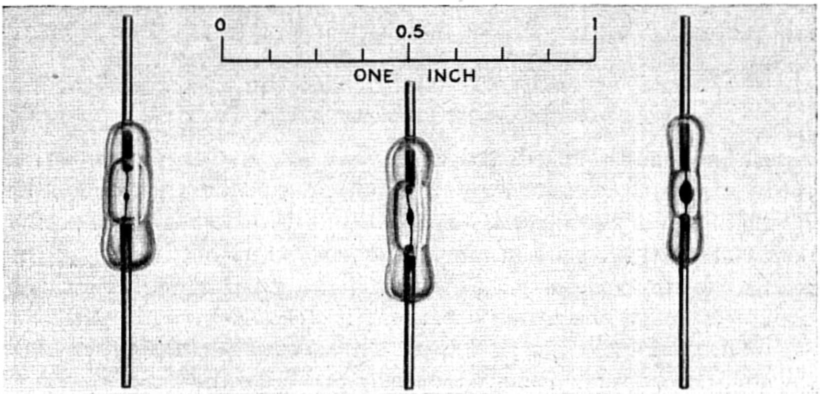

Fig. 19.—Power measuring thermistors with different sized beads.

change in calibration, and can easily be calibrated with direct-current or low-frequency power. For this application the thermistor is used as a power absorbing terminating resistance in the transmission line, which may be of Lecher, coaxial or wave-guide form. Methods of mounting have been worked out which reduce the reflection of high frequency energy from the termination to negligible values and assure accurate measurement of the power over broad bands in the frequency spectrum. Conventionally, the thermistor is operated as one arm of a Wheatstone bridge, and is biased with low frequency or d-c energy to a selected operating resistance value, for instance 125 or 250 ohms in the absence of the power to be measured. The application of the power to be measured further decreases the thermistor resistance, the bridge becomes unbalanced and a deflection is obtained on the bridge meter. A full scale power indication of one milliwatt is customary for the test set described, although values from 0.1 milliwatt to 200 milliwatts have been employed using thermistors with different sized beads as shown in Fig. 19.

Continuous operation tests of these thermistors indicate very satisfactory stability with an indefinitely long life. A group of eight power meter thermistors, normally operated at 10 milliwatts and having a maximum rating of 20 milliwatts, were operated for over 3000 hours at a power input of 30 milliwatts. During this time the room temperature resistance remained within 1.5 per cent of its initial value, and the power sensitivity, which is the significant characteristic, changed by less than 0.5 per cent.

When power measuring test sets are intended for use with wide ambient temperature variations, it is necessary to temperature compensate the thermistor. This is accomplished conventionally by the introduction of two other thermistors into the bridge circuit. These units are designed to be insensitive to bridge currents but responsive to ambient temperature. One of the compensators maintains the zero point and the other holds the meter scale calibration independent of the effect of temperature change on the measuring thermistor characteristics.

Automatic Oscillator Amplitude Control

Meacham,[10] and Shepherd and Wise[11] have described the use of thermistors to provide an effective method of amplitude stabilization of both low and high frequency oscillators. These circuits oscillate because of positive feedback around the vacuum tube. The feedback circuit is a bridge with at least one arm containing a thermistor which is heated by the oscillator output. Through this arrangement, the feedback depends in phase and magnitude upon the output, and there is one value of thermistor resistance which if attained would balance the bridge and cause the oscillation amplitude to vanish. Obviously this condition can never be exactly attained, and the operating point is just enough different to keep the bridge slightly unbalanced and produce a predetermined steady value of oscillation output. Such oscillators in which the amplitude is determined by thermistor nonlinearity have manifold advantages over those whose amplitude is limited by vacuum tube nonlinearity. The harmonic content in the output is smaller, and the performance is much less dependent upon the individual vacuum tube and upon variations of the supply voltages. It is necessary that the thermal inertia of the thermistor be sufficient to prevent it from varying in resistance at the oscillation frequency. This is easily satisfied for all frequencies down to a small fraction of a cycle per second. Figure 20 shows a thermistor frequently used for oscillator control together with its static electrical characteristic. This thermistor is satisfactory in oscillators for frequencies above approximately 100 cycles per second. Similar types have been developed with response characteristics suited to lower frequencies and for other resistance values and powers.

Where the ambient temperature sensitivity of the thermistor is disadvantageous in oscillator controls, the thermistor can be compensated by

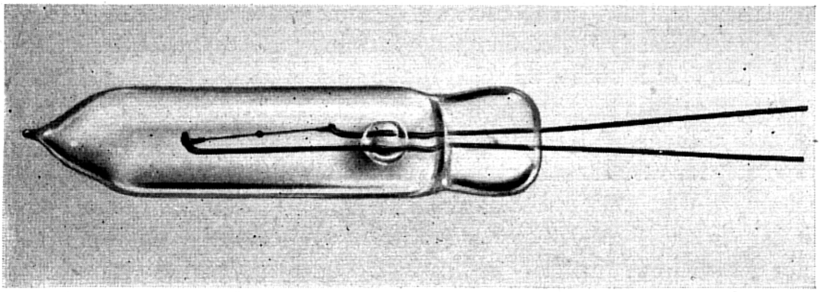

Fig. 20A.—An amplitude control thermistor. The glass bulb is 1.5 inches in length.

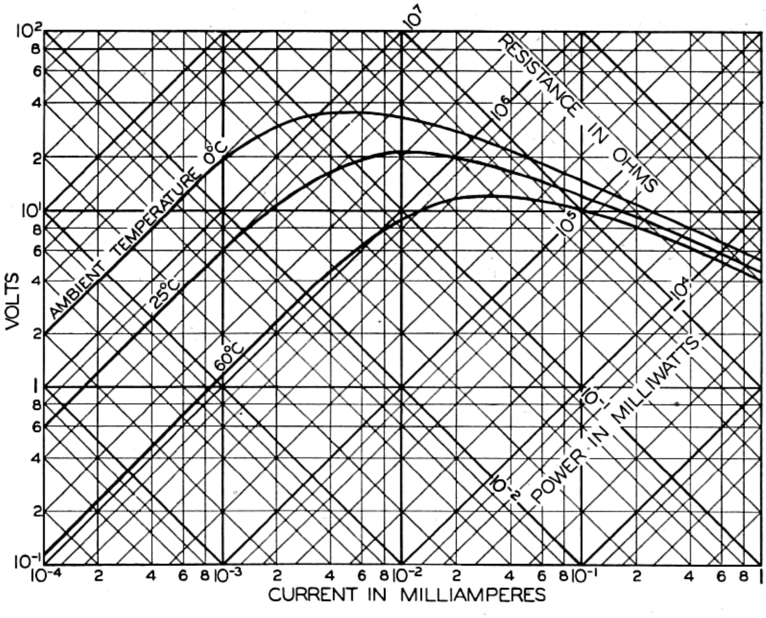

Fig. 20B.—Steady state characteristics of amplitude control thermistor shown in Figure 20A.

thermostating it with a heater and compensating thermistor network, as shown in Fig. 21.

Amplifier Automatic Gain Control

Since the resistance of a thermistor of suitable design varies markedly with the power dissipated in it or in a closely associated heater, such thermistors have proven to be very valuable as automatic gain controls, especially for use with negative feedback amplifiers. This arrangement has seen extensive use in wire communication circuits for transmission level regulation, and has been described in some detail elsewhere.[12, 13, 14] In one form, a directly heated thermistor is connected into the feedback circuit of the amplifier in such a way that the amount of feedback voltage is varied to compensate for any change in the output signal. By this arrangement, the gain of each amplifier in the transmission system is continually adjusted to correct for variations in overall loss due to weather conditions and other factors, so that constant transmission is obtained over the channel at all times. In the Type K2 carrier system now in extensive use, the system gain is regulated principally in this way. In this system the transmission loss variations due to temperature are not the same in all parts of the pass band. The loss is corrected at certain repeater points along the transmission line by two additional thermistor gain controls: slope, proportional to fre-

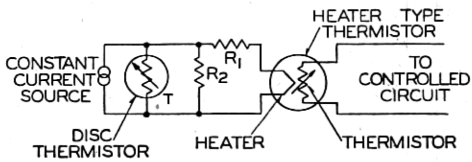

Fig. 21.—Circuit employing an auxiliary disc thermistor to compensate for effect of varying ambient temperature on a control thermistor.

quency, and bulge, with a maximum at one frequency. These thermistors are indirectly heated, with their heaters actuated by energy dependent upon the amplitude of the separate pilot carriers which are introduced at the sending end for the purpose.

In this type of application, the thermistor will react to the ambient temperature to which it is exposed, as well as to the current passing through it. Where this is important, the reaction to ambient temperature can be eliminated by the use of a heater type thermistor as shown in Fig. 21. The heater is connected to an auxiliary circuit containing a temperature compensating thermistor. This circuit is so arranged that the power fed into the heater of the gain control thermistor is just sufficient at any ambient temperature to give a controlled and constant value of temperature in the vicinity of the gain control thermistor element.

Another interesting form of thermistor gain control utilizes a heater type thermistor, with the heater driven by the output of the amplifier and with the thermistor element in the input circuit, as shown in Fig. 22. In this arrangement the feedback is accomplished by thermal, rather than electrical coupling. A broad-band carrier system, Type L1, is regulated with this type of thermistor. In this system a pilot frequency is supplied, and current of this frequency, selected by a network in the regulator, actuates the heater of the thermistor to give smooth, continuous gain control.

By utilizing a heater thermistor of different characteristics, the circuit and load of Fig. 22 may be given protection against overloads. In this application the sensitivity and element resistance of the thermistor are chosen so that the thermistor element forms a shunt of high resistance value so as to have negligible effect on the amplifier for any normal value of output. However, if the output power rises to an abnormal level, the thermistor element becomes heated and reduced in resistance. This shunts the input to the amplifier and thus limits the output. Choice of a thermistor having a suitable time constant permits the onset of the limiting effect to be delayed for any period from about a second to a few minutes.

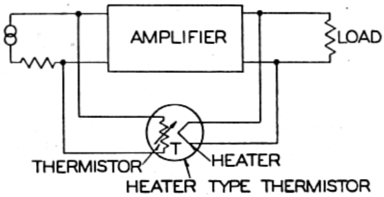

Fig. 22.—Thermal feedback circuit for gain control purposes. This arrangement has also been used as a protective circuit for overloads.

Regulators and Limiters

A group of related applications for thermistors depends on their steady state nonlinear volt-ampere characteristic. These are the voltage regulator, the speech volume limiter, the compressor and the expandor. The compressor and expandor are devices for altering the range of signal amplitudes. The compressor functions to reduce the range, while the expandor increases it. In Fig. 23, Curve 1 is a typical thermistor static characteristic having negative slope to the right of the voltage maximum. Curve 2 is the characteristic of an ohmic resistance R having an equal but positive slope. Curve 3 is the characteristic obtained if the thermistor and resistor are placed in series. It has an extensive segment where the voltage is almost independent of the current. This is the condition for a voltage regulator or limiter. If a larger value of resistance is used, as in Curve 4, its combination with the thermistor in series results in Curve 5, the compressor. In these uses the thermistor regulator is in shunt with the load resistance, so that in the circuit diagram of Fig. 23,

$$E = E_o = E_I - IR_S. \tag{23}$$

Here E is the voltage across the thermistor and resistor R, E_o is the output voltage, and E_I, I and R_S are respectively the input voltage, current and resistance.

If the thermistor and associated resistor are placed in series between the generator and load resistance, an expandor is obtained, and

$$E_o = E_I - E. \tag{24}$$

As the resistance R in series with the thermistor is increased, the degree of expansion is decreased and vice versa.

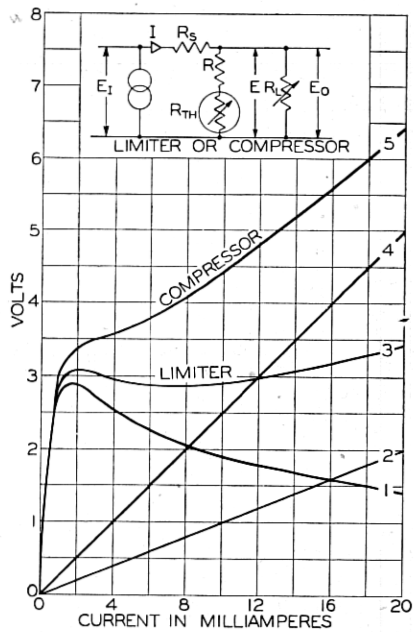

Fig. 23.—Characteristics of a simple thermistor voltage regulator, limiter or compressor circuit.

The treatment thus far in this section assumes that change of operating point occurs slowly enough to follow along the static curves. For a sufficiently rapid change of the operating point, the latter departs from the static curve and tends to progress along an ohmic resistance line intersecting the static curve. For sufficiently rapid fluctuations, control action may then be derived from the resistance changes resulting from the r.m.s. power dissipated in the thermistor unit. In speech volume limiters, the thermistor is designed for a speed of response that will produce limiting action for the changes in volume which are syllabic in frequency or slower, and that will not follow the more rapid speech fluctuations with resulting change in wave shape or nonlinear distortion. Speech volume limiters of this type can accommodate large volume changes without producing wave form distortion.[13,15]

Remote Control Swiches

The contactless switch and rheostat are natural extensions of the uses just discussed. The thermistor is used as an element in the circuit which is to be controlled, while the thermistor resistance value is in turn dependent upon the energy dissipated directly or indirectly in it by the controlling circuit. By taking advantage of the nonlinearity of the static volt-ampere characteristic, it is possible to provide snap and lock-in action in some applications.

Manometer

Several interesting and useful applications such as vacuum gauges, gas analyzers, flowmeters, thermal conductivity meters and liquid level gauges of high sensitivity and low operating temperature are based upon the physical principle that the dissipation constant of the thermistor depends on the thermal conductivity of the medium in which it is immersed. As shown in Fig. 10, a change in this constant shifts the position of the static characteristic with respect to the axes. In these applications, the undesired response of the thermistor to the ambient temperature of the medium can in many cases be eliminated or reduced by introducing a second thermistor of similar characteristics into the measuring circuit. The compensating thermistor is subjected to the same ambient temperature, but is shielded from the effect being measured, such as gas pressure or flow. The two thermistors can be connected into adjacent arms of a Wheatstone bridge which is balanced when the test effect is zero and becomes unbalanced when the effective thermal conductivity of the medium is increased. In gas flow measurements, the minimum measurable velocity is limited, as in all "hot wire" devices, by the convection currents produced by the heated thermistor.

The vacuum gauge or manometer which is typical of these applications will be described somewhat in detail. The sensitive element of the thermistor manometer is a small glass coated bead 0.02 inch in diameter, suspended by two fine wire leads in a tubular bulb for attachment to the chamber whose gas pressure is to be measured. The volt-ampere characteristics of a typical laboratory model manometer are shown in Fig. 24 for air at several absolute pressures from 10^{-6} millimeters of mercury to atmospheric. The operating point is in general to the right of the peak of these curves. Electrically this element is connected into a unity ratio arm Wheatstone bridge with a similar but evacuated thermistor in an adjacent arm as shown in the circuit schematic of Fig. 25. The air pressure calibration for such a manometer is also shown. The characteristic will be shifted when a gas is used having a thermal conductivity different from that of air. Such a manometer has been found to be best suited for the measurement of pressures from 10^{-5} to 10 millimeters of mercury. The lower pressure limit is set by practical considerations such as meter sensitivity and the ability to maintain the zero setting for reasonable periods of time in the presence of the variations of supply voltage and ambient temperature. The upper pressure measurement limit is caused by the onset of saturation in the bridge unbalance

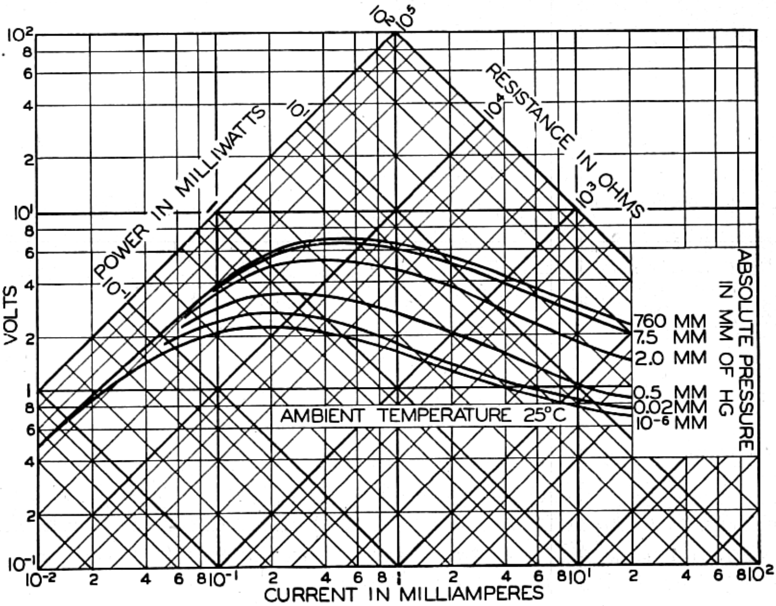

Fig. 24.—Characteristics of a typical thermistor manometer tube, showing the effect of gas pressure on the volt-ampere and resistance-power relations.

voltage versus pressure characteristic at high pressures. This is basically because the mean free path of the gas molecules becomes short compared with the distance between the thermistor bead and the inner surface of the manometer bulb, so that the cooling effect becomes nearly independent of the pressure.

The thermistor manometer is specially advantageous for use in gases which may be decomposed thermally. For this type of use, the thermistor element temperature can be limited to a rise of 30 centigrade degrees or less above ambient temperature. For ordinary applications, however, a temperature rise up to approximately 200 centigrade degrees in vacuum permits measurement over wider ranges of pressure. Special models have also been made for use in corrosive gases. These expose only glass and platinum alloy to the gas under test.

Timing Devices

The numerically greatest application for thermistors in the communication field has been for time delay purposes. The physical basis for this use has

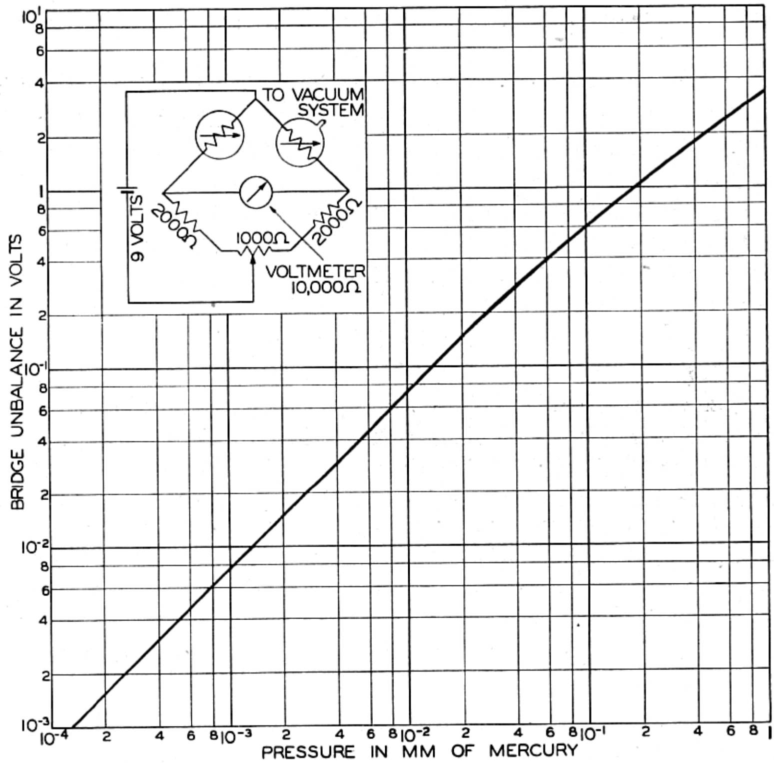

Fig. 25.—Operating circuit and calibration for a vacuum gauge utilizing the thermistor of Figure 24.

been discussed in Part I for the case of a directly heated thermistor placed in series with a voltage source and a load to delay the current rise after circuit closure. This type of operation will be termed the power driven time delay.

By the use of a thermistor suited to the circuit and operating conditions, power driven time delays can be produced from a few milliseconds to the order of a few minutes. Thermistors of this sort have the advantage of small size, light weight, ruggedness, indefinitely long life and absence of contacts, moving parts, or pneumatic orifices which require maintenance care. Power driven time delay thermistors are best fitted for applications where close limits on the time interval are not required. In some communications uses it is satisfactory to permit a six to one ratio between maximum and minimum times as a result of the simultaneous variation from nominal values of all the following factors which affect the delay: operating voltage ± 5 per cent; ambient temperature 20 degrees centigrade to 40 degrees centigrade; operating current of the relay ± 25 per cent; relay resistance ± 5 per cent; and thermistor variations such as occur from unit to unit of the same type.

After a timing operation a power driven time delay thermistor should be allowed time to cool before a second operation. If this is not done, the second timing interval will be shorter than the first. The cooling period depends on particular circuit conditions and details of thermistor design, but generally is several times the working time delay. In telephone relay circuits requiring a timing operation soon after previous use, the thermistor usually is connected so that it is short circuited by the relay contacts at the close of the working time delay interval. This permits the thermistor to cool during the period when the relay is locked up. If this period is sufficiently long, the thermistor is available for use as soon as the relay drops out. Time delay thermistors have been operated more than half a million times on life test with no significant change in their timing action.

To avoid the limitations of wide timing interval limits and extended cooling period between operations usually associated with the power driven time delay thermistor, a cooling time delay method of operation has been used. In this arrangement, two relays or the equivalent are employed and the thermistor is heated to a low resistance-value by passing a relatively large current through it for an interval short compared with the desired time interval. The current then is reduced automatically to a lower value and the thermistor cools until its resistance increases enough to reduce the current further and trip the working relay. This part of the operating cycle accounts for the greater part of the desired time interval. With this arrangement, the thermistor is available for re-use immediately after a completed timing interval, or, as a matter of fact, after any part of it. By proper choice of operating currents and circuit values, wide variations of voltage and ambient temperature may occur with relatively little effect upon the time interval. The principal variable left is the cooling time of the thermistor itself. This is fixed in a given thermistor unit, but may vary from unit to unit, depending upon dissipation constant and thermal capacity, as pointed out above.

In addition to their use as definite time delay devices, thermistors have been used in several related applications. Surges can be prevented from operating relays or disturbing sensitive apparatus by introducing a thermistor in series with the circuit component which is to be protected. In case of a surge, the high initial resistance of the thermistor holds the surge current to a low value provided that the surge does not persist long enough to overcome the thermal inertia of the thermistor. The normal operating voltage, on the other hand, is applied long enough to lower the thermistor resistance to a negligible value, so that a normal operating current will flow after a short interval. In this way, the thermistor enables the circuit to distinguish between an undesired signal of short duration and a desired signal of longer duration even though the undesired impulse is several times higher in voltage than the signal.

Oscillators, Modulators and Amplifiers

A group of applications already explored in the laboratory but not put into engineering use includes oscillators, modulators and amplifiers for the low and audio-frequency range. If a thermistor is biased at a point on the negative slope portion of the steady-state volt-ampere characteristic, and if a small alternating voltage is then superposed on the direct voltage, a small alternating current will flow. If the thermistor has a small time constant, τ, and if the applied frequency is low enough, the alternating volt-ampere characteristic will follow the steady-state curve and dV/dI will be negative. As the frequency of the applied a-c voltage is increased, the value of the negative resistance decreases. At some critical frequency, f_c, the resistance is zero and the current is 90 degrees out of phase with the voltage. In the neighborhood of f_c, the thermistor acts like an inductance whose value is of the order of a henry. As the frequency is increased beyond f_c, the resistance is positive and increases steadily until it approaches the d-c value when the current and voltage are in phase. The critical frequency is given approximately by

$$f_c = 1/2\tau.$$

If τ can be made as small as 5×10^{-5} seconds, f_c is equal to 10,000 cycles per second and the thermistor would have an approximately constant negative resistance up to half this frequency. Point contact thermistors having such critical frequencies or even higher have been made in a number of laboratories. However, none of them have been made with sufficient reproducibility and constancy to be useful to the engineer. It has been shown both theoretically and experimentally that any negative resistance device can be used as an oscillator, a modulator, or an amplifier. With further development, it seems probable that thermistors will be used in these fields.

. Summary

The general principles of thermistor operation and examples of specific uses have been given to facilitate a better understanding of them, with the feeling that such an understanding will be the basis for increased use of this new circuit and control element in technology.

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