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IN THIS ISSUE

COVER:

A stage in the manufacture of transistors.

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Electronic Heat Controls For Appliances and Domestic Heating

Although the use of electricity to produce heat is by no means new to the American household, the extent of electric heating has increased tremendously during the past decade. Today, because of the drastically reduced cost of electric power, electricity is becoming even more popular as a method of home heating.

In the past, most electrical heating systems were controlled by electro-mechanical techniques, usually in the form of a bi-metal switch or a high-column mercury switch. This paper discusses a third technique, electronic control, which has many advantages, including elimination of moving parts and greatly improved sensitivity. The various circuits presented and discussed in the paper exhibit special characteristics for special functions.

by

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Introduction

The use of electronic controls employing solid-state devices is being viewed with considerable interest by the manufacturers of cooking and space-heating equipment. These manufacturers are recognizing that the use of such solid-state devices as transistors, diodes and thyristors can greatly improve both the sensitivity and the reliability of such equipment. The flexibility of electronic control is also a considerable advantage from the design and manufacturing standpoint.

At present, one of the most popular methods of heat control is the bi-metal switch. Although this method will undoubtedly remain very popular, there are many applications where the precision of such a switch is not adequate or where an anticipating control is desirable. Wide-spread use of electronic control techniques is expected in these applications.

Basic Control Circuit

The simplest type of electronic control circuit is shown in Fig. 1. In this circuit, the control function is performed by the thyristor Y_1, in conjunction with the sensing thermistor TH_1. The thermistor and the resistor R_1 form a voltage divider across the thyristor. When TH_1 is cold, its resistance is high and the potential at the junction of R_1 and TH_1 produces sufficient current through the variable resistor R_2 to trigger Y_1 into conduction. As the thermistor heats up, its resistance decreases and the potential at the junction of R_1 and TH_1 drops until the current through

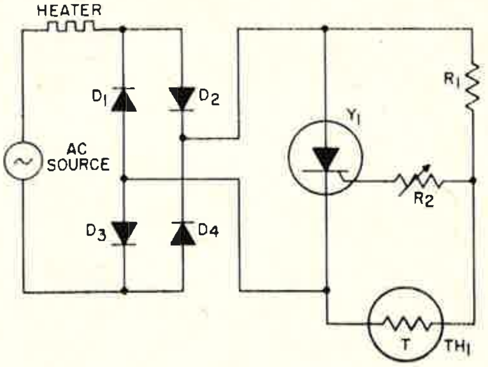

Fig.1 - Simple electronic control circuit using a thyristor (Y_1), a sensing thermistor (TH_1), and a bridge rectifier circuit (D_1 through D_4).

R_2 is insufficient to maintain conduction in the thyristor.

Full-wave operation of the circuit is accomplished through the use of the bridge circuit formed by the four silicon rectifiers, D_1 through D_4. In effect, this bridge circuit steers the current from the source in a unidirection through the thyristor, while allowing alternating current for the heater.

Although the circuit of Fig. 1 has good sensitivity, it has a number of undesirable features for commercial use. It requires a large and relatively expensive power-handling thermistor for TH_1. In addition, it depends on the gate characteristics of the thyristor, which can vary markedly from one device to another and which are considerably affected by both external and internal heating effects. As a result, it has poor ambient-temperature characteristics and also exhibits a lack of uniformity from unit to unit. Furthermore, it has a tendency to fire at the peak of the ac wave and produces very heavy radio-frequency interference which would be disturbing in home radio and television receivers.

The circuit shown in Fig. 2 eliminates the need for a large power-handling thermistor for TH_1, but has all the other undesirable features of the circuit of Fig. 1. The voltage divider and bridge circuit, R_1, R_2, R_3 and TH_1, reduces the amount of power supplied to the thermistor and permits a smaller and less expensive unit to be used for TH_1. With this circuit, however, the bridge rectifier arrangement cannot be used because 120-cycle signals would be required for full-wave operation. Therefore, a second thyristor, Y_2, is connected as a "slave" unit from Y_1 to provide 360-degree conduction.

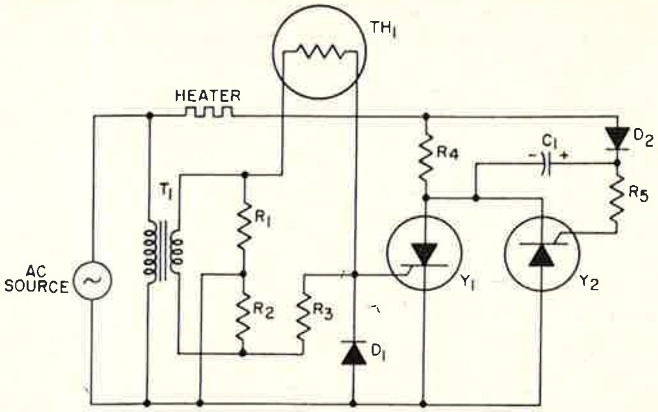

Fig.2 - Circuit using voltage divider and bridge circuit (R_1, R_2, R_3, TH_1) to reduce power-handling requirements of thermistor; a second thyristor (Y_2) is used in place of a bridge rectifier.

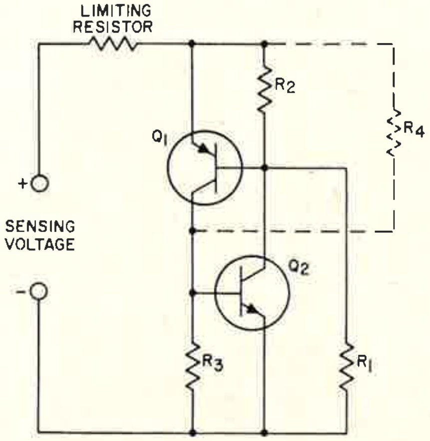

Fig.3 - Two-transistor voltage-sensitive switch for use in electronic control circuits.

Transistor Switch

Fig. 3 shows a two-transistor voltage-sensitive switch which can be used in place of the gate characteristics of the thyristor as a voltage-level control. The use of this switching circuit helps to improve the uniformity and ambient-temperature stability of electronic control circuits. It also helps to reduce radio-frequency interference because it permits conduction at an earlier point in the positive half-cycle of the ac source. (Radio-frequency interference is caused by the steep wave front of the alternating current. Since the interference varies as the square of the power, it is desirable to turn on the thyristor early in the cycle, where the voltage is only a few volts, rather than at the peak, where it is approximately 160 volts.) The voltage level at which the switch turns on is a function of the values used for the control resistors R_1 and R_2. Decreasing the value of R_1 or increasing the value of R_2 reduces the voltage required to trigger the switch into conduction.

Depending on the particular circuit arrangement in which the switch is to be used, it may be more convenient to use R_4 than R_1. The resistor R_1 is then eliminated, and R_4 and R_3 become the control resistors. It is generally most convenient to use a circuit arrangement that permits one side of the sensing resistors to be grounded. For example, if the negative terminal of the sensing voltage source is at ground, it is desirable to use a thermistor for R_1 and a variable control for R_2 so that an increase in temperature will turn the switch on. If it is desired to turn the switch off with an increase in temperature, then R_1 is eliminated, a thermistor is used for R_3, and R_4 is the variable control.

The maximum values which can be used for resistors R_3 and R_2 are determined primarily by the characteristics of the particular transistors used and by the ambient temperature. In most cases, the ratio of R_1 to R_2 (or R_4 to R_3) is approximately 10 to 1. Fig. 4 shows suitable values of R_1 and R_2 (or R_4 and R_3) for an experimental circuit. (These curves are also calibrated in temperature for the particular thermistors indicated.)

Because the basic circuit shown in Fig. 3 does not incorporate temperature compensation, the turn-on potential of the switch may vary with changes in ambient temperature. Fig. 5 illustrates the addition of a silicon diode, D_1, which greatly improves the ambient-temperature stability of the switching circuit.

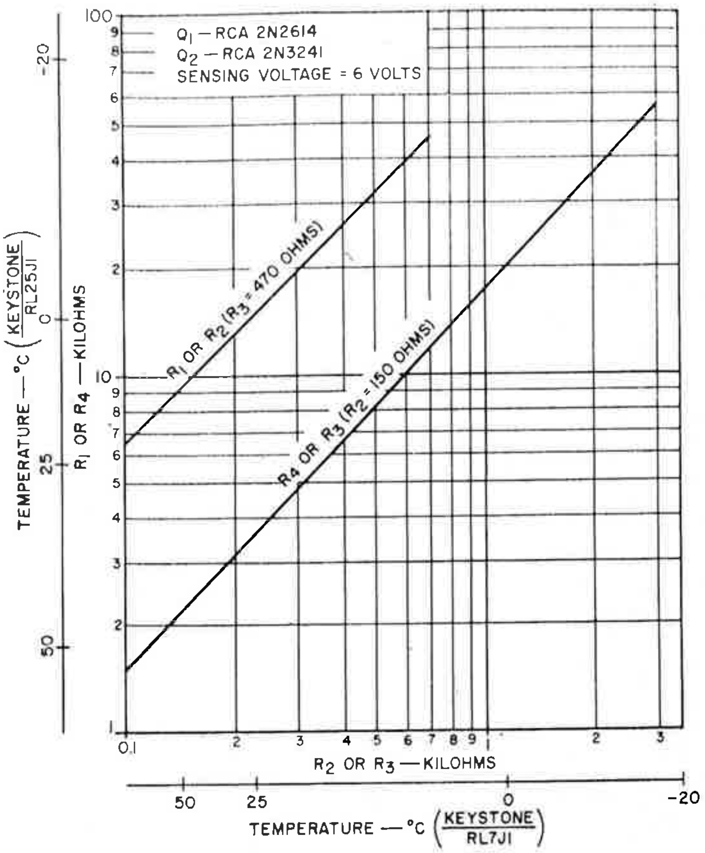

Fig.4 - Suitable resistor values for use in transistor switching circuit of Fig.3.

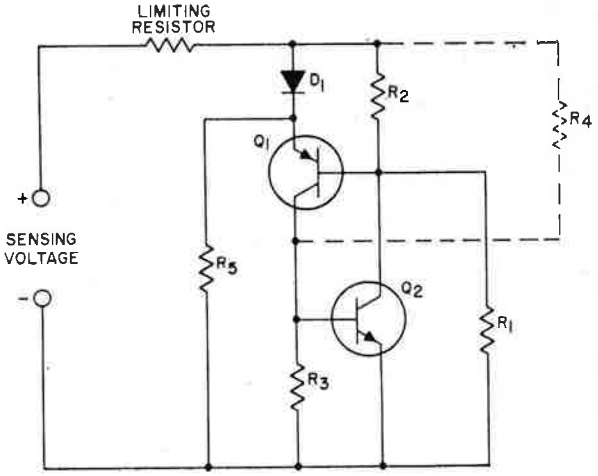

Fig.5 - Transistor switch employing a silicon diode (D_1) for improved ambient-temperature stability.

Fig. 6 shows the effect of this diode on the value of the resistors used in the circuit.

When it is desirable to use a low-wattage sensing thermistor in this transistor switching circuit, a Darlington connection such as that shown for transistors Q_1 and Q_2 in Fig. 7 can be used. This circuit permits values as high as 10,000 ohms to be used for R_2; as a result, a sensing thermistor in the order of 100,000 ohms can be used for R_1. In addition, because this circuit can work with much higher resistances, a much wider range of temperature can be controlled. (Although the Darlington connection is shown in the p-n-p portion of the switch in Fig. 7, it can be used instead in the n-p-n portion if the circuit requires it; R_4 is then used instead of R_1.) Fig. 8 shows the resistance values that can be used in this circuit.

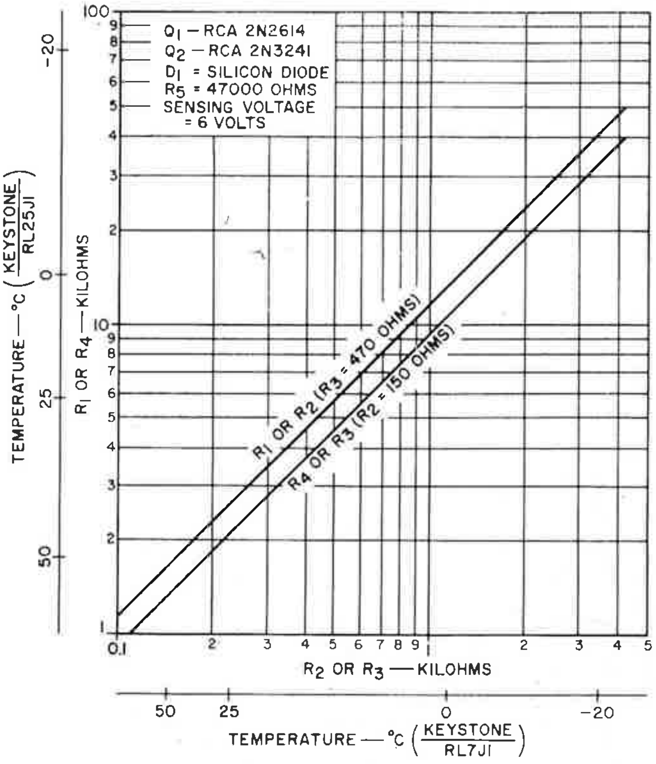

Fig.6 - Resistor values for use in circuit of Fig.5.

Circuits Using Transistor Switch

Fig. 9 shows a simple control circuit which employs the two-transistor voltage-sensitive switch. As mentioned previously, the voltage level at which the switch goes into saturation depends on the value of the thermistor TH_1; the lower the value of TH_1, the lower the turn-on potential of the switch. Fig. 10 shows a similar circuit in which a second thyristor, Y_2, is used instead of the bridge rectifier circuit to provide full-wave switching action. Both of these circuits produce considerably less radio-frequency interference than the circuits shown in Figs. 1 and 2; they also have somewhat better uniformity and temperature characteristics, although further improvements can be made, as described later.

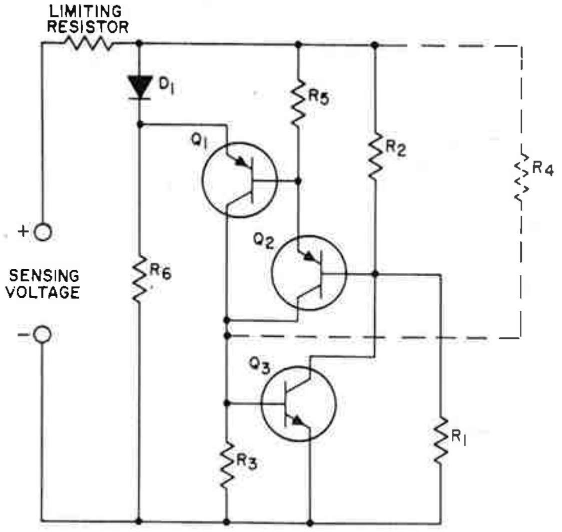

Fig.7 - Transistor switch using a Darlington connection (Q_1, Q_2) to reduce wattage requirements of sensor (R_1).

A disadvantage of the circuit shown in Fig. 10 is the heat dissipation and resulting power loss in the "slaving" resistor R_1 at power levels above 500 watts. In the circuit of Fig. 11, this resistor is replaced by a step-up or auto-transformer T_1. In this particular circuit, which was designed for 3.5-kilowatt control, the transformer was constructed with a $\frac{3}{8}$ inch EI core; the secondary winding (to the gate of thyristor Y_1) consisted of 250 turns of No. 30 wire, and the primary winding (to the anode of Y_2) of 30 ampere-turns. If a varying load is expected, the primary winding should be about 12 to 15 turns of No. 26 wire, and a silicon diode should be connected across it.

Fig. 12 shows a heat-modulating circuit which uses the transistor switch. In this circuit, half-wave power is continuously fed to the heater. During the alternating half-cycle, the thyristor Y_1 performs as in the previous circuits.

Circuits With Improved Temperature Stability

As mentioned above, the circuits of Figs. 9 through 12 are better for temperature stability than the circuits of Figs. 1 and 2, but are still not completely satisfactory. In addition to the two-transistor switch, these circuits also use the gate characteristics of the thyristor as a level switch and thus are affected by internal heating effects in the thyristor. This disadvantage can be overcome by the use of a second two-transistor switch, as shown in Fig. 13.

In the circuit of Fig. 13, when the resistance of the thermistor TH_1 is higher than the series resistance of R_4 and R_5, the switch consisting

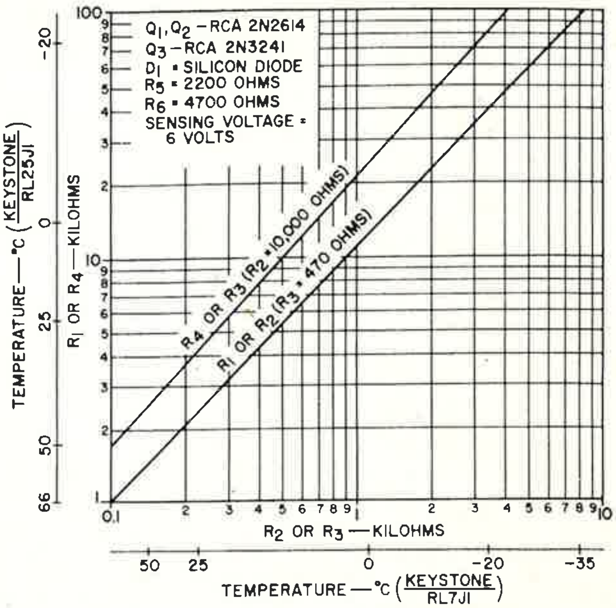

Fig.8 - Resistor values for use in circuit of Fig.7.

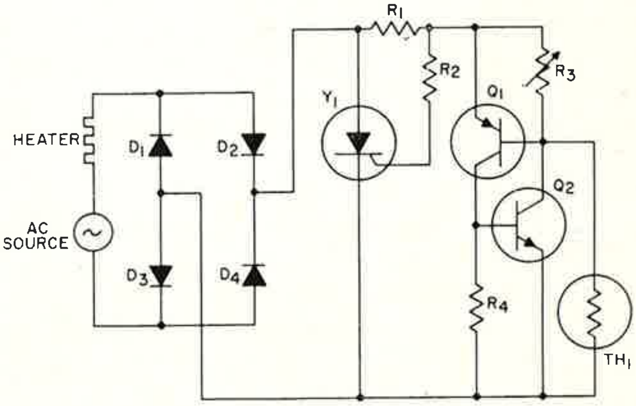

Fig.9 - Simple control circuit using a transistor switch (Q_1, Q_2) and a bridge rectifier circuit (D_1 through D_4).

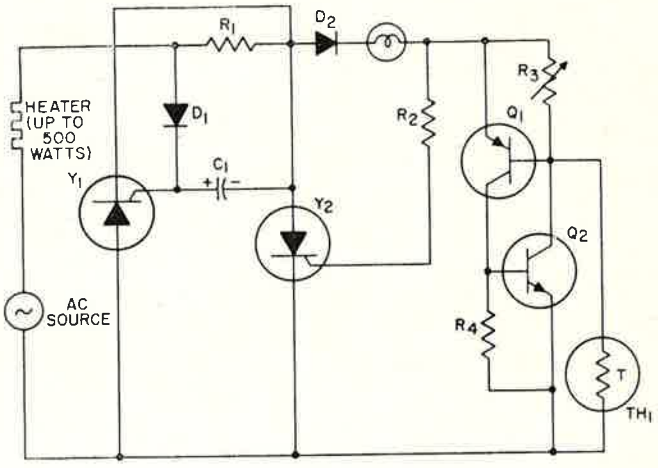

Fig.10 - Control circuit using a transistor switch (Q_1, Q_2) and a second thyristor (Y_2) for full-wave operation.

of transistors Q_1 and Q_2 conducts first and passes the energy from capacitor C_1 to the gate of the thyristor Y_1. If the value of the thermistor is lower than the series resistance of R_4 and R_5, the switch consisting of Q_3 and Q_4 conducts and bypasses Y_1. Full-wave operation is accomplished by use of the bridge rectifier circuit.

Further improvement can be obtained by use of the circuit shown in Fig. 14. The main advantage of this circuit is absolute assurance that no dc component of power is present to saturate the distribution transformer of the power source. In addition, the thermistor TH_1 can be grounded to one side of the line. The 6-to-10-watt lamp which replaces the RC circuit of Fig. 13 not only serves as a "ready" light, but also greatly reduces the possibility of radio-frequency interference because its nonlinear resistance characteristic is helpful in turning on the thyristor at the earliest possible moment in the cycle. If the lamp is not desired it can be replaced by a resistor (about 3000 ohms, 5 watts) and a capacitor (1 microfarad). A 10-ohm resistor should be inserted in series with the capacitor to limit discharge current.

In the circuit of Fig. 15, dual thermistors are used for control; this circuit is particularly useful in such applications as space heating and cooking. For example, when the circuit is used to control a group of radiators for home heating; TH_1 is attached to a radiator fin to sample the radiator temperature and TH_2 is mounted on the wall to sample the air temperature. As the radiator temperature increases, the resistance of TH_1 decreases and the switch Q_1, Q_2 stops conducting. As the room temperature drops, however, the resistance of TH_2 increases and the higher voltage switching level of Q_3 and

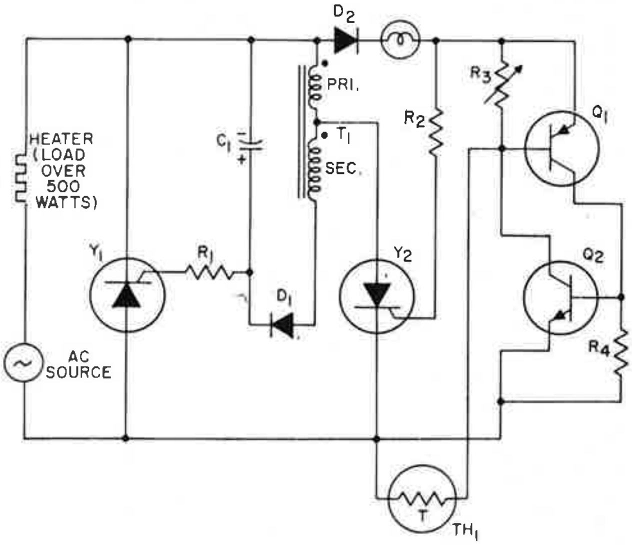

Fig.11 - Control circuit using an auto-transformer (T_1) in place of the "slaving" resistor (R_1) in Fig.10.

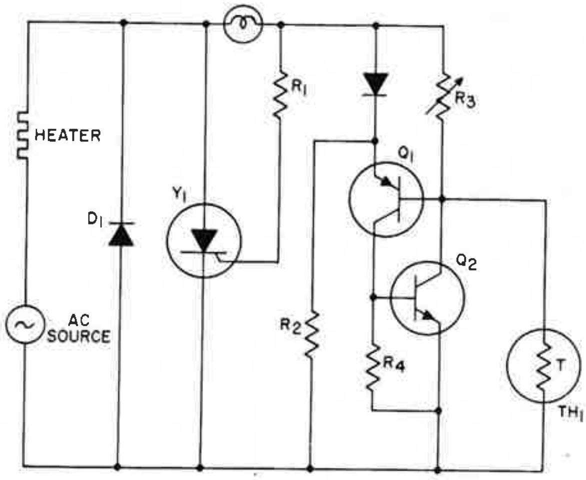

Fig.12 - Heat-modulating circuit using a transistor switch (Q_1, Q_2).

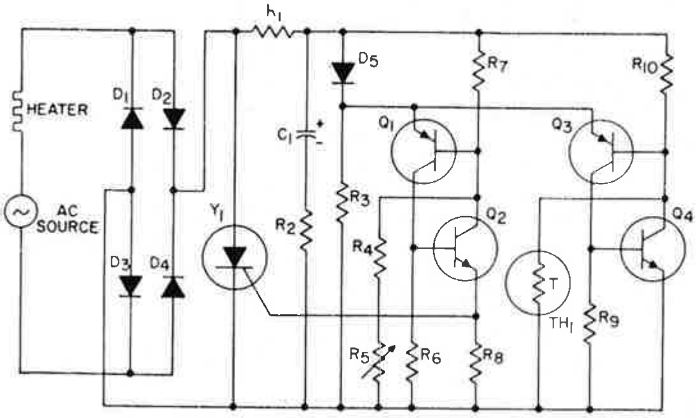

Fig.13 - Control circuit using a second transistor switch (Q_3, Q_4) for improved uniformity and temperature stability.

Q_4 permits the switch Q_1, Q_2 to continue to operate for lower levels of TH_1. In effect, this circuit, which is generally known as an anticipating circuit, adjusts the temperature of the radiator in response to the heat demand.

Fig. 16 shows how additional heat-cutoff circuits can be added to an electronic temperature control. Although as many cutoff circuits as desired can be used, it is usually necessary to adjust R_3 if more than 2 or 3 are required because of the drain effect of each circuit.

Conclusion

The circuits presented have demonstrated some of the possible heat controls that can be developed with solid-state devices. Some disadvantages of the simpler circuits were pointed out, and methods of eliminating them were illustrated. Although the cost of electronic heat control is presently somewhat greater than that of electro-mechanical switches, this cost differential may be outweighed for many applications by such advantages as:

(a) high reliability;

(b) adaptability to unlimited number of operations;

(c) synchronous switching (elimination of radio or television interference);

(d) greatly increased sensitivity;

(e) flexibility to fit almost any requirement with only minor alterations.

It is expected, therefore, that electronic heat control will find wide acceptance and usage in appliances and in domestic heating within the next few years.

With Acknowledgement to RCA

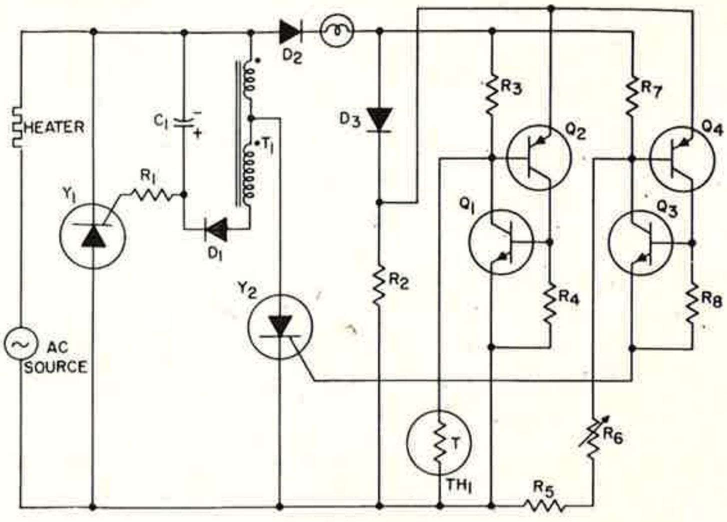

Fig.14 - Circuit using distribution transformer (T_1) and a "ready" light.

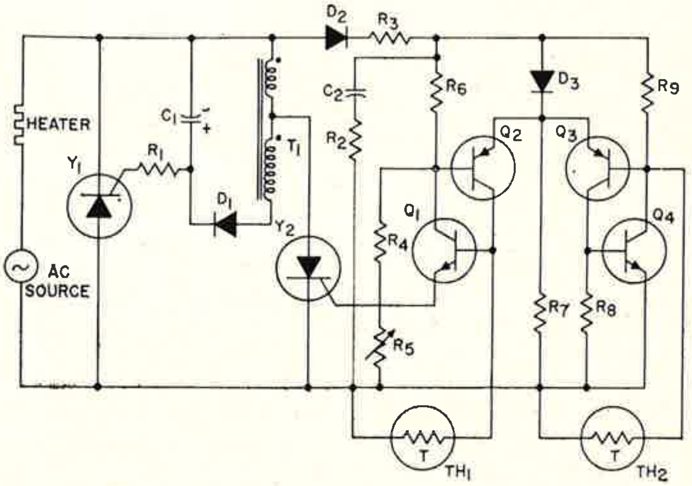

Fig.15 - "Anticipating" control circuit using dual thermistors (TH_1, TH_2) for control.

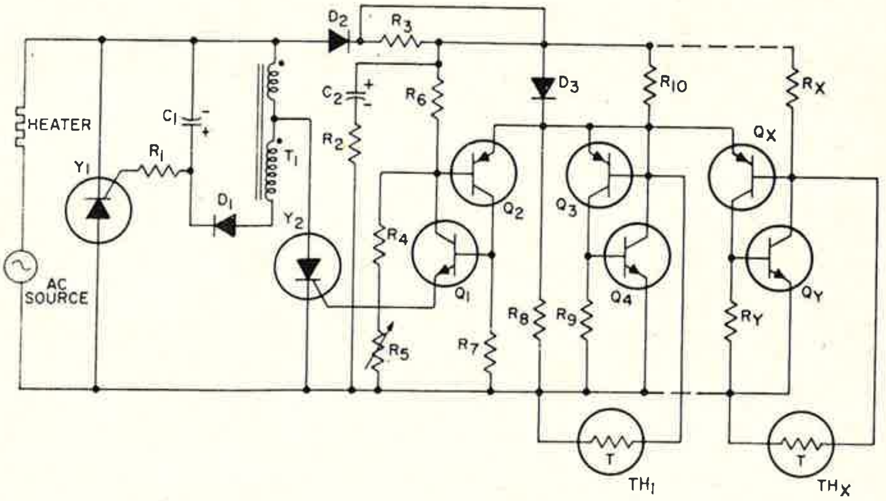

Fig.16 - Temperature control circuit illustrating addition of extra heat-cutoff circuits (Q_x, Q_y).

LOW-LEVEL RF-AMPLIFIER CIRCUIT DESIGN

by
T. J. ROBE

In the design of low-level tuned rf amplifiers, careful consideration must be given to the transistor and circuit parameters which control circuit stability, as well as those which maintain adequate power gain. In addition, if the signals to be amplified are relatively weak, it is important that the transistor and its associated circuit provide low noise figure at the operating frequency. This paper discusses the selection of transistors and the design of circuits which together yield adequate stable power gain with low noise figure.

SELECTING THE TRANSISTOR

Although transistor selection is obviously influenced by the choice between silicon and germanium, and by cost, this discussion will be limited to a selection based upon electrical performance, specifically power gain and noise figure. The relative power-gain capabilities of transistors at high frequencies is indicated by their theoretical maximum frequency of iscillation f_{max}. At this frequency, the unilateralized matched power gain (MAG) is zero db. Fig. 1 shows a curve of MAG (also called maximum available gain) as a function of frequency for a typical rf transistor. This curve shows a rise of approximately 6 db per octave below f_{max}.

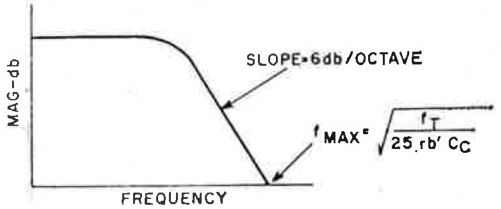

Fig. 1 - Maximum available gain of typical rf transistor as a function of frequency.

The equivalent circuit used to describe the transistor and to evaluate f_{max} in terms of the transistor parameters is shown in Fig. 2.[1] The following expression is obtained from the equivalent circuit for the required condition that MAG = 0 db at f_{max}:

$$f_{max} = (f_T)/(25\ r_b'\ C_c) \qquad (1)$$

where f_T is the current-gain-bandwidth product of the transistor, r_b' is the base-spreading resistance, and C_c is the reverse-biased collector-to-base transition capacitance.

Because a well designed amplifier normally will not provide more gain than MAG and probably will provide less gain because of internal feedback, the transistor used in the circuit must have adequate MAG. If a 6-db-per-octave rise is assumed, the MAG at any frequency f in the 6-db-per-octave region is given by

$$MAG \approx 20\ \log_{10}\ (f_{max}/f) \qquad (2)$$

For high power at high frequency, then, the transistor must have a high f_T and a low collector-to-base time constant $r_b'\ C_c$.

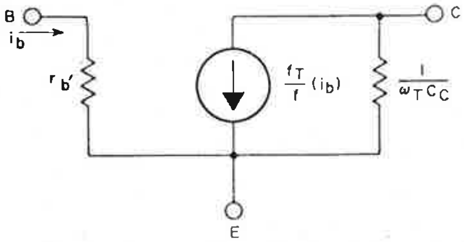

Fig. 2 - Equivalent circuit for rf transistor at frequencies near f_{max}.

Because most practical rf amplifiers are not unilateralized, the maximum usable power gain (MUG) depends upon the amount of internal feedback capacitance, which in general should be as low as possible. A transistor that has a low feedback capacitance in the commonemitter connection generally provides more usable power gain than a transistor that has the same MAG but higher feedback capacitance.

A theoretical expression for junction transistor noise figure (NF) derived by Nielsen[2] is given by

$$NF = 1 + \frac{r_b'}{R_s} + \frac{r_e}{2R_s} + \frac{(r_e + r_b' + R_s)^2}{1 + r_e\ R_s\ \beta o}\left[1 + \left(\frac{f}{f_\alpha}\right)^2\right]\beta o \qquad (3)$$

where r_b' is the base-spreading resistance, r_e is the emitter-diode dynamic impedance ($= 26/I_E(ma)$ ohms), $f\alpha$ is the transistor alpha-cutoff frequency, β_0 is the low-frequency h_{fe}, and R_S is the source reseistance at the transistor input terminals. Fig. 3 shows a curve of this equation as a function of frequency for a fixed values of R_s.

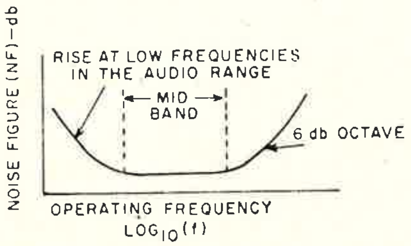

Fig. 3 - Noise figure of a typical rf transistor as a function of operating frequency.

Eq. (3) indicates that transistor rf noise figure depends on four characteristics of the transistor: (1) white noise contributed by the base-spreading resistance r_b'; this factor indicates the importance of keeping r_b' as low as possible; (2) shot noise caused by current in the emitter diode and reflected in the equation by r_e; because r_e appears in the numerator of some terms and in the denominator of others, it is apparent that there is some optimum emitter current for low noise figure; (3) alpha-cutoff frequency, or a reduced correlation between collector and emitter currents as the frequency increases; this frequency should be as high as possible for low rf noise figures; (4) the low-frequency value of h_{fe}; this value need only be moderate for low noise figure.

The transistor requirements for high power gain and low noise figure are essentially the same. The published data for transistors intended for low-level rf applications normally include a minimum power gain and a maximum noise figure in a circuit typical of the intended application. Fig. 4 shows MAG and NF as functions of frequency for the RCA-2N2857 n-p-n silicon planar rf transistor. This transistor has a rated minimum MAG of 12.5 db and a maximum device noise figure of 4.5 db at 450 megacycles.

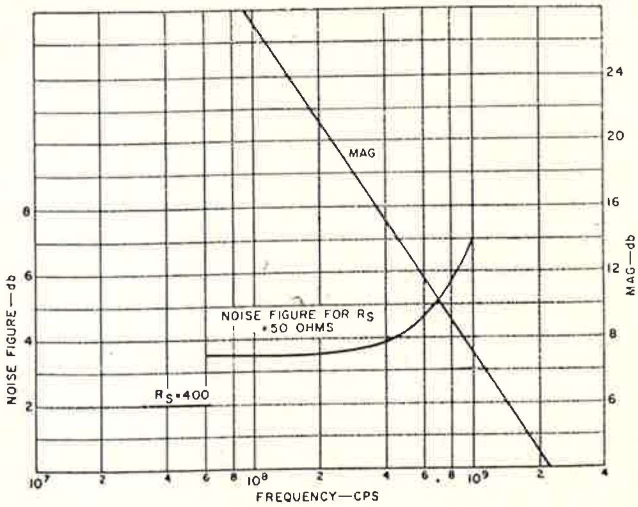

Fig. 4 - Maximum available gain (MAG) and noise figure (NF) of the 2N2857 as a function of frequency.

High reliability versions of the 2N2857 and of the RCA vhf type 2N2708 are being used in various space-communications applications. These high-reliability versions are designated 40294 and 40295, respectively. A high-reliability version of a premium-noise-figure selection of the 2N2857 is designated 40296. For these high-reliability types, extreme care is used in the processing and selection of wafers, and a rigid quality assurance program is followed in the assembly and the electrical testing of the finished transistor. Fig. 5 shows a block diagram of the high-reliability processing program.

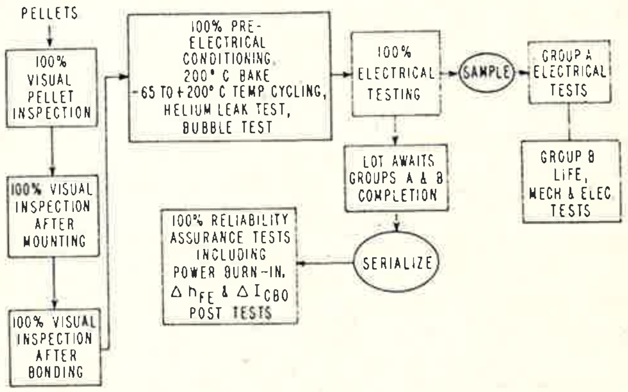

Fig. 5 - Block diagram of high-reliability processing program used for RCA transistors 40294, 40295, and 40296.

DESIGNING THE CIRCUIT

Two objectives must be considered in the design of low-level tuned rf-amplifier circuits, maximum stable power gain and minimum noise figure.

Stable Power Gain

The transistor amplifier can be considered a linear active network characterised by the transistor admittance (y) parameters and the source and load terminating admittances, as shown in Fig. 6. The transducer power gain G_T of the two-port amplifier is given by

$$G_T = \frac{\text{Power Delivered to Load}}{\text{Available Source Power}} \quad (4)$$

$$= \frac{4|y_{21}|^2\, g_S\, g_L}{|(y_{11} + y_S)(y_{22} + y_L) - y_{12}y_{21}|^2}$$

$$y_{11} = g_{11} + jb_{11} \qquad y_{22} = g_{22} + jb_{22}$$
$$y_{12} = g_{12} - jb_{12} \qquad y_S = g_S + jb_S$$
$$y_{21} = g_{21} + jb_{21} \qquad y_L = g_L + jb_L$$

Fig. 6 - Representation of a transistor amplifier as a linear active network characterized by transistor admittance (y) parameters and source and load terminating admittances.

If the two-port amplifier were unilateral (i.e., if $y_{12} = 0$), the source and load could be conjugately matched to y_{11} and y_{22}, respectively, and the transducer gain would be equal to the MAG of the transistor as follows:

$$\text{MAG} = \frac{|y_{21}|^2}{4\, g_{11}\, g_{22}} \quad (5)$$

However, most practical amplifiers are not unilateral. With certain passive terminations (y_S and y_L), therefore, the denominator of 4 in Eq. (5) might vanish and oscillations would be produced. The first problem in the design, then, is to determine whether the amplifier is unconditionally stable regardless of termination. If it is not, then it is necessary to determine what terminations are required to achieve inherent stability (a condition where no adjustment of source and load susceptances can be found which will cause oscillations).

G. S. Bahrs[3] has derived mathematical expressions which establish the criteria for the above conditions of stability. For the active transistor to be stable under any set of passive terminations, the following inequality must exist:

$$g_{11}\, g_{22} > \frac{|y_{12}\, y_{21}| + R_e\, y_{12}\, y_{21}}{2} = \frac{M\,(1 + \cos\theta)}{2} \quad (6)$$

where $R_e\, y_{12}\, y_{21}$ is the real part of the product $y_{12}\, y_{21}$, M is the magnitude of the product $y_{12}\, y_{21}$, and θ is the argument of the product $y_{12}\, y_{21}$. Alternatively, it is shown that if this inequality is not met, the transistor in combination with its conductance terminations can be made inherently stable if the following condition exists;

$$(g_{11} + g_S)(g_{22} + g_L) > \frac{M\,(1 + \cos\theta)}{2} \quad (7)$$

An amplifier circuit which just meets the criteria of Eq. (6) or (7) would be a very marginal design, however, and would have a nonsymmetrical bandpass response. Consequently, an additional safety factor should be included, as shown by

$$(g_{11} + g_S)(g_{22} + g_L) = \rho\, \frac{M\,(1 + \cos\theta)}{2} \quad (8)$$

Although the choice of this safety factor ρ is quite arbitrary, depending on the degree of stability required; Bahrs has given justification for keeping it above 2; for good bandpass response, it is recommended that ρ be between 2.5 and 5.

If the criteria of Eq. (6) are satisfied (including ρ) the optimum values of the source and load terminations are as follows:

$$g_S = \frac{1}{2\, g_{22}} \left\{ [2\, g_{11}\, g_{22} - R_e\,(y_{12}\, y_{21})]^2 - |y_{12}\, y_{21}|^2 \right\}^{1/2}$$

$$g_L = \frac{1}{2\, g_{11}} \left\{ [2\, g_{11}\, g_{22} - R_e\,(y_{12}\, y_{21})]^2 - |y_{12}\, y_{21}|^2 \right\}^{1/2}$$

$$b_S = -b_{11} + \frac{I_m\,(y_{12}\, y_{21})}{2\, g_{22}}$$

$$b_L = -b_{22} + \frac{I_m\,(y_{12}\, y_{21})}{2\, g_{11}}$$

If Eq. (6) is not satisfied, g_S and g_L must be adjusted to satisfy Eq. (8). For this adjustment, either g_S or g_L may be selected and then the other computed, or the input and output mismatch may be set equal (i.e., $g_S/g_{11} = g_L/g_{22} = m$) and Eq. (8) solved for m.

The source and load susceptances which yield maximum power gain are normally adjusted by tuned circuits at input and output. However, it has been demonstrated[3] that the following relation exists for maximum power gain:

$$\frac{b_{11} + b_S}{g_{11} + g_S} = \frac{b_{22} + b_L}{g_{22} + g_L} = \gamma = f\ (\rho,\ \theta) \qquad (9)$$

With known values of ρ and θ, γ can be found from the curves of Fig. 7. Eq. (9) can then be used to calculate b_S and b_L for maximum power gain. Once the source and load admittances are known, the expected transducer gain can be calculated by means of Eq. (4).

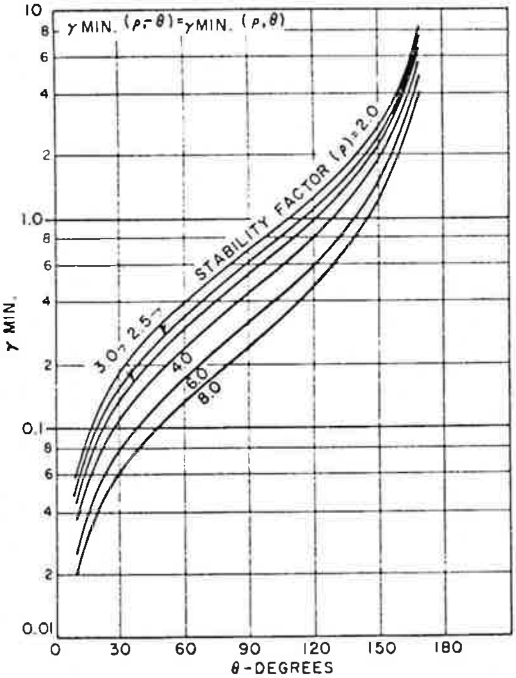

Fig. 7 - Design curves used to calculate γ_{min} $(\rho, -\theta)$ for transistor amplifier.

Low Noise Figure

The design for lowest noise figure includes the following considerations: (1) use of a low-noise transistor; (2) choice of optimum bias current; (3) choice of optimum source resistance; (4) use of low-loss input circuits; (5) use of a transistor rf amplifier and mixer in heterodyne receivers.

The first factor has already been discussed and is repeated at this point only because it is the single most important consideration in the design for low noise. Types such as RCA-2N2857 and 2N2708 are good examples of appropriate transistors.

The optimum low-noise bias current for most low-level rf transistors is about 1 milliampere, although it may be greater in the uhf range because of the need for high f_T. A simple method of determining the optimum current for a given application is to build an amplifier circuit and, using an automatic noise-figure indicator (ANFI), observe the variation in noise figure while varying the bias current.

Fig 8 shows a typical curve of noise figure as a function of the source resistance presented to the transistor. The optimum value of R_S for a given transistor, frequency, and bias current can be determined by means of the following equation:

$$R_S(NF_{min}) = \left[(r_b{}' + r_e)^2 + \frac{(r_b{}' + 0.5\ r_e)(2\beta_o\ r_e)}{1 + (f/f_\alpha)^2(1 + \beta_o)}\right]^{1/2} \qquad (10)$$

For derivation of this equation, Eq. (3) is differentiaed with respect to R_S and the derivative is set to zero.

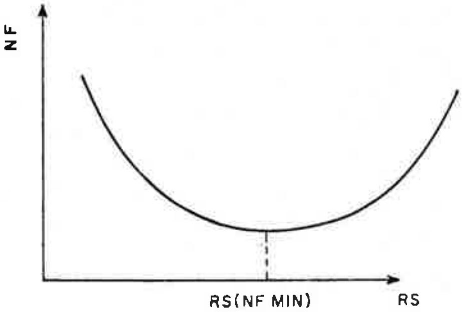

Fig. 8 - Typical curve of transistor noise figure (NF) as a function of source resistance (R_S).

The input circuit to the first stage of the amplifier should have as little loss as possible because such loss adds directly to the otherwise attainable noise figure of the amplifier. In other words, if the loss at the input to the first stage is 2 db, the amplifier noise figure will be 2 db higher than could be achieved with no loss at the input. To minimise such loss, it is generally desirable that the ratio of unloaded to loaded Q of the input circuit be high and that the bias resistors be isolated from the input node by chokes or tank coils, as shown in Fig. 9.

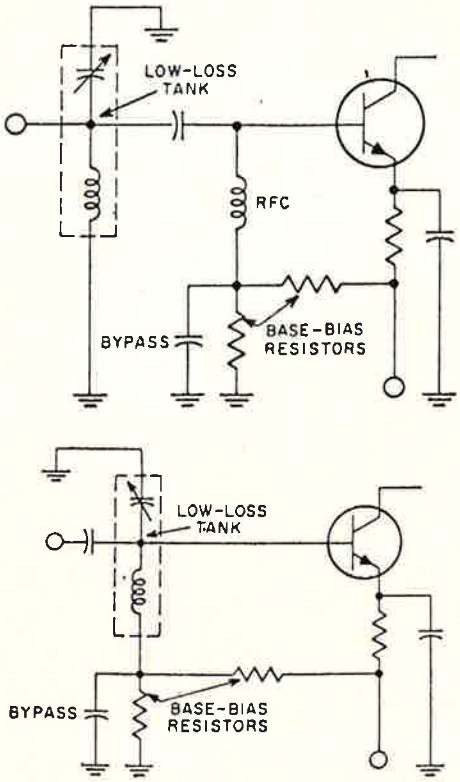

Fig. 9 - Input circuits used to provide low-loss in first stage of transistor amplifiers.

The recommendation that a transistor rf amplifier and mixer stage be used in a heterodyne receiver is based on the following relation for noise figure of cascaded stages:

$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \qquad (11)$$

where F_{sys} is the over-all noise figure of the receiver, F_1 and G_1 are the noise figure and power gain of the first stage in numerics, F_2 and G_2 are those of the second stage, and so on. This equation shows that with sufficient gain in the first stage the system noise figure is almost entirely controlled by F_1; this effect emphasises the advantage of a low-noise rf amplifier. The equation also shows the advantage of a transistor mixer over a diode mixer; the attenuation of the diode mixer (G_2 less than 1) makes the G_1 G_2 product small and magnifies the effect of the third-stage or if noise figure on the over-all system.

With Acknowledgement to RCA

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Important Announcement

Radiotronics' readers please note that effective immediately no new annual subscriptions are being accepted for this publication.

Commencing, January, 1966, Radiotronics will be available quarterly at a cost of 5/- (50c) per copy from the Sales Department, Amalgamated Wireless Valve Co. Pty. Ltd., Private Mail Bag, Ermington, N.S.W.

Readers who have subscriptions current on 31st December, 1965, will receive all 1966 issues without further payment.

Electronic Technology in Medicine

A STATE OF THE ART REVIEW

Electronic techniques and devices are used in medical research, diagnosis, therapy, monitoring and analysis. Ailments are discovered with ultrasonics and isotopes, lasers weld retinas, colour TV monitors sophisticated heart surgery, and computers assist in medical information processing and analysis. Reviewed herein is the present state-of-the-art of medical electronics, including the techniques and instruments now in use in areas of medicine that can be classified as heart engineering, nerve-system engineering, physiological monitoring, prosthetic devices, and medical repairs. In addition to present capability, some current problems and limitations are pointed out that need the attention of electronics engineers. A reference Bibliography to some of the extensive literature in the field is included.

The two applied sciences of medicine and engineering have been searching over the past decade for a common ground. It has been the feeling in engineering circles that medicine and biology could greatly benefit by the application of the principles of the more exact physical sciences.[1] The doctor, on the other hand, is just as anxious to bring to bear on his problems the most up-to-date technology. The two groups have been held apart to a certain extent by a lack of understanding. Each discipline has its own history and its own character and in many cases neither is too sympathetic with the other's mode of expression.

Living systems are difficult to analyse in the terms of the physical sciences, so the engineering approach has been made through many isolated cases rather than through a systematic development of the interdisciplinary area. Many of the first contacts have been made as the result of doctors asking assistance in the operation of new instruments. In the process, the engineer begins to appreciate the problems of dealing with a device as complex and unpredictable as the human system. The doctor, on the other hand, learns something of the limitations as well as the capabilities of engineering methods. Many of the leaders in biomedical engineering today have come from such contacts. The doctors have sought more training in engineering sciences and the engineers in physiology, biophysics, etc. As a result, we are on the threshold of the development of biomedical engineering as a full fledged discipline in its own right. Numerous schools are now offering both undergraduate and graduate courses in biomedical engineering and several are already offering advanced degrees. When this new generation of scientists begins to make its influence felt, the real progress will have begun.

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Accomplishments to date have not been insignificant and the informal, if somewhat uncorrelated, merging of engineering techniques with medical and biological practice has already paid off handsomely in accomplishments, as we can see by looking in detail at a few of the engineering techniques that are being applied to medical problems. We in the electronic field are so interested in the application of electronic techniques to medicine that we created the term *medical electronics* to describe the field. It soon became apparent, however, that possible applications go far beyond electronics into every branch of engineering, i.e., mechanical, hydraulic, chemical, nuclear, etc.

INSTRUMENTATION

However, because instrumentation plays such an important role in most every case, electronics is perhaps the most universally applied branch of engineering in medicine.

Classified according to the use to which engineering techniques and devices are put, they may be used in research, diagnosis, therapy or monitoring with perhaps another justifiable classification, analysis. It was natural that engineering techniques were first applied in the research area in order to gain more insight into the operation of the human machine. As more knowledge is obtained, the techniques are then applied in diagnosis or therapy. (See Table I, which includes a fairly extensive list of examples of current medical instrumentation.

VISUALIZATION TECHNIQUES

Visualization techniques very often play an important part in medicine. The oldest electronic visualization technique is the X-ray itself, which needs no more than a mention at this point. However, a number of electronic devices are now in use as auxiliaries to the conventional X-ray. Some of these are concerned with ways of increasing the brightness of a fluoroscopic image in order to reduce the dosage to which the patient is exposed and at the same time protect the technician from excessive exposure. An image intensifier tube may be used to achieve a high degree of intensification. The intensified image may be viewed directly or for greater convenience may be viewed by a television camera. Some television pickup tubes with proper optical systems are more sensitive than the human eye and may be used to view a fluoroscope screen directly.

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In addition to intensification, electronics can be of help in the study of X-ray images. Because of the flexibility of electronic amplification it is possible to alter the contrast range of an X-ray photograph, selecting and expanding certain contrast ranges at will. Fig. 2 illustrates this contrast enhancement technique.

Television and other scanning techniques find many other uses in medicine.[2,3] The most obvious, of course, is direct observation where the ability of television to transmit visual information to a remote point is used in surgery (Figs. 1, 7), dentistry, medical schools and to provide visual communication between hospital patients and visitors.

The use of television scanning in various analytical processes is very important.[4] The most familiar use is direct observation with the light microscope where the ability of the television system to enlarge and reproduce a microscope image either in monochrome or colour, or translate an image in ultraviolet or infrared into a visible one, can be of great convenience.[5] Television microscopy also permits electronic particle counting and in vivo study of cell metabolism.

HEART ENGINEERING

As another example of an area in which important progress has already been made but which offers a fertile field for further accomplishments, consider the heart. The heart is without a doubt the most important organ in the body. From an engineering viewpoint, it is a mechanically operated hydraulic pump controlled by electricity. The most important measure of performance of the heart is the *cardiac output* — the quantity and pressure of the blood put into circulation with each stroke of the pump. This would be easy to measure if we could insert a meter in the aorta, but it cannot be measured very well in the intact human, so it is necessary to resort to indirect methods. For example, by aiming a beam of ultrasonic energy along the axis of the aorta as it leaves the heart, a doppler measure of blood velocity is obtained. Also, the diameter of the aorta can be measured by injecting a dye and observing it by X-ray; from these measurements the cardiac output can be obtained (Fig. 3).

The pumping energy comes from the contraction of the heart muscle. This action is closely related to and con-

TABLE 1—Current Medical Instrumentation

HEART AND BLOOD VESSELS (BIOELECTRIC POTENTIALS)
Electrocardiography
Phonocardiography
Cardiac output recorders
Cardiotachography
Cine X-ray heart profile recorders
Blood-pressure gauges
Flowmeters
Pacemakers
"Defibrillators"
Heart valve prostheses
Blood vessel prostheses

RESPIRATORY SYSTEM
Respiration rate
Oxygen consumption gauges
Inhaled gas analyzers
Hyperbaric chambers
Respiratory aid apparatus
Diaphragm-nerve stimulators

CENTRAL NERVOUS SYSTEM
Electroencephalography
Ultrasonic encephalography
Brain, nerve stimulators
Implanted electrode techniques
Microelectrodes
Nerve impulse recorders
Integrators
Cryosurgery

SPECIAL SENSE SYSTEMS—HEARING
Acoustic stimulation
Hearing prostheses

SPECIAL SENSE SYSTEMS—SPEAKING
Voice analyzers
Larynx prostheses

SPECIAL SENSE SYSTEMS—SEEING
Optometry
Electroetinography
Intra-ocular tension recorders
Eye movement gauges
Nystagmus recorder
Retinoplastic, thermic and laser beam surgery
Prostheses for the blind

DENTISTRY & SURGERY
Radiography
Telemetry
Focused ultrasonic surgery
Cryosurgery
Electro-cauterization, coagulation
Suturing instruments

OTHER CLINICAL SPECIALTIES
Devices to see inside body
Surface, depth thermometers
Skin voltage, resistance gauges
Telemetry gear to measure temperature, pH, study dynamics of stomach, intestines, uterus, etc.
Infrared recorders

CLINICAL LABORATORY SPECIALTIES
Blood and other cell counters, differentiators
Blood colour analyzers
Flame photometry
Liquid, gas phase chromatography
Sample collectors
Microchemistry apparatus

RADIOLOGY, RADIOISOTOPES
X-ray apparatus
Radiation detectors, dosimeters, spectrometers
Scintillation counters
Image intensifiers, TV systems
Synchronizers
Radiotherapy equipment
Particle accelerators
High energy isotope therapy

MUSCLES AND SKELETON
Nerve impulse recorders
Electromyography
Nerve, muscle stimulators
Bone, limb and articulation prostheses

ANAESTHESIOLOGY, REANIMATION
Gas analyzers
O_2 saturation photoelectric meters
Monitoring systems
Oxygen tents, equipment
Anaesthetic gas apparatus
Breathing apparatus
Pump oxygenators
Dialyzers
Servo-anaesthesia systems

PSYCHOLOGY, PSYCHIATRY
Behaviour monitor systems
Programming apparatus
Electro-narcosis equipment
Electro-convulsive treatment equipment

NOTE: This data was gathered and categorically listed by Dr. John F. Davis, Director, International Institute for Medical Electronics and Biological Engineering, Paris.

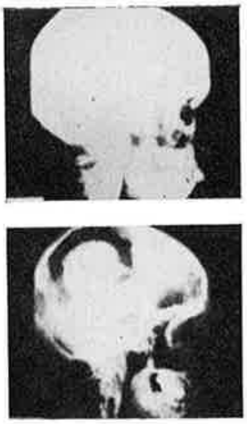

Fig. 2—Contrast enhancement by television techniques. The top photo is the original X-ray while the lower is the same X-ray after contrast enhancement.

trolled by an electrical discharge. Every action of the heart muscles and the valves results in or results from a change in the electrical activity.

We would like to measure this electrical activity deep within the heart. However, we cannot place our electrodes in the right place except during an operation. So, we must usually be content to measure electrical potentials on the surface of the body and deduce from these measurements what actually goes on inside the heart. Electrically, the body acts as a quasi-cylindrical container of salt water, and a lot of research has gone into a determination of what happens to heart potentials as they find their way to the surface of this odd-shaped volume — this is *electrocardiography* and is one of the oldest of the applications of medical electronics. By a combination of basic research and empirical correlation, it has long since emerged from the research laboratory and is used in everyday clinical diagnosis. This is not to say that it is completely understood or that all of the information carried by the electrocardiogram can yet be interpreted. In recent years, three-dimensional *vector cardiography* (Fig. 5) has been studied, using twelve or more electrodes and sophisticated stereo-type displays in order to learn more about the way in which the heart operates. Relatively simple techniques for inserting electrodes, pressure transducers, or miniature microphones directly into the heart by means of catheters inserted through a vein in the arm have been worked out and are daily contributing new information.

Open heart surgery to correct congenital defects or heart difficulty due to accident or disease has become almost as commonplace as any other major surgery. It is hard to realize that many of these operations could not have been attempted even a decade ago. They have been made possible largely by the heart-lung machine, which is a combination pump and oxygenator which is temporarily used to by-pass the heart and lungs so that the natural organs can be repaired (Fig. 8). When the heart is again connected into the system, it must often be coaxed into normal operation in a manner which will best be understood after a brief explanation of the manner in which the heart muscle is triggered or stimulated.

The main heart muscle, the ventricular muscle, if left unexcited, will normally contract rhythmically at 10 to 20 beats per minute. In the right auricular region, there is a small bundle of specialized tissue, called the sino-auricular node, which generates an impulse at the normal heart rate of the order of 60 to 80 beats per minute. This impulse is conducted over a bundle of nerve fibres to the ventricles and acts as a synchronizing pulse to stimulate the ventricular contraction. After the shock of heart surgery, regions of the muscular tissue may rhythmically contract, but in a random and unco-ordinated manner called *fibrillation*. In this case, a strong electric shock may stop the fibrillation and cause the entire muscle to contract together. In the past, such defibrillators have been as crude as two flat, paddle-shaped electrodes connected to a plug which was momentarily inserted into a wall outlet by an assistant to the surgeon. This procedure has since been refined. In spite of defibrillation, the heart may not start normal contraction after surgery. It is often necessary to apply an artificial stimulating pulse to the heart from an external *pacemaker*. This is satisfactory in cases where external stimulation is needed only for a short time until the natural pacemaker regains control. In cases of heart damage where the natural pacemaker is no longer effective, an external pacemaker is not satisfactory because the body tends to reject foreign materials and an infection invariably results at the point of entry of wires.

In these cases, a permanently implanted pacemaker is indicated.[6] Such devices have been built with projected battery life of 5 years. There are now an estimated 5,000 patients leading relatively normal lives with their hearts continuously stimulated by implanted pacemakers (Fig. 4).

The heart-lung machine is in reality an artificial organ. Another device now saving lives is the artificial kidney,[7] which substitutes for the natural kidney but in its present form requires weekly hospital visits by the patient. It appears only a matter of time until the tech-

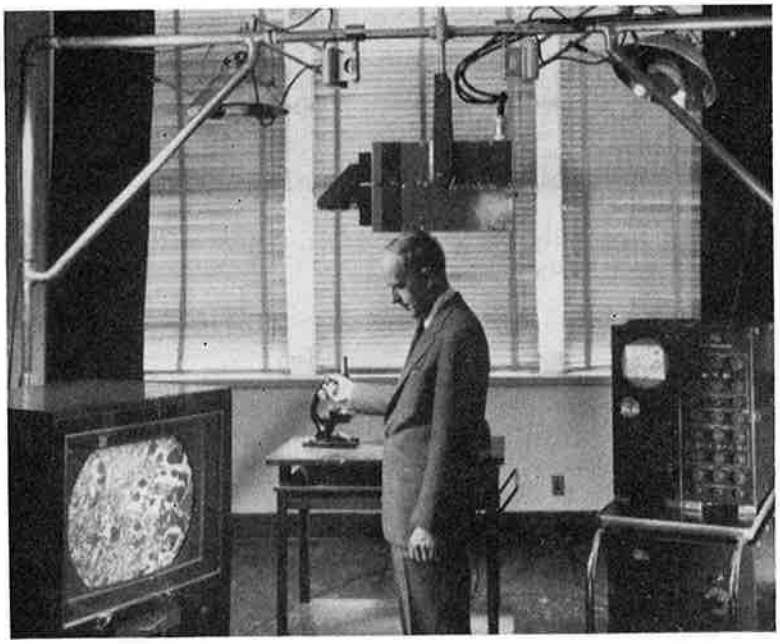

Fig. 1—The author, L. E. Flory, and a colour TV system used to display images from a light microscope.

niques in these areas will be combined to produce completely implanted artificial organs including the heart[8] and kidneys.

Surgeons today frequently instal synthetic "spare parts" in the cardiovascular system. Artificial heart valves made of Teflon have been installed, and it is relatively common to correct even large aneurysms by replacing a section of blood vessel with one made of woven Dacron.

NERVE-SYSTEM ENGINEERING

As with the heart and almost any other active tissue of the body, the activity of the brain and nerve tissue is accompanied by an electrical phenomenon. The nerve signals pass from cell to cell as an electrochemical action which involves a delay which appears as a transit time. The electrical potentials generated in the process carry information regarding the activity in the brain or nerve cells. As with the heart, it is difficult to record from the surface of the skull in the intact human the activity of individual cells deep within the brain because every cell is surrounded by millions of others, all generating electrical potentials. What we do observe on the surface is a pattern of voltages varying in time which can be recorded in a recognizable manner. Rhythmatic variations are found which can be associated with mental activity, relaxation, sleep and wakefulness. The patterns observed during such abnormal activity as an epileptic seizure are clearly differentiated from normal waves. To learn more of what goes on in the depths of the brain without inserting electrodes, the main problem is that of signal-to-noise. When the signal to be studied is a rhythmic one or, as often the case, a response to a stimulus, the wanted signal can be lifted above the noise by integration. Special purpose computers are available for this purpose.

The relationship between the brain's functions and the voltages observed helps the doctor diagnose troubles and leads him to therapeutic measures. In brain surgery, the electroencephalographic waves (EEG) can be observed as the surgeon probes the brain to determine where it is safe to cut to avoid damage to vital nerve fibres which may affect the operation of parts of the brain remote from that being operated on. In the case of Parkinson's disease,[9] it is known that a tiny volume of brain tissue deep inside must be deactivated to relieve the symptoms. The brain is well mapped so the surgeon knows pretty well where the offending cells are located. With very precisely engineered mechanical devices, EEG electrodes are inserted and moved about to find the exact area. Once this is done, the same instrument permits the insertion of another electrode which can provide an electrical shock. A mild shock is applied and if the precise area has been located, the symptoms cease for a few seconds or so. In this case, a greater shock can be applied which permanently destroys the offending tissue. Alternatively, the destruction can be carried out by a cryogenic process or by a drop of chemical.

Fig. 3—This doctor is injecting a dye-indicator into the left side of his patients heart to detect a suspected abnormal hole inside the heart. To do this, he inserted a catheter in a leg vein and threaded it into the left heart chamber, a catheterization technique developed at the National Heart Institute called "transseptal catheterization". (Courtesy of National Institutes of Health.)

PHYSIOLOGICAL MONITORING

Monitoring the physiological variables (Fig. 6) of a patient during an operation or in intensive care requires a formidable array of equipment.[10] To maintain control of a patient's reaction to anaesthetics and to the surgery, the anaesthetist needs to monitor not only the usual variables of heart rate, temperature, blood pressure and respiration, but may also need to know the rate of blood flow in a transfusion, the oxygen in the blood as indicated by an oximeter and the partial pressure of gases in the inhaled and exhaled air. Help in sorting, correlating and analyzing this information would be welcome.

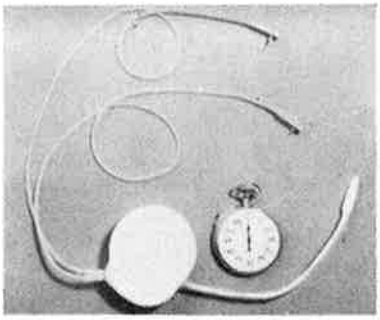

Fig. 4—Implantable Cardiac Pacemaker. (Courtesy of Mennen-Greatbatch Electronics, Inc.)

Physiological monitoring is being extended into post-operative wards, intensive care areas and in some cases where only routine nursing care is required. Certainly, techniques are available to instrument this function even though the experience to date has not been overwhelmingly successful. More study and experience is needed before it can be determined how completely a patient can be instrumented before the system becomes too cumbersome to be practical.[11]

Monitoring of less-routine parameters is now being carried out by means of tiny self-transmitting radio telemetry devices which are attached to the body, ingested into the intestinal tract, or implanted in the body. Present developments in integrated circuits and other miniaturization techniques are contributing rapidly to these areas. One prob-

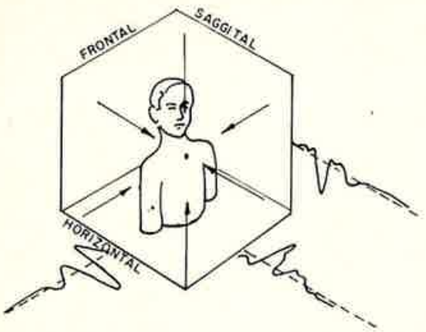

Fig. 5—This principle of vectorcardiography provides a three-dimensional perspective view of heart activity by modulating brightness and size of scope trace. (Courtesy of "International Science and Technology".)

lem common to all active implanted devices is that of supplying the power, although the demand may be small, for long periods. In the pacemaker, for example, 90% of the weight is in the batteries necessary to operate the device over a satisfactorily long operating life. To overcome this limitation, several approaches are being investigated—such as secondary cells recharged by inductive coupling from outside the body, biologically powered devices operated by muscular action, or spring-operated devices that are wound magnetically.

Numerous ingested and implanted monitoring devices have been developed and used, some powered by internal batteries and others externally powered by various means.[12,13,14]

PROSTHETIC DEVICES

Various engineering devices have been devised to relieve the handicapped. Guidance devices as well as reading aids have been made to aid blind subjects. None have been very successful, perhaps because we do not yet know enough about the information processing system of the brain to be able to feed the information to the subject in the proper manner.

Prostheses for limbs has been given considerable research attention.[15] An electrical muscle stimulator operated by a switch on the heel of the shoe facilitates walking by patients who have been deprived of normal control of leg muscles. Artificial hands operating by means of sensors and feedback systems are being produced in some quantities in Yugoslavia.[16] Buttons on the arm are depressed by the other hand to program the hand. A variation of this method uses the voluntary twitching of muscles in the intact part of the arm to operate the controls.

A further development in this direction makes use of biological potentials for control. Potentials generated by muscular activity appear on the surface of the skin where they can be sensed and coupled into the control circuits of a prosthetic limb. Quite sophisticated circuits for analysis and recognition of patterns in these myographic potentials are possible and with modern microcircuitry techniques can be quite practical. The problem of supplying power for artificial limbs (which can require considerable power for lifting) is difficult and needs further investigation.

MEDICAL REPAIRS

Repairing parts of the body damaged in accidents, reconstructive surgery (already mentioned in connection with the artificial heart and kidney but actually much more extensive), substitution of live tissue from other parts of the body or from a "bank" and many other repair jobs from simple broken bones to transplanting of complete muscles, involve many engineering techniques. Any organ replacement or transplantation or replacing a severed limb requires the joining of literally hundreds of blood vessels. The more complete the union down to the smallest vessel, the more chance the operation has of success. An important contribution of mechanical engineering has been the development here and abroad of stapling devices[17] which can, in a single stroke, completely join the two ends of a vessel. Time is of the utmost importance in these cases, and the greater speed with which vessels may be joined and circulation restored contributes greatly to the patient's chances. More recently work has been done to improve techniques of electrocoagulation of tissue for suturing blood vessels. This involves the adaptation of RF dielectric heating techniques to coagulate the tissue to exactly the proper extent to provide maximum adhesion. It is felt that natural healing occurs most rapidly with this type of bonding.

Other special tools for retrieving swallowed objects or for performing other manipulatory or even surgical procedures in inaccessible places has drawn heavily on the ingenuity of engineers with remarkable results.

Even the designer of submarines has been called upon to apply his knowledge to provide practical hyperbaric chambers[18] in order that the advantages of high pressure (2 to 4 atmospheres) and high concentrations of oxygen can be made available to patients suffering from oxygen deficiency due to heart insufficiency, carbon monoxide, or other poisoning which destroys the oxygen carrying capacity of blood cells, or gangrenous infections which are often miraculously cleared up by high oxygen pressure.

INFORMATION PROCESSING AND ANALYSIS

Information of a recurrent nature such as EKG or EEG and that recorded on a time basis in response to a stimulus carries a great amount of information which must be extracted by some sort of analytical process. In the simplest

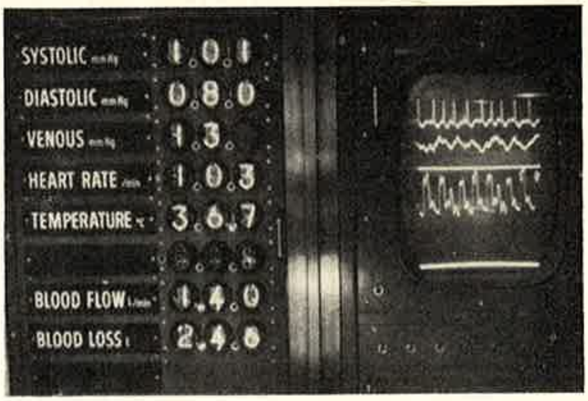

Fig. 6—Physiological parameters are recorded continuously and displayed digitally and as waveforms within a surgical team's glance. (Courtesy of National Institutes of Health.)

case the doctor visually studies the EKG and looks for abnormalities in the height, shape or position of some anticipated elements of the waveform, or for unexpected artifacts which may indicate malfunction. To search for more subtle correlations or to analyze waveforms as complicated as those in vector cardiography or electroencephalography requires a degree of analysis beyond that which one can expect to accomplish by visual examination. Computer analysis of these waveforms is being actively investigated[19,20] and promises to extract many unsuspected correlations from rather routine waveforms. Pattern recognition in waveforms or by scanning two-dimensional plots of information, particle sizing, counting and selection and many other time-consuming tasks, many of them beyond human capacity, are now being undertaken by computers.

Medical diagnosis requires a special type of pattern recognition, a search for correlations in pathological features. The problem in this case is not hardware, because computers exist which have enormous memories and the immediate access necessary. Rather, the problem is in the organization of the data. More thought is needed by doctors on the logic and the process of making a diagnosis and how to feed the medical information into the computer so that it can use the data the way the doctor does in making a diagnosis. Of course, as more is learned about how the information can be handled by the computer, completely new logic steps may be developed to assist the doctor in making more accurate diagnoses. At the very least, once the medical information can be written in computer terms, the doctor will be provided with a memory and retrieval system which will far outstrip his own both for capacity and accuracy and permit him to expend his energies in more fruitful endeavours.

Fig. 7—The use of colour television in the operating room during major heart surgery.

Fig. 8—Complex open-heart surgery can now be performed that was an impossible risk a few years ago; a patient's heart and lungs can now be by-passed for up to six hours without irreversible damage to the brain or other organs through the use of pump-oxygenator, heart-lung machine shown at right and plugged into floor pedestal. (Courtesy of National Institutes of Health.)

CONCLUSIONS

While I have indicated numerous examples of engineering and instruments being used, the medical field is by no means receiving all of the technical help it can use. Many of the devices are still experimental and costly and many of them are far too complicated and temperamental to receive wide-spread use. The developments so far have served to point up possible applications as well as some of the problem areas. The real answers to the challenges to engineering in medicine are still around the corner.

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