Checking DC Parameters of Transistors

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Test circuits for many transistor parameters have been combined to produce a versatile, easily operated tester suitable for large scale parameter distribution studies.

The instrument described in this article was designed to facilitate a study of parameter distributions involving relatively large numbers of germanium and silicon transistors. It is simple to operate and provides accurate and reproducible measurements of transistor dc parameters such as collector-base reverse breakdown voltage BV_{CBO}, static short-circuit forward current transfer ratio h_{FE}, between collector and base currents, collector-base and collector-emitter reverse saturation currents I_{CBO} and I_{CEO}, and emitter-base floating potential V_{EBF}. [1] Although these were the parameters of most interest, it is clear that minor modifications of the apparatus will allow similar quantities involving simple permutations of electrodes, such as BV_{EBO} and V_{CBF}, to be measured.

Fig. 1 shows block diagrams of measuring circuits for each of the above quantities; by appropriate switching these circuits were combined in a single unit. The main elements used in the blocks are a dc VTVM, a constant-current supply, and a feedback amplifier.

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Common VTVM

The use of the same VTVM in all six of these measuring circuits is, of course, desirable but puts very stringent requirements on this instrument when high accuracy is required. For example, in Fig. 1-a it must indicate voltages between about 1 and 300 volts and in Fig. 1-f voltages between 10^{-3} and 10 v. It must not load either of these circuits appreciably. For the remaining measurements, it is used to indicate current, with a maximum voltage of 0.1 v. This low value is required so that true short-circuit conditions are well approximated when necessary and the voltage across the measuring resistor is a negligible fraction of the applied voltage.

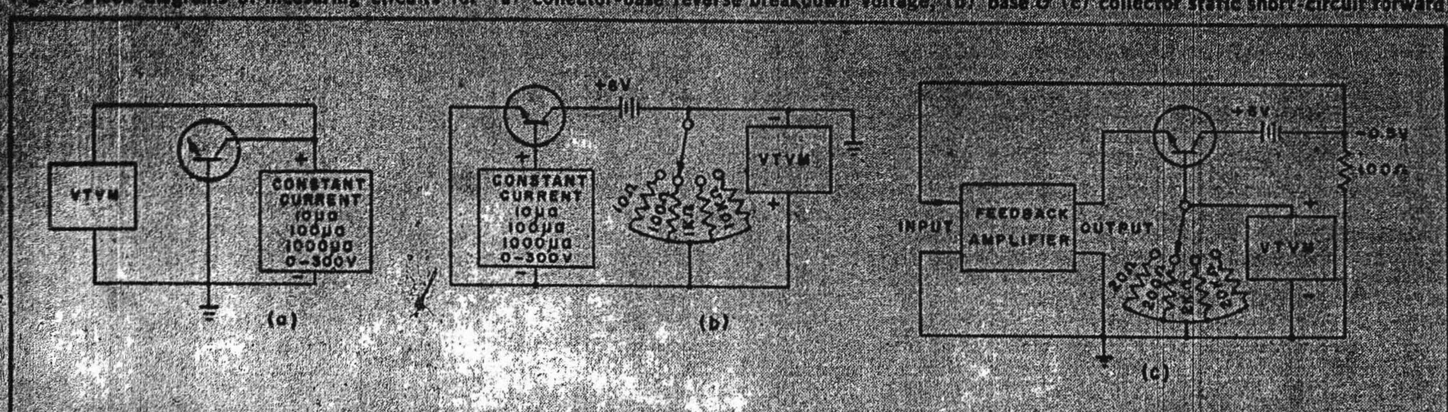
These voltmeter requirements were resolved through the use of the Fluke Model 801 bridge-type VTVM. The unknown voltage is balanced against an accurate internal standard and the measured value is read from the dials of five calibrated switches; at balance the input impedance is infinite.

The maximum reading is 500.00 v. and the minimum resolvable reading is 0.00005 v. Thus, for the above current measurements with 0.1 v. full scale, values within the range of interest, 0.0999 to 0.0100 v., are indicated with three figure accuracy. The use of 0.01 v. full-scale rather than 0.1 v. allows the measurement of currents a factor of ten lower but with corresponding loss in accuracy.

Block Diagrams

Before discussing the other elements of the block diagrams in detail, several of these diagrams themselves require comment. The constant-current supply of Fig. 1-a generates and holds accurately con-

Fig. 1: Block diagrams of measuring circuits for (a) collector-base reverse breakdown voltage, (b) base & (c) collector static short-circuit forward



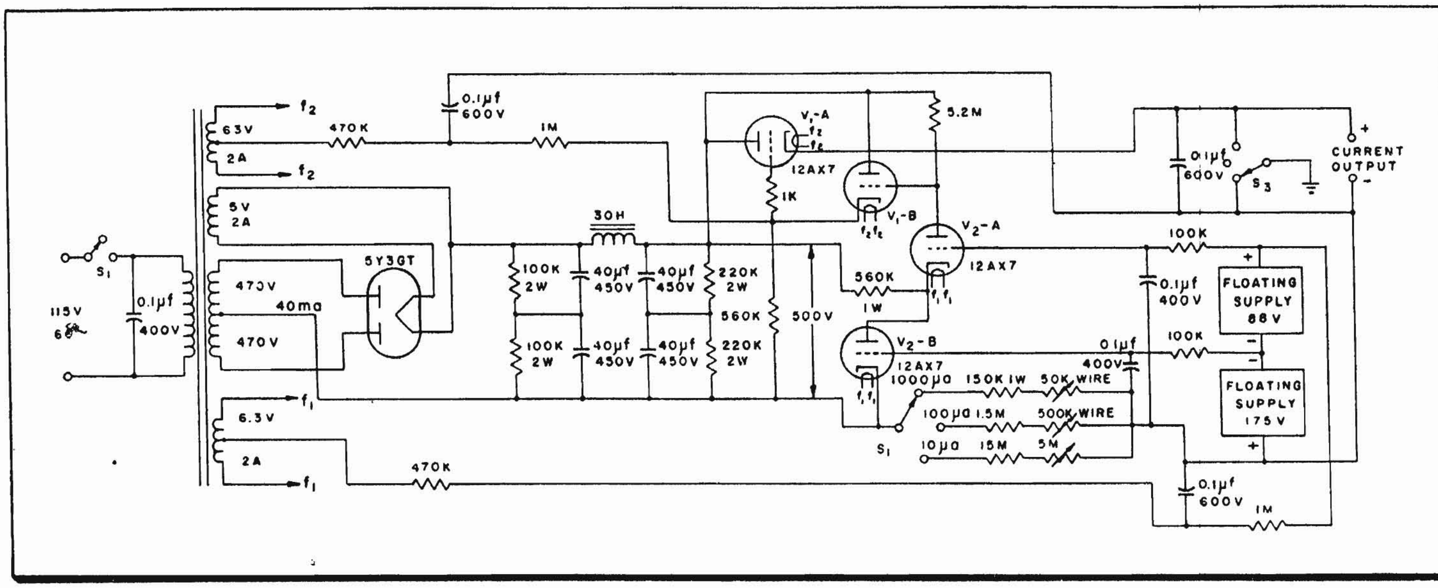


Fig. 2: The constant current supply. The capacitors bridging the floating voltage supplies contribute to the speed of circuit response.

stant any of the three indicated currents in the range of 0 to 300 v.

For collector-base breakdown measurements, the value of 100 μa reverse current has been arbitrarily set as that current at which the breakdown voltage is to be measured. This value is selected to be large compared to ordinary values of I_{CBO} yet small enough to avoid appreciable transistor heating. For silicon transistors, with I_{CBO} values generally less than 0.1 μa, a constant current of 10 μa may be employed but the BV_{CBO} value obtained is usually very close to that found using 100 μa.

Figure 1-b shows a method of measuring h_{FE} in which the base current is held constant at 10 or 100 μa. The current-indicating resistor values are so selected that h_{FE} may be read directly on the VTVM. All current-indicating resistors are adjusted to within 0.1 percent of their indicated values. Table I shows the full-scale values of h_{FE} obtained with 0.1 v. across the various resistors for the two base-current conditions. By measuring h_{FE} for both base currents, an indication of its dependence on current is obtainable. Other values of base current could, of course, be used if desired.

Constant Current

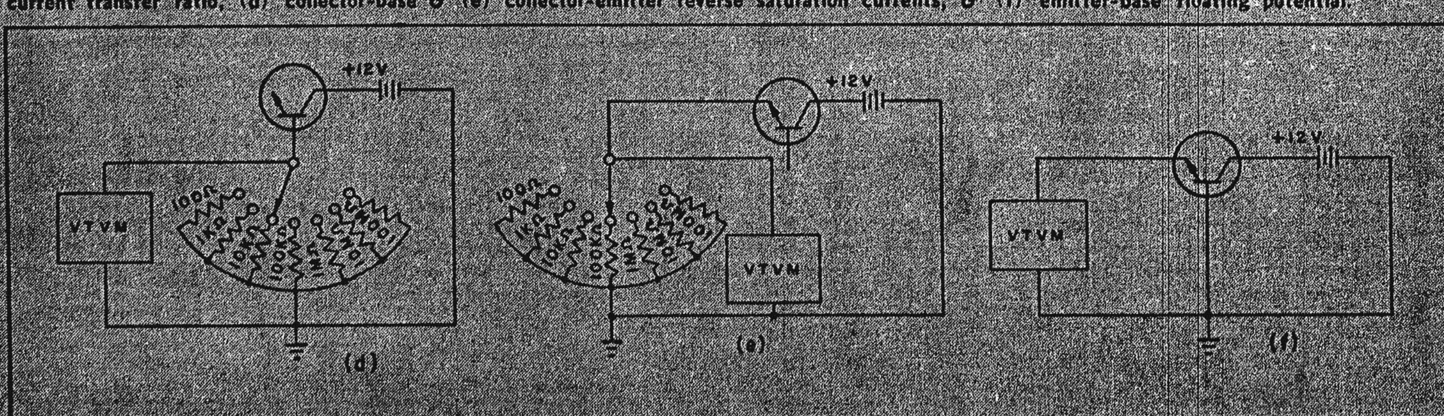
It has become conventional also to measure h_{FE} with a constant collector current, often specified as 5 ma. Figure 1-c shows how h_{FE}^{-1} can be obtained for this operating condition. When 5 ma. is flowing in the collector circuit, −0.5 v. appears across the precision wirewound 100-ohm resistor. This voltage is accurately balanced in the direct-coupled feedback amplifier against an internal stabilized source of −0.5 v. The output of the amplifier, which can supply 15 ma or more of current, is thus constrained to furnish exactly the emitter current which leads to 5 ma of collector current. The resulting base current is then directly read on the VTVM with the full-scale values of h_{FE}^{-1} shown in Table I. These values may be then converted to h_{FE} readings.

Because of the limitation on amplifier output current, a minimum of about 0.3 is set on the value of h_{FE} measurable by this method with 5 ma. collector current. A transistor having this small a value of h_{FE} is virtually useless, however. By changing the amplifier internal reference voltage, and/or the value of the 100-ohm resistor, measurements may be made with constant collector currents other than 5 ma.

It will be noted that in Fig. 1-d and 1-e full-scale currents less than the minimum value of 10^{-3} μa shown in Table I may be read by either measuring voltages in the range of 0.0099 to 0.0010, by using current-indicating resistors greater than 10^8 ohms, or by both changes. When measuring currents of 10^{-4} μa or less by these methods, accuracy is reduced and balance becomes more time-consuming.

Finally, it should be pointed out that the circuit of Fig. 1-f allows

current transfer ratio, (d) collector-base & (e) collector-emitter reverse saturation currents, & (f) emitter-base floating potential.



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the true floating potential to be measured since there is no VTVM loading at balance. Although the circuits of Fig. 1 are arranged to measure NPN transistors, only superficial changes are required to convert to PNP types.

Parameter Transformation

We have discussed two methods of determining the static short-circuit forward current transfer ratio $h_{FE}=I_C/I_B$. Since I_C contains a contribution from I_{CBO}, the latter's magnitude will affect the value of h_{FE} obtained. For many purposes, however, it is desirable to obtain the dynamic small-signal forward transfer ratio, h_{fe}, which includes no direct contribution from I_{CBO}. In this section we shall show how h_{fe} can be obtained from dc measurements of such quantities as I_{CBO}, I_{CEO}, h_{FE}, I_B, and I_C.

For an NPN junction transistor in its linear region, we may write to a good order of approximation

$$I_C = I_{CBO} + h_{fb}I_E, \qquad (1)$$

$$I_E = -(I_B + I_C). \qquad (2)$$

It may be mentioned that the quantity h_{fb} has been previously

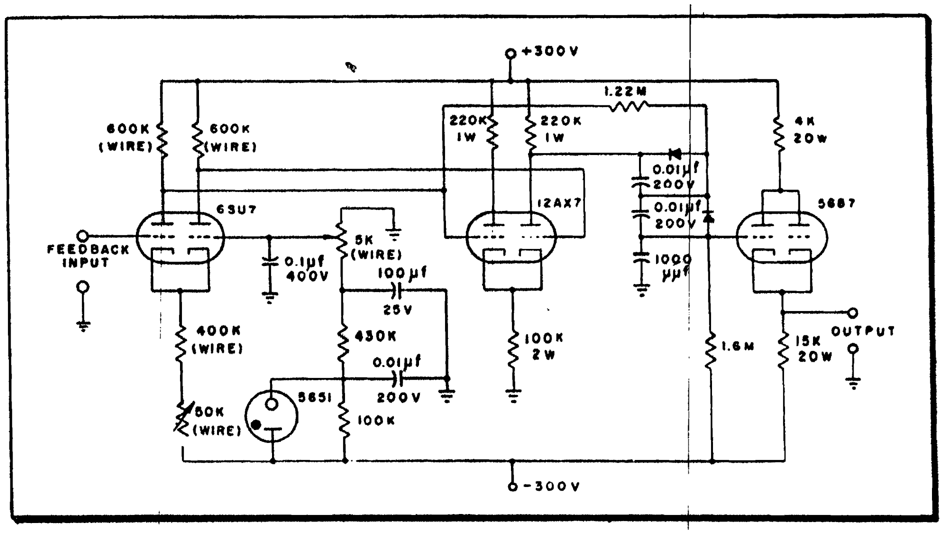


Fig. 4: Feedback amplifier varies emitter current to maintain fixed collector current.

designated as α and is negative. Now from (1) and (2) it follows that

$$I_C = (1 + h_{fb})^{-1}(I_{CBO} - h_{fb}I_B). \qquad (3)$$

To simplify this result further we may use the well-known relation

$$h_{fe} = \frac{-h_{fb}}{(1 + h_{fb})} \qquad (4)$$

obtaining,

$$I_C = (1 + h_{fe})I_{CBO} + h_{fe}I_B. \qquad (5)$$

Finally, if we open circuit the base lead so that $I_B=0$, (5) leads to

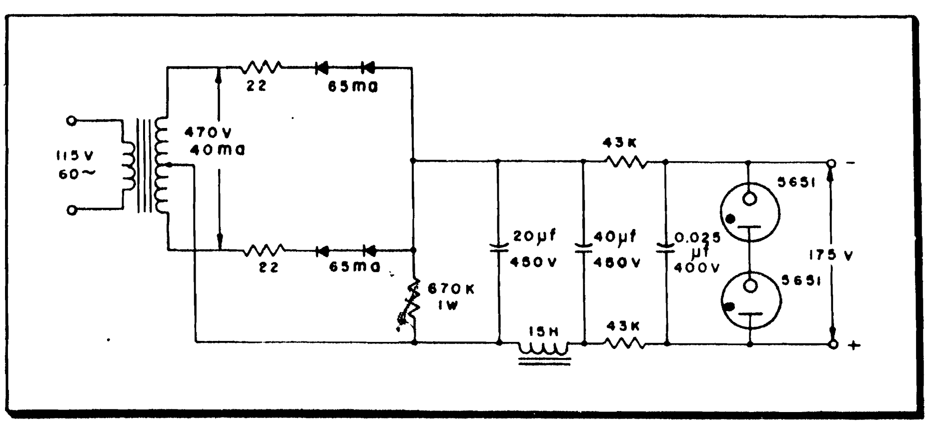
$$I_{CEO} = (1 + h_{fe})I_{CBO} \qquad (6)$$

and,

TABLE I

h_{FE}			h_{FE}^{-1} with I_C = 5 ma.		I_{CBO}	
Resistor Value Ohms	Full Scale Reading I_B = 10 µa	Full Scale Reading I_B = 100 µa	Resistor Value Ohms	Full Scale Reading	Resistor Value Ohms	Full Scale Reading (µa)
10	10^3	10^2	20	1	100	10^3
100	10^2	10	200	10^{-1}	1K	10^2
1K	10	1	2K	10^{-2}	10K	10
10K	1	10^{-1}	20K	10^{-3}	100K	1
					1M	10^{-1}
					10M	10^{-2}
					100M	10^{-3}

Fig. 3: One of the two floating voltage supplies



$$h_{fe} = \frac{I_{CEO}}{I_{CBO}} - 1 \qquad (7)$$

Thus, h_{fe} can be calculated from measurements of only I_{CEO} and I_{CBO}. Since h_{fe} may depend on I_C, the value of h_{fe} calculated from (7) must be specified as that at the collector current of (6).

Next, we need relations between h_{fe} and the measured h_{FE}. Using the definition of h_{FE}, we may rewrite (5) as

$$h_{FE}I_B = I_{CBO} + h_{fe}(I_{CBO} + I_B) \qquad (5')$$

yielding,

$$h_{fe} = \frac{h_{FE}I_B - I_{CBO}}{I_B + I_{CBO}}. \qquad (8)$$

Eq. (8) shows that $h_{fe} \cong h_{FE}$ only when I_B and I_C are large compared with I_{CBO}. When this condition is not satisfied, knowledge of I_B and I_{CBO} as well as h_{FE} is required to calculate h_{fe}. For a given I_B, such as that specified in Fig. 1-b, the value of I_C to which this h_{fe} corresponds may be calculated from $I_C = h_{FE}\,I_B$.

Finally, it is sometimes advantageous to eliminate I_B in (5) obtaining

$$I_C = I_{CBO}(1 + h_{fe}) + h_{fe}h_{FE}^{-1}I_C. \qquad (5'')$$

which leads to

$$h_{fe} = h_{FE}\left(\frac{I_C - I_{CBO}}{I_C + h_{FE}I_{CBO}}\right). \qquad (9)$$

When I_C and I_B are again large compared with I_{CBO}, this equation shows that $h_{fe} \cong h_{FE}$; otherwise, I_C, I_{CBO}, and h_{FE} are needed to calculate h_{fe} for the value of I_C at which measurements were carried out.

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Constant Current Supply

The circuit of this supply is shown in Fig. 2. It is designed to supply accurately constant current over an output voltage range of 0 to 300 v. Three currents, 10, 10^2, and 10^3 µa are available but others both within and outside this range could be obtained with only minor modifications.

Two floating voltage supplies are used in the constant current supply. The circuit of one of them is presented in Fig. 3. It is conventional except that both output terminals are isolated from ground. The 88-v. supply is similar except that only one 5651 stabilizer tube is employed, together with larger isolating resistors.

Circuit Operation

Operation of the circuit is as follows. The external current to be held constant flows also in the series resistors adjacent switch S_2. The resulting voltage drop (near 175 v.) minus the bias necessary for tube V_2-B is balanced against the highly stabilized output of the 175-v. floating supply. Any differ-

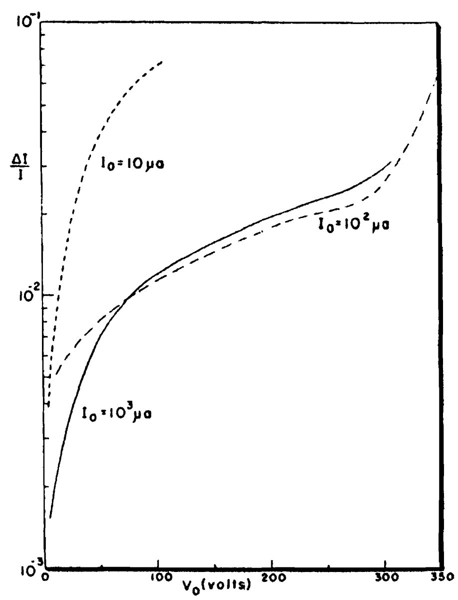

Fig. 5: Results of current stability tests

ence is amplified by the cascode amplifier V_2, passes through the cathode follower V_1-B and determines the bias voltage of the series tube V_1-A. Phase relations are such that the error voltage applied to V_1-A changes its series current in

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such sense that the error is reduced by the feedback. The variable series resistors near S_2 are used to adjust the external current to exactly the rated value for each switch position. It will be noted that either output terminal may be grounded. The 0.1 µf capacitors bridging the floating supplies contribute to the speed of response of the circuit.

Amplifier

The cascode amplifier formed by the two halves of V_2 differs from a usual cascode circuit by the addition of the 560K resistor feeding the plate of V_2-B. The additional current supplied by this resistor greatly increases the g_m of V_2-B which, in turn, increases the voltage gain of the circuit.[2] The gain for a signal applied between grid and cathode of V_2-B and measured at the plate of V_2-A is 4000, an order of magnitude larger than that obtained without the 560K resistor.

A measure of the success of the circuit in holding a given output current, I_0, constant is the relative change in I, $\Delta I/I_0$, versus output voltage. To make such measurements, the output voltage was changed by varying an accurately known resistor across the output. Fig. 5 shows the results obtained for the three nominal current ranges. These currents were adjusted to their correct values at essentially zero output voltage.

It will be noted that for $I_0 = 100$ µa, the current has only deviated from its zero-voltage value by 2.5 percent at 300 v. output. In measuring BV_{CBO} this current value will be most used in the output voltage range of 50 to 200 v. Since the dependence of BV_{CBO} on current around 100 µa is small, deviations of the current from its nominal value of the order of one or two percent are entirely negligible.

Line Variations

Although the relative current deviation for 10 µa nominal current is seven percent at 100 v. output, this current range will generally be used in measuring h_{FE} with output voltages of only a volt or so, where the deviation is negligible.

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The dependence of $\Delta I/I_0$ on line voltage has also been investigated. For $I_0 = 10^3$ μa, $\Delta I/I_0$ varied by about two percent for line voltages ranging from 105 to 130 v. RMS. Slightly greater variations were observed with I_0=100 μa, and 15 percent variation was observed over the range from 110 to 120 v. RMS for I_0=10 μa. This increased variation arises from the reduction of g_m of V_1-A caused by reduced heater voltage. When long-term constancy of I_0 is required for this range, the line voltage should be stabilized.

Although the equivalent supply voltage and internal resistance of the constant current supply vary with output voltage, their values for I_0 = 100 μa in the neighborhood of 10 v. output are 20,000 v. and 200 megohms respectively. At 100 v. output, they have decreased to 8700 v. and 87 megohms. These figures show what large supply voltages and series resistances would be required to duplicate the performace of this constant current supply without the amplification and negative feedback used.

Feedback Amplifier

The circuit of the feedback amplifier is presented in Fig. 4. A voltage proportional to transistor collector current is balanced in the input differential amplifier tube against a stabilized voltage set to -0.5 v.; the error signal is then amplified and appears at the output, which is connected to the emitter of the transistor. Thus, no matter what the h_{FB} or h_{FE} of the transistor, the circuit supplies the necessary emitter current (within the operating range of the amplifier) to produce 5 ma of collector current.

To ensure accurate balance between the input signal and the internal -0.5 v. signal, the input tube is a 6SU7, which is closely balanced. Further, the 600K wire-wound plate resistors for this tube are equal to better than one percent. There are two uncommon features in the circuit of Fig. 4. One is the use of diodes operating in their reverse breakdown region as dc coupling elements. In this region, a voltage drop nearly independent of current appears across them and their dif-

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ferential resistance is hence very low. In the present case, each diode drops approximately 100 v. The use of these diodes increases the gain of the amplifier by a factor of almost two.

Positive Feedback

The other uncommon feature is the use of direct-coupled positive feedback introduced by means of the 1.22 megohm resistor. Without this resistor, the input-output voltage gain of the amplifier is about 1600. When the resistor was connected and adjusted for maximum gain at low frequencies, a value exceeding 6×10^5 was measured. Even in the absence of output-input negative feedback such as that produced by connecting the output and input terminals together, the circuit was stable with this high gain and no oscillation could be produced with any value of the positive feedback resistor. Note that both sides of this resistor are at very nearly the same dc potential. The use of positive feedback to achieve a very high gain is economical and leads to an amplifier of high precision since the extremely high gain reduces the offset voltage between the input signal from the collector and the internal stabilized voltage to a negligible value and reduces the output impedance of the circuit when connected to a transistor to a fraction of an ohm and may even make the output impedance slightly negatitve.

To ensure that adequate emitter currents can be supplied, a high-g_m 5687 miniature double triode with sections paralleled is used as the output tube. The positive and negative supply voltages are derived from the two floating supplies of the constant-current circuit. For the present purpose, no gas-tube stabilization is used with these supplies.

As a test of the amplifier, its input and output were connected and the internal standard voltage adjusted to make the output exactly -0.500 v. as measured with the Fluke VTVM. On changing the line voltage from 105 to 135 v., no more than one mv change in this voltage was noted. Next, with complete feedback of output to input and

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-0.5 v. output, loading of the output with resistances connected to ground was investigated. It was found that the output impedance was slightly negative, causing the magnitude of the output voltage to rise from a no-load value of 0.5000 v. to a maximum value of 0.5227 v. with 29 ohms load connected. Below 29 ohms load, the voltage was equal to the load resistance times the constant current of 18.4 ma. flowing in the cathode resistor of the output tube. If a larger limiting current were required, it could be obtained by increasing the quiescent current of the cathode-follower output stage. Without positive feedback, the output voltage was found to be essentially independent of load until a load of 30 ohms was reached, where the magnitude of the voltage had dropped to 0.4996 v. The above measurement together with operational tests employing transistors showed that the amplifier performed its function most satisfactorily.

References

1. We employ herein the letter-symbol nomenclature proposed for semiconductors by the IRE, 10 October 1955.
2. V. H. Attree, "A Cascode Amplifier Degenerative Stabilizer," Electronic Eng., Vol. 27, pp. 174-177; April 1955.

Police Forces to Try "Line-ups" via TV

Using a microwave radio link for closed-circuit telecasting of "line-ups," the police forces of Euclid, Ohio, and Cleveland are giving a two-month trial to such interchange of information by TV with temporary authority granted by the FCC.

Frequencies granted on a developmental experimental basis are in the area of 2090-2110 mc in the studio-transmitter link and remote TV pick-up band. Dage Electronics equipment is being used, and at no cost to either city for the trial.

3M's Gets into TV Tape Recording Field

Minnesota Mining & Mfg. Co., St. Paul, has entered the TV tape recording field through the purchase of the Electronic Engineering Div., Bing Crosby Enterprises, Los Angeles, for a reported $1,000,-000.