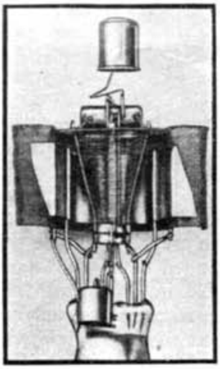
The Variable-Mu Tetrode

A Modified Screen-Grid Receiving Tube of Improved Performance

By George Grammer, Assistant Technical Editor

A TRITE but true expression is that old one about necessity being the mother of invention. It is nowhere more aptly illustrated than in the case of present-day vacuum tubes. Starting out a decade or so with a few "standard" types, the family has grown until tubes for almost every practical radio purpose are available. The demand for broadcast receivers which would work direct from the electric light line brought about a series of tubes designed for that work; the need for "quality" reproduction caused the development of the audio-frequency power tube; the necessity for high-gain r.f. amplifiers brought about the screen-grid tube; while in the transmitting field the development of short waves resulted in tubes designed for high-frequency work. Endless examples could be cited.

The latest addition to the ever-increasing line is the variable-mu tube. It is not a fundamentally new tube; more properly it should be considered as a design which overcomes certain defects of the older types. Since it is highly probable that there will be a great deal of talk about these tubes during the coming season it is well to go over some of the features of the variable-mu tetrode and see just what advantages it possesses over the Type '24, the tube it resembles and is designed to replace — or at least supplement — in broadcast receivers, and to look into its advantages for amateur work as well.



THE CONSTRUCTION OF THE 235

Note the odd shape of the inner screen grid. The spacing of the control grid wires, not visible in the photograph, is narrow at the outer ends and wide in the center. In other respects the tube is about the same as the '24.

The outstanding features of the new tube are first: A much wider range of volume control is attainable than with the Type '24; and second, "cross-talk" is greatly reduced. From an amateur point of view these features may not seem to be greatly important; however, most of us have broadcast receivers, and a consideration of the technical features of the tube is interesting.

The new tube was developed by Stuart Ballantine and H. A. Snow of the Boonton Research Corporation, and was described in a paper presented at a meeting of the Institute of Radio Engineers in Rochester, N. Y., in November, 1930.[1] Much of the material here has been taken from that paper.

THE VARIABLE-MU PRINCIPLE

The name given the tube may have given some readers the impression that there is some sort of thumb-screw adjustment to allow changing the amplification factor to suit circuit conditions. Nothing of the sort. The amplification factor can be actually changed, but the change is brought about by variation of the grid bias. An example used by Ballantine and Snow[1] well illustrates the operation of the tube.

Suppose, as in Fig. 1, we have two tubes connected in parallel, one of them being a high-mu and the other a low-mu tube. The grid bias is variable between a lower limit set by the lowest operating grid bias of the high-mu tube and an upper limit set by the highest operating bias of the low-mu tube. Each tube is connected to a transformer winding of suitable impedance so arranged that the secondary voltages will be in proper phase relationship.

Let us assume that the grid voltage-plate current curves of the two tubes are the dotted lines in Fig. 2, A being the curve for the low-mu tube and B the curve for the high-mu tube. As the grid voltage is increased negatively it will be seen that at a comparatively low value the plate current of the high-mu tube, B, is completely cut off. A much higher value of bias is required to reach A's cut-off point. The combination of the two in parallel would give a curve like the solid line. At low values of grid bias tube B would produce most of the amplification in the stage; at higher values, however, A would become more and more effective, until beyond B's cut-off point all the amplification would be produced by A.

In the variable-mu tube a curve similar to that of the solid line in Fig. 2 is obtained in one envelope by suitably designing the tube elements. Innumerable types of structures could be worked out to give this effect. The photograph of an exploded screen-grid tube of this type shows one method which has been adopted in an experimental

[1] "Reduction of Distortion and Cross-Talk in Radio Receivers by Means of Variable-Mu Tetrodes," Ballantine and Snow, *Proceedings of The Institute of Radio Engineers*, Vol. 18, No. 12, December, 1930. Figs. 1, 2, 5, 6, 8, 9, and 10 are reproduced by courtesy of the Institute.

tube. The inner portion of the screen grid has the approximate shape of an inverted truncated cone, the plate and outer screen being the normal type of construction. The control grid is not visible in the photo, but the pitch of the wires is rather fine at both ends for a short distance and is coarse in the central portion.

Two varieties of this class of tube, known as the 551 and 235, have been produced at the time this is being written. Both are indirectly-heated cathode tubes, designed to be used in the r.f. amplifier stages of a receiver. The 551 is similar in

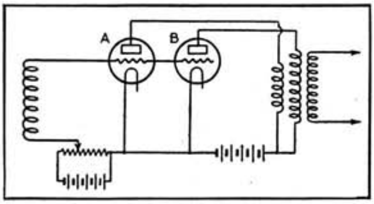


FIG. 1

many respects to the present Type '24 except that the normal operating plate current is slightly higher (5.3 ma. for the 551 as against 4.0 ma. for the '24) and the range of control grid bias over which it may be worked is nearly double that of the '24, or about 30 volts. Provision for the proper grid bias is about the only change that need be made to substitute the tube for the '24 in a receiver. Grid bias may be obtained either from a potentiometer or by the cathode resistor method. The following table gives the average characteristics of the 551:

Filament voltage	2.5 (a.c.)
Filament current	1.75
Plate voltage	180
Screen voltage	90
Grid voltage	−3.0
Plate current	5.3 ma.
Screen current	⅓ of plate current
Plate resistance	400,000 ohms
Mutual conductance	1050 μmhos

Approximate Inter-Electrode Capacitances

Grid to plate	0.01 μμfd. max.
Input	5 μμfd.
Output	10 μμfd.

The second type, the 235, is not generally interchangeable with the Type '24 in broadcast receivers. The plate current is more than double that of the '24 and the plate resistance about half. The lower plate resistance permits more effective amplification per stage than is possible with the '24, with the result that careful shielding between stages is necessary to prevent oscillation. The full volume control range of the tube is secured only when the available grid bias voltage is of the order of 75 volts, which should preferably be obtained independently from a potentiometer. In cases where a 45-volt range gives sufficient volume control, however, the cathode resistor method may be employed. The average characteristics of the 235 are as follows:

Filament voltage	2.5 (a.c.)
Filament current	1.75
Plate voltage	180
Screen voltage	75
Grid voltage	−1.5
Plate current	9.0 ma.
Screen current	Not over ⅓ of plate current
Plate resistance	200,000 ohms
Mutual conductance	1100 μmhos

The approximate interelectrode capacitances are the same as those given above for the 551.

The grid voltage-plate current and grid voltage-mutual conductance curves for the 235 are shown in Figs. 3 and 4.

THE REASON FOR THE VARIABLE-MU TUBE

The new tube overcomes some difficulties attendant upon the use of the Type '24 in high-gain r.f. amplifiers, chiefly the distortion encountered with high grid bias on the tubes. A common method of controlling volume in broadcast receivers is that of control of amplification by variation of grid bias. As the grid bias on a tube is increased negatively the mutual conductance, which is a measure of the amplification produced, decreases also, until a point is finally reached where the plate current is completely cut off and the mutual conductance becomes zero. As the grid bias on the '24 tube is increased beyond a certain point, however, the relation between the signal voltage on the grid and the r.f. output voltage is not linear for some values of signal voltages; in other words, distortion is introduced. In Fig. 5 is a series of curves showing the relation between r.f. output voltage and r.f. input voltage for a single '24 stage for various values of grid bias, plotted to a logarithmic scale.

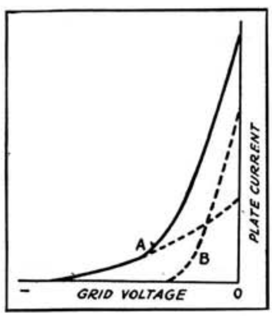


FIG. 2

It will be seen that the relationship between input and output voltages is linear for low values of grid bias with inputs as high as one volt r.m.s.; the 10-volt curve, however, shows distinct curvature at the upper end. As the bias is further increased the curvature becomes more and more pronounced, especially at the higher values of signal voltage.

The effect produced by the non-linearity of these characteristics is that of increasing the percentage of modulation on the incoming signal. There is no simple relationship between the modulation rise and the audio-frequency distortion produced, but as the depth of modulation increases from this cause the distortion becomes greater. The distortion does not become objectionable when the modulation rise is below 20%, and this figure has been arbitrarily selected as the allowable upper limit. The dotted curve in Fig. 5 indicates the operating limits of the tube from this standpoint. For example, if the desired audio output is secured with one volt r.f. output from this particular stage, the r.f. input voltage could not exceed about 0.7 volts before distortion occurs. If the incoming signal were larger than this, as might easily happen if this were the second or third r.f. stage in the receiver and the signal came from a nearby broadcasting station, either the bias would have to be increased beyond the 20% line to keep the volume at the desired level, thus introducing noticeable distortion, or an increase in the volume level would have to be tolerated in order to preserve the quality of reproduction. Thus this characteristic of the tube is particularly important when the volume control is to work satisfactorily on a strong signal. Complaints about poor control of volume on local broadcast stations are common.

The variable-mu feature overcomes this difficulty quite satisfactorily. The new tube gives about the same performance as the '24 at low bias, so that there is no appreciable loss of amplification on *weak* signals. As the bias is increased to handle strong signals, however, the mu of the tube decreases, so that with high bias values the amplification is low. It is characteristic of a low-mu tube that large signal inputs can be handled without distortion; thus when the bias is increased and the mu of the tube decreases, the distortion encountered with the '24 type, as illustrated in Fig. 5, is eliminated. The difference in performance in this respect between the '24 and the 551 is illustrated in Fig. 6. In this figure the r.f. input voltage is plotted against transconductance,[2] which is determined by the operating bias and is a measure of the amplification. The scale is again logarithmic, and the curves represent a 20% modulation rise for each of the two tubes. It will be seen that at low bias (high transconductance) the performance of the two tubes is similar; as the transconductance is decreased, however, there is a wide difference between the points at which distortion becomes noticeable. For example, if the transconductance is 10 μmhos the '24 will handle a signal of only about 0.3 volt, while an 8-volt signal is permissible with the 551. As the region of low transconductance is the important one from the standpoint of volume control, the superior performance of the new tube in this respect is obvious.

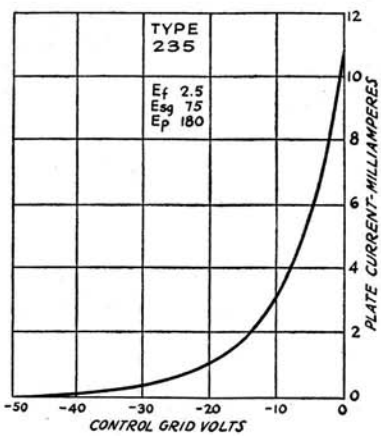


FIG. 3.—THE MUTUAL CHARACTERISTIC OF THE 235

Note the "tailing" of the curve at the higher negative grid voltages. With ordinary tubes the curve would have a shape more like that of the dotted curve B in Fig. 2.

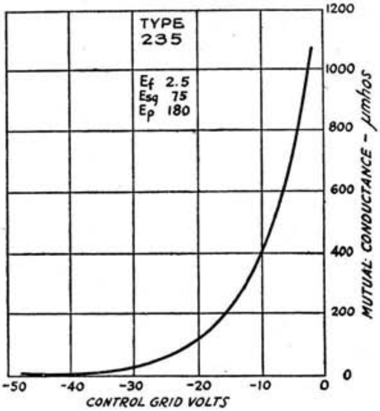


FIG. 4.—THIS GRAPH SHOWS MUTUAL CONDUCTANCE (TRANSCONDUCTANCE) PLOTTED AGAINST GRID VOLTAGE FOR THE 235

This curve is very nearly logarithmic in character. If plotted on semi-log paper an approximately straight line would result.

The curves in Fig. 6 are reproduced from the paper mentioned above,[1] although in commercial production the characteristic of the 551 may vary somewhat from that shown. A technical bulletin on the tube recently released by the Arcturus

[2] The report of the Committee on Standardization for 1930, Institute of Radio Engineers, defines "transconductance" as the "ratio of the change in the current in the circuit of one electrode to the change in voltage on another electrode, all other voltages remaining unchanged." Transconductance is the general case of "mutual conductance" applied to tubes with any number of electrodes; strictly speaking, mutual conductance is a special case applying only to triodes.

Radio Tube Company [3] shows somewhat better comparative performance; the voltage which the 551 will handle at low transconductance is about 20 times that of the '24 type.

THE QUESTION OF CROSS-TALK

The cause of most "cross-talk" in a receiver is the same as the cause of the type of distortion described above, namely the bending of the input voltage-output voltage curves illustrated in Fig. 5. Cross-talk is easily distinguished from simple interference because it occurs only in the presence of a desired carrier. That is, assuming the receiver is tuned to the carrier of a station on say 800 kc.; another station whose frequency is perhaps 1000 kc. may be heard in the background so long as the 800-kc. carrier is on. If the 800-kc. carrier is cut off and the 1000-kc. station can still be heard, the case is one of simple interference and is chargeable to lack of selectivity in the receiver. On the other hand, if the interference disappears when the 800-kc. carrier is cut off, the interference is attributable to cross-talk.

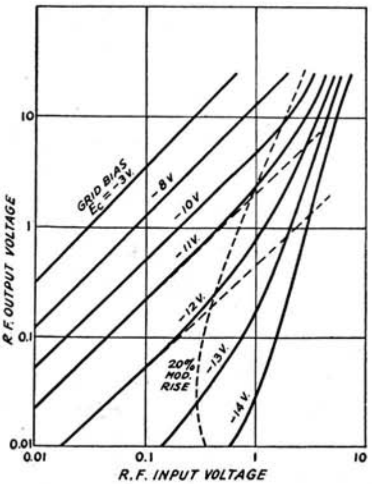


FIG. 5.—INPUT VOLTAGE-OUTPUT VOLTAGE CURVES FOR A TYPE '24 TUBE

The bending of the curves for the higher values of grid bias and large input signals limits the range over which volume may be controlled because of the distortion introduced.

Two principal classes of cross-talk are described by Ballantine and Snow. The first type is that caused by beats between two signals on differing frequencies, both of which are different from the frequency to which the receiver is tuned. For instance, if two strong stations are operating on, say, 1400 and 600 kc., a difference frequency of 800 kc. will be set up, and if the receiver is tuned to a carrier on 800 kc. cross-talk may be present. A common example of this occurs along the east coast, and probably in other places as well, where marine transmitters can be heard on the carriers

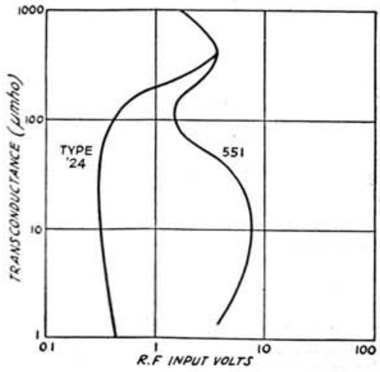


FIG. 6.—INPUT VOLTAGE AGAINST TRANSCONDUCTANCE WITH 20% MODULATION RISE

At low transconductance the 551 will handle many times the voltage that the '24 will. The distortion introduced is the same in both cases.

of certain stations, disappearing as the carrier is tuned out. In Hartford such telegraph signals are occasionally heard on WEAF's carrier, and are presumably caused by beats between WTIC on 1060 kc. and marine transmitters on 400 kc. (750 meters). Although this type of cross-talk is not a function of distortion of the type described above, it has been found that the characteristics of the variable-mu tube are such as to reduce it.

The second class of cross-talk is that encountered when a strong local signal is on a frequency near that of the desired station. The selectivity of the receiver may be such that the interfering signal may not be heard when the desired carrier is not present, yet cross-talk can very easily exist when there is a carrier on the desired frequency. Fig. 7 illustrates possible selectivity curves for a receiver with three tuned stages; the curves may

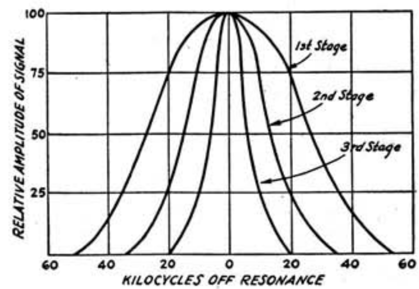


FIG. 7

or may not be representative of actual conditions, but will do for purposes of illustration. Each of the stages alone may have a selectivity curve like

[3] This bulletin and another on the Arcturus Type PZ power output pentode may be obtained by writing the Arcturus Radio Tube Company, Newark, N. J.

that marked "1st Stage," but the cumulative effect of the series of stages gives a progressively higher degree of selectivity, so that by the time the third stage is reached a signal 20 kc. away from the desired one will produce practically no response in the receiver *in the absence of the desired carrier*. Now suppose there is a carrier 30 kc. away from the desired one, and that both are of equal strength. In the *first* tuned stage the extra carrier will have an amplitude approximately 40% of that of the desired carrier, so that there is an appreciable signal on the grid of the first tube from the unwanted signal. The effect of this unwanted signal is explained by reference to Fig. 8.

The solid curve of Fig. 8 represents the a.c. output from the desired signal at various values of grid bias voltage. The bias is assumed to be set at the operating point shown, and the incoming voltage from the undesired signal is shown below the line. This signal, which is assumed to be modulated, in effect swings the operating point over the range indicated by the diagram. For ordinary tubes the grid voltage-a.c. plate current curve is not straight in the region of high grid bias, as explained above and indicated by Fig. 5, so that the amplitude of the desired carrier will increase more when the operating point swings to the right than it decreases when the

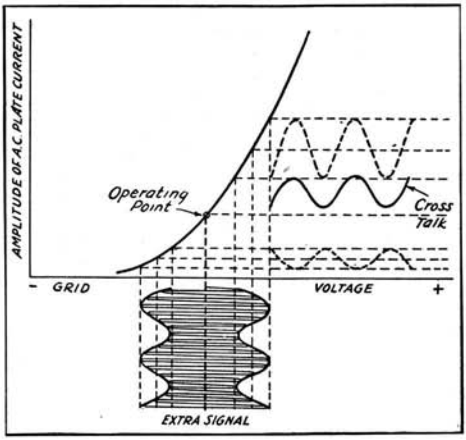


FIG. 8 — THIS DRAWING EXPLAINS THE REASON FOR ONE TYPE OF CROSS-TALK

The solid curve represents a.c. output from the desired signal plotted against grid bias voltage. The unwanted (extra) signal swings the operating point back and forth and actually modulates the desired signal.

operating point swings to the left. In other words, rectification takes place. The effect of such rectification, as mentioned previously, is, in the case of the desired signal, to increase the percentage of modulation; with the undesired signal, however, actual modulation of the desired carrier at the modulation frequency of the undesired signal takes place, and the undesired signal rides through the remaining stages of the amplifier on the desired carrier in spite of the fact that the selectivity of the receiver may be great enough to preclude simple interference.

The curvature of the characteristic shown in Fig. 8 has led to the use of two or more tuned circuits in cascade between the antenna and the

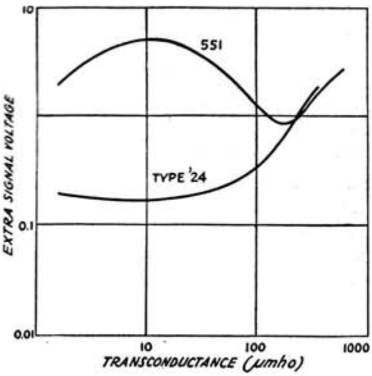


FIG. 9. — AT LOW TRANSCONDUCTANCE THE 551 PRODUCES MUCH LESS CROSS-TALK THAN THE '24

The extra signal voltage required to produce a given amount of cross-talk is much higher with the 551 than the '24. Cross-talk is reduced by a factor of several hundred to one with the variable-mu tube.

grid of the first r.f. tube, the object being to cut out the unwanted signal before it has a chance to modulate the desired carrier. This has naturally increased the cost of receivers so designed, and led to another difficulty in that the attenuation of the desired signal was so great before the first tube was reached that the strength of the signal in relation to tube noises, hum, etc., was considerably below that obtainable when the first tube was coupled to the antenna through a single tuned circuit.

The straightening out of this characteristic in the variable-mu tube has resulted in so much improvement in this respect that it is claimed that no "pre-selection" — the use of several tuned circuits before the first tube — is necessary, with a resulting improvement in the signal noise ratio. An idea of the superiority of the new tube in this respect can be gained by reference to Fig. 9, which shows the amplitude of extra (undesired) signal voltage necessary to produce cross-talk of 10% (based on audio output power) with both types of tubes. In the region of low transconductance the ratio is higher than 20 to 1 in favor of the 551 tube, which, since power varies with the square of the voltage, means an improvement of 400 to 1 and more with the new tube. This is more strikingly illustrated in Fig. 10, which shows the cross-talk produced by the two types of tubes in a typical r.f. amplifier, expressed as a percentage of the audio output from the desired signal. These curves were taken with constant audio output from the desired signal, the grid bias being adjusted to give this result as the desired signal voltage was varied. Cross-talk amplitudes with five different values of interfering signal voltage are shown.

A further advantage resulting from the use of the new tube is reduction in hum in the r.f. stages. Most of us have listened to broadcast receivers on which little or no hum was present when no carrier was tuned in, but in which a definite hum appeared with the carrier. This type of hum is similar to cross-talk in that it is an actual modulation of the carrier caused by curvature of the characteristic illustrated in Fig. 8. The hum voltage cannot reach the detector so long as there is no carrier for it to modulate; with the variable-mu tube the undesired modulation is greatly reduced and consequently the hum is less.

Since the decrease in distortion and cross-talk has been achieved in the new tube by minimizing its rectifying tendencies, a loss of efficiency in detecting properties is to be expected. The 551 is only about half as good as a '24 as a "linear" detector; that is, as a high-bias plate rectifier.

THE VARIABLE-MU TUBE IN THE AMATEUR RECEIVER

The points discussed above, while of interest in a technical sense, do not, at first thought, seem to offer anything particularly helpful from an amateur point of view. Excepting possibly the superheterodyne, most amateur receivers do not use a volume control operating on the r.f. tubes, and plain lack of selectivity rather than cross-talk is the cause of most of the interference troubles. However, a few experimental tubes of the 235 type furnished us by the RCA Radiotron Company have shown some interesting points of advantage over the ordinary '24 type.

It will be remembered that the plate resistance of the 235 is about half that of the '24, and the effect of this reduction, at least in a few tests made on short-wave tuned r.f. receivers, has been to noticeably increase the amplification when the tube was used to replace the '24 in the r.f. stage — this in spite of the fact that no change was made in the bias resistor to bring the operating point to the optimum.

As a grid-leak detector with regeneration, the arrangement most common in amateur receivers, the tube is at least the equal and possibly a little better than the average '24 in sensitivity, and is noticeably more quiet in operation. The small filament hum in one typical set was reduced to the vanishing point when the 235 was substituted for the '24 detector. This, however, may be the result of improved cathode construction rather than any virtue of the variable-mu feature.

AS A DYNATRON OSCILLATOR

The experimental tubes tried were found to be much superior to the '24 as dynatron oscillators. Substituted for the '24 in an a.c. dynatron frequency meter, the 235 was a more vigorous oscillator, so much so that instead of the 90 and 45 volts required on the screen and plate of the '24, the voltages could be dropped to 45 and 22, respectively, with equal strength on all harmonics. The space current necessary for oscillation

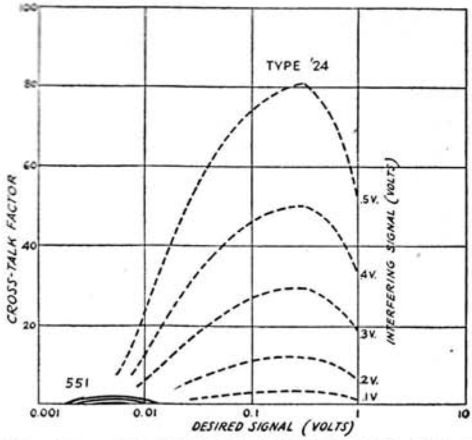


FIG. 10. — CROSS-TALK COMPARISON IN A TYPICAL RECEIVER

A striking illustration of the superiority of the new tube with respect to cross-talk. In obtaining the points for these curves the transconductance and desired signal voltage were varied simultaneously to maintain the audio output from the desired signal constant. Curves for five different values of interfering signal voltage are shown.

also was considerably lower — 2.5 ma. for the 235 as against 6 ma. for the '24.

At the time of this writing no 551 tubes have been received for test.

Few changes will be necessary to substitute these tubes for '24's in ordinary receivers using a '24 r.f. and '24 detector. It might be advisable to reduce somewhat the value of the bias resistor in the r.f. stage when the 235 is substituted for the '24. For instance, if the bias resistor is such as to give a 3-volt drop at 4 ma., the normal plate current for the '24, or approximately 800 ohms, it should be decreased to give a 1.5-volt drop at 9 ma., or about 175 ohms. No changes need be made in the detector circuit. With the 551 no alterations should be necessary in either r.f. or detector stages. As both types of these tubes are more or less experimental in nature it is possible that the design finally adopted for commercial production may have somewhat different characteristics.

Strays

W6AZL puts half a dollar across the terminals of his amateur ammeter as a shunt. The half dollar comes in handy, too, in case pay-day looks too far away.

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W8DMA is owned by O. H. Mills, who has some high-resistance initials.