



A New, High-Efficiency Linear Amplifier

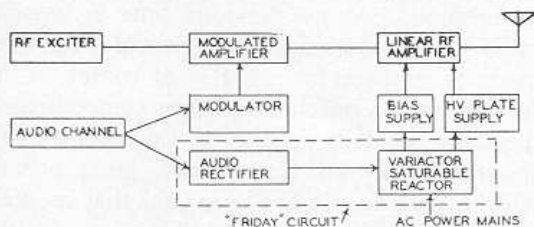
By J. N. A. HAWKINS, W6AAR

The first step toward the principle of dynamic shift in a vacuum tube amplifier occurred with the invention of the class B audio amplifier by Gordon and Barton working independently. The idea behind class B audio amplification was to find a way to cut down the input and plate

A new wrinkle applied to linear amplifiers which greatly increases the output from a given tube, effects a saving in power, and results in 60 percent unmodulated plate efficiency. All the advantages of a controlled carrier linear amplifier from a power standpoint, and yet the carrier remains constant. The system is based on what the author tentatively terms "dynamic shift".

picture studios. Normally, a film sound track is recorded by modulating a fixed light source both

up and around a mean value of light. In other words, the unmodulated sound track receives one half the maximum peak value of light available. Then sounds alternately increase and decrease this average light value. It was found that the background noise could be greatly reduced by reducing the unmodulated light on the track; so a resting bias was placed on the light gate to shut it nearly to zero. When an audio signal comes along through the recording amplifier, part of the signal is rectified and applied to the light gate so as to oppose the resting bias and open it up to its normal operating point of one half the peak value. Thus there is a dynamic shift in the axis about which the light values vary. This axis shift occurs in accordance with the syllabic modulation (0 to 20 cycles per second) in the signal to be recorded, whether voice or music. R.C.A. developed a similar dynamic shift device for their



Block Diagram of Expanding Linear Amplifier System

loss to a power amplifier when no signal is present on the grid. The plate efficiency of a class A amplifier is zero when no signal is present on the grid. Thus *all* the plate input must be dissipated from the plate as heat when the amplifier is resting, and low overall output efficiency results. The class B audio amplifier makes the signal on the grid release the flow of plate current from the plate power supply so that the plate input and plate loss is low when the amplifier is resting. Strictly speaking, the class B audio amplifier is not a dynamic shift amplifier, as the bias axis is fixed. However, the objective behind the dynamic shift class BC linear amplifier is exactly the same as that which mothered the invention of the class B audio amplifier. The idea is to reduce the unmodulated plate loss by increasing the unmodulated plate efficiency and by reducing the plate power input. In the class B audio amplifier the input is reduced in the resting condition by reducing the d.c. plate current, keeping the plate voltage constant. In the dynamic shift linear amplifier the plate current is kept constant while the d.c. plate voltage is reduced when unmodulated.

The first real use of dynamic shift amplification came when the Bell Laboratories developed the "ground noise reduction amplifier" for use in sound-on-film recording in the motion

SCOOP

The new Hawkins expanding class BC linear amplifier effectively doubles the output obtainable from a conventional class B amplifier, and probably will result in a radical change in the design of phone transmitters. 200 watts of carrier may be obtained from a pair of 211's without the necessity for well-regulated power supplies or more than 15 watts of audio power. In this new system the average carrier amplitude is constant and is entirely independent of the modulation. We believe broadcast stations will look with interest on this new development which will cut tube costs 50% in the final linear amplifier.

The figures given in the tables are quite conservative, and for amateur use may be exceeded considerably with certain types of tubes, much as is being done with controlled carrier linear amplifiers. When resting, a controlled carrier linear amplifier operates at reduced input, but at *reduced efficiency*. The expanding linear amplifier works at reduced input when resting, but at *increased efficiency*, and the average carrier does not vary as it does in the controlled carrier system.—EDITOR.

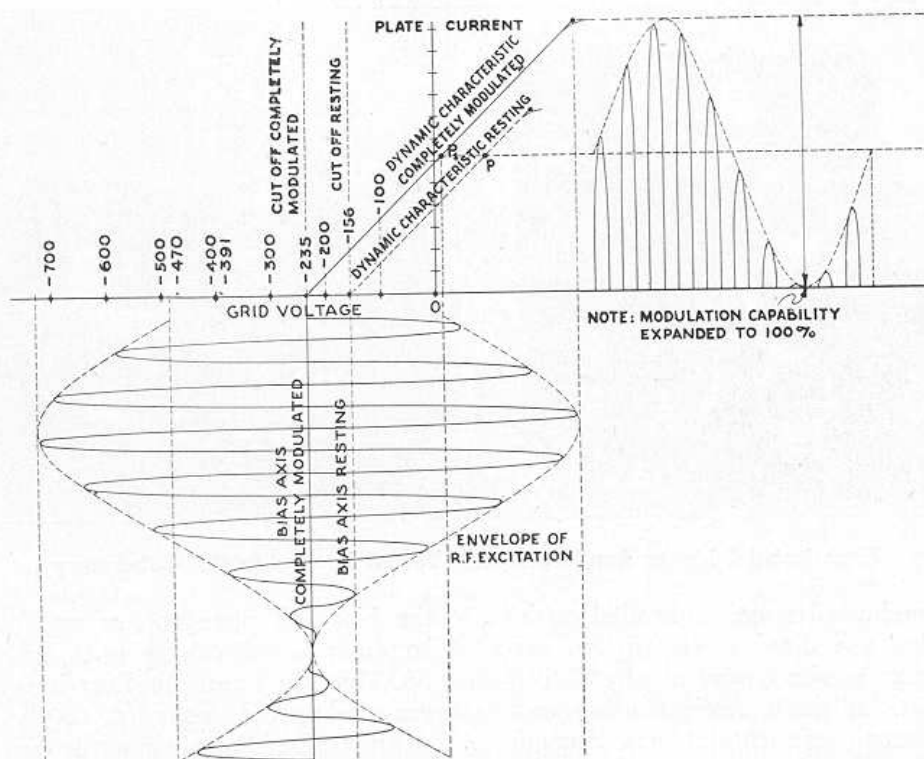


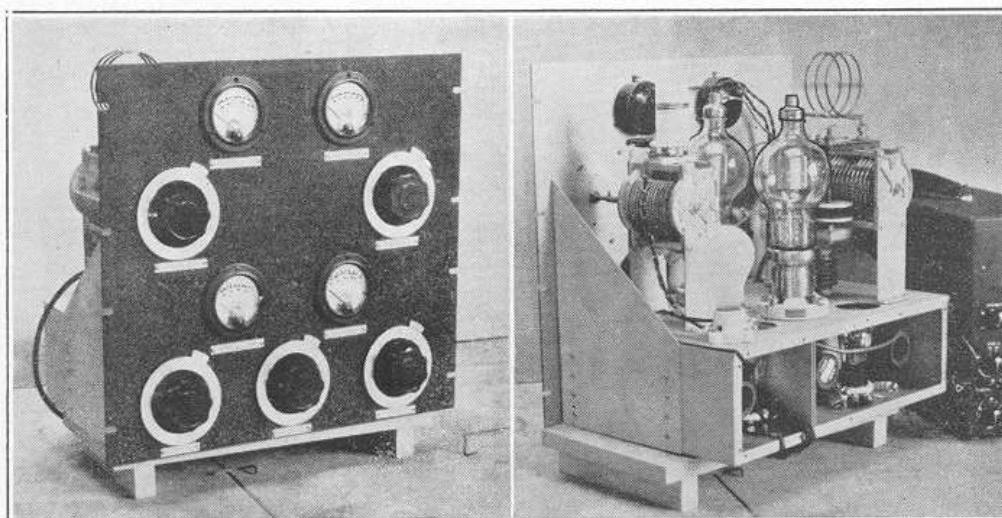
Figure 1
The Class B Expanding Linear Amplifier, 100% Modulated

type of film recording which "blackened out" the unused portion of the sound track.

The next application of the dynamic shift amplifier was the compandor developed by the Bell Laboratories for use on their transatlantic telephone circuits. Volume range of a communications channel describes the range in sound amplitude that the system can handle. The minimum value is set by circuit noise, and the maximum value is set by the overload, or distortion point. The volume range of the human voice is somewhat greater than the volume range of the transatlantic telephone circuits; so the compandor is used to compress the volume range at the transmitter and to re-expand it again at the receiver so that the distant listener hears approximately the same volume range as the sender puts into his telephone. Volume range compression and expansion both utilize dynamic shift amplification, although the two work in opposite directions. In the range expander (which also is used in the new R.C.A. electric phonograph) the gain of the audio channel is controlled by the incoming signal. When no signal is present the gain is low, due to high resting bias. When a signal is applied to the input of the expanding channel, part of it is bypassed to a rectifier which applies the

syllabic components to buck the bias voltage which controls the amplifier gain. The larger the signal the *higher* the gain. Thus a loud sound is amplified more than a weak sound and if two sounds applied to the amplifier input had a loudness ratio of five, they might come out of the channel with a loudness ratio of twenty or more. Thus note that volume range expansion works exactly opposite to the automatic gain control system used in most modern receivers. The autogain circuit in a receiver is really a special form of volume range *compressor*. It tries to bring all signals to the same level. Therefore, to a certain extent, autogain utilizes the principle of reverse dynamic shift.

Controlled carrier modulation utilizes dynamic shift amplification in exactly the same manner as the various systems used by the motion picture industry to reduce ground noise on sound tracks. However, the object is to reduce QRM and resting plate loss and not to reduce ground or background noise; but the dynamic shift process takes place in the same way. Some of the audio signal is rectified and used to control the average carrier output of the modulated amplifier. This syllabic variation in average carrier output, in turn controls the input and output from a linear class B amplifier which



Experimental Linear Amplifier Being Tested in the "Radio" Laboratory

follows the modulated stage. Controlled carrier modulation has one disadvantage in that variation in average carrier output usually distorts the received signal in a receiver using conventional automatic gain control. The dynamic shift linear amplifier is simply a controlled carrier system without any syllabic variation of the carrier.

The bias shift class A audio amplifier (see RADIO for June, 1935, page 21) utilizes a rectifier circuit to increase the bias at low signal levels and thus cut down the resting plate loss. This amplifier is strictly class A as plate current flows throughout the cycle and the use of the push-pull circuit is unnecessary to reduce even-harmonic distortion, as the distortion is approximately the same as in any class A amplifier. This is one of the simplest applications of the dynamic shift principle.

The class BC linear or bias modulated amplifier, developed by the writer in 1933, also is a form of dynamic shift amplifier although it is not analyzed in the same manner. The shift in bias axis does not occur at a syllabic frequency rate but at an audio frequency rate, which greatly simplifies mathematical analysis.

The analysis of dynamic shift is still rather complex although it looks as if the conception and its analysis may become greatly simplified by a method which we hope to be able to present in the near future.

In any case the operation of the expanding class B linear amplifier may be visualized by imagining the presence of a good man "Friday", who stands watching the volume level indicator on a phone transmitter and who "cranks up"

the bias and plate voltage on the linear r.f. amplifier as the volume level indicator swings up. Thus the linear amplifier is allowed to put out undistorted peaks of 100% modulation when required, but the input is way down when resting so that the tubes actually can dissipate less heat resting than they do when running wide open. The man "Friday" has to keep his wits about him because he has to increase the plate efficiency of the linear amplifier when unmodulated by reducing its modulation capability in order to keep the average carrier amplitude constant. However, this is not difficult to do if the "Friday" circuit is properly adjusted.

A block layout of a typical transmitter using an expanding linear amplifier is shown in diagram A. Note that the rectified audio signal is used to control the plate and bias voltage to the linear amplifier. The voltage outputs of the plate and bias supplies must vary together in order to maintain the fixed bias at the cut-off value.

The plate and bias voltages are varied together by means of a saturable reactor (Variactor) whose a.c. winding is in series with the 110 volt a.c. line which supplies power to the plate and bias transformers for the linear amplifier. See figure 4. When direct current flows through the saturating winding on the primary reactor it reduces the a.c. voltage drop across the reactor. The more d.c. the lower the voltage drop. Thus the saturable reactor affords a convenient means of dropping the line voltage to the primaries of the plate and bias transformers. The d.c. controlling current is obtained by rectifying some of the audio output of the mod-

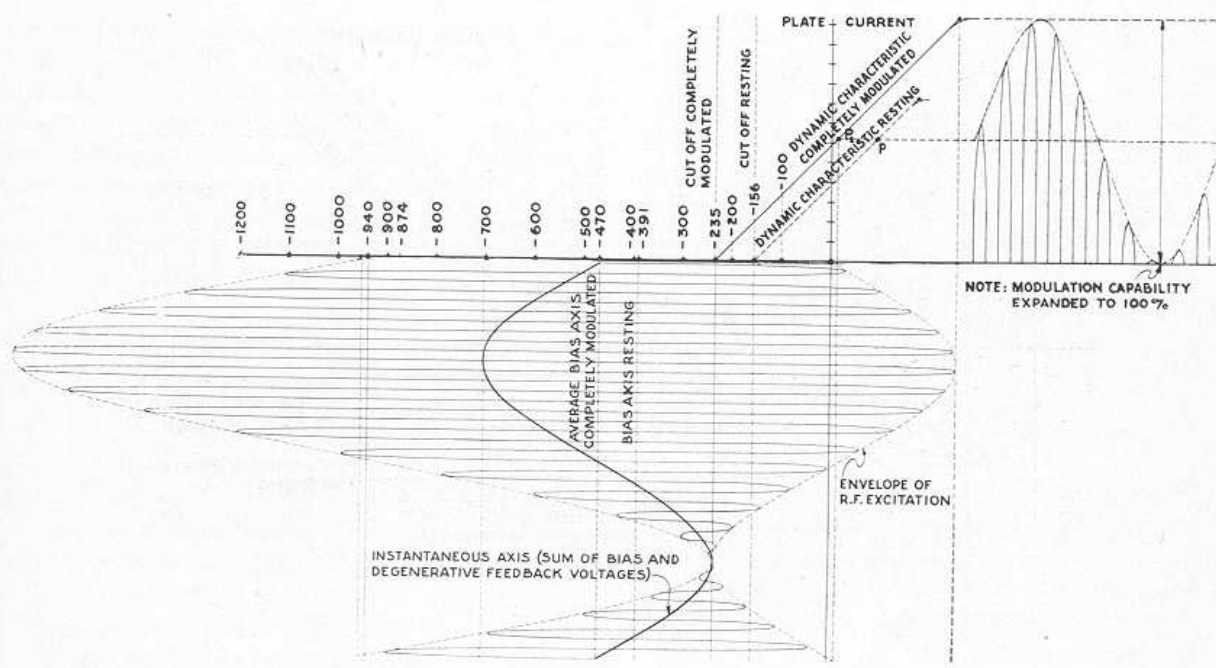


Figure 2
The Class BC Expanding Linear Amplifier, 100% Modulated

ulator and applying it to the saturating winding. This is quite similar to the Variactor system of effecting carrier control. For more data on the theory and construction of these saturable control reactors see RADIO for March, 1935.

The Expanding Linear Amplifier

Figure 1 shows a graph of a conventional class B linear amplifier, completely modulated. The operating point on the dynamic characteristic (solid line) is P_1 , and as it is just half-way up the characteristic, the amplifier has 100% modulation capability and the *average* plate efficiency is three quarters of the maximum *instantaneous peak* plate efficiency. As the maximum *instantaneous peak* plate efficiency of a class B amplifier has a theoretical limit at 79.17% and a practical limit at about 66%, the maximum attainable *average* plate efficiency under complete sine wave modulation is about three quarters of 66%, or 50%.

Ordinarily, when a conventional class B linear amplifier is unmodulated the *average* plate efficiency drops to one half of the *instantaneous peak* value. Thus few class B linear amplifiers with 100% modulation capability have an average unmodulated plate efficiency above 33%. However, if the modulation capability is purposely limited to some value below 100% modulation the unmodulated plate efficiency can be materially increased.

The unmodulated average plate efficiency is related to the modulation capability by the fol-

lowing formula (applicable only to class B operation):

$$\text{Eff}_R = \frac{6600}{100 + M_c}$$

Where Eff_R is resting, or unmodulated plate efficiency and M_c equals percentage modulation capability.

Thus if the modulation capability of a linear amplifier be purposely limited to 66%, the *average unmodulated* plate efficiency becomes 40% instead of the 33% unmodulated efficiency which was obtained with 100% modulation capability. The expanding class B linear operates with 66% modulation capability (16.6% axis shift) unmodulated, but the *modulation capability is expanded up to 100% when the amplifier is modulated*. Thus the use of dynamic axis shift allows the class B expanding linear amplifier to utilize the advantages of low modulation capability when resting, yet allows full sideband output when completely modulated. This feature means a net increase of about 33% in the class B linear r.f. carrier output that can be obtained from any given tube. This limitation of modulation capability to 66% in the resting condition is effected by reducing the d.c. plate and bias voltages 16.6% under the maximum values used when the amplifier is operating completely modulated.

watts of unmodulated carrier, while the use of expanding class BC amplification allows 100 watts of unmodulated carrier to be obtained from the 211 type of tube. The gains in output possible through the use of expanding class BC operation are even more marked with the 150T-354 type of tube, where the *momentary* plate loss can be 150% of the normal tube loss rating without any damage.

The operation of the expanding class BC linear amplifier can best be seen by the two curves of operation, figures 2 and 3. In figure 2 the amplifier is shown operating fully modulated. This curve is exactly the same as that for any conventional class BC linear amplifier. The amplifier uses the dynamic grid voltage, plate current characteristic indicated by the solid line. The operating point is P_1 and the average bias, when completely modulated, is 470 volts. (The d.c. plate voltage at this point was slightly over 2800 volts for this particular set-up.)

Note the point P on the characteristic indicated by the dashed line parallel to the solid line characteristic (figure 2). This is the op-

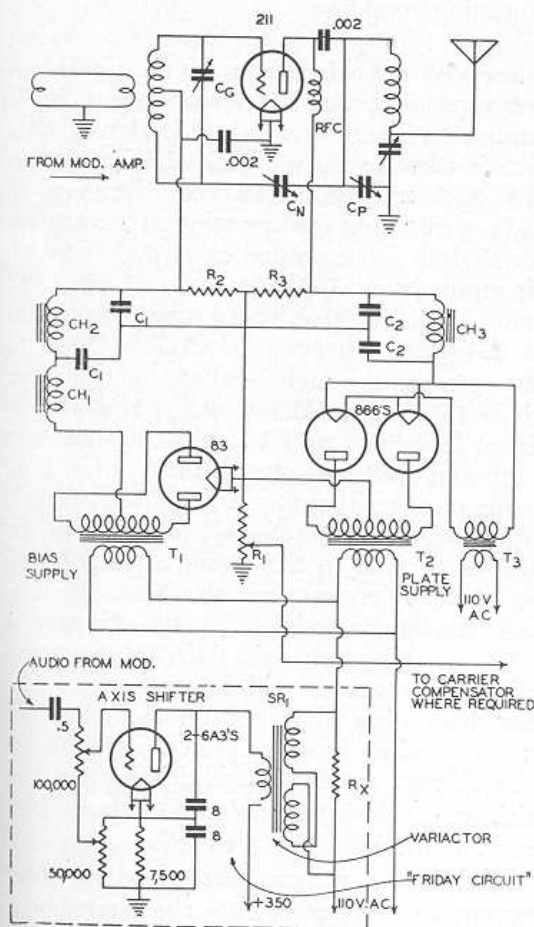


Figure 4

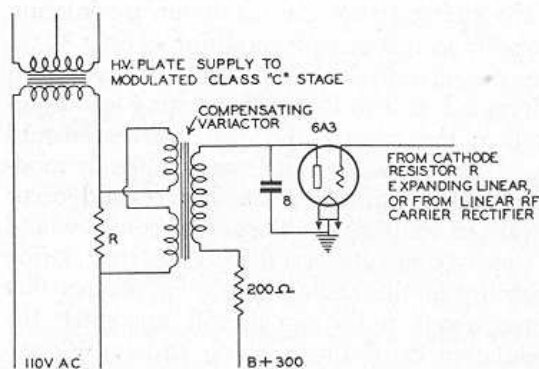


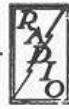
Figure 5
Carrier Compensator (Required Only Under Certain Conditions).

erating point when the transmitter is unmodulated. The dashed characteristic is that of the resting or unmodulated condition, thus indicating the dynamic characteristic shift between the resting and fully-modulated conditions.

Figure 3 shows a curve similar to that of figure 2 except that the transmitter is resting, or unmodulated (33% axis shift), while figure 2 shows the 100% modulated condition. Note that the total bias is now only 391 volts, (plate voltage about 1900 volts, resting). The operating point on the resting dynamic characteristic is the point P. Note that the points P and P_1 represent the same average value of plate current. Thus the *average* d.c. plate current (as measured on a meter) is the same resting or 100% modulated. As the plate load impedance (antenna coupling) is the same resting or completely modulated, constant plate current means that the average carrier amplitude remains constant and independent of axis shift.

Note that the average r.f. excitation voltage is the same in the resting and the completely modulated conditions, but that the average d.c. grid current is *greater in the resting condition*. Thus the average load on the driver stage is greatest when unmodulated, which is just the opposite of the conventional linear amplifier. It follows that less artificial stabilization of the driver load is necessary with the expanding linear amplifier than with conventional linear amplifiers.

The operating point P on figure 3 represents point of 60% average plate efficiency when unmodulated (assuming 80% as maximum class BC positive peak efficiency). If the point P were just halfway up the dynamic characteristic (halfway between plate current cut-off and the diode bend, or quasi-saturation points), the modulation capability would be 100%. However as the point P is three quarters of the way



up the characteristic the maximum modulation capability in this resting condition is only 33%. The modulation capability could have been maintained at 100% for the resting condition but then the average d.c. plate current would have dropped to two thirds its completely modulated value and the same drop would occur in carrier amplitude. Thus the result would be simply controlled carrier. 33% modulation capability in the resting condition ensures that a steep-front audio signal will not catch the modulation capability napping and cause over-modulation (flattening of the positive audio peaks).

The resting plate voltage in the set-up described above is 33% under the maximum plate voltage applied during periods of 100% modulation. In other words, the plate voltage increases 50% above the resting voltage when completely modulated. This represents an axis shift of 33%.

As the maximum output from the expanding linear amplifier is usually limited by plate loss in the completely modulated condition, it is always necessary, when designing such an amplifier, to start with the 100% modulated condition and then work backwards to determine the resting conditions. Thus we will define dynamic axis shift as a percentage *drop* in plate voltage and bias from the completely modulated condition, rather than a percentage rise above the resting condition.

It should be noted that the 33% dynamic axis shift discussed above is an arbitrary choice. The shift can be anything between zero shift and 50% shift. The shift can not exceed 50% and still keep the carrier constant. The following table (applicable only to class BC operation) shows the effect of various percentages of axis shift downward from 100% modulation on the plate efficiency and modulation capability in the resting condition.

CLASS BC OPERATION		
Percentage drop in plate and pack bias voltage (axis shift)	Resting plate efficiency (taking 80% as peak)	Resting modulation capability
0 %	40 %	100%
20.83% *	50 %	60%
25 %	53.3%	50%
33 % **	60 %	33%
50 %	80 %	0%

* The 20.83% axis shift is recommended for those tubes whose plate loss limit may not be exceeded even momentarily.

** The 33% axis shift is recommended for those tubes whose plate loss limit may be exceeded momentarily under voice modulation by 50%.

The relationships shown in the preceding table were obtained from the use of the following formulae from which the resting plate efficiency and resting modulation capability can be obtained for any degree of dynamic axis shift.

$$\text{Eff}_R = \frac{100 \text{ Eff}_p}{100 + M_c}$$

$$M_c = 100 - 2S$$

$$\text{Eff}_R = \frac{50 \text{ Eff}_p}{(100 - S)}$$

Where Eff_R equals resting, or unmodulated plate efficiency.

Eff_p equals maximum attainable instantaneous peak plate efficiency.

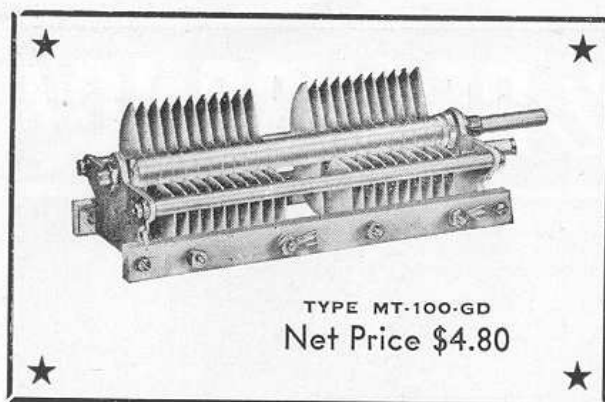
M_c equals percentage modulation capability.

S equals percentage dynamic axis shift downward from 100% modulated to resting condition.

Note that these formulae can be applied to either expanding class B or expanding class BC operation by inserting a suitable value of Eff_p , which is taken as 80% for class BC operation and as 66% for class B operation. These values will be about right for operation of most tubes at or slightly above normal rated plate voltage. This means about 750 volts for a 210 or 801; about 1250 to 1500 volts for tubes of the 800 and 211 general types, and at least 1750 to 2000 volts on the higher-voltage low C tubes such as 150T, 354, HF300, etc. 852's will require at least 2500 to 3500 volts to make them get up and really go due to their rather high average plate resistance at lower plate voltages.

With an axis shift of 33% downwards the plate loss is least in the resting condition and rises 50% under complete sine wave modulation. As the unmodulated plate efficiency is 60% with this much axis shift the maximum carrier power output will be one and a half times the resting plate loss on the tube used in the expanding linear amplifier. The tube has to be able to stand the additional plate loss which occurs during modulation without damage. All the tantalum plate tubes and some of the moly and carbon plate tubes will stand a momentary overload of 50% above rated plate loss.

[Continued on Page 74]



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Expanding Linear Amplifier

[Continued from Page 14]

When using those tubes that should not be operated with more than rated plate loss at any time, there is no point in using more than 20% axis shift. *With 20% axis shift the plate loss is the same resting or completely modulated.* The increase in plate input during modulation (25% increase) is approximately equal to the increase in r.f. output from the amplifier caused by the presence of sidebands.

The following table shows typical conditions for a single 211 tube operating with 100% modulation, resting with 20% axis shift and resting with 33% axis shift.

EXPANDING CLASS BC OPERATION TYPE 211			
100 Watts of Carrier Output			
Max. plate loss.....	100 watts	100 watts	12
Max. plate current.....	150 ma.	150 ma.	12
	Completely Modulated	Resting 20% shift	Resting 33% shift
Modulation capability	100%	60%	33%
Plate efficiency (av.)	60%	50%	60%
Plate input power	250 W	200 W	166 W
Carrier output	100 W	100 W	100 W
Sideband output	50 W	0 W	0 W
Plate loss	100 W	100 W	66 W
Plate volts (net)	1666 V	1333 V	1111 V
Plate mills	150 Ma.	150 Ma.	150 Ma.
Pack bias	-135 V	-108 V	-90 V
Cathode bias	-135 V	-135 V	-135 V
Cathode bias resistance	900 to 1000 ohms

The 20% axis shift is generally most satisfactory except where the last possible watt of output is desired, when the 33% shift may be used, assuming the tube used can stand an increase in plate loss during modulation. 20% shift requires less rectified audio power to saturate the primary reactor in the 110 volt line to the plate and bias supplies of the expanding linear amplifier. Also a cheaper saturable reactor can be used. Unless the bias supply is carefully designed and built there will be difficulty in making the bias and plate voltage "track" over a wide range of axis shift.

There is no point in exceeding 33% axis shift as it is rarely desirable or necessary to reduce the resting plate loss to lower than 66% of the plate loss fully modulated. Most users of linear amplifiers would be perfectly happy if they could keep the *unmodulated* plate loss down to the value at 100% sine wave modulation, let alone dropping it below 66% of that loss!

As tubes of the 150T-354 and HF300 type can easily stand 50% overloads in plate loss momentarily without shortening their life, the following table is based on 33% axis shift. Note that 225 watts of carrier output is obtained with this amount of axis shift.

EXPANDING CLASS BC OPERATION
TYPE 150T-354

225 Watts of Carrier Output

11	12	
Max. continuous plate loss.....	150 watts	
Max. intermittent plate loss.....	225 watts	
Max. plate current.....	200 ma.	
	<i>Completely modulated</i>	<i>Resting 33% shift</i>
Modulation capability	100 %	33 %
Plate efficiency (av.)	60 %	60 %
Plate input power	563 W.	375 W.
Carrier output	225 W.	225 W.
Sideband output	112 W.	0 W.
Plate loss	225 W.	150 W.
Plate volts (net)	2813 V.	1875 V.
Plate ma.	200 Ma.	200 Ma.
Pack bias	—235	—156
Cathode bias	—235	—235
Cathode bias resistance	1170 to 1200 ohms

If it is not necessary to get the last possible watt of output, the use of 20% axis shift is suggested. At 20% dynamic axis shift the maximum attainable carrier power output is 150 watts. The following table shows operation with 150 watts of carrier output for both the 20% and 33% values of axis shift. It will be evident that there is no particular advantage in the use of 33% axis shift under the conditions shown below.

EXPANDING CLASS BC OPERATION
TYPE 150T-354

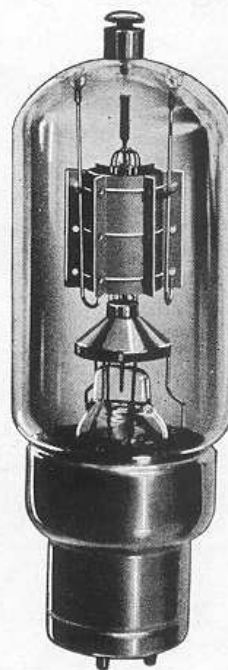
150 Watts of Carrier Output

11	12		
Max. continuous plate loss.....	150 watts		
Max. intermittent loss limited to.....	150 watts		
Max. plate current.....	200 ma.		
	Completely modulated	Resting 20% shift	Resting 33% shift
Modulation capability	100 %	60 %	33 %
Plate efficiency (av.)	60 %	50 %	60 %
Plate input power	375 W.	300 W.	250 W.
Carrier output	150 W.	150 W.	150 W.
Sideband output	75 W.	0 W.	0 W.
Plate loss	150 W.	150 W.	100 W.
Plate volts (net)	1875 V.	1500 V.	1250 V.
Plate ma.	200 Ma.	200 Ma.	200 Ma.
Pack bias	155 V.	125 V.	105 V.
Cathode bias	155 V.	155 V.	155 V.
Cathode bias resistance	750 to 800 ohms		

These values given above indicate maximum values of output at the lowest usable values of plate voltage. Other combinations of plate voltage and current may be used but the following limitations must be kept in mind. The maximum average plate efficiency for class BC operation when completely modulated will rarely exceed 60%. Thus given the rated plate loss on the tube to be used it is easy to calculate the maximum allowable plate input. Once the allowable plate input is known the plate voltage, plate current, and pack bias voltage for the completely modulated condition can easily be determined. Remember that with 115 volts a.c. line voltage, the voltage on the load side of the saturable reactor used to effect axis shift

[Continued on Next Page]

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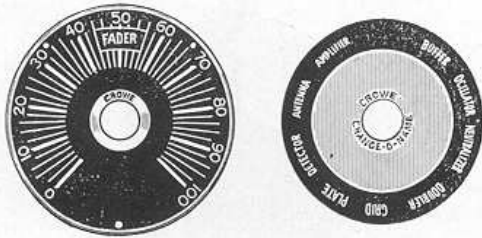
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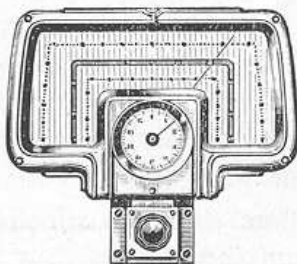
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will usually be from 70 to 90 volts *when the reactor is completely saturated*. Unless a primary autotransformer is used the plate and bias pack transformers will have to give desired maximum plate voltage with from 70 to 90 volts on the primary side. We hope to be able to present curves on all available saturable reactors soon which will simplify matters greatly in power supply design for the expanding linear amplifier.

When the expanding linear amplifier first began to dawn it was felt that the zero bias triodes such as the 838, 805, RK31 and the ZT4B would provide an ideal answer as no pack bias would be necessary and only the plate voltage would have to be varied. It was a fine idea and we haven't given it up yet, but we found that the zero bias tubes are zero biased to cut-off at one value of plate voltage only (zero plate voltage, strictly speaking!). Thus shifting pack bias is just as necessary with the "zero bias" group as with the lower μ types. Also, due to the materially higher grid current in the zero bias group, the bias and plate supplies are very hard to make "track" over the range of axis shift. The point is that the d.c. plate current won't stand still as the axis shifts on the high μ tubes. However, we are working on a compensation circuit, one example of which is shown in figure 5, to exercise a secondary reverse axis shaft over the grid excitation applied to the linear amplifier. The compensator circuit can be actuated by either the d.c. plate current on the linear stage or by rectifying some of the r.f. output of the linear stage. Thus if the d.c. plate current or the average carrier amplitude start to rise when the rig is modulated, the compensator causes a slight reduction in grid drive on the linear stage and backs the output off enough to flatten out the average carrier output. It is, in effect, automatic gain control applied to the modulated buffer stage that feeds the linear amplifier. Very little compensation is necessary under normal conditions as most variations are under 10%.

The compensating control can be applied to the class C modulated buffer in a number of ways. The simplest way is to use another saturable reactor in the primary side of the plate supply to the class C stage. See figure 5. As little control is needed, this reactor would be quite cheap.

The ramifications of dynamic shift, including bias modulation, are so numerous that they will have to wait until next time.

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