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DR. HULL JOINS OUR STAFF

An agreement has been made with the Radio Frequency Laboratories of Boonton, New Jersey, whereby on certain problems the facilities of each laboratory will be available to the other. The most important part of the plan, however, is that Dr. Lewis M. Hull will become Director of Research of both organizations, making his headquarters at our laboratories, here at Cambridge.

Dr. Hull is well known in the radio field and particularly for his active participation in the discussion of papers presented before the New York meetings of the Institute of Radio Engineers. He received his doctor's degree from Harvard University, where he specialized in physics, particularly in radio problems, under the direction of Dr. Pierce. He has taught at the University of Kansas, and was associated for four years with the Bureau of Standards in the capacities of consultant physicist, and then associate physicist. Since the founding of the Radio Frequency Laboratories nearly six years ago, Dr. Hull has been a member of the organization.

Factors Governing the Choice of Power Tubes

By C. T. BURKE, Engineering Department

The proper selection of tubes is of primary importance in the efficient design of an amplifier, that is, in obtaining an amplifier which gives the desired results at least cost, yet the frequent appearance of amplifiers in which a wiser selection would have resulted in a better or more economical amplifier bears testimony to lack of consideration of the factors involved.

Before considering the characteristics of the various tubes it is helpful to review the voltage and power relations in vacuum tubes in general. The following considerations apply to all types of tubes. In Fig. 1 the plate circuit of the tube is shown.

The voltage μE_g appears across the plate circuit as a result of the impressed grid voltage E_g and the amplification factor μ. R_p represents the internal plate impedance of the tube. R_L represents the load in the plate circuit, i. e., the input impedance of a coupling unit or reproducer. R_L is in most cases a reactance rather than a resistance, but it is convenient to consider it as a resistance, and no serious inaccuracies are introduced.

The following relations follow from the laws of electrical circuits.

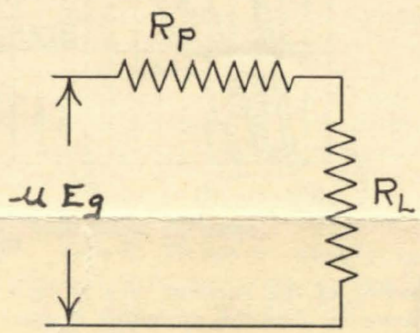

FIG. 1

Plate current (alternating) $I_P = \dfrac{\mu E_g}{R_P + R_L}$ (1)

Voltage across $R_L = \mu E_g -$ (2)

$$\frac{\mu E_g R_P}{R_P + R_L} = \mu E_g \frac{R_L}{R_P + R_L}$$

Power produced in $R_L =$ (3)

$$\frac{\mu E_g R_L}{R_P + R_L} \times \frac{\mu E_g}{R_P + R_L} = \frac{\mu^2 E_g{}^2 R_L}{(R_P + R_L)^2}$$

These equations are fundamental for all vacuum tubes, assuming the tube to be acting on the straight portion of its characteristic, i. e., that plate and grid voltages are properly adjusted.

Since the voltage across R_L is the useful output voltage of the tube, equation (2) summarizes the behavior of the tube as an amplifier. The voltage amplification of the tube and coupling device is seen to depend on three things, the amplification factor of the tube (μ), the plate impedance (R_p) and the load impedance (R_L). Increasing or R_L increases the amplification while increasing R_p reduces amplification The natural conclusion is that a tube with a high μ, low plate impedance and a high load impedance will achieve ideal results. Unfortunately, however, perhaps due to a particularly regrettable oversight on the part of the inventor of the device, amplification factor and plate impedance are not independently variable, but are so tied together in the design of the tube that changes tending to raise the amplification factor also increase the plate impedance. Furthermore, practical considerations limit the impedance of the load. If a resistance coupling device is used, the voltage drop in the resistor limits its value, and cost is a limiting factor when using other forms of coupling devices. The equation does show, however, the desirability of high input impedances in the coupling device. In practical tube design, a compromise is made between amplification factor and plate impedance, resulting in several classes of tubes for different purposes, i. e., the "high mu" type where a high load impedance is used, the "general purpose" for the conventional types of amplifier, and the power tubes which work into a low load impedance. Substitution of values in the equation shows that despite its low amplification factor, a tube having an amplification of 3 and a plate impedance of 2000 will have a greater amplification per stage when feeding a load of 2000 ohms than will a tube having an amplification factor of 8 and a plate impedance of 10,000 ohms. An important fact to remember.

The voltage equation will also answer the question frequently asked, may a "high mu" tube be used with coupling impedances designed for use with general purpose tubes. Suppose a "high mu" tube is used with a low value of coupling impedance, e. g.

$\mu = 30$, $R_P = 15{,}000$, $R_L = 30{,}000$

Voltage across $R_L =$

$$E_g \frac{30 \times 30{,}000}{180{,}000} = 5.0\ E_g$$

Compare with $\mu = 8.4$, $R_P = 10{,}000$, $R_L = 30{,}000$

Voltage across $R_L =$

$$E_g\ 8.4\ \frac{30{,}000}{40{,}000} = 6.3\ E_g$$

The answer is evidently, that under these conditions, the amplification per stage is less than with a "general purpose" tube, if the "high mu" tube is used.

Considering now the power equation, it can be seen that the power also is increased by increasing the amplification factor. As has been pointed out, however, this cannot be done without changes in the load impedance. It may be shown readily that the power output is a maximum when the plate and load impedances are equal. Thus the equation for maximum power output becomes

$$P\,Max = \frac{\mu^2 E_g^2}{4\ R_P} \qquad (4)$$

Comparison of the power and voltage equations reveals the fact that the same load impedance is not favorable both for obtaining a large voltage amplification and for obtaining a large power output. Thus it is seen that the fundamental distinction between a "voltage" and a "power" amplifier is in the load impedance connected in the plate circuit of the tube. In the interstage coupling device, a large increase of voltage per stage is desirable since the output of the last stage is governed primarily by the voltage impressed on its grid. The power required from the plate circuit of the interstage tubes is small, only sufficient to supply losses in the coupling device. Even with a coupling device of as high impedance as is practicable, the tube supplies sufficient power for these losses.

Equation (4) represents the maximum power that may be obtained from an amplifier tube. The behavior of the vacuum tube is such, however, that the operating characteristics are somewhat affected by the load impedance, a low impedance shortening the straight portion of the characteristic. This occurs, and distortion is introduced if a load impedance as low as the plate impedance of the tube is used. It has been experimentally determined that the maximum UNDISTORTED output of the tube is obtained when the load impedance is equal to about twice the plate impedance of the tube. Substituting these values in equation (3) we get,

$$P\ (max.\ undis.) = \frac{2\ \mu^2 E_g^2}{9\ R_P}$$

which is very little less than the maximum power of equation (4).

The result is in watts if Eg is the root mean square value of the signal voltage applied to the grid. It is generally more convenient to consider the peak value of the signal voltage, since this is limited to a value approximately equal to the grid bias voltage if tube overloading is to be avoided.

Then

$$P\ max.\ undis. = \frac{\mu^2 E_g^2}{9\ R_P}$$

where Eg is the PEAK signal voltage applied to the grid.

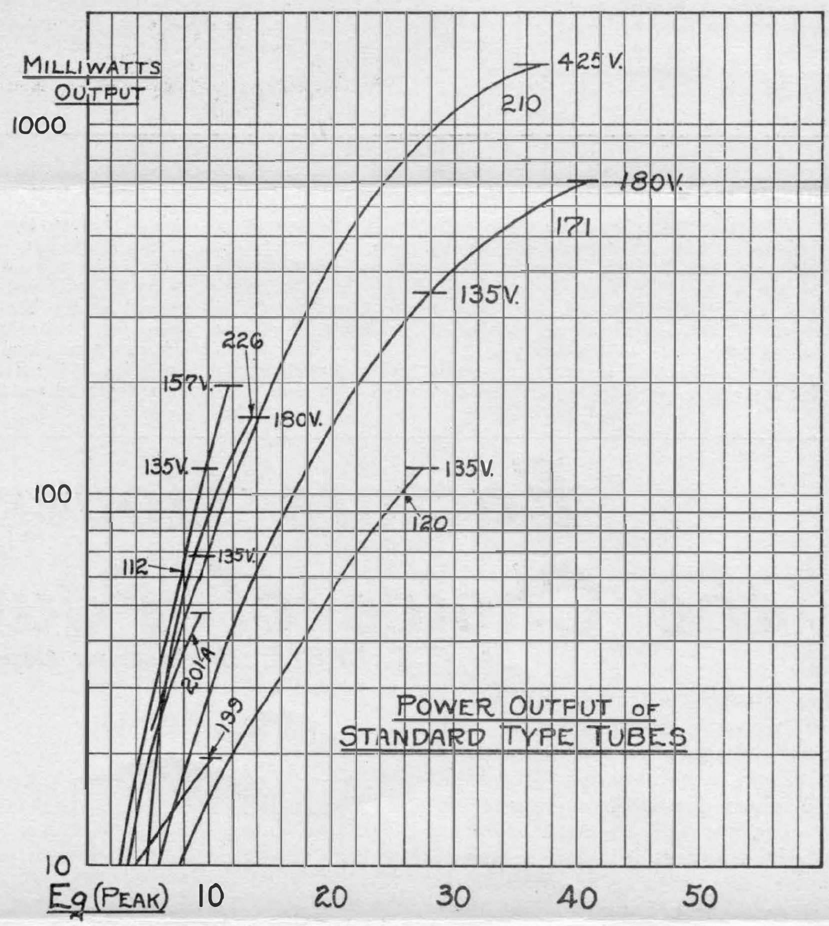

Fig. 2

We are now in a position to judge from the characteristics of the different types of tubes as to the best choice for a given use.

The power equation may be readily extended to include special output combinations, i. e., tubes in parallel and in "push pull" connection.

For the parallel connection, μ is unchanged, but Rp is reduced to half

Then

$$P\ max.\ undis. = \frac{2\ \mu^2 E_g^2}{9\ R_P}$$

Rp=plate impedance of one tube, or the output for any applied grid voltage up to the maximum permitted by the bias voltage is doubled. The allowable maximum signal voltage is not increased, and the load impedance must be halved.

This may be accomplished with a suitable output coupling device.

We are now in posses ion of the facts necessary for the proper design of the amplifier, saving excess material and expense as well as preventing bottle necks which limit the capacity of the amplifier at some points,

Three factors are to be considered in designing the amplifier-voltage input at the detector, power output desired, and the power supply available. The importance of the lact factor is often overlooked, resulting in the common use of tubes at too low a plate voltage.

Fig. 2 shows the variation of power output with grid voltage (peak) of the standard amplifier tubes. In the vacuum tube data table on page 4 is shown the plate voltage required to maintain emission at the grid voltages specified. It is assumed that a peak signal voltage equal to the grid bias voltage may be used. This is not strictly true, the maximum allowable grid peak voltage being slightly less than the bias voltage. It will be further assumed that the amplification per stage is 0.9 μ times the transformer ratio. This relation is approximately correct, provided the coupling device has been properly designed.

It will be seen from the curves of Fig. 2 that when considerable loudspeaker power is required, the power stage cannot operate directly out of the detector. In order to obtain a power output in excess of 10 milliwatts, with any tube, a signal voltage of about 3 is required. The signal voltage in the detector plate circuit is usually 0.1 to 0.5 volts. We will assume 0.3 is an average value in the rest of this discussion. The importance of input voltage is apparent. The importance of the power supply as a limiting factor in the choice of tubes will be demonstrated presently.

Examination of the curves of Fig. 2 shows that at low input voltages the power outputs are bunched closely together. On the basis of the power required for 10 milliwats output, the tubes range as follows, 112, WD11, 210, 201A, 199, 226, 171 and 120. Up to 10 volts input, the 112 is superior to all other types. In comparing the output of the 210 with that of other tubes, it must be borne in mind that a high plate voltage is required for this tube. The output of the 210 at 180 volts plate is but 145 milliwatts.

The use of the curves can best be demonstrated by discussing a few typical cases.

Case 1.

Receiver—1 stage audio 201A tube 1:2.7 transformer—to add a power stage—no restrictions on power supply. There is available at the primary of the transformer a signal voltage of 0.3 x 0.9 x 8 x 2.7 (following the assumptions stated) =5.8

(a) input turns ratio to second stage 1:2.7; Eg=12. Inspection of the curves show that a 112 tube will be overloaded at this signal voltage. The 112 tube is so much superior to other types at low input voltages, however, that a greater power output will be obtained if the signal is reduced sufficiently to avoid overloading the 112 than if any other type of tube is substituted.

(b) input turns ratio 1:5.95;
Eg=35

The 210 would be chosen in this case. If the plate supply voltage had been limited, the 171, or perhaps two 171's in parallel or push-pull would be used.

Case 2. Battery operated receiver.

3-volt filament—135 volts plate
1st. stage 1:2.7 transformer

Voltage at primary of second stage
0.3 x 0.9 x 6 x 2.7=4.4

Voltage on tube grid (6:1 transformers) 26 volts.

The battery requirements limits the selection to the 120 tube which would be overloaded, requiring either a reduction in signal voltage or the use of a lower transformer ratio.

Suppose it is desired to operate a separate power stage, with A. C. filament supply permitting the use of a 5-volt tube. If there is no limit to the plate voltage, a 210 would be used. This is another case where the parallel or push-pull connection could be used to advantage, to avoid high plate voltage.

Case 3. Receiver—detector only. It is desired to design an amplifier to supply the full output of a 210 type tube.

The curve shows the grid swing required to be 35 volts.

Assuming 0.3 volts in the detector plate:

$$\text{Required gain} = \frac{35}{.3} = 117$$

(between detector and the grid of the power tube).

Examine the following possibilities.

1. 1:2.7 transformer—201A—
   1:2.7 transformer; gain=53
2. 1:2.7 transformer—201A—
   1:6 transformer; gain=118
3. Double impedance—201A—
   Double impedance—201A—
   Double impedance; gain=49
4. Double impedance—201A—
   Double impedance—201A—
   1:2.7 transformer; gain=147
5. Double impedance—201A—
   Double impedance—201A—
   6:1 transformer; gain=330

It is apparent that neither the arrangement 1, nor 3 would be satisfactory. Arrangement No. 2 would just "get by," but would not be desirable as it permits no factor of safety. Arrangement No. 4 would be satisfactory, but some might prefer No. 5 which could be worked with lower signal voltages in the detector.

New General Radio Apparatus

TYPE 446 VOLTAGE DIVIDER

The experimenter or home set builder who is building a plate supply unit requires an adjustable resistance, in order to get the correct plate voltages for the several tubes in his receiving set. In the construction of the General Radio Type 445 Plate Supply Unit, a similar requirement existed, and to meet it, a separate wire wound resistance card with four adjustable sliders was developed. There have been so many requests to supply this card separately that we are now prepared to release it under the title of Type 446 Voltage Divider. The list price is $4.00.

The unit is wound in two sections, the larger section having a resistance of 15,000 ohms, and being provided with three adjustable sliders. This section is used for the plate supply. The second section has a resistance of 1500 ohms, and is provided with a single adjustable slider. This section is used for C biasing. The card, while rugged, is thin so as to keep inductance effects at a minimum. Convenient mounting brackets are provided.

ADJUSTABLE CENTER TAP RESISTANCE

While a resistance to go across the filament of the alternating current tubes usually requires a tap at its exact center, conditions often arise, due to unbalancing, when it is desirable to have the tap slightly off center.

To meet this condition, we have developed a center tap resistance similar to the Type 439, except that the tap is made by means of an adjustable slider. This enables the tap to be placed at the neutral point, thus reducing hum to a minimum.

This new unit, listing for 75c, and designated as Type 437, is now available for distribution.

VACUUM TUBE DATA TABLE

TYPE	FILAMENT VOLTS	FILAMENT AMPS.	B VOLTS	C VOLTS	PLATE CURRENT MILS	PLATE IMP. OHMS	MUT. COND. M.MHOS	AMP. FACTOR	PEAK EMISSION MILS.	OUTPUT MILLIWATTS UNDIST.	OUTPUT MILLIWATTS AS OSC.	CAPACITY COLD M.M.F.	MAX. DIA. INCHES	MAX. HEIGHT INCHES
WD 11	1.1	.25	22	0	.4	22000	260	6	25		6			
WD 12			45	-1.5	1.1	18000	345	6.2			30	G-F 6		
CX 11			67	-3	1.8	17000	365	6.2			85	G-P-5.5		
CX 12			90	-4.5	2.6	16000	390	6.2		12	150	P-F 7.5	1 7/16"	4 7/16"
$2.50														
UX 199	3.3	.063	22	0	4	26000	230	5.9	9		6			
CX 199			45	-1.5	1	19500	320	625			30	G-F 3.6		
UV 199			67	-3	1.7	16500	380	625			80	G-P 3.5		
CV 199			90	-4.5	2.5	15000	415	6.25		7.5	150	P-F 4.5	1 1/16"	3 1/2"
			135											
			90	-7.5	1.3	19000	330	625		15	80			
$2.25														
UX 120	3.3	.130	22	0	1	10000	320	3.2	24		16	G-F 4.5		
CX 120			45	4	2	8500	390	3.3			60	G-P 5.4		
			67	9	3	8000	410	3.3			140	P-F 4.4	1 3/16"	4 1/8"
			90	16.5	3.2	7700	430	3.3			200			
			135	22.5	7	6600	500	3.3		105	650			
			135	27	5.5	7500	430	3.2		110	500			
$2.50														
UX 201 A	5	.25	22	0	.5	26000	325	8.4	45		8	G-F 5.8		
			45	1.5	.9	18500	460	8.4			28	G-P 10.1		
			67	3	1.5	14000	600	8.4			70	P-F 6.1	1 13/16"	4 11/16"
			90	4.5	2	12000	710	8.5		15	130			
			135	9	2.5	11000	775	8.5		50	230			
			180	13	3	9000	940	8.5						
$2.00														
UX 112	5	.5	22	0	1.1	14500	550	8	150		17			
			45									G-F 9		
			67									G-P 11	1 13/16"	4 11/16"
			90	-6	2.4	8800	890	7.9		40	150	P-F 7.5		
			135	-9	6	5000	1640	8.2		120	550			
			157	-10.5	8	4800	1700	8.2		195	850			
$4.50														
UX 171	5	.5	22	0	4	3500	850	3	80		60			
			45	-5	6							G-F 6.8		
			67	-12	7						320	G-P 9.5	1 13/16"	4 11/16"
			90	-16.5	11	2500	1200	3		110	680	P-F 6.5		
			135	-27	16	2200	1320	2.9		350	1500			
			180	-405	20	2100	1380	2.9		700	2500			
$4.50														
UX 210	6	1.1	90	-4.5	3	9700	775	7.5	500	18	240	G-F 7		
			135	-9	5	8000	940	7.5		64	600	G-P 8		
			180	-10	7	7000	1070	7.5		145	1100	P-F 7		
	7.5	1.25	250	-18	12	5600	1340	7.5		340	2700		2 3/16"	5 5/8"
			350	-25	18	5100	1460	7.6		950	5500			
			425	-35	20	5000	1540	7.7		1500	7500			
$9.00														
UX 222 (RADIO)	3.3	.132	135	1.5	1.5	850,000	350	300					1 13/16"	5 3/8"
UX-222 (AUDIO)	3.3	.132	180	1.5	.3	150,000	400	60					1 13/16"	5 3/8"
UX 200A	5	.25	22		1.2	35000	570	20						
			45		1.5	30000	670	20					1 13/16"	4 11/16"
$4.00														
N (215 A)	1	.25										G-F 4.4		
												G-P 4.2		
			67	-6	1	20000	300	6		8	40	P-F 3.8	5/8"	2 1/2"
V (102 D)	2	.97											2 3/8"	4 1/2"
			130	-1.5	.75	60000	500	30		4.2	50			
L (216 A)	5-6	1											2 3/8"	4 1/2"
			130	-9	8	6000	980	5.9		60	600			
E (205 D)	4.5	1.6											2 3/8"	4 1/2"
			350	22.5	33	3500	2000	7		890	8000			
UX 226	1.5	1.05	90	6	3.5	9400	875	8.2		20				
			135	9	6	7400	1100	8.2		70			1 13/16"	4 11/16"
			180	13.5	7.5	7000	1170	8.2		160				
UY 227	2.5	1.75	45		2	10,000	800	8						
			90		7	8000	1000	8					1 13/16"	4 11/16"
UX 240	5.0	.25	135	1.5	.2	150,000	200	.30						
			180	3	.2	150,000	200	30					1 13/16"	4 11/16"
UX 280	FULL-WAVE RECTIFIER					FIL. TERM. VOLTS 5 V. FIL. CURRENT 2 A. A.C. PLATE VOLTS 300 V. (MAX. PER PLATE) } R.M.S.			MAX. D.C. OUTPUT CURRENT BOTH PLATES 125 M.A.				2 3/16"	5 5/8"
UX 281	HALF-WAVE RECTIFIER					FIL. TERM. VOLTS 7.5 V. FIL. CURRENT 1.25 A. A.C. PLATE VOLTS 750 V. (MAXIMUM) } R.M.S.			D.C. OUTPUT CURRENT RECOMENDED 65 M.A. MAXIMUM 110 M.A.				2 7/16"	6 1/4"

Note: Except for half ampere filament, UX-112 and UX-171 characteristics are