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CHARACTERISTICS OF FILAMENT TYPE RECTIFIERS

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THE first socket-power device sold in any quantity was the "B" eliminator which at the time when these devices were first offered, some three years ago, commonly utilized the general purpose tube, type cx-301A, as the rectifier. Some of these were single-wave rectifiers, capable of supplying 10 to 15 mA., at 90 volts, while others were full-wave rectifiers using two tubes and with an output of 20 to 30 mA. The outputs mentioned were obtainable only with tubes in which the filament was in the best of condition, and the slightest drop in filament emission became noticeable immediately in a reduction in output current and voltage.

These "B" eliminators gave good service at the time they were introduced, the conditions differing considerably from present day requirements in several important respects, the most important one being the plate current drain of the sets then in use. Five-tube sets were just becoming popular, with six-, seven-and eight-tube sets quite rare. The average receiver was of the three- or four-tube type, requiring from 10 to 20 milliamperes, at a maximum voltage of 90 volts. The rapid increase in the number of tubes per receiver soon raised the maximum demand to 30 mA. in the case of the five-tube receiver in which the "C" battery was omitted altogether. Two years ago, power-amplifier tubes were introduced, the 371 type adding nearly 15 mA., to the total receiver current drain when operated at 135 volts, and 20 mA. when operated at 180 volts. As a result of this increase the maximum current requirements became 50 to 60 mA. Other developments were the type of receiver in which cx-299 tubes were operated in series from socket power, requiring 65 to 75 mA. and those using type cx-301A in series and requiring 250 to 300 mA.

The rectifier using cx-301A tubes, soon became adequate in the face of the rapidly increasing current demand, and types cx-313, a full-wave rectifier, and cx-316B, a half-wave rectifier, were introduced, the cx-313 providing an output of 65 mA., the maximum allowable transformer voltage being 220 volts a.c. per anode. The cx-316B also, has a rating of 65 mA., but the design is such as to permit the use of a higher transformer voltage, 550 volts. With an efficient filter the cx-313 provided a maximum voltage of 180 volts, and the cx-316B, 450 to 500 volts. These types are now being superseded by the cx-380 (full wave) rated at 125 mA. and 300 volts a.c. transformer voltage, per anode and the cx-381 (half wave) rated at 110 mA., and 750 volts a.c. The latter two tubes have only been in production a short time, and the data presented in connection with them is subject to slight modifications.

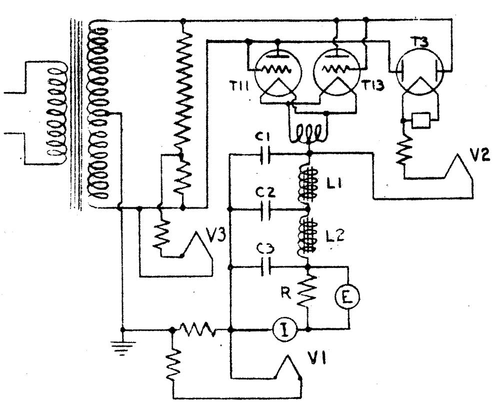


Fig. 1

The circuit diagram of one of the early types of rectifiers designed to use cx-301A tubes, is shown in Fig. 1. This circuit diagram also shows the placing of the oscillograph vibrators used in testing the performance of this unit as shown in the following figures. As indicated, vi-

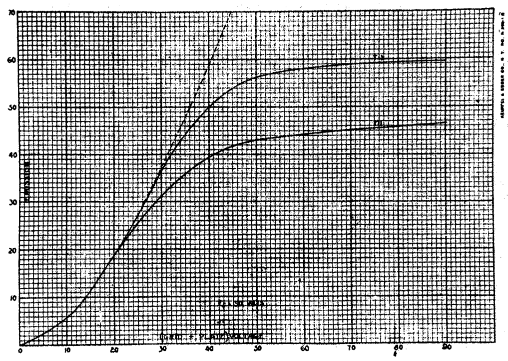


Fig. 2

brator V_3 is arranged to show the full transformer secondary voltage, which with 110 volts applied to the primary, was 230 volts R. M. S., or 115 volts per tube, the applied voltage to each rectifier being one half of the total transformer voltage because of the full-wave connection. Vibrator V_1 reads the instantaneous current through the tube, while V_2 by means of a special circuit arrangement reads the voltage across the tube only during the time it is conducting current. The back voltage across each tube is blocked off by means of the auxiliary full wave rectifier tube, T_3 in the diagram.

With this arrangement it is possible to get a complete record of the performance of each rectifier and to determine the exact point at which overloading, due to limited filament emission, begins. The power lost in the tube can also be computed, and the efficiency determined.

In taking the records, high sensitivity vibrator elements requiring about one milliampere per millimeter deflection, were used and a 10-millimeter deflection was satisfactory for most of the work. The current required, 10 mA., could not be disregarded in taking some of the voltage readings, but the effect of this current, for instance, the current flowing through the vibrator V_2 was eliminated by making an extra exposure on the film, the vibrator V_1 being opened when V_2, was being read, and vice versa. Tubes T_{11} and T_{13} were cx-301A's while T_3 was a cx-380 rectifier tube.

In Fig. 2 the emission characteristics of the cx-301A tubes used in the tests on this older type of socket power device are shown. The tubes were prepared for service by an ageing treatment so that the emission would remain entirely steady during the taking of the film. A voltage of 100 volts was applied to both plate and grid, under which voltages the full emission current of 40 to 60 milliamperes was drawn over to these electrodes. Under this very severe overload the emission dropped slowly, and after the current had dropped to 20 mA. the voltage was cut off and the filament reactivated at 7.0 volts for a few minutes. After a few cycles of this treatment the emission remained steady for a long period of operation at the high voltage.

The curves show that practically the full emission current flows when a voltage of 50 volts is applied to the anode (that is, to the grid and plate connected together as an anode) and that there is very little increase as the applied voltage is raised to 90 volts or above. Tube T_{11} had a slightly lower emission than the T_{13}, but was close to the average for cx-301A tubes, 45 mA.

A cx-313 was substituted for the two cx-301A tubes in taking the record shown in Fig. 2 and as a matter of reference the emission curve of one filament and anode of this tube is indicated for comparison with type cx-301A as shown by the dotted line (Fig. 2), which shows no evidence of saturation within the limits of the figure.

In the oscillograph record, Fig. 3, each figure contains two separate records of the performance of the socket-power unit in question. The records made by vibrators V_2 and V_1 labelled "A" in the Figure, show in each case the performance under a load current of 20 mA. the normal maximum for this unit, while curves B show the performance at 50 mA. output. Referring to Fig. 3A, the upper record, Vibrator V_3, is that of the voltage developed across the secondary of the transformer. The wave form is slightly irregular, due partly to some harmonics present in the generator output, and especially evident at the peak of the wave; and partly to the irregular load imposed upon the transformer by the rectifier. The voltage scales between the two records in this figure apply to both, and as indicated by this scale the peak was 340 volts, total or 170 volts per tube. The R. M. S. value was 240 volts, or 120 volts per side.

OSCILLOGRAPH RECORDS OF PERFORMANCE

VIBRATORS V_2 and V_1 trace somewhat similar records, since V_2 is the voltage developed across the tube when the current indicated by V_1 is flowing. It can be noted in the curves showing the current wave form that the voltage rises rather rapidly as the current starts to flow, and then less rapidly as it reaches higher current values. This is partly due to the fact that the resistance offered by the tube to the flow of current decreases as the current increases until the full emission current flows, and partly to the less rapid increase in instantaneous transformer voltage, when near the peak of the wave. The current does not begin to flow at the instant the transformer voltage increases, but lags about 40°, this lag being due to the voltage existing across the first filter condenser. In this particular case the voltage across the load was 108 volts, and the voltage

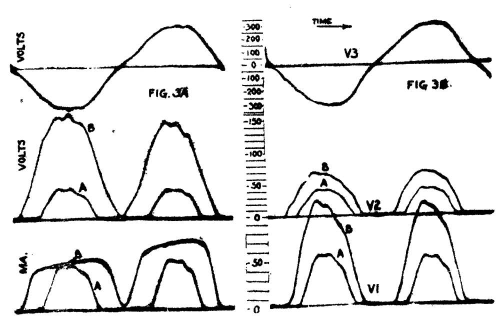


Fig. 3

across the first filter condenser somewhat higher. At the instant the current started to flow the transformer voltage was approximately 120 volts, indicating that this value of voltage existed across this condenser, Current then flows for the next 100° of this alternation, and at the time it ceases to flow the transformer voltage is 145 volts, as a result of the charging of the concondenser. During the remaining part of the alternation the rectifier is idle.

The voltage, across the tube just reaches the value required for full emission current, 50 volts, and the current was slightly higher than was expected from the d.c. readings, (above 50 mA). Tube T_{11} shown in the Figure was the tube through which current was flowing on this alternation. On the second alternation the current reached a slightly higher value, 55 mA., but because of the higher emission given by tube T_{13} the peak voltage drop was 43 volts.

Conditions indicated by record B on these two vibrators were with maximum obtainable load current, 50 mA., to obtain which the output terminals were shorted except for the resistance of the vibrator. As a result the d.c. voltage across the first filter condenser is lowered to a negligible value and current begins to flow almost immediately after the transformer voltage begins to rise, the current quickly building up to the full emission available. The current rose higher than the values found on the d.c. test shown in Fig. 2, approaching 75 mA. with Tube T_{13} but whether this was due to the heating up of the tube as a result of the large amount of energy dissipated in the bulb, or to some other cause, was not determined, but the record suggests that it was partially due to the heating as the current gradually increased at a steady rate during the period heat was being developed in the tube.

The voltage across the tubes reached a value close to the full transformer voltage, the peak with tube T_{11} being 160 volts, and with T_{13} just under 150 volts. Practically all of the energy delivered by the transformer, 16 watts exclusive of the filament energy, was dissipated in the rectifier tubes, accounting for the fact that the output terminals had to be shorted to reach this current value,

In Fig. 2, the same readings are repeated with all conditions the same except that a single cx-313 tube was substituted for the two cx-301A's.

At the lower current output, 20 mA., the performance is practically identical with that obtained from the cx-301A tubes, but at 50 mA., the cx-313 has ample available emission so that the saturation current is not reached, the peak value rising to 115 mA. The voltage drop across the tube is much smaller as a result, the peak being 70 volts, as compared with 160 and 150 volts respectively with the cx-301A tubes. Since less voltage is consumed in the tube, more power is available in the output circuit and it is no longer necessary to short the output terminals to obtain this current. The output voltage, in fact reached 60 volts, the output current being practically the same as before, 51 mA.

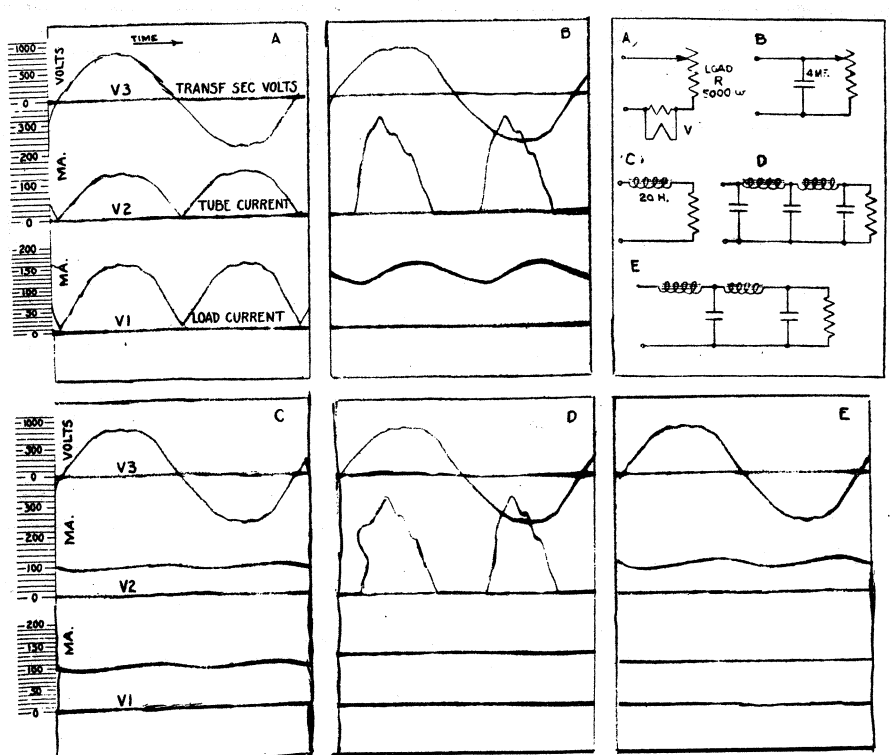


Fig. X 5

As a result of this increased load voltage the voltage across the first filter condenser is increased, and the current no longer starts flowing as soon as the transformer voltage begins to rise, although it does carry current earlier in the cycle than was the case with the lower load current.

The results are tabulated in Table I below.

Fig. 4, together with the following one, Fig. 5, shows the effect of various filter elements upon the maximum plate current the filament is called upon to supply, and upon the output current wave form and amplitude. The series shown in Figs. 4A to 4E, record the performance of a half-wave rectifier, the type used being cx-381. The transformer voltage, indicated by vibrator V_3 on each record, was maintained throughout 750 volts a.c. The load resistance was also kept constant at 5000 ohms.

PERFORMANCE OF HALF-WAVE RECTIFIER

In the first oscillograph record, 4A, all filter elements are omitted as indicated in the corresponding circuit diagram, the tube feeding directly into the load resistance. As a result the same pulsating current flows through the load as through the tube as indicated by the similar wave forms traced by vibrators V_2 (tube current), and V_1 (load current). The difference in amplitude is due to the fact that V_2 was shunted by a lower resistance shunt to reduce the sensitivity, as indicated by the scale adjacent to this figure. The peak current value was 140 mA., while a d.c. meter in the load circuit indicating the average current, gave a reading of 47 mA. Thus the tube filament was called upon to supply, momentarily, three times the average load current. This is an important fact, since the filament must be made large enough to supply the emission current for the peak value. The ratio between peak and average current will be noted for each figure, in order to determine the relative load imposed by each circuit upon the tube filament. For this simple circuit it was 3:1, as noted above. The power input to the

TABLE I

Rectifier Tube	Line Voltage V	Load Resistance Ohms.	Load Current M. A.	Load Volts	Power Delivered to load Watts.	Remarks
2-cx-301A	110	5400	20	108	2.2	*Max. filament emission required*
2-cx-301A	110	0	50	0	0	*Tubes severely overloaded.*
1-cx-313	110	5400	20	108	2.2	*Tube lightly loaded.*
1-cx-313	110	1200	51	60	3.1	*Tube load 78 % of maximum.*

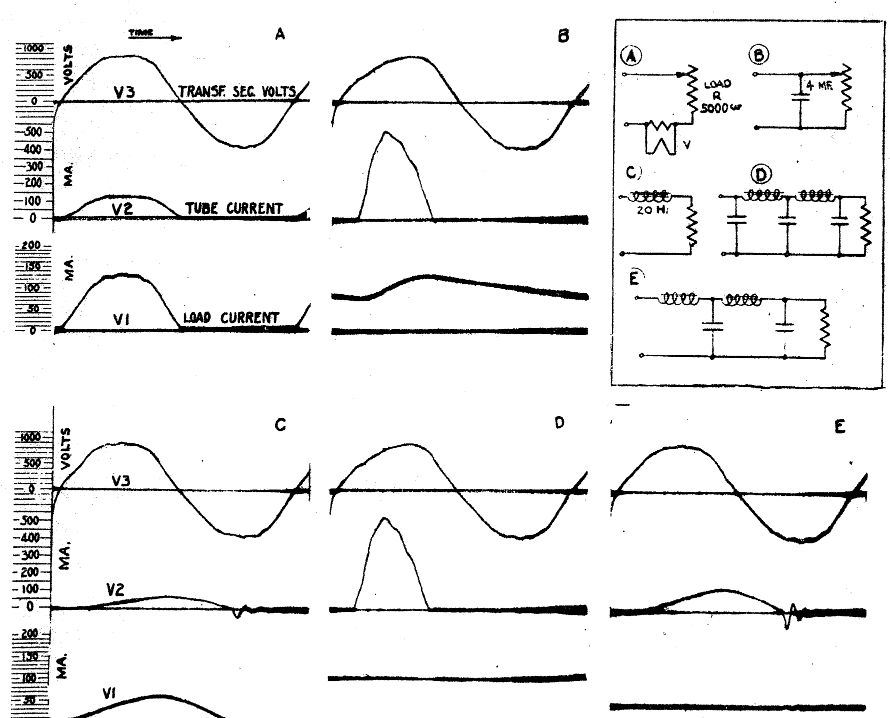


Fig. ~~5~~ 4

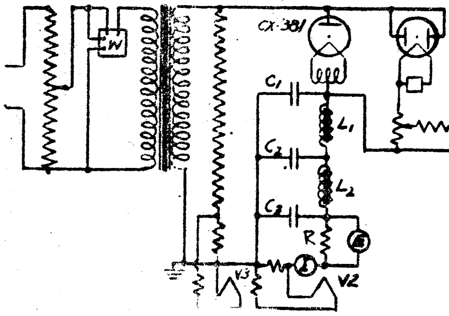


Fig. 6

transformer, and power output were recorded, as tabulated below.

The second exposure Fig. 4B, was taken after adding a 4 mfd. condenser across the load, no other changes having been made. The charging of this condenser permitted a much larger current to flow through the tube, because of the reduced load impedance and the output current not only increased greatly in value to 102 mA., but continued to flow during the alternation when the rectifier was idle. The back voltage developed across this condenser reduced the time during which the tube carried current, thus further increasing the peak current demand upon the tube, which, as indicated by V_2, rose to the value of 535 mA. The ratio of peak to average current was thus increased to $\frac{535}{102}$ or 5.2:1.

In Fig. 4C, a 20-henry choke was placed in series with the load. The effect of the self inductance of the choke in causing the current to lag behind the voltage is quite evident on this film, and it also caused a marked decrease in the peak current to 70 mA., as well as in the average current, (26 mA.). The current flowed for a longer portion of the cycle, however, the ratio of peak tube current to average load current being reduced to the more favorable value of 2.8:1. A transient voltage was developed at the moment the current ceased to flow through the tube, caused by the self-inductance of the choke.

In the next figure in the series, 4D, the usual filter system was added, the performance being similar to that obtained with a condenser alone, except for the improved filtering of the output current. The peak tube current was practically the same as in 4B, 540 mA., the output current 102 mA., a ratio of 5.3 to 1.

In the fifth figure, 4E, the usual input condenser was omitted, resulting in greatly reduced demand on the tube and also in a marked reduction in output. The results are similar to those of Fig. 4 C. except that the choke was smaller, 10 henrys, and, therefore, had a smaller effect in reducing both peak and *load* current. The peak tube current was 130 mA., and output 45 mA., a ratio of 2.9:1. The transient voltage which appeared in Fig. 4C was again present, and was sufficiently severe to result in an appreciable ripple in the output current.

This series shows quite clearly that omission of the first filter condenser in a half-wave rectifier circuit causes an undue drop in output voltage, because of the reactive drop in the choke, to compensate for which the transformer voltage would have to be greatly increased. The filter action was also impaired. The favorable factor was that this connection did result in a much lower ratio of peak tube current to average load current, reducing the maximum required emission to a low value. Note Table II on this page:

DETERMINING OVERALL EFFICIENCY

In determining the overall efficiency, the transformer, the tube, and filter losses were included, but the power supplied to the filament was omitted because it remained constant and if included would have affected the readings taken with low load current, 4C and 4E, disproportionately. The reduced efficiency in these two cases was caused by the fact that the internal resistance of the tube rises rather rapidly at small plate current values. Had the transformer voltage been increased to maintain the load current at a higher value, much higher efficiency would have been obtained. It should be noted that in Figs. 4A to 4C, the power delivered to the load could not be determined from the average reading of output current and voltage because of the irregular wave form.

TABLE II

Circuit Connection	*Transformer Input Watts*	*Load Volts*	*Load Current M.A.*	*Peak Tube Current M.A.*	*Output Watts*	*Ratio Peak Average Current*	*Overall Efficiency per cent.*
4A	43.	225	47	140	25.5	3:1	59
4B	90.	525	102	535	54.5	5.2:1	60+
4C	19.5	132	26	70	5.9	1.5:1	30
4D	90.	525	102	540	54.5	5.3:1	60
4E	25.	225	45	130	10.1	2.9:1	40

Summary of Fig. 4

Circuit Conditions:

Line Volts	110 a.c.
Transformer Volts	750 a.c.
Filter Chokes	10 Henrys
Filter Condensers	4 mfd.
Load Resistance	5000 Ohms.

Fig. 5 shows the more favorable results obtained with a full-wave rectifier tube in the same circuit combinations covered in Fig. 4. The rectifier tube was a

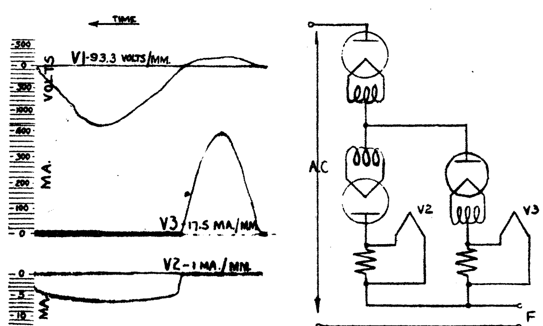


Fig. 7

cx-380, operating at 600 volts, or 300 volts per anode.

In Fig. 5 A, with a resistance load, the load current flows during nearly the entire cycle since current is flowing through one or the other of the two tubes except at the time the transformer voltage passes through zero. The ratio of peak to average current is, therefore, reduced 50 per cent. as compared with the half-wave rectifier, being 150 and 103 mA., respectively, a ratio of 1.4:1.

In Fig. 5B, the 4 mfd. condenser is added, the increase in load current being much less marked than with the half-wave circuit, rising 19 mA., to 122 mA. The peak current through the tubes rises to 310 mA., ratio 2.5:1.

The next, Fig. 5C, shows the effect of the choke placed in series with the load. In this case it is interesting to note that the choke has quite a different effect from the condenser, since it reduces the peak current carried by the tube while it also keeps current flowing through one anode or the other during the entire cycle. The ratio of peak to load current is very low, 105 mA., to 97 mA., or 1.1:1.

Fig. 5D, shows the performance of the full-wave rectifier with the usual filter. The ratio of peak to average current is again high, 290 mA., to 118 mA., or 2.5:1.

Fig. 5E, shows the performance with the first filter condenser of Fig. 4 removed. The peak current is now only 110 mA., or only 1.15 times larger than the average load current, which is 96 mA. The output voltage was only 45 volts, or 18 per cent. lower than that obtained with the usual filter, Fig. 5D. The readings were, Fig. 5D, 250 volts, Fig. 5E, 205 volts. The various readings, including power output and efficiency are tabulated at length in Table III on this page.

TABLE III

Circuit Connection	*Transformer Input watts*	*Load volts*	*Load Current mA.*	*Peak Tube Current mA.*	*Output Watts*	*Ratio Peak Average Current*	*Overall Efficiency per cent.*
5A	45.	219	103	150	23.6	1.4:1	52.5
5B	59	258	122	310	33.5	2.5:1	56.5
5C	38	204	97	105	21.2	1.1:1	55
5D	57	276	118	290	33.1	2.5:1	58
5E	38	215	96	110	20.8	1.15:1	55

Summary of Fig. 5

Circuit Conditions:

Line Volts	110 a.c.
Transformer Volts	600 a.c.
Filter Chokes	10 Henrys
Filter Condensers	4 mfd.
Load Resistance	2350 ohms.

The ripple voltage present at the output of the filter arrangements shown in Figs. 4 and 5 have not been measured, but a few tests indicated that there was not a marked difference, especially if the condenser omitted was added across the output of the filter. The only disadvantage noted in using the arrangement shown in Fig. 5, was the fact that the transformer voltage had to be increased 22 per cent. to obtain a load voltage equal to that obtained with the usual filter. The very greatly reduced peak current demand on the rectifier tubes makes the use of this circuit arrangement highly desirable. Furthermore the efficiency improves rapidly as the load current is increased, and with equal current outputs it was found that the energy dissipated in the tube was lower and the efficiency slightly higher with the filter arrangement shown in 5E than with that of 5D. The possibilities of this arrangement were called to our attention a short time ago by Mr. J. C. Warner of the General Electric Research Laboratory, and these tests have shown clearly the advantages obtained in the full-wave rectifier circuit, Fig. 4 indicating that the arrangement is not suitable for single wave rectifiers.

Fig. 6 shows the circuit arrangement used in taking data shown in Fig. 4, and also in Fig. 7, except for the placing of vibrators. As arranged, vibrator V_1 records the voltage across the tube when it is conducting current, the auxiliary rectifier blocking off the reversed voltage across the tube. In taking the series shown in Fig. 4, this vibrator was shifted over to read the current through the tube. Vibrator V_2 shows the load current, V_3 the transformer voltage.

EFFECT OF REVISED FILTER CIRCUIT

The remarks made in discussing the lower emission requirements with the revised filter arrangements shown in Fig. 4E, might lead the experimenter to believe that this change would permit much higher load currents to be obtained from the rectifier. However, the amount of energy dissipated in the tube must be considered, as that is one of the important factors limiting the output obtainable from a rectifier. Fig. 7 shows a condition which may occur if an excessive load is placed on the tube, the tube used being type cx-381.

Vibrator 1 in this Figure reads the full voltage across the tube both in the conducting and in the non-conducting direction. The transformer voltage was 750 volts, and the peak approximately 1050 volts. You will note that the peak voltage across the tube reached a much higher value, 1400 volts, due to the fact that the voltage across the first filter condenser is added to the voltage across the tube. In the conducting direction the voltage was quite low, as would be expected, 185 volts. Vibrator V_3, shows the current through the tube, which reached a peak value of 450 milliamperes. The load current is not shown on the film, but was 140 mA., an overload of 37 per cent. on this tube type, a value which resulted in excessive heating of the plate. As a result of the heat developed by the excessive current, the plate reached a temperature at which a slight amount of electron emission occurred which is shown on an exaggerated scale by vibrator V_1. The average value of this reversed current was 4.5 mA., and the peak value 6.8 mA. The fact that during a portion of the cycle this emission was drawn across to the filament at an instantaneous voltage of 1400 volts means that considerable energy was dissipated on the filament and the overheating of the filament became

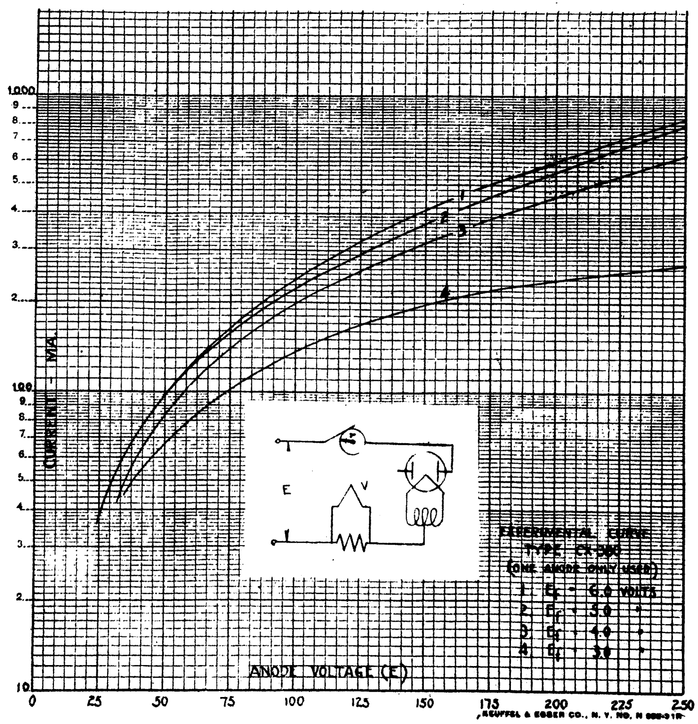


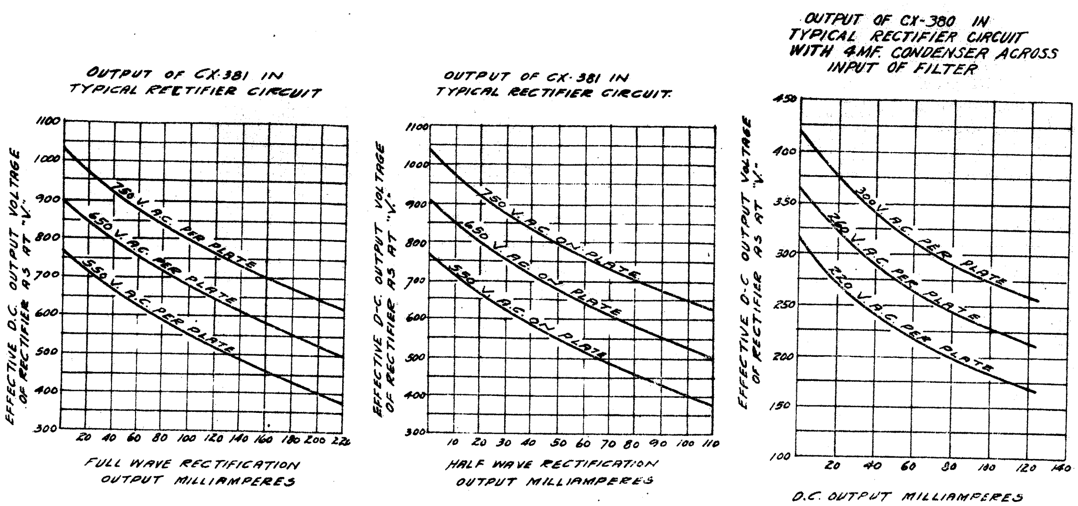
Fig. 8

evident in a visible increase in brightness in the center. The circuit arrangements and placing of the vibrators in obtaining this record are shown in the circuit diagram, the double rectifier arranged in series with the tube under test being necessary to separate the two components of the current through the rectifier tube. A small biasing voltage, not shown in the diagram was added to prevent a circulating current between these two rectifier tubes. In taking the voltage across the tube the vibrators recording the current through the tube were opened, as the current flowing through the voltage vibrator would have otherwise added to the reversed current. Similarly the voltage vibrator was open when the current values were being recorded.

Since the heating through the tube would be nearly as great with the improved type of filter connection, it will probably not be possible to increase the current rating of this tube to any extent when used under such conditions, even though the maximum current required is much decreased.

In Fig. 8, an experimental emission curve taken on one anode of a cx-380 tube is shown. It is not possible to read the full emission current of the tube on a d.c. test without damaging the tube as is the case with all tubes in which a large filament is used. In taking this film, voltages up to 250 volts were applied directly to the anode for a very short time at the proper intervals by means of a synchronous contact mounted on the oscillograph motor. In this way the current peak occurred at the same instant each cycle and gave a deflection on the oscillograph vibrator at a fixed point on the screen. In this way the amount of energy dissipated in the tube was kept low, and by calibrating the oscillograph vibrator the current readings were determined. The curves taken showed clearly the very satisfactory characteristics of the oxide coated filament developed for this tube. Curve 1 shows the performance with a filament voltage of 6 volts, giving a slightly higher anode current than that obtained at 5 volts. The current was still increasing rapidly as the applied voltage was increased to the maximum used, 250 volts d.c. The filament voltage of 6 volts is not of course the normal operating voltage, and Curve 2 shows the emission obtained at the rated voltage of 5 volts, the current reaching the high value of 800 mA. with 250 volts applied. Curve 3 shows the performance at the reduced voltage of 4 volts. Even at this voltage the current was still increasing rapidly at 250 volts and was 620 mA. Curve 4 was taken with the filament voltage reduced to 3 volts, and this curve shows more definite evidence of saturation. The emission current still reached the surprisingly high value of 270 mA.

The fact that the oxide coated filament does not give a definite saturation current is well known, and has been pointed out by many experimenters. It is probably due to the uneven surface of the filament, combined with the space charge effect. The electrons which are leaving the filament exert a repelling force on those closer to the filament and it is only at very high voltages that a large percentage of available electrons are pulled over to the plate. It is evident that if it were possible to reduce the space charge, which

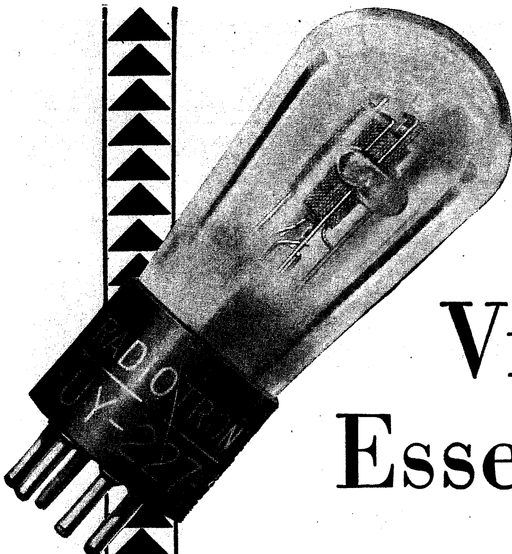


A

Fig. 9

would also reduce the energy dissipated in the tube in the form of heat, considerably higher currents would be obtainable from this filament.

The performance curves of the cx-381 as a full-wave and as a half-wave rectifier, and also the performance of the cx-380 rectifier are shown in Fig. 9. The filter connections being arranged as in Figs. 4D and 5B. These curves show the average voltage delivered to the input of the filter, and if the resistance of the filter chokes is known, the voltage at the output of the filter can be computed with good accuracy for any given load condition.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