LB-1035

TRANSISTORIZED HIGH VOLTAGE OSCILLATOR POWER SUPPLY

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Transistorized High Voltage Oscillator Power Supply

Approved

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This bulletin describes a high voltage power supply, of the r-f oscillator type operating at a frequency of 12.5 kc. A high gain power transistor is used as the oscillator. The output voltage is doubled, rectified and held to 10 kv by three series-connected high voltage corona regulators in a shunt regulator configuration. It is designed for use as a kinescope ultor voltage supply and can deliver 10 watts of power at the regulated voltage. The same oscillator converter also delivers the focus potential needed for an electrostatic focus type monitor kinescope (10SP4) in a television repeater. The filament excitation for the 1X2-A high voltage rectifiers (1.25 volts at 200 milliamperes each) is supplied from windings on the oscillator coil. The only external power needed to operate this converter is a -30 volt d-c collector supply.

Introduction

The transistor, from the moment of its discovery, was recognized as having great possibilities as a power converting device. The reason for this lies mainly in its ability to function from a low voltage direct current source and to deliver considerable power even at low collector potentials. A myriad of power transistors might be equally suitable for the application described in this bulletin, and the number of such transistors is steadily increasing. In the course of the present study, several different transistors were used. Transistors of the types described in *LB-1010 Recent Advances in Power-Junction Transistors* were used, as were several commercial types of various manufactures.

The purpose of this bulletin is: (a) to describe a circuit which has been built and operated as a high voltage power converter; and (b) to present the data obtained in testing the unit.

General Considerations

In order to achieve large power output from a device which is supplied by low voltage, it is necessary for that device to pass high currents. The two limiting factors on power obtainable from a single transistor are its allowable collector dissipation and its current gain at high average levels of emitter current. Since the current gain falls off with increasing emitter current, it becomes quite apparent that, beyond a given value of emitter current, high power outputs can be had only at the cost of efficiency. For the transistors used in the present study, this value lies in the order of 500 milliamperes. Thus with an input of 30 volts, an input power of 15 watts may be handled by the transistor. Assuming an efficiency of 60 percent, it would be capable of delivering 9 watts to the load. Assuming the same current and efficiency, operating at 60 volts would be expected to deliver an output power of 18 watts. However, the present maximum dissipation rating of units of this type is only 10 watts. It is therefore readily concluded that the reduction in alpha for high currents limits the power output at low voltages, while the transistor dissipation and collector voltage rating limit the power output at the higher voltages. At higher temperatures, increased collector current will cause greater transistor dissipation with consequent loss in overall efficiency. To allow for this factor, it is necessary to derate the output power sufficiently to keep the transistor junction temperature within safe limits. This rule has been observed in the converter described here, although to date no problem of working in high ambient temperatures has been faced with the circuit described. On the basis of published specifications, it appears that germanium power transistors are capable of operating at reasonable power levels to temperatures as high as 70 degrees Centigrade. The use of silicon power transistors might elevate this limit considerably.

Basic Operation

This power supply uses the well known switching

*This work was done under contract to the U.S. Naval Bureau of Ordnance.

properties of junction transistors. Fig. 1 shows a simplified circuit in which it may be seen that the transistor has two operating conditions. When the switch is in Position 1, the emitter is reverse-biased and the collector current is almost equal to the leakage current I_{co} of the reverse-biased collector base diode. Since I_{co} is usually very small, the collector dissipation $(V_{BC} - I_{co} R_L) \times I_{co}$ is extremely small.

When the switch is moved to Position 2, the value of emitter current that flows depends on V_{BE} and the resistance of the forward biased base emitter diode. This resistance is very low and hence the current that flows is quite large. The collector can never reach a collector current greater than V_{BC}/R_L and for this value of collector current, the voltage V_C actually appearing at the collector is equal to zero, thereby causing the collector dissipation to be zero also. At this time, however, the power in the load is quite sizeable, being equal to V_{BC}^2/R_L. If sufficient emitter current can be supplied to "bottom" the collector, an appreciable amount of power can be handled in the collector with negligible dissipation in the collector itself.

While the switch is in Position 2, however, power must be supplied to the emitter. This power can be held to a minimum by choosing a value of V_{BE} just large enough to bottom the collector for the value of R_L used. Because of a peculiar characteristic of the collector in the zero and slightly positive region, it is advantageous to supply an extra bit of emitter current (beyond the collector bottom point) which contributes power to the load and increases efficiency to some degree. This condition will be discussed in more detail in the section that follows.

The low input resistance of the transistor allows small magnitudes of V_{BE} to supply the required emitter current for collector bottoming. The high current alpha of the transistor should permit making $V_{BC} - aI_e R_L = 0$ with reasonable values of emitter current.

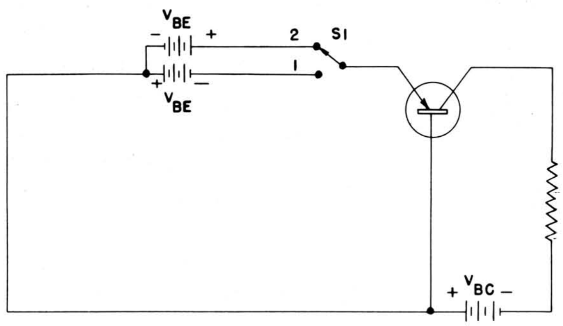


Fig. 1 – Basic circuit.

Actual Circuit Operation

A sketch of the entire power converter is shown in Fig. 2. The transistor functions with positive feedback from the collector to the emitter. When the transistor begins to conduct, the voltage developed across the primary winding T_1 induces a feedback signal in the tickler winding which increases the forward bias on the emitter. This increased drive further increases the collector current and the collector is driven to a bottom condition. A voltage approximately equal to the supply voltage (30 volts) appears across the primary winding of T_1.

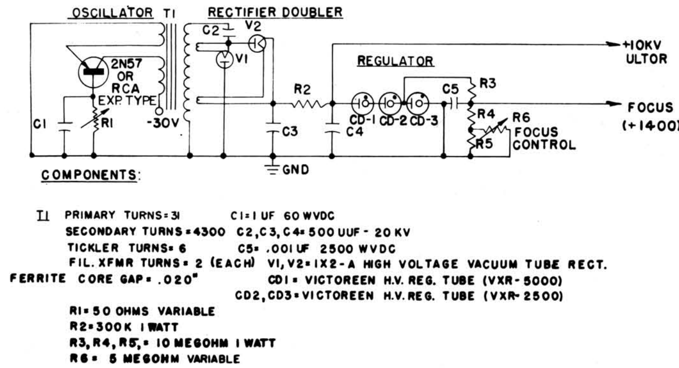


Fig. 2 – Power converter schematic.

For the collector to remain at bottom, the magnetic flux must continue to increase according to the expression $E = -m\, d\phi/dt$. This can be accomplished with very little exciting current until the core is saturated. Upon core saturation, however, the demand for exciting current rises so sharply that at some point the transistor is unable to sustain the flux increase. As a result, the voltage across the primary winding of T_1 now decreases. This causes a reduction in emitter drive, further reducing collector current. The transistor, therefore, quickly proceeds to a "shut-off" condition.

At this time the collector voltage V_C will reach a value on the order of twice the collector supply voltage or even slightly more (that is, -60 to -70 volts). This order of voltage is in the breakdown region of the collector but the reverse-biased base emitter diode insures that no appreciable current will flow. With restraining bias on the emitter, tests have shown that the collector can in most cases be safely driven to voltages of the order of -100 volts, although not all transistors will meet this requirement.

When the transistor is completely shut off, the cycle is then repeated at a rate determined by the resonant frequency of T_1 (inductance and distributed capacity). In the present equipment, this frequency was approximately 12.5 kc. The voltage waveform was found to be nearly square: It is very close to zero during the conduction period and approximately twice the supply voltage during the shut-off period. This waveform is shown in Fig. 3 along with the emitter voltage which is quite similar. The output voltage waveform is also of the same shape.

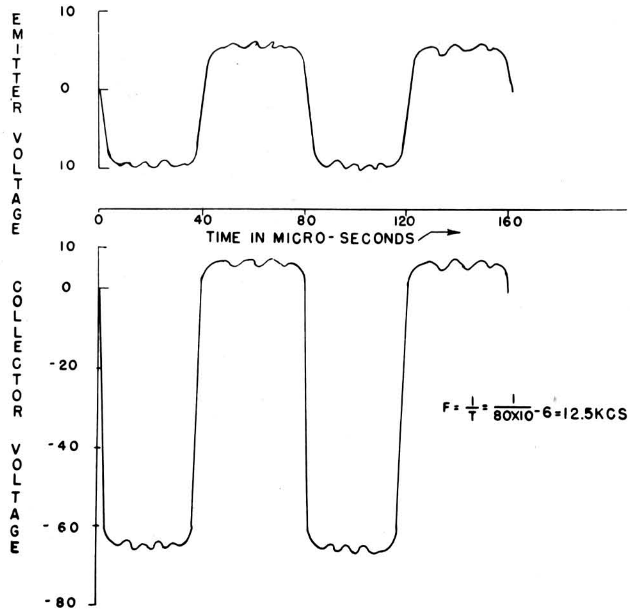


Fig. 3 – Collector and emitter voltage waveforms.

The efficiency of the circuit of this type will be naturally high because of the fact that the transistor conducts only when the collector is bottomed. It is therefore reasonable to state that the efficiency of the transistor should approach a limit established by its inherent losses when it is considered as an on-off switch. Moreover, these losses are nearly all attributable to the emitter power necessary to establish the desired collector currents. For any given condition, greater power output can be obtained by increasing the supply voltage. An increase obtained in this way comes about with no additional losses. It is thus to the designer's favor to employ the highest supply voltage possible. The peak inverse collector voltage, however, is a limiting factor. It was mentioned that the collector voltage rises to approximately twice the supply voltage during the shut-off interval. The choice of supply voltage is thereby fixed to a value of approximately one-half the rated maximum collector voltage. The maximum collector voltage rating for the transistors used in the present equipment (in the common base configuration) is 60 volts. Thus the supply voltage was chosen to be 30 volts.

It may thus be seen that the largest transistor losses take place in the emitter. The collector does suffer small power losses during the switching period, but tends to redeem itself by actually delivering power back to the transformer. This is the peculiar condition that was mentioned above. When and if the emitter is subjected to over-drive, the collector characteristics can pass through zero into the positive region. Fig. 4 shows a family of collector characteristic curves of a typical transistor. Attention is invited to the region around zero collector voltage. The sharp break in the characteristic does not take place until the collector is slightly positive. There can be no doubt that if the collector is driven to exactly zero volts during the conduction period, the collector dissipation at that time must be zero. If the collector voltage is now driven still further it becomes positive. Under this condition, the product of collector-to-base voltage with collector current represents power delivered to the primary of T_1. In terms of transistor losses, it is apparent that this extra power can be considered deductible from the power supplied to the emitter. One might say that the emitter supplies power directly to the load during this interval of positive operation. Such a condition, therefore, is one which decreases the net losses and boosts the oscillator efficiency. The limit to this desirable situation occurs at the break in the collector characteristic. Beyond this point the emitter power requirements exceed the rate at which the collector can return power to the transformer, T_1. Thus the efficiency will start falling if the emitter be driven further.

This situation brings to light a few interesting facts. First, the matter of feedback can now be considered uncritical; small variations in the feedback signal should not affect the efficiency very much because the collector is heavily overdriven. Second, supply voltage changes will not contribute as much to efficiency variations as they would if the collector were driven to zero volts. Third, the interchangeability of transistors should not be as critical as it might be in a non-overdriven circuit.

The remainder of the circuit employs a frequently used method of a-c to d-c conversion. The high voltage

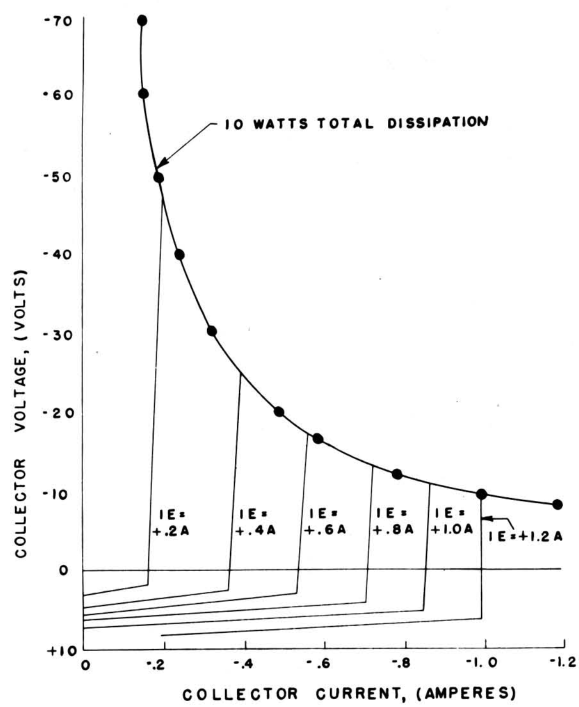


Fig. 4 – Typical power transistor collector characteristics (common base).

square wave on the secondary of T_1 (approximately 15 kv peak-to-peak) is applied to two type 1X2A high voltage rectifiers in a half wave doubler arrangement. Filament power for the rectifiers is obtained from windings on T_1. The smoothing is done by the capacitor input pi-section filter comprised of C_3, R_2 and C_4. This voltage is then applied across three corona regulator tubes connected in series. *CD-1* regulates at 5000 volts; *CD-2* and *CD-3* regulate at 2500 volts. The operating current range of these regulator tubes is 25 microamperes to 1000 microamperes (see Table I).

CD-3 is shunted by a 30 megohm bleeder (three 10-megohm resistors in series). The resistor nearest ground (*R5*) is in parallel with a 5 megohm focus potentiometer. The 10 kilovolts required for the kinescope ultor is picked off at the anode of the VXR-5000 regulator tube. The variable focus voltage is picked off from the junction of *R3* and *R4*.

Test Data

Power conversion efficiency tests for overall d-c to d-c conversion were performed for 6 different output conditions. The data for these tests are plotted in Fig. 5. These tests were performed without the corona discharge regulator tubes. In these tests, the rectifier doubler output was filtered and applied across a variable load (6BD4A). The load circuit is also shown in Fig. 5. It will be seen that runs 2 and 3 are very much shorter than the others. The reason was that in these cases, at the lower currents (for 11 kv output), the peak inverse collector voltage was approaching excessive values. Thus no data could be obtained beyond this limit.

The procedure used in this test was as follows: (a) the oscillator and load were adjusted to deliver a given voltage output and maximum current. (b) The load current was then reduced from the original starting current and the overall efficiency plotted against the load

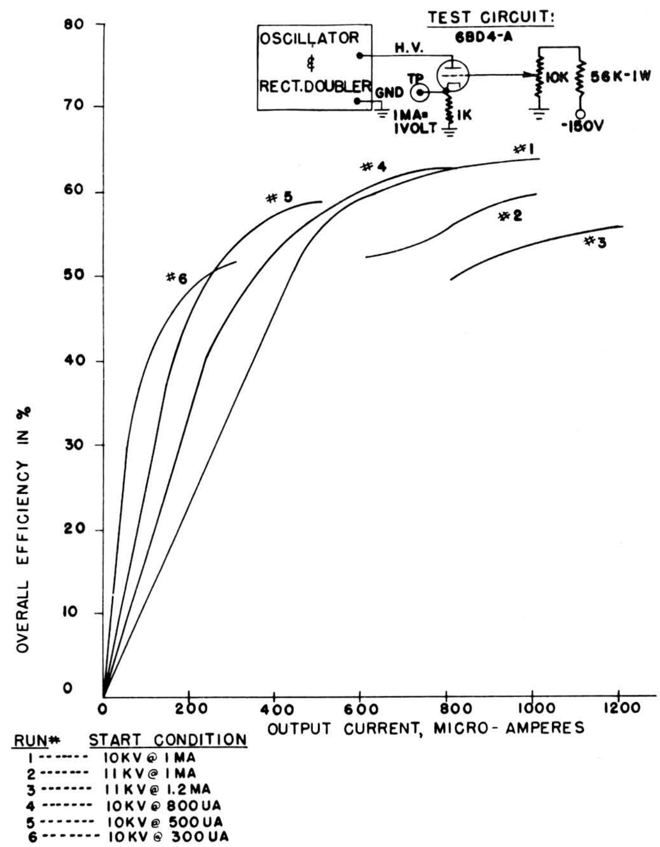


Fig. 5 — Load current vs. efficiency.

current. The starting conditions for these 6 runs were as follows:

Run #1	=	10 kv	@	1 ma
Run #2	=	11 kv	@	1 ma
Run #3	=	11 kv	@	1.2 ma
Run #4	=	10 kv	@	800 μa
Run #5	=	10 kv	@	500 μa
Run #6	=	10 kv	@	300 μa

The maximum overall d-c to d-c conversion effi-

TABLE I

Corona Regulator Characteristics

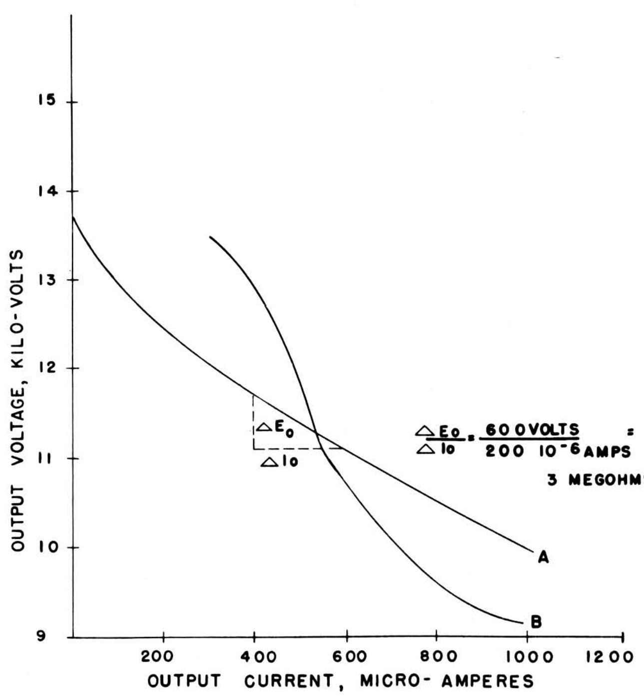
Type	Circuit Designation	Nominal Operating Volts	Voltage Tolerance %	Regulation %/50 μa	Maximum Starting Volts	Maximum Current μa
VXR-5000	CD-1	5000	±5	1	5500	1000
VXR-2500	CD-2 & 3	2500	±5	1	2750	1000

ciency for this particular transistor and circuit was 64 percent. This occurred at 10 kilovolts with 1 milliampere output. Efficiencies as high as 66 percent were reached by tuning the primary of T_1. This expedient, however, made the efficiency dependent on the tuning and thus far more critical. It was therefore discarded in favor of the more stable efficiency characteristics realized without tuning. During these tests, transistor dissipation was also recorded by monitoring the shell temperature. The transistor efficiencies alone were calculated to be in the neighborhood of 80 to 85 percent.

The tests of output voltage versus load variation (i.e., regulation) produced the data shown in Fig. 6. This test was also conducted without the corona discharge tubes. A set of measurements was made as a function of incremental changes in core gap. The gap was varied from 0 to 0.050 inches in 0.005 inch steps. The optimum gap was found to be approximately 0.020 inches (0.010 inches on each side of the *C* core). Thus the curves in Fig. 6 show only the 0 and 0.020 inch gap plotted from no load to 1 milliampere load current. This data fixed the supply impedance at approximately 3 megohms (derived from the slope of Curve *A* between the 400 and 600 microampere points).

In another test, seven transistors of the H2 type were tried in the circuit. In these tests, d-c to d-c conversion efficiencies ranged from 46.7 percent to 60 percent. The average was 54.3 percent. This is considerably better than that found in a test of 15 other transistors with lower "high current" alphas.

TEST CIRCUIT:
SAME AS IN FIGURE 5.



CURVE A: .020" CORE GAP
CURVE B: 0 CORE GAP

Fig. 6 – Supply impedance.

Design Notes and Conclusion

It was concluded from the experience gained in the development of this converter that the design of the transformer is not exceedingly critical. Most core materials normally used for audio functions could be used with reasonably good success. The leakage inductance, however, should be kept to a minimum. This is desirable in order to avoid large voltage spikes on the collector during the transistor shut-off interval or in case of load removal. Such spikes could be troublesome and might even cause transistor failure.

The ratio of primary turns to tickler turns is arrived at by the ratio of collector voltage swing to emitter voltage swing necessary to produce the collector current variations desired. The number of primary turns is a compromise between copper losses and the need for restraining excitation current. The operating frequency also enters into the compromise. The boundaries of operating frequency are established on the low end by size and economical design and on the high end by the switching ability of the transistors. Naturally the higher end is more desirable from a filtering standpoint. The transistors used in this study should produce good results from 2 Kc to 14 Kc. The fact that the oscillator produces a square wave output signal is not considered detrimental since the higher harmonics therein are heavily filtered by any conventional network which is effective against the fundamental.

It is felt that a transistor type regulator system might possibly prove more efficient than corona discharge tubes. However, the development necessary to confirm this belief would be one of considerable magnitude and was not within the scope of the present work.

The vacuum tube rectifier (1X2A) was chosen in preference to a semiconductor type rectifier for the following reasons: stacked dry rectifiers would not have conserved any more space; furthermore, they are not reputed to be as efficient as the vacuum tube type rectifier at voltages used in this converter.

High ambient temperature is certain to be a problem with circuits of this type which employ germanium power transistors. The advent of silicon power transistors will very likely make units like the one described in this bulletin very useful and desirable in high temperature applications.

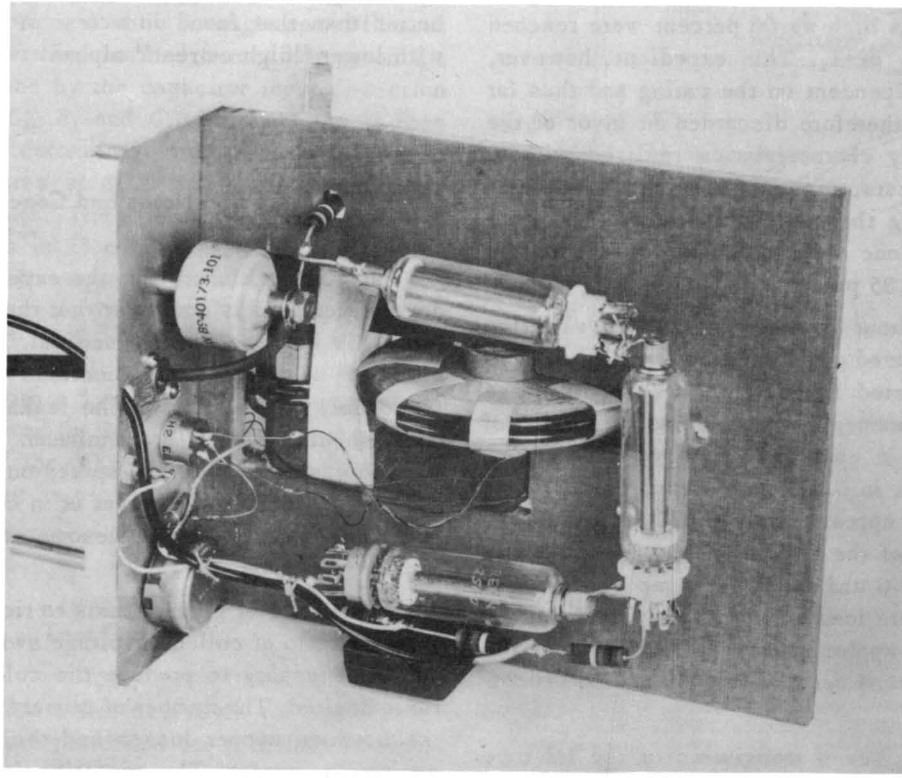


Fig. 7 – Under chassis view of power supply showing the transistor and the regulators.

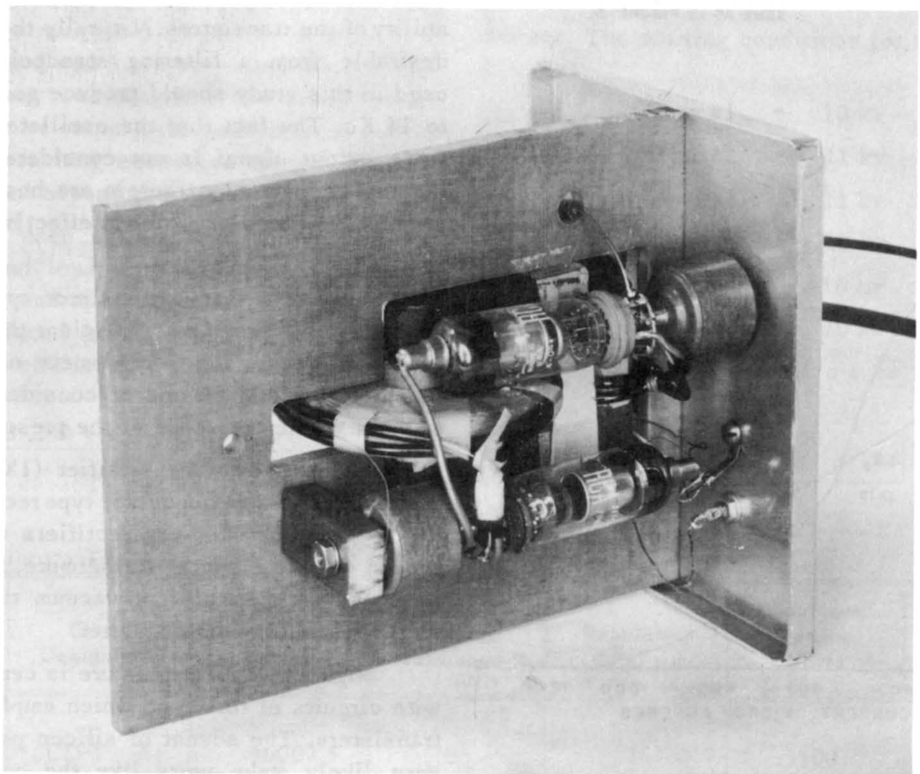


Fig. 8 – Under chassis view showing the rectifiers.

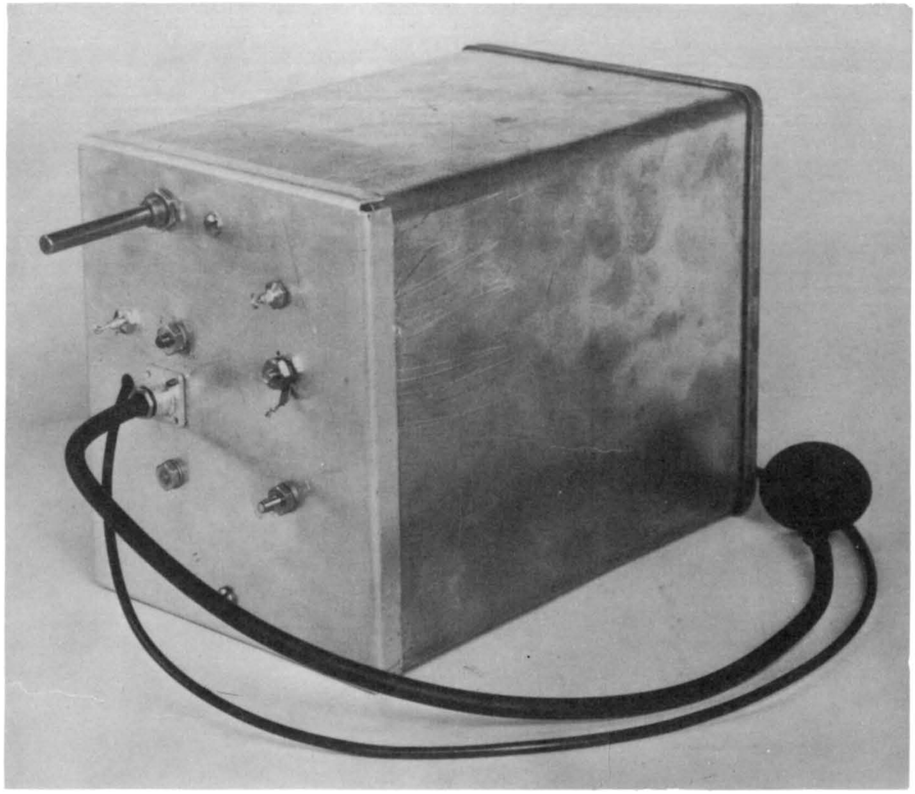


Fig. 9 – Complete unit in its shield.

Photographs of the supply are shown in Figs. 7, 8 and 9. The dimensions of the unit are 5 inches by 5 3/4 inches by 7 inches. It weighs 5.45 pounds. These are the measurements in weight of the breadboard as it now stands, enclosed in a steel can. It is certain that further reductions in size and weight could readily be made.

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