MEASURING TECHNIQUES FOR THE
723A REFLEX KLYSTRON

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By

WILLIAM G. WORTH JR.

Bachelor of Science

Oklahoma Agricultural and Mechanical College

Stillwater, Oklahoma

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APPROVED BY :

Attie L. Betts
Chairman, Thesis Committee

Herbert L. Jones
Member of the Thesis Committee

A. Naeter
Head of the Department

D. C. McIntosh
Dean of the Graduate School

PREFACE

From the beginning of World War II to the present time, the use of Ultra High Frequencies has seen an advancement comparable to no other era. Ideas, experiences and equipment of yesterday are being used as the basic foundation for the more complex problems immediately following.

Ultra High Frequencies belong to a new and highly specialized field. The concepts of resistance, resonance, inductance and capacitance, which were sufficient for the lower frequency levels, need to be supplemented by the concepts of field configuration, velocity of propagation, reflection coefficient and many more. The Ultra High Frequency Engineer has to be able to include these heretofore neglected equation components in the present day formulas.

The present and potential uses of Ultra High Frequency are so great that the Communications Engineer is impelled to be familiar with the basic ideas associated with this great field. To ignore the potentialities of this field, would put the Communications Engineer in a closed field which, in the author's opinion, will soon be outdated.

With the above ideas in mind, the Electrical Engineering Department of Oklahoma A. and M. College initiated a basic course in Ultra High Frequency, compulsary for all senior students in the Communication Option. This course number for college reference is Electrical Engineering 4X3.

A summary of all subjects covered in Electrical Engineering 4X3 would approach book size, therefore the laboratory klystron section was chosen because of its relative importance as explained in the general section. This paper is not intended to stress the theory of klystron and wave guide operation, but rather to give several laboratory techniques, which when followed, will give complete operational characteristics for frequency and power output of a 723A/B reflex klystron.

The design considerations given in the thesis body are those of the author and were developed specifically for the techniques embodied in the thesis. For this reason, the application of the equipment is limited to other experiments similar to those described.

The author wishes to acknowledge with gratitude the assistance of Professor A.L. Betts, who read the manuscript and offered many valuable suggestions, and of Mr. Wilbur B. Canfield, who spent much time in reading the proofs.

William G. Worth Jr.

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GENERAL CONSIDERATIONS

At frequencies of 9000 megacycles, the reflex klystron is perhaps the most extensively used tube for low power sources. Its value for use in receiving and test equipment cannot be approached by any other vacuum tube on the market at the present time. Its only serious deficiency is that a continuous broad band of frequencies cannot be covered by any one unit.

In the design of local oscillators for receivers, the frequency range and power output for this frequency range is the most important aspect. Since the voltages required by the klystron are generally below 1000 volts, the power supplies can be of a conventional regulated type. Also since UHF receivers are subject to alignment and calibration, a signal generator capable of delivering calibrated frequency and power output is necessary, therefore, for these signal generators, it is almost essential that a klystron be employed as the oscillator. The klystron tube circuit can also be designed so that amplitude modulated or frequency modulated outputs may be easily obtained. This is especially valuable in signal generators.

The most essential characteristics for ordinary vacuum tubes can be found in any of the several tube manuals. Also the same type tube is essentially the same regardless of the manufacturer, The klystron is not an ordinary tube. The name klystron is a patented name originated by the Sperry Gyroscope Company. Essentially it is a "war baby". Klystrons were known and developed before the war and most texts still carry them under the title "velocity modulated tubes". The demand for high frequency radar equipment during the progress of the war was so great, that nearly all companies with large contracts, developed their own models of the velocity modulated tubes. Each company's model met the specified output power and frequency characteristics as given by government specifications, but the models were very different physically. Consequently, the operating voltages for each company's model vary. This property along with different physical sizes make the klystrons non-interchangeable with any except another of the same type. As an example of this, in the 10 cm. band, the 726A manufactured by Western Electric, the K417A manufactured by Sperry Gyroscope Company, and the 707A/B manufactured by Western Electric and Raytheon will each produce the same electrical output, but to replace one by the other in a circuit means both electrical and mechanical changes.

As a result of each company's research, several models are on the commercial market now. The majority of these are obtainable thru war surplus channels. The klystron originally had the War and Navy Departments Secret classification and later a Confidential classification. As a result, the published literature on klystron operational characteristics is in limited quantities. Operational data is not as a rule supplied thru surplus channels, therefore the only absolute method of obtaining specific data for a particular type klystron is by a written request to the manufacturer.

The operational data from the manufacturer is in very general terms. The principle mode of operation is stressed and most data is given for that mode, since this mode was the only one used for most radar sets. General terms are given because physical manufacturing tolerances cannot be ± 0 %. This means that grid spacings, grid-repeller spacings, etc., will vary by minute amounts, thus changing the output frequency and power for specified voltages. Hence operational curves for several klystrons of the same type will differ.

Calculation of performance data for a specific klystron from the general data is almost impossible. Therefore for most of those who wish more complete operational data for any particular klystron tube, it is necessary to apply laboratory methods of analysis to obtain such.

For undergraduate laboratory work, 3 cm. wavelengths are not too satisfactory, because of the low power outputs of the reflex klystron. Particularly, the 723A/B klystron is not the best tube to be used because it does not furnish enough power to allow sufficient isolation from the remainder of the circuit in the form of attenuation inserted between the klystron and other circuit components. Insufficient isolation may result in 'pulling' of the klystron as the load is changed. 'Pulling' is defined as the changing of klystron frequency with changes in load. For these reasons, best laboratory results by inexperienced personnel, 10 cm. wavelengths would be more advantageous because the output power is much greater.

It was originally intended to cover both 10 cm. and 3 cm. wavelengths in the Electrical Engineering 4X3 laboratory. However, to completely equip a laboratory for ultra high frequency measurements requires a large amount of money and as the large amount of money was not available, the Electrical Engineering Department sought equipment from sources other than by direct purchases. Most of the equipment now on hand was obtained from either AAF surplus or by donations from private companies. Between these two sources, enough equipment is now on hand to offer a very complete laboratory course in Ultra High Frequencies.

The material obtained was used originally in radar research or in actual radar sets. Since only about 30 per cent of the 10 cm. radar sets use wave guides and about 98 per cent of the 3 cm. radar sets use wave guides, the greatest amount of wave guide and associated material on hand is for 3 cm. wavelengths. It is for this reason that the following klystron techniques are for the 3 cm. band. This is advantageous in the respect that 3 cm. wavelength techniques are much more critical with respect to tuning, fitting etc., than 10 cm. wavelengths. Thus with suitable experience in the 3 cm. field, the 10 cm. field is practically mastered except for concepts of physical component sizes.

PART I: MEASUREMENT OF FREQUENCY AND RELATIVE POWER UNDER STATIC CONDITIONS.

EQUIPMENT:

All possible precautions were taken to minimize effects of line voltage variations, room temperature variations, capacity to ground or capacity to operator variations and meter reading inaccuracies.

Since the 115 volt A.C. house service is subject to voltage variations due to poor regulation, all power to the test bench is thru a constant voltage transformer of 2 KVA rating. The main D.C. power source is one taken from a SCR 547 Radar Set and numbered RA 57A. This furnishes a regulated supply voltage up to 1000 volts. The D.C. voltages applied to the klystron are further regulated by a power pack designed for this special application.

The result of the above regulators is a negligible variation in klystron voltages for a 20 % variation in house voltage or a one cycle per second change in frequency. The D.C. supplies are designed with the positive lead grounded, so that the klystron shell and all parts of the wave guides and frequency meter, etc., will be grounded and therefore will have no capacity to ground. Any part of the external wiring, meters, etc., may be touched by the operator with no change in meter readings.

Ambient temperature variations of the air surrounding the klystron were held to 2° Fahrenheit by shielding the klystron from air currents in the vicinity of the test bench.

Meters used for voltages and currents are Weston instruments and have been calibrated before and after test runs against standards and the average calibration used.

Wave guide components used are by several manufacturers, however all components are of the same inside dimensions. Single or double choke joints are used at all wave guide component connections.

Figure 1 is a block diagram of electrical connections. Components shown

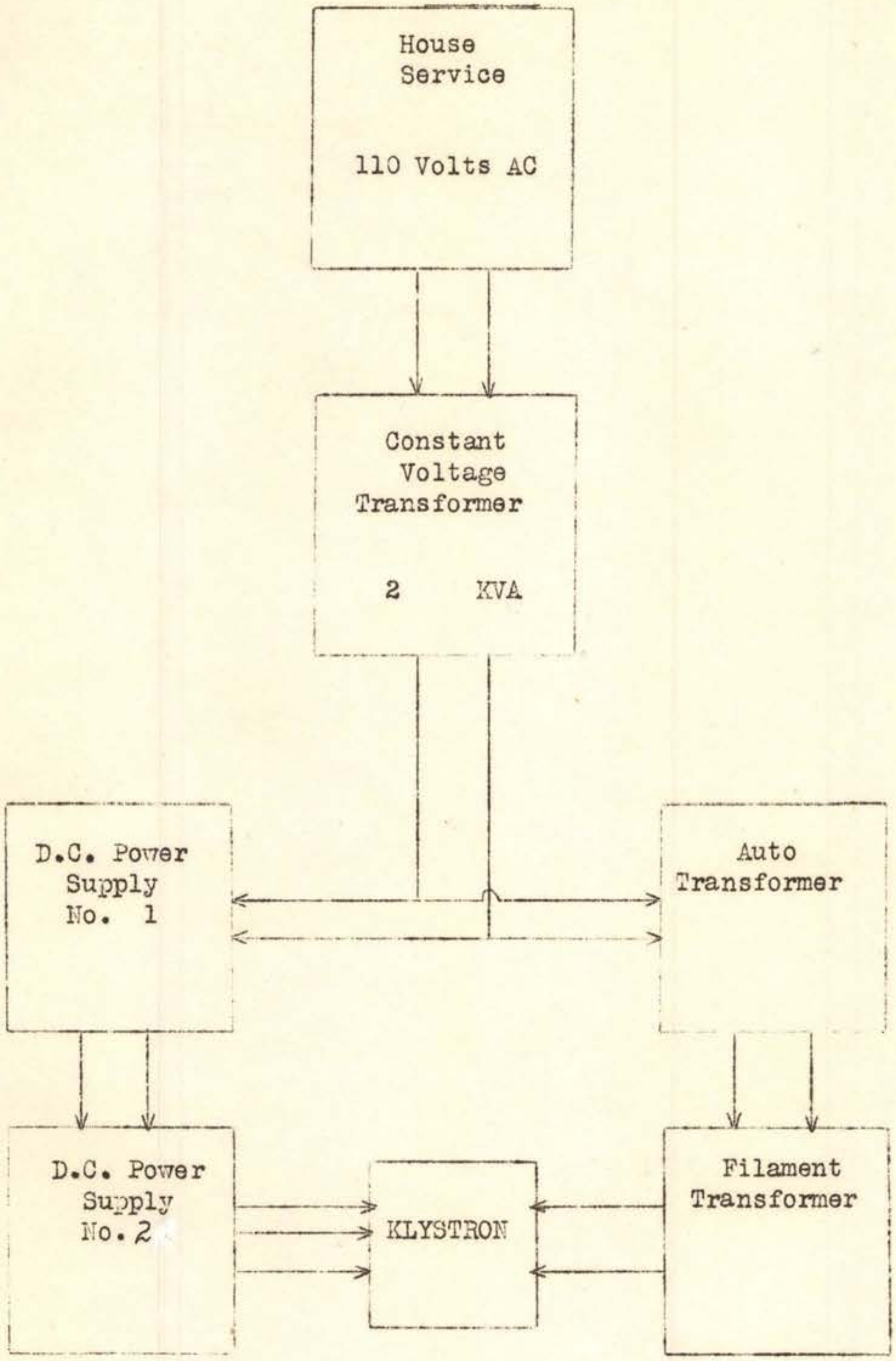


Figure 1 : Block diagram of electrical components.

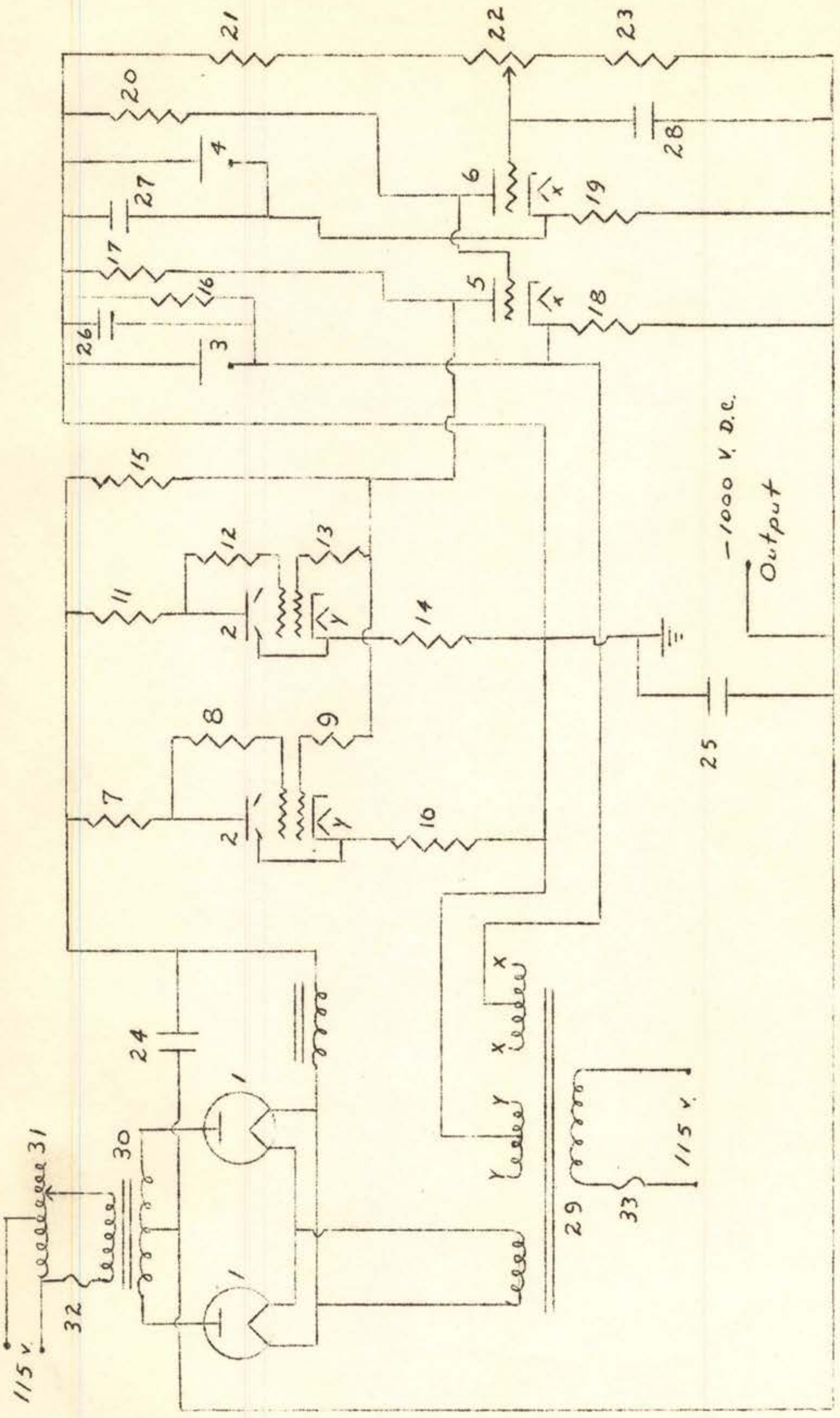


Figure 2 : Electrical diagram for D.C. power supply No. 1.

Description of components shown in Figure 2

Item	Description	
1	Vacuum Tube	Type 836
2	Vacuum Tube	Type 6L6
3	Vacuum Tube	Type VR 105/30
4	Vacuum Tube	Type VR 150/30
5	Vacuum Tube	Type 6SF5
6	Vacuum Tube	Type 6SF5
7	Resistor	50 ohm
8	Resistor	50 ohm
9	Resistor	500 ohm
10	Resistor	50 ohm
11	Resistor	50 ohm
12	Resistor	50 ohm
13	Resistor	500 ohm
14	Resistor	50 ohm
15	Resistor	5 Megohms
16	Resistor	100,000 ohm
17	Resistor	500,000 ohm
18	Resistor	50,000 ohm
19	Resistor	45,000 ohm
20	Resistor	500,000 ohm
21	Resistor	120,000 ohm
22	Resistor	100,000 ohm (variable)
23	Resistor	600,000 ohm
24	Condenser	6 microfarad
25	Condenser	6 microfarad

Continued from Page 6a.

Item	Description	
26	Condenser	.25 microfarad
27	Condenser	.25 microfarad
28	Condenser	.15 microfarad
29	Filament Transformer	
30	Plate Transformer	
31	Auto Transformer	
32	Fuse	6 ampere
33	Fuse	2 ampere

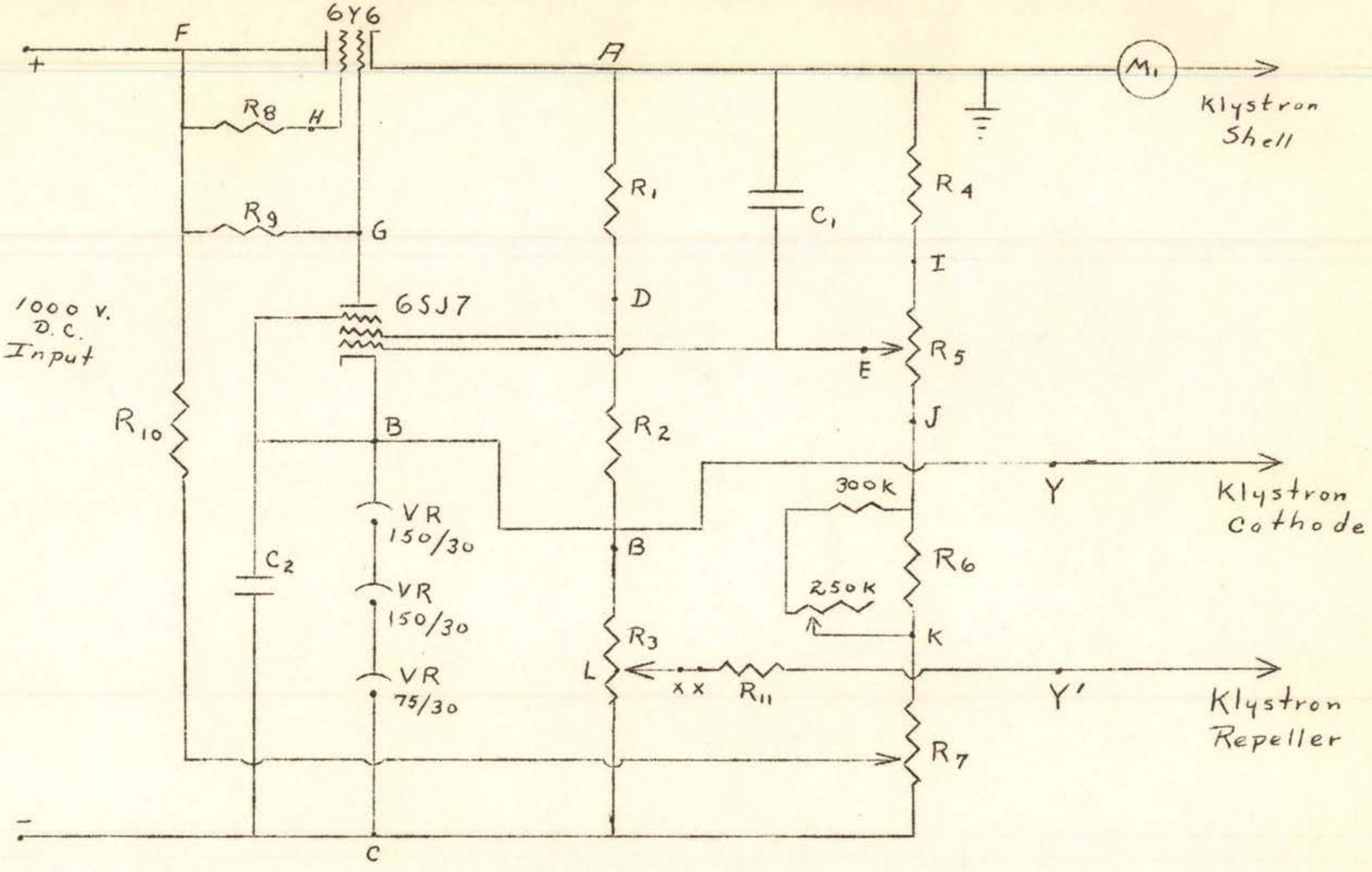


Figure 3 : Electrical diagram for D.C. power supply No. 2.

as blocks in Figure 1 will be described in the following sections and a complete electrical circuit given. Figure 2 is an electrical diagram of D.C. power supply No. 1. This power supply will produce a regulated output of 1000 volts at 100 ma. Note that the positive lead is grounded. Figure 3 shows the electrical connections for D.C. power supply No. 2. It is of a conventional regulated nature but will produce an output variable from 250 volts D.C. at 26 ma. to 400 volts D.C. at 43 ma. simultaneously with a second output variable from 0 to – 350 volts D.C. with reference to the negative side of the first named output. Either output may be set at any value independent of the other and both outputs are regulated.

The following synopsis of circuit action is given as a prelude to actual design of D.C. power supply No. 2.

The 6Y6 acts as a variable resistor in series with the output. Its bias determines the plate resistance and hence the voltage drop across it. The bias of the 6Y6 is essentially Voltage GB minus Voltage AB (Figure 3). If the load current is increased, Voltage AB and hence Voltage AC will tend to decrease. Voltage BC is essentially constant. The Voltage EC would decrease, making the bias on the 6SJ7 more negative. This increases the tube drop across the 6SJ7 and makes the grid of the 6Y6 less negative. Thus the plate resistance of the 6Y6 is reduced, reducing the 6Y6 tube drop and increasing the output voltage. The action is the same in the design except that the extreme maximum and minimum voltages are used.

DESIGN OF POWER SUPPLY NO. 2 :

Input Voltage FC to be 1000 volts D.C. at all times.

Voltage AB to be 250 volts D.C. minimum at 21 ma.

Voltage AB to be 400 volts D.C. maximum at 38 ma.

Voltage BL to be 0 volts minimum and 350 volts D.C. maximum.

There is no current drain from Voltage BL.

The bleeder current thru R_4, R_5, R_6 and R_7 is approximately 1.3 ma. This current is essentially constant, i.e.,

$$\frac{\text{Voltage AC}}{R_4+R_5+R_6+R_7} = \frac{700}{550{,}000} = 1.3 \text{ ma.}$$

This assumes that bleeder resistance will be approximately .5 meg ohms so that the current will be small. Actual resistance of bleeder components will be determined in a following section. Again to limit the current to a small value, choose R_1 and R_2 to have a total of 80K ohms. This is an approximation but will enable the average bleeder current thru R_1 and R_2 to be calculated. This current is approximately 4 ma.

Combining the above loads gives the following maximum and minimum ratings of the power supply.

Maximum output Voltage AC = 770 volts at 43 ma.

Minimum output Voltage AC = 620 volts at 26 ma.

Since the input Voltage FC is constant at 1000 volts D.C., it is apparent that Voltage FA is 230 volts for maximum output voltage and Voltage FA is 380 volts for minimum voltage output.

The screen current of the 6Y6 is assumed constant at 3 ma. for all screen voltages when the plate voltage is approximately 200 volts. This is an approximation but is within 10 %.

For maximum voltage output (Voltage AC), the plate load for the 6Y6 is 770 volts / .043 ampere = 18,000 ohms. For minimum voltage output, the plate load resistance for the 6Y6 is 24,000 ohms. Since the voltage drop across the 6Y6 is a minimum for maximum output voltage, the screen supply voltage is a minimum at this point. The screen voltage should not be below 120 volts D.C. With the screen current assumed constant at 3 ma. for this plate voltage range, the resistor $R_9 = \frac{230 - 120}{.003}$ or 40K ohms. Using this resistor value in the screen circuit will therefore cause the screen voltage to rise as the Voltage FA increases.

Voltage FA is a maximum for minimum output and is equal to 380 volts. Due to the increased plate supply, the screen current will decrease. Approximately, the screen current will be halved by doubling the plate voltage, so that the screen current is approximately 1.5 ma. when the plate voltage is 380 volts. The drop across R_9 will be 60 volts. Therefore the screen voltage will be 320 volts. This increase in screen voltage will be taken into consideration later.

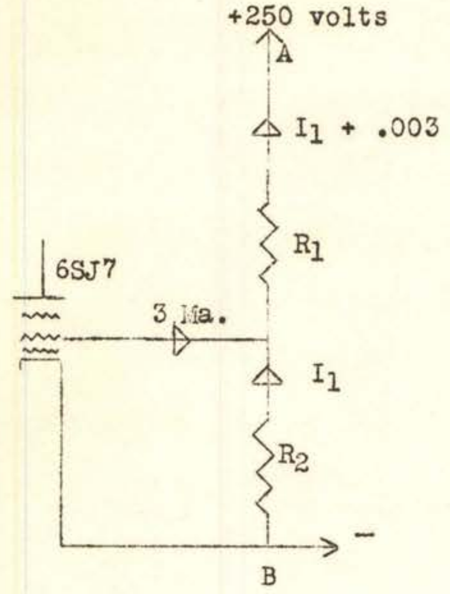
Voltage regulation occurs because of the drop across the 6Y6 tube. Hence the grid bias voltages for the 6Y6 must be determined for maximum and minimum output voltages. For minimum Voltage AC = 620 volts at 26 ma., the Voltage FA = 380 volts, Voltage HA = 120 volts, plate load resistor = 24K ohms and E_{bb} = 1000 volts. Using this data in conjunction with the 6Y6 tube characteristics, the grid bias necessary for the data to hold is −20 volts. However, the curves are for a screen voltage of 135 volts where now the screen voltage is 320 volts, which indicates that the grid bias has to be more negative than − 20 volts. Theoretically the bias should at least be (320/135) x (−20) or − 48 volts. To be sure that the tube will have sufficient bias to increase the tube drop to 380 volts, the bias circuit will be designed to give − 70 volts grid bias for the 6Y6, when the output Voltage AC is a minimum.

For maximum Voltage AC = 770 volts D.C. at 43 ma., the Voltage FA = 230 volts, Voltage HA = 120 volts, E_{bb} = 1000 volts and the plate load resistance equals 24K ohms. Using this data in conjunction with the 6Y6 tube characteristics, the grid bias necessary for the data to hold is − 16 volts D.C. To be sure that the bias will be low enough to decrease the tube drop to 230 volts, the bias circuit will be designed to give − 15 volts bias for the 6Y6 when the output Voltage AC is a maximum.

From Kirchhoff's law, the bias for the 6Y6 is Voltage GB minus Voltage AB or the tube voltage drop of the 6SJ7 minus the output Voltage AB. Both of these voltages vary with output voltage changes. When the output Voltage AC is a maximum of 770 volts, the Voltage AB $=$ 400 volts. From preceding calculations, the bias of the 6Y6 is to be $-$ 15 volts. Hence the tube drop of the 6SJ7 $= 400 - 15 =$ 385 volts or Voltage GB. The plate supply voltage for the 6SJ7 equals Voltage AB + Voltage FA $= 400 + 230$ or 630 volts. When the output Voltage AC is a minimum of 620 volts, the Voltage AB $=$ 250 volts. From preceding calculations, the bias of the 6Y6 is to be $-$ 70 volts. Hence, the tube drop of the 6SJ7 $= 250 - 70 =$ Voltage GB $=$ 180 volts. The plate supply voltage for the 6SJ7 $= 250 + 380$ or 630 volts which is the same as before.

Since the I_{bo} vs E_{bo} curves of the 6SJ7 are to be worked with, the screen voltage should be known, so it will now be calculated. The screen supply voltage is the Voltage AB. Screen voltage is obtained by a divider network consisting of R_1 and R_2. As before, assume the sum of these resistors to be approximately 80K ohms. The current in R_1 and R_2 also passes through the VR tubes and is a regulating factor in the firing of these tubes.

When the plate voltage of the 6SJ7 is 180 volts, the screen supply voltage is 250 volts. The screen voltage should be approximately 100 volts. The screen current can be assumed practically constant for a pentode with varying plate voltage. The screen current will be assumed at 3 ma. The screen current drop in R_1 will have to be taken into consideration. Figure 4 shows the equivalent screen circuit and the calculations necessary to determine R_1 and R_2. The calculations in Figure 4 will give a screen voltage of 100 volts with Voltage AC a minimum. However, with Voltage AC a maximum, the screen voltage will increase. The screen current remains at approximately 3 ma. Figure 5 shows the equivalent screen circuit for this condition. The approximate screen resistance equals $100/.003 =$ 30K ohms $= R_s$. With Figures 4 and 5 as reference, the load resistor, R_9, for the 6SJ7 can now



$$I_1R_2 + (I_1 + .003)R_1 = 250 \text{ volts}$$

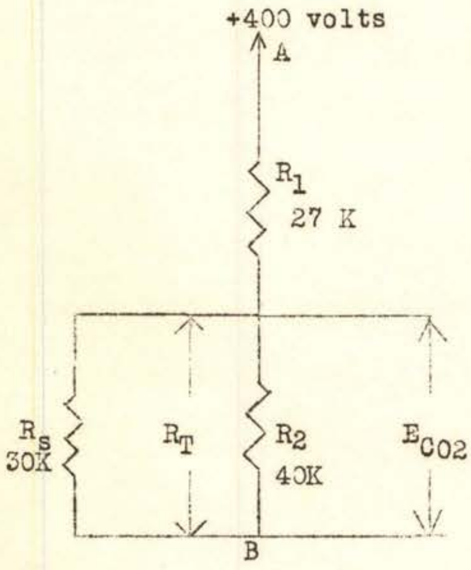
$$I_1R_2 = 100 \text{ volts}$$

Assume $R_2 = 40{,}000$ ohms

Then $I_1 = 2.5$ ma.

Therefore $R_1 = 27{,}000$ ohms

Figure 4 : Equivalent screen circuit for 6SJ7.



$$R_T = \frac{30K \times 40K}{30K + 40K} = 17K \text{ ohms}$$

Screen Voltage $= E_{CO2}$

$$E_{CO2} = (17/44) \times 400 = 155 \text{ volts}$$

Figure 5 : Equivalent screen circuit.

be calculated.

With Voltage AC a minimum, Voltage AB = 250 volts, the 6SJ7 tube drop equals 180 volts and E_{bb} = 630 volts. Assume that the grid bias will be zero for this condition. (This is from the circuit analysis, since the drop of the 6SJ7 has to be small, the tube current would have to be large.) By drawing a load line for these conditions, R9 = (630 − 180)/ .009 or .50K ohms. To overdesign, R_9 will be used as 60K ohms in order that the 6Y6 bias will be − 70 volts with zero bias on the 6SJ7. The load line for the other extreme of Voltage AB = 400 volts will be the same, since later in the design, provision will be made to reduce the 6SJ7 bias enough to secure 385 volts tube drop.

When Voltage AB = 400 volts, the 6SJ7 tube drop should be 385 volts. Using R_9 = 60K ohms as the load line, the 6SJ7 bias should be − 2 volts. However at this point, the screen voltage = 155 volts so that the bias should be (155/100) x (−2) = −3 volts. In the following design this bias will be used as − 4 volts.

The bleeder resistances (R_4, R_5, R_6 and R_7) can now be calculated. Point C will be used as the reference voltage. Assume that the Voltage BC equals 370 volts. This will vary with temperature, but will be compensated for later. For minimum Voltage AC = 620 volts, the bias for the 6SJ7 equals zero. Also the point E (variable) approaches point I. The Voltage BC = 370 volts. Hence the Voltage EC = 370 volts. The Voltage AC = 620 volts. Therefore the ratio of resistance AE and resistance EC can be calculated. EC/ (AE+EC) x 620 = 370 volts. From this equation, the resistance ratio AE/EC = .66. Assume that the divider sum = 550K ohms as before. Therefore resistance AE + EC = 550K ohms. From the preceding resistance ratio of EC and AE, EC = 332K ohms and AE = 218K ohms.

To allow for temperature variations in the VR tubes, choose resistance of R_5 to be 100K ohms, and resistance EI to be 30K ohms, so that if the VR tubes raise Voltage BC to 375 volts, the 6SJ7 grid can still be zero. With these values, then $R_4 = 218K - 30K$ or 188K ohms and $R_5 = 100K$ ohms as before. Therefore, resistance EJ = 70K ohms, EC = 332K ohms and $R_6 + R_7 = 332K - 70K$ or 262K ohms. Choose R_7 to be 50K ohms. This leaves R_6 to be 212K ohms. With these resistance values, the 6SJ7 grid bias for maximum output voltage can be checked.

With maximum output, the Voltage AC = 770 volts and Voltage JC = $(R_6 + R_7)/550K \times 770 = 366$ volts. The maximum negative bias possible on the 6SJ7 is 366 − 370 or − 4 volts. This is sufficient as − 4 volts is all that is necessary in accordance with preceding specifications.

The condenser C_1 is added to make the grid of the 6SJ7 more sensitive to the output ripple voltage. It essentially puts the grid at ground potential as far as ripple voltage is concerned. Therefore voltage regulation will take place for the ripple components.

Since the output ripple voltage is smaller than the input ripple voltage due to the ripple drop in the 6Y6, a provision is made to make the 6SJ7 grid sensitive to the input ripple. R_7 is a 50K ohm potentiometer, with the center tap connected thru 4 megohms to the input positive supply. Hence the input ripple will cause variations in the 6SJ7 grid circuit and the regulation will be such to counteract the input ripple.

With consideration of the purpose of the power supply, the following refinement was added so as to permit a more flexible Voltage AB. R_6 is shunted by a 250K ohm potentiometer in series with a 300K ohm resistor as shown in Figure 6. This enables a vernier control of the Voltage AB with R_5 so that the full range of R_5 can be used giving greater accuracy in setting Voltage AB.

In the repeller circuit, potentiometer R_3 is chosen in size to meet wattage specifications. The maximum voltage across the potentiometer is Voltage

BC and is equal to 380 volts. R_3 is chosen as a 250K ohm, 1 watt potentiometer so that the dissipated wattage is .65 watts. The center tap of the potentiometer is connected to the repeller of the klystron and no current is drawn, since the repeller is always negative with respect to the klystron cathode. Further refinements for this power supply will be given in a later section, when circuits requiring additional voltages will be used.

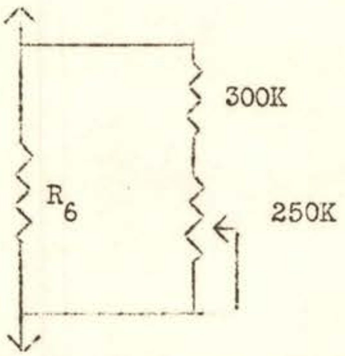


Figure 6 : Vernier control for Voltage AB.

The power pack was built in accordance with the preceding calculations and the outputs were tested using the klystron as a load. All voltages were within those in the design calculations.

It may be noted that the cathodes of the 6Y6 and the 6SJ7 are at different potentials. This necessitates a filament transformer with two separate 6.3 volt secondaries. As a special transformer was not available, a standard plate transformer with a 5 volt and a 6.3 volt secondary was used. The 6Y6 operates with 6.3 volts and the 6SJ7 with 5 volts on the filament. Since the power pack was originally overdesigned, this low voltage on the 6SJ7 filament does not mar the operation of the power pack.

PHYSICAL COMPONENTS :

Figure 7 shows the physical component arrangement for the wave guide assembly. Connections between sections of wave guides are by single or double choke joints as shown in Figure 7a. The rectangular wave guide is excited in the H_{01} mode of transmission by virtue of the klystron probe placement.

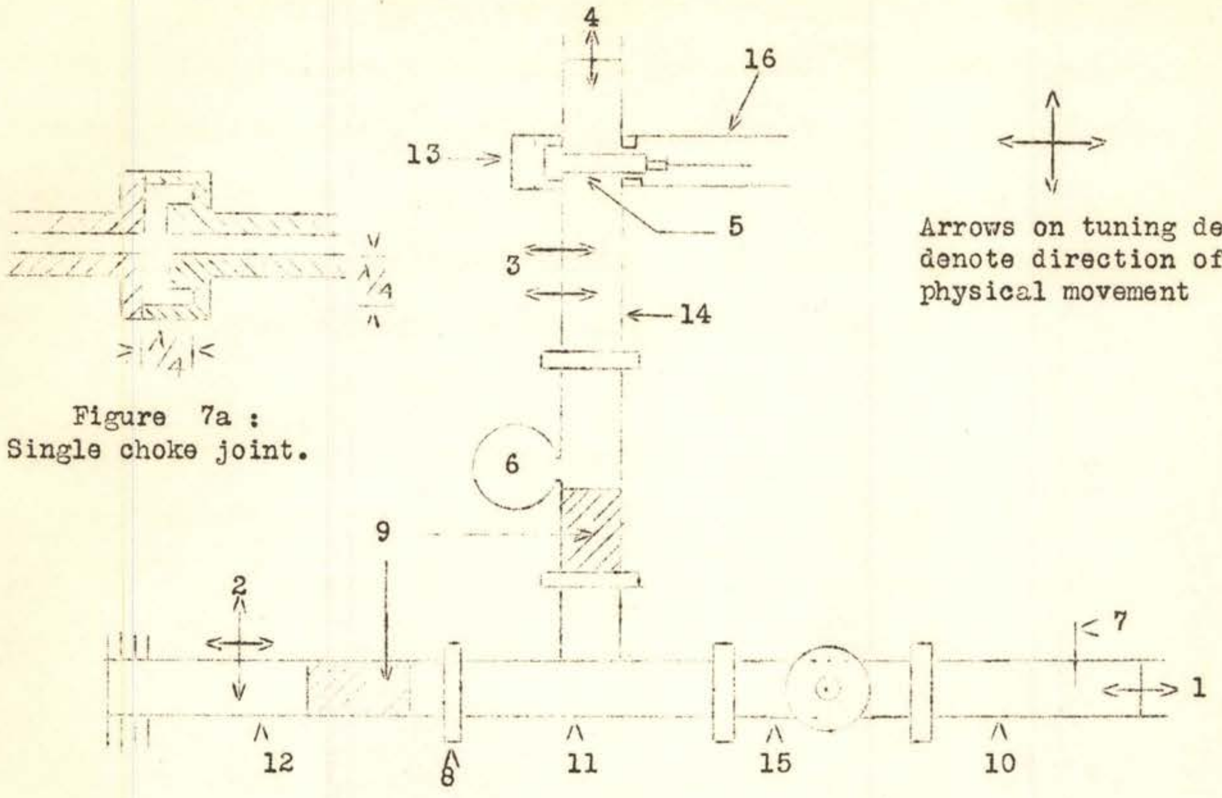


Figure 7a :
Single choke joint.

Arrows on tuning devices
denote direction of
physical movement

1. Shorting plug, variable position
2. Tuning stub, variable length and position
3. Tuning stubs, variable length, fixed position
4. Shorting plug, variable position
5. Crystal
6. Wavemeter
7. Klystron probe
8. Choke joint
9. Cross section
10. Tube mount
11. Series Tee
12. Variable load
13. Crystal cap
14. Crystal mount
15. Attenuator
16. Coaxial lead

Figure 7 : Wave guide assembly.

The wave meter is a circular cavity with variable length and is excited in the TE_{111} mode since the E vector in the wave guide is parallel to the E vector in the wave meter. As the wave meter is directly connected to the side of the wave guide perpendicular to the E vector, the TE_{011} mode is eliminated. Note Figure 7 for this mode elimination.

Ample tuning arrangements are suitably located, to assure optimum loading of the klystron. The tuning of one stub affects the tuning of the others, therefore when obtaining maximum crystal current, it is necessary that all tuning arrangements be dealt with simultaneously. This has to be done for each point of data, when relative power measurements are being taken. The individual role of each tuning arrangement can be clearly demonstrated in the dynamic characteristic section. Referring to Figure 7, the following correlation of tuning arrangements is given for clarification. (1) essentially matches klystron to wave guide. (2) matches load to wave guide. (3 & 4) match crystal to wave guide.

Using Figure 7 as reference, the following theory is given to cover the actual conditions occurring when the frequency and approximate power of the klystron are being measured. Energy flows from the klystron to the load (12) and the crystal (5). The meter (in detail later) will indicate crystal current and when the wave meter is not tuned to resonance, matching adjustments are made to make the crystal current a maximum. When the frequency meter is tuned to resonance, a low impedance is presented to the wave guide at the wave meter coupling and power will be absorbed by the wave meter. This decreases the power flowing to the crystal and a dip will occur in the crystal current. This dip is large enough to assure an accurate frequency reading for all modes except the mode corresponding to the smallest negative repeller voltage.

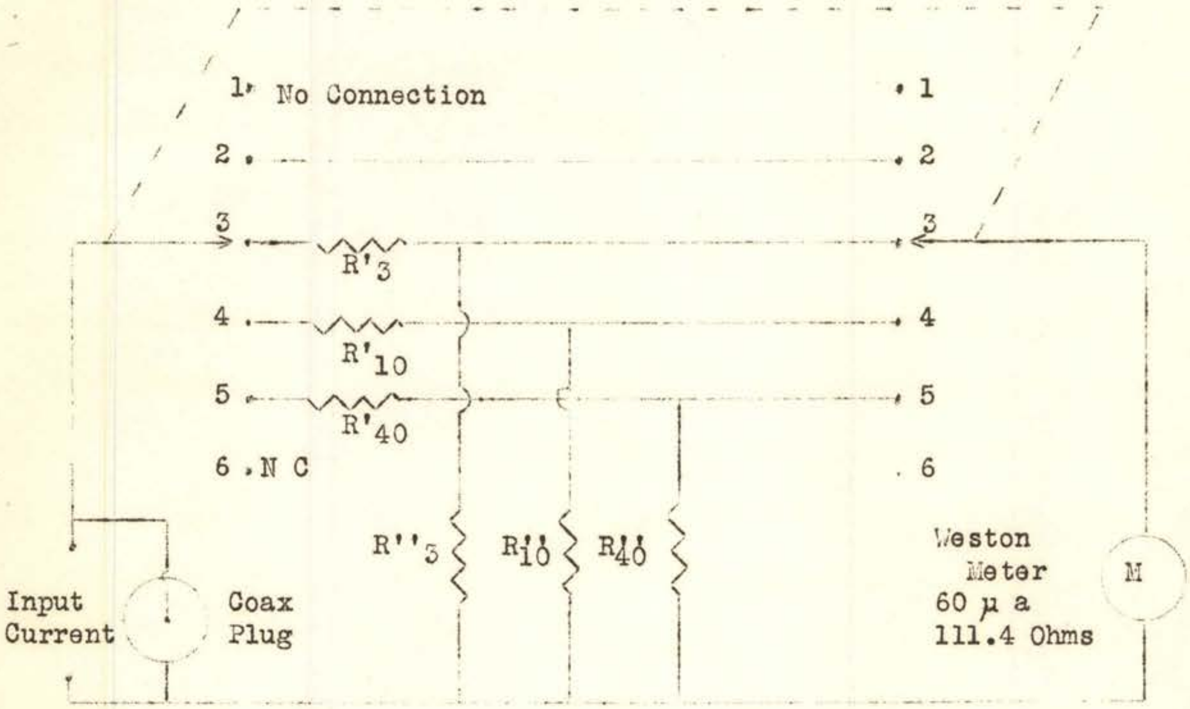
The wave meter is such that one part in 9000 can be measured for the frequency range of 8430 megacycles to 9660 megacycles. The accuracy of the crystal current meter does not enter in, since a minimum reading is seen on the meter, not a direct current reading when measuring frequency. When measuring relative power of the klystron, the meter reading does enter in and accuracy of relative power measurements will depend on the meter accuracy. This will be discussed later.

The crystal is located in the maximum E field of the wave guide and presents an impedance to the E field, hence crystal current will flow. It is this current that is measured on the meter. The crystal operates as a square law detector. The power in the wave guide is proportional to E^2. Therefore neglecting the slight current that flows in the reverse direction, since the crystal is not a perfect rectifier, it is possible to measure the relative power output of the klystron in its various modes. The current in the meter $= KE^2$. Where K is a constant as long as the crystal is not over-loaded. From this, the meter reading is proportional to the power in the wave guide. This current reading for relative power measurements is taken when the wave meter is off resonance.

The actual power delivered by the klystron cannot be measured, since an impedance meter for 3 cm. wave guides is not available. Therefore the impedance of the crystal branch and the load branch as presented to the series tee section cannot be determined. The crystal current is therefore, only the relative power output of the klystron. In a later section of this paper, a circuit is shown for actual power measurements.

CRYSTAL CURRENT METER :

The meter to measure crystal current was chosen so as to be of such impedance to obtain a maximum power transfer from crystal to meter. The meter is a 60 microampere movement manufactured by Weston. The meter resistance is 111.4 ohms measured to four significant figures. Since the power output



$R'_3 = 74.27$ ohms

$R'_{10} = 100.3$ ohms

$R'_{40} = 108.6$ ohms

$R''_3 = 55.70$ ohms

$R''_{10} = 12.38$ ohms

$R''_{40} = 2.859$ ohms

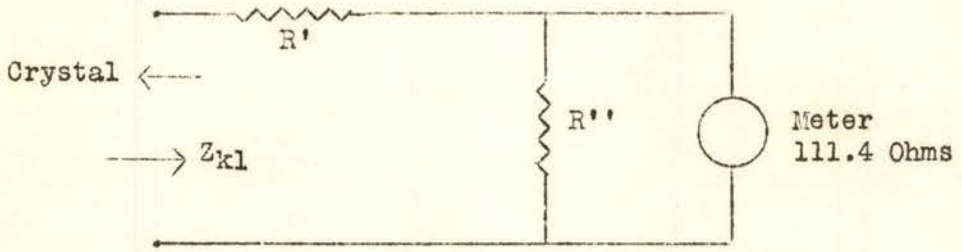
Switch Positions

1. No Connection
2. Meter x 1
3. Meter x 3
4. Meter x 10
5. Meter x 40
6. No Connection

Figure 8 : Crystal current meter circuit.

of the klystron varies with modes of oscillation, it is necessary to extend the range of the meter to cover the high power modes. To keep the impedance presented to the crystal constant, an L pad is incorporated with the meter for the different ranges. This gives a 111.4 ohm impedance on all ranges. Figure 8 shows the complete meter circuit.

The following design considerations are given for the meter multiplier circuit. Using an inverted L pad as in Figure 9, the impedance presented to the crystal should be approximately 110 ohms. To simplify calculations, Z_{k1} is made equal to the impedance of the meter or $Z_{k1} = 111.4$ ohms.



$$R' = Z_{k1} \frac{(\alpha' - 1)}{\alpha'} \qquad R'' = \frac{Z_{k1}}{(\alpha' - 1)}$$

$$\text{Where } \alpha' = \frac{\text{Current in meter without attenuator}}{\text{Current in meter with attenuator}}$$

Figure 9 : Inverted L pad for crystal current meter.

The following ranges are desired.

60 microampere or meter x 1
180 microampere or meter x 3
600 microampere or meter x 10
2400 microampere or meter x 40

Attention is invited to the fact that with this choice of scale ranges, full scale on a lower range will give at least $\frac{1}{4}$ full scale reading on the next higher range, so that the range of 60 microampere to 2400 microamperes can be fully covered.

Following is the calculation of meter pad resistances.

180 microampere range

$$\alpha' = 1/.333 = 3$$

$$R'_3 = 111.4 \frac{(3-1)}{3} = 74.27 \text{ ohms}$$

$$R''_3 = 111.4/(3-1) = 55.70 \text{ ohms}$$

For the 600 and 2400 microampere ranges, the calculations are similiar to the preceding ones. Final values for all ranges are shown in Figure 8. These resistors were hand wound and cut to four significant figure accuracy by means of a Leed Northrup Resistance Bridge. The final unit was tested, and the results were well within the accuracy of the meter.

With reference to Figure 8, note that in case of meter overload, the meter can be switched out of the crystal circuit by clockwise or counter-clockwise rotation of the selector switch. This switching operation can be performed in a fraction of a second and therefore will protect the meter from damage.

The input to the meter consists of a coaxial connector for this particular circuit and pin jacks are in parallel with the coaxial connector for other circuits that may be used later.

PART II: DISCUSSION AND APPLICATION OF RESULTS OF PART I.

Very often in electronic design work, absolute voltages as called for in design specifications cannot be met at low costs. Probably voltages within 10% of specifications can be met by using commercial products already on the market. The question then arises, will the frequency range and power output of the klystron be within the design limits when operated on design voltages ±10%. With reference to Figure 1 and Figure 3, it may be seen that any combination of repeller voltage, cavity voltage or filament voltage applied to the klystron may be obtained. This enables complete coverage of the operating voltage ranges of the klystron and static data can be taken for any desired conditions.

Obtaining static data for klystron operation is a tedious undertaking. However, it can be accomplished and experimental curves for the complete range of operation for a particular klystron were taken by use of the equipment as explained. Figure 10 shows a plot of relative power and frequency vs repeller voltage for the optimum operating voltages. For this curve, the filament voltage = 6.3 volts A.C. and the cavity voltage = 300 volts D.C.

Five modes are shown in Figure 10. Whether or not more modes will appear to the right on the diagram depends on the spacing of the cavity grids and the ratio of the starting current to the beam current. One mode does exist to the left of the curves shown, but its power is so small, that even with the crystal current meter on the lowest range, the mode cannot be tuned for measurement. The dynamic section will show this small mode, because of the high amplification of the oscilloscope. Generally seven modes can be obtained with this particular klystron. In the direction of increasing negative repeller voltage, the last mode may be larger or smaller than the preceding mode. This depends on the tube characteristics along with operating voltages.

Variations in klystron loads cannot be shown simultaneously for the various modes. Therefore, the effect of load changes will be discussed in the dynamic section.

The tendency of the 723A/B klystron to pull into high power output, or the 'pulling' of the klystron can be clearly shown, when the static data is taken. When trying to obtain a half power point or any point not at maximum power, it is necessary to tune the system so as to eliminate mis-matches between the components. As this tuning proceeds, it is noticed that the crystal current increases beyond the half power point and eventually climbs to maximum power. When this happens, the data has to be cancelled and the mode data retaken. Elimination of this situation is discussed in an earlier section.

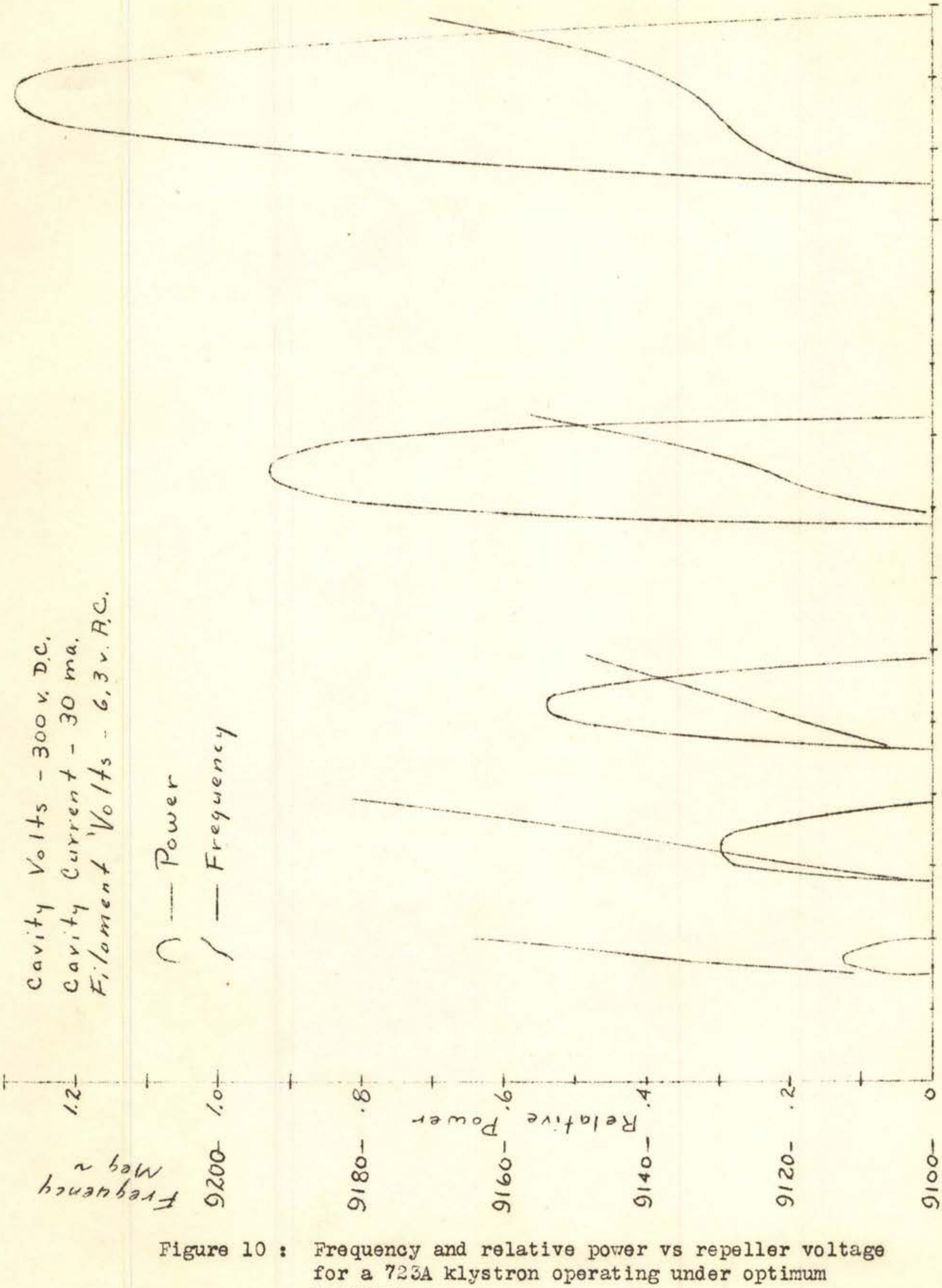


Figure 10 : Frequency and relative power vs repeller voltage for a 723A klystron operating under optimum conditions.

PART III : MEASUREMENT OF FREQUENCY AND RELATIVE POWER UNDER DYNAMIC CONDITIONS.

As stated in Part II, the determination of klystron characteristics by the static method is a tedious and exacting undertaking. The relatively long periods of time consumed by data taking may be wasted because the actual over-all results of tuning for maximum power and measurement of frequency are not immediately apparent. The results have to be plotted on coordinate paper before one can determine whether or not they are sufficiently accurate.

The 723A klystron was originally designed so that forced cooling was not necessary. The maximum ambient temperature is approximately 248^0 Fahrenheit. This does not mean that the tube characteristics are the same for all temperatures between room temperature and 246^0. Design considerations have minimized expansion and contraction effects so that the power and frequency shifts with temperature are low, but not ± 0 %. For this reason, the static data may be in error due to temperature changes. This error is not apparent until the data is plotted.

Modification of circuits shown in Part I, in conjunction with an oscilloscope, make it possible to view all operating modes of the klystron at the same time. When the frequency meter is not at resonance, the oscilloscope picture will be approximately as Figure 10 for the output power. From the students view point, this dynamic picture enables a visual opportunity to see the correlation between theory, laboratory techniques and the actual electrical changes taking place.

Many different klystron circuit features may be shown such as : individual effect of each tuning arrangement, cavity voltage changes, load changes, grid spacing changes, determination of faulty klystron tubes, elimination of 'pulling', filament voltage variations, output frequency and relative power. The preceding features if properly applied, can give much more information for the klystron, than the static method in about 2% of the time. In fact the effect of load changes for each mode cannot be determined by static methods as outlined in Part I.

Dynamic klystron operation originally had its most important role in the automatic frequency control section of radar receivers. The effect of repeller voltages on the output as shown in Figure 10, makes frequency modulation an easily obtainable characteristic. Negligible power is needed, simply because the repeller circuit has no current flow. In radar receivers, the maximum frequency variations are not utilized. Only a very small portion is used because of the magnetron stability under normal operating conditions. However, for laboratory work, the maximum frequency range is utilized so that all characteristics of the klystron may be shown.

For automatic frequency control in radar receivers, a saw tooth voltage wave is applied to the klystron repeller. This wave is of the same form as the sweep voltage of an oscilloscope, that is, the voltage change has an almost linear variation with time. The saw tooth modulation circuit is too complicated for use in the laboratory. It is a special circuit and serves its purpose in the radar receiver admirably.

Frequency modulation will take place as long as the repeller voltage is varied, and for ease in the laboratory, the klystron repeller circuit voltage will be an A.C., 60 cycle wave superimposed upon a negative D.C. bias voltage. The magnitude of this voltage will be discussed later.

For dynamic operation, the oscilloscope sweep voltage is not used. Instead, the A.C. component of the repeller circuit is used as the horizontal sweep. The rectified klystron output from the crystal is connected to the vertical plates. These facts are correlated in Figure 11, a simplified diagram. In Figure 11 note that the D.C. component of the repeller voltage does not appear as a deflection voltage. Therefore the output of the various klystron modes will be as a function of the sweep voltage and since the variations in repeller voltage and sweep voltage are the same, the output would be as in Figure 10.

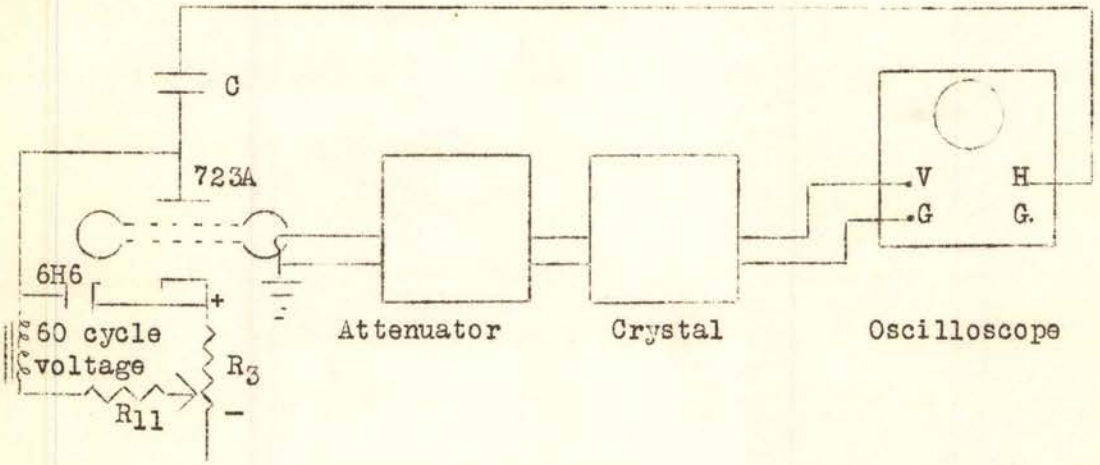


Figure 11 : Block diagram of components for dynamic characteristics.

Modulation by A.C., rather than by a saw tooth voltage has one disadvantage. The A.C. sweep voltage superimposes the left to right and right to left portions of the sweep which occur during one cycle of A.C. modulation voltage. The two wave forms thus obtained do not correspond exactly, because of the lead resistance, charge and discharge of the coupling capacitor, and the hysteresis effect of the coupling capacitor and the hysteresis effect of the klystron repeller field. This disadvantage is not predominant, except with a large horizontal amplification, and when viewing all modes simultaneously, can hardly be noticed. This will be discussed more fully in a later section. The double image disadvantage is not as great as the disadvantage caused by the complicated circuit, when a saw tooth modulation voltage is used.

For Part III, the physical placement of the wave guide and related components will be as shown in Figure 7. The crystal output will be fed to the vertical plates of the oscilloscope instead of to the crystal current meter.

The attenuator (Part 15, Figure 7) can be used for all measurements because of the vertical amplification of the oscilloscope. The attenuator could not be used for all measurements in the static tests because of the low power output of the klystron.

It is necessary to modify power pack No. 2 for the dynamic tests. The additions are in such an external manner to the power pack chassis, that the changes take only a few minutes and the power pack can be used interchangeably for the static and dynamic tests.

The repeller modulation transformer is a 1:3 plate transformer and is designed for 110 volts r.m.s. operation on the primary. The modulation circuit to be added to Figure 3 is shown in Figure 12. The A.C. output x-x is connected to the points x-x shown in Figure 3. The short between x-x is removed. Thus the repeller voltage is the A.C. voltage x-x superimposed upon the negative D.C. voltage LB in Figure 3.

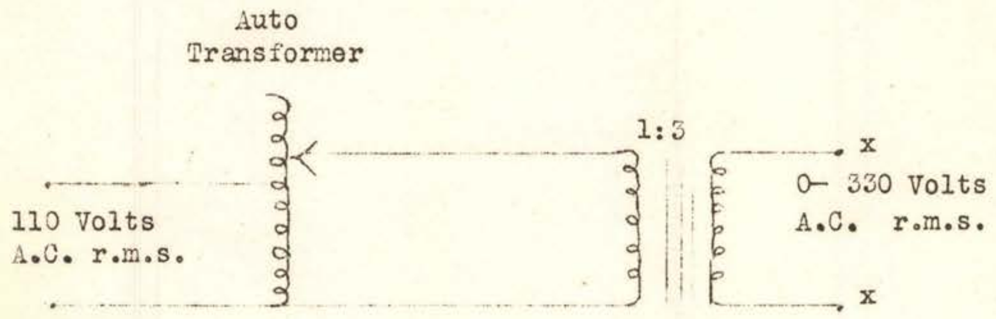


Figure 12 : Modulation voltage circuit for dynamic operation.

Voltages LB and X-X are both variable and either may be set independently of the other. The maximum D.C. voltage obtainable is – 370 volts as previously stated. The repeller is not designed to be positive with respect to the cathode, therefore the A.C. voltage should be 370 volts peak. The repeller voltage diagram is shown in Figure 13. The 370 volts peak voltage corresponds to 262 volts r.m.s. The output of the modulation transformer is normally 330 volts r.m.s. with 110 volts r.m.s. applied, thus the reason for the auto transformer in Figure 12 is to prevent a positive voltage from being applied to the repeller. A limiting stop is placed on the auto transformer.

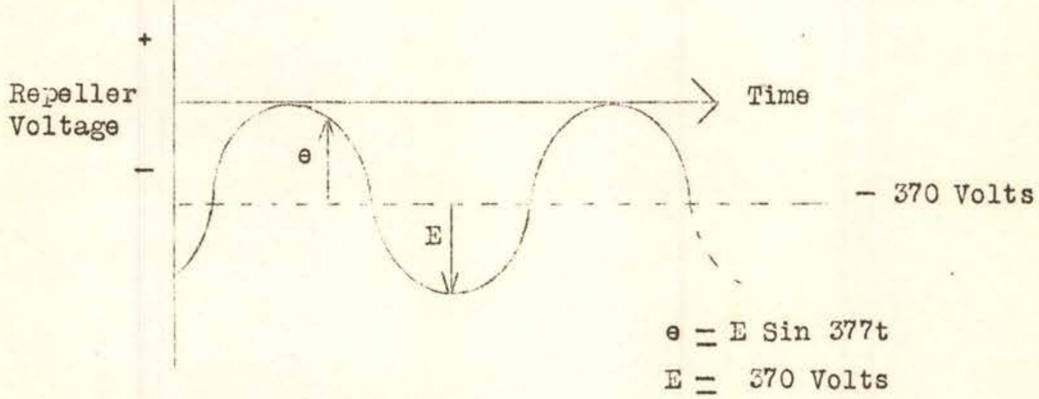


Figure 13 : Repeller voltage with reference to time.

As a further protection to the repeller circuit, a clipper tube is connected between the repeller and cathode. Figure 14 shows this circuit. In Figure 14, YY' refers to connections relative to Figure 3. The cathode of the clipper tube is at the same potential as the klystron cathode, thus the clipper filament power may be obtained from the klystron filament transformer.

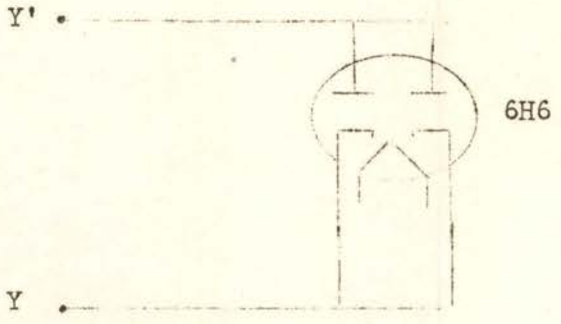


Figure 14 : Clipper tube.

The clipper tube does not conduct when the repeller is negative with respect to the klystron cathode. When the repeller goes positive, the clipper tube conducts causing a voltage drop in R_{11} (Figure 3). This drop is of the same polarity as the voltage LB, so that when the tube conducts, the positive excursion of the repeller voltage is limited. R_{11} is 100K ohms so that with a small current flowing in the clipper tube a large voltage drop is introduced in R_{11}.

Figure 13 shows the maximum voltage in the repeller circuit. The excursion of the repeller voltage is from zero to − 740 volts. This variation in voltage is large enough to include all modes for a 723A/B klystron. Figure 10 will be altered to show seven modes, which is the total possible for this particular tube.

With the power circuit connected for dynamic operation, it is possible to use any value of negative D.C. bias simultaneously with any value of A.C. modulation voltage superimposed upon the D.C. This is a very valuable characteristic, since any mode of operation may be selected by suitable values of D.C. and A.C. components. For any particular mode, the D.C. bias is set at the value corresponding to the peak power of the mode and the A.C. is increased until the repeller voltage swing is sufficient for this mode. By this method, any number of successive modes may be examined. This feature is very valuable when measuring the frequency excursion of the mode.

When the wave meter is tuned to resonance, the effects are clearly shown on the oscilloscope picture. As the reflector voltage sweeps thru a mode, the frequency of oscillation changes as shown in Figure 10. When the frequency of the klystron corresponds to the tuning of the frequency meter, power will be absorbed as explained in the static section and the dip in crystal output will be shown in the oscilloscope curves. This is illustrated in Figure 15.

To calibrate the horizontal axis in Figure 15, it is necessary to apply a known peak to peak value of A.C. voltage to the horizontal plates instead of the repeller voltage. Thus the horizontal sweep of the oscilloscope can be calibrated in volts per inch. When the repeller voltage is connected as the sweep, the peak to peak value can be measured. The D.C. bias voltage can be measured, therefore the repeller voltage for any part of a mode can be found from the oscilloscope picture.

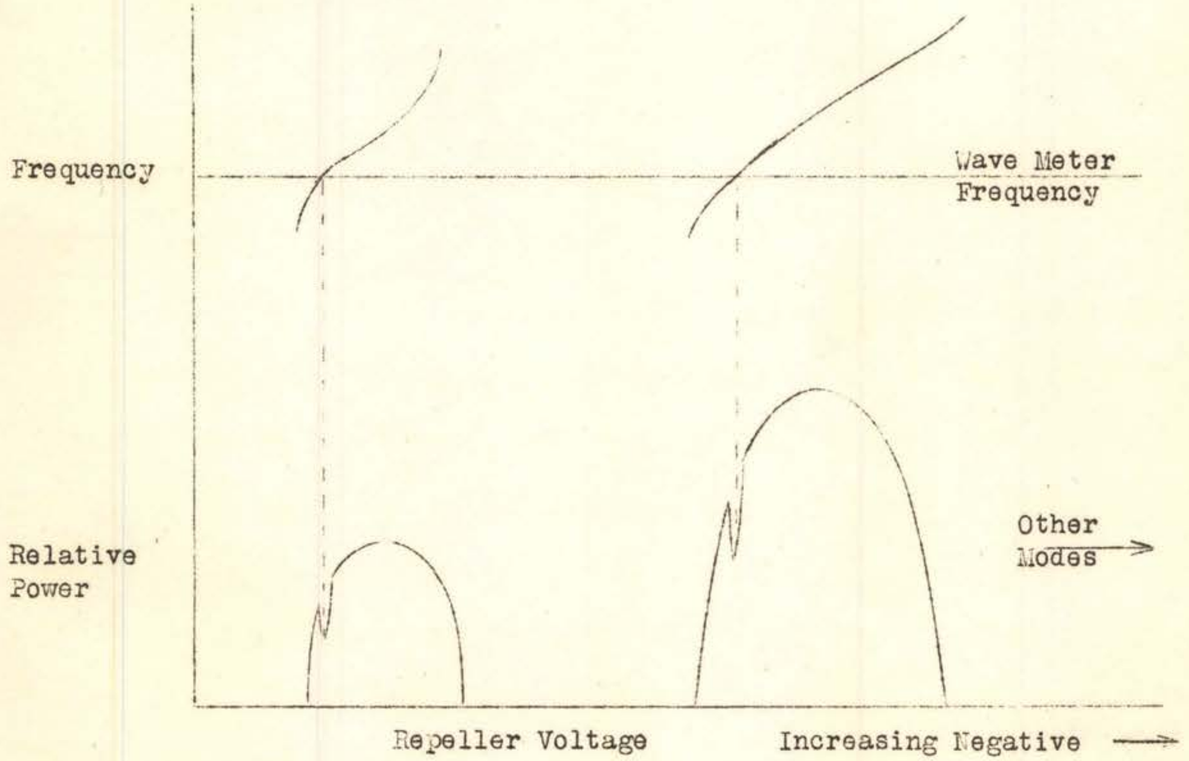


Figure 15 : Dynamic frequency measurement.

The effect of the load upon the power output of each mode can be examined by varying the load tuning adjustment. (Figure 7, Part 2) The mode power output will depend upon the load value.

For light loads, the power output will be small. Increasing the load, increases the power output up to a optimum value and increasing the load further, decreases the power output. The width of the mode in terms of the reflector voltage decreases with loading. By viewing one mode on the oscilloscope, a picture similiar to Figure 16 will be obtained for the three load values mentioned. Note from this figure that the advantage of linear frequency changes vs repeller voltage can only be obtained from over-loading. The data for the frequency curves (Figure 16) is obtained as stated previously for this section.

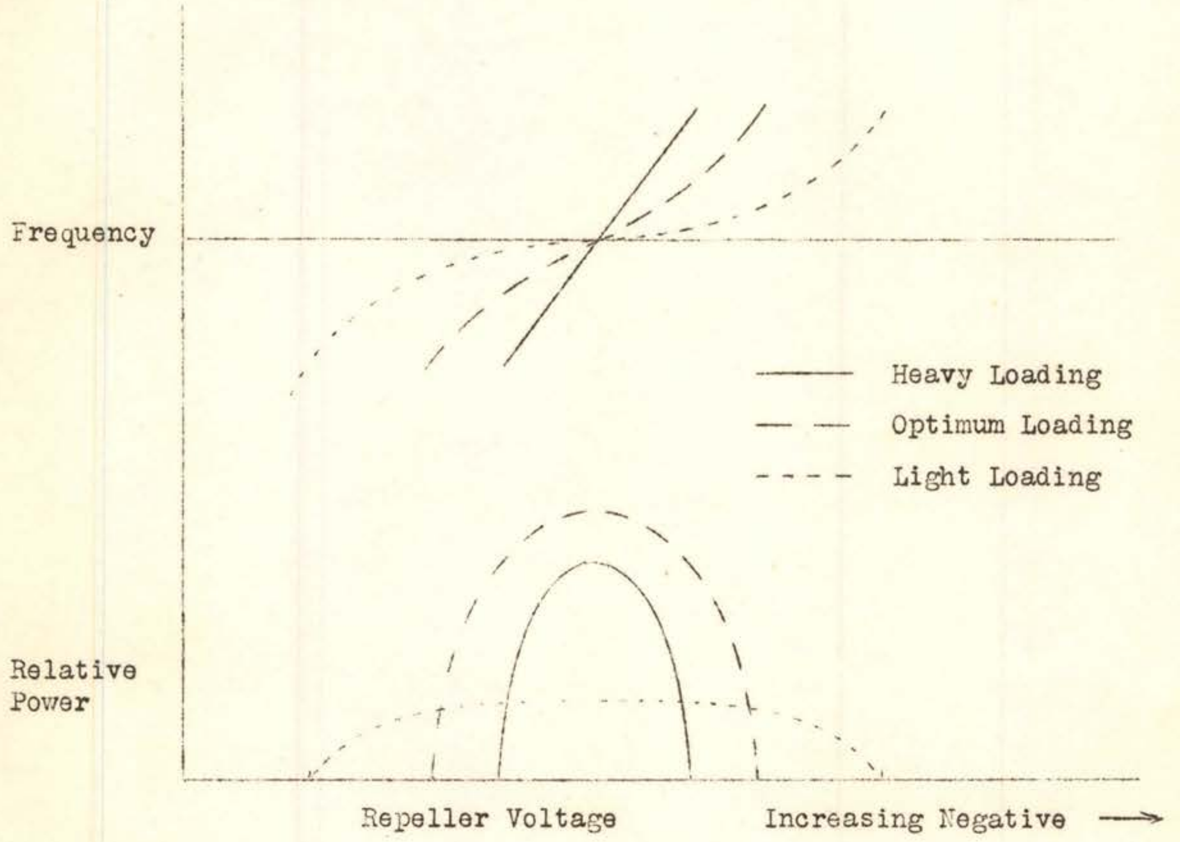


Figure 16 : Mode power variations with respect to loading.

The effects of load variations are different for the various modes. That is, a particular change in klystron loading will not effect all modes in the same manner. If the klystron is lightly loaded, all of the modes will be relatively small and as the load is increased, the power of all modes will increase. As the load is further increased the mode corresponding to the largest negative repeller voltages will increase to a maximum. Increasing the load further, decreases this large mode and the next mode to the left (smaller repeller voltage) will increase to its maximum. If the load is increased still further, the mode that reached its maximum first may disappear entirely.

The dynamic procedure to this point is sufficient to determine the effect on output power and frequency for each of the klystron circuit features listed on page 23.

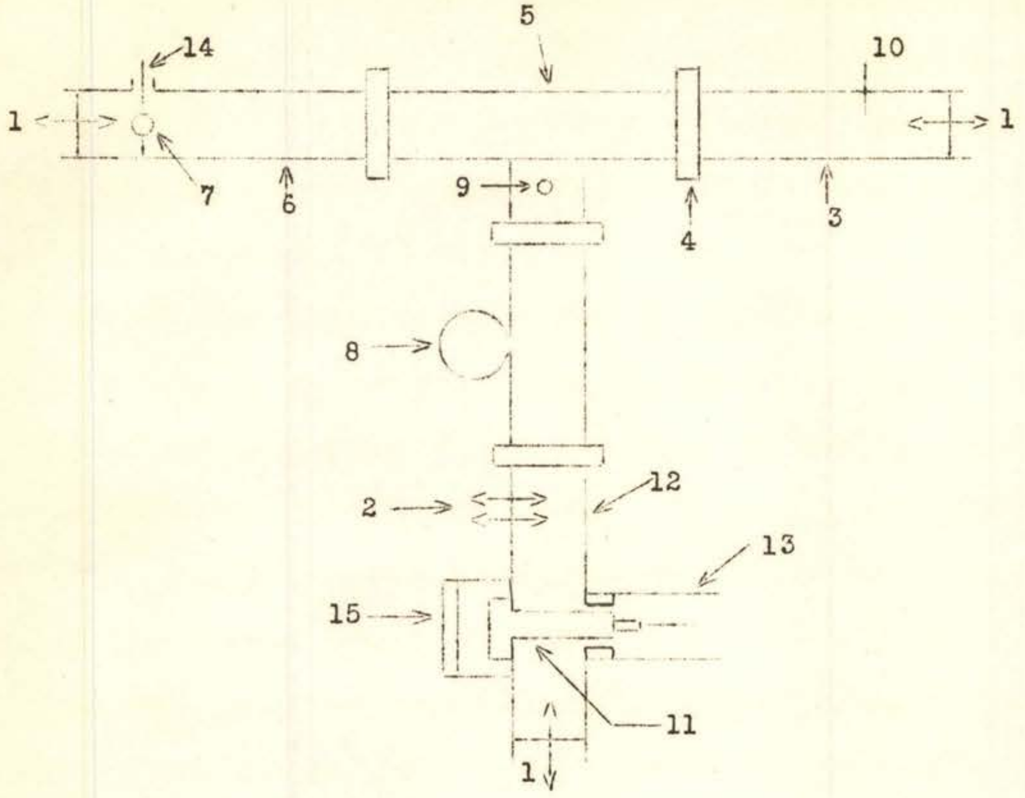
With all modes shown on the oscilloscope, the effect of each matching adjustment upon the power output of the klystron may be shown as well as the relative effective value of the tuning adjustments. Results of the dynamic tests substantiate the theory very well.

Power output of the klystron depends very much on the D.C. cavity voltage. As the cavity voltage is increased to the optimum operating value of 300 volts D.C., the power for each mode increases. At cavity voltages over 300 volts D.C., the maximum power output experiences relatively little change. However, the frequency characteristics of the modes undergo continual changes for D.C. cavity voltage.

The minimum filament voltage at which the klystron will operate satisfactory can also be clearly shown, since the power output as shown on the oscilloscope can be viewed simultaneously with reduction of klystron filament voltage.

PART IV : THERMISTOR BRIDGE WATTMETER.

A special physical component arrangement is used for this circuit. Components are at ground potential as explained for Figure 7. To eliminate 'pulling' and other loading effects, the thermistor is the only load component for taking output power data. Sufficient matching devices are incorporated to assure an impedance match for the range of frequencies covered for both klystron to wave guide and Thermistor T_1 to wave guide. The frequency measuring portion is the same as in Figure 7 and the theory given previously holds for this section. Figure 17 shows the physical component arrangement.



1. Shorting plug, variable position

2. Tuning Stub, fixed position, variable length

3. Klystron tube mount

4. Choke joint

5. Shunt Tee

6. Thermistor Mount

7. Bead Thermistor

8. Wavemeter assembly

9. Tuning stub

10. Klystron probe

11. Crystal

12. Crystal Mount

13. Coaxial Crystal lead.

14. Thermistor lead

15. Crystal cap

Figure 17 : Physical arrangement of wave guide and associated components for thermistor bridge.

The D.C. power for the klystron is supplied from the power packs previously mentioned, thus the additional electrical circuits necessary will be for the thermistor.

The thermistor bridge wattmeter measures power by the use of a variable resistance element incorporated in a bridge circuit. The thermistor is the variable resistance element. Its resistance decreases with increasing temperature and vice versa. Changes in the thermistor temperature and hence resistance, may be caused by several factors : (1) Thermal changes in air surrounding bridge. (2) By A.C. or D.C. currents flowing thru thermistor. (3) By absorbed R.F. power. All three of these items should be considered in the bridge circuit design.

The power measuring thermistor is a bead type. It has a small mass and is affected currently by the three factors mentioned above. It is enclosed in an evacuated glass bulb as shown in Figure 18. Another type of thermistor is the disc type. It is several times larger than the bead type and has a much larger mass. Its resistance is relatively insensitive to current flowing thru it, and is therefore dependent upon the ambient temperature. The disc type will be used in temperature compensating networks. A physical sketch for the disc type thermistor is shown in Figure 19.

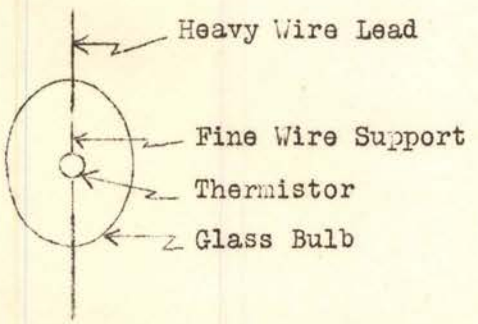


Figure 18 : Bead type thermistor

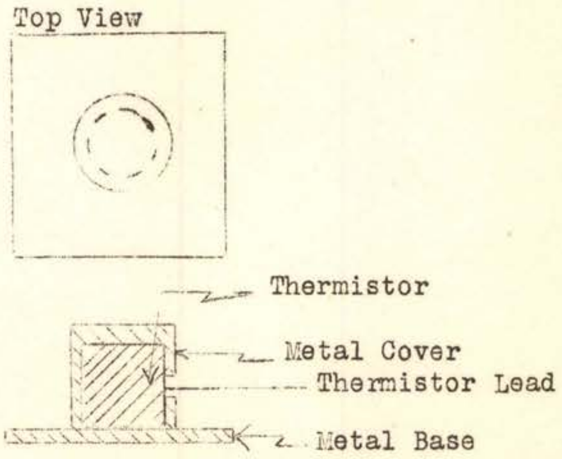


Figure 19 : Disc type thermistor.

The basic thermistor bridge circuit is shown in Figure 20. The Wheatstone Bridge circuit consists of R_3, R_4, R_5 and Thermistor T_1. The balance equation for the bridge is (R_3 / T_1) = (R_4 / R_5) and the meter will show no current indication when this equation is effective.

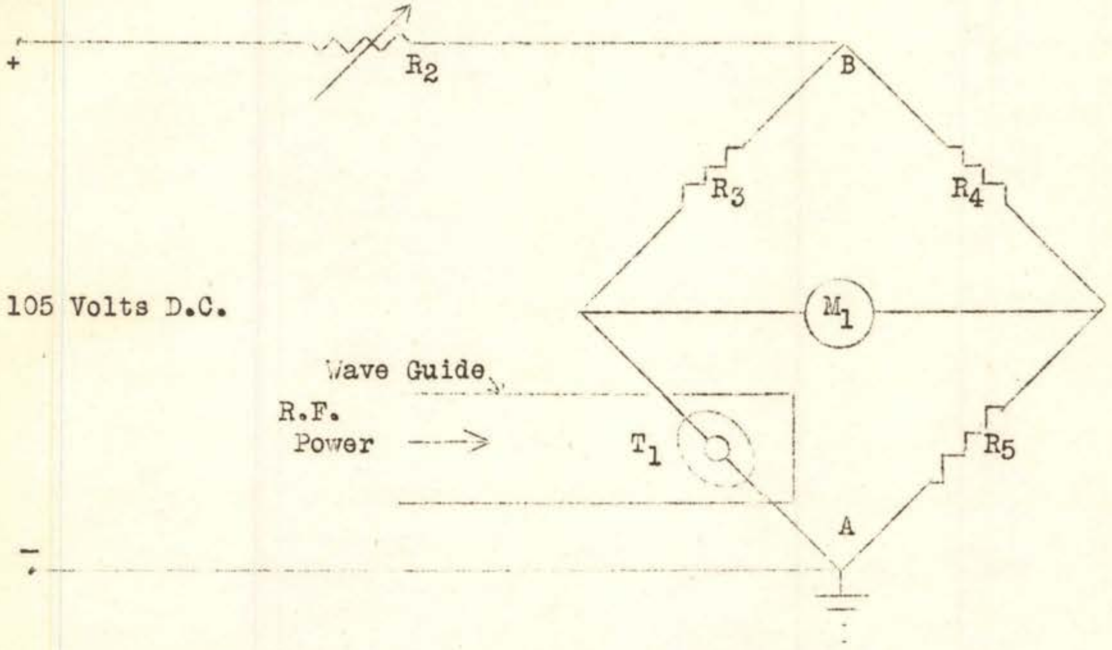


Figure 20 : Basic Thermistor Bridge

With no R.F. applied to the thermistor T_1 , the bridge may be balanced by varying the D.C. current in the thermistor. This varies the thermistor temperature. Since the thermistor resistance changes with temperature, the resistance of the thermistor can be adjusted by R_2 (Figure 20), which will be called the Zero Adjustment.

After meter M_1 has been set to zero, the R.F. power can be measured when the klystron is placed in operation. The R.F. power absorbed by the thermistor increases its temperature and hence, decreases its resistance, thus unbalancing the bridge and allowing current in meter M_1. The current in the meter is proportional to the R.F. power of the klystron.

If the ambient room temperature could be held constant, the basic circuit shown in Figure 20 could be used as shown. Since the ambient temperature is not constant, the measuring sensitivity of the circuit will vary with temperature. The measuring sensitivity is defined as unit meter current per unit R.F. power and for this circuit is microamperes / milliwatt.

The bridge circuit in Figure 20 increases in sensitivity with a decrease in ambient temperature. This is not due to the thermistor sensitivity change since the ohms / watt of the thermistor remains constant over a broad temperature range. However, as the temperature decreases, the thermistor resistance tends to increase, making it necessary to adjust R_2 to apply a higher voltage across points A and B in Figure 20. Therefore the current through the meter due to a given change in thermistor resistance is greater at a lower temperature because of the higher voltage across the input. If the resistance of the meter M_1 could be automatically changed, then the bridge sensitivity could be held constant over a large room temperature change.

Since the sensitivity increases with a decrease in temperature, the variation in sensitivity could be compensated for by increasing the meter resistance as the temperature decreases. Since thermistors have this characteristic increase in resistance with a decrease in temperature, a disc type thermistor in series with the meter, would give the desired compensation.

To avoid the higher cost of a special thermistor for meter M_1, in order to obtain the correct rate of change of resistance with temperature, resistors are added in series and parallel with meter thermistor T_2. Figure 21 shows the meter thermistor circuit details.

The preceding compensation does not compensate for the need of zero adjustment with temperature changes. For continuous operation of the bridge, potentiometer R_2 would have to be reset before each measurement, unless the ambient temperature is constant. Thus an automatic method of increasing the current through T_1 with decrease in temperature is required.

If a disc type thermistor whose resistance increases with decreasing temperature were placed in parallel with the bridge, more current would flow thru the bridge at a lower temperature because the ratio of the shunting thermistor resistance to the bridge resistance (resistance AB, Figure 22) is greater at a lower temperature. This is shown in Figure 22. The resistors are used in series and parallel with the thermistor as explained previously.

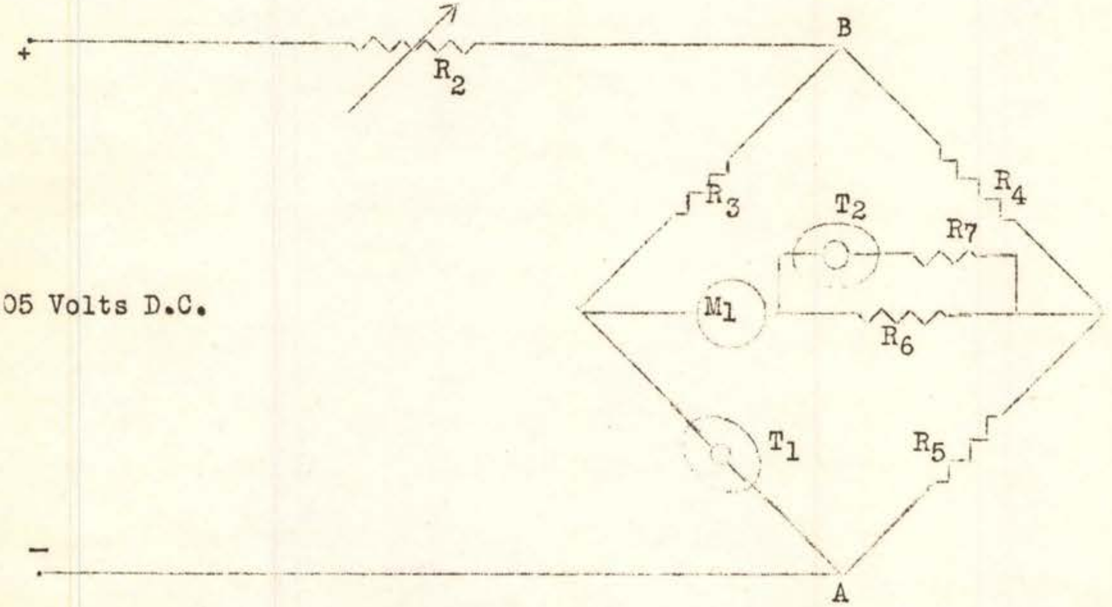


Figure 21 : Details of meter sensitivity thermistor.

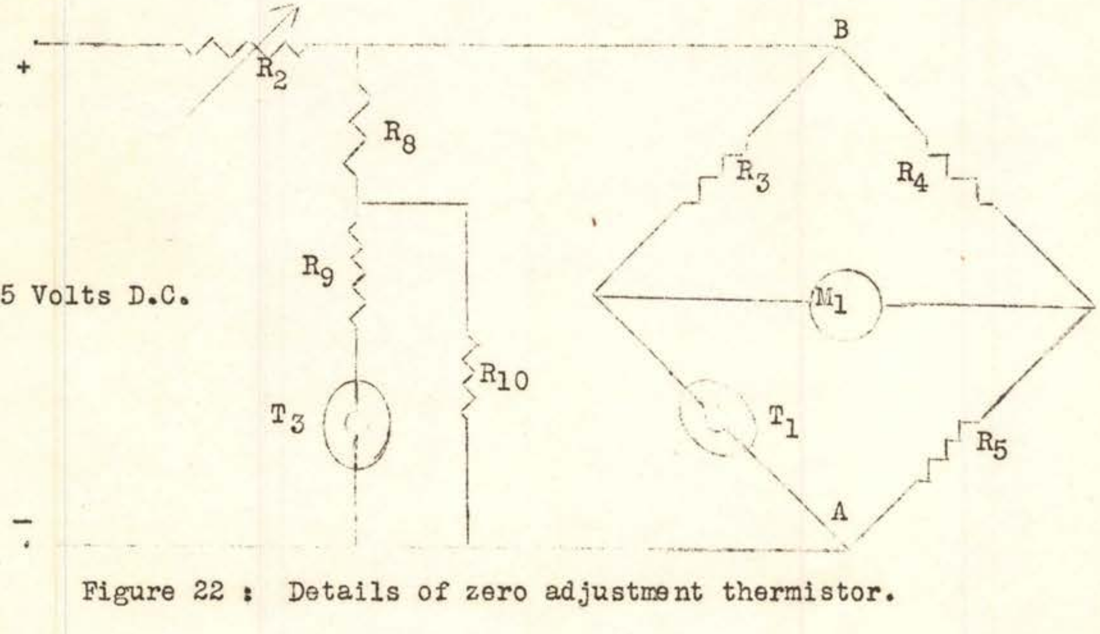


Figure 22 : Details of zero adjustment thermistor.

The complete electrical bridge circuit with numerical values is shown in Figure 23. The input D.C. voltage should be from a regulated power supply similar to power supply No. 1, but with a 200 volt output and the negative terminal grounded.

Thermistors T_1 and T_3 are physically constructed so that one lead may be grounded. Thermistor T_2 is a disc type thermistor similar to T_3 except that due to its electrical connections, both leads are ungrounded. T_2 and T_3 are placed as close as possible physically to T_1 so that the ambient temperature of T_1 will affect the compensating thermistors.

The thermistor bridge circuit has the advantage over the circuits given previously in that when properly calibrated, the actual power output of the klystron may be measured. Item 9 (Figure 17) is a detuning stub incorporated in the physical wave guide system. When pushed and locked so that the probe extends in the wave guide, the frequency measuring portion of the circuit draws negligible power from the main wave guide. Since the remainder of the coupling impedances are matched, all of the klystron power is used in heating the thermistor T_1.

In working with frequencies of the order 9×10^9 cycles per second, tolerances cannot be made ± 0 %. Rather than try this, it is easier to build the set-up using elements of a very close tolerance and then calibrate the set. This system may be used with the thermistor bridge. By removing the klystron probe from the wave guide and inserting in its place the probe from a calibrated signal generator, the actual power fed into the wave guide is known. Thus the actual bridge meter reading can be calibrated against the known power and a calibration chart drawn. R_{11} is placed in parallel with meter M_1 so that the calibration chart may be drawn on an easy to read scale.

If dynamic characteristics for relative power are desired, then the meter

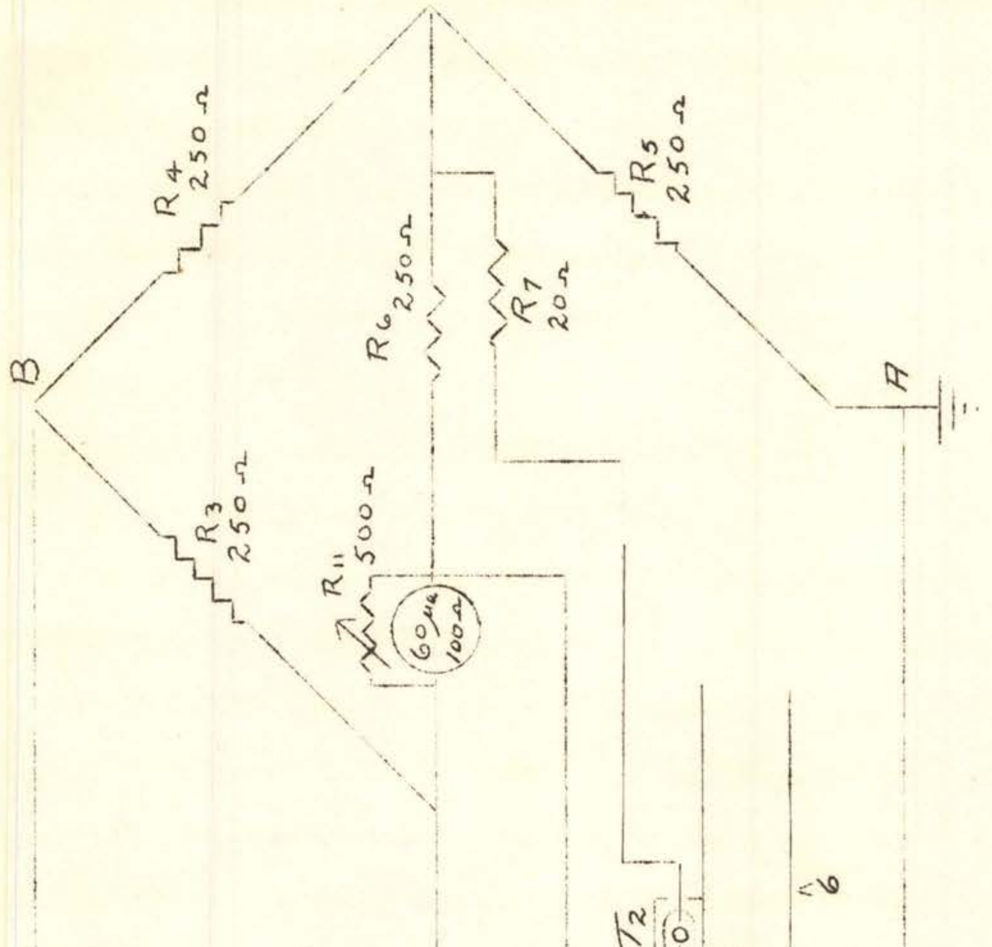


Figure 23 : Complete electrical circuit for thermistor bridge.

M_1 should be replaced by a 70 ohm resistor. The vertical oscilloscope leads are connected across this resistor. Formerly the oscilloscope case was at ground potential, however, due to the electrical connections, the oscilloscope will now be approximately 3 volts D.C. above ground. To eliminate any possibility of circuit complications, the A.C. horizontal sweep voltage should be obtained from a separate secondary winding of the repeller modulation transformer. This will give the same oscilloscope pictures as referred to in the dynamic section.

The circuit does not lend itself to actual dynamic power measurements because of the oscilloscope calibration difficulties and internal wiring changes for the oscilloscope. Therefore this phase of measurement will not be further discussed because of the applications to be made of this paper.

Figure 24 shows the I vs E and I vs Resistance curves for the thermistor T_1. It can be seen from the curves that the resistance decreases almost linearly with the current, when the current is greater than 13 ma.

Since the bridge is to be balanced by D.C. and then subjected to R.F. power, the portion of the resistance curve to be worked with is below 250 ohms. This choice will keep operation on the inverse part of the I vs E curve.

For convenience, the D.C. balance point is located at 250 ohms or point A on Figure 24. This corresponds to a thermistor current of 14 ma. and a thermistor voltage of 3.45 volts. For the bridge to be balanced, the D.C. voltage BA (Figure 23) should be 6.9 volts D.C. The arrangement of R_1 and R_2 shown in Figure 23 enables the operator to select the bridge voltage. R_1 is for large variations in the supply voltage applied to the bridge, and R_2 is for zero adjustment necessitated by the ambient temperature.

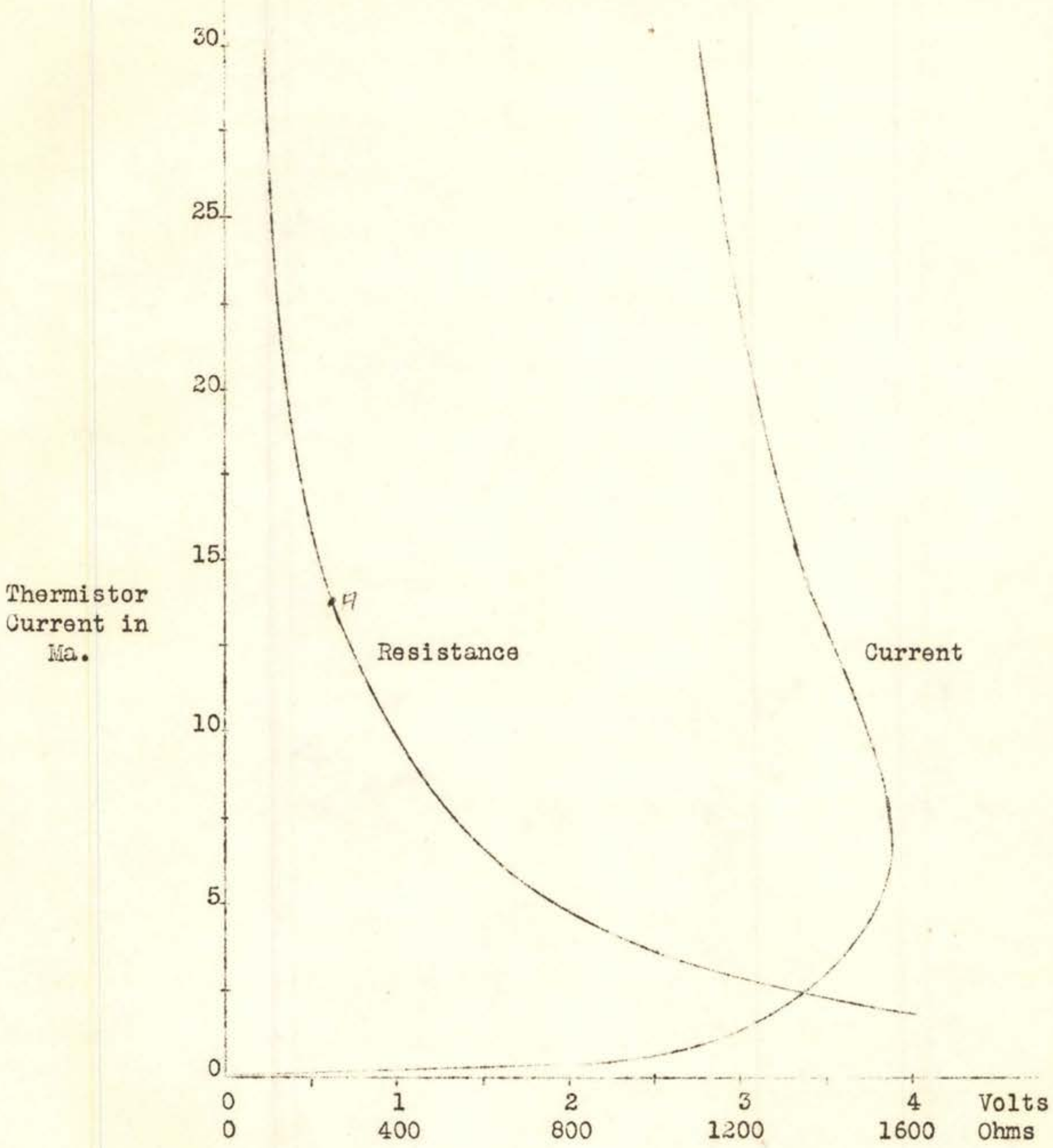


Figure 24 : Calibration of Thermistor T_1.

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William G. Worth Jr.