DESIGN OF DETECTION SYSTEM TO BE USED
WITH INFRA-RED SPECTROMETER

By
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PREFACE

Because of low energies available in the infra-red the detectors to be used must be very sensitive. The ideal detector would be one which counted each quantum of incident radiation. The most common method of detection in the infra-red is by heat detectors, such as bolometers and thermopiles. While these instruments will react to very small changes in temperature their efficiency is low and the subsequent output voltage from a thermopile is in the order of microvolts. This, of course, may be varied by allowing either more or less radiation to fall on the junctions. It has been attempted in this work to build an amplifier which will amplify this small signal up to one or two volts. Many problems interfered and not all of them have been solved. The following paper includes the work done toward eliminating these problems.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Professor Sherman W. Eager for his aid in procuring materials necessary for the construction of the apparatus; Professors C. Freemont Harris and Ralph Snyder for their invaluable supervisory aid in connection with the experimental work and the writing of this thesis; and to Mr. Ludwig Weigert for his aid in obtaining much of the data. Without their aid and encouragement this work would not have been completed.

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INTRODUCTION

In recent years much effort has been put forth to determine the instantaneous temperatures of high temperature sources. Spectroscopic measurements have been used widely for the investigation of the reactions occurring in flames. This work has been directed toward the determination of temperature by the proper analysis of infrared spectra.

However, to determine the temperature of the flame, the flame must remain stationary for extended periods or the detecting system must be able to measure and record the temperature in an interval of time in the order of a second. For this work a steady, high temperature source was used in hopes that the ensuing instrument could be modified to give the temperature of an unsteady flame.

For this source it was decided to use a tungsten filament. The spectrum and temperature of tungsten filaments have been thoroughly investigated and they are readily adaptable for our purpose.

INFRARED INSTRUMENTATION

Infrared instrumentation has many problems to combat. Materials which can be used for prisms, mirrors, and windows are very sensitive to atmospheric conditions (such as humidity) and are also very fragile. Yet these materials must be very transparent to infrared radiation since even the best sources are relatively weak in energy in the infrared. The most effective method to date for detecting infrared radiation is the use of a thermal detector, such as a bolometer or a thermocouple. The bolometer is a device which changes in resistance when subjected to a change in temperature. The thermocouple is a device which will develop an electromotive force between junctions when heat is applied. This signal may then be fed into an amplifier and recorded by some means. However, the sensitivity of the device is very low, and thus the temperature change in the detector is in the order of 10^{-5}°C.[1] With the temperature change being so small a potential of approximately one microvolt is set up in the detector. To amplify this low signal the amplifier must have a very high gain. This small change in temperature brings up another problem. If the temperature of the room in which the instrument is located is not constant, this ambient temperature will cause a drift in the instrument. Because of this drift the output of the

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[1] M. D. Liston, J. Opt. Soc. Am. 37, 515(A) (1947).

thermocouple depends not only on the intensity of the radiation to be measured but also on the temperature of its surroundings. However, if the desired radiation can be interrupted an a.c. voltage will be set up in the thermocouple. This will eliminate the effect of ambient temperature which only changes the average output of the detector.

THE OPTICAL SYSTEM

The optical equipment used in this experiment consists of a source of continuous radiation; a front surfaced mirror to focus the source on the entrance slit of the spectrometer; the infrared spectrometer, which is a monochromator and disperses the infrared radiation by means of a prism; and a mirror to focus the narrow band of nearly monochromatic radiation on the exit slit and the thermocouple.

The L235 Gaertner Infrared Spectrometer was the major instrument used in this work. This instrument has a collimating mirror and a telescope mirror. These are parabolic, off-axis mirrors especially designed to reduce spherical and chromatic abberation. This makes it possible to focus the instrument with visible light and have it remain in focus in the infrared. The mirrors are also gold surfaced to reduce absorption of the radiation. Adjustment of the mirrors is done by three screws on the back of the mirrors. However, the readjustment of internal stresses set up in the chassis will cause the instrument to drift out of alignment. It was necessary to check this periodically. The method of alignment of the instrument can be found in data furnished by the manufacturer and will not be taken up here.

The spectrometer has two bilateral slits which are controlled by independent micrometer screws calibrated in .01 mm. and may be varied from 0 to 2 mm. For optimum operation the entrance slit should be curved slightly so that the emergent beam will be parallel to the exit slit, but this was not incorporated in the instrument used. When adjusting these slits the operator should take care to approach the desired width from the closed side to insure greatest accuracy.

A micrometer screw controls a Wadsworth mounting which controls the wave length or frequency that will pass through the exit slit. This mounting is a device using a prism and a plane mirror to obtain constant deviation. The mirror is a gold surfaced optical flat and rotates with respect to the prism. The scale attached to the screw reads directly in microns and has a range from 0.589 to 12 microns. In choosing the prism material the requirements of a prism in the infrared must be observed. It must be very transparent, have high dispersion for the wave lengths in the region to be studied, have a low index of refraction to minimize reflection losses, be uniform, unirefringent and economical. The material used in any case must represent a compromise between these.

Rocksalt, the material used in this instrument, is a unirefringent crystal with a wide range of transmission - 0.2 to 17 microns. Its index of refraction is acceptable and it occurs in nature in large quantities. However, it is easily defaced and is slightly hygroscopic, especially when subjected to temperature fluctuations. If the humidity is higher than 80% the material will dissolve. With 60% humidity the surface will become fogged and will not readily pass visible light. However, fogged windows transmit much better in the infrared than in the visible.[1]

The instrument has two baffles which are used to limit the amount of scattered light falling on the thermocouple and thereby being measured by the thermocouple.

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[1] J. J. Mcgovern, R. A. Friedel, J. Opt. Soc. Am. 37, 660 (1947).

THE DETECTION SYSTEM

The most difficult problem in any phase of infrared spectrometry is that of detection. This stems from the fact that the minimum power detectable at 4000 A° by a thermal detector is 10^5 to 10^6 times higher than that detectable by many other devices such as a photomultiplier.[1] Two of the major difficulties of detection are that the thermal detector must have a short response time and the amplifier must have a wide frequency-band-pass.

In its simplest form the response time of a thermocouple is the time necessary for it to dissipate the heat added. This time is a function of both the pressure and composition of the gas surrounding the thermocouple.[2] By using a pin-type thermocouple and evacuating it the Perkin-Elmer Company was able to get 90% of the maximum possible output when chopping the beam at the rate of 10 cycles per second. However, for optimum performance, the response time should not exceed 30% of the duration of each light pulse.[3] For maximum output from the Eppley thermopile used in this experiment the light pulse must last at least

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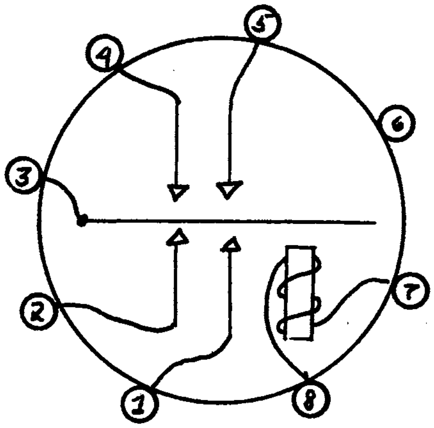
[1] P. J. Wheatley, E. R. Vincent, D. L. Rotenberg, and G. R. Cowan, "A Fast-Scanning Infrared Recording Spectrometer," J. Opt. Soc. Am. 41, 10 - 665 (1951).

[2] Instruction Manual for Infrared Spectrometer, Model 12C, The Perkin-Elmer Company, Glenbrook, Conn. (1949).

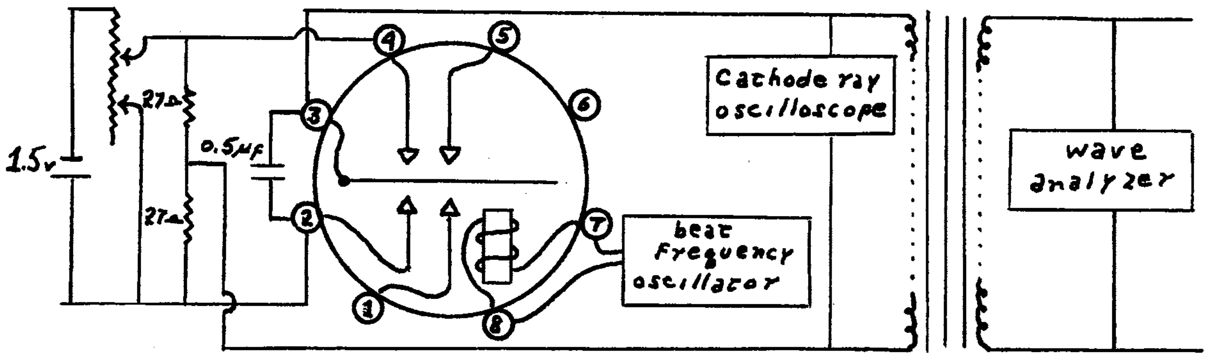
[3] D. F. Hornig, G. E. Hyde, and W. A. Adcock, "A Ratio-Recording Double-Beam Infrared Spectrophotometer with Automatic Slit-Control", J. Opt. Soc. Am., 40, 8, 497 (1950).

two seconds. If the thermopile is evacuated the time of the light pulse can be reduced to 2/7 of a second. Since this can exceed the time of the light pulse by 30% it is possible to chop the radiation from the source at the rate of five cycles per second. However, building an amplifier which would operate at such a low frequency did not seem feasible at this time and our attention was directed toward chopping the output from the thermopile. During the designing of the amplifier the output from the thermopile was replaced by a voltage divider circuit and a dry cell battery. From this voltage divider circuit was taken a voltage in the order of one microvolt.

The chopper used was the Western Electric mercury contact relay No. 276 F. It is a hermetically sealed mercury wetted contact type of switch. This type of switch insures clean contacts at all times and nearly instantaneous break of contacts both of which are necessary to decrease noise. This switch has a permanent magnet bias which permits the chopper to be factory adjusted. The switch is called a biased relay when the magnet is adjusted so that the relay will release when the current through the winding is equal to zero. Following is a diagram of the 276F:



The instrument has polarized operating characteristics which allows it to follow any periodic voltage applied to the windings of the core within 60 - 100 c. p. s. The highest rate depends upon the applied voltage and wave form. The amplification of the input transformer to be used was determined. The step-up was in the order of 145 and the method used to measure this will be discussed later. With this information and using a beat frequency oscillator to drive the armature and a wave analyzer to measure the output from the input transformer it was determined that the noise level of the chopper could be lowered to below four microvolts. By putting the output from the chopper on the scope it could be seen that the output was nearly a square wave and that the armature dwelled almost equal time intervals on each set of contacts. Below is the diagram of the chopper and accompanying components used for the measurement.



The next phase of the problem consisted of building an amplifier circuit to amplify the output of the detector. The first consideration at this point was the available signal output from the thermopile. This was calculated to be approximately one microvolt using maximum deflection from a Leeds and Northrup No. 2284 galvanometer. This must be amplified until it becomes a sufficiently large voltage to be read on a meter or to operate a recording device. Since no amplifier had been designed to fit our exact purpose, it was necessary to design one. During the designing of the amplifier it was kept in mind that with only one microvolt signal the internal noise and pick-up must be kept to less than one microvolt. Chopping the output from the thermopile meant an a.c. signal and therefore an a.c. amplifier had to be built.

A voltage gain of approximately a million must be accomplished to amplify the signal sufficiently and this would seem to necessitate several stages of amplification. However, just previous to this work, the theory of the starved amplifier was published. If the screen voltage of a pentode is lowered below 10% of its plate-supply voltage and the resistance of the plate load increased 10 or more times beyond conventional values, the amplification factor of the tube is greatly increased in spite of a decrease of its mutual transconductance.[4]

W. K. Volkers, "Direct-Coupled Amplifier Starvation Circuits," Electronics, 24, 3, 127, (1951).

Because of this design and high gain it was readily adaptable to the problem and it was decided to incorporate this as one stage in the amplifier.

In order to design the amplifier it was necessary to know the characteristic curves of the tube to be used. The 6AU6 pentode was selected, but since the curves were not available for the tube operating under starved conditions, it was necessary to determine them. Following is the circuit used, data, and curves obtained from this work. The current, in microamperes, was read on a 0 to 100 microampere scale which was the lowest available.

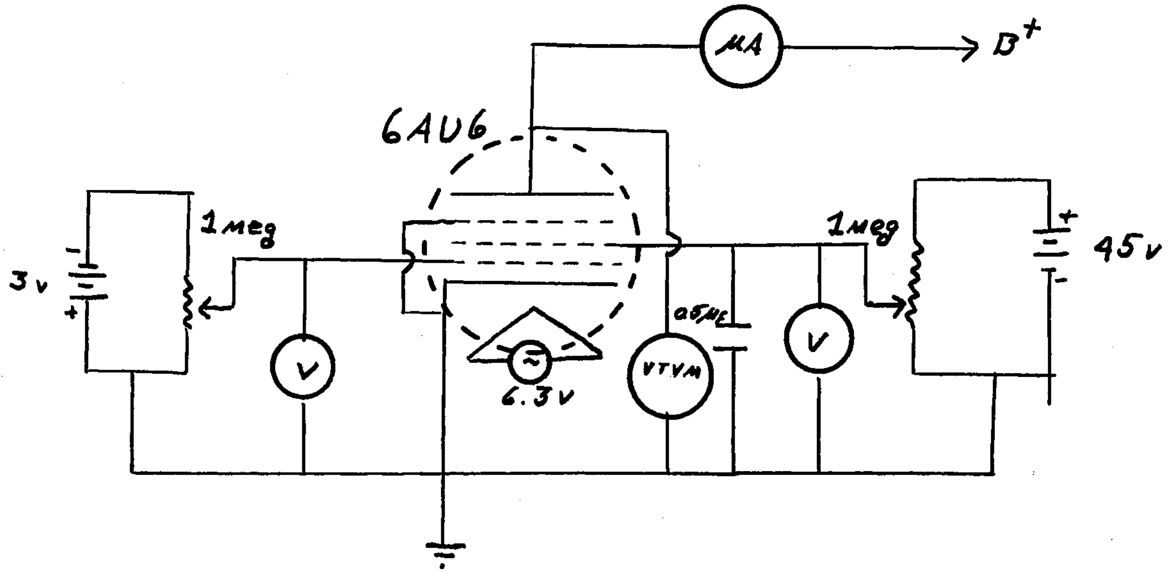


TABLE I

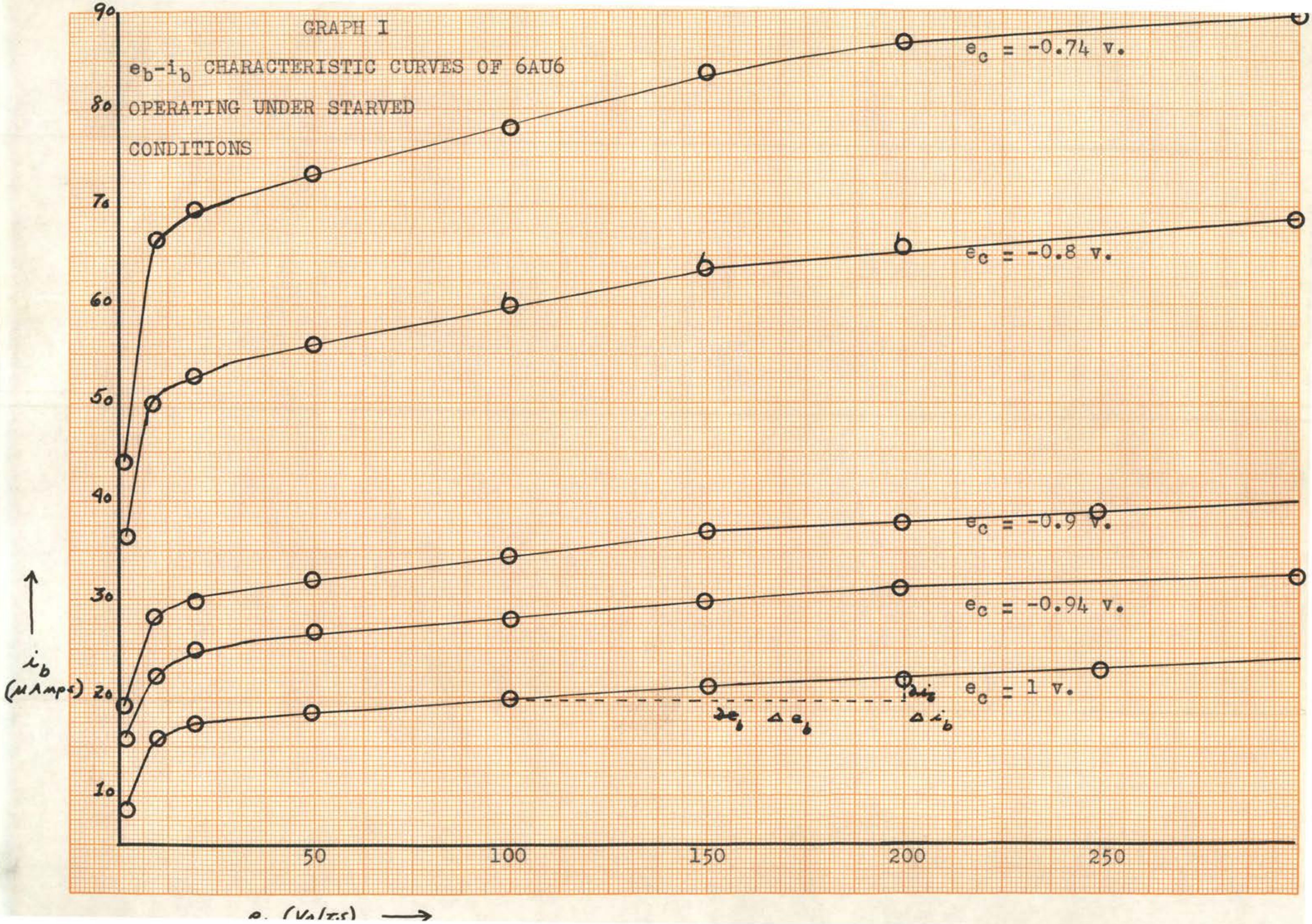
Data taken to determine dynamic plate resistance of a 6AU6 pentode operating under starved conditions.

$e_s = 15$ volts									
$e_c = 1$ v.		$e_c = -0.94$ v.		$e_c = -0.9$ v.		$e_c = -0.8$ v.		$e_c = -0.74$ v.	
e_b volts	i_b μamps	e_b	i_b	e_b	i_b	e_b	i_b	e_b	i_b
2	8	2	16	2	19	2	36	2	44
10	16	10	23	10	29	10	51	10	67
20	17.5	20	25	20	30	20	53	20	70
50	18.5	50	26.5	50	32	50	56	50	73.5
100	20	100	28	100	34.5	100	60	100	78
150	21.5	150	30	150	37	150	64	150	84
200	22	200	31.5	200	38	200	66	200	87
250	23	300	32.5	250	39	300	69	300	89.5

TABLE II

Data taken to determine mutual transconductance of a 6AU6 pentode operating under "starved" conditions.

$e_b = 100$ volts									
$e_s = 5$ v.		$e_s = 10$ v.		$e_s = 15$ v.		$e_s = 20$ v.		$e_s = 25$ v.	
e_c volts	i_b μamps	e_c	i_b	e_c	i_b	e_c	i_b	e_c	i_b
.46	89	.62	100	.77	85	.90	100	1.07	90
.50	67	.72	54.5	.81	76	.99	68	1.26	38
.58	44	.85	25	1.01	27	1.08	44	1.36	24
.66	23	1.02	9	1.14	12.5	1.22	22	1.49	12.5
.77	11	1.22	4	1.27	7	1.34	12	1.63	7
.85	6	1.53	2	1.42	4	1.42	8	1.71	5
.92	4			1.6	3	1.50	6	1.80	4
1.02	2.5					1.60	4		

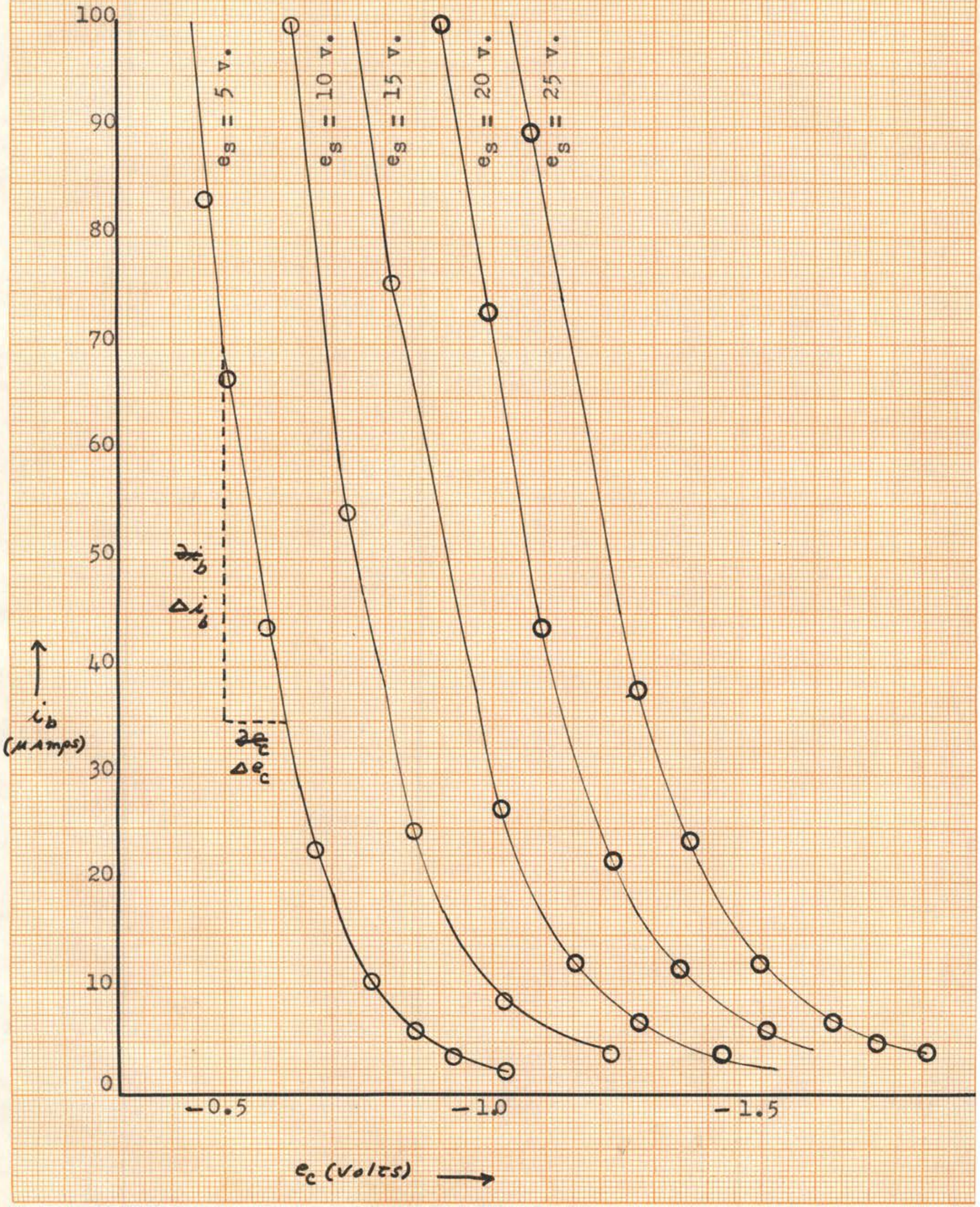


GRAPH I

e_b-i_b CHARACTERISTIC CURVES OF 6AU6 OPERATING UNDER STARVED CONDITIONS

GRAPH II

e_c-i_b CHARACTERISTIC CURVES OF 6AU6 OPERATING UNDER STARVED CONDITIO



With the above curves it was possible to determine the tube characteristics.

Mutual transconductance $(g_m) = \left.\frac{\partial i_b}{\partial e_c}\right|_{e_b}$ fixed

From graph: $g_m = 330$ micromhos

Plate resistance $(r_p) = \left.\frac{\partial e_b}{\partial i_b}\right|_{e_c}$ fixed

From graph: $r_p = 75$ megohms

Voltage amplification factor $(\mu) = g_m r_p$

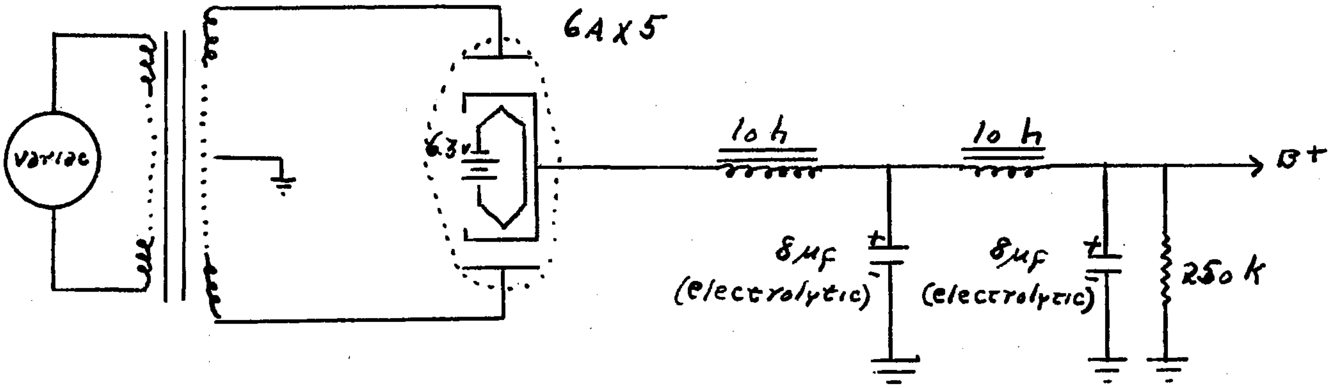
From computation: $\mu = 24{,}750$

By way of comparison, values for "g_m" and "r_p" for a 6AU6 operating under typical conditions are 4000 micromhos and 0.5 megohm respectively.

It was decided to use about 200 volts on the plate of this stage. With a plate load resistor in the order of 20 megohms and a desired plate current of 20 microamperes there would be a potential drop across this resistor of approximately 400 volts. This necessitated the construction of a 600 volt power supply. A full wave rectifier was built using a transformer with 300 volts on either side of the center tap. The original design contained a 6X5 rectifier tube and since the highest output voltage obtainable was desired, a capacitor input filter was used. However, as the work progressed, the input capacitor broke down and the transformer was damaged. A new transformer was purchased with 900 volts a.c. output and, with ample voltage available, the filter was converted to a choke input design.

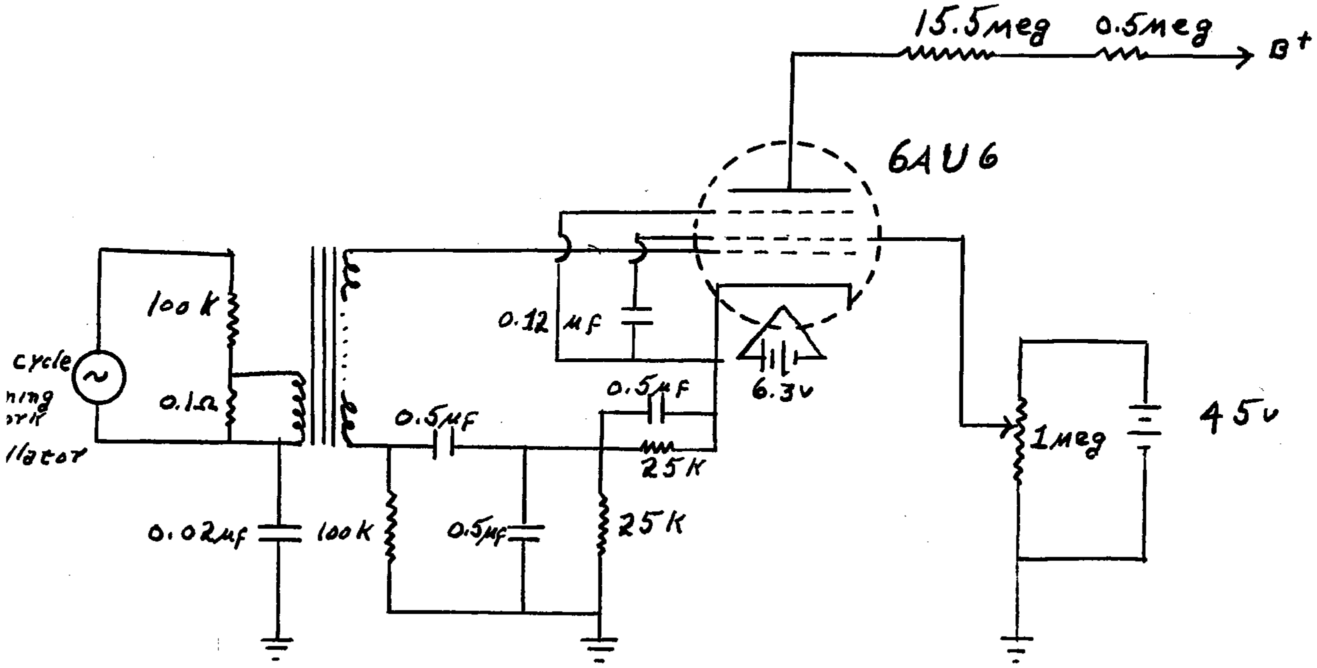
Also, the 6X5 rectifier tube was replaced by a 6AX5 because of the latter's higher ratings. It was also decided to use d.c. for heating all filaments, thus reducing the possibility of 60 cycle pick-up and also avoiding difficulties due to high voltages between cathode and filament.

The power supply was fused at 2 amperes in the input to protect against further break-down and, with the input taken from a variac, the power supply was complete. Following is a diagram of this finished power supply.



With characteristic curves plotted and the power supply completed work started on the amplifier. In order to provide a higher signal on the grid of the first stage it was decided to use a United Transformer Company LS-14 transformer at the input. Tests were run to determine the gain of this transformer. By using a 1000 cycle tuning-fork oscillator and a voltage divider circuit at the input to the transformer and a General Radio wave analyzer at the input and the output the gain was determined to be approximately 145. This transformer is well shielded and the greater part of the pick-up will come from the leads to it. Thus, these leads should be interwound and kept as short as possible.

Using the characteristic curves the operating point was chosen and the value of the components computed. Following is the diagram of the first stage and input transformer.



The cathode bias resistor gives -1.2 volts bias and the screen potential is taken from a battery. This potential was taken from the cathode resistor of the second stage in the final arrangement. The plate load resistor in this stage was varied to determine the best value appropriate with the other values. Sixteen megohms gave the best amplification. However, this led to the problem of measuring the a.c. and d.c. voltages across this high plate load resistor, since the internal resistance of the vacuum tube voltmeter available is only 11 megohms and would therefore shunt 16 megohms appreciably. For this reason, the one large resistor was replaced by a 15.5 megohm resistor and a 0.5 megohm resistor allowing the output to be measured across the 0.5 megohms with reasonable accuracy. This reading was then multiplied by 32 to give the total drop across the plate load resistor. Another problem arising was the measurement of the d.c. plate voltage. The d.c. resistance of the tube, operating under starved conditions, is in the order of the resistance of the vacuum tube voltmeter. Therefore the d.c. plate voltage could not be measured directly. To obtain the value of this voltage the power supply was measured and the drop across the plate load resistor subtracted from this B^+ value. Following are the approximate values obtained in the first stage.

$B^+ = 600$ v
$e_b = 225$ v
$e_c = -1.2$ v
$e_s = 20$ v
$i_b = 20\,\mu A$

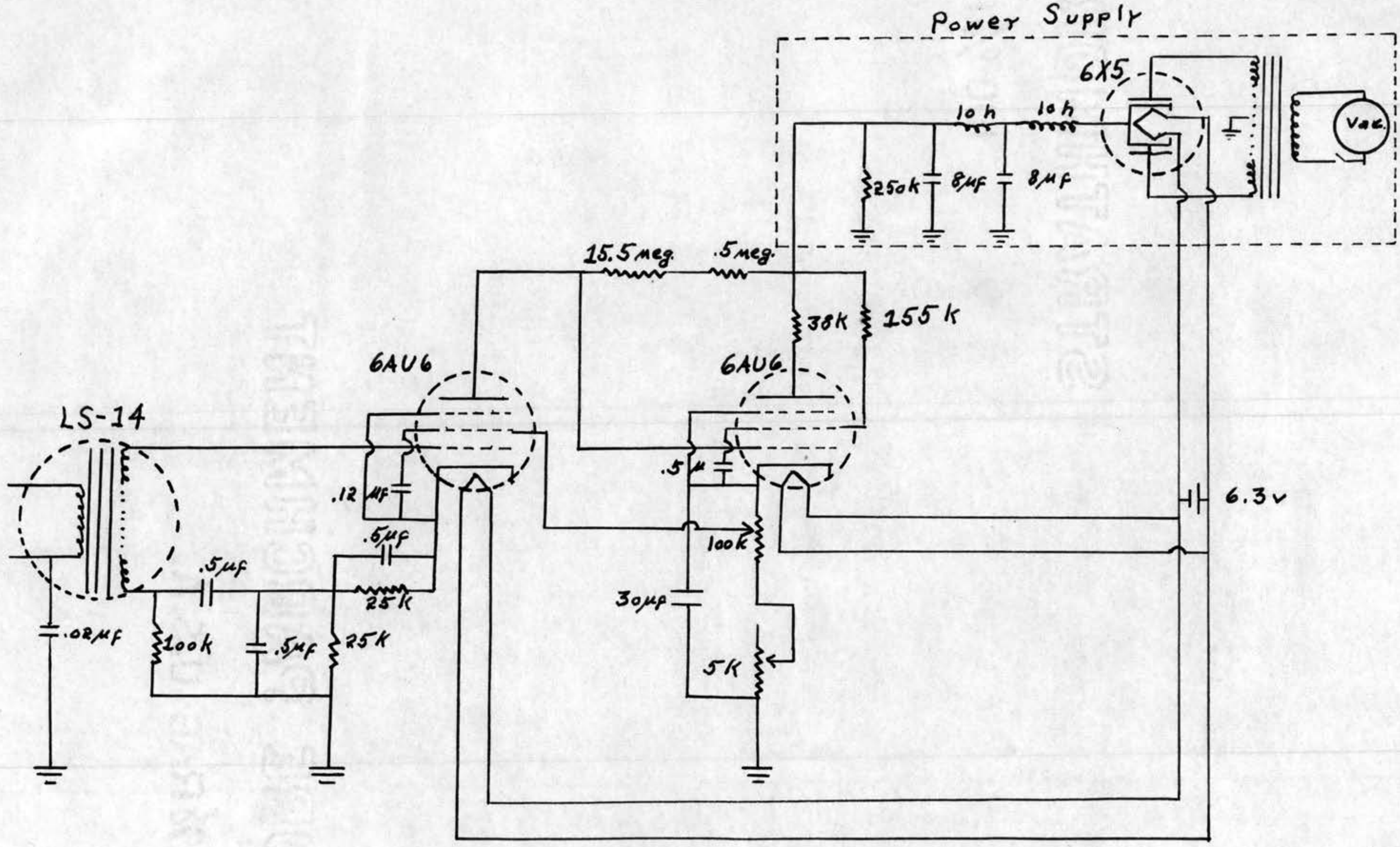
It should be pointed out that the value of e_b may not be considered as accurate as the other values because of the afore mentioned difficulties in obtaining this value.

The second stage of the amplifier utilizes a pentode operating under typical conditions. The tube is the same as that in the first stage - 6AU6. At first the second stage was capacitance coupled and the bias was to be developed by the small leak of electrons through the tube base. But both the floating grid and the capacitance coupling were unsatisfactory since the operation was very unstable. The stage was then changed to a direct coupled amplifier. This meant that the grid of the second stage would be at the same high positive potential as the plate of the first stage. To develop a bias on this grid the cathode must be raised to a correspondingly high potential. Since this potential was not known accurately and the actual plate current could not be determined before the stage was in operation it was necessary to use a variable resistor in the cathode circuit. A second variable resistor was placed in this circuit so that the necessary screen potential for the first stage could be tapped off. With this voltage variable the total gain of the amplifier may be varied widely and the circuit can be made to oscillate by increasing the screen potential of the first stage.

This introduced another problem which is as yet not corrected. As the line voltage varies, the supply voltage follows. This brings about a change in plate voltage of the first stage and grid voltage of the second stage, and, consequently, a change in the bias. This varies the gain of the second stage. The solution to this is the construction of a voltage regulated power supply.

Many measurements were made at this point to determine the overall gain. These measurements showed little or no gain in the second stage of the amplifier. The reason was found to be inverse feedback due to inadequate by-passing of the cathode resistor. This was corrected by inserting a large by-pass capacator in the cathode circuit of the second stage. Then the gain was measured using only the two stages of the amplifier. This gain proved to be approximately 4000. This can be improved

Through the use of a voltage regulated power supply by at least a factor of two. The overall gain, including that of the input transformer, would then be well over the million mark which was the goal of the design. An accurate measurement of the gain will be difficult to obtain because of the inability to measure small values of input voltage. Following is a diagram of the completed amplifier.


Power Supply
6X5
10h
10h
Vac.
250k
8μf
8μf
15.5 meg.
.5 meg.
38K
155 K
6AU6
6AU6
LS-14
.5 μ
.12 μf
.5μf
.5μf
25 K
25 K
100k
.5μf
.02μf
100k
30μf
5K
6.3v

THE CALIBRATION STANDARD

If, in the final analysis, we are to determine relative temperatures, we must have some "standard" to calibrate our instrument. To gain this information a Leeds & Northrup galvanometer (2288) and an Epply thermopile were used in conjunction with the Gaertner infrared spectrometer. Since the temperature of the tungsten filament has been thoroughly worked out, this was used as our "standard."

Table III gives the information gained by varying the potential on the tungsten filament and recording the deflection of the galvanometer. As may be seen from Graph III the peak intensity of the tungsten filament shifts toward the visible wave lengths as the voltage is increased. From this graph the wave lengths of the peak intensities for each voltage given was estimated. With these wave lengths (λ_{max}) known the temperaturesin degrees Kelvin were computed from Wien's displacement law.

$$\lambda_{max}T = 0.2897$$

λ_{max} is the maximum wave length expressed in centimeters; T is the temperature in degrees Kelvin. This law assumes black body radiation and the tungsten filament, although not a true black body, is a very close approximation.

Using the estimated values of the maximum wave lengths and the computed values of the corresponding temperatures Table IV and Graph IV were constructed.

In order to construct a curve from which the temperature of any steady flame can be obtained it is necessary to plot deflection of the galvanometer against temperature of the tungsten filament. It is hoped that at a later date a correlation between the deflection of the galvanometer and the output voltage of the amplifier can be obtained. The values for Table V and Graph V were taken from Graph III keeping the wave length constant at 1.65 microns.

It should be pointed out here that although the tungsten filament is enclosed in glass, which does not pass readily infrared radiation beyond 3μ, this did not interfere with the experiment since the maximum energy output of the tungsten filament occurs below 3μ where absorption is negligible. During the course of the experiment it was discovered that the leads from the thermopile to the galvanometer must be interwound to reduce the pick-up from the earth's magnetic field to a minimum.

Both the entrance and exit slit widths were varied to determine the desired widths for this work. The slits must be wide enough to allow sufficient energy to fall on the thermopile to produce a readable kick to the galvanometer, yet the slits must be narrow enough to allow sufficient resolution of the wave lengths. The data and graphs following show the deflection of the galvanometer against the wave length, the relative change in the peak deflection with respect to change in voltage, and the relative temperature of the filament with respect to deflection of the galvanometer.

TABLE III

Data taken to determine effect of voltage on peak intensity of tungsten filaments.

Slit widths = 0.50mm.							
Wave Length (microns)	v = 70 d (in mm)	v = 80 d	v = 90 d	v = 100 d	v = 110 d	v = 120 d	v = 130 d
.8	5.5	7	10.5	13	16.5		
.9	10	12.5	19	23	26		
1.0	15.5	20	26.5	32.5	38		
.1	22	27	35.5	43.5	49		
.2	29.5	35.5	45.5	55	62.5		
.3	37.5	44	55	65	74.5		
.4	43.5	51	64	74.5	84		
.5	49.5	58.5	71.5	82.5	95	106	119
.6	53	62	77	88	100.5	113	126
.7	55	65	78.5	89.5	102	113	126
.8	54.5	63	76	87.5	98.5	110	121
.9	53	61	72.5	84	93		
2.0	50	59	68.5	77	85		
.1	46.5	55	63	71	80		
.2	42.5	51	58	65	73.5		
.3	37.5	46	51.5	58.5	65.5		
.4	33	39	44.5	50	56		
.5	27	30.5	36.5	41	46		

TABLE IV

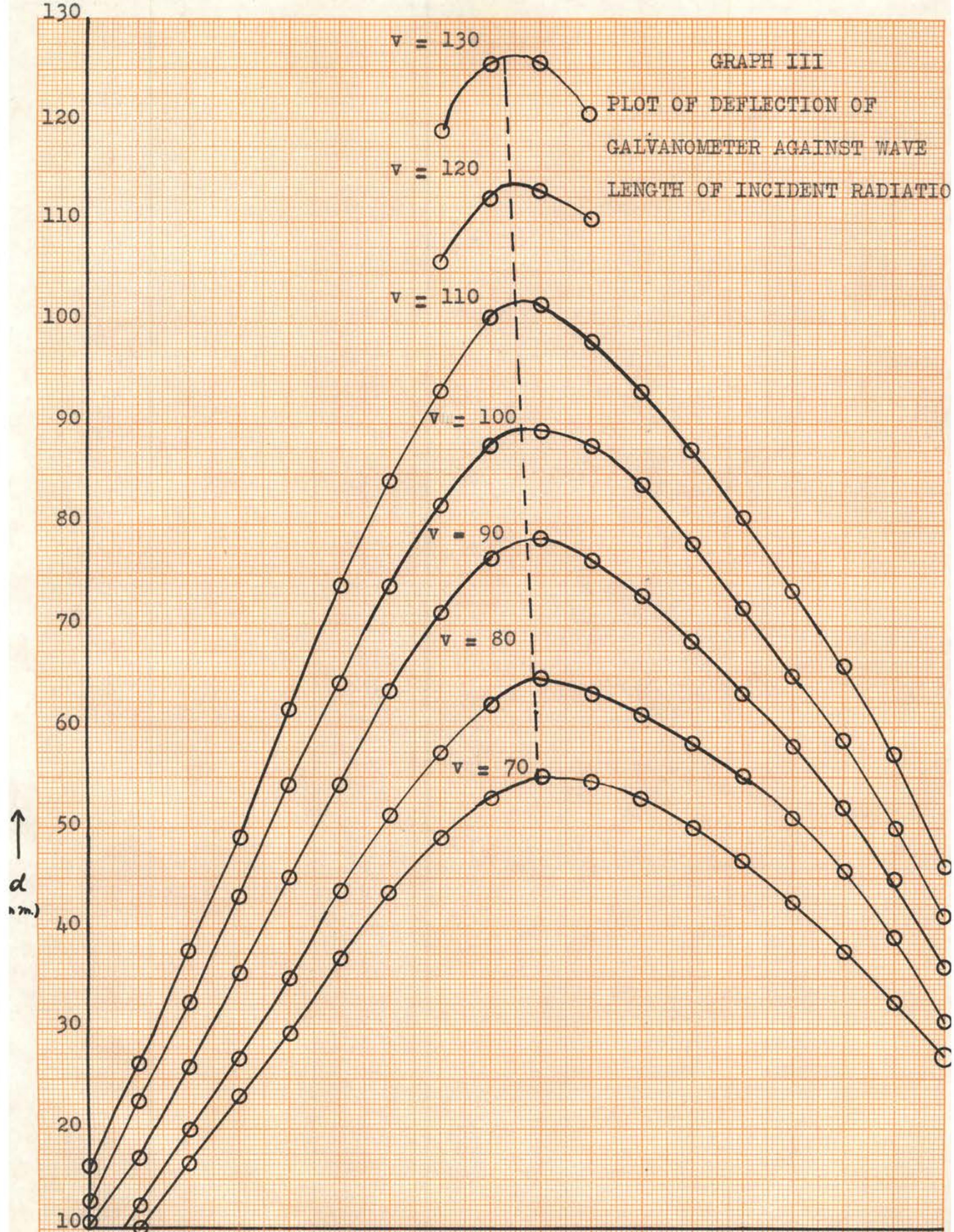
Data computed to determine temperature of tungsten filament at peak intensity.

voltage	λ_{max} (microns)	T (°K)
70	1.70	1705
80	1.69	1714
90	1.68	1723
100	1.66	1745
110	1.65	1756
120	1.64	1765
130	1.63	1775

TABLE V

Data taken from calculation of temperatures and corresponding deflection of the galvanometer at 1.65 microns for those temperatures.

T (°K)	d (in mm.)
1705	54.5
1714	64.5
1723	78
1745	89
1756	102
1765	113.5
1775	126.5

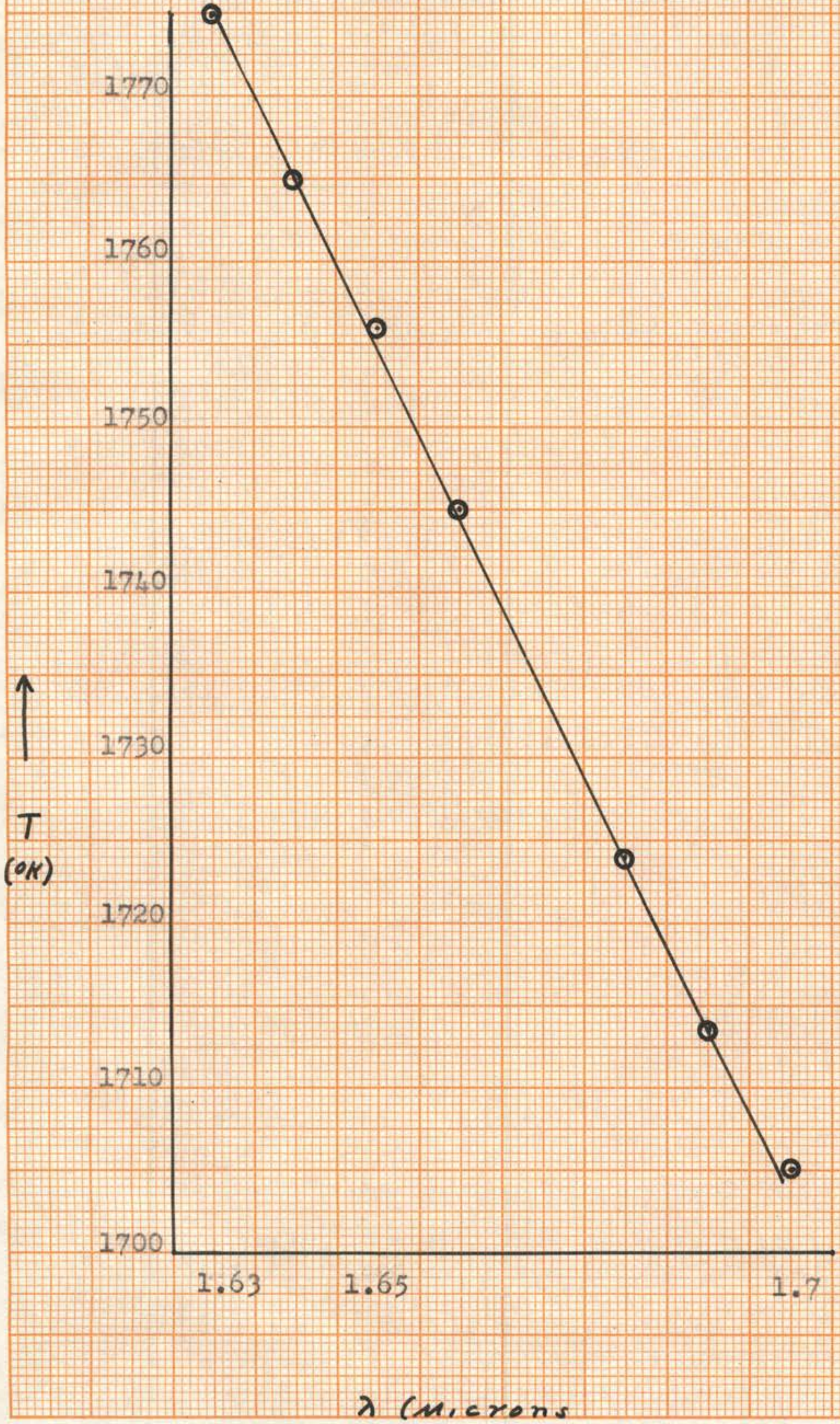


GRAPH III

PLOT OF DEFLECTION OF
GALVANOMETER AGAINST WAVE
LENGTH OF INCIDENT RADIATIO

GRAPH IV

TEMPERATURE OF TUNGSTEN FILAMENT AGAINST WAVE LENGTH OF MAXIMUM INTENSITY FOR THAT TEMPERATURE



GRAPH V

GALVANOMETER DEFLECTION AGAINST TEMPERATURE OF TUNGSTEN FILAMENT WITH THE WAVE LENGTH CONSTANT AT 1.65 MICRONS

CONCLUSION

The problem in this work was to build a high gain amplifier which would amplify a d.c. signal in the order of a microvolt. The methods of testing and construction are outlined in this paper. Not all of the problems have been answered but the author feels that by the use of a voltage regulated power supply, more refinements in the chopper supply system, and keeping all external leads as short as possible the amplifier may be made to amplify a one microvolt input without noise cutting out the desired signal.

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TYPIST PAGE

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