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Radiation Laboratory Magnet Regulations, Service and Operation

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RADIATION LABORATORY MAGNET REGULATORS, SERVICE AND OPERATION

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November 14, 1949

Berkeley, California

RAD[illegible] LABORATORY MAGNET REGULATORS,
[illegible] AND OPERATION

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Introduction

The present use of electro-magnetic fields in the cyclotron magnets, focussing magnets, beam turning magnets, and analyzing magnets have at times required a stability in the magnetic field of 1 part in 3,000 for an hour or more. Normally the magnetic hysteresis of the iron may be ignored, and assuming no magnetic saturation of the iron, the magnet current must be held to 1 part in 3,000 or 0.03 percent. If partial magnetic saturation of the iron is present, a larger variation of magnet current may be allowed and the field still held to the desired accuracy.

The four main causes of variation in a closed loop current regulation system are:

1. Variation in load resistance due to heating. The effect of load resistance change is reduced if ample loop gain is provided in the regulating system.
2. A change in the reference voltage. This will cause an error proportional to the voltage change, irrespective of the loop gain.
3. Transient line voltage changes which reflect in the generator voltage or in the regulator output. Here again, the stabilizing effect is a function of the loop gain.

4. Hunting of the regulator. Hunting is usually due to phase shifts associated with the time lags in the control system.

Stabilization

If magnet windings are allowed to have a 20 degree C rise in temperature, it will cause a 7.6 percent change in resistance. This requires a stabilizing factor of 250 to reduce the effect to 0.03 percent.

Fig. 1 shows typical values that might be needed in a regulating loop. This indicates that for typical values the amplifier voltage gain should be 125,000. Most of the voltage gain is required because of the small fraction of the output voltage at the shunt.

The present regulator 5Z1694A (Fig. 2) is an outgrowth of the regulator developed by Frank Trainor, and known as 2L2404A. The present regulator has four output voltage ranges; these are selected by the a.c. voltage applied to the plates of the final power stage. The following table shows the output voltages and gains that might be expected in each case.

A-c plate voltage input to final power stage	Rated d-c power output to field of generator	Max. voltage gain, inductive load
350-0-350	240 v at 5 amp.	1.5×10^6 v
*240-0-240	165 v at 5 amp.	1×10^6 v
*120-0-120	82 v at 5 amp.	0.5×10^6 v
60-0-60	34 v at 5 amp.	94×10^3 v

* See Fig. 3 for curves of regulator output voltage vs. a change in test shunt voltage applied to the input of the regulator.

Reference Voltage

The standard reference voltage must have a stability equal to or greater than that required in the magnet current to be regulated. It was found that VR105's that have been selected on a VR dynamic tester at their operating current of 17.5 milliamps have a better temperature stability than four aged Burgess Number 4F dry cells that were connected in parallel. The batteries will change 0.06 percent per degree centigrade; the VR105's are at least a factor of six better.

Voltage regulator tubes are known to have steps in their operation, but since the load on the VR tube is constant and is fed from a voltage regulated d.c. power supply, it is thought that the selected tubes will give no trouble.

It is recommended that the filament power be left on 24 hours a day to aid in the stability of the standard reference voltage.

Reference Voltage Controls

The reference voltage is controllable over two ranges by the control panel in Fig. 4; either of these ranges may be selected by a toggle switch on the regulator chassis. The low range controls from 0.2 mv to 51.5 mv. The high range controls from 1.4 mv to 564 mv. See Figs. 5A and 5B for a simplified diagram. The control consists of a coarse step control, and a continuous 25 ohm fine control that overlaps the steps of the coarse control. The range of the fine control is 3.1 mv on the low range and 35 mv on the high range.

In some cases, such as the constant frequency cyclotrons, a super fine control to cover a smaller range must be used. This is done by inserting a 25 ohm ten-turn helipot in place of or in series with the present fine control. See Fig. 17.

Transient Voltage

Changes in the line voltage feeding the induction motor would probably not be sufficient to effect the output of the generator.

The line voltage input to the regulator has been varied from 105 to 125 volts without effecting the regulation point of the regulator.

Hunting

The likelihood of hunting is reduced because the regulator output constitutes an electronic exciter with a very short time constant. If a rotating exciter were used, an additional time lag would be present. This would limit the allowable loop gain and require auxiliary damping and control devices to prevent instability.

In the event a rotating exciter is used, provision is made in the standard voltage circuit for introduction of a voltage feedback signal for reduction of hunting; see Fig. 6. This plug may also be used to introduce a correction signal from a device such as the proton moment field measuring equipment.

Operation of the Regulator

For the regulator in Fig. 1 to operate, it is necessary to apply a d.c. voltage E3 to the field of the generator that is some function of the difference voltage between a standard reference and the shunt voltage. The input section of the regulator (Fig. 2) is simplified in Fig. 6.

The output of the Brown converter transformer is approximately a square wave whose magnitude and sign is proportional to the voltage difference between the standard and the shunt voltage. This signal is then amplified in a push-pull two stage amplifier and applied to the grids of the thyratrons in the output stage. See Figs. 7 and 8. The signal on the grids of the thyratrons, FG-57, is then the sum of the amplified square wave and a phase shifted a.c. signal derived from the 60 cycle power system.

When the difference voltage between the standard and reference voltage is zero, the phase shifted a.c. grid voltage causes the thyratrons to fire at about 90 electrical degrees before the plate voltage goes to zero. When the standard voltage is higher than the shunt voltage, the firing angle is advanced so as to increase the output of the regulator; conversely, if the magnet current is too great, the firing angle is retarded. (See Fig. 3).

Regulator Testing

General

In Fig. 9 is shown a block diagram of the interconnections between the various chassis that comprise the regulating unit and generator field power supply. Care should be taken in connecting the power supply to the plate transformer of the final stage (Fig. 10) that points 2 and 5 of TS-1 of the power supply have the same instantaneous a.c. polarity. The regulator and power supply neutral is not tied to the regulator chassis, but normally has a one point ground at the shunt used as the input signal to the regulator. If a separate d.c. voltage source is used as an input signal for testing, it is necessary to ground the neutral of the regulator. (See Fig. 9).

Power Supply

The power supply in Fig. 11 furnishes the following power for the regulator chassis:

1. 5 v, 60 cps at 9 amp. total to filaments of FG57's.
2. 6.3 v, 60 cps at 1.2 amp. to filaments of 6SJ7's.
3. 115 v, 60 cps at 2 ma for phase shifted a.c. to grids of FG57's.
4. 6.3 v, 60 cps to Brown converter; this voltage has a phase shift control R11 that allows the converter.

voltage to be phase shifted ahead between +10 to +40 electrical degrees with reference to the input a.c. line voltage.

5. 250 v d.c., 17.5 ma to standard reference V1.

6. 250 v d.c. at 12 ma to plate and screen of the 6SJ7's.

   The regulated 250 v d.c. should regulate over a load range of 10 to 60 ma with an a.c. ripple not to exceed 0.005 v.

7. 350-0-350 v d.c. or less, depending upon the load, passes through the power supply from the power output transformer to feed the plates of the FG-57.

Regulator

The following voltages should exist on the various tubes as listed below when the regulator amplifier is powered with the interconnecting cable from the power supply.

	E Plate	E Screen	E Cathode
V1	105 v	--	0
V2	85 v	32 v	.6 v
V3	85 v	32 v	.6 v
V4	105 v	50 v	1.2 v
V5	105 v	50 v	1.2 v

These voltages should be within 10 percent when measured with a vacuum tube volt meter, but may be changed by selection of the 6SJ7's. (The phase shifted a.c. signal to the grids of the FG57's should lead their respective a.c. plate voltage by about 85 electrical degrees to give proper grid control of the thyratrons.)

The phase of the a.c. applied to the Brown converter should be shifted by adjusting R11 of the power supply, so that the time when the contacts of the converter are closed will coincide with the time the a.c. line voltage supplied to the power supply is zero.

Heater voltage leakage from the heater to cathode of the 6SJ7 amplifier tubes will cause an extraneous 60 cps signal to be applied to the grids of the thyratrons in the output stage. This pickup may be detected as distortion on the 60 cps grid signal of the thyratrons. To minimize this grid signal distortion, the following procedure should be used:

1. Turn the regulator amplifier attenuator to zero
2. Connect the scope to pin jack 1 or 3 of the regulator
3. Adjust the filament balancing resistor R28 to give minimum distortion on the a.c. grid signal of the thyratron

The relationships of the signal voltages existing in the regulator amplifier as compared with the a.c. line voltage may be seen in Fig. 6.

2-1/25 watt neons in series are used as a limiter to limit the positive excursion of the plates of the second stage of amplification. This is to limit the amount of power delivered to the grids of the FG-57.

Operational Test

The regulator is usually used to supply the field excitation of a generator that in turn furnishes the excitation power of a magnet. The input of the regulator is then a voltage supplied from a shunt that measures the magnet current. When a test is desired of the regulator system it is usually sufficient to supply a steady d.c. voltage to the regulator in place of the shunt signal, and if a generator field is not available, a resistance may be used as a load in place of the generator field.

The d.c. voltage input can be supplied from either of the circuits shown in Figs. 12A or 12B. Fig. 12A is satisfactory to check the functional operation of the regulator, but Fig. 12B should be used when a curve of regulator output vs. input is desired. This circuit (12B) allows a curve to be plotted on a direct coupled oscilloscope, thus making the plot in a short time, and thereby eliminating any correction factors due to battery drifts in the supplied d.c. voltage.

The controls on the control panel (Fig. 4) are used under the test condition to set the difference voltage between the input d.c. voltage and the standard reference voltage to within the operating range as shown in Fig. 3. For operation the difference voltage should be within ± 0.3 mv.

Fig. 3 indicates that the output curve of the regulator is dependent upon the load impedance angle. The two curves shown in Fig. 3 show the output for a resistance load and for a typical inductance load as found in the field circuit of d.c. generator. The inductive load gives a higher amplifier gain.

When the regulator is used in a regulating loop, the only ground of the regulator neutral occurs at the shunt through the shunt leads. The generator field circuit must not be connected to ground or spurious signals will be applied across the 100 ohm resistance that isolates the amplifier and output stage of the regulator and cause faulty signals on the grids of the FG-57's.

Applications

184-Inch Cyclotron Magnet

See Fig. 13 for an open loop voltage curve of the regulator as it now feeds the 552 kw M.G. set. A 1500 amp., 500 mv shunt is used. These curves show that over the normal operating range, the loop gain is approximately 750. This amount of loop gain will hold the magnet current well within the limits set up for this circuit. Any drift that occurs is probably due to variations in the standard voltage.

In one test the regulator reference voltage drifted down to 0.09 percent over an eight hour period. The ambient temperature around the VR standard raised 7 degrees C during the same time.

20 Kw M.G. Set

See Fig. 14 for a typical application of this regulator as used with a 20 kw portable M.G. set. The loop gain is approximately 500, depending upon the load and shunt resistance.

Analyzing Magnet, Building 10

See Fig. 15 for the characteristics of this circuit. The loop gain is 830 at the 36 amp. operating point of the magnet. This gain will reduce the effect of resistance variation during heating to 1 part in 10,000.

60-Inch Cyclotron Magnet

See Figs. 16 and 17 for the characteristics of this application. The loop gain is 100. It should be noticed that in this case an a.c. input voltage of 350-0-350 is used into the final thyratron stage. This loop gain might be a little low, but since monitoring of the field is necessary for optimum beam (the oscillator frequency changes with beam loading) it is thought that a loop gain of 100 would be sufficient.

Acknowledgment is gratefully recorded for the able assistance given the author by various members of the Electronics Maintenance Group, i.e., N. Fletcher, B. Jensen, C. Jones, J. McMorrow, and J. Mitchell.

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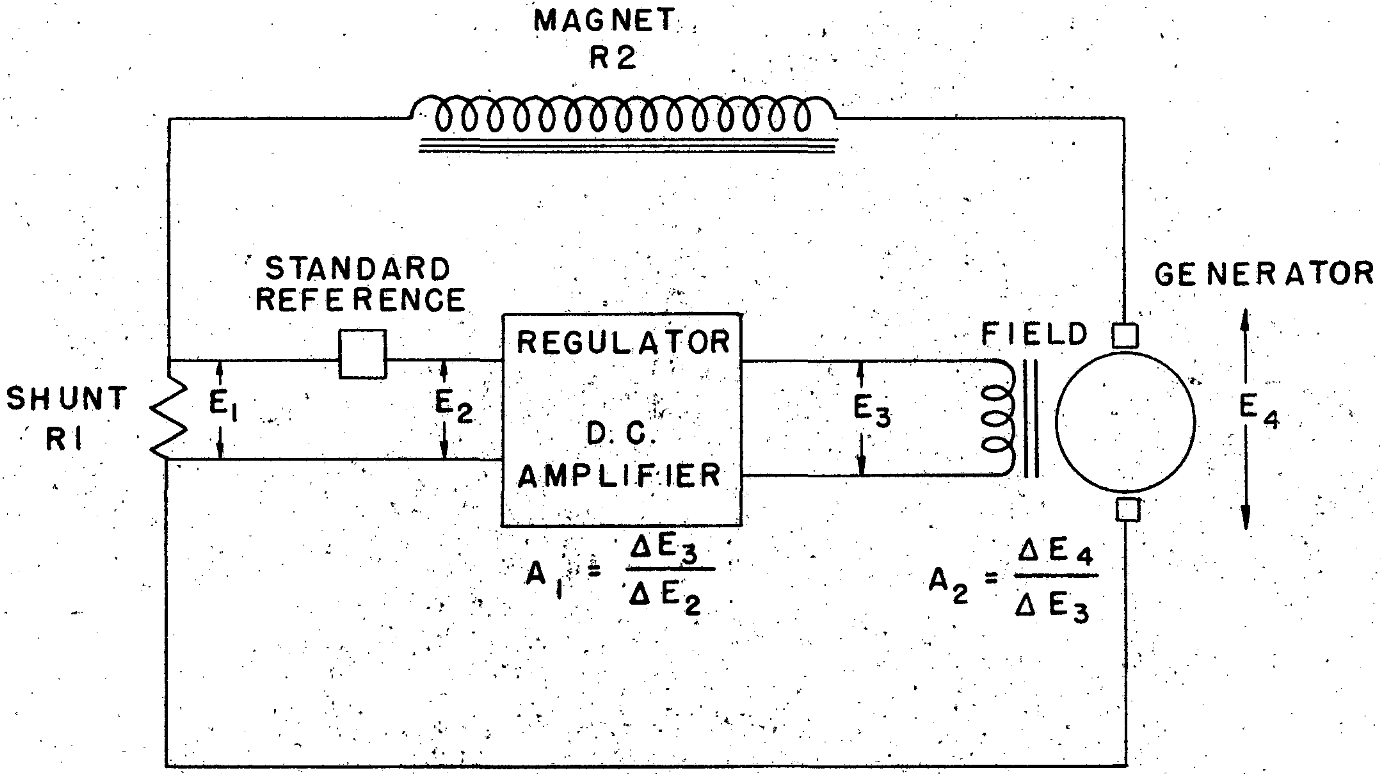
Information Division
ead/11-22-49

MAGNET REGULATOR
TYPICAL REGULATION LOOP



$$A_1 = \frac{\Delta E_3}{\Delta E_2} \qquad A_2 = \frac{\Delta E_4}{\Delta E_3}$$

$$\text{FEED BACK } A_f = \frac{\Delta E_1}{\Delta E_4} = \frac{E_1}{E_4} = \frac{R_1}{R_1+R_2}$$

LOOP GAIN $G = A_1 A_2 A_f$

STABILIZATION FACTOR $S = G - 1$

TYPICAL VALUES FOR $S = 250$

$A_1 = 125{,}000$

$A_2 = 2$

$A_f = 0.001$

SEE FIGURE 3

$G = A_f \tan \alpha$

FIG. 1

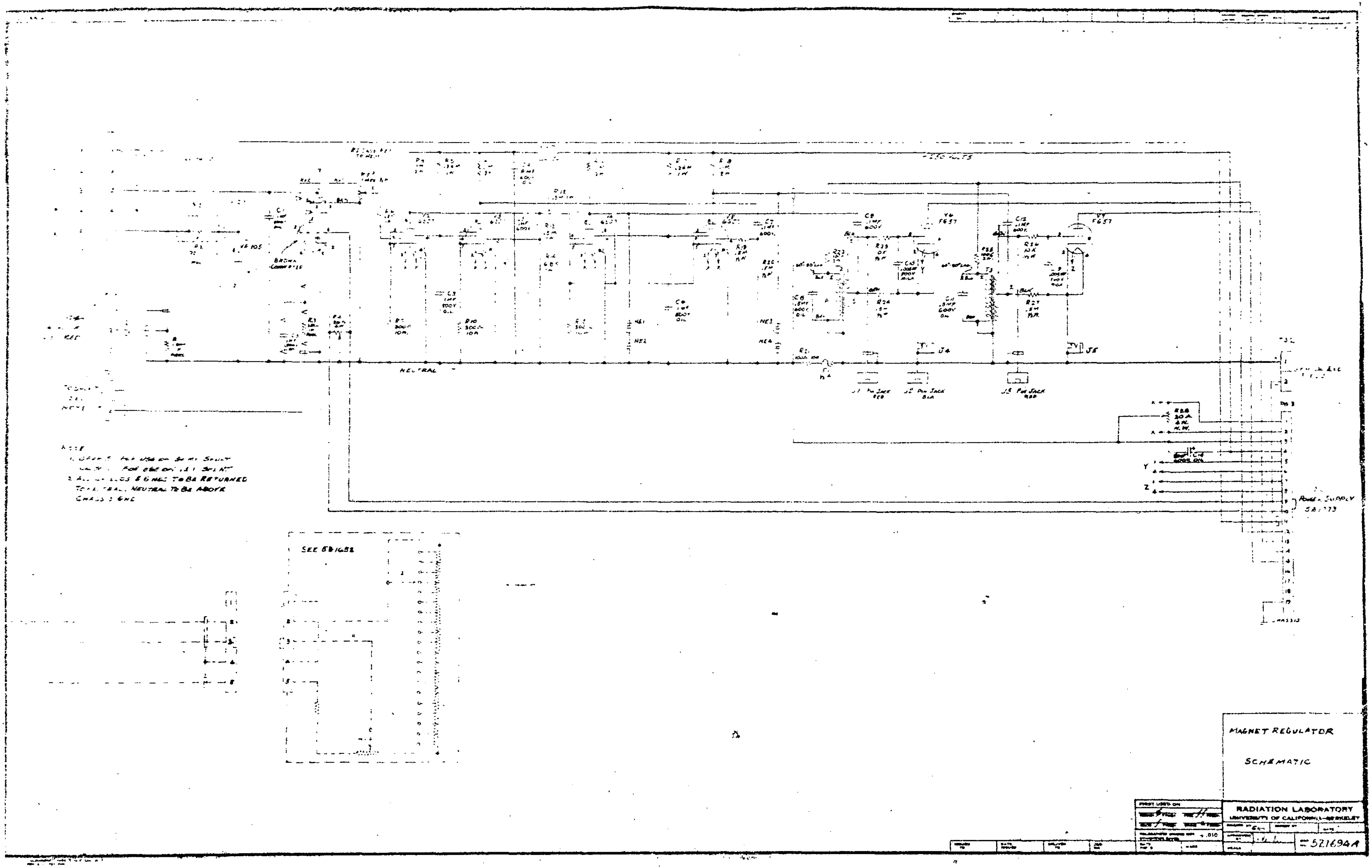

+250 VOLTS
NEUTRAL
BROWN CONVERTER
J1 PIN JACK RED
J2 PIN JACK BLK
J3 PIN JACK RED
J4
J5
SEE 5B1652
CHASSIS
NOTE
TO BE RETURNED
NEUTRAL TO BE ABOVE
MAGNET REGULATOR
SCHEMATIC
RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA—BERKELEY
± .010
FIRST USED ON
521694A

FIG. 2

MAGNET REGULATOR 5Z1694 OUTPUT vs INPUT

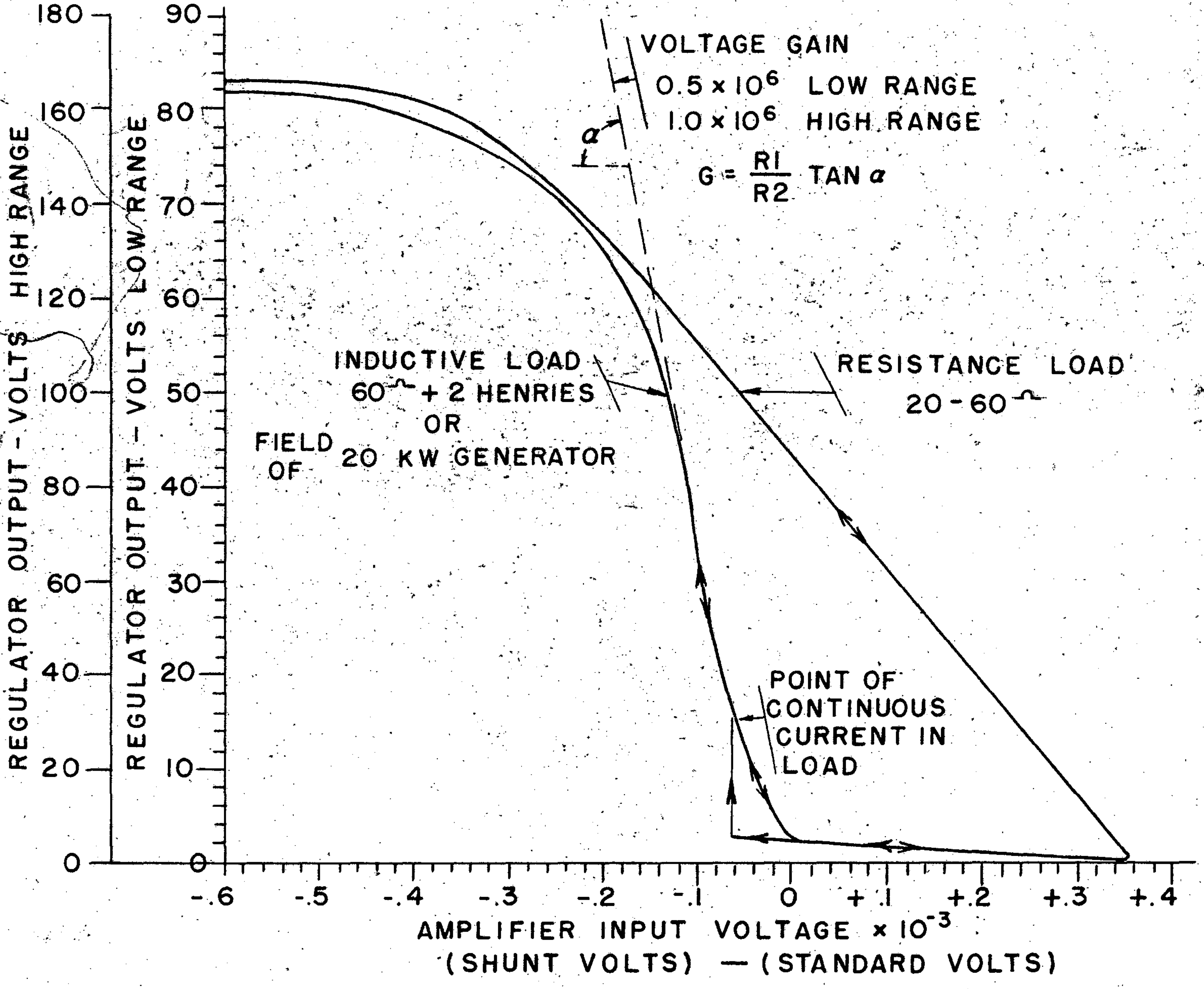


FIG. 3

SHOWN ON									CHANGE LETTER	DRAWN BY	CHECK BY	DATE	CHANGE
ISSUED TO	DATE ISSUED	DELIVER TO	JOB NO	DATE REQ'D	MAKE								

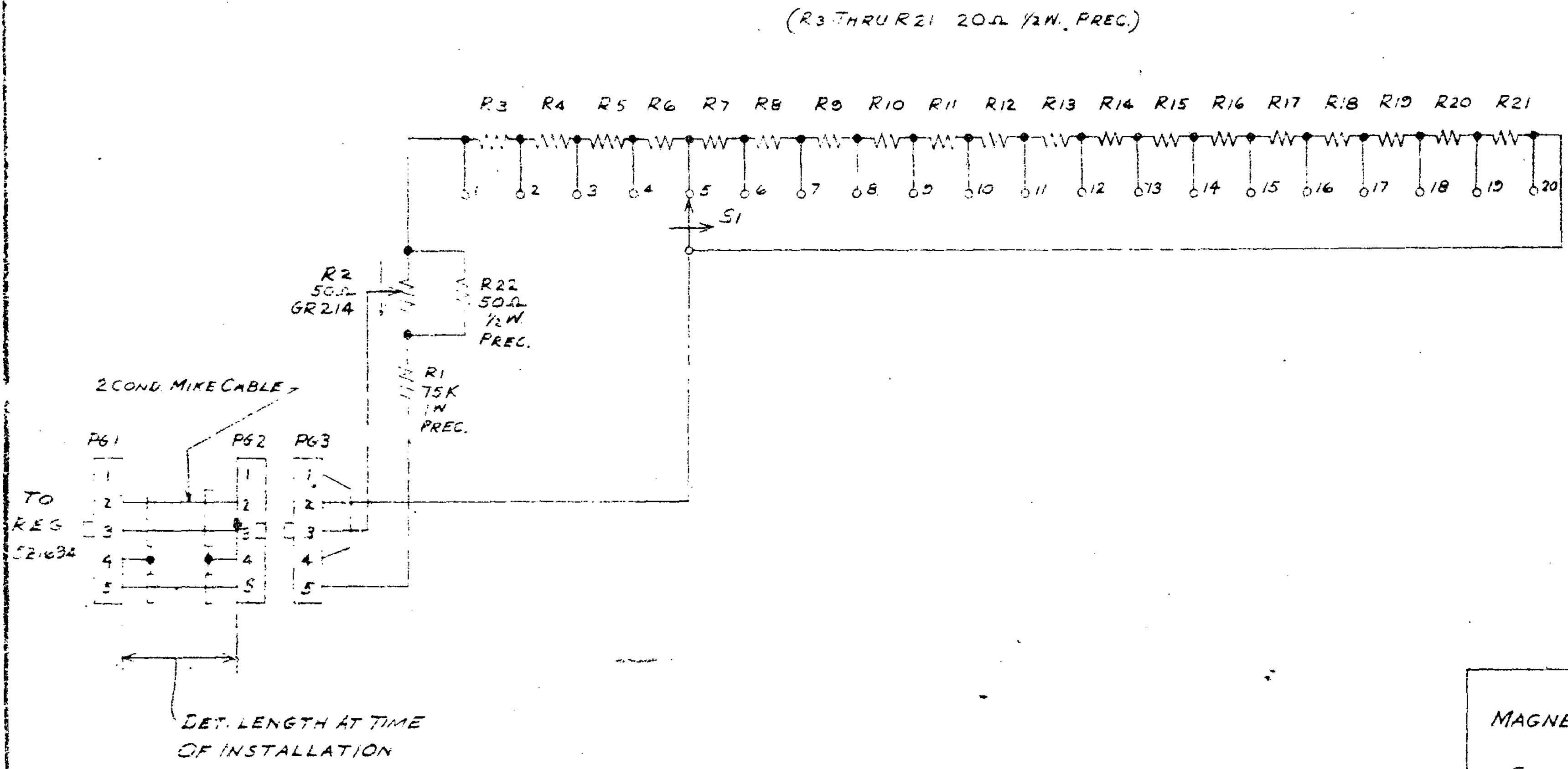


FIG. 4

MATERIAL

MAGNET REGULATOR

CONTROL PANEL
SCHEMATIC

RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA—BERKELEY

DRAWN BY	CHECK BY	DATE
APPROVED BY		DRG. NO. 5Z1652
SCALE		

ELEC. 1281

MAGNET REGULATOR 5Z1694
STANDARD REFERENCE VOLTAGE

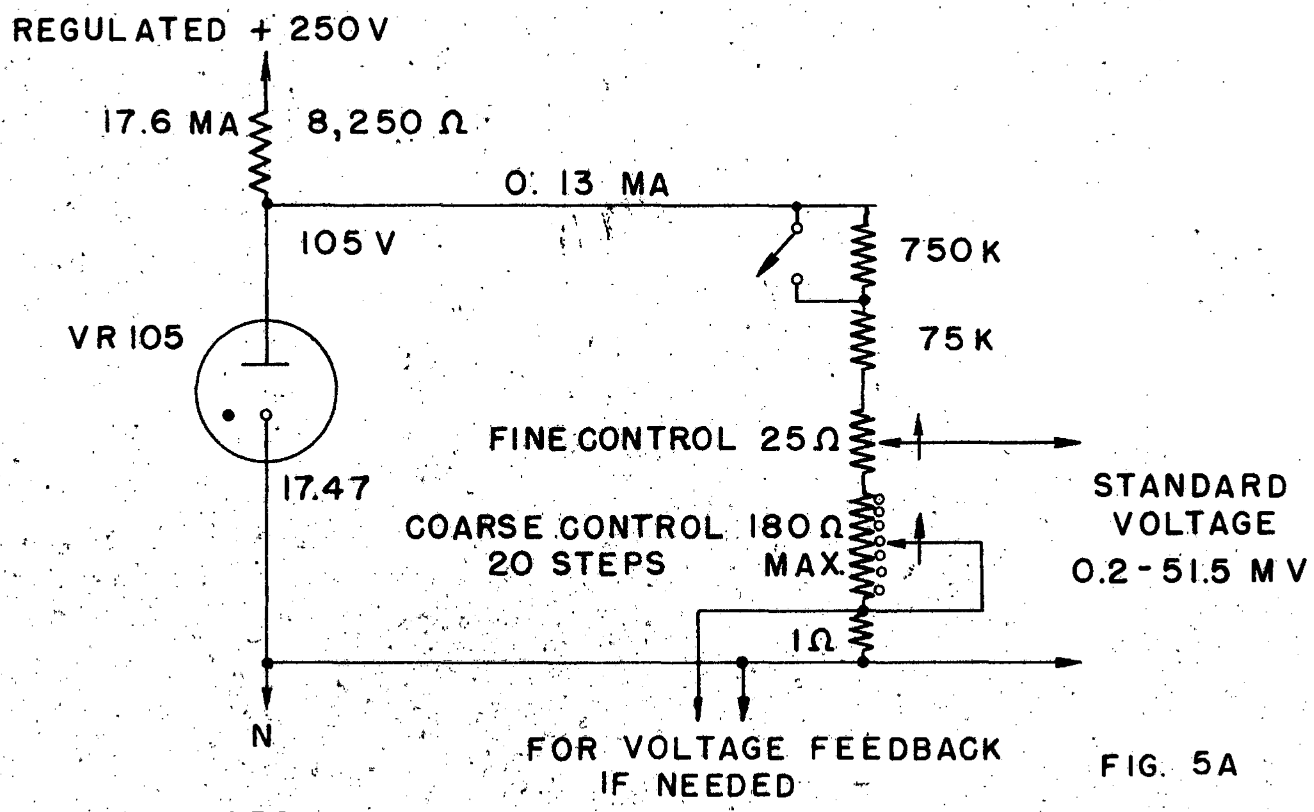


FIG. 5A

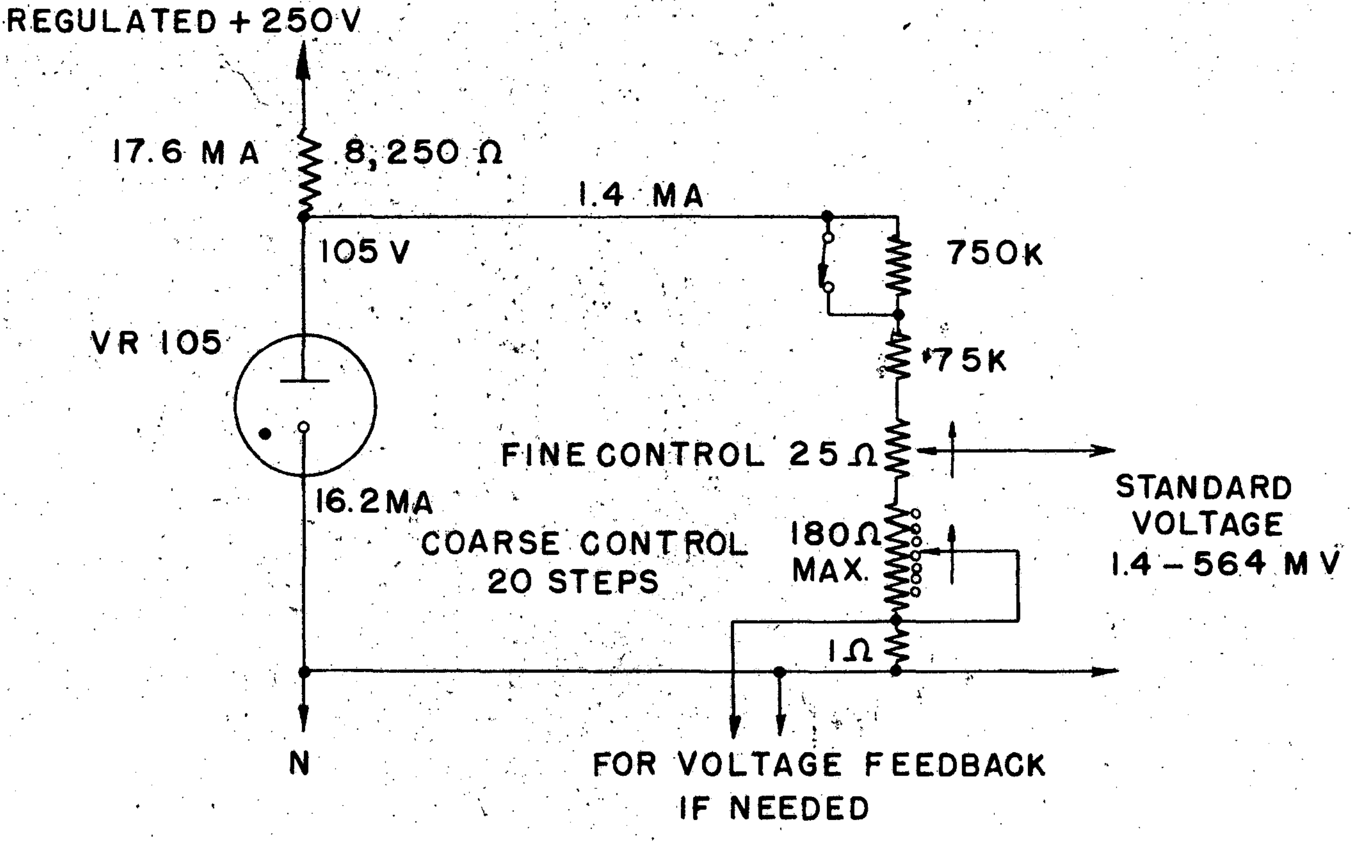


FIG. 5B

MAGNET REGULATOR 5Z1694 INPUT SECTION

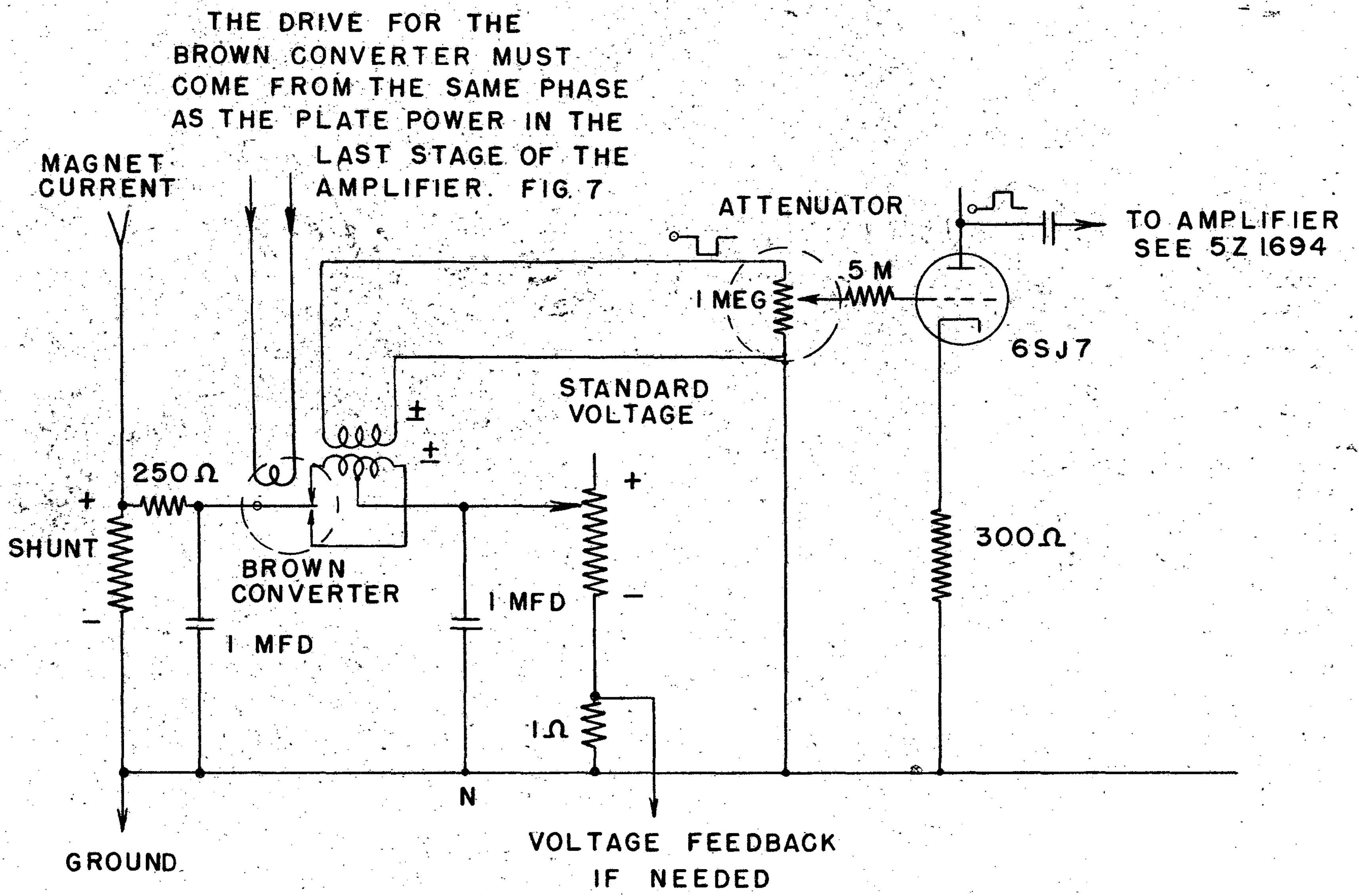
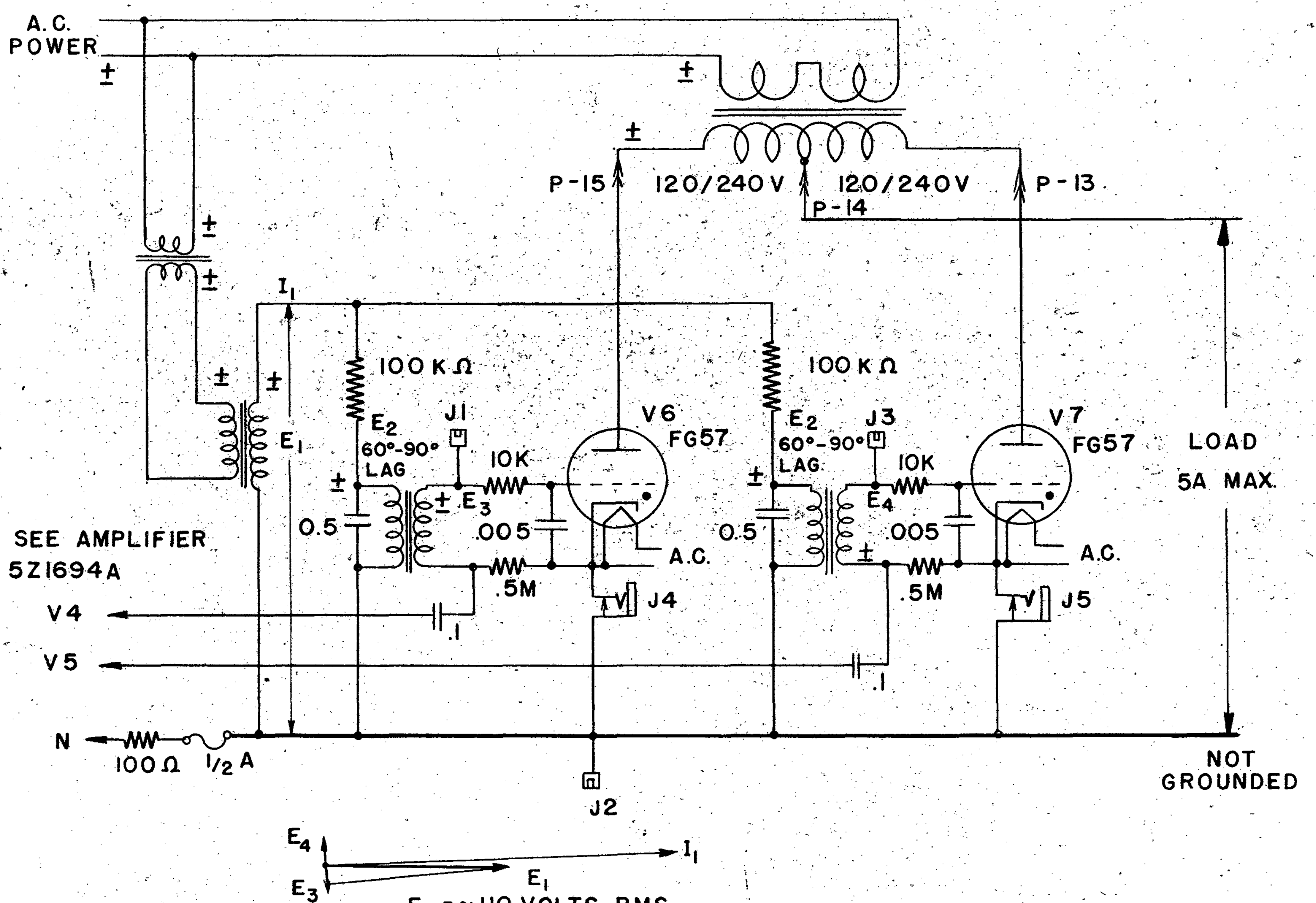


FIG. 6

MAGNET REGULATOR 5Z1694



E_1 = ~110 VOLTS RMS

E_2 = 7 VOLTS RMS

$E_3 = E_4$ = ~ 10 VOLTS RMS

FIG. 7

MAGNET REGULATOR 5Z 1694A 5Z 1773A

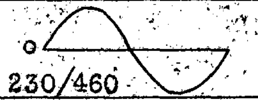
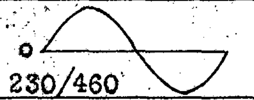
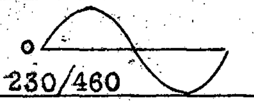
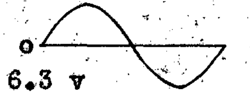
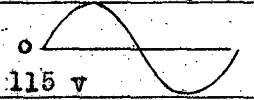
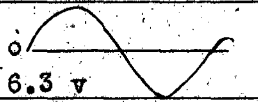
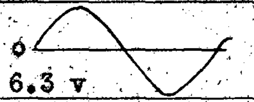
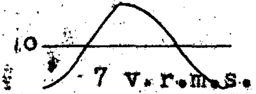
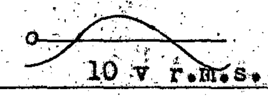
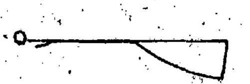
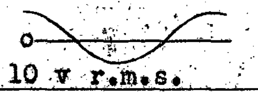
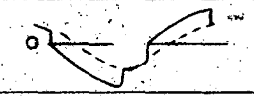
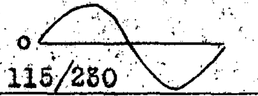
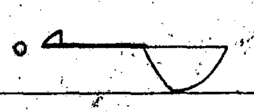
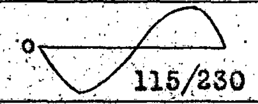
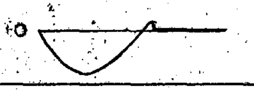
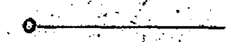
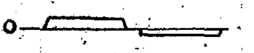
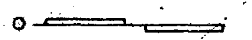
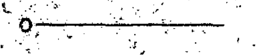
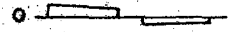
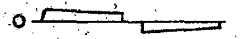
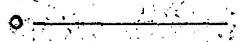
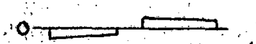
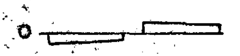
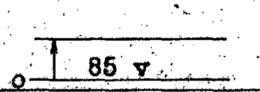
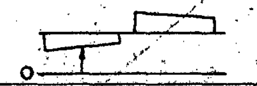
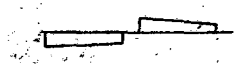
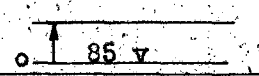
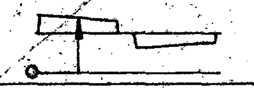
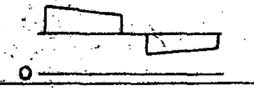
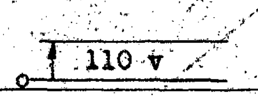
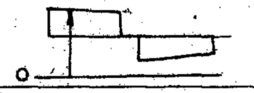
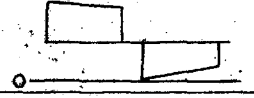
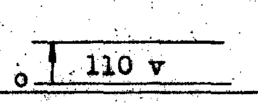
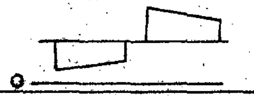
Sync. the sweep to the line. SCOPE POSITION GROUND	PROBE	Plate power on. Loan connected. FG-57^s removed. Brown conv. out.	Plate power on. Loan connected. FG-57^S removed. Brown conv. in. Stnd. volts a little above dummy shunt volts.	Plate power on. Load connected. FG-57^S in place. Brown conv. in. Stnd. volts a little above dummy shunt volts.
Power Supply TS1-1	Power Supply TS1-2	 115 v		
Power Supply TS1-3	Power Supply TS1-5	 230/460	 230/460	 230/460
Power Supply PG1-9	Power Supply PG1-10	 6.3 v	 6.3 v	 6.3 v
Power Supply PG1-6	Power Supply PG1-12	 115 v	 115 v	 115 v
Regulator Brown converter pin-6	Regulator socket pin-1	 6.3 v	 6.3 v	 6.3 v
Regulator neutral	Regulator high side of C-8 or C-11	 7 v r.m.s.	 7 v r.m.s.	 7 v.r.m.s.
Regulator neutral	Regulator V-6 pin 3 or pin jack J-1	 10 v r.m.s.		
Regulator neutral	Regulator V-7 pin 3 or pin jack J-3	 10 v r.m.s.		
Regulator neutral	Regulator Plate lead of V-6	 115/230		
Regulator neutral	Regulator Plate lead of V-7	 115/230		
Regulator Brown converter pin-5	Regulator Brown converter pin-3			
Regulator neutral	Regulator V-2 pin 4 grid			
Regulator neutral	Regulator V-3 pin 4 grid			
Regulator neutral	Regulator V-2 pin 8 plate	 85 v		
Regulator neutral	Regulator V-3 pin 8 plate	 85 v		
Regulator neutral	Regulator V-4 pin 8 plate	 110 v		
Regulator neutral	Regulator V-5 pin 8 plate	 110 v		

FIG. 8

MAGNET REGULATOR - BLOCK

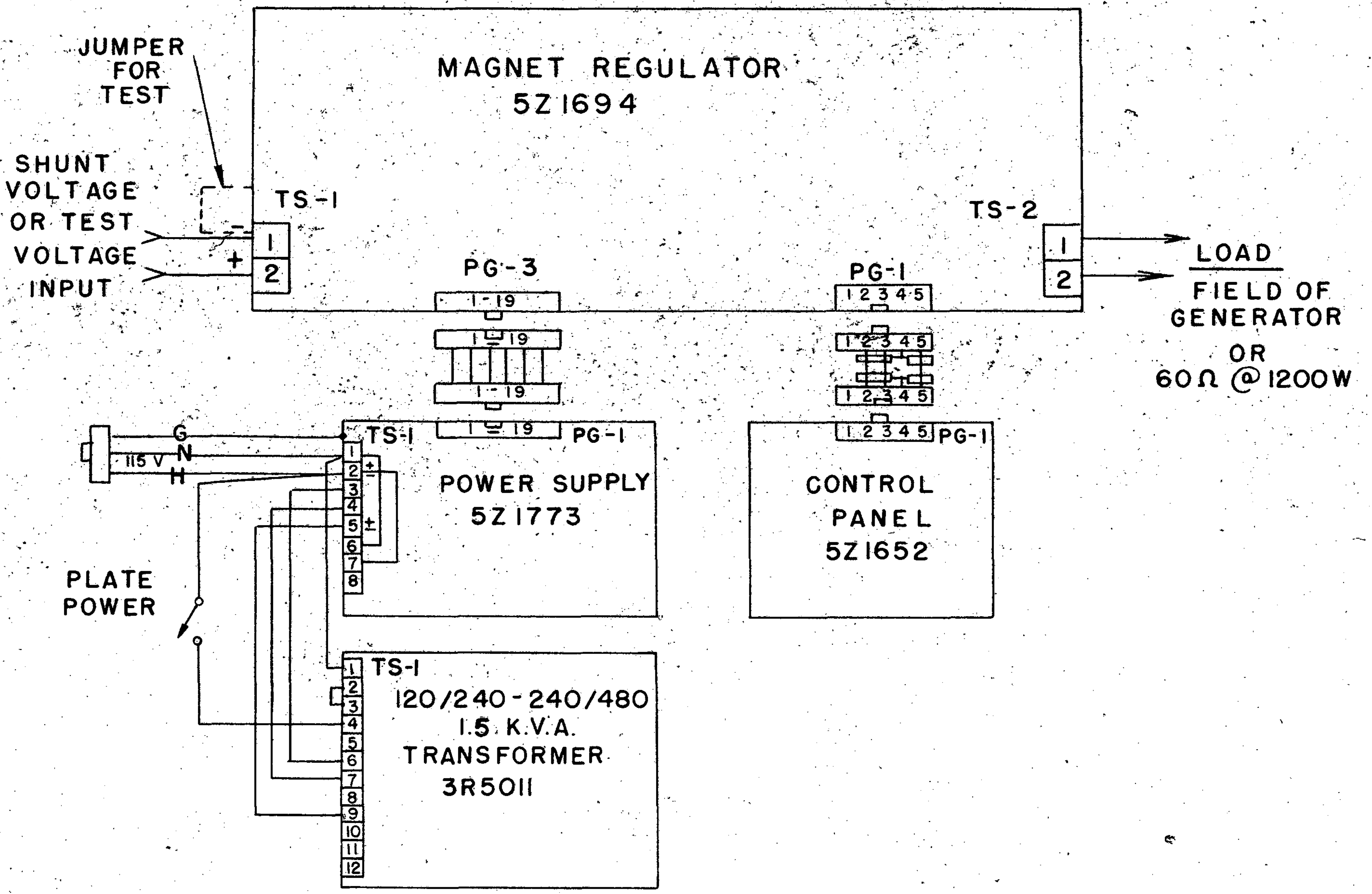


FIG. 9

14388-

DELIVER TO	JOB NO	DATE REC'D	MAKE
		TOLERANCES WHERE NOT OTHERWISE GIVEN	

5.-6

RADIATION LABORATORY

UNIVERSITY OF CALIFORNIA-BERKELEY

DRG. NO

DRAWN

CHECK

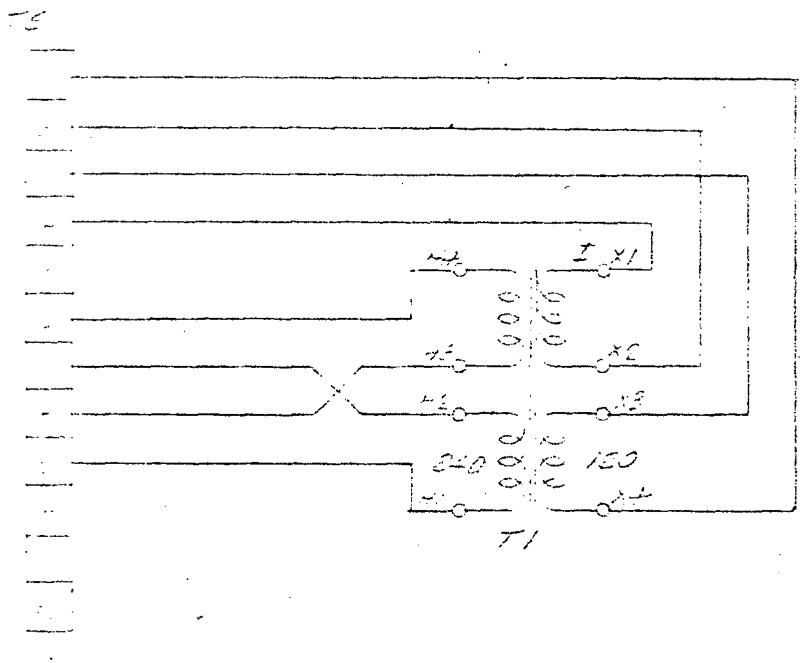
DATE

APPROVED BY

SCALE

G.E. TRANSFORMER
76G130
120/240-240/480 @ 1.5 KVA
PANEL
SCHEMATIC

REF. DWG.
3R5023 - PANEL DETAIL



PARTS LIST

DESIG.	QUAN.	SPEC'S
TS1	1	TERMINAL STRIP, 12 POINT, GE #16EB1AB3
T1	1	TRANSFORMER, 120/240-240/480, 1.5 KVA GE # 76G130
	HARDWARE	
10Z1132-12	1	STD G.E. TERM STRIP SUPPORT

CHANGE LETTER	DRAWN BY	CHECK BY	DATE	CHANGE

MATERIAL

Fig. 10

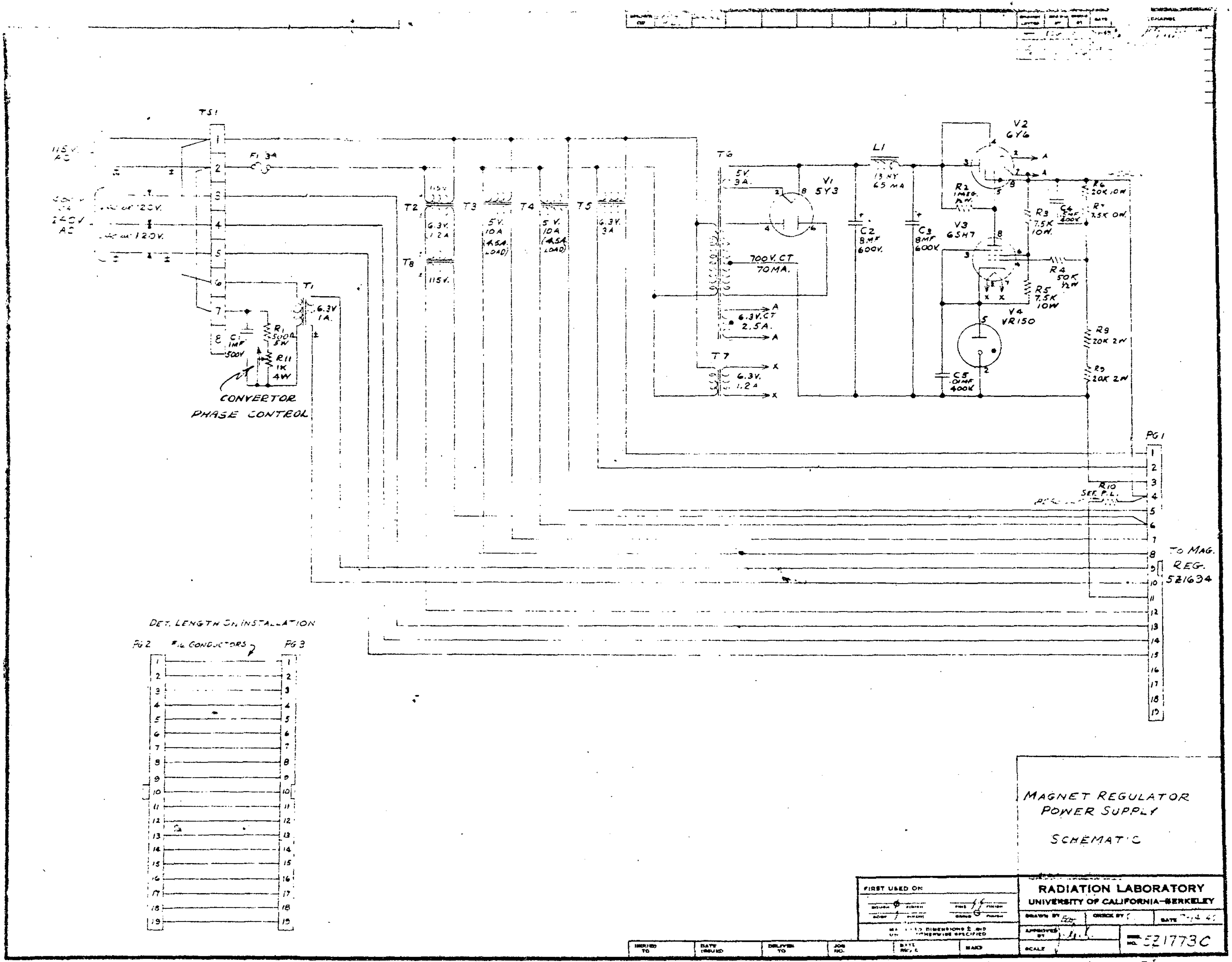


FIG. 11

ELEC 1283

MAGNET REGULATOR 5Z1694

DUMMY-SHUNT INPUT VOLTAGE

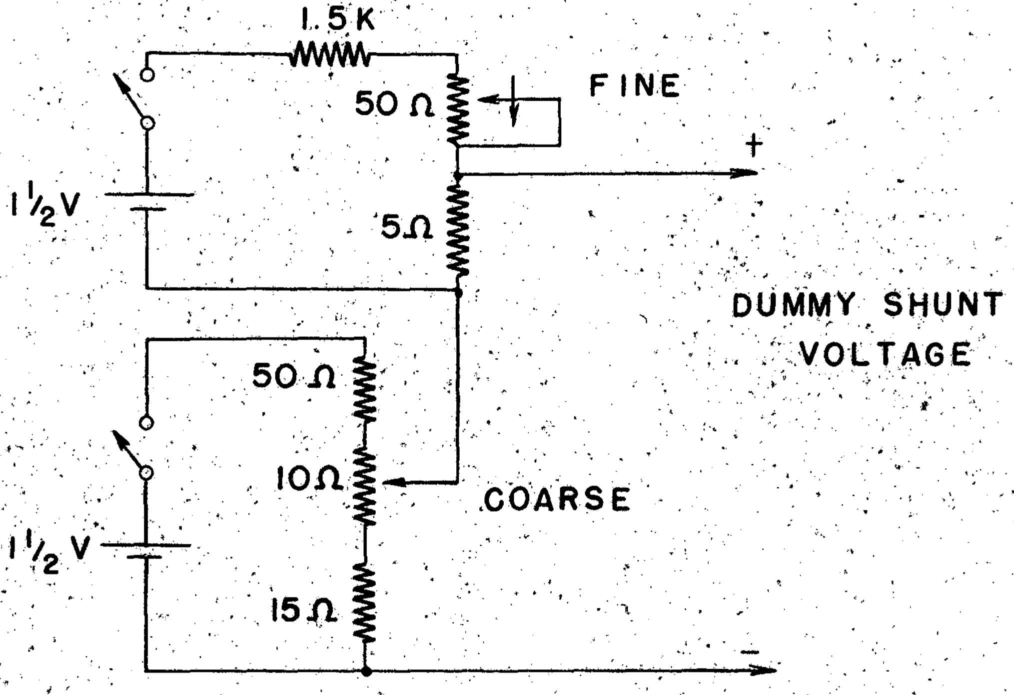


FIG. 12A

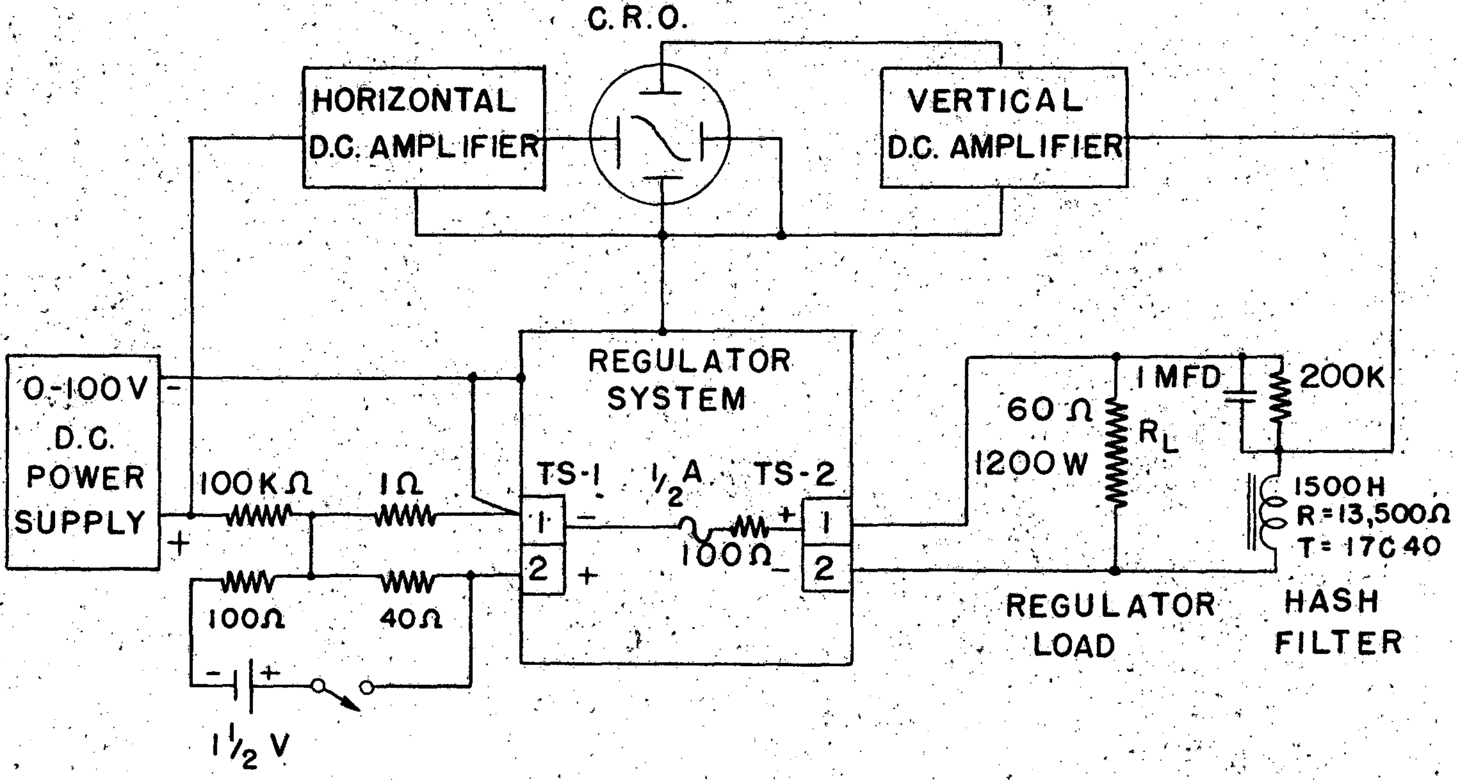


FIG. 12B

184" 552 KW REGULATOR CHARACTERISTICS

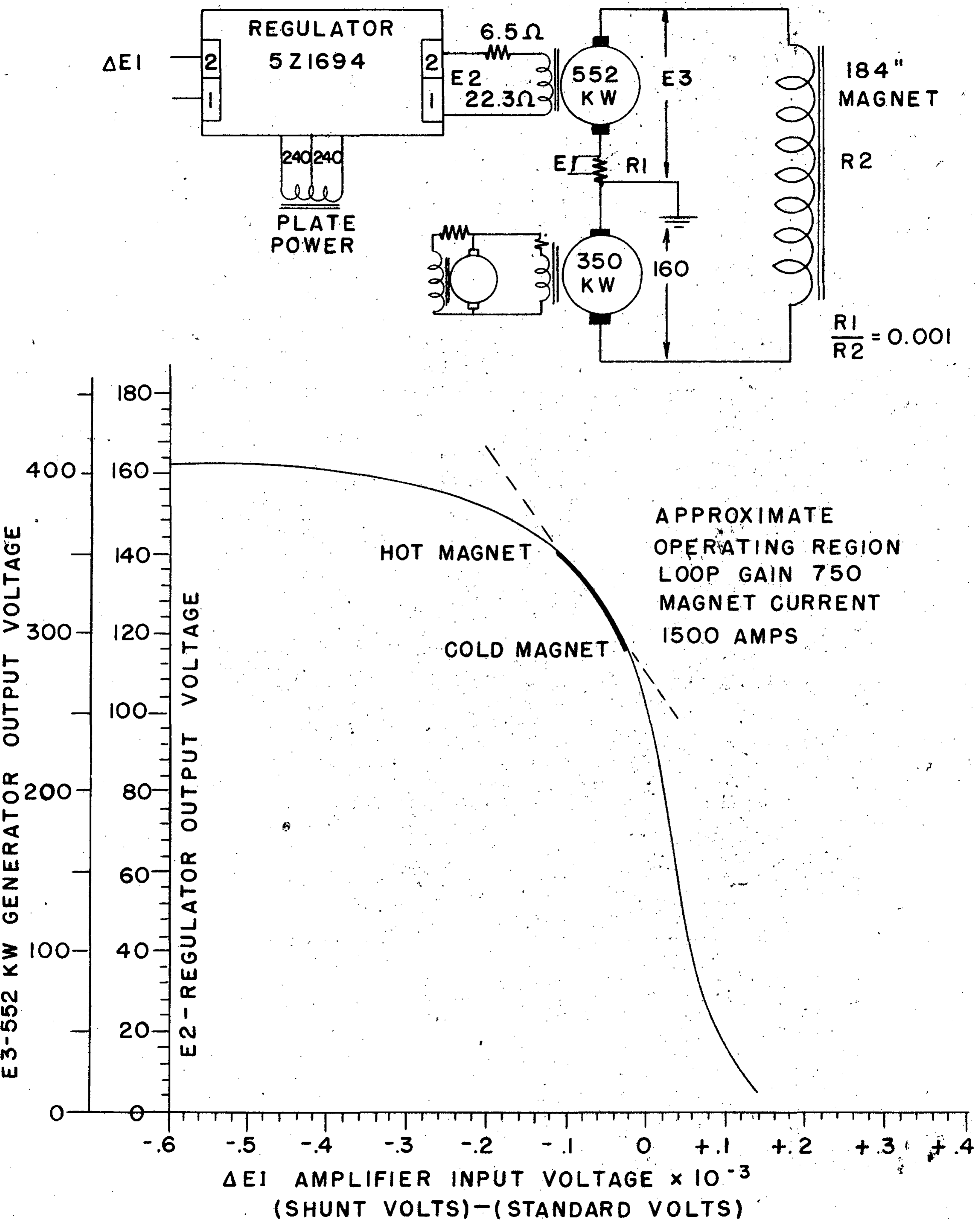


FIG. 13

20 KW PORTABLE M.G. SET

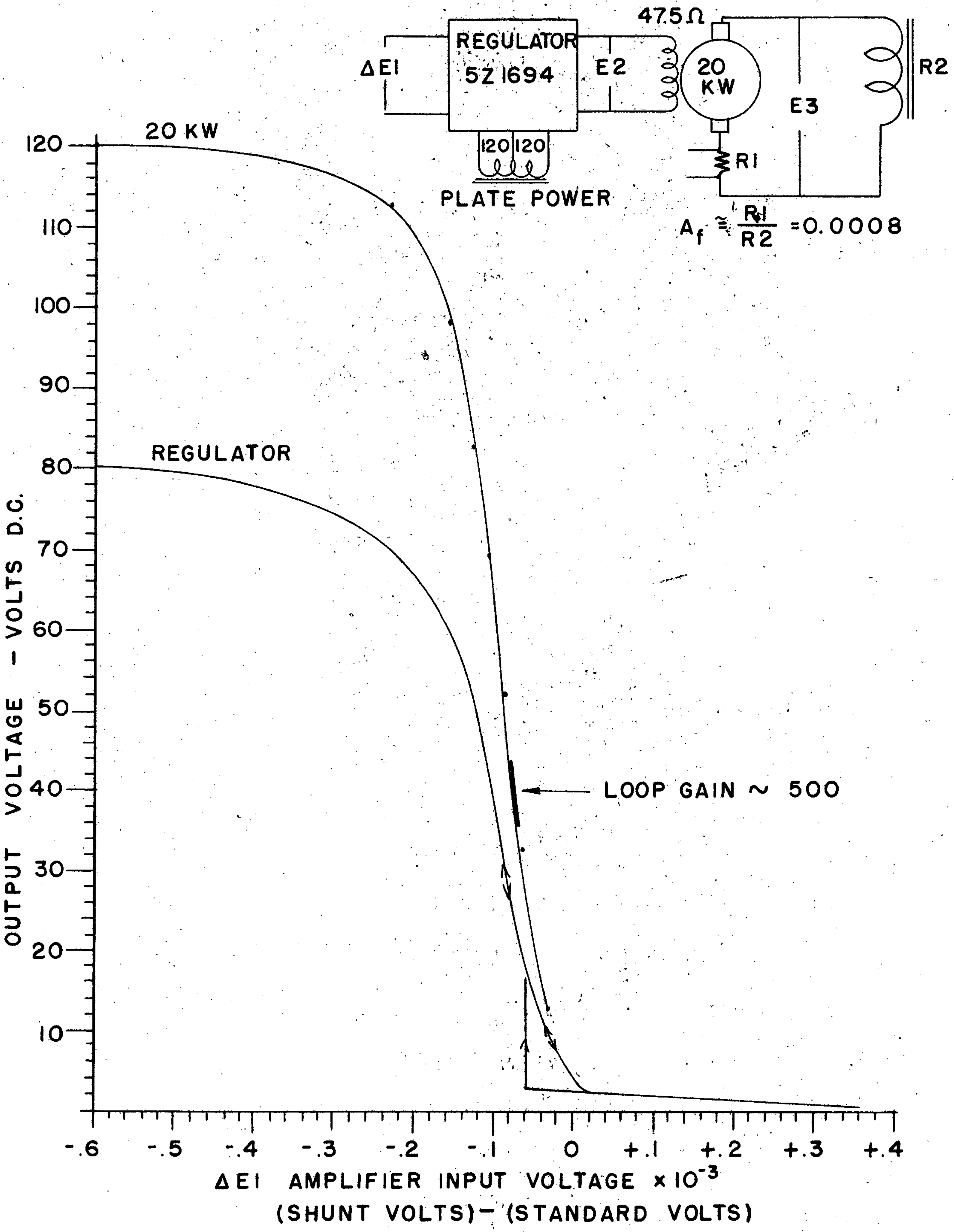


FIG. 14

BLDG. 10 ANALYZING MAGNET REGULATOR

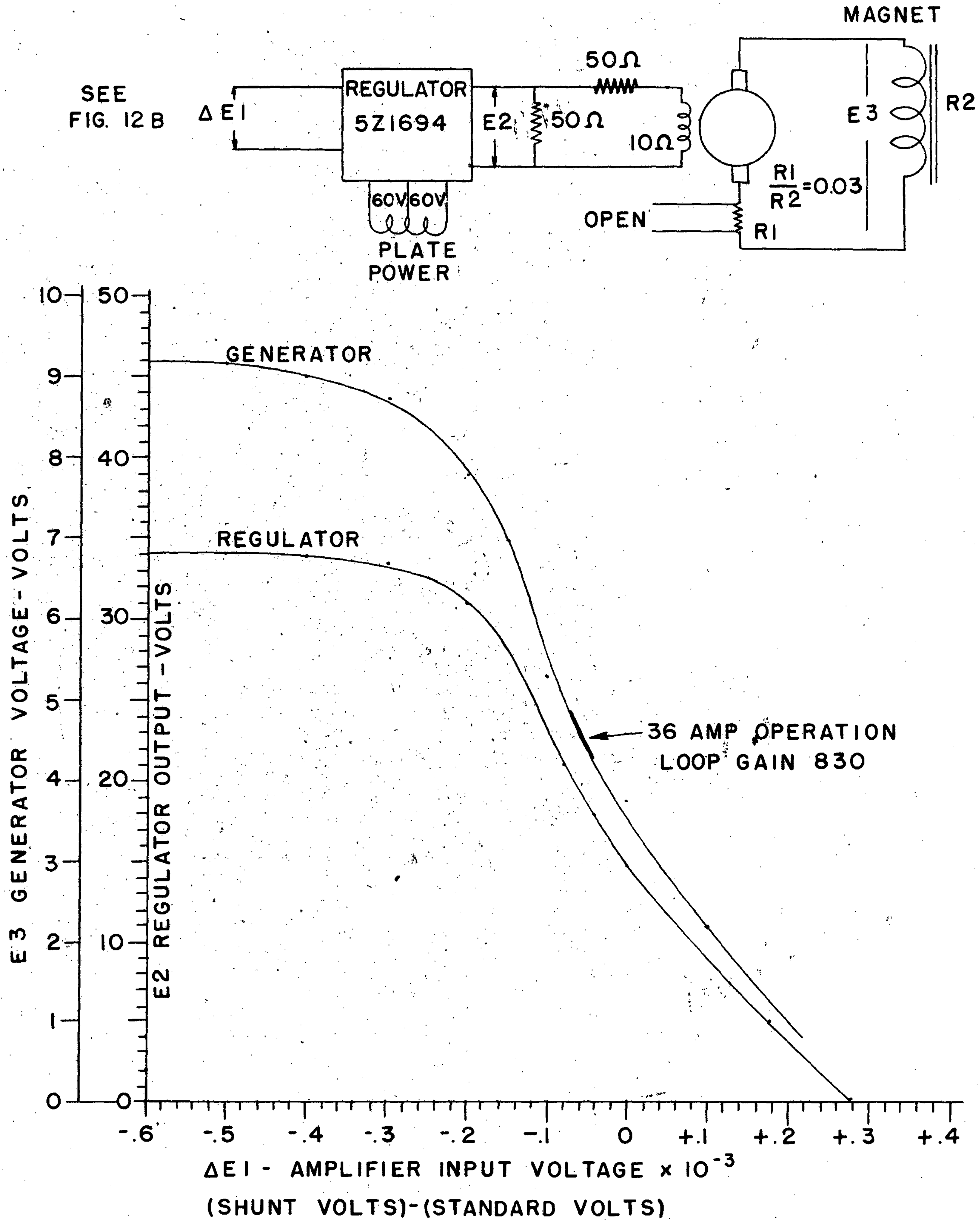


FIG. 15

60" CYCLOTRON MAGNET REGULATOR OPERATION

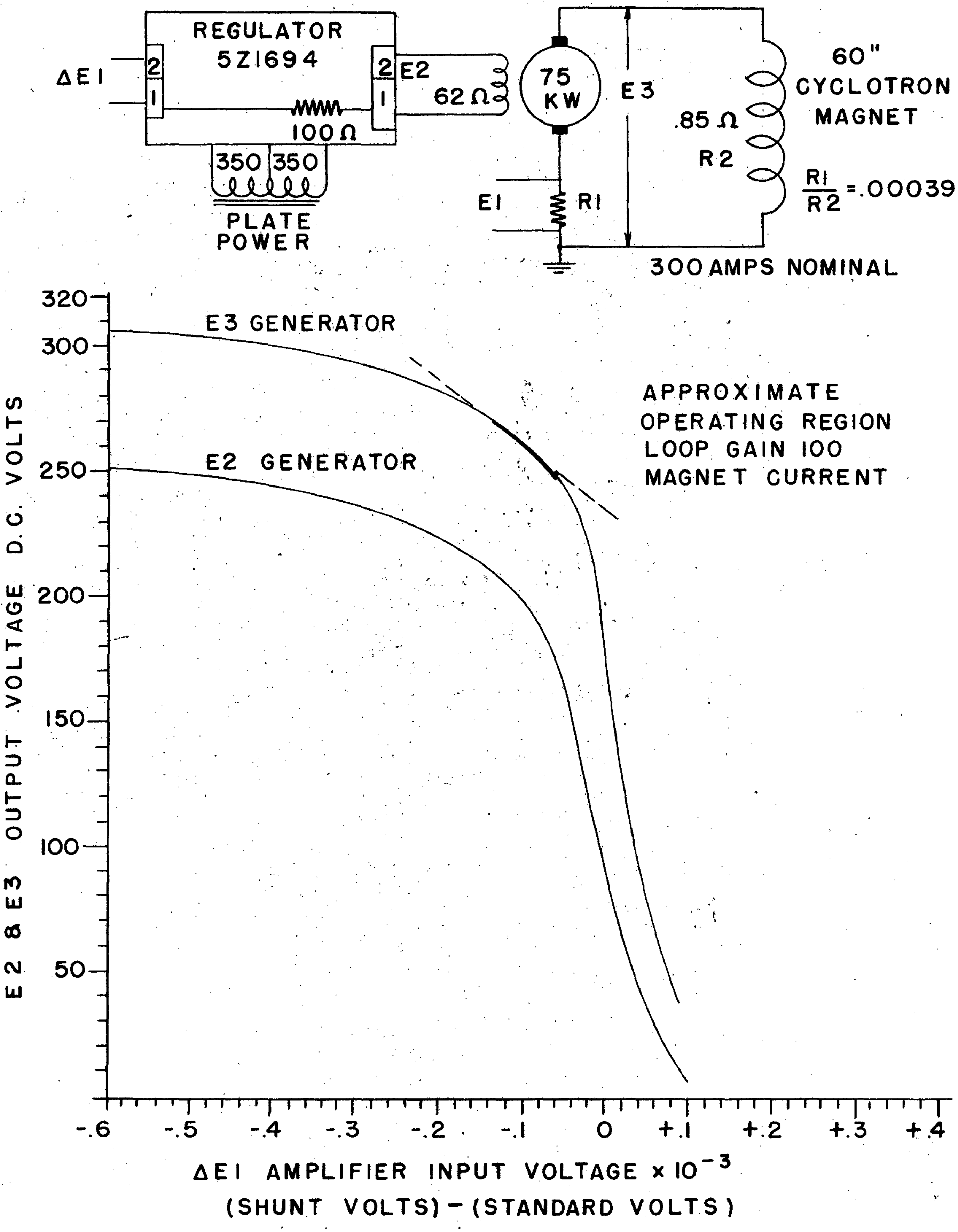


FIG. 16

60" CYCLOTRON MAGNET REGULATOR CIRCUIT

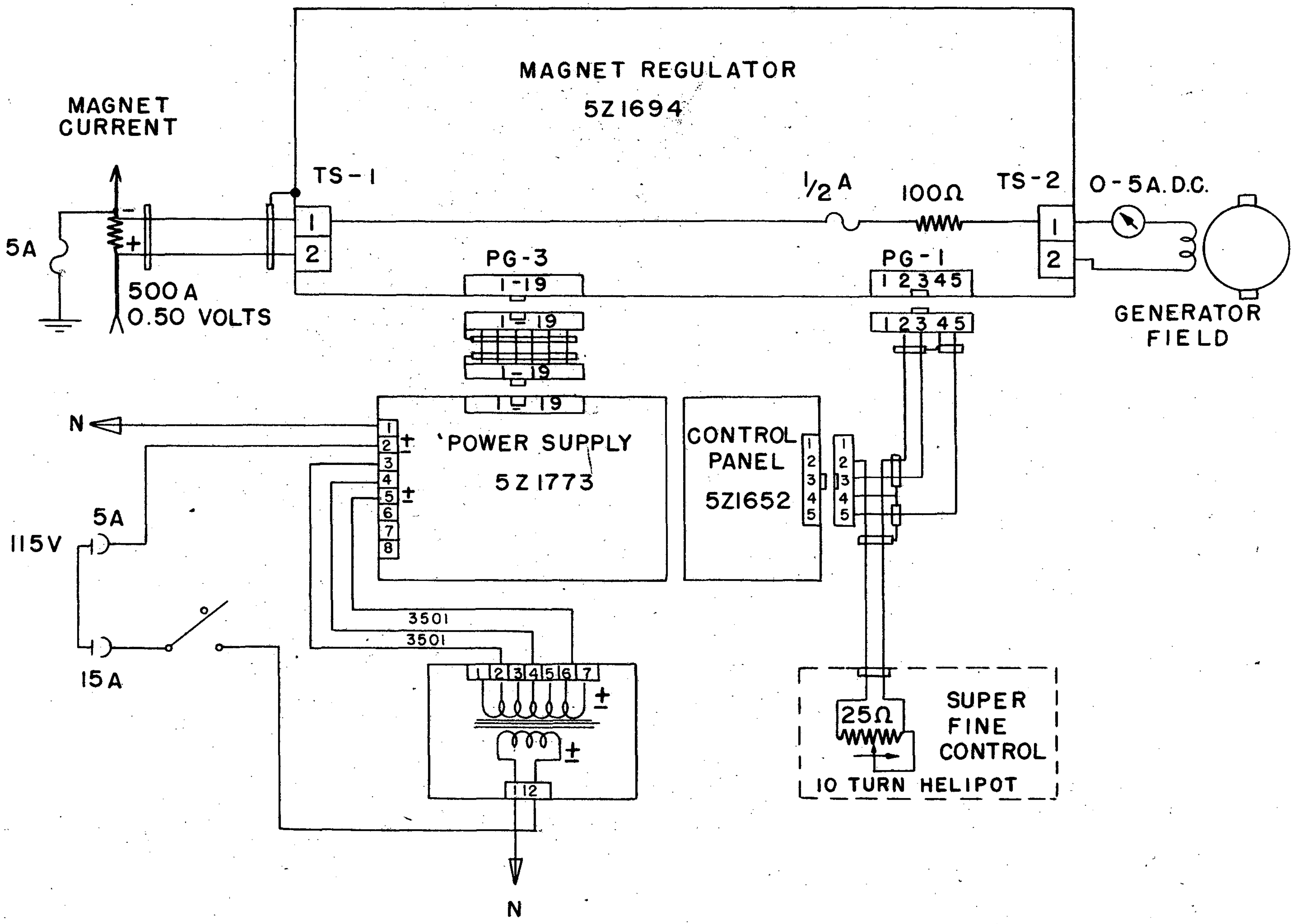


FIG. 17