A FEEDBACK CONTROL SYSTEM

FOR ELECTRON BEAM WELDING GUNS

by

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Glen Merril Hartzler

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ABSTRACT

A feedback control system was designed for electron beam welding guns, using silicon controlled rectifiers to control cathode temperature. Response speed of the gun was increased and stable operation achieved.

A wiring diagram and complete operating instructions are included in the appendix.

INTRODUCTION

Industrial electron beam equipment has been developed largely since World War II to work with the exotic refractory metals which were just starting to find use in quantity. This development was accelerated by advances made in large oil-diffusion pumps for the necessary vacuum systems. Since then, vacuum chambers have grown larger, and electron gun powers have increased to 250 KW or more.[1]

The Welding Laboratory at M.I.T. has a laboratory type system consisting of a 5 KW (500mA at 10 KV) power supply and a chamber 18" in diameter and 24" high. When the need arises, a 4 KW (150mA at 27 KV) supply can be connected to the chamber. The equipment is used primarily for vapor plating and brazing, and occasionally for melting and welding.

Electron gun emission drifts during operation, and continuous adjustments must be made to maintain a constant current. For some of the more sensitive guns, these adjustments are difficult to make

1. Robert Bakish, editor, Introduction to Electron Beam Technology, page 1, Wiley, 1962

manually with the usual variac controls, so an automatic control system was designed to replace the manual control.

CHAPTER 1

DESCRIPTION OF THE GUN

The gun for which the control system was principally designed is a Convergent Pierce type with an electron bombardment heated solid cathode. In contrast to the usual laboratory size Pierce type guns which use fine wire coils for the main cathode, it is capable of much higher operating currents because of the increased effective cathode area.

The Pierce type gun creates a beam by assuming that the desired beam is a small section of much larger flow and designing electrodes to provide an electric field at the edge of the desired beam which would correspond to the field seen in larger flow. Thus to form a parallel beam, electrodes as in Figure 1 are used. This beam immediately diverges once it passes the anode, and renders focusing impossible. If the beam is made to converge rapidly, it will focus somewhere beyond the anode. This focus can be repeated on the work by a magnetic lens. The appropriate electrodes for the convergent guns are much too difficult to develop mathematically, and so empirical methods are used. Spangenberg has done this for various geometries, and some of his results are given on page 90 of "Introduction to Electron Beam Technology", edited by Robert Bakish.

The Pierce gun in the laboratory was made according to Spangenberg's drawings. The cathode is a 3/8" diameter dished tantalum disc which is heated by a spiral tantalum filament 3/32" from its back surface. The filament is operated at temperatures slightly above that which is required for space charge limited operation, and the accelerating voltage between the filament and cathode is varied to attain desired emission from the cathode. When the gun was first used, both the filament temperature and accelerating voltage between filament and cathode were controlled by hand operated Variacs. Constant emission current was difficult to maintain by this method because of drift resulting from temperature rise of the non-emitting parts. Feedback control was the logical choice to attain stable operation.

The first step in designing the control system was to measure the response of the gun. This gun operates at around 10 KV to 20 KV with emission currents up to 2½ amps. A small power supply is used to heat the cathode; the output of this power supply is varied to regulate the temperature of the cathode, thereby controlling gun emission.

The anode of the gun operates at ground potential with the cathode and filament operating at the power supply voltage. The heater power supply must therefore be insulated to at least the operating voltage of the gun, and any control of its output must be done in the primary circuit of an isolation transformer.

To measure the response of the gun and heater power supply, a Variac was arranged with a crank connected to a variable speed motor so that the RMS output voltage of the Variac could be made to vary sinusoidally. The amplitude of this variation was controlled by regulating the input to the Variac. The output of the oscillating Variac was added to that from another Variac so that the gun could be brought into its operating region and then the amplitude of oscillation around the normal operating voltage increased and its effect on emission current monitored. Upon doing this, it was found that the transfer characteristic of the gun and heater supply was essentially $\frac{K}{S+.32}$. K, the gain, is very much dependent on the gun current magnitude and on the amplitude of the variation. Below the roll-off point, it ranges from 5mA/volt to 50mA/volt.

About 6 to 8 seconds was required for 90% of the full rise to a step taking the gun current from approximately 10mA to 250mA. It does not display the expected exponential rise, but rather an almost uniform ramp, caused by change in the gain.

CHAPTER 2

DESCRIPTION OF THE POWER SUPPLIES

The main high voltage power supply is a 10 KV 500mA power supply operated from a three-phase 220 volt line. The output voltage is controlled by a Variac in the primary of the plate transformer which feeds a full wave bridge vacuum rectifier operating with a minimum of filtering into the gun. The power supply contains appropriate interlocks and a fast acting circuit breaker to protect the power supply from the common arcs in the chamber, and an over-voltage cutout. The power supply output voltage drops from 10 KV at no load to about 6.5 KV at 500mA output. The output voltage at 500mA can be brought back to 10 KV by increasing the setting of the Variac while this current is being drawn.

The power supply for heating the cathode of the gun is a single phase unit operating on 110V with vacuum rectifiers and is isolated from the line with insulation capable of withstanding 40,000 volts. The output voltage of this supply is 1700 volts no load at full input voltage and drops to about 500 volts at its 350mA full output capacity.

CHAPTER 3

BASIC REQUIREMENTS OF A CONTROL SYSTEM

One of the foremost requirements of the control system is that it be easy to operate. It must include appropriate interlocks with the rest of the equipment to prevent damaging the gun. It should include a power supply for the gun filament, and meters for monitoring the output current and voltage, the emission current, and the power supply voltage. If possible, provisions should be made for remote control.

The unit should have as high a gain as can be used stably and should have rapid response. It must be capable of controlling approximately a kilowatt at 110 volts in the primary of the heater power supply transformer. It should have current adjusting controls that allow operation in several ranges of maximum current and permit continuous adjustment in any of these ranges. Because the gun requires several seconds to warm up to emitting temperatures, the control system should have a standby position which will operate the gun at as small a current as can be easily monitored.

CHAPTER 4

DESIGN

Silicon controlled rectifiers were chosen as the main power control elements because of cost, availability, their rather high response speed, and the associated circuit simplicity. The silicon controlled rectifier is a very high gain device so that little or no amplification of the feedback signal would be required. In fact, it was found necessary to use attenuation.

The internal ground of the main high voltage power supply is broken and brought through a shunt inside the control system. This develops a voltage which is subtracted from a reference voltage. The difference of these voltages is used to advance the triggering time of the silicon controlled rectifiers, thus increasing the output power. The control system includes an internal loop to limit the output current should the filament of the gun short to the cathode. Zener diodes are used to protect the meters and transistor circuits from excessive voltages appearing across the shunt when the gun shorts out the power supply.

Figure 2 shows a block diagram of the control system. At the left is a reference power supply which puts out from 0 to 15 volts depending upon the desired output current. This voltage is fed into the summing network and then into the unijunction transistor triggering circuit. Increasing this voltage causes a unijunction transistor which is synchronized to the line frequency to generate pulses earlier in each half cycle of line frequency. These pulses are fed into a silicon control rectifier amplifier which converts them into semirectangular pulses lasting for the rest of each half cycle. These semirectangular pulses are necessary to make sure that the main silicon controlled rectifier turns on when operated with an inductive load. The output current is monitored by a current transformer which feeds back to the summing network a dc voltage proportional to the output current. When this voltage reaches a certain value it retards the trigger pulses, thus limiting output current. When the gun emission is at the desired level, the voltage developed across the shunt subtracts enough from the reference voltage to retard the trigger pulses to the point necessary to maintain the desired current.

CHAPTER 5

TEST OF THE SYSTEM

The completed control system was connected to the 10 KV power supply and gun, and response measurements made. The system works stably at all currents within the range of the power supply. It has a step response of from 2 to 3 seconds for 90% rise which is significantly faster than the 6 to 8 seconds step response of the gun without feedback. Warm-up to emission from a cold start is less than 5 seconds. Gain of the control system is sufficient so that current variation is less than 5% for 50% variation in anode voltage.

A low frequency function generator was connected into the control system and used to introduce a small perturbation. With the gun operating at 200mA at 7 KV with perturbations of 70mA, the response to a square wave for 90% rise was 1½ seconds.

The beam was allowed to heat a steel bar to such a temperature that rapid evaporation was taking place. Even under these conditions of violent ionization, the gun remained stable.

The standby current is approximately 1/2mA, which is just enough to allow one to see the beam yet not enough to do any significant heating of materials in the chamber. This makes focusing and positioning of the beam very easy for the operator.

When more emission current is desired, the operator turns a control and emission current rises to the desired value. Emission current can also be controlled by a remote control or the unit can be operated with emission current controlled from the panel and the control system going from the standby mode with 1/2mA emission current to any desired emission current simply be pressing a foot pedal.

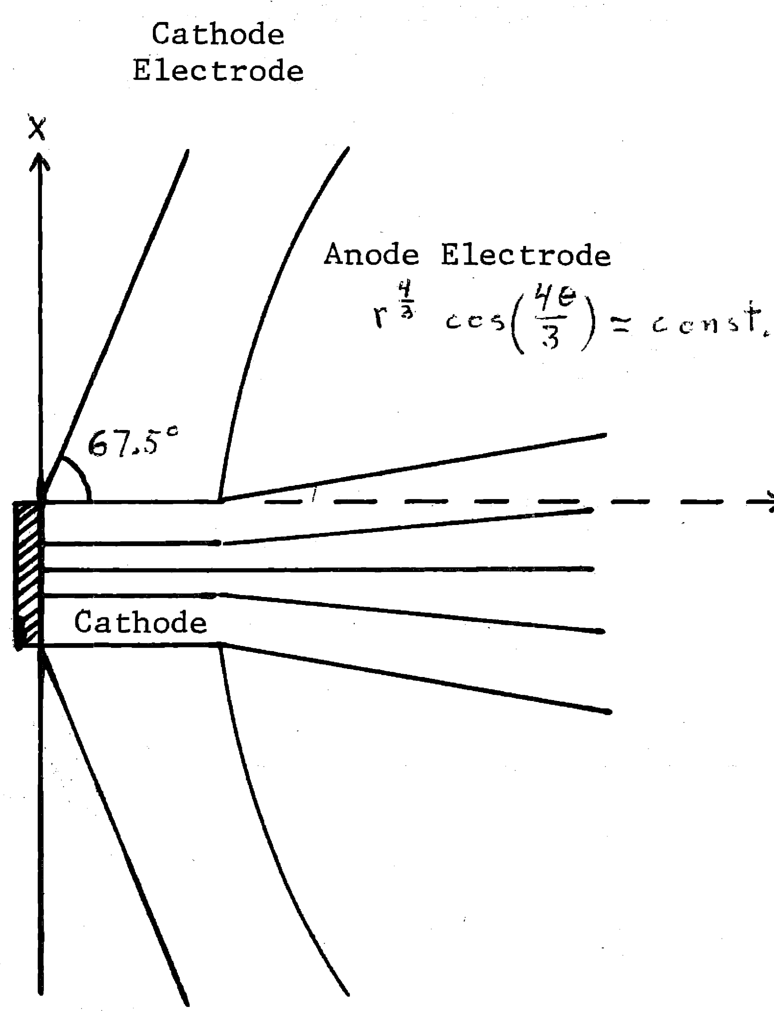


FIGURE 1. PIERCE SHAPES FOR PARALLEL BEAM

(Bakish, Introduction to Electron Beam Technology, Page 86, Wiley, 1962.)

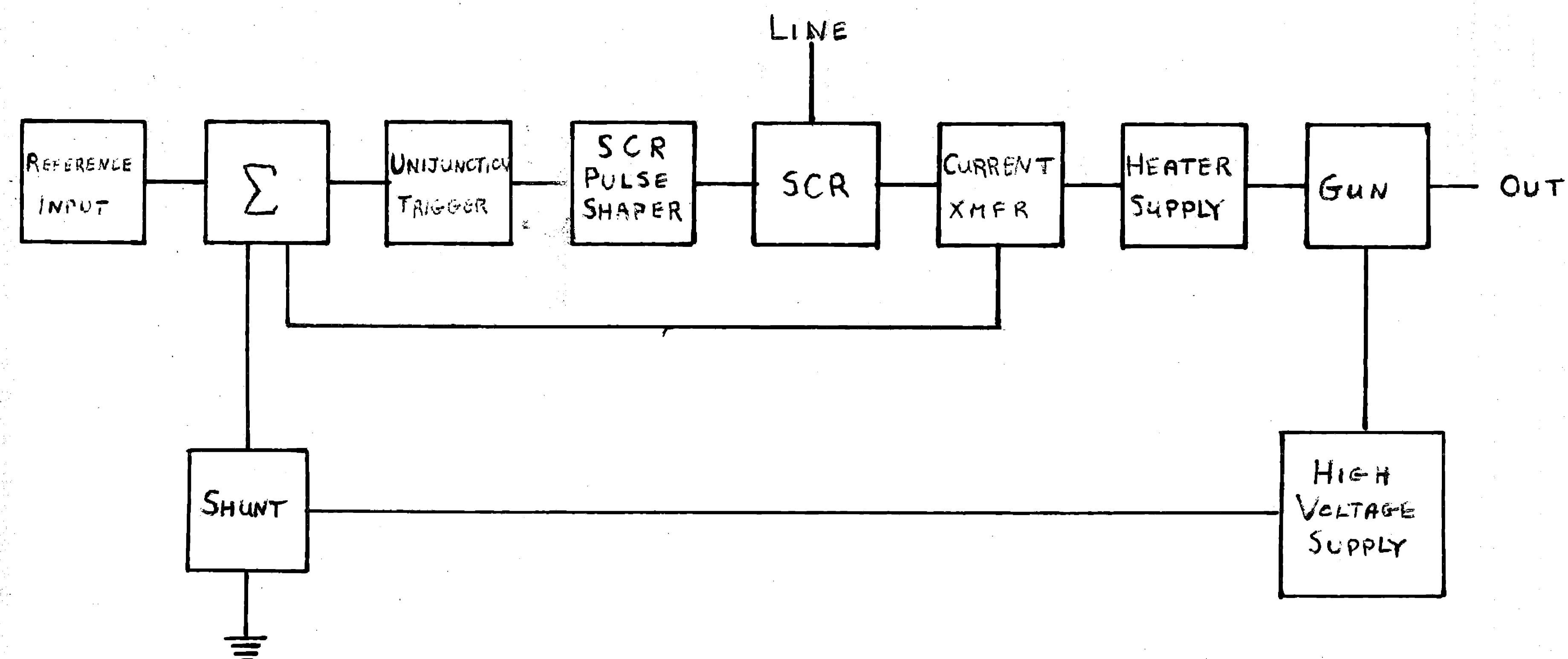


FIGURE 2. BLOCK DIAGRAM OF THE CONTROL SYSTEM

APPENDIX

OPERATING INSTRUCTIONS

Section I: Bombardment Heated Cathode Gun

Part A. Connection to system:

1. Connect heater power supply plate transformer to terminals 10 and 11.
2. Connect heat power supply filament transformer to terminals 8 and 9.
3. Connect gun filament transformer to terminals 6 and 7.
4. Connect internal positive lead of high voltage power supply (ground potential) to terminal 1.
5. Connect external positive ground lead from chamber and gun to terminal 3.
6. Connect voltmeter lead of high voltage power supply to terminal 2.
7. Connect to 110 volt line.

Part B. Calibration:

1. Turn on control power.
2. Turn high voltage power supply on.
3. Set voltage at 5 KV.
4. Adjust relay sensitivity so that blue light turns on at about 5 KV.

Part C. Operation:

1. Turn on control power.
2. Turn on filament power and set current at 1.1 amp.
3. Turn on high voltage power supply and set to desired voltage. Blue light should come on when high voltage exceeds the 5 KV minimum.
4. Set anode current meter switch and operating range switch to desired positions.
5. Set mode switch to panel operation.
6. See that current control is in off or standby position.
7. Press beam start button:

   Blue light will go out, red light will come on.

   Control system output meters will go to about 90 volts and 10 amps for about 5 sec. and then drop to about 50 volts and 4 amps when gun is emitting.

   If emission is not attained within 10 seconds, press stop button and see Part D, step 3.

In standby position, gun current is between ½ and 1mA.

8. Turn current control to attain desired emission current.
9. System may be returned to standby position anytime.
10. To stop beam at any time, press stop button. This removes power from the heater power supply. To restart beam go back to step 7.
11. If gun arcs and trips power supply circuit breaker, control system will stop. If this occurs, go back to step 3.

Part D. Trouble shooting:

1. If system is unstable reduce setting of gain control on rear panel, and advance bias so that emission with current control just above off position is less than 5 mA. See step 4.
2. If desired emission is unattainable with control output below 10 amp, increase filament current 10%.
3. If emission is not attained in step 7 of Part C, check:
    a. for blown fuse, indicated by lights.

       Replace fuse:

Control power	AGC 1.5A
Filament power	MDL 2.5A
Main power	ABC 12A

b. for insufficient filament emission, as shown by low output current, (less than lamp) at high voltage (near 120 volts). In this case, check filament current ammeter, and increase setting by 10%.

c. for filament shorted to cathode, which is indicated by high output current (10 to 12 amp) at low voltage (50 to 70 volts). In this case, open chamber and check gun.

4. If emission with current control near off position is not around 1 to 2mA, adjust bias so that it is. Little or no variation in output of the control system should be noted as current control is switched on and off.

Section II: Direct Emission Gun

Part A. Connection to system:

1. Connect gun filament transformer to terminals 10 and 11.

2. Connect to high voltage power supply as in Section 1, Part A, steps 4, 5, and 6.

3. Connect to 110 volt line.

Part B. Operation:

1. Turn on control power and filament power.

2. Turn on high voltage power supply and set to desired voltage. Blue light should come on when voltage exceeds 5 KV minimum.

3. Set anode current meter switch and operating range switch to desired positions.
4. Set mode switch to panel operation.
5. See that current control is in off or standby position.
6. Press beam start button:
   Blue light will go out, red light will come on.
   Emission should be attained in less than 1 or 2 seconds.
   Output should be around 60 volts and 1 amp for normal emission.
7. Turn current control to attain desired emission current.
8. System may be returned to standby position any time.
9. If gun arcs and trips power supply circuit breaker, control system will stop. If this occurs, go back to step 2.

Part C. Trouble shooting:

1. Emission with current control near off position should be 1 to 2mA. If it is not, adjust bias control so that little or no variation in control system output is noticed as current control is switched on and off.

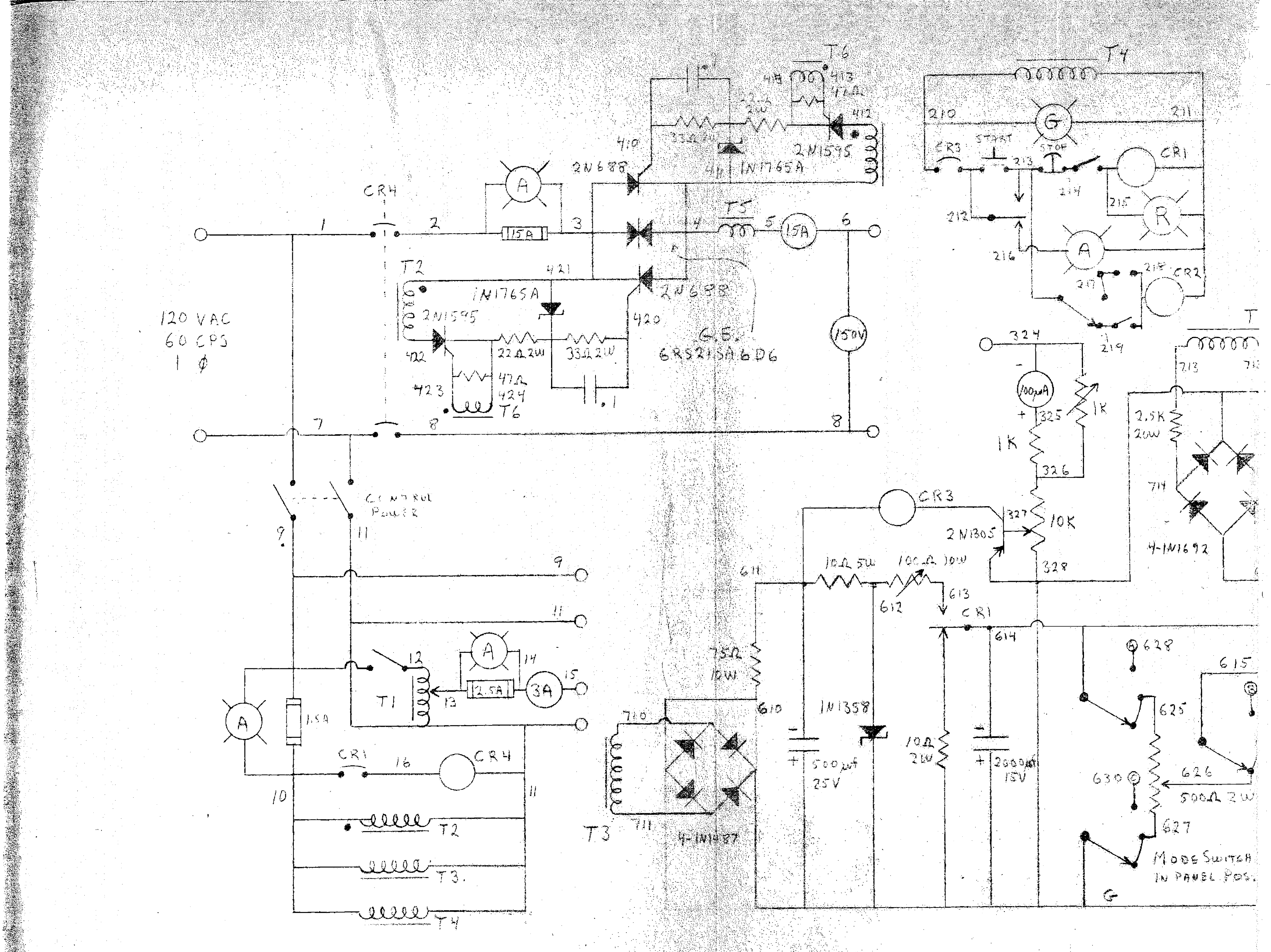
2. If emission is not attained, check:

   a. for blown fuse, indicated by lights.

      Replace fuse:

Control power	AGC 1.5A
Filament power	MDL 2.5A
Main power	ABC 12A

   b. open filament, indicated by high output voltage (110 volts) and no output current. Replace filament.


120 VAC
60 CPS
1 φ
CR4
15A
2N688
410
330Ω 2W
22Ω 2W
411
1N1765A
413
47Ω
412
2N1595
T6
T5
15A
150V
T2
421
1N1765A
2N1595
422
423
22Ω 2W
33Ω 2W
47Ω
424
420
2N688
G.E.
6RS21SA6D6
.1
CONTROL
POWER
T1
2.5A
3A
1.5A
CR1
CR4
T2
T3.
T4
T4
210
211
CR3
START
STOP
213
214
CR1
215
R
212
216
217
218
CR2
219
324
100μA
1K
325
1K
326
CR3
327
10K
2N1305
328
10Ω 5W
100Ω 10W
612
613
CR1
614
611
75Ω
10W
610
T3
710
711
4-1N1187
1N1358
500μf
25V
10Ω
2W
2000μf
15V
713
2.5K
20W
714
4-1N1692
628
615
625
630
626
500Ω 2W
627
MODE SWITCH
IN PANEL POS.
G

Control System For Electron Beam Guns
by Glen M. Hartzler
May 1964

T1; 2.2 mc Variac
T2; 12.5V, 12.6V Fil Transformer
T3; 24V Fil Transformer.
T4; 135V, 6.3V power Transformer
T5; 2.5V 20A Fil Transformer
T6; Transistor pulse Transformer

Numbers near wires correspond to wire markers.