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MANUAL FOR PARTICLE TRAJECTORY CALCULATOR AND COMPONENT POISSON CELL

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I. GENERAL INTRODUCTION TO EQUIPMENT

1.1 Application of System

The particle trajectory tracer provides a means for solution of many boundary value problems involving the Poisson equation. Basically, the solutions are obtained by analog techniques. Solutions may be obtained for two-dimensional rectangular and cylindrical geometries. Though useful for many other applications[1], this manual will cover its use in electron beam studies.

This section will serve to give the reader a general introduction to the equipment. Section II concerns the physical operation of the system and Section III will describe the use of the system in the solution of trajectory problems. Section IV discusses the maintenance and trouble shooting of the system, while Section V consists of figures illustrating the physical aspects of the system. Finally, Section VI contains the drawings necessary for the servicing of the entire system.

1.2 Introduction to Components of System

A general view of the particle trajectory tracer is shown in Fig. V.1. The flow diagram and the interrelationship of the various components is given in Fig. V.2. These major components are the Poisson cell complex, analog computer, current source console, and the recording

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1. Martin, R. J., Masnari, N. A. and Rowe, J. E., "Analog Representation of Poisson's Equation in Two Dimensions", IRE Trans. on Electronic Computers, vol. EC-9, No. 4; December, 1960.

x-y plotter. A general introduction to each of these major components is given below.

1.3 Poisson Cell Complex

This unit (Figs. V.3 through V.10) consists of a Poisson cell mounted on an Electronic Associates 205-S x-y plotter.

The cell is the means by which an analog of the problem is set up and upon which the actual solution of the problem occurs. The plotter serves as a support for the cell as well as providing a means for obtaining the electric fields from the analog. The Poisson cell is mounted on a vacuum hold-down unit which contains 2688 spring-loaded plungers. Currents are injected through these plungers and into the cell and this provides the method of simulating the effects of space charge in the analog.

The electric field measuring probe is mounted on the servo driven arm of the plotter. In this manner, the probe provides readings of the electric field on the analog that are fed into the computer. The two positional outputs of the computer are fed back to the plotter and drive the probe causing it to move over the cell analogous to the motion of an electron in an actual device.

1.4 Computer

The computer is a modified Electronic Associates 231-R computer (see computer manuals). The computer is used to solve the two-dimensional ballistic equations for an electron moving in a given field configuration. The inputs to the computer are the voltages that simulate electric fields from the Poisson cell. The output voltages from the computer are the two-dimensional coordinates of the position of an electron. The two ballistic equations and an error check circuit are "patched" into the computer by means of the computer patch panel. This one wired patch panel board will serve both rectangular and cylindrical geometries. The error check circuit is an energy comparitor which compares the energy equivalent of velocities as determined in the computer with the positional potential of the probe on the Poisson cell.

1.5 Current Source Console

Various views of the current source console are shown in Figs. V.11 through V.15. In this unit are mounted sixteen hundred separate high-impedance current generators. Each of these generators, called current sources, are used to inject space-charge simulating currents into discrete regions of the Poisson cell. It is by this means that the effect of space charge can be represented in the solution of electron gun problems.

The input to the current source console is the setting of the current sources. These values are determined from calculations. The console output is the space-charge simulating currents which are injected into the Poisson cell.

1.6 Recording x-y Plotter

The Electronic Associates series 1100-E x-y recorder is utilized to give a permanent record of the trajectories of electrons (Figs. V.1 and V.2). From this record the space-charge distribution is determined that will be injected into the Poisson cell during the solution of a problem. Also, a record is obtained of the completed solution trajectories. The inputs to the recorder are the two-coordinate electron position outputs from the computer, i.e., the same inputs that go to the electron simulating probe of the Poisson cell complex.

II. OPERATION OF SYSTEM

2.1 Introduction

In general, this system is used to solve two types of problems. The first is the analysis type, i.e., given a desired set of boundary conditions (electrode geometry), find the electron beam configuration. The second is the synthesis type, i.e., given a desired beam configuration, find a practical electrode structure that will produce the desired beam. In either case, one starts with a given or assumed set of boundary conditions and wants to find a beam configuration. The solution of the problem is obtained by analog methods, that is, an analog is created whose variables will follow the same laws and satisfy the same boundary conditions as those of the desired problem. The desired solution is then arrived at by conversion of variables between the actual and analog problem after the analog solution is obtained.

In the trajectory tracer, the analog of the problem is set up on the Poisson cell. This is a volume conducting material which when boundary conditions are established with electrodes sets up fields that satisfy the Laplace equation. The Poisson equation is satisfied by adding in space-charge simulating currents through the base of the cell (see Fig. V.4). The potential and electric field distribution can be determined by probing the surface of the cell.

The operation of the system can be seen in the flow diagram, Fig. V.2. There are two closed loops. The first is the trajectory tracing loop which ties together the Poisson cell and the computer, and the second is the space-charge injection loop. This latter loop is the outer one in Fig. V.2 and includes all parts of the system as well as human calculation and adjustment of the space-charge simulating current sources.

First, it should be noted that if the space-charge injection loop is not utilized one obtains solutions to the problem in which the space-charge effects have been disregarded.

To solve a problem, one first sets up the boundary conditions, i.e., the electrode configuration is set up in the Poisson cell. The Laplace equation is now satisfied. To solve for the beam configuration, the trajectory tracing loop is utilized. The probe (see Fig. V.3) is the analog of an electron; it reads the electric fields analogous to those which an electron would see, and because the computer is programmed to move the probe ballistically as an electron, the probe follows a path analogous to an electron trajectory. This is simply what the trajectory loop does--it traces trajectories of individual electrons. When one has traced a representative number of electron trajectories consistent with the boundary conditions, the space-charge-free solution is obtained.

In order to determine the space-charge solution, one utilizes the space-charge loop. After the space-charge-free solution is obtained (recorded upon the 1100-E Variplotter), the resulting space-charge distribution is computed and set into the Poisson cell. However, this changes the electric field distribution of the problem and thus the electron trajectories. Therefore, the beam trajectories are again taken and the space charge recomputed. If the loop is repeated often enough (generally two or three times), there will be no change in beam configuration or space-charge distribution and thus a self-consistent solution has been obtained.

In this section, the operation of various parts of the system will be described.

2.2 Poisson Cell Complex

2.2.1 Introduction. The Poisson Cell is mounted upon a 205-S Variplotter which serves as an adjustable support for the cell. The plotter also contains the mechanism for moving the probe that serves as input to the computer. The cell is a volume-conducting slab which is supported upon a vacuum hold-down. The injection of currents into the slab through spring-loaded plungers in the hold-down allows solutions of the Poisson equation. Various parts of the Poisson cell complex are discussed below.

2.2.2 Poisson Cell (Graphite Plates). The volume-conducting plates are made of graphite and Hydrostone, a plaster binder. The conductivity of these plates is due to the graphite which is mixed homogeneously with the Hydrostone. Various degrees of conductivity can be obtained by varying the ratio of Hydrostone to graphite in each mixture. The present percentages being used are 24.5 percent graphite, 75.5 percent Hydrostone. This combination produces a plate with a conductivity of approximately 2.5×10^{-4} mhos/cm.

In preparing the mixture for molding, a definite procedure is followed. The powdered mixture of graphite and Hydrostone is ball-milled for a 24-hour period previous to adding any liquid to it. The purpose of this is to produce a homogeneous mixture, to separate any agglomeration of particles, and generally to improve the mixture's texture. This mixture is then removed from the mill and sifted into a water solution. This solution contains a negative catalyst, sodium citrate, which prolongs the set-up time of the mixture. The actual mixing can be done either mechanically or manually.

Next the mixture is put into an air-tight vessel and the pressure in this vessel reduced by 25 feet of water. The purpose of this is to remove air bubbles trapped in the mixture during mixing. The mixture is then poured into a mold, leveled, and allowed to set. When it has set enough to move, it is put into a humidity-controlled drying room to dry thoroughly.

After remaining in the drying room for approximately a week, the plate is tested to see if it has the conductive and linear qualities needed for use in the trajectory tracer system. This testing procedure involves various steps. First, the plate is trimmed and electrodes are silver painted on the edges of the plate which run parallel to the proposed electron gun axial direction. Second, the conductivity of the plate is determined by taking a resistance measurement between the painted ends (i.e., a planar or cylindrical diode-type measurement); it can then be calculated from the dimensions of the plate. Finally, equipotentials are probed out on the plate's top and bottom surfaces. This is done by applying + 100 volts to one of the painted electrodes and grounding the other. Then the 10, 20, 30, etc., volt equipotentials are probed out and recorded. If the plate has the desired conductivity and the potential distribution does not vary more than ±1 percent from the theoretical distribution, the plate is acceptable for use.

The acceptable plates are trimmed down to 21-1/4 x 18-1/4 inches in preparation for silver imprinting of the base of the plate. The purpose of silver imprinting (see Fig. V.4) is to assure a uniform area of current injection into the plate when it is placed on the vacuum hold-down. This imprinting is accomplished by use of a template and a spraying technique.

2.2.3 Vacuum Hold-Down. Use of the vacuum hold-down provides a highly flexible method of injecting space-charge simulating currents into the graphite plates. To change plates, all that is necessary is to release the vacuum, remove the plate, insert a new plate and resume the vacuum. When positioning the new plate care should be taken to make sure that the plate is snugly against the three positioning posts. The plates should be held in this position until the vacuum takes effect. If the plate draws down too tightly or doesn't draw far enough down, its position can be adjusted by regulating the pressure via the pressure adjustment valve on the vacuum pump system.

The construction of the vacuum hold-down facilitates extreme ease of current injection into the plates. The spring-loaded plungers compensate for any irregularities in the contact surface of the plate. In addition, with the springs and vacuum there is a nearly uniform distribution of force over both surfaces of the plate.

2.2.4 Plotter. The 205-S Variplotter has been modified to contain the vacuum hold-down, various associated space-charge simulating equipment, and a probe assembly. As mentioned previously, the vacuum hold-down provides a very flexible means of current injection into a graphite plate. The associated equipment, contained in the plotter, such as the connector and plug boards, supplies a compact central location from which currents may be directed to the various sources on the plate, and by which sources may be shorted to establish desired electrode configurations. The probe assembly is spring loaded; hence, as it moves along, the probes maintain uniform contact with the plate. These springs also provide the electrical connection between the probes and their wiring.

The controls used on the 205-S Variplotter for operation of the equipment as a trajectory tracer are the power switch, vacuum switch, pen operate switch, parallax potentiometers, scale factors and associated potentiometers. For detailed information on the functioning of these various components reference should be made to pages 14 through 16 of equipment manual on the Variplotter, Model 205-S and 205-T, which is supplied by EAI.

The probe assembly, using either 4 or 5 probes, permits the measurement of potentials and potential gradients that are to be continuously taken from the Poisson cell. Generally, however, the four probe system is used to read the potential gradients from the Poisson cell. For discussion of associated wiring and operation of this system, refer to Section III of this manual.

2.3 Computer

The Electronic Associates 231-R computer has been modified to the extent necessary to its inclusion in the trajectory tracer system. It is connected in the system by means of one cable. Removing this cable and attaching the shorting cable connector will allow its use totally isolated from the remainder of the system.

As detailed in Section 2.1, the computer serves to solve the ballistics equation. An additional circuit, the energy balance circuit, aids in checking for error in the trajectory tracing loop of the system. Referral to Fig. VI.13 and a general knowledge of the computer are all that are necessary for running trajectory traces.

Mounted in the bay above the patchboard on the computer is the unloading amplifier attenuator panel. These attenuators are connected in according to the roadmap, Drawing VI.13. The circuit is used to unload the gradient reading probe of the Poisson cell complex. The theory of the operation of the unloading amplifier is in the literature[2]. To balance these amplifiers, one opens the input. If the amplifier output voltage rises or falls, the system is unbalanced. One then adjusts the feedback potentiometer (the unloading amplifier attenuators) until the output voltage remains at a fixed potential. The unloading circuit is then properly adjusted.

2.4 Current Source Console

2.4.1 Introduction. In the Poisson cell, space charge is simulated by a change in the current flowing through the volume conducting medium. The space charge simulated is

$$\rho_\tau = \frac{i_s}{K\, d\tau_s} ,$$

where $\rho_\tau \triangleq$ tube space-charge density,

$d\tau_s \triangleq$ Poisson cell volume element,

$K \triangleq$ a constant dependent upon the resistivity of the volume-conducting medium of the cell,

$i_s \triangleq$ the change in current flowing in the volume element $d\tau_c$.

This i_s is the current injected into each particular volume element $d\tau_s$ through the base of the Poisson cell.

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2. Korn, G. A. and Korn, T. M., Electronic Analog Computers, McGraw-Hill Book Co., p. 317; 1956.

Each source supplying the current i_s for each volume element $d\tau_s$ is a separate supply and will henceforth be called a current source. The current sources are constructed in modular form and packaged in panels in units of 32. There are fifty of these panels in the current source console. Each panel of sources may be connected by cable to any 32 unit section called groups of the Poisson cell. Thus, 1600 current sources can flexibly be utilized to serve 1600 of the 2688 discrete volume elements ($d\tau_s$) of the Poisson cell.

In the following, a single current source module is first discussed. This includes the theory of operation, output impedance, stability, and panel controls. Then, the panel unit is covered followed by a discussion of the source console and its operation. Finally, the system of addressing of space-charge simulating areas of the Poisson cell is discussed.

2.4.2 Current Source Module

2.4.2a Theory and Operation of Current Source. Figure VI.22 shows the schematic of a current source module. It consists of a 6661-6BH6 pentode with a large amount of degenerative feedback in the cathode circuit to provide plate current stability. The screen grid of the tube is directly connected to its power supply to increase the tube output impedance. The control grid is maintained at a fixed potential. The current range of approximately 1 to 500 microamperes is adjusted by varying the resistance in the cathode circuit. To provide the desired sensitivity of adjustment, the current range adjustment is accomplished in two stages by a lever switch. The center position of the lever switch opens the cathode circuit.

The tube filament is undervoltaged and is series connected to the heater of a bimetal switch. In this manner, a panel mounted neon light indicates if there is an open tube filament.

Operation of the push button connects the particular current source to a digital voltmeter for adjustment of the space-charge simulating injection current. The voltmeter is connected across a 10 kilohm precision resistor which is in series with the plate (injecting current) circuit. This push button also contains an "idiot" circuit which indicates if two or more current sources are simultaneously connected to the voltmeter. The indication is an audible noise and a light on the console power panel.

As seen in the picture of the operating controls of a current source, Fig. V.12, the lever switch adjusts the two ranges of the current source with center position off. The push button connects the current source to the voltmeter. The knob adjusts the injecting current value. The neon light is numbered to indicate the current source address and lights either if the push button connects the source to the voltmeter or if there is no cathode heater current.

2.4.2b Output Impedance. It is very desirable for this application that each current source have an output impedance that is as high as possible. This minimizes the loading effect of one supply upon another. Because one could need 1600 supplies that must be adjusted, it can be readily understood that high output impedance is a necessity. As shown in Fig. II.1, the current sources are designed to have a minimum output impedance of six megohms in the range of 1 to 500 microamperes. This value of impedance is determined on the basis of a plate voltage variation of 100 volts. This plate voltage variation is

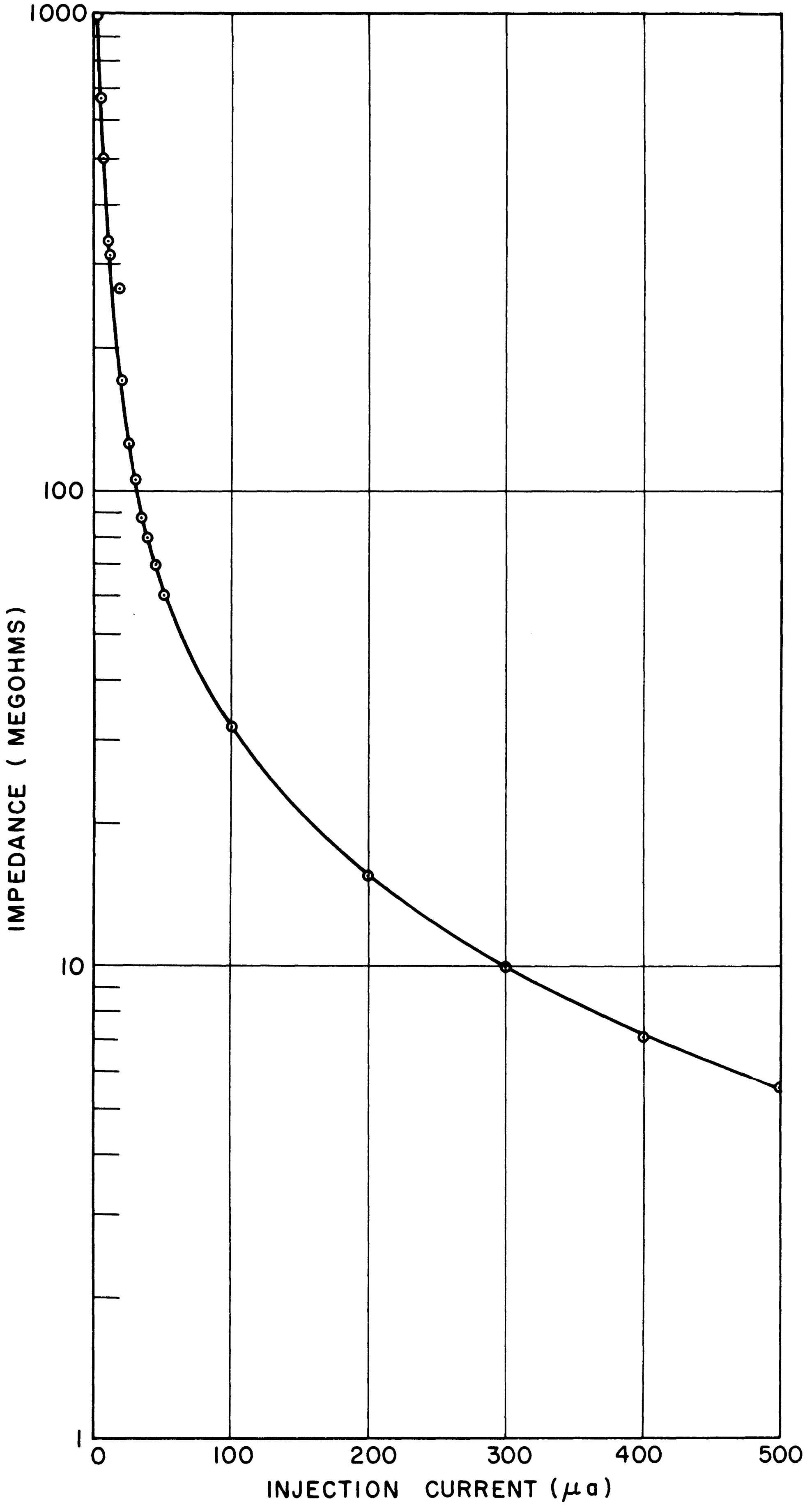

FIG. II.1 IMPEDANCE CHARACTERISTIC OF CURRENT SOURCE.

greater than any change that should occur due to loading in the trajectory calculator. Thus, the maximum loading effect upon any current source should be of the order of one percent of the injecting current.

2.4.2c Stability. From life tests, it was determined that stability was better than 2 percent for an operating time of 2000 hours. This was with some selection of tubes. In order to obtain good stability it is advisable to age new tubes at maximum plate dissipation and then select for stability. The failure rate of the tubes utilized in these current sources will be small because the cathode heater is undervoltaged and only small currents are drawn from the tube.

2.4.3 Current Source Panel. Figures V.12 and V.13 show front and back views of a current source panel. A panel contains 32 current source modules numbered successively from 1 to 32. These numbers specify the source numbers of one group (panel) of sources. At the top right-hand corner is a numbered amber light, which indicates the group number. This number may be changed from 1 to 84 by replacing the numbered lens. Both of the above sets of numbers (group number, 1-84, and source number, 1-32) relate to the region of the Poisson cell to which the current source panel is connected. The replaceable number in the top center of the panel indicates the position of the panel in the console.

2.4.4 Current Source Console. The current source console (Figs. V.11 through V.15) consists of seven vertical relay racks connected together to form the console. The center rack contains the power supplies and controls necessary to operate the console. Two current source panels are also included in this rack. The four remaining racks each contain eight current source panels. The sum total of source panels is 50, making a total number of 1600 current sources.

The center rack contains a voltmeter, console control panel, and, behind the removable door, the three power supplies that operate the current sources. Behind the blank panel, there is also a small power supply supplying power to the neon panel lights. The operation of the control panel will now be discussed, followed by a description of the operation of the power supplies.

2.4.4a Console Control Panel. The current sources console is separately controlled from the console control panel (Fig. V.14). Mounted on the panel are two push-button switches, lettered "FIL" and "DC", voltmeter input switch, a panel light, and three fuse holders. The operation and use of each control are detailed below.

"FIL" Switch. For initial warm-up of console. Supplies power to:

a. filaments of current sources

b. filaments of 200 volt supply

c. blowers

d. neon lights power supply

e. digital voltmeter

This is a push to operate, push to release switch. The switch is lighted if power is supplied to the filament power supply. It is advisable to allow a half hour warm-up period.

"DC" Switch. Applies the d-c power to the current sources. Supplies power to:

a. 200 V-screen grid supply (Lambda)

b. 15 V control-grid supply (Kepco)

Again, this is a push-push type switch. When shutting down, be sure to release this switch before releasing the "FIL" switch.

Voltmeter Input Switch. This eight-unit switch controls the input to the panel mounted Hewlett-Packard Digital Voltmeter. The Digital Voltmeter is used for adjustment of the current sources and monitoring of the console power supplies. The eight positions of the switch are:

200 - monitors the output of the 200 volt screen grid supply

15 - monitors the output of the 15 volt screen grid supply

FIL - monitors the output of filament transformer supply

+100V - monitors the +100V computer reference supply

-100V - monitors the -100V computer reference supply

I_s - connects the digital voltmeter to distribution panel for monitoring of currents from current source

LINE - monitors the 110V 60 cycle output to the console

OFF - connects voltmeter input to connectors on front panel of voltmeter. This is for the purpose of utilizing the voltmeter in trouble shooting.

NOTE: The front panel connectors must not be shorted to the frame for correct measurements in other positions (remove shorting bar).

Panel Light. This is an incandescent light called an "idiot" light. Since pushing the push-button switch of a current source connects the source output to a common buss, having more than one current source connected to this buss will cause errors in the source currents. An auxiliary circuit, therefore, has been included to cause this "idiot" light to light and an audible alarm to sound if two or more current source push buttons are in the "on" position. In order to deactivate this light and alarm, all of the current source push-button switches must be in the "off" position.

Fuses. These fuses are associated with the application of power to control functions within the console itself.

2.4.4b Console Power Supplies. The three power supplies necessary for the operation of the current sources are shown in Fig. V.15. These are mounted in the center rack behind a removable door. The bottom supply is a Lambda 1.5 ampere, 125-325 volt supply. This supply, set at 200 volts, supplies the screen grids of the 6661-6BH6 pentode in each of the current sources. The next supply supplies heater current to the filaments of the pentodes. It is a constant voltage transformer with a 250 ampere output. The supply is adjusted to operate the filaments at below rated current. The third supply, a Kepco, supplies the 15 volts to the pentode control grids. Note that the control grid connection is positive.

2.4.5 **Addressing System.** In this trajectory tracer, bookkeeping is a very important factor. One must definitely know which current source is connected to which discrete region ($d\tau_s$) of the Poisson cell. Also, one must know the positions of these discrete regions with respect to the coordinate axis of the particular problem. Again, in calculating space-charge densities the particular regions of the Poisson cell must be known.

Thus, a common addressing system is utilized throughout the trajectory calculator and must be rigidly adhered to in doing any mathematical calculations. Figure II.2 shows a plan of the Poisson

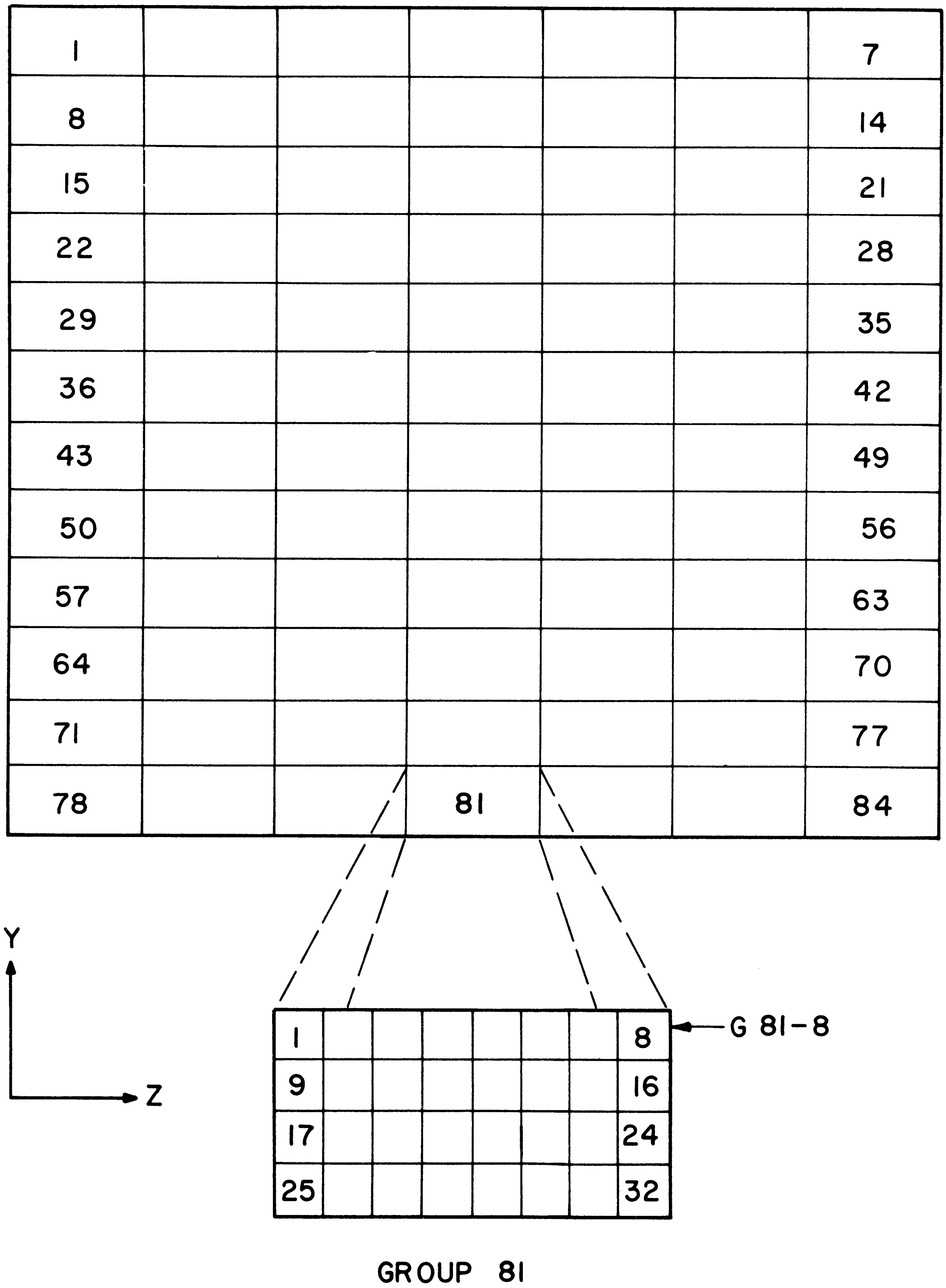

FIG. II.2 PLAN DIAGRAM OF CURRENT SOURCE ELEMENTS OF POISSON CELL (TOP VIEW).

cell and the spring-loaded plungers that supply the space-charge simulating currents. There are 2688 of these plungers, i.e., there are 2688 discrete regions on the cell. These regions are divided into 84 groups of 32 regions. Each discrete region is addressed as follows: first, the group number (1-84) is given and then the number of the region (1-32) in each group; as an example G71-6 indicates the sixth source of the seventy-first group as indicated on the plan. All other places where this kind of addressing is important are also numbered accordingly.

The connector board and plug board (see Figs. V.6 and V.7) are connected in a one-to-one correspondence with the cell. Each is addressed as above with the group numbers marked on the boards. The current sources are connected into the Poisson cell through the connector panel. Since there are only 50 groups of 32 current sources, only 50 of the 84 connectors on the connector board can be connected to current sources, thus the reason for the amber light (group number indicator) on each current source panel. When a current source panel is plugged into a desired group of the Poisson cell at the connector panel, the lens of the amber panel light is changed to correspond to the proper group number. By this method, the 50 groups of current sources can serve the 84 groups of the Poisson cell and give continuity of addressing.

2.5 Recording x-y Plotter

The input to the 1100E Variplotter is the electron position output from the computer. This then serves to record the various trajectories that are plotted upon the Poisson cell by the gradient reading probe. Initially, the record of these trajectories is utilized to determine the amount of space charge to be injected into the Poisson cell. The final set of trajectories serves as a record of the solution of the problem.

III. THE USE OF THE SYSTEM IN THE SOLUTION OF TRAJECTORY PROBLEMS

3.1 Introduction

The integrated components in this system can be divided into two main groups: a nonlinear function generator called a Poisson cell which is used to simulate fields analogous to those in the device under consideration, and an analog computer which uses the information from the nonlinear function generator to determine the ballistic equations for electrons in the device. The flow diagram of the tracer is shown in Fig. V.2. The nonlinear function generator consists of the following three components.

1. The Poisson cell, a conducting media on which potential gradients satisfy Laplace's equation in two dimensions.

2. The 205-S x-y plotter which has been modified to carry a probe for determining gradients and potentials on the Poisson cell.

3. The current source module from which currents can be adjusted and directed to any of the 2688 sources on the Poisson cell making possible the solution of Poisson's equation on the cell. As a whole, the system operates as follows. The probe system, which simulates an electron, reads the gradients from the Poisson cell and passes the information to the computer; the computer, which is programmed to solve the electron ballistic equations, uses these gradients to determine the relative velocity and direction in which an electron would move when faced with these conditions and relays this information to the pen of the modified 205-S plotter; the probe then moves to the new position as directed by the computer and starts the cycle over again by picking up

the gradients at this new position. This process is continuous making it possible to solve for and plot the paths of electrons as they move in the actual device. This section will describe in detail the purpose of each of the various components and illustrate how each can be used to accomplish its purpose.

3.2 The Poisson Cell

In order to generate the electric-field distribution analogous to that in the actual device, a model must be constructed which has some convenient variable satisfying Laplace's and Poisson's equations. As a model, the function generator uses a conducting medium, called a Poisson cell, on which the electrode geometry of the device is constructed; as a variable, it uses the potential on the surface of this Poisson cell.

To demonstrate how the potentials satisfy Laplace's equation on the Poisson cell, consider an infinitesimal element of the cell with y and z components of current density passing through it (see Fig. III.1). Continuity requires that the net current leaving the surfaces of this volume be zero. Thus

$$\left(i_y + \frac{\partial i_y}{\partial y}\, dy\right) dz + \left(i_z + \frac{\partial i_z}{\partial z}\, dz\right) dy - i_y\, dz - i_z\, dy = 0 , \qquad (3.1)$$

$$\frac{\partial i_y}{\partial y}\, dy\, dz + \frac{\partial i_z}{\partial z}\, dz\, dy = 0 ,$$

$$\frac{\partial i_y}{\partial y} + \frac{\partial i_z}{\partial z} = 0 . \qquad (3.2)$$

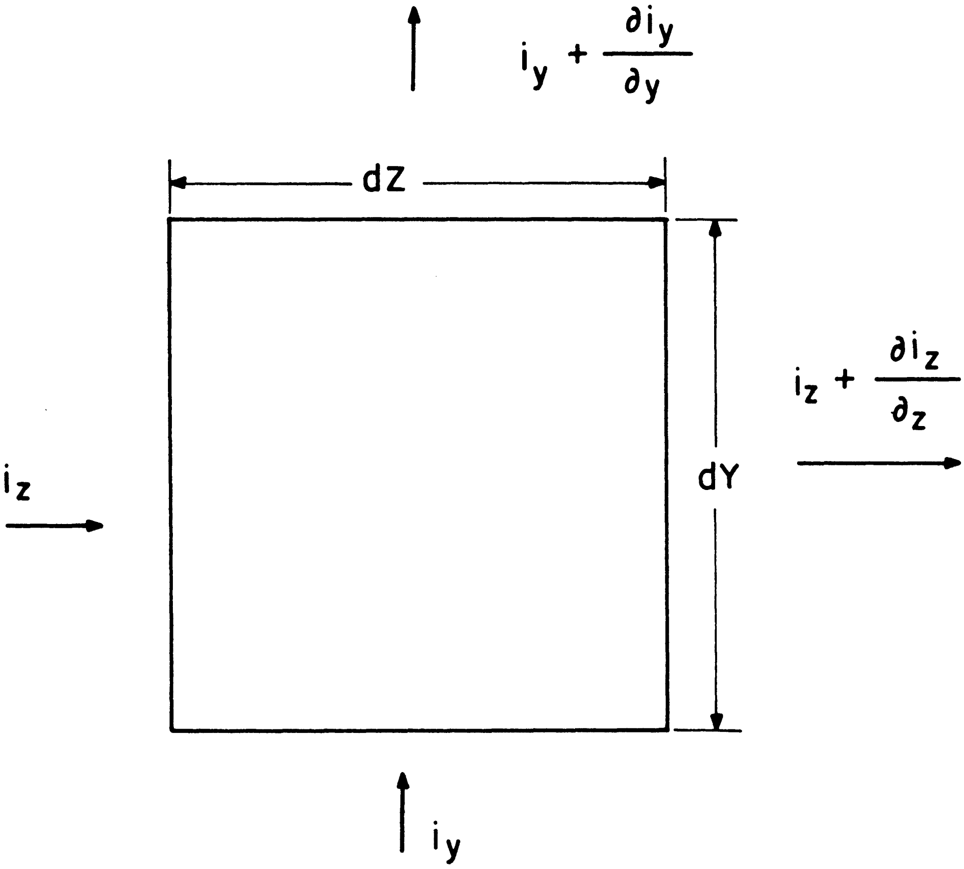

FIG. III.1 DERIVATION OF LAPLACE'S EQUATION.

Writing the currents in terms of the voltage gradients, in the two directions, and substituting into Eq. 3.2 yields:

$$i_y = -\frac{1}{R}\frac{\partial V}{\partial y} ,$$

$$i_z = -\frac{1}{R}\frac{\partial V}{\partial z} . \qquad (3.3)$$

$$-\frac{1}{R}\left[\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right] = 0 ,$$

$$\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 . \qquad (3.4)$$

R = resistivity of the conducting medium (ohms/meter).

Thus the voltages on the surface of the Poisson cell satisfy Laplace's equation and can be scaled to represent the voltages of the actual device in areas free of sources or sinks.

In order for the potential distribution to satisfy Poisson's equation, sources must be introduced throughout the plate. With a source of current i_ρ connected to the bottom of the element in Fig. III.1, the continuity relation, Eq. 3.1, becomes:

$$\left(i_y + \frac{\partial i_y}{\partial y}dy\right)dz + \left(i_z + \frac{\partial i_z}{\partial z}\right)dy - i_y\,dz - i_z\,dy - i_\rho\,dz\,dy = 0 ,$$

$$\frac{\partial i_y}{\partial y} + \frac{\partial i_z}{\partial z} = i_\rho . \qquad (3.5)$$

Substituting Eq. 3.3 in Eq. 3.5 yields

$$\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = - R i_\rho \quad . \qquad (3.6)$$

Therefore, the potential in a region of the cell over a source (or sink) of current also satisfies Poisson's equation in two dimensions, establishing the Poisson cell as a model to simulate the conditions in an electron device where space charge is a factor. Thus, the existence of a relationship between the fields in an electron device and the potentials on a Poisson cell have been established, and it remains only to set up the scaled electrode geometry of the device on the Poisson cell to complete the model. In order to set up this geometry, it is necessary to establish equipotentials throughout the thickness of the cell in positions which correspond to the actual electrode positions in the device under study.

There are two methods of establishing these equipotentials on the Poisson cell. The first, utilizing surface electrodes and shorting on the underside of the cell, is the more versatile in that geometry changes can be made without changing plates. However, it does not provide a good representation of the real device near these electrodes because it does not establish a definite equipotential plane through the thickness of the cell.

The second method involves drilling holes under the electrodes and painting the holes with conducting paint to better establish this equipotential plane. This method also utilizes the surface electrodes and shorting techniques of the previous one and, thus, creates a more accurate analog. The disadvantage of this second method is that any increase in dimensions of the geometry necessitates a new plate. For our use, it has been found that, if the cathode is cut out and this edge painted with conducting paint, the surface electrodes provide a good enough representation elsewhere for crossed-field geometries. For axially symmetric geometries, the error introduced by using only surface electrodes and underside shortings becomes larger as the radial distance of the electrodes increases because the thickness of the plate increases. In some cases, the geometry or the nearness of trajectories to electrodes may make it necessary to use the second method. The use of the vacuum hold-down makes the second method more feasible by eliminating the time consuming wiring involved in changing plates on the older system.

In the case of the wedge, an additional problem is introduced by the finite thickness of the edge. Ideally, the plate should taper down to an infinitely thin section at the axis, and to keep the analogy between the Poisson cell and the corresponding volume in the actual device, a resistance network must be constructed to simulate the resistance of the missing thin edge. A one-dimensional resistance network, which maintains the missing edge resistance between the sources of the last row of the plate, is sufficient for this purpose (see Fig. III.2). If R is the volume resistivity of the plate, $\Delta \ell$ is the axial length between sources, t is the thickness of the existing thin edge, and r is the projected distance from the existing thin edge to the axis. The resistance to be connected between the sources is

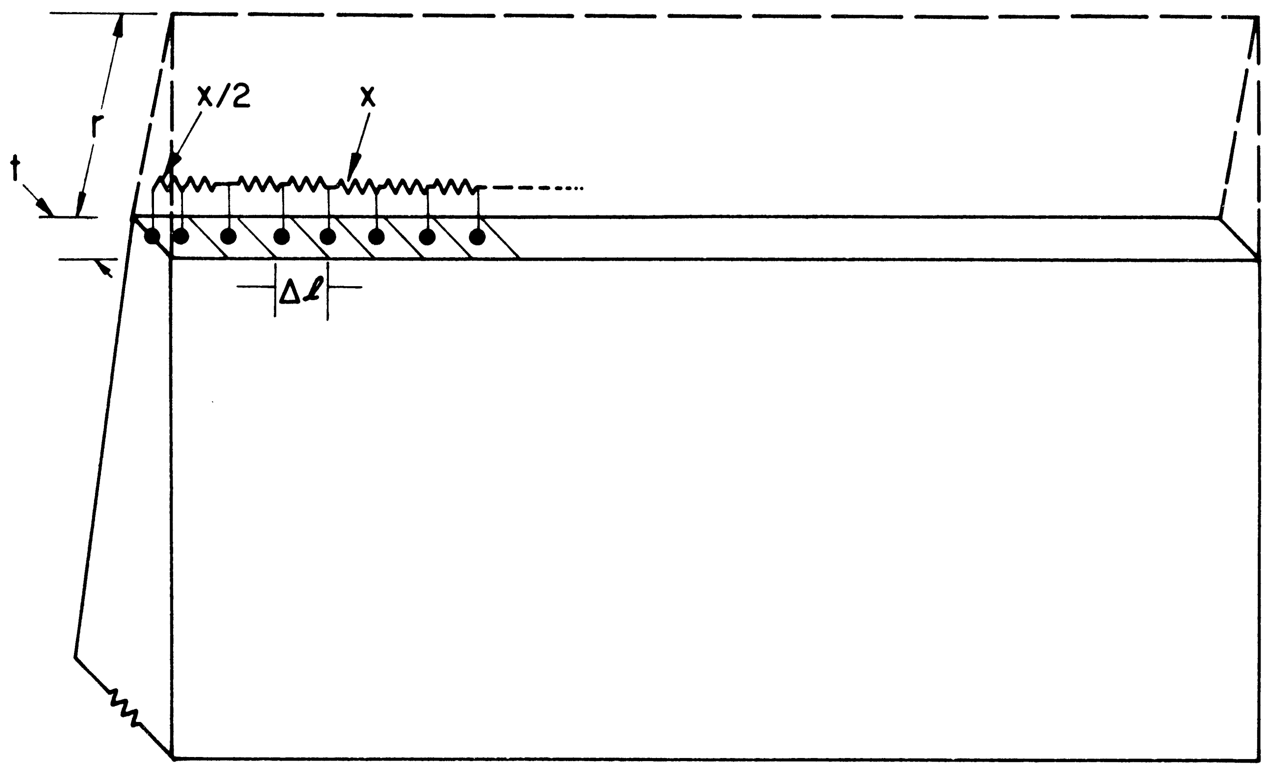

FIG. III.2 SIMULATION OF THIN EDGE OF WEDGE-TYPE POISSON CELL.

$$x = \frac{R\Delta\ell}{A} = \frac{R\Delta\ell}{\frac{1}{2}rt} = 2\frac{R\Delta\ell}{rt} \quad . \qquad (3.7)$$

Since the resistor between the edge of the plate and the first source simulates only half as much volume as the others, this resistance is only half as large as shown in Fig. III.2.

3.3 Probe Assembly

The 205-S plotter has been modified to carry a probe assembly from which voltages on the surface of the cell can be read. These probes are connected directly to the computer and continuously supply it with the electric field information it needs to solve the ballistics equations for the device being tested. The servomechanisms on the plotter, which control the probe position and velocity, receive instructions from the output of the computer. Connected as such, the probe system simulates an actual electron and traces the path that an electron would take if faced by the field configuration on the cell.

The plotter can be used with either a four-probe or a five-probe assembly. The probe positions for the two cases are illustrated in Figs. III.3 and III.4. With the four-probe system, the y and z gradients are approximated as follows:

$$\frac{\partial V}{\partial y} \cong \frac{\Delta Vy}{\Delta y} = \frac{1}{2\ell}\left[V_A + V_C - V_B - V_D\right] \qquad (3.8)$$

and

$$\frac{\partial V}{\partial z} \cong \frac{\Delta Vz}{\Delta z} = \frac{1}{2\ell}\left[V_C + V_D - V_A - V_B\right] \quad . \qquad (3.9)$$

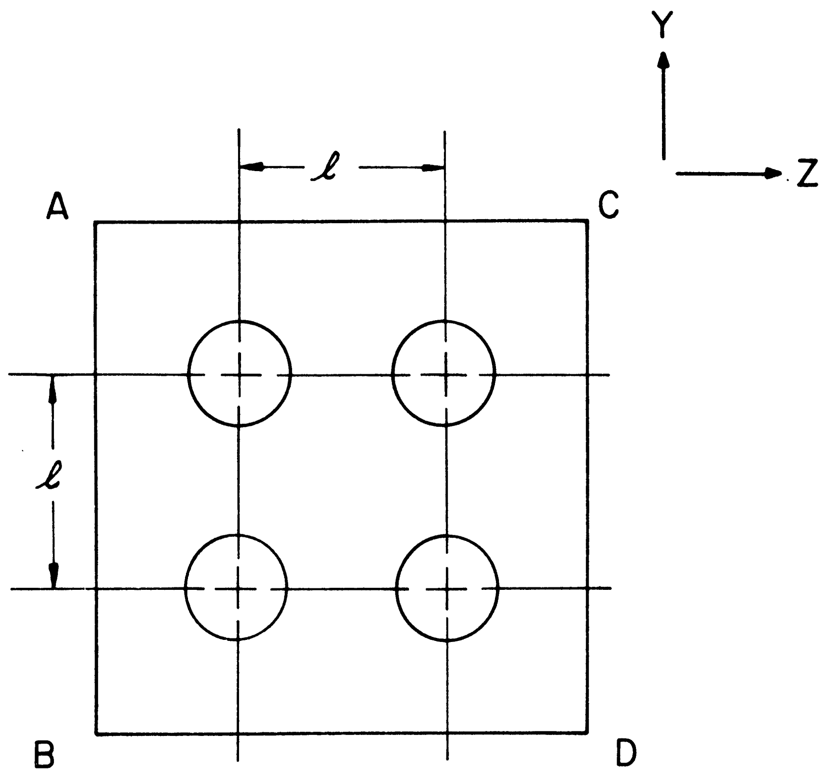

FIG. III.3 FOUR-POINT PROBE GEOMETRY.

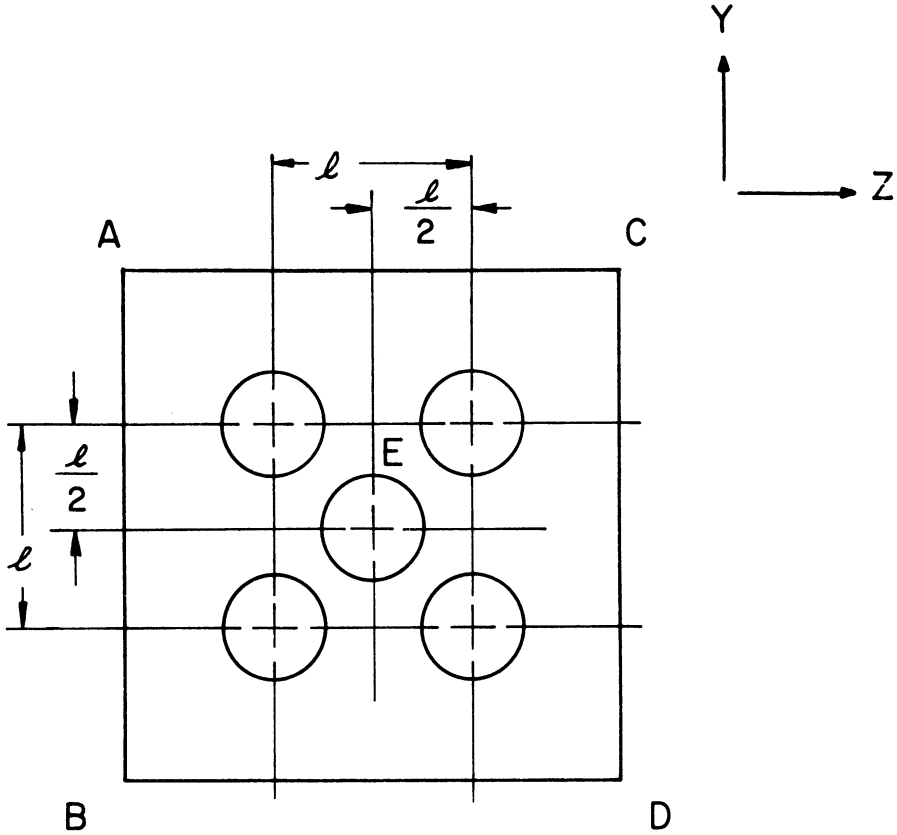

FIG. III.4 FIVE-POINT PROBE GEOMETRY.

For an approximation of the voltage at the center of the assembly, the four-probe voltages are averaged as follows:

$$V = \frac{1}{4}\left[V_A + V_B + V_C + V_D\right] . \tag{3.10}$$

The five-probe assembly utilizes the same technique for determining the gradients. In addition, the fifth probe makes it possible to obtain the center voltage exactly and makes possible an approximation of the second-order partial derivatives. The second-order partial derivatives can then be used in Poisson's equation to obtain an approximation of the space-charge density present at the particular position of the probe assembly.

$$\frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = -\frac{\rho}{\epsilon_o} ,$$

$$\frac{\Delta}{\Delta y}\left(\frac{\Delta Vy}{\Delta y}\right) \cong \frac{\partial^2 V}{\partial y^2} \cong \frac{1}{\ell/2}\left[\frac{\frac{1}{2}(V_A + V_C - 2V_E)}{\ell/2} - \frac{\frac{1}{2}(2V_E - V_B - V_D)}{\ell/2}\right]$$

$$\cong \frac{2}{\ell^2}\left[V_A + V_B + V_C + V_D - 4V_E\right] ,$$

$$\frac{\Delta}{\Delta z}\left(\frac{\Delta Vy}{\Delta z}\right) \cong \frac{\partial^2 V}{\partial z^2} \cong \frac{1}{\ell/2}\left[\frac{\frac{1}{2}(V_C + V_D - 2V_E)}{\ell/2} - \frac{\frac{1}{2}(2V_E - V_A - V_B)}{\ell/2}\right]$$

$$\cong \frac{2}{\ell^2}\left[V_A + V_B + V_C + V_D - 4V_E\right] ,$$

thus

$$\rho = -\frac{4\epsilon_c}{\ell^2}\left[V_A + V_B + V_C + V_D - 4V_E\right] .$$

The advantage of the five-probe system is that it provides an independent method of calculating the amount of space charge present at any one place on the analog. This calculation can then be compared with the value used to calculate the injected currents, giving an idea of the accuracy of the representation and providing a method by which it can be improved. The distinct disadvantage is that the introduction of the fifth probe requires an increase in probe spacing, making the gradient determination less accurate. Thus, the four-probe system is always utilized for the calculation of trajectories.

3.4 Analog Computer

With the nonlinear function generator (i.e., Poisson cell) set up to generate the gradients in the device, the next step is to set up the computer to use these gradients in solving the ballistic problem.

To derive the equations that the computer must solve, consider first a particle traveling in a crossed-field device (the equation from this derivation can be used for electrostatically-focused devices if the magnetic field is made zero) as shown in Fig. III.5.

From the generalized force equation,

$$\vec{F} = m\vec{a} = q(\vec{E} + \vec{v} \times \vec{B})$$

and the simplification of the geometry,

$$\vec{B} = \vec{i}B_x ,$$

$$\vec{E} = \vec{j}E_y + \vec{k}E_z ,$$

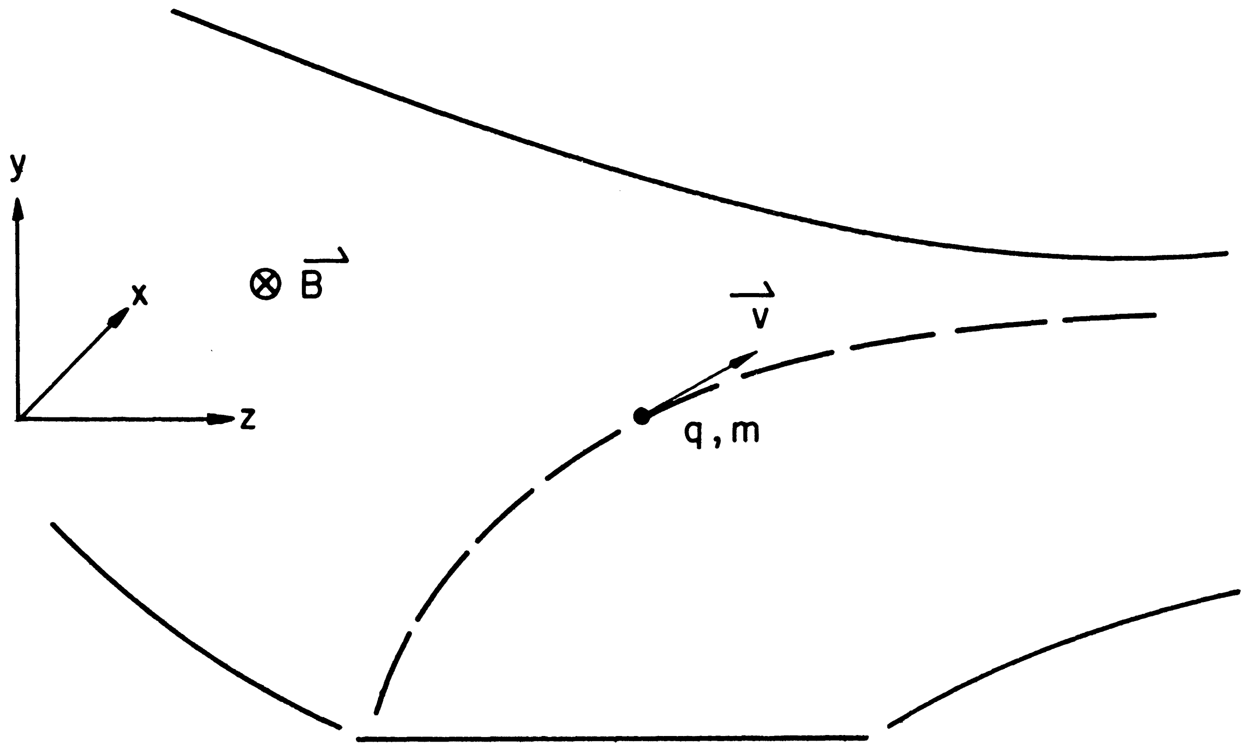

FIG. III.5 SOLUTION OF THE BALLISTICS EQUATIONS.

$$m\left[\frac{d^2x}{dt^2}\vec{i} + \frac{d^2y}{dt^2}\vec{j} + \frac{d^2z}{dt^2}\vec{k}\right] = q\left[(E_y + B_x v_z)\vec{j} + (E_z - B_x v_y)\vec{k}\right] .$$

Thus

$$\frac{d^2x}{dt^2} = 0 ,$$

$$\frac{d^2y}{dt^2} = \frac{q}{m}[E_y + B_x v_z]$$

and

$$\frac{d^2z}{dt^2} = \frac{q}{m}[E_z - B_x v_y] .$$

Since the field is conservative, the electron will also satisfy the following energy equation and it can thus be used to check the accuracy of the output.

$$\frac{1}{2}mv^2 = -qU + C_o ,$$

where U = the tube potential

$$-\frac{2q}{m}U = \overline{\frac{dy}{dt}}^2 + \overline{\frac{dz}{dt}}^2 + C_o ,$$

C_o is dependent upon the initial conditions of the problem.

Defining,

$$\frac{q}{m} \triangleq -N \qquad p \triangleq \frac{d}{dt}$$

$$\frac{q}{m}B \triangleq -\omega_c \qquad p^2 \triangleq \frac{d^2}{dt^2} .$$

The equations to be programmed for the computer are

$$p^2y = - N E_y - \omega_c pz \quad . \tag{3.11}$$

$$p^2z = - N E_z + \omega_c py \quad . \tag{3.12}$$

$$2NU = \overline{py}^2 + \overline{pz}^2 \quad . \tag{3.13}$$

Next, these equations must be converted to machine equations for use in the computer*[2,3]. To simplify this conversion, the following symbols, definitions, and scale factors will be used:

y, z tube coordinates in meters,

y_a, z_a analog coordinates in meters,

t tube time,

T machine time,

$p = \frac{d}{dt}$ tube time derivative,

$P = \frac{d}{dT}$ machine time derivative,

Y, Z machine variables proportional to y and z,

$\dot{Y}, \dot{Z}$ machine time derivatives of variables proportional to py and pz,

u tube potential,

u_o maximum tube potential,

V analog potential,

V_o maximum analog potential.

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* It is presumed that the reader is familiar with the operation of analog computers. See References 2 and 3.

3. Johnson, C. L., Analog Computer Techniques, McGraw-Hill Book Co.; 1963.

$$a_y \equiv \frac{Y}{y} = \frac{Y_{max.}}{y_{max.}} = \frac{1\ MU}{|y_{max.}|} \left(\frac{MU}{meter} \right) ,$$

where MU = machine units.

$$a_z \equiv \frac{Z}{z} = \frac{Z_{max.}}{z_{max.}} = \frac{1\ MU}{|z_{max.}|} \left(\frac{MU}{meter} \right) ,$$

$$b_y \equiv \frac{\mathring{Y}}{Py} = \frac{\mathring{Y}_{max.}}{|Py|_{max.}} = \frac{1\ MU}{|Py|_{max.}} \left(\frac{MU - sec.}{meter} \right) ,$$

$$b_z \equiv \frac{\mathring{Z}}{Pz} = \frac{1\ MU}{|Pz|_{max.}} \left(\frac{MU - sec.}{meter} \right) ,$$

$$M \equiv \frac{y_s}{y} = \frac{z_s}{z}$$ (Magnification of analog relative to actual device.) ,

$$k \equiv \frac{V}{U} = \frac{V_o}{U_o} = \frac{1}{U_o} \left(\frac{MU}{volt} \right) ,$$

$$A = \frac{T}{t} = \frac{p}{P} \left(\frac{\text{machine time}}{\text{tube time}} \right) .$$

Equations 3.11, 3.12, and 3.13 must be written in terms of machine variables in order to be solved. Substituting computer time for tube time yields

$$P^2 y = -\frac{N}{A^2} E_y - \frac{\omega_c}{A} Pz , \qquad (3.14)$$

$$P^2 z = -\frac{N}{A^2} E_z + \frac{\omega_c}{A} Py , \qquad (3.15)$$

$$2\,\frac{N}{A^2}\,U + C_o = (Py)^2 + (Pz)^2 \quad . \tag{3.16}$$

The gradients in the y and z directions are obtained from the probe voltages and probe spacings.

$$E_y = -\frac{(\Delta U)_y}{\Delta y} \quad ,$$

$$E_z = -\frac{(\Delta U)_z}{\Delta z} \quad .$$

In terms of analog quantities,

$$\Delta y = \Delta\left(\frac{y_a}{M}\right) = \frac{\Delta y_a}{M} = \frac{\ell}{M} = \Delta z \quad ,$$

where ℓ is the analog probe spacing. Then,

$$E_y = -\frac{M}{k\ell}\,(\Delta V)_y \quad ,$$

$$E_z = -\frac{M}{k\ell}\,(\Delta V)_z \quad .$$

With these changes, Eqs. 3.14, 3.15, and 3.16 become

$$P^2y = \frac{NM}{k\ell A^2}\,(\Delta V)_y - \frac{\omega_c}{A}\,Pz \quad , \tag{3.17}$$

$$P^2z = \frac{NM}{k\ell A^2}\,(\Delta V)_z + \frac{\omega_c}{A}\,Py \tag{3.18}$$

and

$$\frac{2N}{kA^2}\,(V + V_o) = (Py)^2 + (Pz)^2 \quad . \tag{3.19}$$

The integrators in the computer respond such that an input of Pf produces an output, -f, i.e.,

$$\int PfdT = \int \frac{df}{dT} dT = \int df = -f + \text{const.}$$

Therefore, to obtain an output of $Y = a_y y$ or $Z = a_z z$, the input must be of the form $- a_y Py$ or $- a_z Pz$, respectively. Similarly, to obtain $\dot{Y} = b_y P_y$ or $\dot{Z} = b_z Pz$ as outputs, the inputs must be of the form $- P\dot{Y} = - b_y P y$, or $- PZ = - b_z P z$, respectively. To simplify the calculation and the resulting equations, let $b_y = b_z = b$. Thus $\dot{Y}$ and Z can be easily generated with the circuits as shown in Fig. III.6.

To put the equations in their final form, multiply Eqs. 3.17 and 3.18 by b and Eq. 3.19 by b.

$$bP_y^2 = \frac{bNM}{k\ell A^2} (\Delta V)_y - \frac{\omega_c}{A} \dot{Z} \quad ,$$

$$bP_z^2 = \frac{bNM}{k\ell A^2} (\Delta V)_z + \frac{\omega_c}{A} \dot{Y} \quad ,$$

$$\frac{2Nb^2}{kA^2} (V + V_o) = (\dot{Y})^2 + (\dot{Z})^2 \ .$$

Defining

$$C_1 \triangleq \frac{bNM}{k\ell A^2} \quad ,$$

$$C_2 \triangleq \frac{\omega_c}{A} \quad ,$$

$$C_3 \triangleq \frac{2Nb^2}{kA^2}$$

gives

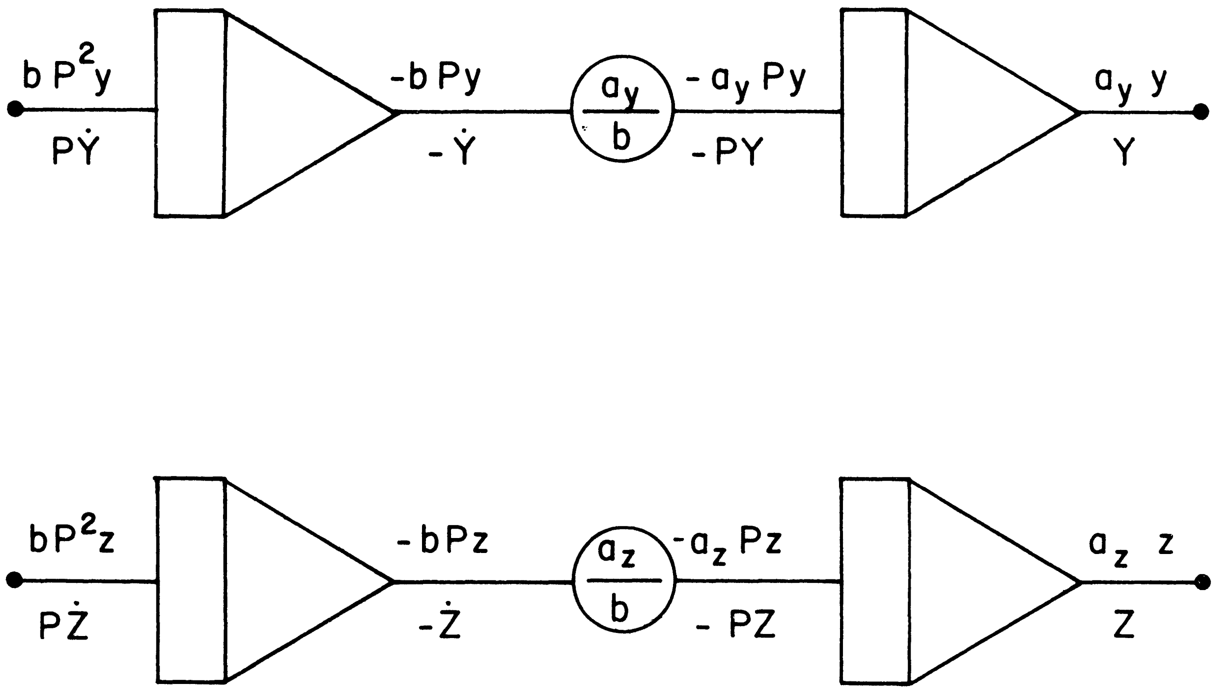


FIG. III.6 GENERATION OF ELECTRON POSITION BY COMPUTER.

$$bP^2y = C_1 (\Delta V)y - C_2 \dot{Z} \quad , \tag{3.20}$$

$$bP^2y = C_1 (\Delta V)_z + C_2 \dot{Y} \quad , \tag{3.21}$$

$$C_3 (V + V_o) = \dot{Y}^2 + \dot{Z}^2 \quad . \tag{3.22}$$

In addition, define

$$C_4 \triangleq \frac{a_y}{b} \quad , \tag{3.23}$$

$$C_5 \triangleq \frac{a_z}{b} \quad . \tag{3.24}$$

Some of the scale factors can be written in a more useful form to simplify the computation of constants C_1 through C_5. For instance, the time scale factor, A, can be reformulated as follows:

$$A = \frac{T}{t} = \frac{p}{p} \cdot \frac{y}{y} = \frac{py}{P\ (y_a/M)} = M \frac{py}{P\ y_a}$$

$$= M \frac{(py)_{max.}}{(Py_a)_{max.}} \quad .$$

Since the field is conservative, $(py)_{max.}$, the maximum tube velocity can be related to the maximum tube potential as follows:

$$(py)_{max.} = \sqrt{2N\ U_o}$$

and Eq. 3.15 becomes

$$A = \frac{M\ \sqrt{2N\ U_o}}{(Py_a)_{max.}} \quad .$$

Also, the maximum probe velocity on the analog, $(Py_a)_{max.}$, is limited by the system and is specified to be some value that the 205-S plotter can easily achieve. In most cases, $(Py_a)_{max.} = 1/40$ m/sec. is satisfactory.

The velocity scale factor b can also be restated as follows:

$$b = \frac{1}{\left(P\frac{y_a}{M}\right)_{max.}} = \frac{M}{(Py_a)_{max.}} \qquad (3.26)$$

Using Eqs. 3.25 and 3.26 and recalling that $k = 1/U_o$, C becomes

$$C_1 = \frac{bNM}{k\ell A^2} ,$$

$$C_1 = \frac{(Py_a)_{max.}}{2\ell} .$$

Similarly,

$$C_3 = \frac{2Nb^2}{kA^2} = 1, \text{ for all cases.}$$

Since a_y and a_z can be rewritten as

$$a_y = \frac{1}{y_{max.}} = \frac{M}{|(y_a)|_{max.}}$$

and

$$a_z = \frac{M}{|z_a|_{max.}} ,$$

therefore,

$$C_4 = \frac{a_y}{b} = \frac{M}{|y_a|_{max.}} \frac{|Py_a|_{max.}}{M} = \frac{|Py_a|_{max.}}{|y_a|_{max.}}$$

and

$$C_5 = \frac{|Pz_a|_{max.}}{|z_a|_{max.}} .$$

Thus the five constants can be rewritten:

$$C_1 = \frac{|Py_a|_{max.}}{2\ell} ,$$

$$C_2 = \frac{NB}{A} ,$$

$$C_3 = 1 ,$$

$$C_4 = \frac{|Py_a|_{max.}}{|y_a|_{max.}} ,$$

$$C_5 = \frac{|Pz_a|_{max.}}{|z_a|_{max.}} .$$

In addition to their use in solving the ballistic and energy equations, several of the computer's components are used in the actual measurement of the probe voltages, in forming the gradients, and in averaging the four-probe voltages. (This last circuit is needed only when using the four-probe assembly.)

In order to obtain an accurate measurement of the probe voltage, it is necessary to introduce unloading amplifiers in the probe circuits. These make it possible for the computer to read the voltages without drawing current from the cell. If the amplifiers were not used, current would be drawn through the probes and the high contact resistance between the plate and the probes would introduce a significant drop in the voltage at the computer. The gradients and average voltage are computed according to Eqs. 3.8, 3.9, and 3.10.

The computer roadmap for the furnished wired computer plugboard is shown in Drawing VI.13.

3.5 Solution for Space-Charge Distribution

Before the space-charge effects existing in the actual device can be simulated in the nonlinear function generator, an exact relationship must be derived between the current injected into an element on the Poisson cell and the space-charge density at the corresponding point in the actual device. Lastly, a method must be devised by which the space charge at any point in the device can be computed from measurable quantities taken from the Poisson cell. In this section, these two relationships will be derived and then combined to give the final form of the formula for calculating the injection currents in terms of the Poisson cell quantities.

In the following two derivations, these scaling constants will be used.

$$V_t = kV_s \quad \text{voltage scaling} \quad ,$$

$$d_t = Md_s \quad \text{distance scaling} \quad . \qquad (3.27)$$

Also, the subscript "t" will refer hereafter to actual quantities in the device under study, whereas "s" will refer to the simulated quantities of the Poisson cell.

Using these relations, the exact relationship between the injection currents and the space-charge density in the device can be derived as follows:

$$i = \int_{A_s} J_s \, dA_s \quad ,$$

whereas A_s is the area of the volume element into which the current will be injected, and J_s is the current density in that volume.

Using the Divergence theorem,

$$i = \int_{\tau} \nabla \cdot J_s \, d\tau \quad , \qquad (3.28)$$

where τ is the volume of the element into which i is injected.

To get the integrand in a more useful form, express the current density in the Poisson cell in terms of the field in the cell and the conductivity of the cell,

$$\vec{J}_s = \sigma \vec{E}_s \quad ,$$

apply the Laplacian operator to both sides, and convert to actual device quantities

$$\nabla_s \cdot \vec{J}_s = \nabla_s \cdot \sigma \vec{E}_s$$

$$= M \nabla_t \cdot \sigma \left(\frac{M}{k} \right) \vec{E}_t \quad .$$

For this application, the field is constant with respect to time and is conservative; thus, it can be derived from a potential in accordance with

$$\vec{E} = - \nabla V \quad .$$

Therefore,

$$\nabla_s \cdot \vec{J}_s = \sigma \frac{M^2}{k} \nabla_t \cdot (- \nabla_t V_t)$$

$$= \sigma \frac{M^2}{k} [- \nabla^2 V_t] \quad .$$

Use of Poisson's equation gives

$$\nabla^2 V = - \frac{\rho}{\epsilon_o} \quad ,$$

$$\nabla_s \cdot \vec{J}_s = \frac{\sigma M^2}{k} \frac{\rho_t}{\epsilon_o} \quad . \tag{3.29}$$

Substituting Eq. 3.29 into Eq. 3.28 yields

$$i = \int_\tau \left(\frac{M^2}{k} \right) \frac{\rho_t}{\epsilon_o} \, d\tau$$

and assuming the integrand constant over the volume

$$i = \frac{\sigma M^2}{k \epsilon_o} \cdot \rho_t \cdot \Delta\tau_s \quad , \tag{3.30}$$

where $\Delta\tau_s$ is the volume of the element into which i is to be injected. Thus, Eq. 3.30 allows a simulation current to be calculated from the space-charge density at the point in question in the actual device.

The next problem to be tackled is the determination of the space-charge density at any point in the device in terms of Poisson cell quantities. This can be approached from two different angles, both of which utilize data taken from the analog.

The first method is based on the following formula:

$$J_t = \rho_t v \qquad \text{or} \qquad \rho_t = \frac{J_t}{v} \quad , \tag{3.31}$$

where J_t = the current density at the point in question in the actual device,

ρ_t = the space-charge density at that point, and

v = the velocity of the electrons at that point.

In order to determine the current density at a specific point, the electron flow must be assumed laminar so that a relation can be established between the current density at a point and the current density at the cathode. With this assumption, the region between any two electron trajectories can be considered a flux tube and the following relationship exists:

$$J_t = G\, J_c \quad , \tag{3.32}$$

where G is the ratio of the cross-sectional area of the flux tube at the cathode to the area at the point in question, and J_c is the current density at the cathode (see Fig. III.7).

Since the field is consërvative the velocity of the beam at a point can be related to the potential at that point using conservation of energy as follows:

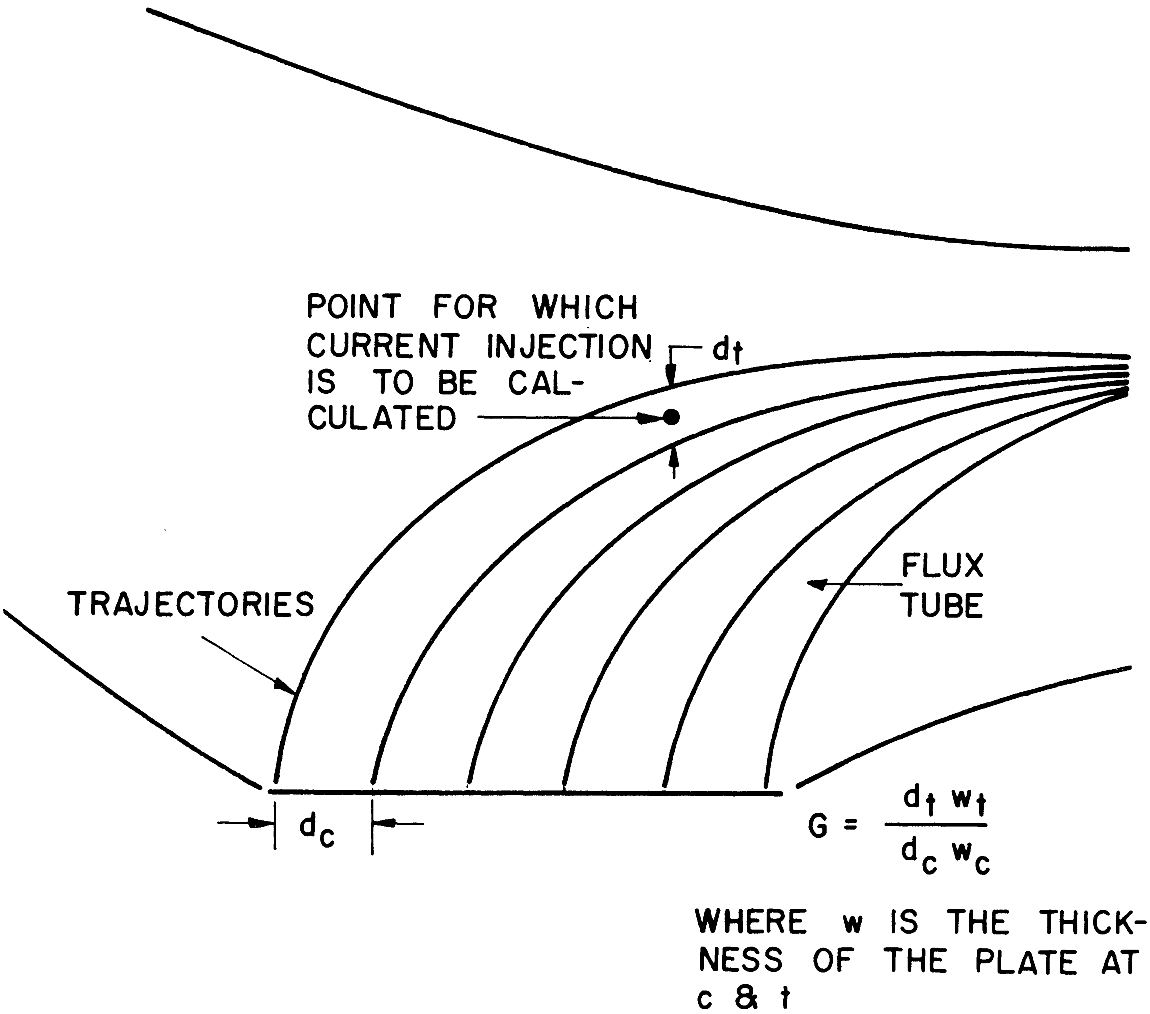


FIG. III.7 CALCULATION OF SPACE-CHARGE DENSITY (LAMINAR FLOW).

$$\frac{1}{2} mv^2 = q V .$$

Thus

$$v = \sqrt{2\eta V_t} = \sqrt{2\eta k V_s} , \qquad (3.33)$$

where η is the charge-to-mass ratio of an electron and V_t is the potential at the point in question. Substituting Eqs. 3.32 and 3.33 into Eq. 3.31 yields

$$\rho_t = \frac{G J_c}{\sqrt{2\eta V_s k}} . \qquad (3.34)$$

Thus, from Eq. 3.30, the injection current is

$$i = \frac{\sigma M^2}{k\epsilon_o} \Delta t \frac{G J_c}{\sqrt{2\eta V_s k}}$$

$$= C_1 \frac{G \Delta t}{\sqrt{V_s}} , \qquad (3.35)$$

where

$$C_1 \triangleq \frac{M^2 J_c}{k^{3/2} \epsilon_o \sqrt{2\eta}}$$

and C_1 is constant for any one particular flux tube.

On the Poisson cell, the trajectories correspond to the boundaries between flux tubes. Thus on a plate with constant thickness (a flat), G reduces to the ratio of the trajectory spacing at the cathode to the trajectory spacing at the point in question. On a wedge the thickness is proportional to the radius, thus the radial distance of the point in question is also required to determine G. The volume element, $\Delta\tau$, is merely the volume into which the source is injecting current; it is constant for a flat plate, a function of the radial distance for a wedge. The voltage over each current source can be picked up by the probe assembly on the 205-S plotter and monitored on the computer's voltmeter. Correct positioning of the 205-S probe can be accomplished by tying the 1100-E plotter in with the 205-S plotter and positioning the 1100-E pen over the source in question on a scaled drawing of the Poisson cell which shows the relative source positions.

Calculating the injection currents with this method then involves individual determinations of the voltage, the distance between trajectories, and, in the case of a wedge, the axial distance for each source, and it can be correctly applied only in the region where the flow remains laminar--from the cathode to the first interaction.

The second method of computation is based on the fact that the space charge present in any region at any instant is equal to the sum of the individual charge contributions of electrons in the region. Assuming a small but finite volume, this statement can be written in equation form as follows:

$$\rho_t = \sum_{j=1}^{n} \frac{q_j}{\Delta\tau_t} , \qquad (3.36)$$

where q_j is the charge contribution made by the jth electron as it passes through the volume $\Delta\tau_t$, and n is the number of electrons passing through the volume. Further, since

$$q = \int i dt \quad ,$$

$$\rho_t = \sum_{j=1}^{n} \frac{\int i_j \, dt}{\Delta\tau_t} \quad , \qquad (3.37)$$

where i_j is the current associated with a single electron trajectory, and it is integrated over the time that the electron spends in the volume element. Since $\Delta\tau$ is small, i_j can be assumed constant in the volume; thus

$$\rho_t = \sum_{j=1}^{n} \frac{i_j \Delta t}{\Delta\tau_t} \quad , \qquad (3.37)$$

where Δt is the length of time spent in the volume element. On the Poisson cell the electron beam is broken up into a finite number of trajectories, the current associated with any one trajectory being determined by the current density at the cathode. Thus, for this application, i_j can be interpreted as the total current associated with the jth trajectory that passes through the volume element under consideration on the Poisson cell, and n becomes the number of such trajectories. In terms of analog quantities then,

$$i_j = \frac{J_j A_j}{M^2} \quad , \qquad (3.38)$$

where A_j is the Poisson cell cathode area associated with the jth trajectory, J_j is the current density at the cathode for the area A_j, and M is the distance scale factor (see Fig. III.8). Since the field is conservative, Δt can be rewritten in terms of the voltage at the point as follows:

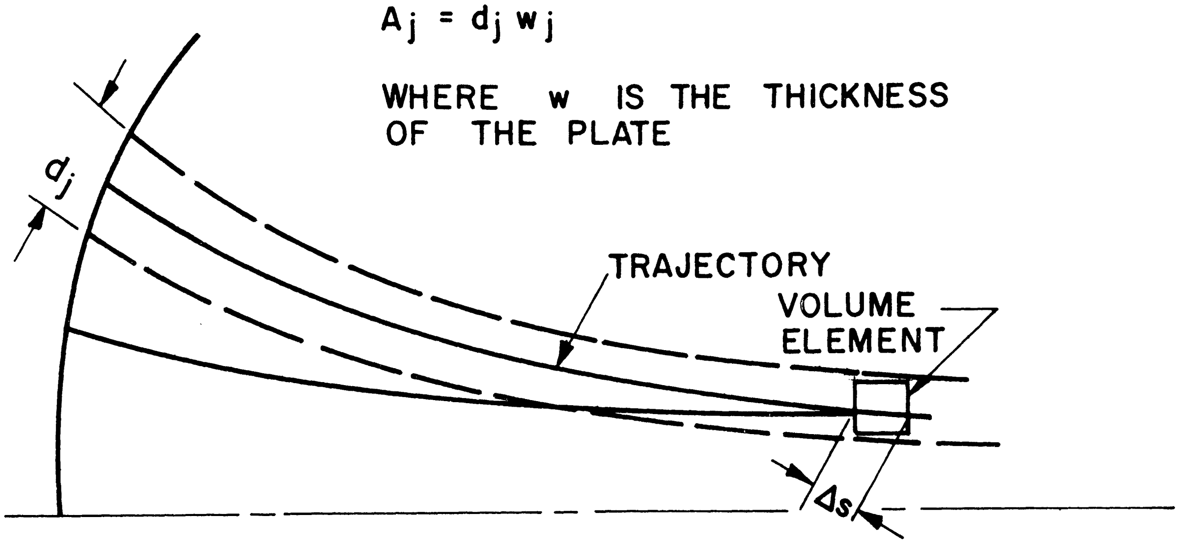


FIG. III.8 CALCULATION OF SPACE-CHARGE DENSITY FOR CROSSING TRAJECTORIES.

$$\Delta t = \frac{\Delta s_t}{v_t}$$

$$= \frac{\Delta s_s}{M} \frac{1}{\sqrt{2\eta\, kV_s}} \quad , \qquad (3.39)$$

where Δs_s is the length of the trajectory inside the volume element and V_s is the voltage in the element--both measured on the Poisson cell. Writing the volume element in terms of analog quantities and substituting Eqs. 3.38, 3.39, into Eq. 3.37 gives the final expression for the space-charge density.

$$\rho_t = \sum_{j=1}^{n} \frac{J_j A_j}{M^2} \frac{\Delta s}{M\sqrt{2\eta kV}} \frac{M^3}{\Delta\tau_s}$$

$$= \frac{\Delta s_s}{\Delta\tau_s \sqrt{2\eta kV}} \sum_{j=1}^{n} A_j J_j \quad , \qquad (3.40)$$

where

$$\Delta\tau_t = \frac{\Delta\tau_s}{M^3} \qquad (3.41)$$

and all the quantities to be measured are analog quantities.

Substituting Eq. 3.40 into Eq. 3.30 gives the injection current:

$$i = \frac{\sigma M^2}{k\epsilon_o} \Delta\tau_s \frac{\Delta s_s}{\Delta\tau_s \sqrt{2\eta kV}} \sum_{j=1}^{n} A_j J_j \qquad (3.42a)$$

and

$$i = \frac{\sigma M^2}{k^{3/2} \epsilon_o \sqrt{2\eta}} \frac{\Delta s_s}{\sqrt{V}} \sum_{j=1}^{n} A_j J_j \quad . \qquad (3.42b)$$

Since laminar flow was not assumed in this derivation, this method can be applied in areas where the trajectories cross. In Eq. 3.42 the first term is constant for the entire problem; further, $A_j J_j$ will be constant for any one trajectory. Thus Δs, the trajectory length in the volume element, and V, the voltage at that element, are the only quantities that need to be determined for each current calculation. The voltage can be read using the computer's voltmeter as outlined above. The trajectory segment can be measured using a plot of the trajectories from the 1100-E plotter superimposed on a scale drawing of the Poisson cell and its sources.

It is important to note at this point that the quantities from which the space-charge simulating currents are calculated, using either method, are all dependent on a particular field configuration on the Poisson cell--the field configuration which existed at the time the data for these calculations was taken. However, this field configuration is changed by the injection of these currents, and although the space-charge effects caused by these currents improve the analogy between the field on the cell and the field in the actual device, the desired analogy cannot be obtained from one set of calculations but can only be approached through a series of such calculations.

3.6 Solution of a Problem

There are three main steps to be followed in analyzing a device with this system. The first step more or less programs the system for the geometry of the device, and the last two steps involve the determination of space charge for the particular operating conditions being analyzed.

The first step is to scale up the geometry of the device by some convenient number so that it utilizes the space on the Poisson cell to best advantage. It is important that the scale factors in the y and z directions be the same because of Poisson's equation.

Once the scaling factor is decided upon, the electrode configuration can be calculated and established on the Poisson cell by one of the methods mentioned in the previous section. It is also necessary to make a scale drawing of the Poisson cell showing the location of the current sources and the electrodes for the 1100-E plotter. This drawing is usually one half the scale of the Poisson cell geometry.

Also included in this step is the calculation of the potentiometer settings (constants for the machine equations) for the computer's program. A record should be kept of these settings so that they can be checked regularly.

The second step is to simulate the space-charge effects for a given field configuration on the Poisson cell. It can be accomplished with the following sequence of steps. First, trajectories are run for this field configuration and are recorded on the 1100-E plotter. Second, using the recorded trajectories and the scale drawing of the Poisson cell, enough data is taken to calculate the injection currents by one of the methods mentioned in the last section. Third, the injection currents are calculated and injected into their respective volume elements in the Poisson cell. These three steps will successfully accomplish the simulation of the space charge for the original field configuration, but, as mentioned earlier, this is not the final solution since the injection of these currents change the original field.

Step three consists of arriving at the final solution, and it has either one or two degrees of freedom depending on the data available about the emission at the cathode. The easiest situation to analyze arises when the current distribution at the cathode is known. In this case, the known current distribution can be used in the calculations of step number two and only the final space-charge distribution needs to be determined. This can be arrived at by repeating step number two until two consecutive sets of trajectories are exactly the same.

A much harder situation to analyze arises when the emission is space-charge-limited. In this case, the emission current distribution at the cathode is not known, and this distribution must be arrived at by trial and error. A distribution at the cathode must be assumed and consistent trajectories obtained as above. The correctness of the assumed distribution must then be checked by observing the potential variation near the cathode. Under space-charge-limited operation, the relationship between current density, voltage, and cathode distance is given by Child's Law,

$$- J = 2.33 \times 10^{-6} \frac{V^{3/2}}{X^2} \text{ (amps/m}^2\text{)}. \qquad (3.43)$$

Thus, Child's Law will give a current density distribution from the voltages near the cathode and, if this distribution agrees with the assumed distribution, the problem is solved. If not, the assumed distribution is incorrect and must be altered, and the process of arriving at consistent charge trajectories must be repeated for this altered distribution. This is repeated until Child's Law is satisfied near the cathode.

The number of iterations required for a consistent space-charge solution to a specific cathode current distribution depends on the amount of the beam being analyzed and the accuracy required. Thus in the case of the space-charge-limited problem, a few iterations of the current sources near the cathode is usually enough to get an indication of whether or not the assumed distribution is approximately correct. Needless to say, the work associated with the space-charge-limited problem can be greatly reduced by intelligent estimates of the cathode current distribution.

3.7 Test Problem

It is necessary to occasionally run a check on the probe system, the plotter, and the computer to be certain that they are operating correctly. This can be done quite easily, utilizing the vacuum hold-down, by running space-charge-free trajectories on a crossed-field planar diode. Since the check does not involve the space-charge injection system, a thin surface conductor* can be used on which to set up the planar diode geometry. It is important that the underside of the plate with this conducting surface be insulated so that any geometry on the vacuum hold-down has no effect on this test problem. Space-charge-free trajectories are then run in the usual manner and the results checked against the analytic solution. The solutions should agree to within about one

---

* Surface conductors can be purchased from Electronic Associates Inc., Long Branch, New Jersey.

percent; if they do not, either the computer or the probe system is not functioning correctly. The trouble can be isolated to one system or the other by injecting the electric field gradient into the computer directly with a potentiometer and again running the trajectories. Agreement of this second solution with the analytic solution would indicate trouble in the probe system and disagreement would indicate trouble in the computer. Once the geometry for this check is set up on a conducting surface and the scaling constants and analytic solution worked out, the check can be run easily and quickly, justifying frequent use.

IV. MAINTENANCE AND SERVICING

4.1 Introduction

A very important factor in the use of this equipment is maintaining it in good operating condition. The system is complex enough; the additional factor of having equipment breakdowns can greatly increase the time required for problem solutions. A technician who is well checked out in the maintenance and servicing of the equipment is a definite asset and, also, continuous maintenance of the equipment will offer definite savings.

The section on maintenance of this system has been derived from our (The Electron Physics Laboratory) experience with this system. It is suggested that this procedure and/or the maintenance programs outlined by Electronic Associates and the manuals of the other manufacturers be religiously adhered to in order to use this equipment to the best advantage.

The last section on servicing will serve as an introduction to the trouble shooting of the trajectory tracer. The servicing of the commercial items of the system will not be covered. The standard factory manuals should be consulted for work with these items of equipment.

4.2 Maintenance

4.2.1 Computer and Plotters. Note: Before any operation of the computer, balance all the amplifiers and reference supplies. Also, check voltage source output values.

4.2.1a Operational Amplifiers--(Performed Biweekly). For noise, offset, frequency response, and amplifier output checks, refer to maintenance section of d-c amplifier manual.

While making the checks, record values. Each amplifier is checked in turn following the suggested procedures. After completing the day's checks, the troubles should be investigated and corrected. Some of the more common noise faults that may occur are:

1. Excessive ambient noise--common causes are generally in the d-c section. Usually it is caused by the 6U8 and sometimes the 6072. (Note: The majority of the ambient noise is 2900 cps. Approximately the 13th harmonic of the 94 cps chopper frequency.)

2. Sudden bursts of noise--the usual cause is an output tube, a Tung-Sol 7719 Type (Spec.) (particles flaking off of the cathode).

3. Excessive 60 cycle signal in the output--usually this is caused by heater-cathode leakage near the input end.

4. Square wave noise--the chopper may need adjustment; check the 6AW8 tube.

5. 120 cycle spikes--check the 300 V and other regulated power supplies.

6. High microphonic noise--almost always caused by 6U8; replace it. Sometimes caused by the chopper. Common causes of offset trouble: a. input tube; b. chopper.

Insufficient frequency response is generally caused by one or more tubes in the d-c section being below standard.

4.2.1b Reference Supply, Output Noise Check--(Performed Biweekly). A lead is connected from the +100 volt reference connection on the patch board to the y-input of a Cathode Ray Oscilloscope (CRO). The ground of the CRO is connected to the ground terminal on the VTVM panel.

The CRO is operated at about 0.1 msec/cm horizontal sweep frequency and at 5 mv/cm vertical sensitivity. Now the output of the reference supply may be observed on the CRO by setting the computer into operate mode. The output noise observed on the CRO should not exceed 10 mm p-p. To check for microphonic noise, tap the front of the reference supply. The vertically expanded peaks (microphonic noise) should not exceed 20 mv p-p. Also, the entire waveform should not change d-c level. Repeat the procedure for the -100 volt reference. The sources of trouble are the same as in the operational amplifier.

4.2.1c Power Supplies Check--(Performed Biweekly). Patch the CRO to the external voltmeter terminals on the VTVM panel.

With the computer in operate mode the different voltage supply outputs can be scanned through depressing the corresponding push buttons on the VTVM panel. Observe the amount of ripple voltage present and record it. Note any unusual behavior of the supply. Next, observe the supply voltage on the panel meter. Turn the voltage adjust screw and see if the adjustment operates properly. Repeat the procedure for each power supply in turn. Common causes of trouble:

1. If voltage does not adjust properly check tubes; 6U8, 5651 and 12Ax7,

2. Excessive noise--check same as above,

3. Plate fuse blows repeatedly, check the capacitors,

4. Voltage goes up and will not come down or large noise bursts, check 6336 (gassy).

4.2.1d Multiplier Check--(Performed Biweekly)

Gain and Damping--Rough Adjustment. Patch in the circuit in Fig. V.1. Operate the CRO at about 0.5 sec/cm. With the computer in operate mode, switch the input between +10 and -10 and observe the trace on the CRO. Adjust the gain and damping for one over-shoot. Repeat for each multiplier.

Common causes of trouble: (1) if gain and damping do not operate properly check the tubes; (2) if multiplier operates improperly, check the tubes and also the cathode fuse on the 6500 tube.

Follow-Up Gain and Damping, Fine Adjustment, Noise and Cup Alignment. Patch the circuit shown in Fig. IV.1 on the following page. With the computer in initial condition mode, switch S(00) to the left, S(01) to the center, S(02) to the left, and S(03) to the left. Also, switch the pen lift switch to up. Then put the computer in operate mode. The 1100-E plotter will trace the ground line.

Switch the pen lift switch to down. Return the computer to I.C. (initial condition) mode and switch S(00) to the right and S(01) to the right. Switch the computer to operate mode and switch the pen lift switch to up. Now, the variplotter will trace out (SM-MF). With the scale factor settings on the variplotter as shown in the circuitry of Fig. IV.2 shown on the next page, the vertical scale is 1 v/in. Adjust the gain and damping controls so that the (SM-MF) trace is as close to the ground line as possible with minimum jitter. After the gain and damping adjustments have been made, put the computer in I.C. mode. Switch S(00) to the left, S(01) to the center, S(02) to the center. Put the computer in operate mode to trace the ground line. Switch the

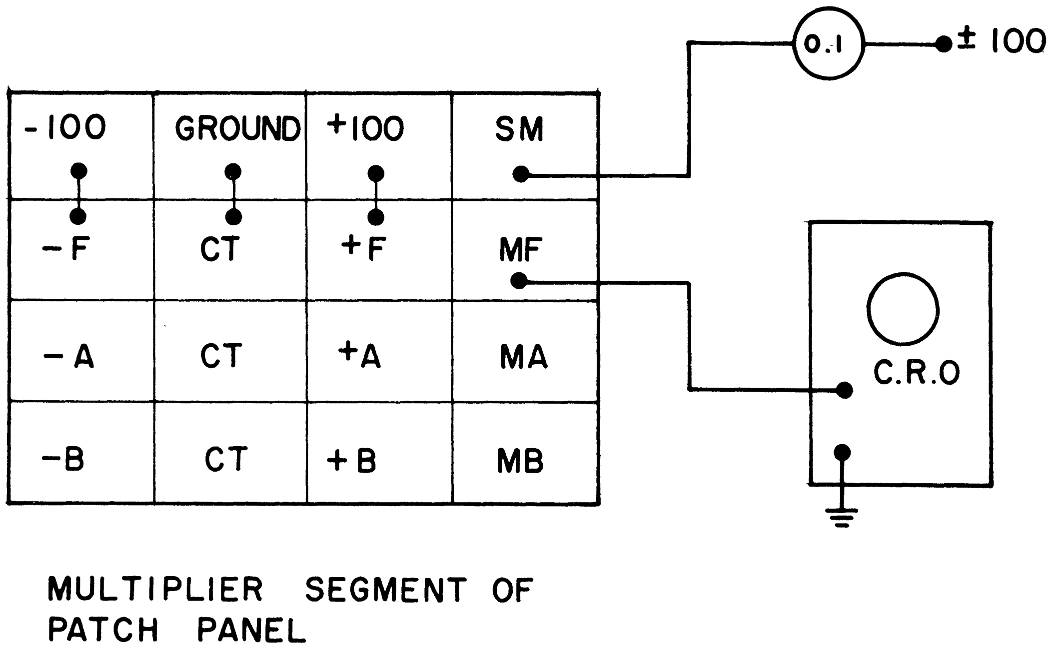
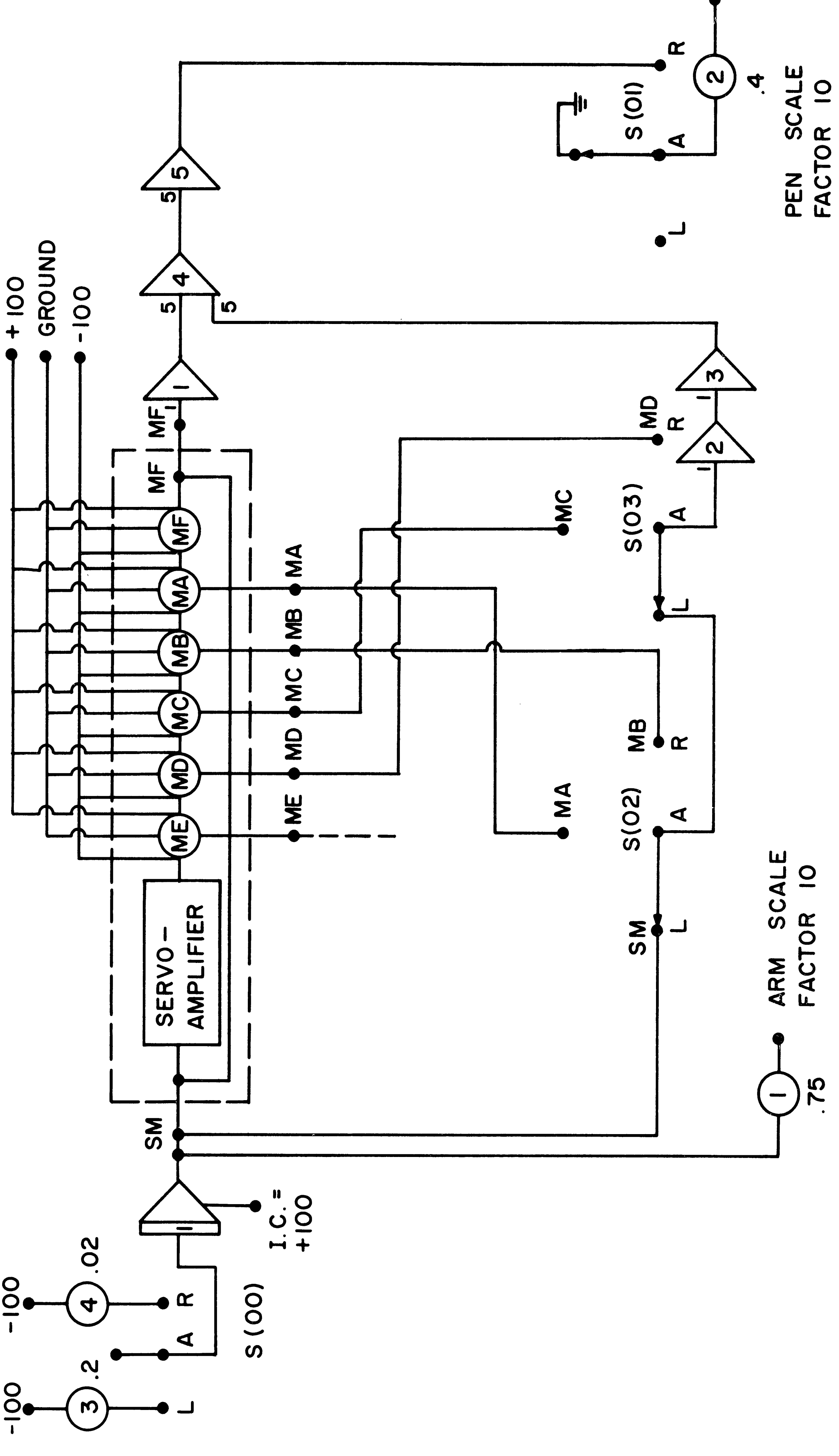


FIG. IV.1 CIRCUIT FOR GAIN AND DAMPING ADJUSTMENT OF SERVO MULTIPLIERS.


PEN SCALE FACTOR 10
ARM SCALE FACTOR 10
+100
GROUND
-100
SERVO-AMPLIFIER
MF
MA
MB
MC
MD
ME
SM
S(00)
S(01)
S(02)
S(03)
I.C. = +100
-100
.02
.2
.4
.75
R
A
L

computer to I.C. mode. Switch S(00) and S(01) to the right and again put the computer into operate mode. The variplotter will trace (MA-MF). Repeat this for each cup. The following positions of S(02) and S(03) will give:

S(02)	S(03)	Input to Amplifier 2
Left	Left	SM
Center	Left	MA
Right	Left	MB
Right	Center	MC
Right	Right	MD
Remove lead from MD to S(03)R and replace it with lead from ME to S(04)R.	Right	ME

Common faults are:

1. Bursts of noise on follow-up trace--decrease gain slightly. If this does not help remove the multiplier and look at the wiper and follow-up cup. The trouble may be due to either or both of these being dirty. Clean with carbon tetrachloride and apply a light film of oil to the wiper assembly. If noise persists in sufficient magnitude, the multiplier should be sent back to the factory for repair.

2. Cups not aligned to follow-up cup (trace going too far above and/or below the ground trace). The cups are difficult to realign. A bad case should be sent back to the factory.

3. (SM-MF) trace too far above ground trace. Check the tubes; one or more are probably low in gain.

4.2.1e Variplotters--(Performed Biweekly). Clean the ways on the 205-S and 1100-E Variplotters with methanol. Apply a thin film of light machine oil (spindle oil) to the ways after they are clean.

4.2.1f Attenuators--(Performed Biweekly). Check the pot fuse (continuity) by applying a voltage to it with its associated switch. See if there is any output voltage that can be read using the digital voltmeter.

4.2.1g Reference Supplies and Electronic Digital Voltmeter--(Performed Monthly). Check all the tubes in the +100 and -100 volt supplies. Adjust the electronic digital voltmeter.

4.2.1h Computer Fan Filters--(Performed Monthly). Clean the filters which are located under the computer by removing and vacuuming them. Replace any badly soiled filter.

4.2.1i Variplotters--(Performed Quarterly). Check all the tubes in the 1100-E Variplotter. Log these values. Periodically flush the vacuum pump on the 1100-E Variplotter. Add oil to intakes of variplotters.

4.2.1j Standard Cells--(Semiannually). Change the standard mercury cells in the 205-S and the 1100-E Variplotters and the computer ±100 volt reference cells.

4.2.2 Poisson Cell Complex. The probe pick-up is very touchy. Dirt particles will hinder the free sliding motion of the metal pins. This system should be washed with soap and water if the probe does not function properly. Wear of the probe tips will necessitate replacement of these probes. It will be necessary to hand fit these probes. Figure IV.3 contains the information required for manufacturing these probes as well as the probe springs.

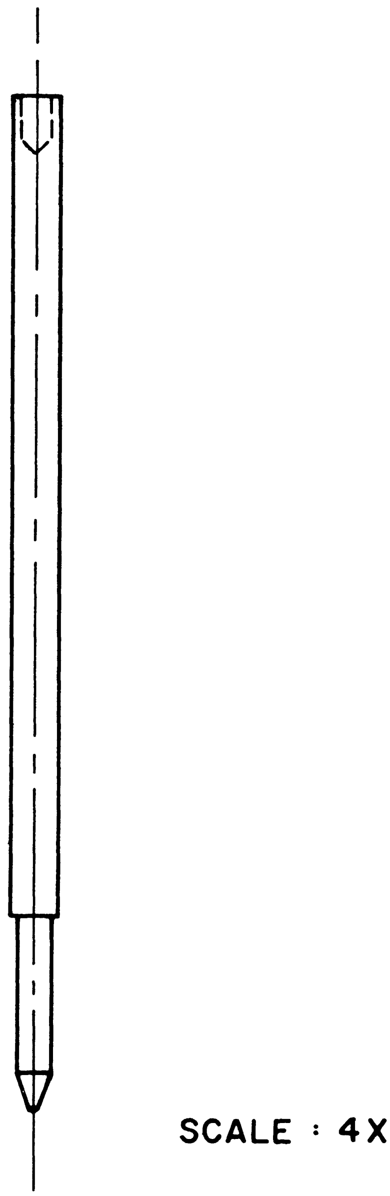


FIG. IV.3 PROBES FOR PROBE ASSEMBLY.

Very little other maintenance is required on the Poisson cell complex. As listed previously the mechanical system of the plotters should be maintained as well as the vacuum pump and replacement of the mercury cells. The only other problem spot is the plungers in the vacuum hold-down. These should be protected from dust and dirt at all times.

4.2.3 Current Source Console. Very little is required to maintain this unit. Cleaning of the permanent intake filters and checking of tubes in the Lambda supply should be done periodically. The Hewlett-Packard digital voltmeter should be maintained according to the factory manual. The current sources should be continuously monitored for maximum injection current output. This will allow for replacement of tubes for deterioration in emission current.

4.3 Servicing

4.3.1 System as a Whole. The inter-unit wiring of the trajectory tracer is shown in **Figure** IV.1. The inter-unit control cable is the only connection between the computer and the remainder of the system. The material on the connections in this cable is in Figure IV.2. All of the wiring to the Poisson cell complex is in the metal overhead duct. The duct contains a continuation of the inter-unit cable and the fifty 32 wire cables from the current sources. The power input to the current sources console also powers the Poisson cell complex.

The 1100-E Variplotter may be incorporated into the system through either of two places. One connection is beneath the floor-plate of the computer console. The other connector is at the base of the vertical section of the overhead duct. Except for the means of obtaining 110 volt 60 cycle power, these connectors are in parallel.

Facilities have been incorporated for the operation of the computer from the 205-S plotter console. The wiring for this convenience are in Drawings VI.3, VI.4, VI.9, VI.10, VI.11, and VI.16.

4.3.2 Poisson Cell Complex. The circuitry in the Poisson cell complex can be divided into two sections:

1. The space-charge simulating current injection wiring,
2. The power and control wiring.

The space-charge current injection wiring is shown schematically in Figure IV.6. The Poisson cell vacuum hold-down probes, the plug board, and the connector panel are connected together in a one-to-one correspondence, i.e., one point on each of the three units is common. The interconnecting wiring is by means of 32 wire cables. This corresponds with the groups of 32 utilized in the common addressing system of the trajectory tracer.

All power and control wiring enters the plotter complex at the terminal strip T. B. 16 (see Fig. V.8). The only exception is the 110 volt 60 cycle input which goes to T. B. 5. The standard input connection to the sevo systems of the plotter, as shown in the manufacturer's manual, therefore, comes from T. B. 16. The additional wiring involves the fact that a system control panel has been incorporated into the plotter console. This control panel includes operation of the analog computer, control of the operation of the plotters, control of the probe pickup voltages, control of reference voltages, and setting of the initial conditions of the trajectories. The wiring diagrams of these circuits are in Drawings VI. 7 through VI.12. Drawings VI.3 and VI.4 contain the circuits for the probe switching and plotter control.

4.3.3 Computer. The computer is a standard Electronic Associates 231-R. The only modifications are those necessary to its incorporation in the trajectory tracer system. Except for the listed changes, one should refer to the factory manuals for servicing of the unit. First, wiring to the inter-unit cable had to be incorporated into the computer. This is listed in Drawing VI.14. Behind the upper-right door above the computer patch-bay a panel unit has been added. The panel contains the feedback potentiometers used in the unloading amplifiers (Drawing VI.15). The remaining additions are components that have been connected into the back of the patch bay within the oven (Drawing VI.17).

4.3.4 Current Source Console

4.3.4a Current Source Modules. The current source console consists of 1600 individual source modules and the circuitry and power supplies necessary for their operation. The circuit diagram for the module is shown in Drawing VI.22. As shown, the source is a pentode amplifier with degenerative feedback in the cathode circuit. Variation of this resistance controls the plate current. The plate lead is connected into the Poisson cell. The precision resistor is used to measure the injection current by means of switching into the voltmeter circuit. The additional contacts of the switch activate the module neon light and also connect into the "idiot" circuit. The pentode filament is in series with a bimetallic switch which is utilized to indicate a burned-out filament.

Individual current sources may be removed from the panel in the following manner:

1. Remove the potentiometer knob.

2. Remove the potentiometer nut.

3. Remove the lever switch nut.

4. Disconnect the module cable by unplugging the kliptite connectors at the rear of the current source panel.

Thirty two of these current sources are mounted together on a relay rack panel. Each panel is mounted upon slides for accessability for servicing. Complete removal of the panel requires disconnecting the black power cables and the grey current source cable. Except for the current source lead of each source all leads from the 32 modules are connected in parallel. This is done with kliptite connectors at the rear of each current source panel. Each current source lead connects to the connector at the rear of the panel and thence to the Poisson cell by means of the grey 32-wire cable.

The power and current source cables from each panel then feed into the console ducting (Drawings VI.20 and VI.21). The current source cables then go into the overhead duct to the Poisson cell complex. The black power leads go to the distribution panel and to the filament power supply in the center rack. The black power leads are interrupted at the intra-console terminal boards. This is to allow for ease of transportation by separation of the console into three parts.

4.3.4b Power Distribution Panel. The power distribution panel (see Drawing VI.24) contains the common busses for all power except the filament supply. It also contains the d-c supply for powering the neon lights of the current source modules. The fuse for power into the Poisson cell complex is also located here.

4.3.4c Control Panel. Depressing PBS-1 (fil., on-off) switch (see Drawing VI.23) energizes relay CR1, the time delay relay TDR1 and the filament supply contactor. Energizing the CR1 relay applies power to the console fans, the digital voltmeter, and supplies filament power to the H.V. supply (200v screen supply) and all current sources. Relay TDR1 is a three minute time delay relay which assures filament warm-up before the plate, screen and bias supplies may be turned on. After the three minute warm-up, PBS2 (d-c on-off) may be depressed to turn on the d-c voltages.

Transformer T1 supplies 6.3 VAC to the indicator lamps in the digital voltmeter selector switch. PBS1 and PBS2 indicator lamp voltages are supplied by the main filament supply. Resistors R1 and R2 are voltage dropping resistors because the filament supply voltage is 9 VAC.

Also located on the control panel chassis is a simple transistorized audio oscillator. When more than one current source push button at a time is depressed an erroneous digital voltmeter measurement will result; the audio alarm and warning lamp L1 serve to indicate this condition to the operator. Depressing two or more current source push buttons at one time will energize relay CR4 which energizes relay CR3. Energizing relay CR3 turns on the audio oscillator, warning lamp, opens the input connections to the VTVM, and opens the +100v reference supply from the computer.

4.3.4d Filament Supply. The current source filament supply, Drawing VI.25, is located in the lower center section of the console. It consists of a line and load regulating transformer with fused outputs to the current source panels. Each fused output supplies filament voltage to two current source panels.

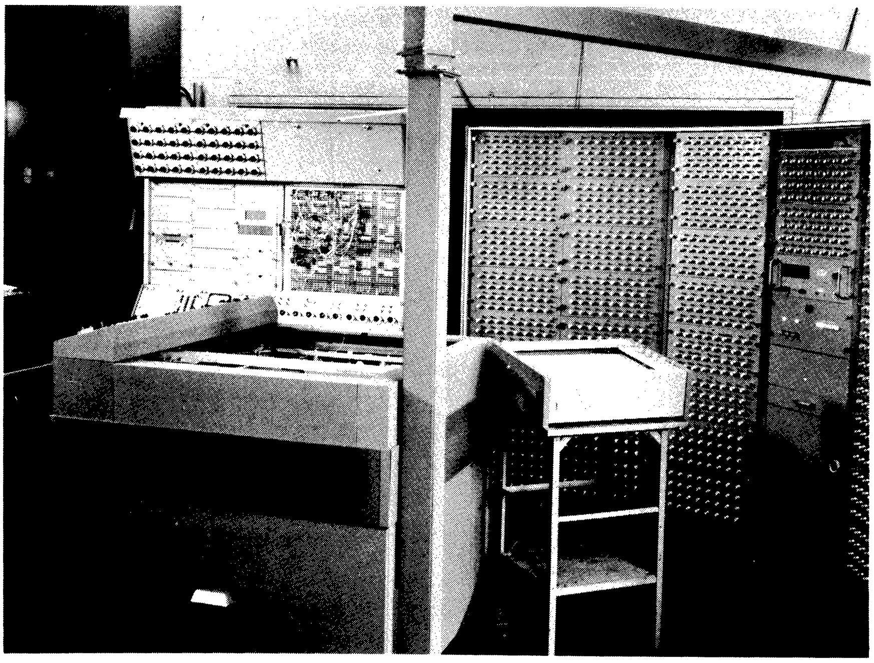


FIGURE V.1

Particle Trajectory Tracer

In the background left is an Electronic Associates 231-R analog computer. To the right is the current source console. In the foreground left is the Electronic Associates 205-S x-y plotter containing the Poisson cell complex and at the right is the 1100-E recorder. All cabling to the plotter is by way of the overhead duct shown at the top of the figure.

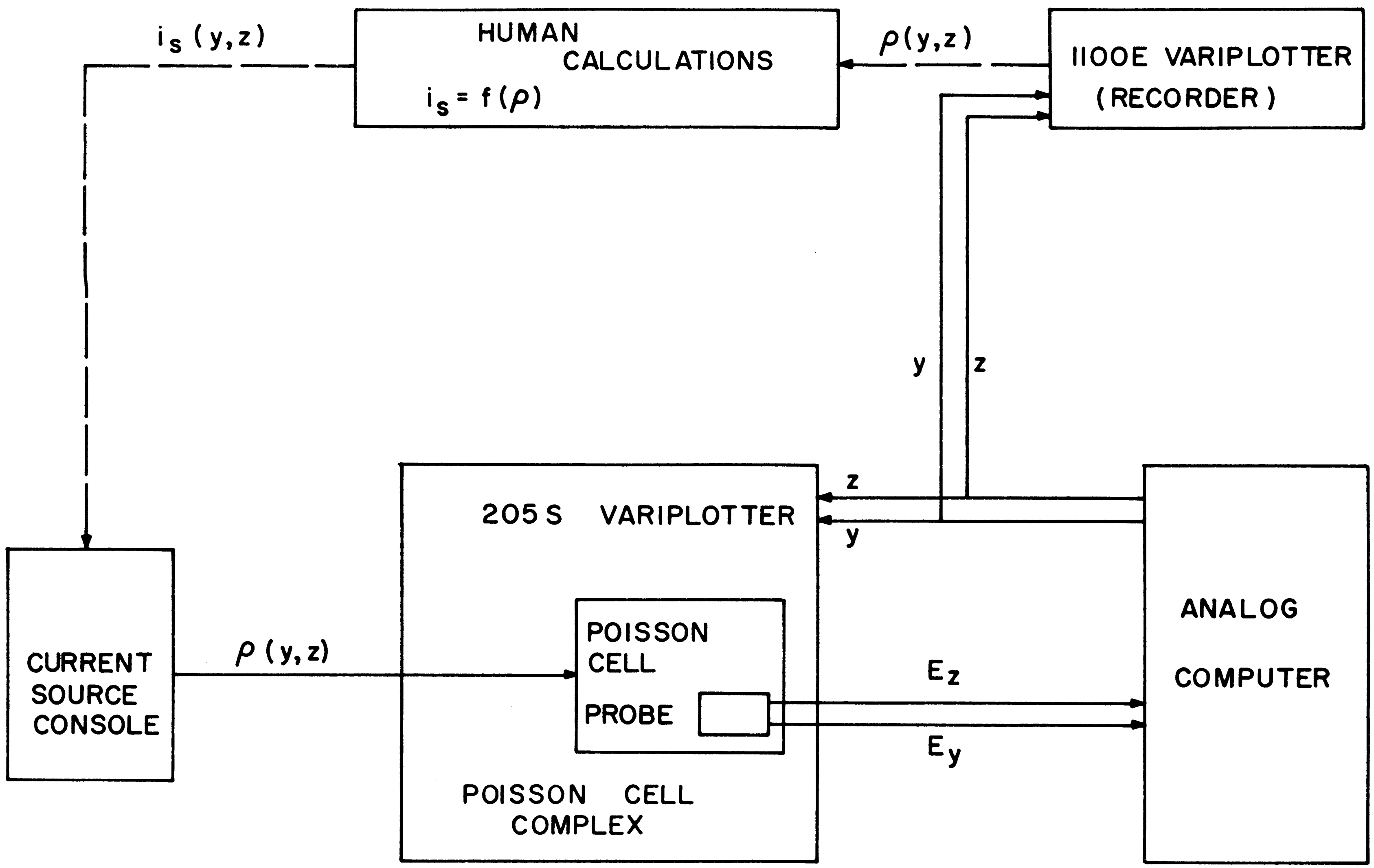


FIG. V.2 FLOW DIAGRAM OF OPERATION OF TRAJECTORY TRACER.

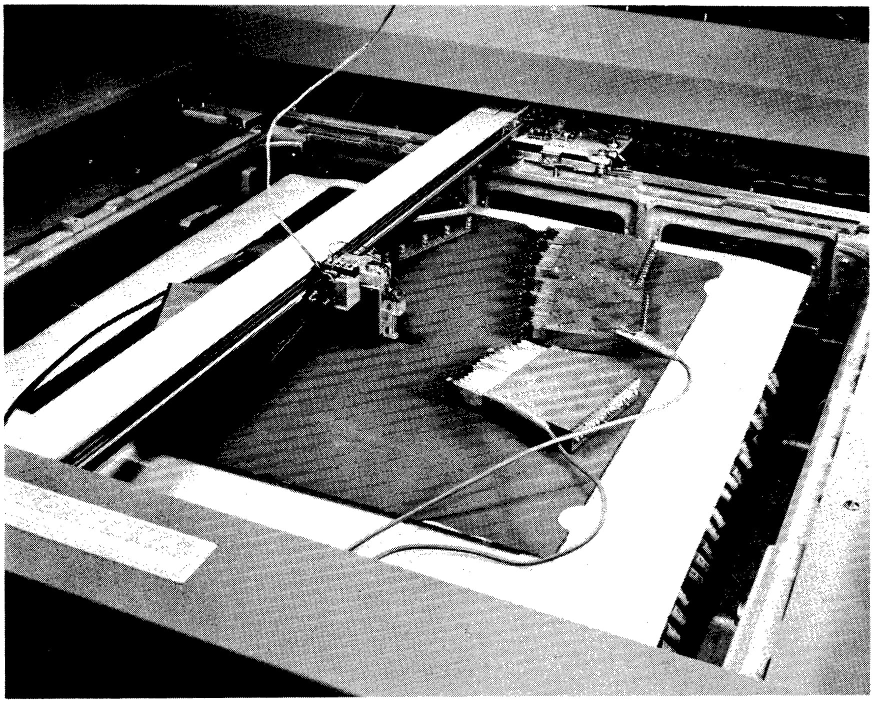


FIGURE V.3

Operation of Poisson Cell

A view of the Poisson cell installed on vacuum hold-down and ready for tracing of trajectories. Placed upon the surface of the cell are electrodes that determine the space-charge-free field configuration; a gradient reading probe is connected to the plotter arm.

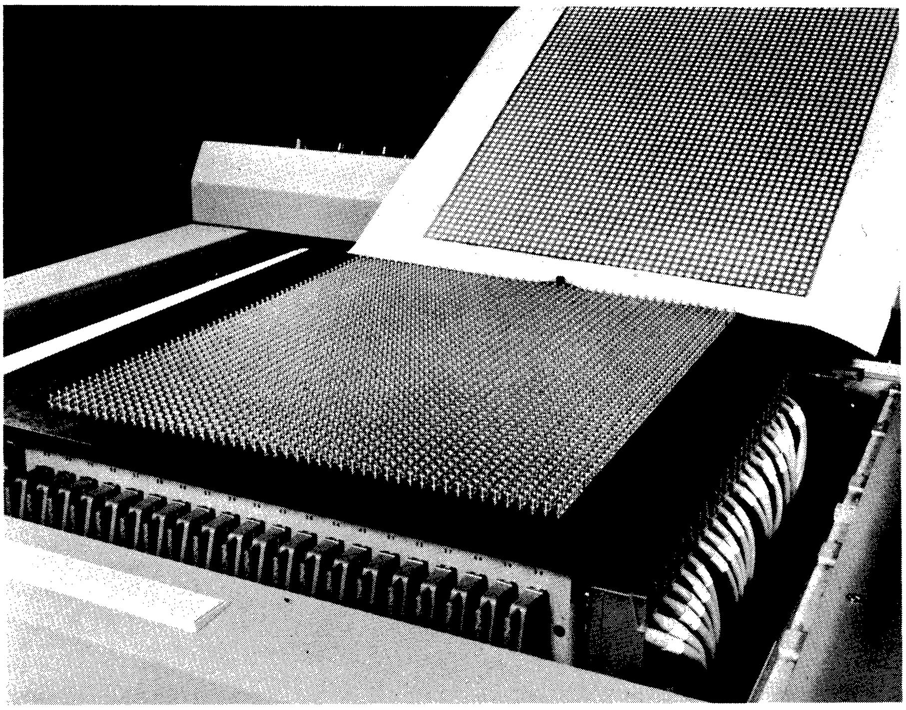


FIGURE V.4

Poisson Cell Vacuum Hold-down

A view of the top of the 205-S plotter showing the vacuum hold-down with 2688 spring-loaded plungers; each plunger is an injection point for space-charge simulating currents. In the top background is a Poisson cell showing the bottom side that lays on the plungers.

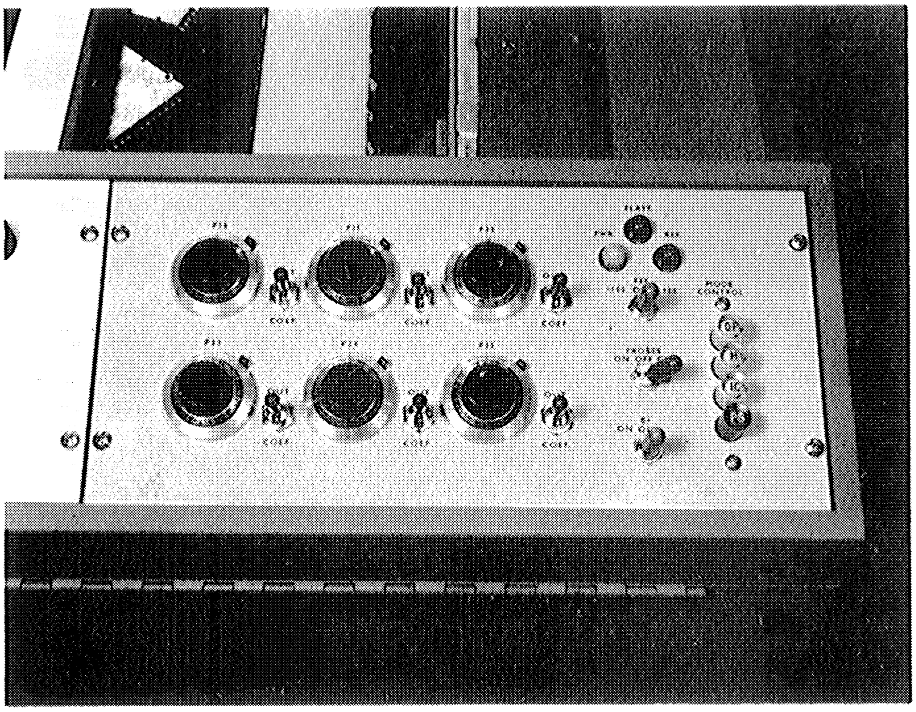


FIGURE V.5

Plotter Control Console

This panel contains all controls necessary for the running of the trajectories. At left are six coefficient setting potentiometers. At right is the computer mode control and in the center are three lever switches; the top lever switch applies reference voltage to the Poisson cell, the center switch controls the probe voltages and the lower switch activates the plotter arms.

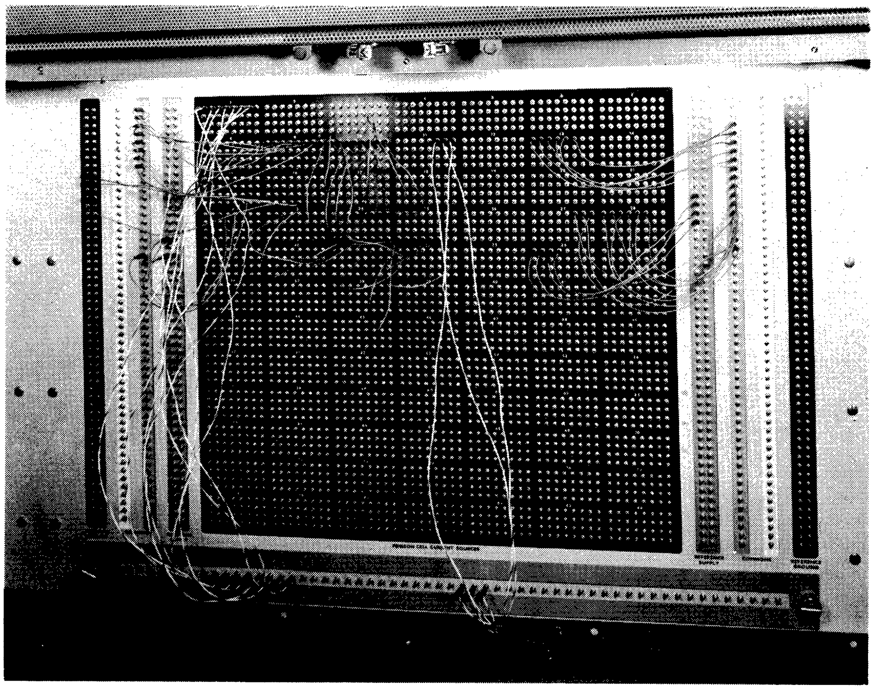


FIGURE V.6

Plotter Plugboard

The plugboard is used for application of external wiring to vacuum hold-down current injection plungers. A resistance network is at the bottom of the board. The plugboard is located in the base of the 205-S plotter.

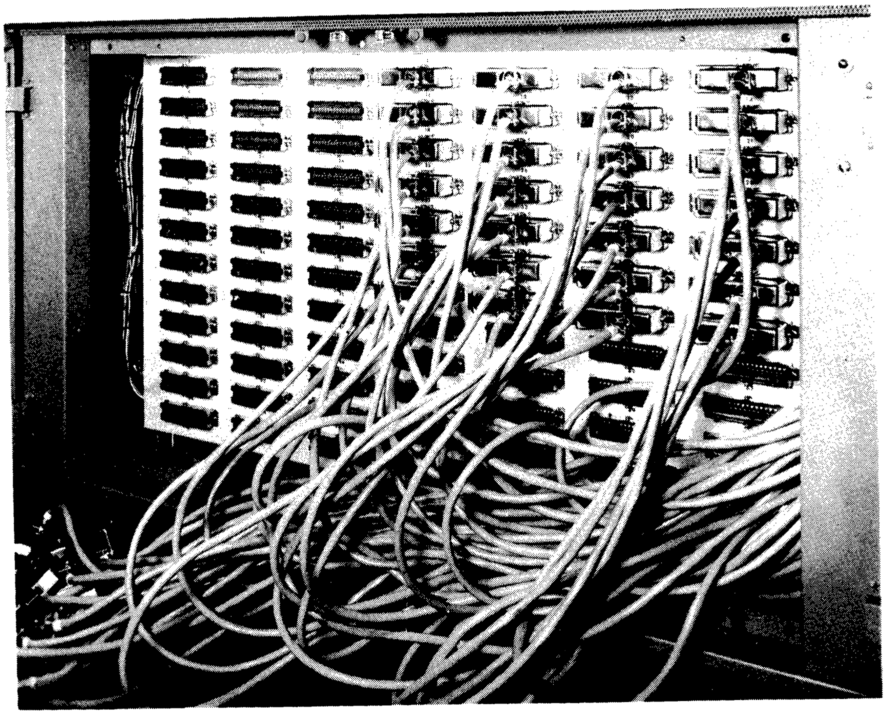


FIGURE V.7

Plotter Connector Panel

A view of the side of the plotter with doors open showing connector panel. At this panel, cables from the current source console are connected into various areas of the Poisson cell.

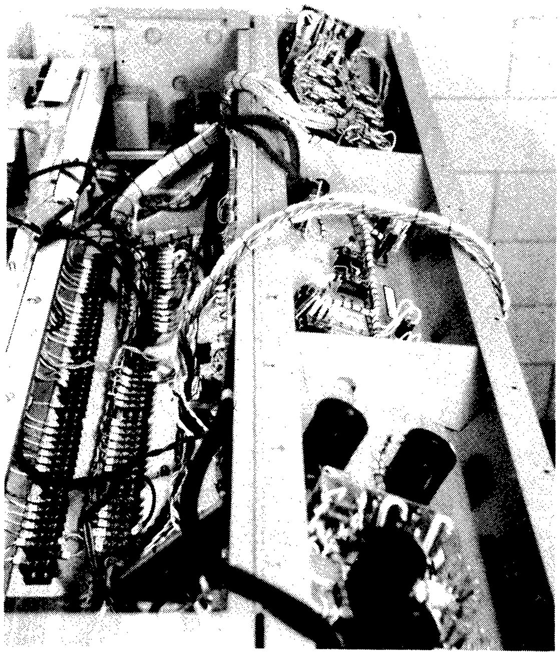


FIGURE V.8

View of 205-S Plotter With Control Panel Lid Raised

This view shows T.B.-16 (the two rows of terminal boards). The majority of the incoming power and control wiring is terminated here.

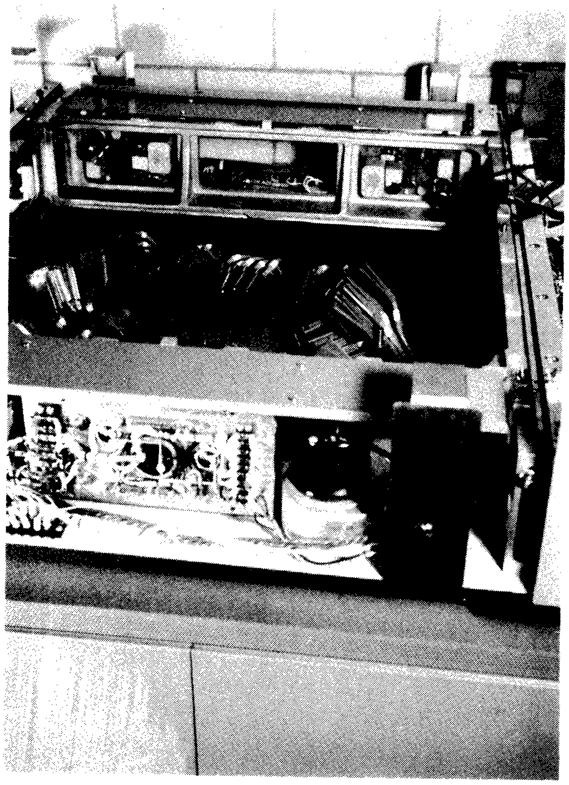


FIGURE V.9

View of 205-S Plotter with Cover Removed

In this view, the Poisson cell, vacuum hold-down, and its supporting structure are removed. In the center are the cabling connectors that connect to the vacuum hold-down for injection of space-charge simulating currents into the Poisson cell.

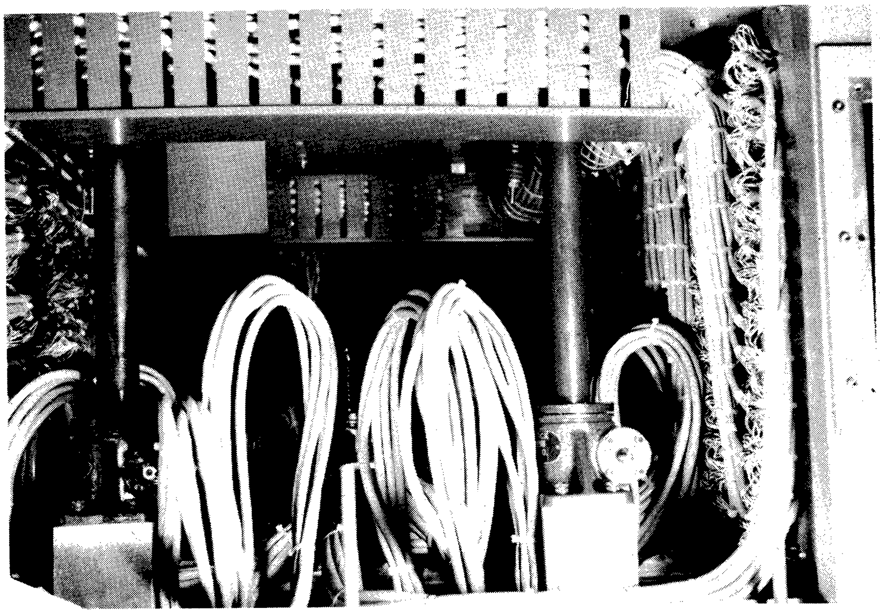


FIGURE V.10

Interior of the Supporting Stand of the 205-S Plotter

The connector panel and plugboard are at the left and right, respectively.

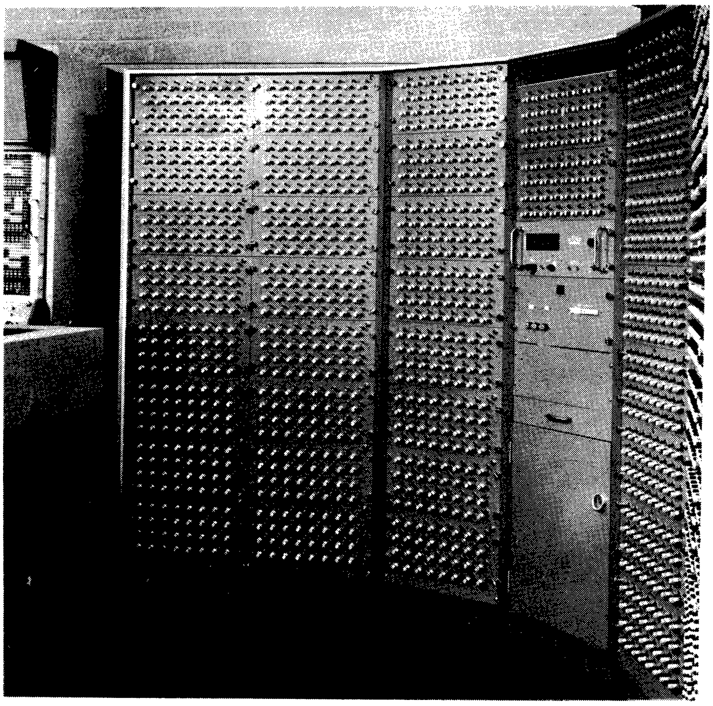


FIGURE V.11

Current Source Console

The console contains 50 panels of current sources. In the center rack is shown the voltmeter, console control panel, a sliding shelf, and the door which covers the console power supplies.

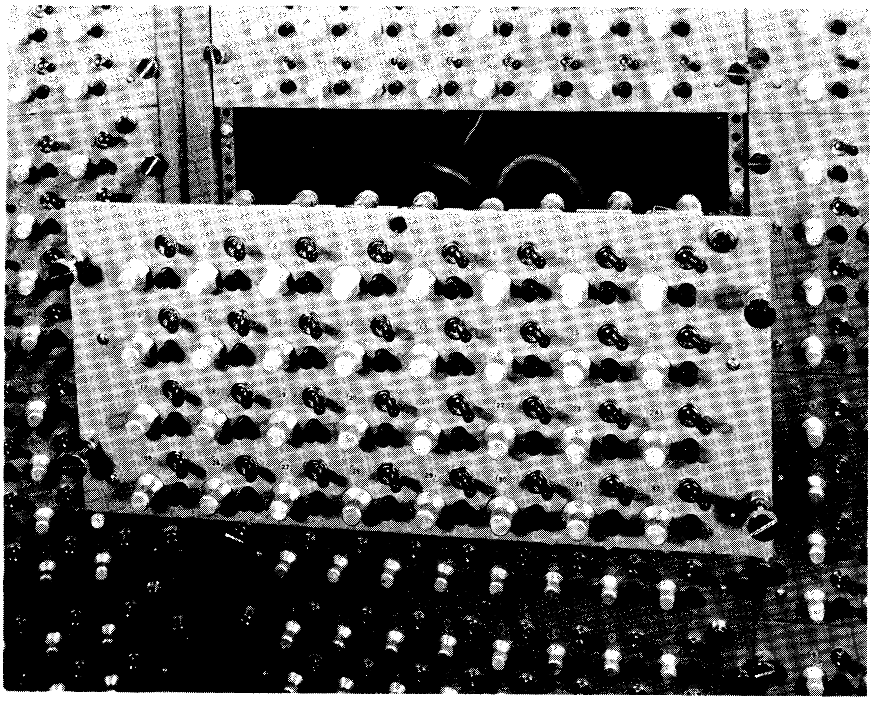


FIGURE V.12

Current Source Panel (Front View)

A front view of one of the current source panels when pulled out on its slides. There are 32 sources. The panel controls of a source consist of a lever switch, numbered neon light, push button switch, and a potentiometer knob. Note the extra panel light in the upper right-hand corner. This light is numbered and is used in the address system of the trajectory tracer.

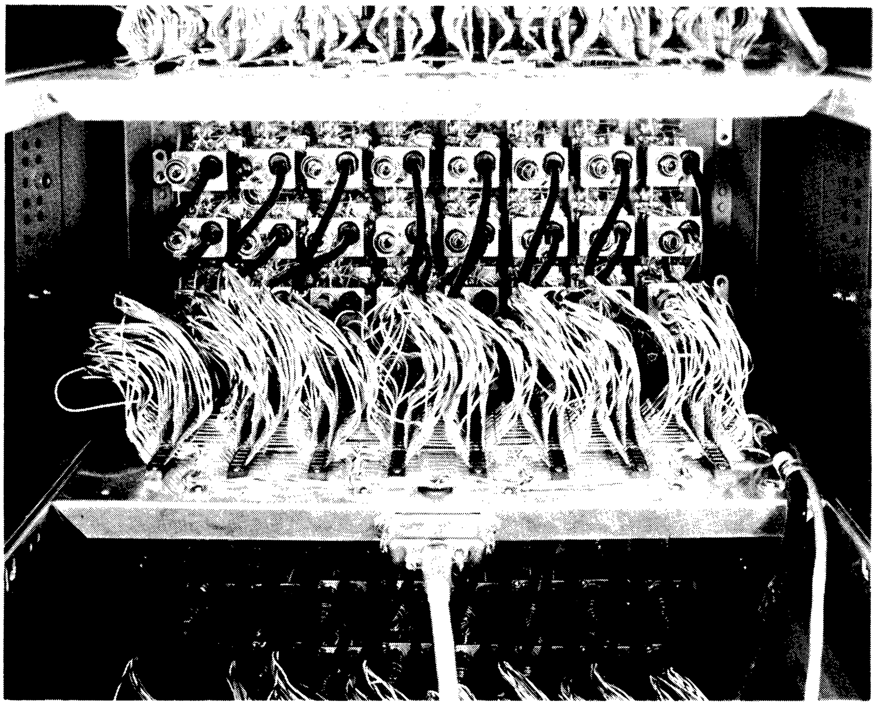


FIGURE V.13

Current Source Panel (Rear View)

A rear view of a current source panel installed in the console. The lead in the center foreground is the 32 conductor cable carrying the injection currents to the Poisson cell. The leads entering at the right are the power leads. In the background is shown the individual current source chassis. The foreground shows the kliptite connectors where the individual current sources are connected into the system.

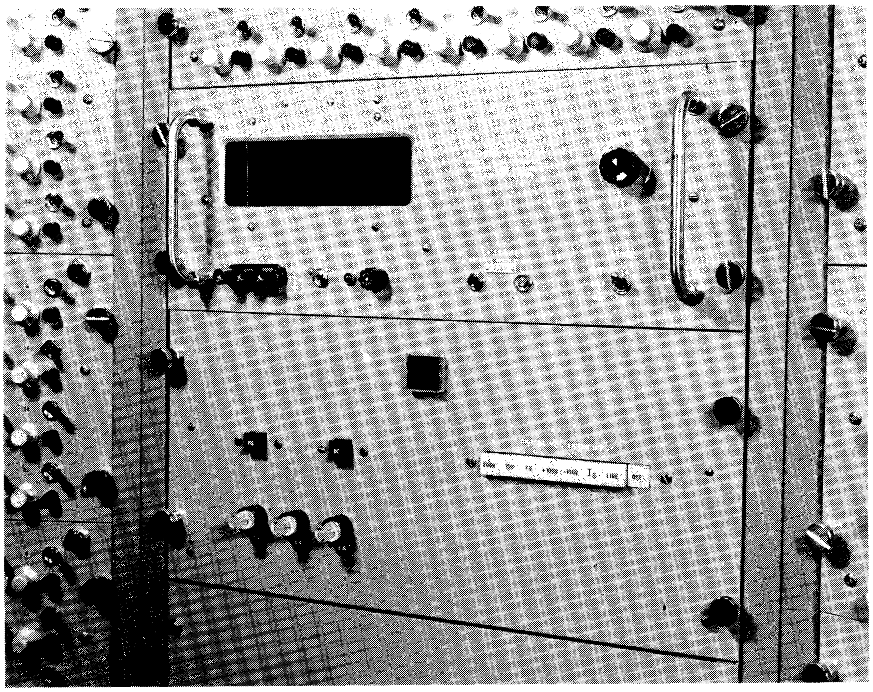


FIGURE V.14

Voltmeter and Control Panel of Current Source Console

A view of the center rack of the console showing the digital voltmeter and the control panel. The voltmeter is used in adjusting currents of sources; the control panel allows operation of the current source console separately from the computer control system.

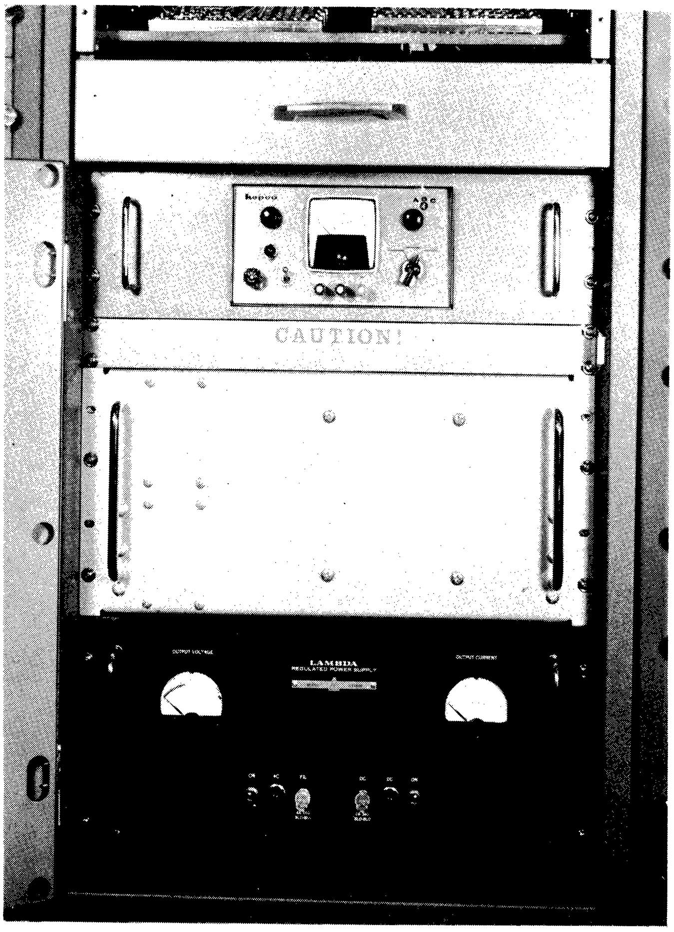


FIGURE V.15

Current Source Console Power Supplies

At the bottom is the Lambda 200V supply that serves the screen grids of the current sources; above it the filament constant voltage transformer. Above the transformer is the Kepco supply that supplies the grids of the current sources. Just visible above the sliding shelf is the distribution panel. This distribution panel is mounted behind a blank panel between the console control panel and the sliding shelf.

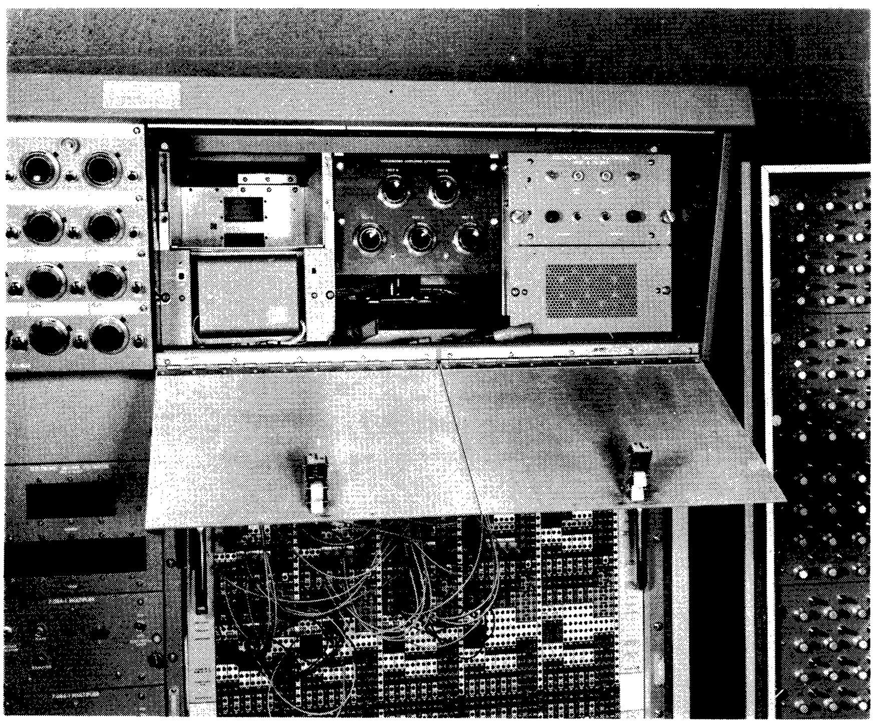
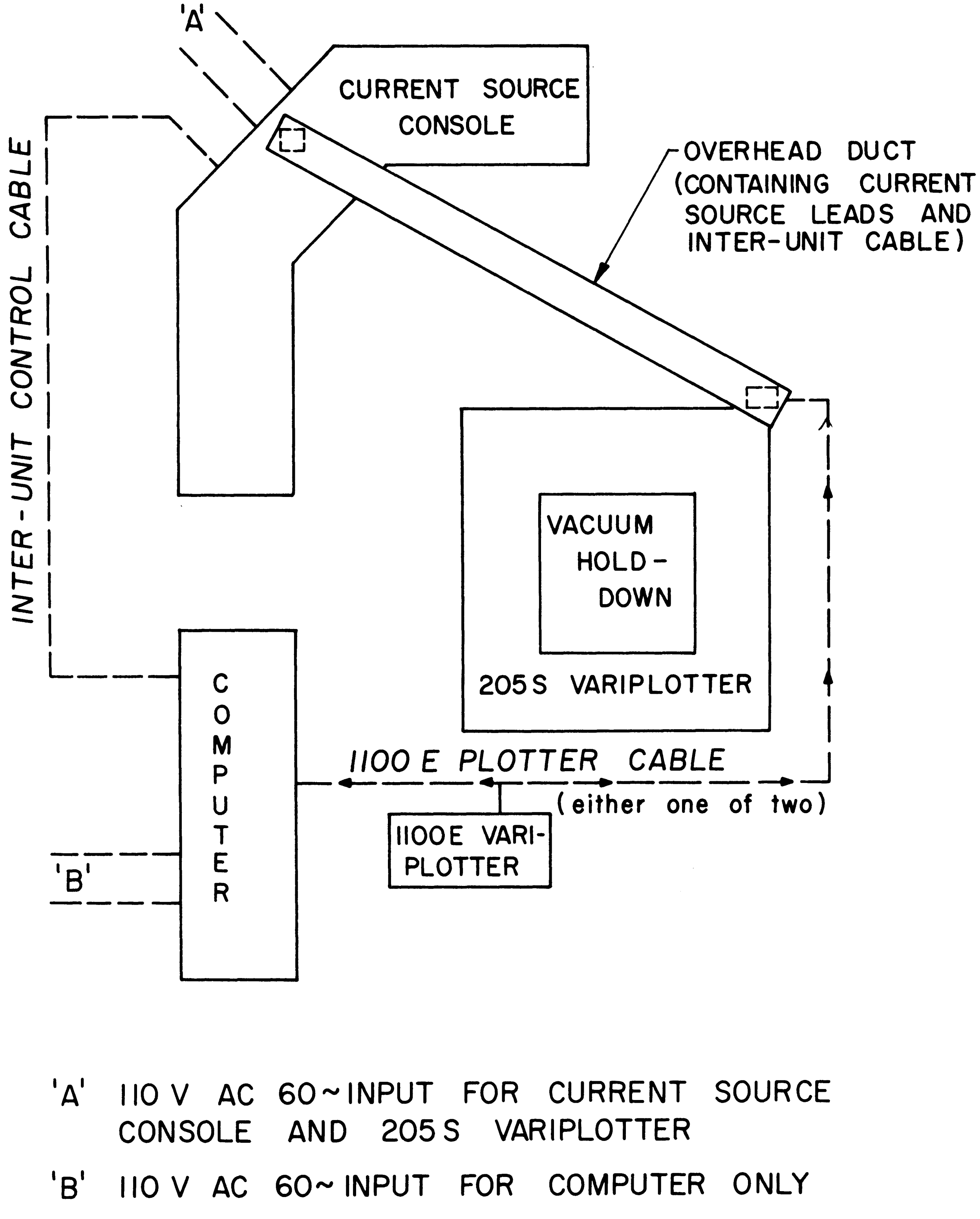


FIGURE V.16

Unloading Amplifier Attenuators

A view of the top right section of the Electronic Associates analog computer showing the location of the attenuators used to adjust the stability of the probe unloading amplifiers.



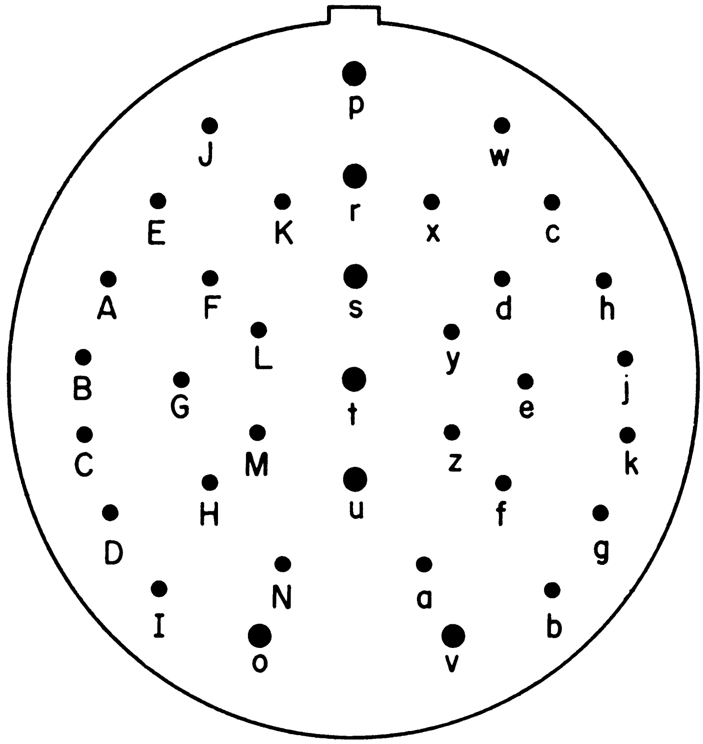
DRAWING VI.1 SCHEMATIC OF INTER-UNIT WIRING.

TERMINAL	WIRE COLOR	DESTINATION (COMPUTER)
o	Black	H.Q. GND Buss
v	Red	+100 Volt Buss
u	Blue	-100 Volt Buss
t	White	B+ Switch on Computer
s	Wh/Yel	B+ Switch on Computer
r	Wh/Brn	B+ Switch on Computer
p	Wh/Blu	B+ Switch on Computer
b	Blue	RP2-J5-20
a	White	RP2-J5-21
g	White	MC-J1-1
f	Purple	RP2-J1-37
k	White	TB2-2(DJ1-52)
j	White	RP2-J5-23
e	Gray	RP2-J5-22
z	Wh/Red	TB2-5(DJ1-55)
y	Brown	TB2-3(DJ1-53)
d	Pink	TB2-14
h	Yellow	PS6-TP1-21
c	Red	PS6-TP1-8
X	Wh/Grn	PS6-TP1-7
W	Black	TB2-1(DJ1-51)
I	Red	MC-J1-51
N	Purple	RP2-J1-42
D	Gray	MC-J1-50
C	Green	MC-J1-52
H	Gray	MC-J1-15
M	Purple	RP2-J5-39
G	White	RP2-J5-24
B	White	RP2-J5-25
L	Orange	TB2-6(DJ1-56)
F	Purple	RP2-J1-35
A	Brown	MC-J1-8
K	Wh/Blk	TB2-4(DJ1-54)
E	Purple	PS6-P Buss
J	Green	TB2-18

REAR VIEW OF

INTER-UNIT WIRING CONNECTOR NO.1

(Back of Computer Console)



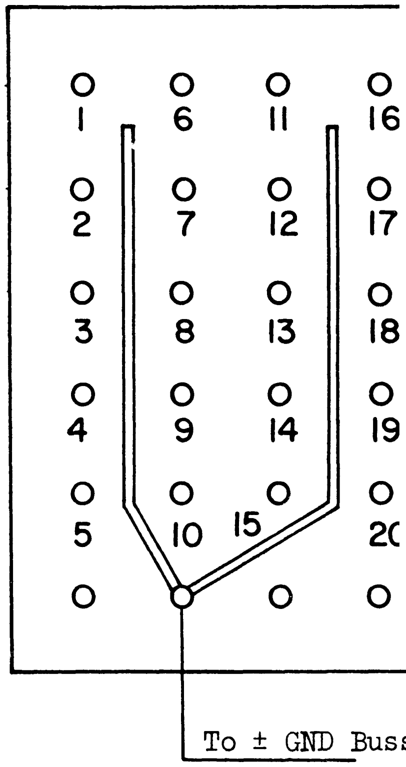
NOTE: When Inter-Unit Cable is Disconnected from Connector No.1 the Shorting Plug Must Be Attached to the Connector in Order for the Computer to Function Properly.

DRAWING VI.2 INTER-UNIT WIRING - LIST OF INDIVIDUAL WIRING CONNECTIONS.

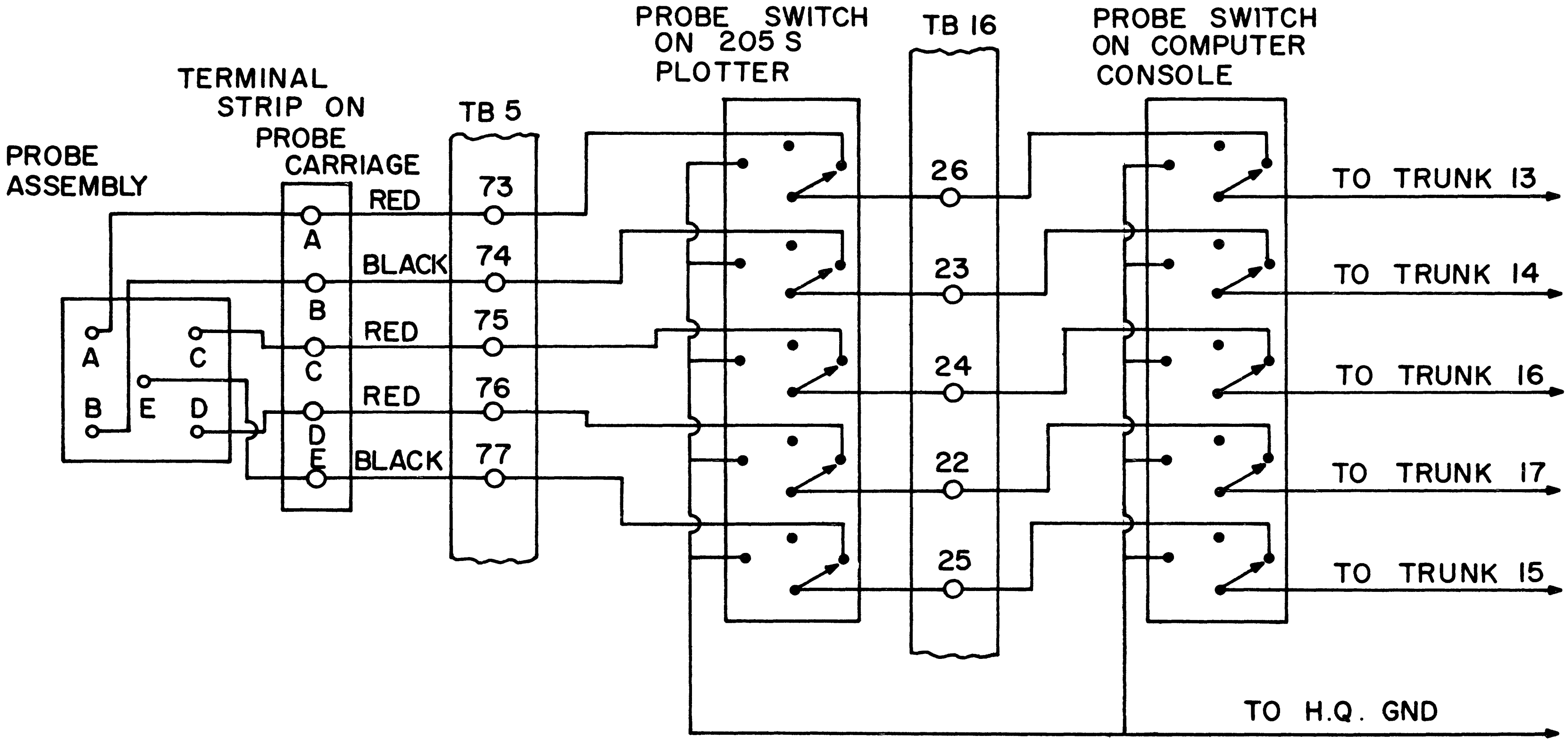
TERMINAL	WIRE TYPE	FUNCTION	DESTINATION (COMPUTER)
1	Coax	Probe A Lead	Trunk 13
2	Coax	Probe B Lead	Trunk 14
3	Coax	Probe C Lead	Trunk 15
4	Coax	Probe D Lead	Trunk 16
5	Coax	Probe E Lead	Trunk 17
6	Coax	X-Input to 205-S Variplotter	X-Input on Patch Panel
7	Coax	Y-Input to 205-S Variplotter	Y-Input on Patch Panel
8	Coax	X-Input to 1100-E Variplotter	X-Input on Patch Panel
9	Coax	Y-Input to 1100-E Variplotter	Y-Input on Patch Panel
10	Coax	Hi Side of Pot. P30	Hi Side of Pot. P30 on Patch Panel
11	Coax	Wiper of Pot. P30	Wiper of Pot. P30 on Patch Panel
12	Coax	Hi Side of Pot. P31	Hi Side of Pot. P31 on Patch Panel
13	Coax	Wiper of Pot. P31	Wiper of Pot. P31 on Patch Panel
14	Coax	Hi Side of Pot. P32	Hi Side of Pot. P32 on Patch Panel
15	Coax	Wiper of Pot. P32	Wiper of Pot. P32 on Patch Panel
16	Coax	Hi Side of Pot. P33	Hi Side of Pot. P33 on Patch Panel
17	Coax	Wiper of Pot. P33	Wiper of Pot. P33 on Patch Panel
18	Coax	Hi Side of Pot. P34	Hi Side of Pot. P34 on Patch Panel
19	Coax	Wiper of Pot. P34	Wiper of Pot. P34 on Patch Panel
20	Coax	Hi Side of Pot. P35	Hi Side of Pot. P35 on Patch Panel
21	Coax	Wiper of Pot. P35	Wiper of Pot. P35 on Patch Panel

REAR VIEW OF INTER-UNI

WIRING CONNECTOR NO. 2

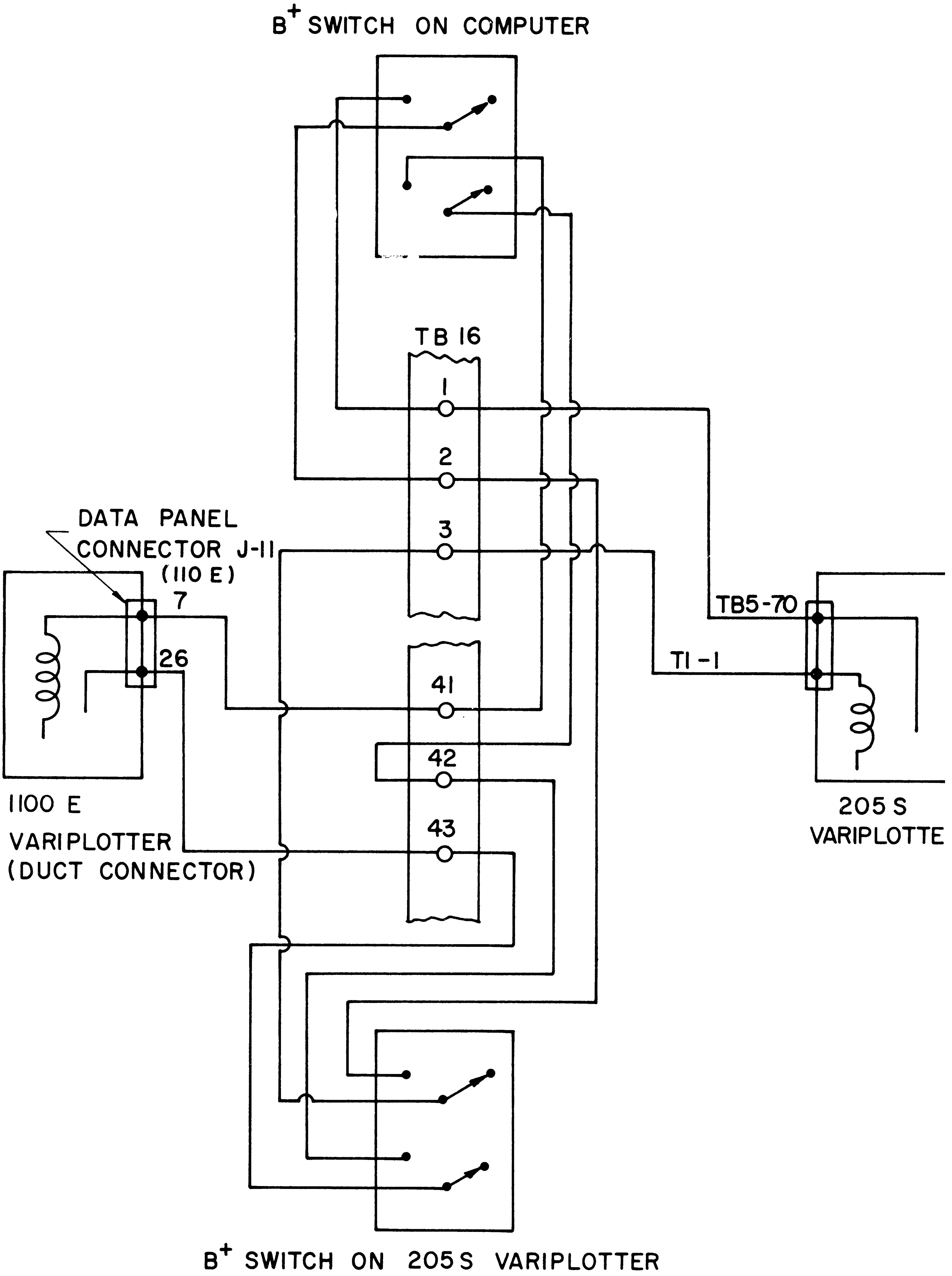


DRAWING VI.2 (cont'd)

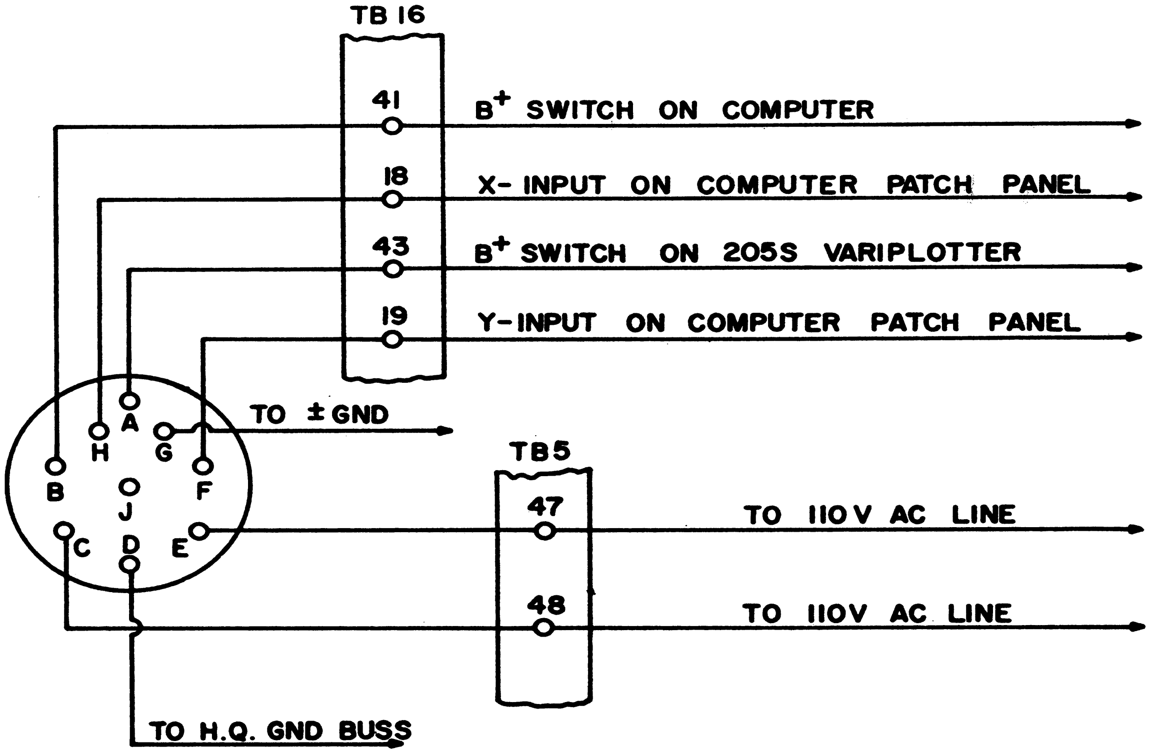


NOTE: ALL WIRES ARE SHIELDED

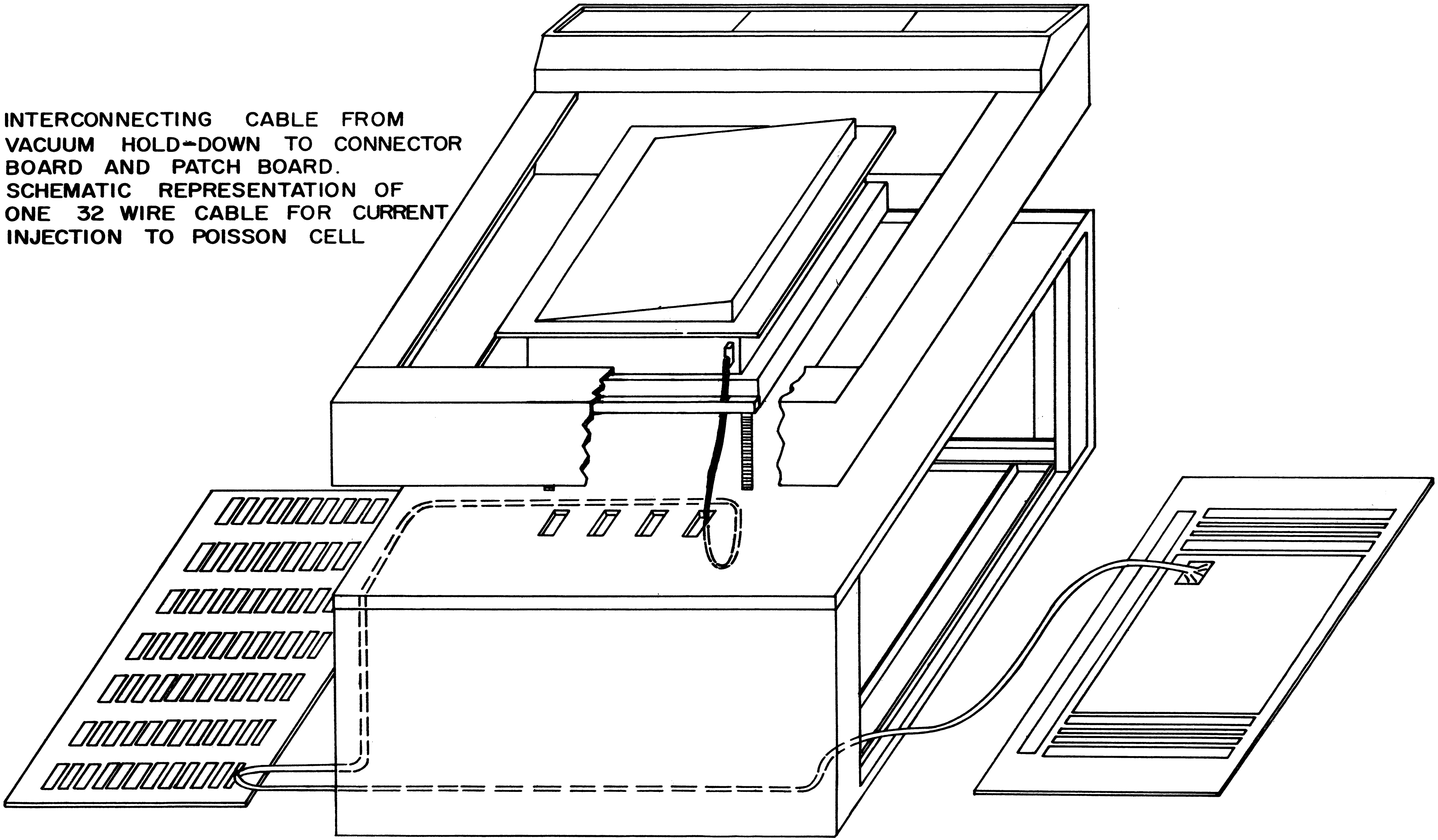
DRAWING VI.3 WIRING DIAGRAM OF POISSON CELL PROBE SWITCHING.



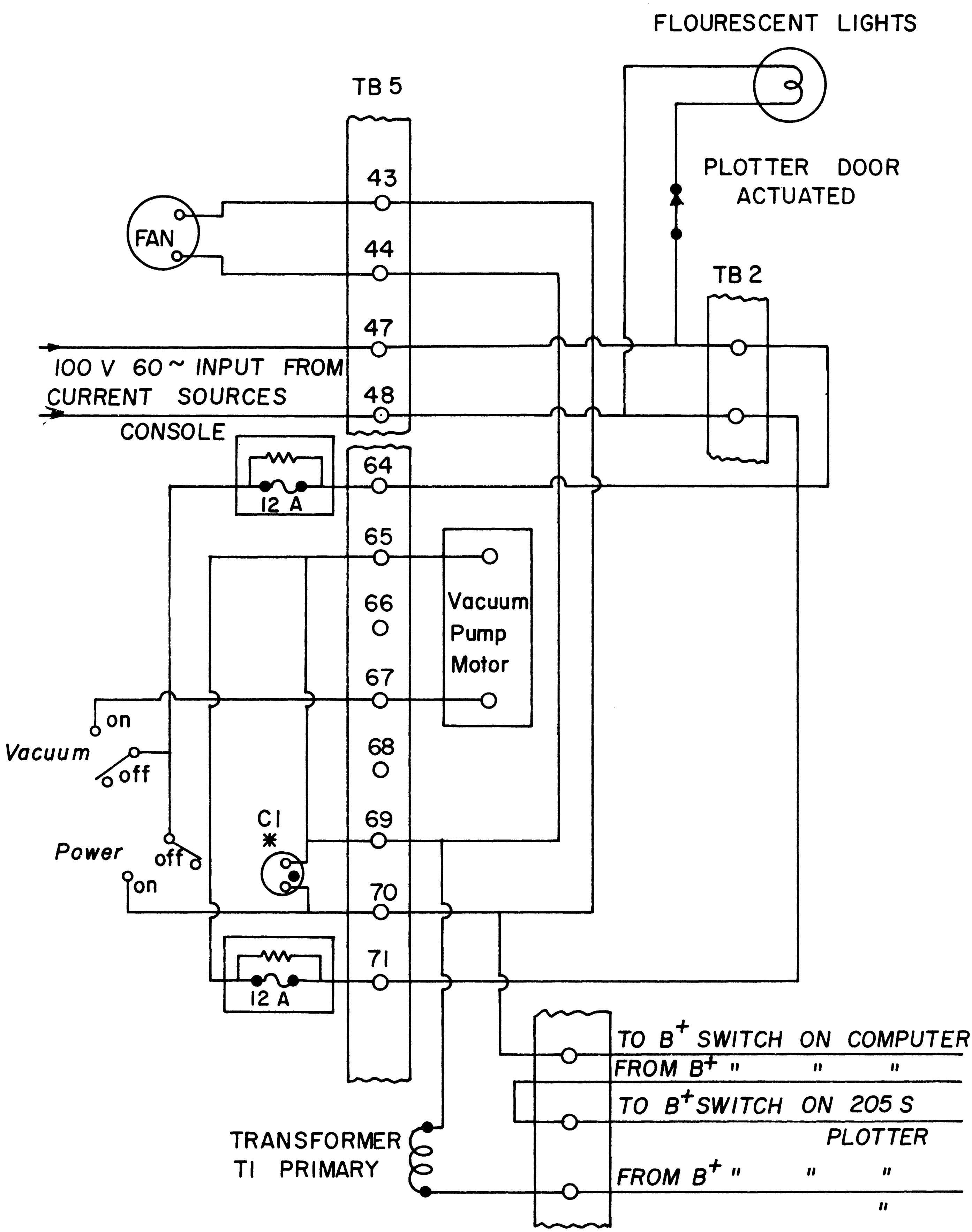
DRAWING VI.4 WIRING DIAGRAM OF EXTERNAL SWITCHING OF 205-S AND 1100-E VARIPLOTTERS.



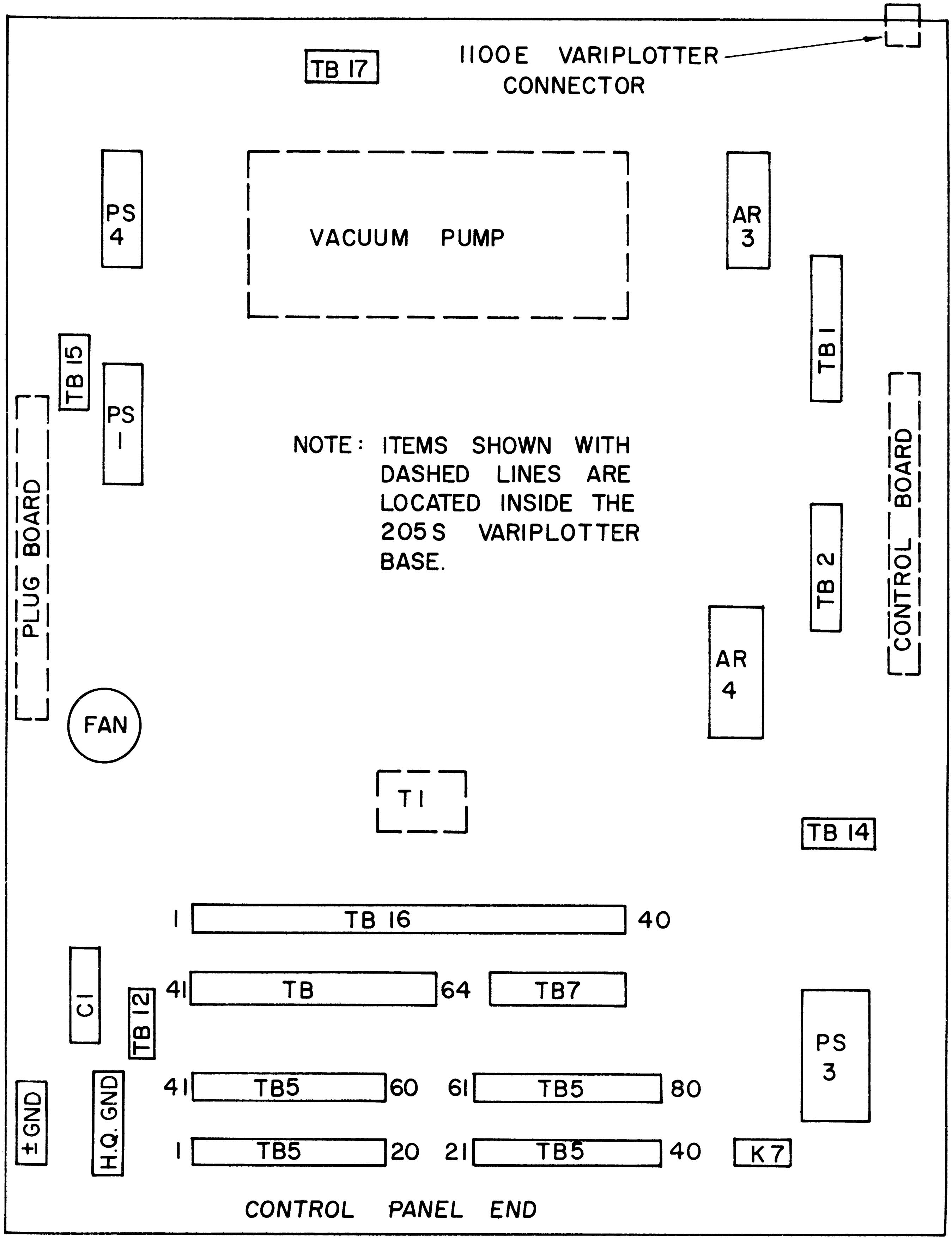
DRAWING VI.5 WIRING DIAGRAM OF 1100-E VARIPLOTTER CONNECTOR MOUNTED AT BASE OF VERTICAL WIRING DUCT.



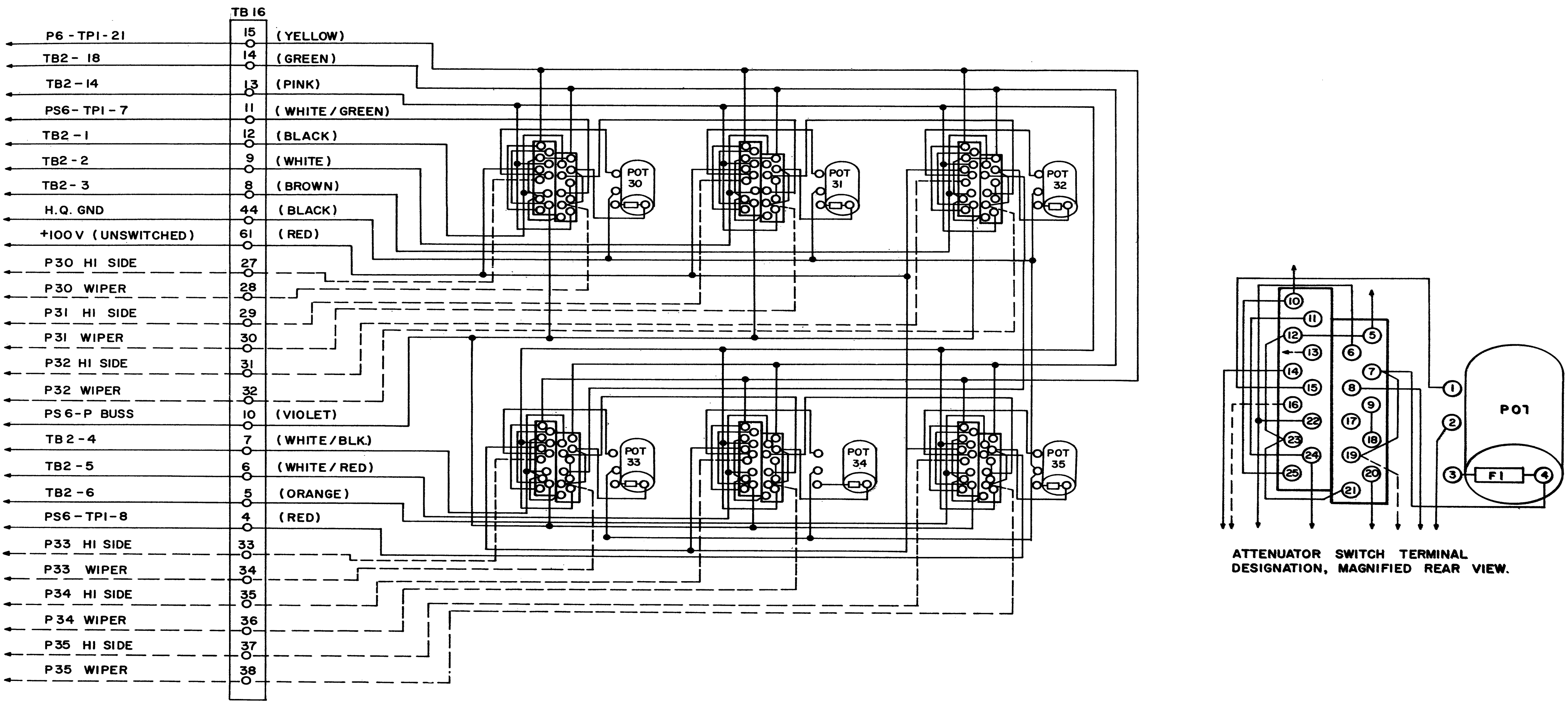
DRAWING VI.6 SCHEMATIC DRAWING OF CURRENT INJECTION WIRING BETWEEN CONNECTOR PANEL, PLUGBOARD, AND VACUUM HOLD-DOWN.



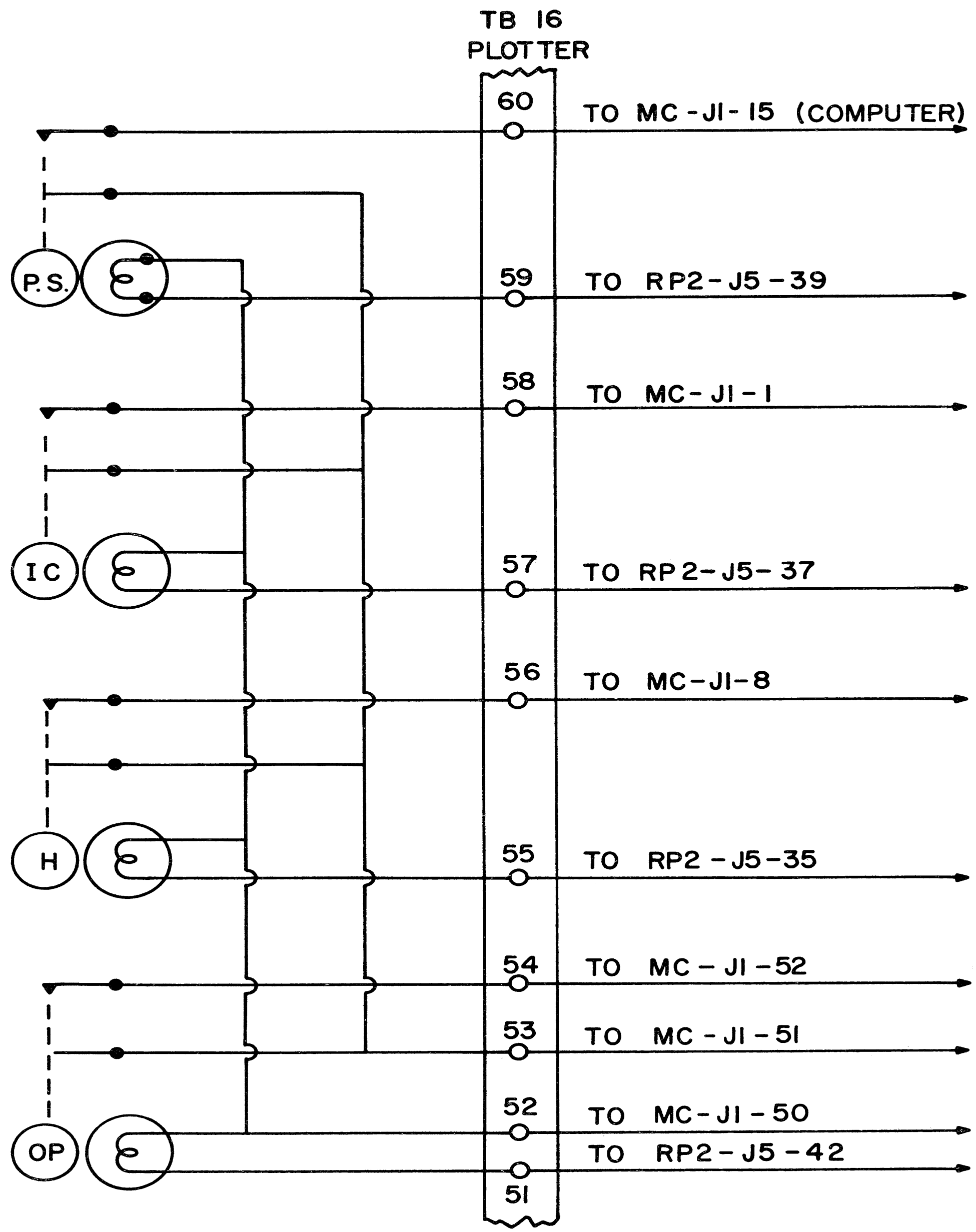
DRAWING VI.7 110 VOLT 60 CYCLE POWER DISTRIBUTION IN 205-S PLOTTER



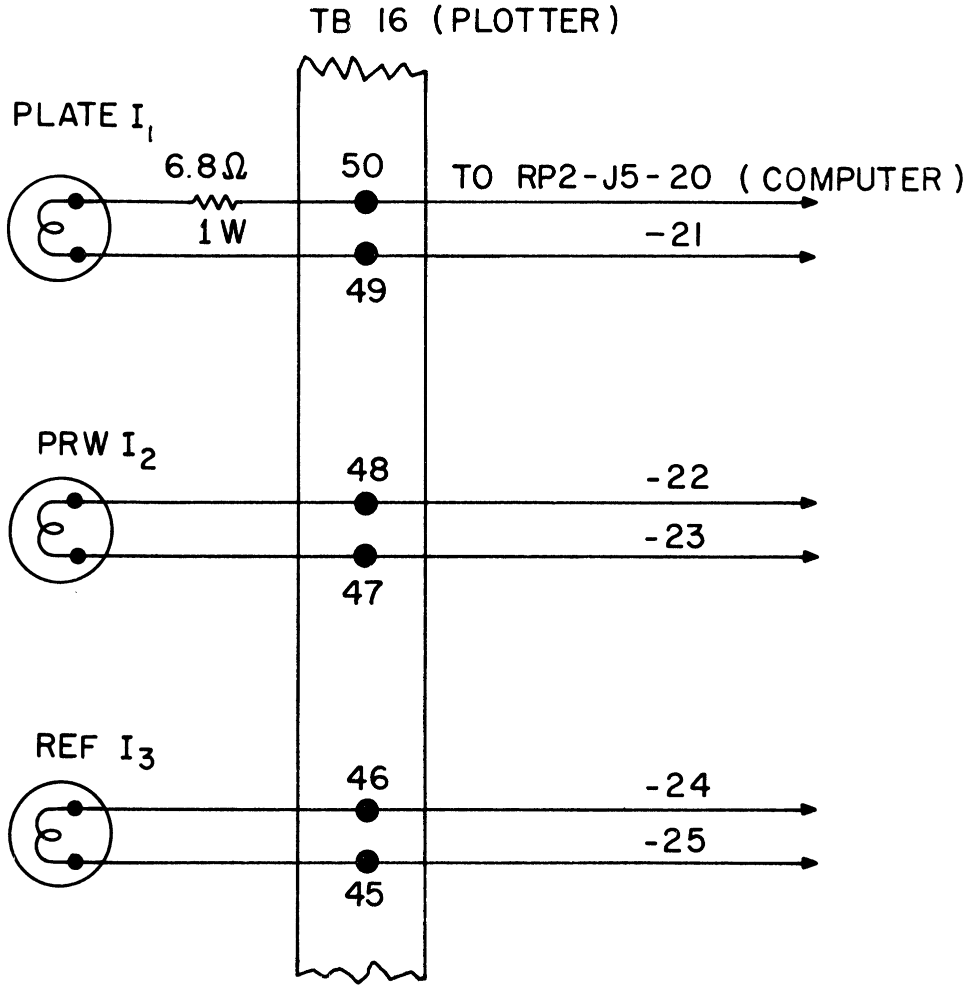
DRAWING VI.8 BLOCK DIAGRAM OF COMPONENT PLACEMENT IN 205-S PLOTTER.



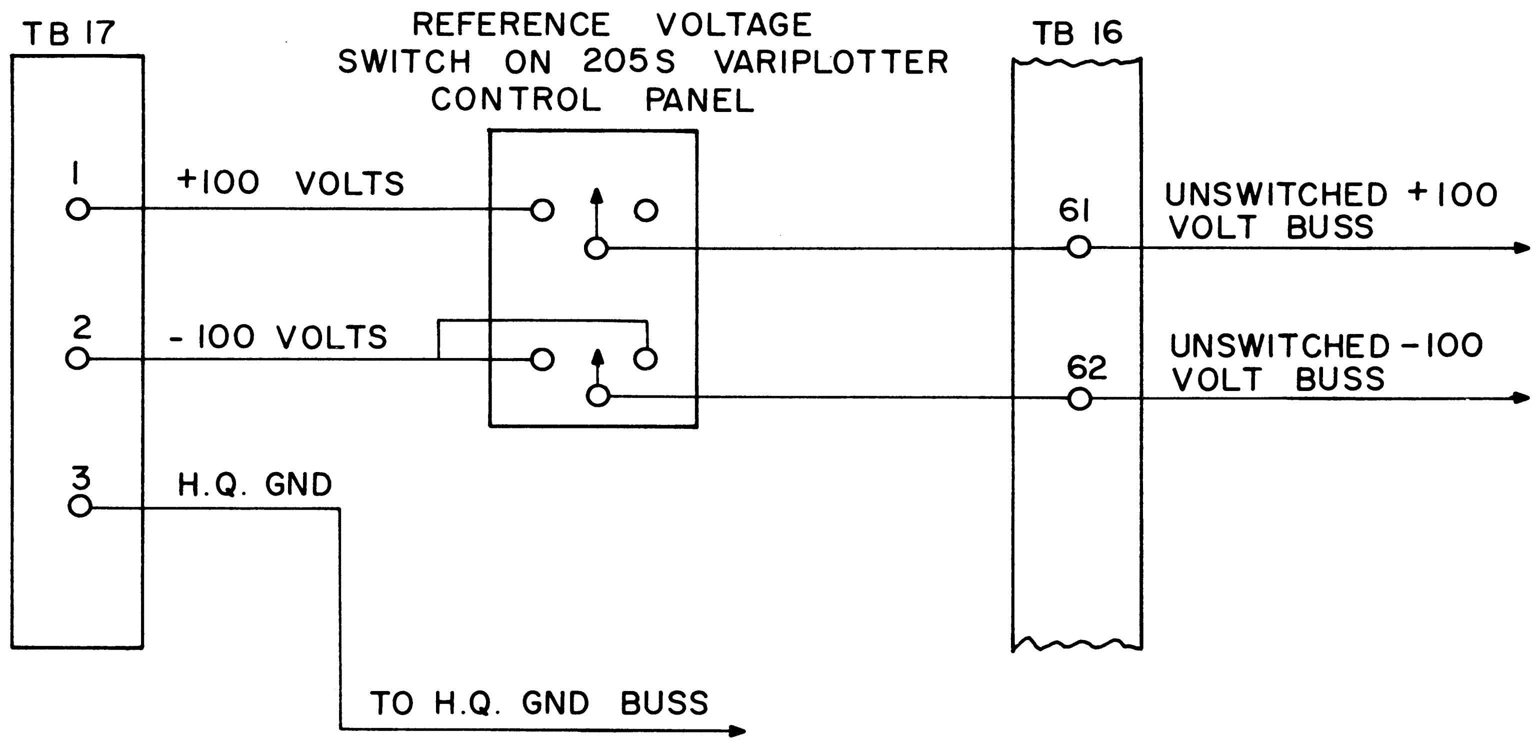
DRAWING VI.9 PLOTTER CONTROL PANEL - SCHEMATIC DIAGRAM OF COEFFICIENT SETTING POTENTIOMETER.



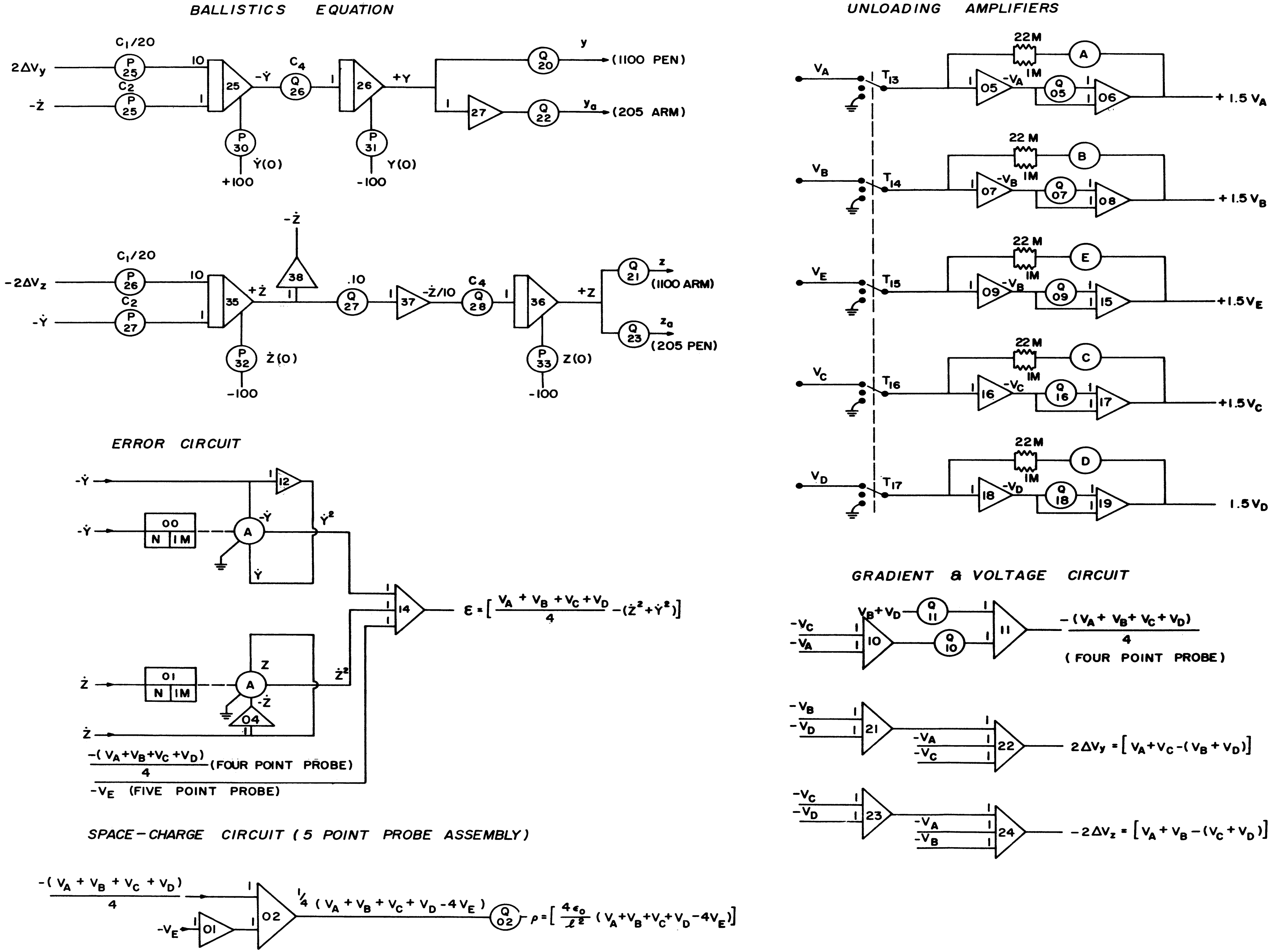
DRAWING VI.10 PLOTTER CONTROL PANEL - WIRING OF MODE CONTROL SWITCHING.



DRAWING VI.11 PLOTTER CONTROL PANEL - WIRING OF INDICATOR LIGHTS.



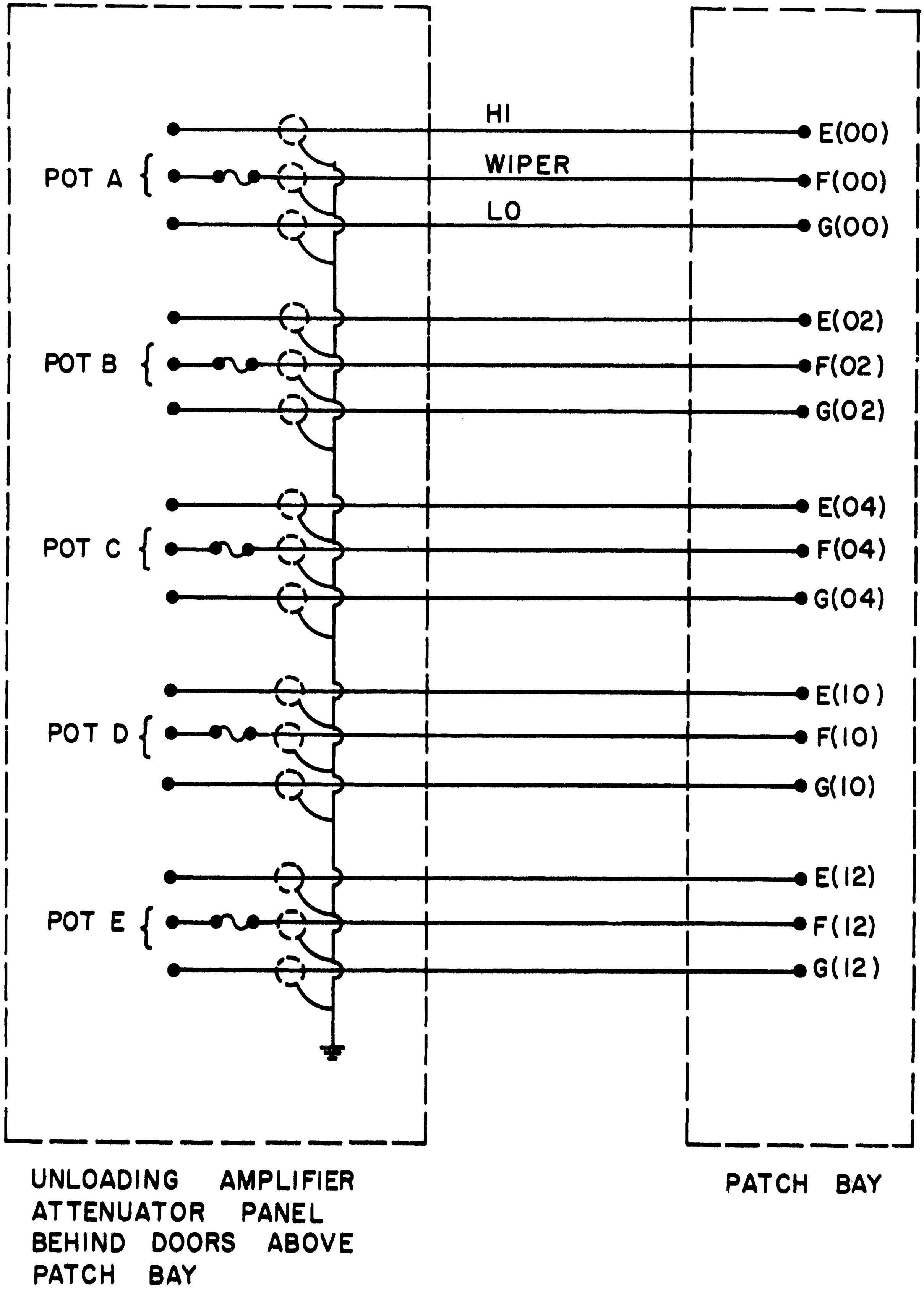
DRAWING VI.12 PLOTTER - UTILITY REFERENCE VOLTAGE SOURCE FOR POISSON CELL.



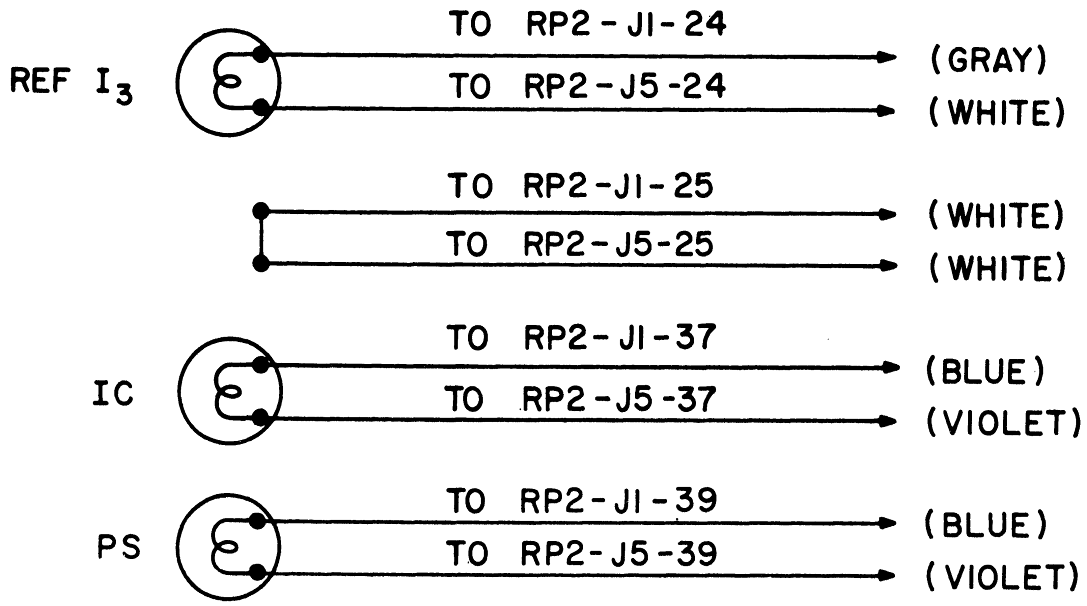
DRAWING VI.13 COMPUTER ROADMAP OF TWO-DIMENSIONAL BALLISTICS PROB'

TERMINAL	FUNCTION	DESTINATION	COLOR
TB16-1	205-S Variplotter External Switching	B+ Switch on Computer	Wh/Blue
TB16-2	205-S Variplotter External Switching	B+ Switch on Computer	Wh/Br
TB16-3	205-S Variplotter External Switching	B+ Switch on 205-S Variplotter	Wh/Gry
TB16-4	Pot. Buss Output to D.V.M.	PS6-TP1-8	Red
TB16-5	Units Address	TB2-6(DJ1-56)	Or
TB16-6	Units Address	TB2-5(DJ1-55)	Wh/R
TB16-7	Units Address	TB2-4(DJ1-54)	Wh/Blk
TB16-8	Units Address	TB2-3(DJ1-53)	Br
TB16-9	Units Address	TB2-2(DJ1-52)	Wh
TB16-10	P and Q Hundreds Print Code	PS6-P Buss	Vi
TB16-11	Pot. Buss to D.V.M.	PS6-TP1-7	Wh/Grn
TB16-12	Units Address	TB2-1 (DJ1-51)	Blk
TB16-13	Tens Print	TB2-14	Pink
TB16-14	Print Signal (Tens Units)	TB2-18	Grn
TB16-15	Print Control (Hundreds)	P6-TP1-21	Yel
TB16-16	-100 V Reference	-100 V Buss	Bl
TB16-17	+100 V Reference	+100 V Buss	Red
TB16-18	X-Input to 1100-E Variplotter	X-Input Location on Patch Panel	Coax
TB16-19	Y-Input to 1100-E Variplotter	Y-Input Location on Patch Panel	Coax
TB16-20	Y-Input to 205-S Variplotter	Y-Input Location on Patch Panel	Coax
TB16-21	X-Input to 205-S Variplotter	X-Input Location on Patch Panel	Coax
TB16-22	Lead for Probe D	Trunk 17 Via Probe Switch on Computer	Coax
TB16-23	Lead for Probe B	Trunk 14 Via Probe Switch on Computer	Coax
TB16-24	Lead for Probe E	Trunk 15 Via Probe Switch on Computer	Coax
TB16-25	Lead for Probe C	Trunk 16 Via Probe Switch on Computer	Coax
TB16-26	Lead for Probe A	Trunk 13 Via Probe Switch on Computer	Coax
TB16-27	Hi Side of Pot. P30	Pot. P30 Location on Patch Panel	Coax
TB16-28	Arm of Pot. P30	Pot. P30 Location on Patch Panel	Coax
TB16-29	Hi Side of Pot. P31	Pot. P31 Location on Patch Panel	Coax
TB16-30	Arm of Pot. P31	Pot. P31 Location on Patch Panel	Coax
TB16-31	Hi Side of Pot. P32	Pot. P32 Location on Patch Panel	Coax
TB16-32	Arm of Pot. P32	Pot. P32 Location on Patch Panel	Coax
TB16-33	Hi Side of Pot. P33	Pot. P33 Location on Patch Panel	Coax
TB16-34	Arm of Pot.P33	Pot. P33 Location on Patch Panel	Coax
TB16-35	Hi Side of Pot. P34	Pot. P34 Location on Patch Panel	Coax
TB16-36	Arm of Pot. P34	Pot. P34 Location on Patch Panel	Coax
TB16-37	Hi Side of Pot. P35	Pot. P35 Location on Patch Panel	Coax
TB16-38	Arm of Pot. P35	Pot. P35 Location on Patch Panel	Coax
TB16-39	Arm of Pot. P35	Pot. P35 Location on Patch Panel	Coax
TB16-40	± GND	--	--
TB16-41	1100-E Variplotter External Switching	B+ Switch on Computer	Wh/Yel
TB16-42	1100-E Variplotter External Switching	B+ Switch on Computer	Wh
TB16-43	1100-E Variplotter External Switching	B+ Switch on 205-S Variplotter	Wh
TB16-44	H.Q. GND	H.Q. GND Buss	Blk
TB16-45	Mode Panel Reference Light	RP2-J5-25	Wh
TB16-46	Mode Panel Reference Light	RP2-J5-24	Wh
TB16-47	Mode Panel Power Light	RP2-J5-23	Wh
TB16-48	Mode Panel Power Light	RP2-J5-22	Gry
TB16-49	Mode Panel Plate Light	RP2-J5-21	Wh
TB16-50	Mode Panel Plate Light	RP2-J5-20	B
TB16-51	Mode Switch Operate Light	RP2-J5-42	Vi
TB16-52	Common for Mode Switch Lights	MC-J1-50	Gry
TB16-53	Relay Common for Mode Switch	MC-J1-51	R
TB16-54	Operate Control	MC-J1-52	Grn
TB16-55	Mode Switch Hold Light	RP2-J5-35	V
TB16-56	Hold Control	MC-J1-8	Br
TB16-57	Mode Switch Initial Condition Light	RP2-J5-37	V
TB16-58	Initial Condition Control	MC-J1-1	Wh
TB16-59	Mode Switch Pot.-Set Light	RP2-J5-39	Vi
TB16-60	Pot.-Set Control	MC-J1-15	Gry
TB16-61	+100 Volts to Electrode Connection Terminal Strip	Unswitched +100 Volt Buss	R
TB16-62	-100 Volts to Electrode Connection Terminal Strip	Unswitched -100 Volt Buss	B
TB17-1	+100 Volt Electrode Connection	TB16-61	R
TB17-2	-100 Volt Electrode Connection	TB16-62	B
TB17-3	H.Q. GND	H.Q. GND Buss	Blk

DRAWING VI.14 COMPUTER CONSOLE WIRING OF INTER-UNIT CABLE.

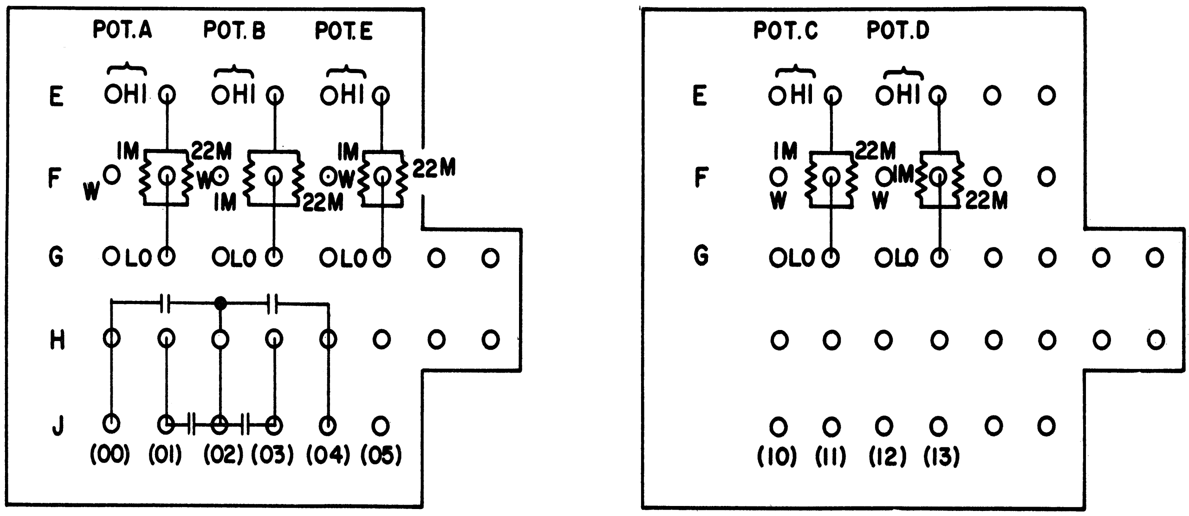


DRAWING VI.15 WIRING OF UNLOADING AMPLIFIER ATTENUATORS.



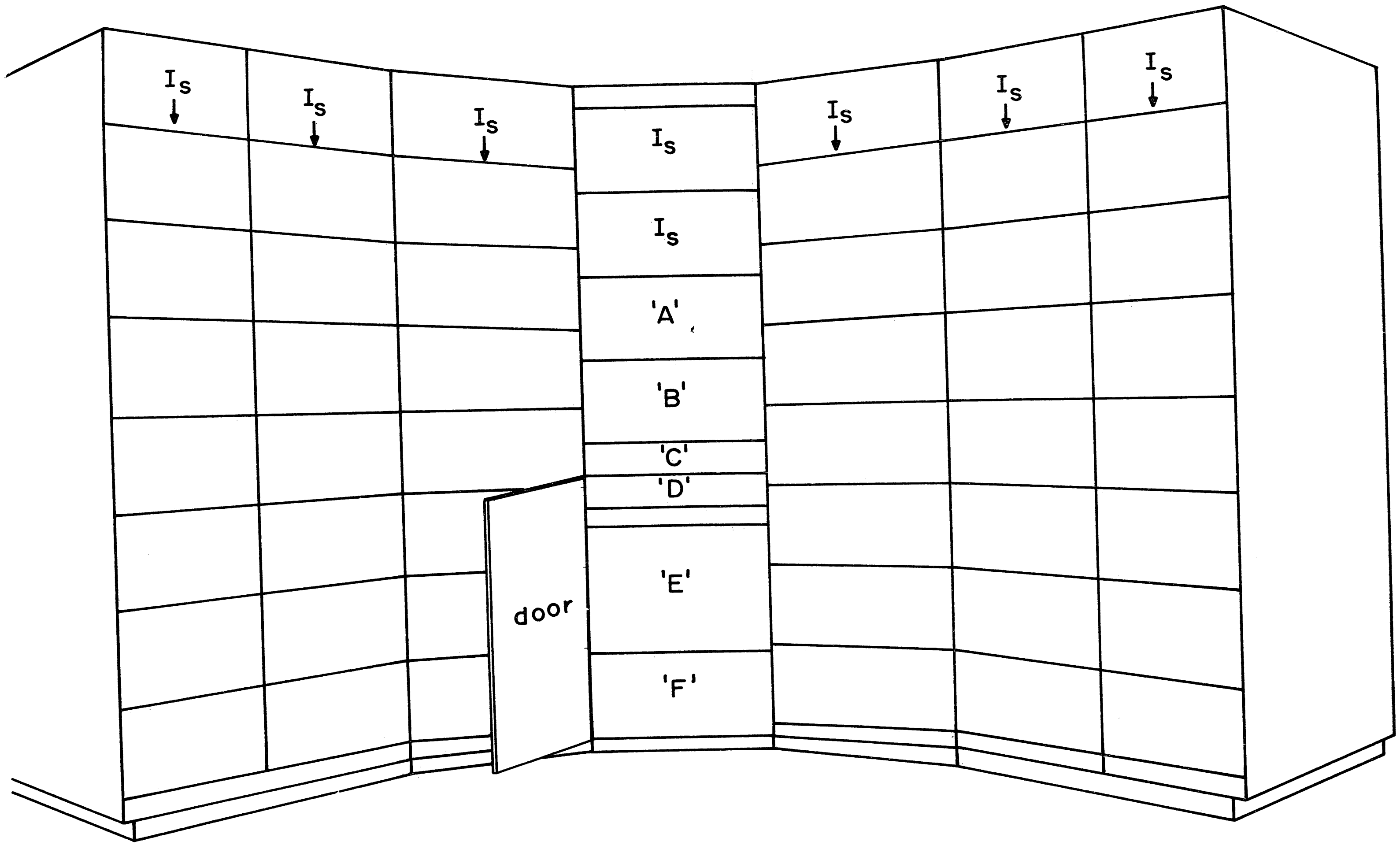
The No. 2 terminals on the PS and IC lights were open circuited from MC-J1-50 on the mode control panel so as to allow a series connection through connector No. 1 (located in rear of computer) to IC and PS lights on 205-S Variplotter. From the No. 2 terminals on these lights the gray wire running from TB16-52 back to the computer completes the circuit to MC-J1-50. Similarly, by connecting the No. 2 terminal of the reference light I_3 to the wire from RP2-J5-24 and shorting the removed wire from RP2-J1-25 to the wire from RP2-J5-25, this reference light is in series with the I_3 reference light on the 205-S Variplotter.

DRAWING VI.16 WIRING CHANGES IN COMPUTER MODE CONTROL PANEL.



NOTE: THE ABOVE AREAS SHOWN ARE PAINTED WHITE AND CALLED "UNASSIGNED" ON THE PATCH PANEL. THE RESISTORS AND CONNECTIONS WERE ADDED DURING MODIFICATION OF THE COMPUTER.

DRAWING VI.17 ADDITIONS OF COMPONENTS AT BACK OF COMPUTER PATCH BAY.



DRAWING VI.18 SCHEMATIC DIAGRAM OF CURRENT SOURCE CONSOLE (FRONT VIEW).

'A' Control Panel

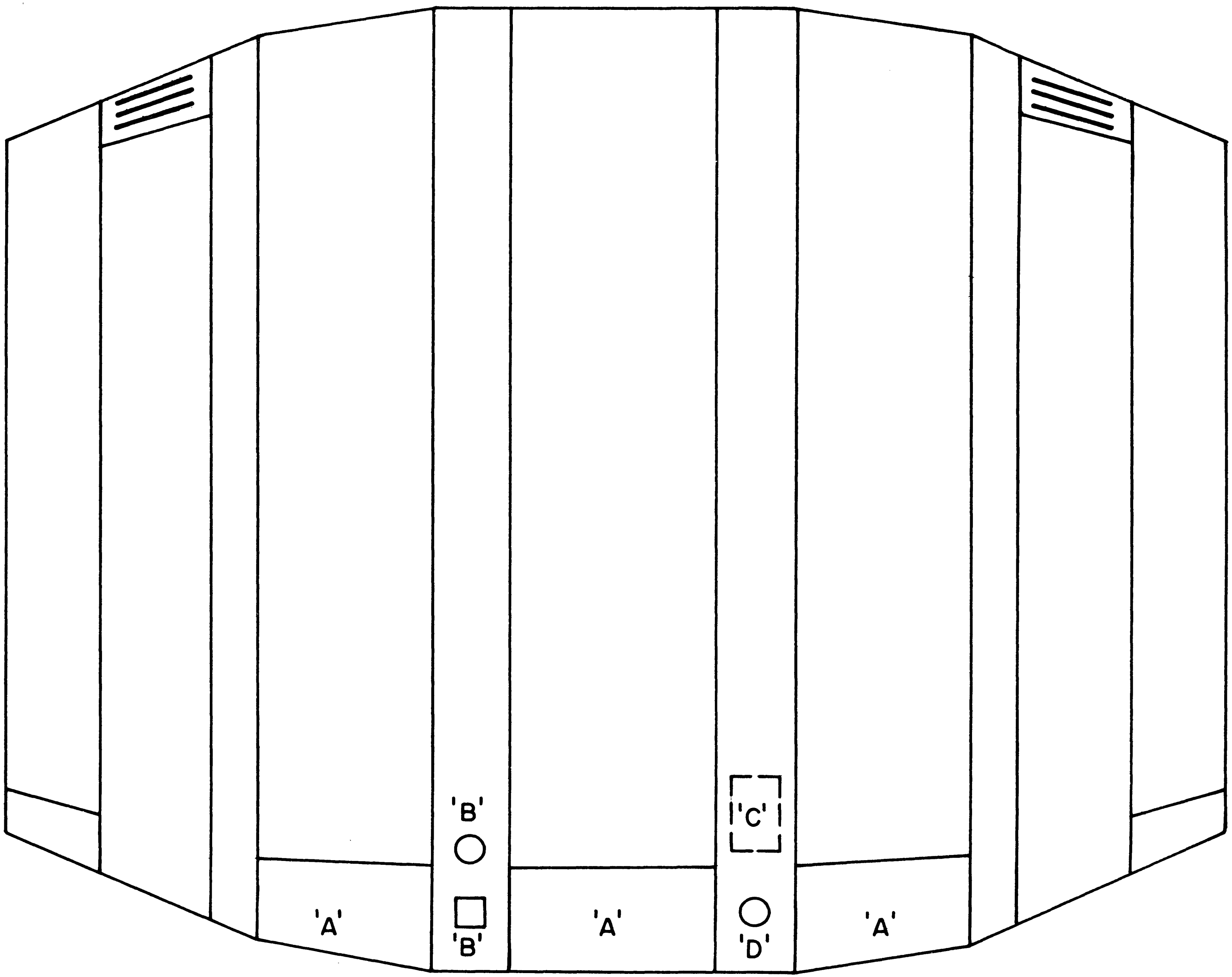
'B' Power Distribution Panel (Inside enclosure)

'C' Drawer

'D' 15 Volt Supply

'E' Filament Supply

'F' 200 Volt Supply



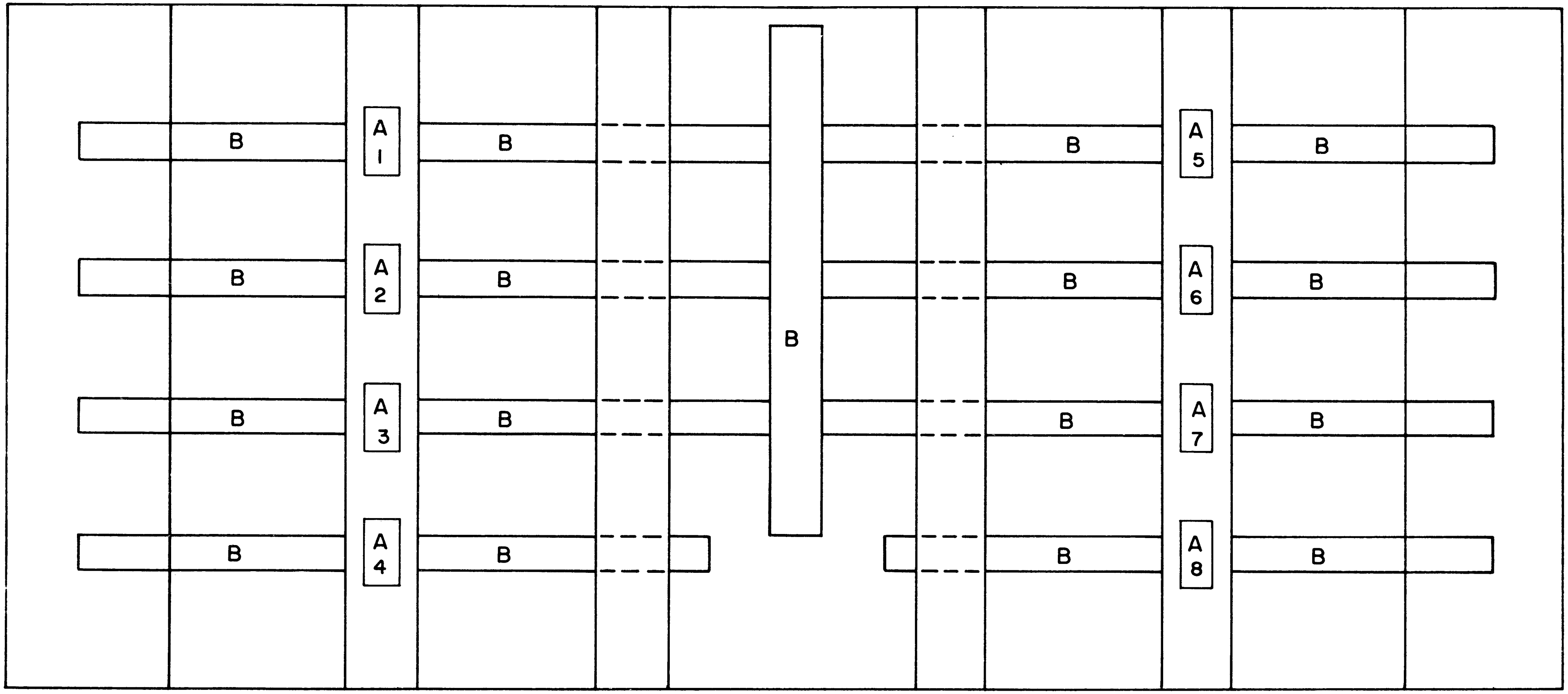
'A' FANS & FILTERS

'B' CONNECTORS FOR INTERCONNECTING CABLE FROM THE COMPUTER

'C' FILAMENT CONTACTOR (INSIDE ENCLOSURE)

'D' A.C. POWER INPUT

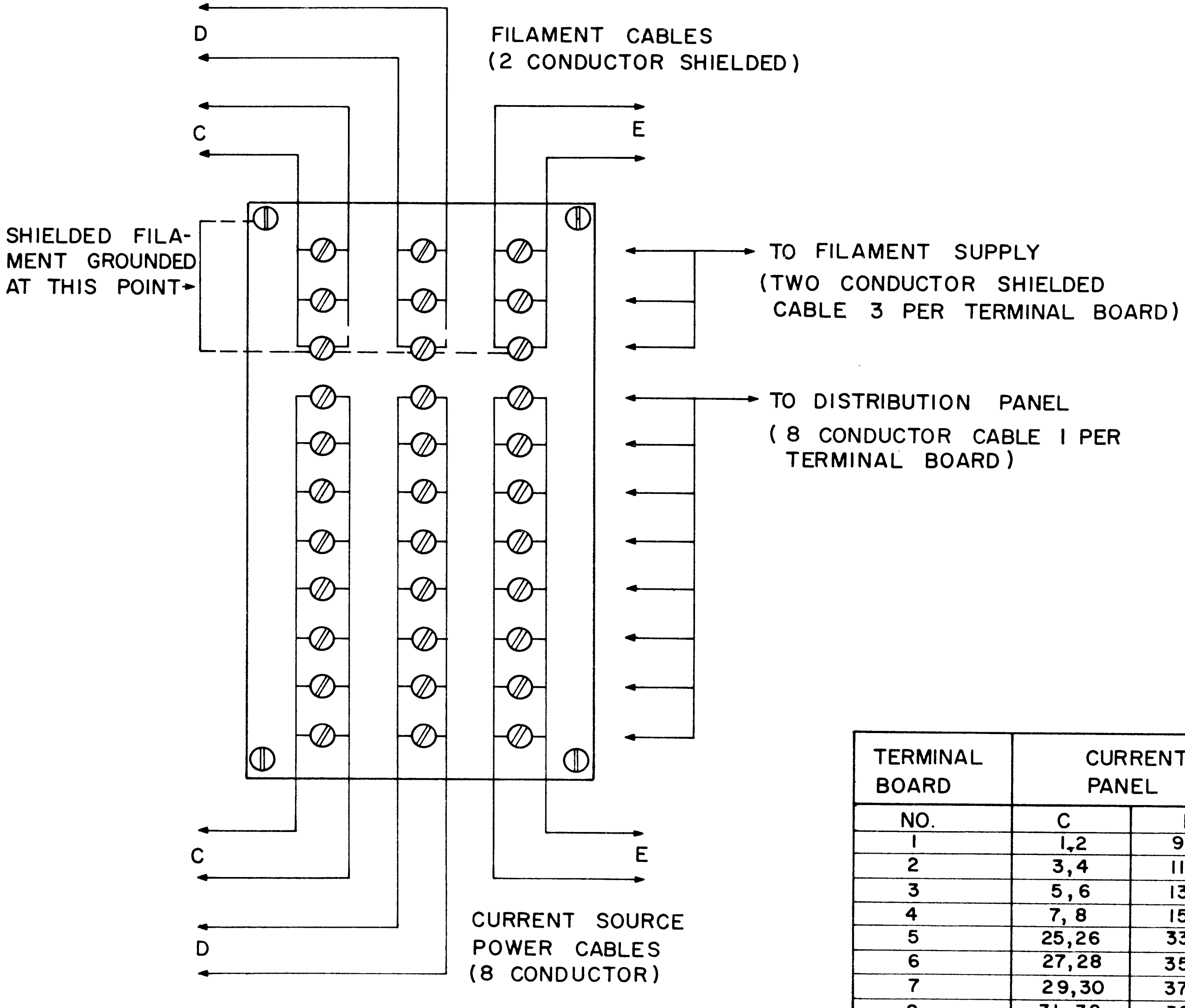
(FRONT VIEW)



Ⓐ INTRA-CONSOLE WIRING TERMINAL BOARD

Ⓑ PLASTIC WIRE DUCT

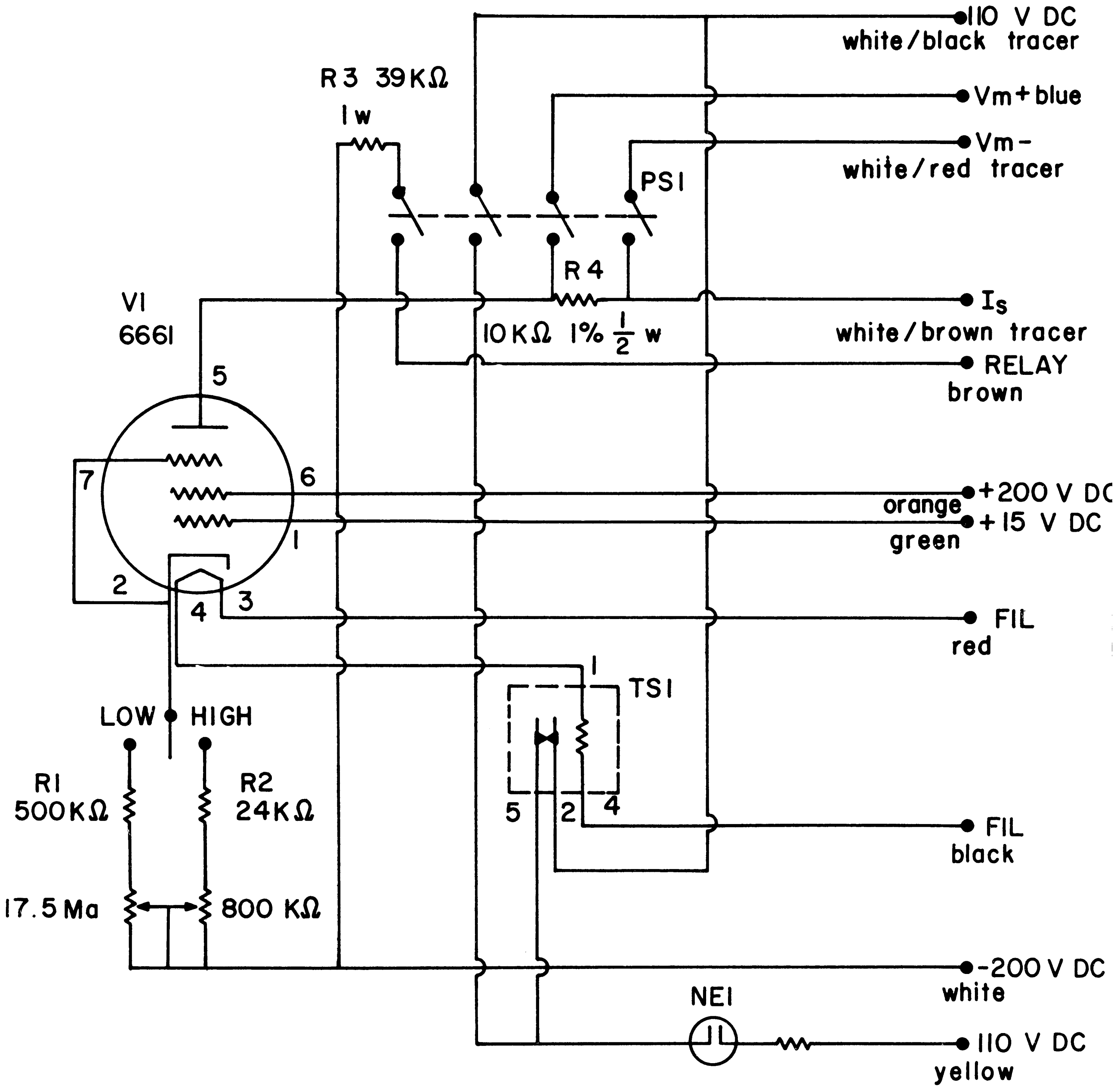
DRAWING VI.20 SCHEMATIC OF CONSOLE WIRING.



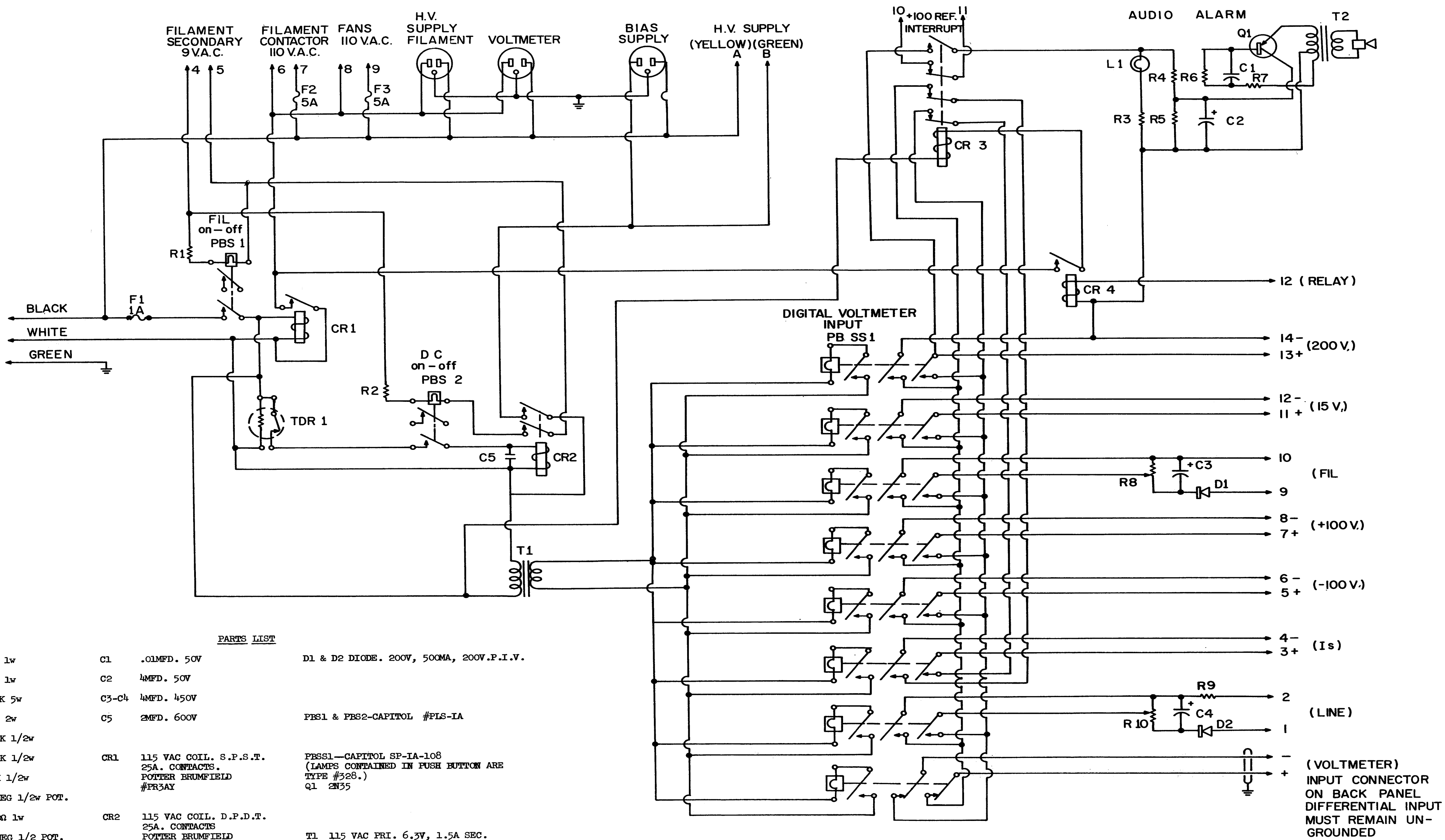
TERMINAL BOARD	CURRENT SOURCE PANEL NUMBER		
NO.	C	D	E
1	1,2	9,10	17,18
2	3,4	11,12	19,20
3	5,6	13,14	21,22
4	7,8	15,16	23,24
5	25,26	33,34	41,42
6	27,28	35,36	43,44
7	29,30	37,38	45,46
8	31,32	39,40	47,48

PANELS 49,50 FED DIRECTLY FROM DISTRIBUTION PANEL

DRAWING VI.21 SCHEMATIC DIAGRAM OF INTRA-CONSOLE TERMINAL BOARD.



DRAWING VI.22 WIRING DIAGRAM OF CURRENT SOURCE MODULE.



PARTS LIST

R 1 15Ω 1w
R 2 15Ω 1w
R 3 1.5K 5w
R 4 39K 2w
R 5 5.6K 1/2w
R 6 270K 1/2w
R 7 20K 1/2w
R 8 1 MEG 1/2w POT.
R 9 120Ω 1w
R10 1 MEG 1/2 POT.

TDR1—AMPERITE #115 NO 180

C1 .01MFD. 50V
C2 4MFD. 50V
C3-C4 4MFD. 450V
C5 2MFD. 600V

CR1 115 VAC COIL. S.P.S.T. 25A. CONTACTS. POTTER BRUMFIELD #PR3AY

CR2 115 VAC COIL. D.P.D.T. 25A. CONTACTS POTTER BRUMFIELD #PR11AY

CR3 115 VAC COIL. 4.P.D.T. POTTER BRUMFIELD #GA17A

CR4 PLATE CHT. RELAY POTTER BRUMFIELD #IM11. 5000Ω

D1 & D2 DIODE. 200V, 500MA, 200V.P.I.V.

PBS1 & PBS2-CAPITOL #PLS-IA

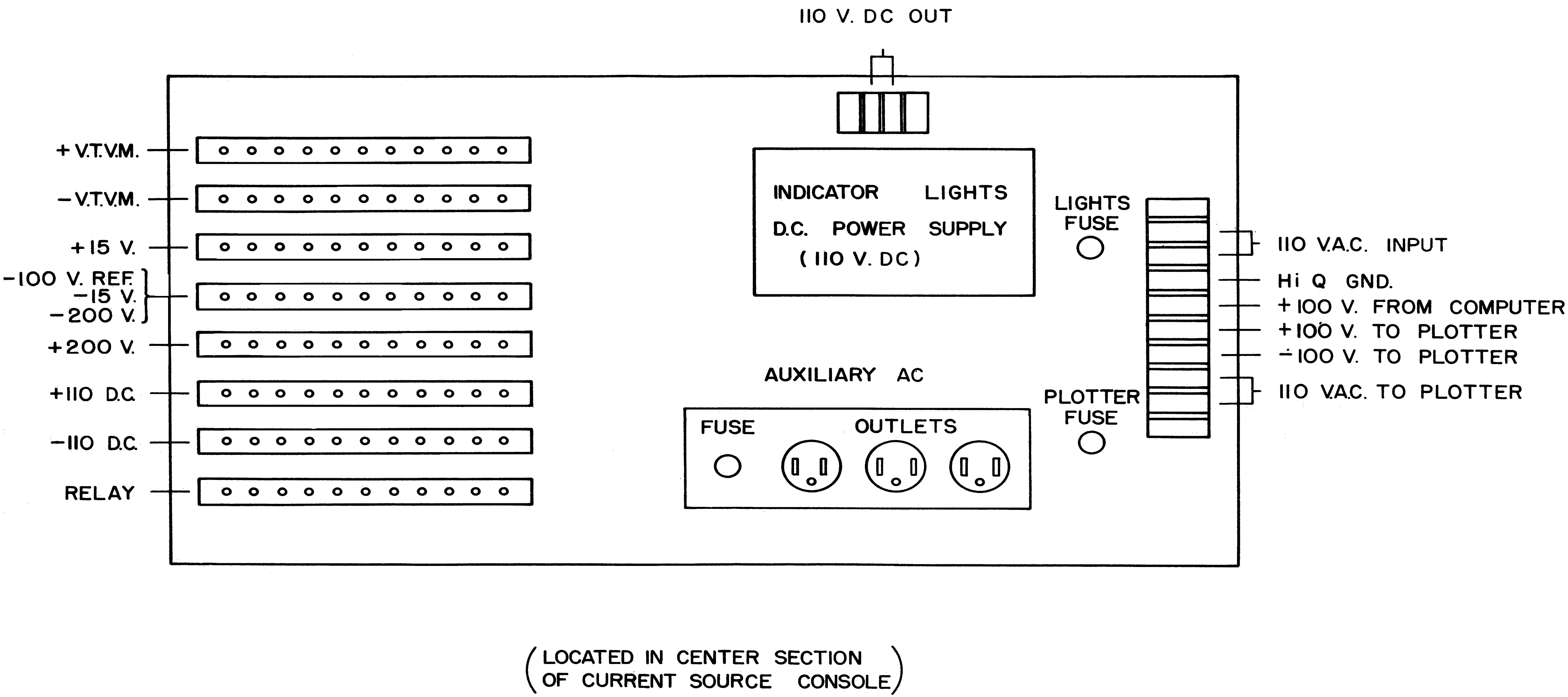
PBSS1—CAPITOL SP-IA-108 (LAMPS CONTAINED IN PUSH BUTTON ARE TYPE #328.)
Q1 2N35

T1 115 VAC PRI. 6.3V, 1.5A SEC.
T2 OUTPUT TRANS. STANCOR #TA-33

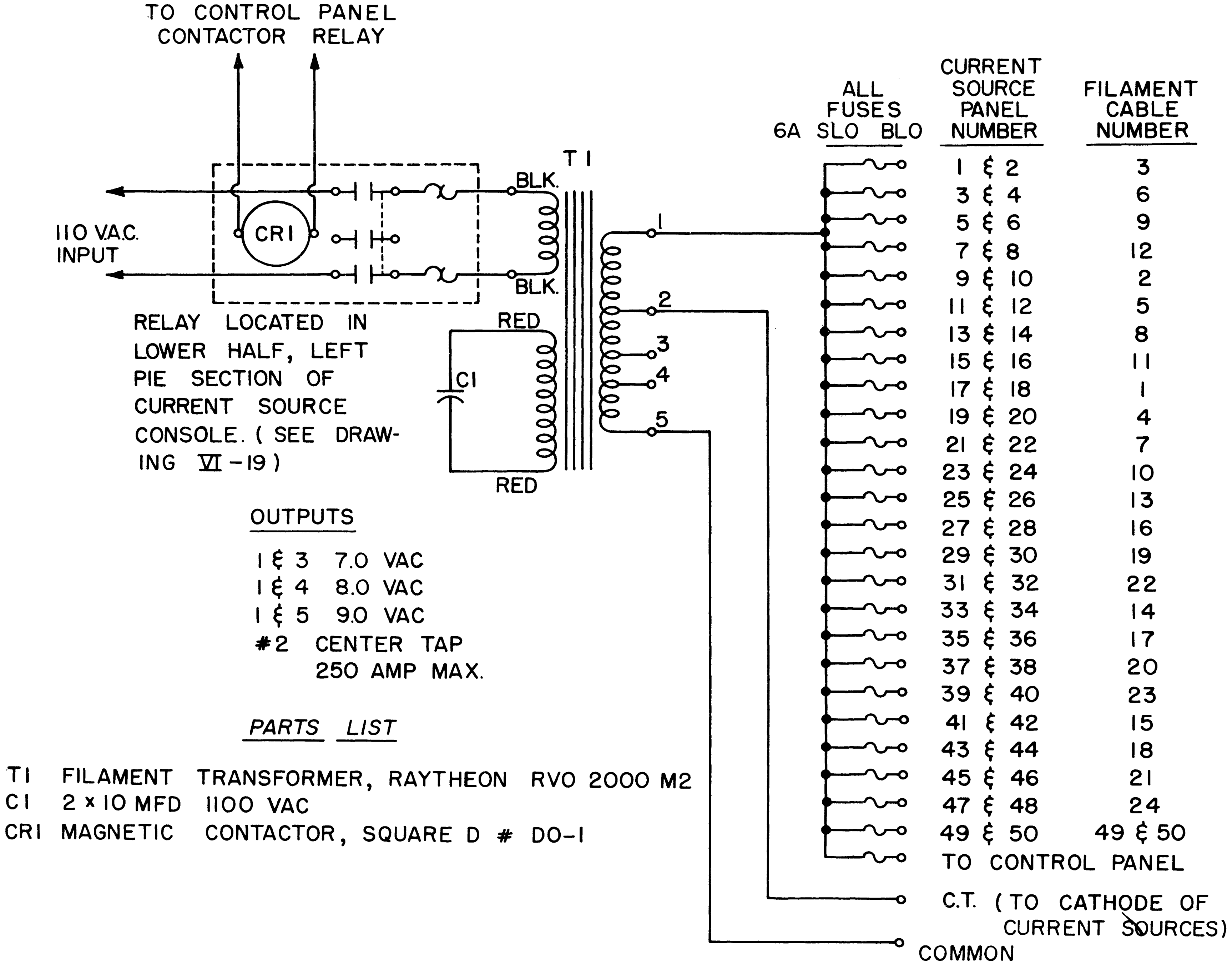
L1 120V, 3w

INDICATING PUSH BUTTON LAMPS GE328

DRAWING VI.23 WIRING DIAGRAM OF CONTROL PANEL.



DRAWING VI.24 SCHEMATIC OF POWER DISTRIBUTION PANEL.



DRAWING VI.25 WIRING DIAGRAM OF CONSTANT VOLTAGE-FILAMENT TRANSFORMER SUPPLY.