AD NUMBER	
AD640599	
CLASSIFICATION CHANGES	
TO:	UNCLASSIFIED
FROM:	RESTRICTED
LIMITATION CHANGES	
TO: Approved for public release; distribution is unlimited.	
FROM: Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 02 OCT 1947. Other requests shall be referred to Army Office of the Chief of Ordnance, Ordnance Research and Development Division, Washington, DC 20310.	
AUTHORITY	
EO 10501, 5 Nov 1953; BRL, 22 NOv 1986	

[redacted]EARCH LABORATORIES

REPORT NO. 654

Differential Analyzer---
Electrical Aspects of Operation

JEREMIAH LYNCH

ABERDEEN PROVING GROUND, MARYLAND

[redacted] UNCLASSIFIED

BALLISTIC RESEARCH LABORATORIES

REPORT NO. 654

DIFFERENTIAL ANALYZER-

ELECTRICAL ASPECTS OF OPERATION

JEREMIAH LYNCH

Ordnance Research and Development Division
Office Chief of Ordnance
Project No. TB3-0007

DECEMBER 1947

ABERDEEN PROVING GROUND, MARYLAND

TABLE OF CONTENTS

BALLISTIC RESEARCH LABORATORIES
REPORT NO. 654

Lynch
Aberdeen Proving Ground, Md.
2 October 1947

Problem No. TB3-0007

DIFFERENTIAL ANALYZER-ELECTRICAL ASPECTS OF OPERATION

ABSTRACT

Hitherto most of the electrical circuit diagrams for the Differential Analyzer have not corresponded accurately with the actual circuits. This has been due principally to the fact that the drawings did not keep pace with the many changes made during the development of the circuits. It has therefore become extremely difficult for maintenance technicians to use the drawings effectively in tracing circuits. The present study has therefore become imperative. Its purpose is four-fold: (1) to bring up to date all of the circuit diagrams of the Differential Analyzer; (2) to make available for operating and maintenance personnel a handbook of general information on the electrical circuits of the Analyzer; (3) to describe the most common malfunctions that occur in the circuits and methods for correcting them; (4) to provide a means for transmitting to new maintenance or operating personnel the benefits of the experience of present incumbents.

It is not essential that maintenance technicians have an intimate understanding of the Differential Analyzer as a device for solving differential equations. It is felt, however, that the more they know about it the better they will function within their own sphere of responsibility. For this reason the Introduction to this report will consist of some general remarks on the machine and a brief elementary description of the "integrator", which is the essential component of the Differential Analyzer.

There has been a considerable amount of literature written on differential analyzers. The inquiring reader is referred to the paper named in the footnote for a well-written and lucid description of the basic principles involved in differential analyzer operation.*

Following the Introduction, this report continues with descriptions of the electrical circuits, an outline of operational procedures with reference to electrical components, and instructions regarding trouble-shooting and adjustment.

Also accompanying this report is a complete set of circuit diagrams indicating the wiring as of September 1, 1947.

*Bush, V. and Caldwell, S. H., "A New Type of Differential Analyzer", Jour. Frank. Inst., Vol. 240, No. 4:255-326, 1945

INTRODUCTION

The Differential Analyzer is a device for mechanically solving ordinary differential equations. The fundamental component of the machine is the integrator of which there are ten on the Aberdeen Differential Analyzer (Positions 1-10 in Fig.1)

The integrator is composed essentially of the elements as shown in Fig. 2: a glass turntable A. lying in a horizontal plane, and a steel wheel B of radius r which rests on the turntable. The axis of the wheel is parallel to a diameter of the turntable. Rotation of the turntable results in rotation of the wheel by friction.

Let us suppose that the wheel is resting at a distance R from the center of the turntable. Call the point of contact "a". Now let the turntable be turned through an angle dΘ (measured in radians) as shown in the diagram. The wheel will then rotate until the point of contact changes from "a" to a point "c". It is seen that

$$\text{arc } \widehat{ab} = \text{arc } \widehat{ac} = Rd\Theta$$

so that the wheel rotates through an angle $\frac{Rd\Theta}{r}$ radians. Thus, if R varies continuously, while Θ goes from an initial value Θ_1 to Θ_2, the angular rotation of the wheel in radians is

$$\frac{1}{r}\int_{\Theta_1}^{\Theta_2} Rd\Theta$$

Means are provided on the machine for continuously varying the radial distance R.

Each variable arising in the solution of a differential equation is associated with a shaft. In all cases the magnitude of the variable is proportional to the total angular rotation of the shaft starting from a known initial position. The sign of the variable is indicated by the direction of rotation of the shaft.

In addition to the integrators the Analyzer has a number of auxiliary facilities in the form of planetary differential gears to make possible addition and subtraction, "input tables" for introducing functional values from a graph (Fig. 1), a "vector table" for finding the resultant of two component vectors, (Fig. 1) and an "output-input table" that can be used either for drawing output curves, or for introducing a function into the machine (Fig.1). Multiplication of a variable by a constant is accomplished by the use of spur gears. Ordinarily results of the machine's computation are recorded by means of the "printer", which may be controlled either manually or automatically (Fig. 1).

One of the outstanding and essential features of the Differential Analyzer is its flexibility. It is so constructed that the shafts housed in the gear bed (Fig.1) may be interconnected in any desired combination provided that certain elementary rules are followed to insure consistency; i.e., the interconnections must correspond to a mathematical equation or system of equations. Likewise, shafts may be connected to the integrator positions, table positions and printer positions in any desired consistent manner. Naturally, the specific interconnections used will be dependent on the requirements of the problem.

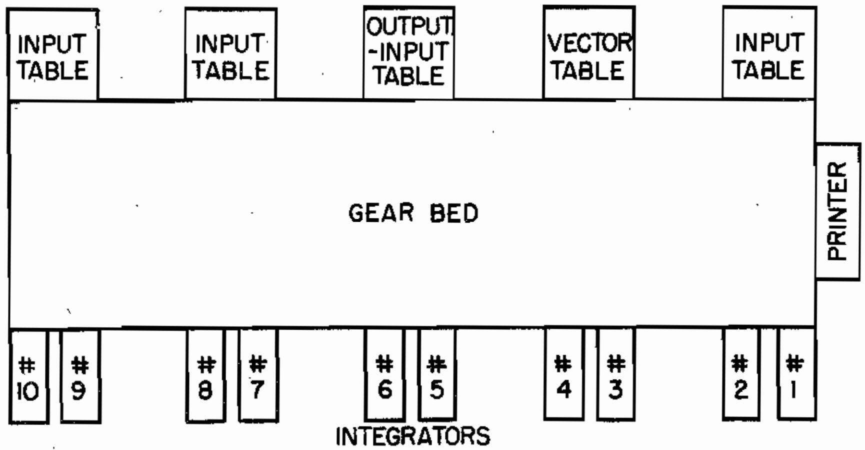


FIG. 1

SCHEMATIC LAYOUT OF ABERDEEN DIFFERENTIAL ANALYZER

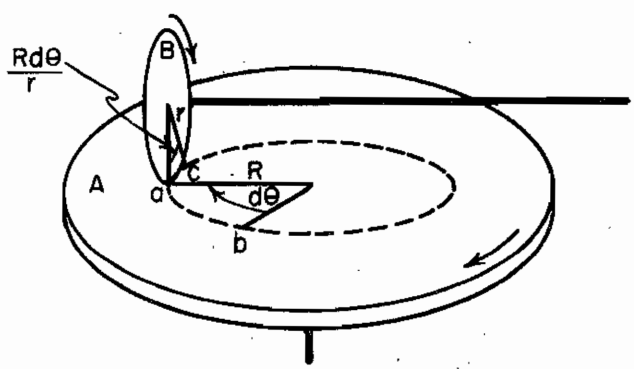


FIG. 2

INTEGRATOR

PART ONE: GENERAL DESCRIPTION OF ELECTRICAL COMPONENTS OF ANALYZER

In the light of the foregoing introductory statements, a brief description is made in this Part of each of the several electrically operated components. The discussion is not more detailed than necessary to permit a comprehensive explanation of the over-all function of each component, and of its mode of operation. The components may be enumerated as follows:

(A) The integrators and associated circuits
(B) The tables and associated circuits
(C) The independent-variable motor and its controls
(D) The printer
(E) Auxiliary units

Whereas items C, D and E are unique components, it will be recognized that items A and B each includes a number of identical units.

Section One: The Integrators and Associated Circuits

In the introductory discussion of integrator operation it was shown that the desired integral is proportional to the angular rotation of the integrating wheel. Since the slippage between the wheel and the turntable is to a great extent a function of the load being borne by the wheel, it is necessary in order to minimize slippage that the wheel be made as light as possible and that there be little or no mechanical load on the wheel to give it greater inertia. This problem is met by the use of a "non-mechanical clutch", connecting the wheel to the output shaft in such a way that the output will follow the wheel as it rotates, and that the power which moves the output will be sufficiently great to operate the gear train connected to it, without loading the wheel in any way.

The following arrangement is therefore erected at each integrator position. (see drawing no. 14). The integrating wheel is connected through a short shaft to a circular polaroid disc. The output is also connected in a similar manner, so that its own polaroid disc is adjacent to, and parallel with, the first disc. A "servo-follower is then erected upon the structure which holds the wheel in position. The servo-follower consists of a lamp which is made to shine through two circular apertures upon two identical photo-electric tubes. One of these apertures is a pair of polarized plates with a fixed (45°) angle between their axes of polarity. The other aperture is separated from a photo-tube by the variable pair of discs described above. The tubes are connected electrically with a D.C. amplifier. The output stage of the amplifier consists of two tubes so connected to an inductive load that the output current of one tube tends to cancel the output of the other, in terms of the magnetic flux produced at the load. The amplifier is initially "balanced" in such a way that the total magnetic flux at the load becomes zero when the same amount of light reaches each one of the two photo-tubes. This means that the "balance point" occurs in the amplifier when the axes of polarity of the variable pair of discs are 45° apart. It is readily seenthat an increase in light will reach the affected photo-tube if the misalignment of these discs occurs in one direction, while a misalignment in the opposite direction must cause a decrease in light to the affected tube. The increase so affects the amplifier that it unbalances the output current to the inductive load in one direction, while the decrease unbalances the outputs in the opposite direction. Moreover, the amount of unbalance in either direction is made to be of approximately the same magnitude but oppositely directed, as it would have been for a like displacement of the discs in the opposite direction. The exact manner in which all of these reactions are brought about within the amplifier will be explained in detail at a later point. (See Part Two, Section Four).

The inductive load referred to above is actually the field of an amplidyne generator, which is not actually on the machine, but in a special cabinet nearby. This device may be thought of as performing the function of a power amplifier.

The output of the amplidyne generator, which is rotated at constant speed by a driving motor, is introduced into the armature of a D.C. motor, separately-excited and of constant field strength. This motor is connected to the output gears of the integrator, and its rotation is such as to cause the output to rotate in the correct direction to decrease the misalignment of the polaroid discs from the balance position.

In order to compare the amplifier and associated circuits with the analogous components of a general servo mechanism, refer to drawing no. 15.

Section Two: The Tables and Associated Circuits

Since the output-input table is of a purely mechanical construction, we may immediately eliminate it from the discussion of electrical components. The other four tables are constructed alike from the electrical standpoint, and have servo mechanisms identical to those on the integrators, excepting only for the mechanical and optical elements in the servo measuring devices, or "servo-heads". In these, the photo-tube which receives the variable light depends not on the amount of light passing through two polaroid discs, but on the light reflected from a surface. The table amplifiers are so adjusted that they are in the balanced condition when approximately one-half of the area of the constant projected light beam is reflected from the white template surface into the affected photo-tube. Too much reflected light would cause a correction in the output gear to reduce the amount of white surface in the light beam. Too little reflected light is a signal for the amplifier to cause a correction in the output gear in the opposite direction. In all other respects, such as pertain to the operation of the amplifiers, amplidyne generators and servo-motors, the table servos operate in the same manner as do the integrator servos. In fact the three components last mentioned are identical to, and completely interchangeable with, the corresponding integrator equipment.

Section Three: The Independent-Variable Motor and its Controls

This motor is driven by D.C. power which is derived from a special control panel. Starting, accelerating, decelerating, stopping, and reversing of the motor may all be accomplished by moving the controls of any one of ten control boxes, arranged at points around the gear bed. A more detailed description of this control system follows in a later section of this report. (See Part Two, Section Five).

Section Four: The Printer

This is a mechanical-electrical-air pressure system which is powered by compressed air under the control of a circuit which is supplied with 110V D.C. This system is used to cause the six counters on the printer mechanism to print when impulsed from any one of several available impulsing devices. These are discussed at greater length in a later section of this report. (See Part Two, Section Six).

Section Five: Auxiliary Units

In addition to the electrical components which are mentioned above, there are three subsidiary units. These units are the "Independent Variable Control Panel", the "Amplidyne Cabinet" and the "Balancer Control Cabinet".

(1) Independent Variable Control Panel: This unit controls the operation of the independent variable drive motor. The connections from the panel are brought to the machine through several conduits which extend from the panel under the floor.

(2) The Amplidyne Cabinet: This is a large sound-proofed cabinet containing all of the amplidyne motor-generator sets used on the fourteen servo-mechanisms. These are arranged in racks, and are connected to the machine through an overhead cable duct. Beneath the amplidynes is the balancer set and terminal box. These are associated in operation with the Balancer Control Cabinet.

(3) The Balancer Control Cabinet: This cabinet contains the power switches which supply both A.C. and D.C. power to operate the electrical equipment. The relation of the balancer set to this cabinet is to convert 220V D.C. to 110V, to be applied through the appropriate terminals in the cabinet to the machine. Connections from this cabinet to the machine are also brought through the overhead cable duct.

In the Introduction the operation of the Differential Analyzer as a unit is discussed. In this Part, general statements have been made on each of the subdivisions of electrical equipment which contribute to this operation. In the next Part, these subdivisions are discussed in detail, with references to the appropriate schematic and wiring diagrams.

Section One: The Balancer Control Cabinet

The right half of drawing no. 1 contains all of the wiring in this cabinet. A two-wire D.C. supply of 220 volts enters the room through a hand-operated switch above the cabinet. This supply is connected to terminals L_1 and L_2 of the balancer starter. An examination of the internal circuit diagram of the balancer starter (drawing no. 2) will reveal that terminals L_1 and A_1 will become connected when the start-stop switch, drawn below the unit, is pushed to "start". (This switch is in the door to the cabinet.) By reference to the 16 terminal block in the Balancer Control Cabinet, it may be seen that terminals 11 and 13 become connected to this 220V supply, through this starter, when the button has been pushed. These terminals are directly connected to terminals 2 and 4 of the separate control box for the balancer set. (See left side of drawing no. 1.) This box is in the bottom of the Amplidyne Cabinet, directly between the twin balancer units. An examination of the schematic circuit diagram of the balancer set (drawing no. 3) will reveal that a new potential, equal to the mid-point between the two input potentials, is now developed in the balancer and brought out to terminal 7 in the balancer control box. Terminal 7 connects back to terminal 12 in the original terminal block referred to. Hence, we have three D.C. potentials at terminals 11, 12, and 13, which are shown on drawing no. 1 and indicated by the voltmeters on the door of the cabinet.

The D.C. supply which has now been developed on terminals 11, 12 and 13 must be transferred by some means to two other sets of terminals on the same block, before it can be used by the machine. These terminal sets are 1, 2, 3, and 14, 15, 16, respectively. 1, 2 and 3 are eventually wired to the lights in the servo-units; 14, 15 and 16 are used to supply the servo-motor fields and the amplidyne motors.

Terminals 14, 15 and 16 are connected into three terminals in the lower, or "load side", of the D.C. starter. In addition, terminals 1 and 3 are connected into 14 and 16 respectively, through ammeters and rheostats in series. (The use of these meters is discussed in Section Two of this Part.) Terminal 2 is connected into 12 on the D.C. starter. Also, it may be seen that the upper terminals of the D.C. starter automatically receive the D.C. voltages of terminals 11, 12 and 13.

It is now seen that the closing of the D.C. starter will supply the desired potentials to the two sets of terminals, 1, 2, 3, and 14, 15, 16. However, the D.C. starter will not close until its coil is energized. (See drawing no. 4.) To discuss the energizing of this coil, it is necessary that attention be brought to the subject of A.C. power.

A conduit enters the base of the Independent Variable Control Panel on the extreme left, as one faces the panel from the rear. This brings 110V, 60 cycle, single-phase A.C. power into the machine from a wall switch behind the panel. This supply is in no way electrically connected to the panel as it first comes in, but it is wired into another conduit which connects by way of the aerial cableway, into terminals 7 and 8 on the 16 terminal block in the Balancer Control Cabinet. (See drawing no. 6.) The Amplidyne Trouble Circuit in the Balancer Control and Amplidyne Cabinets derives its power directly from terminals 7 and 8. Also, the utility outlets on the machine derive their power directly from the incoming line. However, barring these exceptions, all other components of the machine which use A.C. power for their operation derive this supply from terminals 9 and 10 in the Balancer Control Cabinet. These two terminals receive their power from terminals 7 and 8 through the operation of the A.C. starter. Refer to drawing no. 5. It is seen here that, in order for terminals 7 and 8 to close on 9 and 10, the coil must be energized.

Connected into the starter are lines from the three terminals 4, 5 and 6. These terminals are in turn connected by the cableway, (wiring not shown in drawing no. 1), into the machine. The machine wiring of these lines is shown on drawing no. 6. It is represented schematically on drawing no. 5. In the line through terminal 5 there are two separate contacts and a set of two (See drawing no.5). The D.C., or "light control", relay set is pictured again in drawing no. 1 at the top of the Balancer Control Cabinet (its actual location). The limit switch contact represents a group of switches in series which are, as shown, normally closed. These are the red-top limit micro-switches which may be seen under the glass disc on the left side of each integrator, and also all of the limit micro-switches which are located on the table side of the machine. These switches open by means of arms or plates connected to the traversing mechanisms, when the displacement of the mechanisms tends to go beyond the limits available. A detailed view of the limit switch wiring at an integrator is shown in drawing no. 10. The A.C. control relay opens the line to terminal 5 whenever A.C. power is off of terminals 9 and 10. (See drawing no. 1.)

With the contacts as shown in drawing no. 5, a circuit thru the coil in the A.C. starter is completed when one of the three start buttons on the machine is pushed. This is a momentary-type button, and opens the circuit at the instant the finger is moved away. Before the circuit opens, however, a chain of events occurs which holds the starter closed by means of a circuit through the line between terminals 4 and 5. While the finger is on the start button the A.C. starter coil is energized. This closes terminals 7 and 8 with 9 and 10 respectively, and the A.C. control relay coil shown in drawing no. 1 is energized. This closes its contact in the line to terminal 5 (See drawing no. 5). Since, as shown in drawing no. 1, the A.C. starter coil is connected with the coil in the D.C. starter, this latter coil is also energized. This will throw the D.C. starter on, completing the D.C. connections which have been previously discussed. Provided that the light circuits involving the lines to terminals 1, 2 and 3 are completed on the machine, the light control current relays in lines 1 and 3 will be energized. Thus the line between terminals 4 and 5 is completed, and the finger may be removed from the start button without opening the circuit which keeps the starter coils on the line. Notice in particular that neither the A.C. nor the D.C. starter would remain on when the finger is removed from the start button if either the line to terminal 1 or to terminal 3 failed to carry current, or if any of the limit switches mentioned were opened.

Section Two: Circuits Connecting the Balancer Control and Amplidyne Cabinets to the Machine

The operations described in Section One of this Part will result in placing A. C. power on terminals 9 and 10, and D.C. power on the two sets 1, 2, and 3, and 14, 15, 16. These three sets, then become the terminals to which all but two of the electrically-operated machine components are connected. The exceptions are the printer (See Section Six of this Part), and the magnetic clutches on the integrators. The clutch circuit is discussed in the next to last paragraph of this Section.

It should be noted in particular that the Independent Variable Control Panel is also dependent on these three sets of terminals; thus the operation of the panel is dependent on the prior functioning of the A.C. and D.C. starters. (See drawing no. 6.)

Next, examine drawing no. 6, which shows in the lower left hand corner the 16 terminal block in the Balancer Control Cabinet (Section One). On this drawing, all of the control and power feeder circuits leading from the Balancer Control and Amplidyne Cabinets are shown, except for the amplidyne cable connections which are shown on drawing no. 9. The lines from terminals 1, 2, 3, 9, 10, 14, 15 and 16 are extracted from drawing no. 6 into the three separate sections of drawing no. 7. This is for the purpose of clarifying the relationships of the various load circuits to each other and to the power source.

In (1) of drawing no. 7 it is seen that the D.C. from terminals 1, 2, and 3 is supplied to the amplifiers in series connections, one series for the integrator side (line 3) and one for the table side (line 1). The discussion in Section Three of this Part explains that this D.C. power is used only to feed the lamps in the servo-heads and followers. Thus, if one light goes out on either side the associated light control relay opens a contact in the line to terminal 5 in the Balancer Control Cabinet. The discussion in Section one explained that this would ultimately drop out both the A.C. and D.C. starters.

At this point it is suggested that drawings no. 1 and no. 6 be examined concurrently in order to trace the light feeder circuit from the terminals of the D.C. starter, through the ammeters and rheostats on the door of the Balancer Control Cabinet, to the light circuit shown in drawing no. 6. The upper ammeter and the two upper rheostats indicate and control the current to the integrator side; the lower ammeter and rheostat pertain to the table side. The normal operating current is 2.2 amperes in each side.

The A.C. applied to the amplifiers from terminals 9 and 10 conforms to (2) of drawing no. 7. The connections are parallel, and any amplifier may be connected or disconnected by means of its own switch, marked "A.C.", on the front of the associated integrator or table junction box.

In (3) of drawing no. 7 it is shown that there is a 110V D.C. source provided for each integrator and table from the circuit leading to terminals 14, 15 and 16. These are also parallel connections. The discussion in Section Three of this Part explains that these connections are used to supply the fields of the servo-motors, and to drive the amplidyne generator drive motors, through the switches marked "D.C." on the front of each integrator and table junction box.

The clutch and printer feed circuit, shown in drawing no. 6, is a two-wire line extending from terminals 4 and 7 in the terminal box of the balancer set, through the aerial cable-way, to a rigid conduit containing 3-inch boxes. A detailed description of the clutch circuit beyond the 3-inch boxes is afforded by drawing no. 10. It should be pointed out that these circuits are supplied with driving potential at the moment the balancer set is started, and do not depend on the prior operation of the D.C. and A.C. starters. The clutches are used to disconnect the integrand lead screws from their respective driving shafts under either of two conditions: (a) the clutch push-button is pushed, or (b) the green-top limit micro-switch on the associated integrator is actuated. The normal, unmagnetized, condition of the clutch connects the integrand lead screw to its driving shaft; the magnetized condition disconnects it. The green-top limit switches require a greater translation of the integrand than do the red-top switches, which are able to drop out the A.C. and D.C. starters. The intention here is to prevent damage to a turntable due to the possible failure of a red-top switch, or to excessive over-riding of the lead screw after the A.C. and D.C. starters have dropped out.

Thus far the conditions have been discussed which lead to supply of power to the integrator and table positions, to the Independent Variable Control Panel, to the clutches and to the printer. The next section describes the integrator and table junction boxes.

Section Three: The Connections at Integrator and Table Junction Boxes

All connections to the integrators and tables, except for those pertaining to the clutches and limit switches, are made to 8" x $28\frac{1}{2}$" junction boxes located beneath each pair of integrators, or to 8" x 14" boxes located beneath the gear bed adjacent to each table. A general view of the conduit and cables leading into these boxes is afforded by drawing no. 8. Notice that there is one table for each table junction box, but that there are two integrators for each integrator junction box.

Each integrator or table is connected to a junction box through twelve terminals. The A.C. and D.C. connections to the integrators are shown in drawings no. 11 and no. 12, respectively. The wiring represented by both drawings occurs in the same junction box; it is shown separately only for clarity.

Drawing no. 11 shows that the two integrators are in parallel with respect to A.C. power, and that each can be supplied with A.C. at terminals 11 and 12 by closing an "A.C." switch. Also, the indicating light on the switch is in parallel with the load.

Drawing no. 12 shows that power reaches terminals 1 and 2 on each integrator when its "D.C" switch is closed. It also shows that the light for this switch is in parallel with the field of the servo-motor, which is connected to the black and white leads (F_1 and F_2). However, the lamp and this load cannot be supplied from terminals 1 and 2 until the A. C. switch has been turned on, and a time delay relay has had time to operate. Also, it is observed that any potential which may exist between terminals 3 and 5 (namely, the armature voltage of the amplidyne generator) will not be connected between terminals 3 and 4 until the same time delay relay closes. The significance of this delay relay is brought out in Section Four of this Part. Finally, it is seen from drawing no. 12 that the D. C. supply which feeds terminals 9 and 10 of each integrator feeds them in series with the same terminals on the other integrator.

An examination of the diagram showing connections to the tables (drawing no. 13) will show that these connections closely compare with those to the integrators. However, a double-pole-double-throw switch is added to enable one to reverse the black and white leads to the servo-motor (i.e., the field leads). This reverses the effect which the amplifier will have upon the servo-motor's direction of rotation, and it is a function of whether the servo-head is to follow the upper or lower edge of the white area on the template.

Section Four: The Amplifier and Associated Circuits

Drawing no. 16 shows the electrical relationships which exist within the amplifier and the servo-head. The power input to the amplifier is plug no. 2. Terminals 1 and 3 in this plug receive the A.C. potentials of terminals 11 and 12 in the junction box. Terminals 2 and 4 in plug no. 2 receive the D.C. potentials of terminals 9 and 10 in the junction box.

The mechanical arrangement of the servo-follower (or head) requires it to be connected to the amplifier proper through plug no. 3. A simplified schematic diagram (drawing no. 17) eliminates this plug and should be used as a reference in the following discussion.

The 5W4 is a full-wave rectifier, the output of which is smoothed through a π network and expressed across an output resistance. This supply is positive with respect to ground and is used to feed the two photo-electric tubes in series, and the plates of the 6SJ7 and 6J5. It also feeds the screen grid of the 6SJ7. The 5U4 is also a full-wave rectifier. It is wired in essentially the same manner as the 5W4, except that its output potential runs somewhat higher than that of the 5W4. (Since the 5U4 is used to supply the plates and screen grids of the two 6L6's, it is reasonable to infer that its regulation would have seriously hampered the operation of the first two stages, had these two stages been connected to it. Hence, two separate plate supplies are provided.)

The 929 photo-electric tubes are such that the amount of resistance they offer to current flow is a function of the amount of light admitted to them. They may thus be thought of as variable resistors. The upper tube receives a constant amount of light. The lower tube receives a variable amount, as mentioned in Section One of Part One. The resistor R_1, being 10 megohms in value, is effectively in parallel with the lower tube. Also, the two photo-tubes are in series with a D.C. potential. Increases and decreases in the light flow to the lower tube will cause increases and decreases in its effective resistance. These changes will increase and decrease the current flow through both tubes. Since the effective resistance of the upper tube is constant (constant source of light), the voltage drop across the upper tube will increase or decrease in an amount proportional to the change in current. This drop is applied to the grid of the 6SJ7.

The resistor R_2 is a cathode bias resistor. The variable tap on it enables one to change the grid bias of the tube, through R_1, to a value suitable for correct operation.

The 6SJ7 is a pentode amplifier, and as such it has a large plate resistance. This fact means that the current in the plate circuit of the tube is little affected by the phase angle of the load impedance. If a change in the grid voltage of the tube is brought about, there will be a change in plate current through an inductive impedance L, in series with a resistor R_5. The voltage across any coil is proportional to the rate of change of current through it. Hence, the potential of the Point A with respect to ground may be made to rise or drop through a large amplitude if the signal is changing rapidly. The resistor R_5 has a drop which is proportional, not to the rate of change of current, but to the amount of

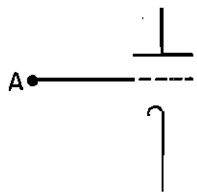


FIG. 3

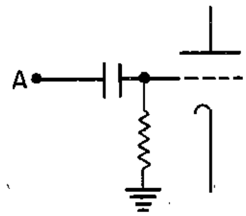


FIG. 4

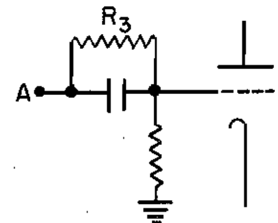


FIG. 5

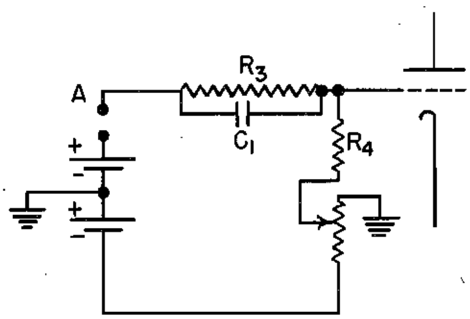


FIG. 6

current. Thus, the potential at A may also be affected by relatively slow or constant deviations in the plate current. The RC circuit C_1R_3 transmits the signal to the grid of the 6J5 phase-inverter stage.

Let us explain the method of coupling shown in the diagram by first considering alternative methods of coupling. Point A is obviously quite high in potential with respect to ground. To feed its potential directly into the grid of the 6J5 (Fig.3) wouldmean that the cathode of the 6J5 would have to be raised to the neighborhood of that potential for correct operating bias. The plate of the tube would have to be raised a like amount; and these changes in the operation of the tube would be inadvisable. To feed the potential of point A to the grid through a condenser alone (Fig. 4) would get rid of the D.C. potential at the grid if a grid leak resistor were provided and connected to ground. But such an arrangement would indicate constant deviations in the potential of point A from the "balanced" potential as merely transients. The coupling resistor R_3 (Fig. 5) is therefore necessary.

The D.C. circuit which would thus be provided between point A, through R_3 and the hypothetical grid leak resistor, and ground would enable the grid potential of the 6J5 to represent constant deviations in the potential of point A. The fraction of the D.C. change in potential of point A which reaches the grid could be kept high by making R_3 small relative to the grid leak resistor. However, because the drop across R_3 would be small, the D.C. potential on the grid side of R_3 would remain essentially near the potential of point A. Thus, additional steps are necessary to bring the D.C. potential of the grid down to a value reasonably close to cathode potential.

The device here used involves the operation of the 879 tube, shown in the lower part of the drawing. This is a half-wave rectifier wired to yield negative potentials as high as -1000 volts. The resistor R_4 is connected into the load of this rectifier, so that we have a circuit which may be represented as shown in Fig. 6. It is immediately seen from Fig.6 that the D.C. potential at the grid might conceivably be made near to cathode potential by a proper choice of resistors. This is the essence of the system here applied at the input to the 6J5. The steady state value of the grid potential is close to cathode potential and yet any fluctuations in the potential of point A (including the very slow or constant ones) are transmitted with little loss to the grid of the 6J5.

The 6J5 is a triode phase-inverter, the output of which is twofold. One output is taken directly from the cathode, and the other from the plate. If the current through the tube increases, the plate voltage becomes closer to ground, and the cathode potential becomes more positive with respect to ground. Thus, the two outputs vary at all times oppositely with respect to ground.

The manner in which these outputs are connected into the grids of the two 6L6's is essentially the same as that in which the plate potential of the 6SJ7 is transmitted to the grid of the 6J5, with resistors in parallel with condensers for coupling, and with high negative potentials used to "buck out" the positive D.C. potentials which would otherwise be transmitted to the grids. The plate supply for these two tubes feeds the current in opposite directions through the field of an amplidyne generator. The direction and magnitude of the magnetic flux in this field, then, is dependent on which tube carries the most current. The possibility for changing either of the 6L6 grid biases, or the bias of the 6J5, assists one to balance the amplifier at an angular misalignment of 45 degrees in the polaroid discs which admit light to the lower 929, and also for a given amount of current in each output tube at that point. Efficient operation is gained when about 5 milliamperes flows through each 6L6 at the balance point.

The output of the amplifier is a three-conductor line connected from plug no. 1 to the terminal box of the integrator or table. The actual connection to the amplidyne generator is made as shown in the diagram of the D.C. wiring in the terminal box (drawing no. 12 or 13).

As explained in Section Three of this Part, the output of the generator (i.e., the armature voltage) reaches the armature of the servo-motor only if the "A.C." which feeds the amplifier has been turned on. Then, the time-delay relay connects the servo-motor field to the D.C. source, and the output of the amplidyne generator to the armature of the servo-motor. This prevents transient conditions in the amplifier (while warming up) from having an effect on the output motor.

An important characteristic of operation in this amplifier is understood when it is recalled that the eventual output from the power stage depends on the deviations in the potential of point A, which is in the plate circuit of the first stage. The rapid deviations result from changes in the current through the inductance L. At the same time, the slow and constant changes in potential in this stage are expressed to the grid of the 6J5 because of the resistor R_5, the voltage drop across which depends, not on the rate of change of current, but upon the magnitude of current flow. The introduction of the inductance L increases the sensitivity of the amplifier to rapid changes in the error.

The function of the anti-hunt circuit may be explained as follows. First, assume that the anti-hunt **circuit** were removed. An error in the alignment of discs occurs which causes a change in output favoring current flow through the upper 6L6. As a consequence of this, the servo-motor is eventually caused to rotate in such a direction as to decrease the original error. However, because of the high inertia and low friction in the physical system as a whole the servo-motor does not cease rotation at the instant the error becomes zero, but has a tendency to over-ride. At the moment it over-rides an error is caused which favors current in the lower 6L6. Again, the inertia in the motor causes it to ride back over the zero error point; and so on. An oscillation of this nature can be eliminated if the amplifier is made relatively insensitive at the natural frequency at which the oscillation occurs. A condenser in series with resistance, and connected between the grids of the 6L6's, is a device which accomplishes this damping effect. As the two grid potentials begin to recede and approach each other at the oscillating frequency of the servo-mechanism, the capacitance draws current; hence, it tends to stabilize both potentials, and reduces the outputs of the respective tubes to values which, in conjunction with the natural damping in the mechanical system, will prevent further oscillation.

Section Five: The Independent-Variable Control Panel

The complete function of this panel is to control the speed and direction of rotation of the independent-variable drive motor. Drawing no. 6 shows the wiring which connects the panel to the A.C. and D.C. supply sources. The only other wiring external to the panel which is associated with its operation is represented in drawings no. 23 and no. 24. The motor-generator set which is in front of the panel is connected to it by two shortlengths of B-X cable.

Drawings no. 19 through no. 24 completely describe the wiring of the control panel and its associated control circuits. However, for the purpose of explaining the details of the operation, schematic drawing no. 18 is provided. The following description is best understood by reference to this drawing.

A preliminary view of the schematic circuit will reveal certain basic facts regarding the inter-relationships which should be remembered as the analysis procedes into a discussion of specific control conditions. These facts are as follows:

(1) The letter"A" following the numerical designation of a relay indicates that its coil is in parallel with the other relay having the same number.

(2) Every relay coil in the panel, plus every indicating light, and the field of the rheostat motor, is grounded on one side to the A.C. source. This lead is also the ground side of the A.C. lines; hence it is at the same potential as the frame of the machine.

(3) Relay no. 1 is used to reverse the leads from the D.C. generator to the independent variable drive motor. The left-hand contacts on no. 1A cause the "reverse" lamp to light whenever relays no. 1 and no. 1A are energized.

(4) Relay no. 2 acts to open the leads connecting the D.C. generator and the independent variable drive motor. The left-hand contacts on no. 2A cause the "stop" lamp to light whenever relays no. 2 and no.2A are energized, and the "operating" lamp to light when the relays are not energized.

(5) The left-hand contacts of relay no. 3 will connect the A.C. line across relays no. 2 and no. 2A, (hence preventing the operation of the independent-variable motor), except when relay no. 3 itself is energized. Once energized, relay no. 3 cannot be dropped out except by opening the A.C. power source. To energize the relay, limit switch "A' must be actuated, which means that the driven contact on the rheostat must reach the starting position before relay no. 3 will energize and permit relays no. 2 and no. 2A to drop out. For these reasons, relay no. 3 is referred to as the "initial reset" relay. Its usefulness in the circuit is restricted to the case where the A.C. power is applied to the panel at a moment when the driven contact on the rheostat is not at the "initial (zero voltage) position.

(6) Relay no. 5 functions to open the circuit of the series-connected rheostat motor.

(7) Relay no. 6 functions to reverse the armature leads of the rheostat motor with respect to the field. This will cause a reversal in the direction of rotation of this motor when power is applied.

(8) Two conditions must be satisfied before the rheostat motor will rotate:
(a) line no. 29 must be connected to the high side of the A.C. supply, and
(b) relay no. 5 must be unenergized.

These same conditions, it will be observed, determine the energizing of relay no. 7. This relay is used to switch 115V D.C. into the magnetic clutch circuit through a current-limiting resistor. Thus, the clutch acts to connect the rheostat motor to the pulley mechanism only when the motor is to rotate, and disconnects the motor from the pulley at the instant the voltage is removed from the motor. The purpose of this clutching device is to decrease the tendency for the driven tap on the rheostat to "override" after the motor voltage is removed.

(9) One side of every hand control switch is connected to the high side of the A.C. line (line no. 32). The numbering of the control lines corresponds to the terminals in the lower terminal strip to which they are connected.

The closing of the A.C. and D.C. starters in the Balancer Control cabinet simultaneously applies 110V A.C. and 110V and 220V D.C. to the panel as indicated in Section Two of this Part. The A.C. power immediately starts the motor of the motor-generator set, and brings power to the relay system. The D.C. power is supplied simultaneously to the field of the independent-variable motor and to the 635-ohm rheostat. The field receives 110V, while the rheostat receives 220V. The field of the generator in the motor-generator set receives the portion of 220V which is determined by the instantaneous position of the driven tap on the rheostat.

It is assumed that the driven tap is at some initial position other than at the zero voltage end of the rheostat. Therefore, limit switch A is open, relay no. 3 is not energized, and relays no. 2 and no. 2A pick up through the left hand circuit on no. 3. This in turn causes the "stop" lamp to light and prevents the independent-variable motor from receiving the generated voltage otherwise available to it. With switch "D" closed there is also a circuit through the left-hand contacts of no. 3 and switch "D" which causes relays no. 4 and no. 4A to be energized. The left-hand contacts of no. 4 now form a hold-circuit for relays no. 2 and 2A which will hold them up until relays no. 4 and no. 4A drop out. The right-hand contacts of no. 4 form a holding circuit for no. 4 and no. 4A until contact "C" is opened. The contacts on no. 4A respectively apply the high side of the A.C. line to control line no. 29, which feeds the rheostat motor, and the coil in relay no. 6 through control line no. 31. The resulting rotation of the rheostat motor is in such a direction that the driven tap approaches the zero voltage end of the rheostat, actuating in turn switches "D", "B", and simultaneously the group "A", "C", "E". When switch "D" opens, relays no. 4 and no. 4A are forced to depend on their hold circuit to remain energized. When switch "B" closes, relays no. 2 and no. 2A have an added hold circuit which is independent of relays no. 4 and no. 4A. When switches "A", "C" and "E" are functioned, relay no. 3 picks up, thus opening the circuit which originally picked up relays no. 2, no. 2A, no. 4 and no. 4A. Also, the hold circuit for relays no. 4 and no. 4A opens, dropping out these two relays. The opening of the contacts on no. 4A drops out relay no. 6 and thus opens the line which applies voltage to the rheostat motor. The rheostat motor is thusstopped at the moment the last of the switches is actuated.

The foregoing operations may be thought of as the "initial reset operation". It was performed without the necessity for any control switch manipulation.

To start the independent variable motor in the forward direction, the control switch is moved toward "increase". This closes lines no. 29 and no. 30 to the high side of the A.C. line. Line no. 29 closes the rheostat motor to the line, causing it to drive the driven tap on the rheostat toward the high-voltage end. The first switches to de-actuate are "A", "C" and "E". "A" has no effect since relay no. 3 is already energized. "C" has no effect since relays no. 4 and no. 4A have dropped out. "E" has no effect since line no. 31 is not connected to the high side of the A.C. line. Switch "B" opens next, and since it was in the only hold-circuit for relays no. 2 and no. 2A at this time, relays no. 2 and no. 2A drop out, causing the "operating" lamp to light, and causing the independent-variable motor to receive the output voltage of the D.C. generator. When switch "D" closes, the circuit through it to pick up relays no. 4 and no. 4A is dead; hence the relays are not energized. (Notice that relays no. 4 and no. 4A would have been energized, thus initiating the "initial reset" operation, if switch "D" had not been adjusted to close after switch "B" had opened).

The circuit conditions which exist after the closing of switch "D" remain unchanged until some one of the following conditions occurs:

(1) The "increase" switch is restored to neutral. In this case, only the rheostat motor stops, causing the driven tap on the rheostat to stop, and hence causing the independent-variable motor to remain at constant speed.

(2) The switch is moved to "decrease". This keeps the rheostat motor on the line and reverses it. If the "decrease" is held on long enough, the limit switches will eventually be actuated as follows: "D" will open, thus preventing relays no. 4 and no. 4A from energizing; "B" will close, thus actuating relays no. 2 and no. 2A, stopping the independent variable motor; switches "A" and "C" will have no effect, while "E" will pick up relay no 5 through line no 31, which is connected through the control switch to the high side of the A.C. line. Thus, the rheostat motor is again stopped.

(3) The control switch is held at "increase" until limit switch "F" is closed. Since line no. 30 is connected to the high side of the A.C. line through an "increase" switch, relay no. 5 becomes energized, thus stopping the rheostat motor. This motor can thenbe started only in the reverse direction.

(4) The control switch is moved to "stop". This action connects line no. 34 to the high side of the A. C. line, and thus causes relays no. 2 and no. 2A to be picked up. Relays no. 4 and no. 4A are also picked up through switch "D". These relays perform the initial reset operation as previously described. In this case, however, it is performed without the aid of the relay no. 3 contacts. Relays no. 4 and no. 4A hold until switch "C" opens. The opening of switch "D" has no effect. The closing of switch "B" provides an additional hold circuit for relays no. 2 and no. 2A, which keeps them energized when, finally, switches "A", "C" and "E" are actuated, and relays no. 4 and no. 4A drop out. The "stop" impulse need only be momentary in order to start this reset operation.

The following conditions govern the reversal of the independent-variable motor: Relays no. 1 and no. 1A must be picked up initially through the right-hand contacts of relay no. 2A. This is possible only when no. 2A is picked up and the independent variable motor is at "stop". A hold circuit for relays no. 1 and no. 1A is then provided through the right-hand contacts on no. 1A as long as the control switch is at "reverse". At the moment relay no. 2A drops out, because of the starting of the independent variable motor, the hold circuit for no. 1 and no. 1A is supplemented by a circuit through the center contacts of no. 2A, which prevents relays no. 1 and no.1A from dropping out, once energized, until relays no. 2 and no. 2A are again energized, and the independent-variable motor stopped.

The toggle switch on the front of the control panel opens the indicating lamp feeder lines and enables one to change burned-out bulbs without danger of being shocked, and without regard for the conditons of relays no. 1A and no. 2A, which feed them.

Simultaneous operations of more than one control station produce conditions which are intended to increase the safety of the control system.

Any switch moved to "stop" will initiate the initial reset operation regardless of how any other control switches are moved. Also, in the event that one switch is moved to "increase" while a second is moved to "decrease", the "decrease" control switch will predominate.

All voltages may be removed from the panel, except for the D.C. leads to the rheostat, to the field of the independent-variable motor, and from the rheostat to the field of the D.C. generator, by opening the knife switch in back of the panel above the lower terminal strip.

Section Six: The Printer Circuits

In Section Two of this Part a brief reference was made to the fact that the printer is supplied through the clutch feeder circuit. This power supply is made to actuate a mechanical-air-pressure system, the effect of which in turn is to print the values of the output counters at any desired instant on a sheet of paper.

We are not here concerned with the mechanical construction involved in the printing operation. It is sufficient from the electrical point-of-view to say that the mechanical system is actuated by a magnetic bar which can be seen in drawing no. 25. This bar is capable of translating back and forth along the line of its main axis a short distance. Motion of this bar to either of its two extreme positions will result in a printing. The means of initiating the printing operation are three in number: (1) a push-button labeled "punch" on the printer control box, (2) a push-button on the end of a cord attached to the output end of the gear bed, and (3) a set of switching devices mounted on the gear bed, each of which is caused to close a circuit every time a shaft revolves once. This enables one to print automatically at definite intervals of the variable associated with the particular shaft to which the switching mechanism is attached. These devices are all connected in parallel. For simplification, they are all represented as S in drawing no. 25. When S closes, the magnetic bar must be made to move from one extreme to the other in order to operate the printer.

Coils L_1 and L_2 are associated with the two groups of contacts C_1, C_2, C_3 and C_4, C_5, C_6, respectively. When coils L_1 and L_2 are de-energized, these contacts remain as shown in drawing no. 25. Coils L_3 and L_4 are the solenoids which move the magnetic bar back and forth. One side of each of these coils is connected to the lower input line. The other leads from these coils are connected, respectively, to C_2 and C_5, open sides.

With all contacts as shown, including S, it may be seen that nothing will happen in the circuit when power is applied.

When S is closed, with contact C_7 closed, L_1 becomes energized. This brings down contacts C_1, C_2 and C_3. Since C_2 is down, coil L_4 is energized and the bar moves to the right. C_7 is now broken, and C_8 is is closed. But the breaking of C_7 does not cut off L_1 because the contact C_1 is down. In addition, the contact C_3, in moving down, keeps coil L_2 from being energized. (Notice that L_2 would have been energized otherwise, with the making of contact C_8.) Thus, a stable situation occurs while S is down, with L_1 and L_4 energized and the magnetic bar moved to the right.

When the switch S opens, L_1 and L_4 are de-energized. As soon as this happens, contacts C_1, C_2 and C_3 go up and the system is again dead.

Because C_8 and C_3 are now closed, the next closing of S will energize L_2. Contacts C_4, C_5 and C_6 will move down. The making of C_5 now closes the circuit to L_3. This moves the magnetic bar to the left, opening contact C_8 and closing C_7. But the opening of C_8 does not cut off L_2 because the contact C_6 is down. In addition, the contact C_4 moving down, keeps L_1 from being energized. (Notice that L_1 would have been energized, otherwise, with the closing of C_7.) Thus, a stable situation again occurs while S is down, with L_2 and L_3 energized and the magnetic bar to the left.

When S opens the system will become dead, and will be in its original condition.

The foregoing description leads to the conclusion that, should either L_3 or L_4 ever fail to bring the bar far enough over to actuate one of the micro-switches C_7 or C_8, the system would not be able to print again without some form of intervention. Because of this, a "reset" button is provided. The "reset" operation is performed only when the printer will not punch without it. The method is to press simultaneously on the "punch" and "reset" buttons. The "reset" button closes the circuit across C_7 and thus allows L_1 and L_4 to be energized.

Thus, the making and breaking of S will move the magnetic bar alternately to the left and to the right each time. This arrangement will operate effectively for the push-button-type actuating devices. However, because of the "chattering" tendency of the actuating contacts which are closed by rotating shafts, a "one-shot" circuit is provided. Drawing no. 27 shows the circuit in use. The switch S is the pair of contacts on the output relay. The actuating devices. all in parallel, are now placed across the "plus-minus" leads at the input to the circuit.

The physical lay-out of the printer circuit is shown in drawing no. 26.

Refer to drawing no. 27 during the following discussion of the one-shot circuit.

The 5Y3 is a full-wave rectifier tube which supplies the plate voltages of all three stages in this device. The output is smoothed by a choke and condenser.

When power is applied by closing switch SW, (pulse line assumed open) the circuit will reach a steady-state condition, and will remain in this condition until the pulse line is closed. Stage P_1 of the 6SN7 will be conducting, with its grids somewhat less than 4.5 volts above cut-off. Stage P_2 will not be conducting because of the grid bias applied to it across R_2. The current through R_2 is supplied through R_1. Condenser C_4 is charged to B+ and the plate of the 631P1 is also at B+. The control grid of the 631P1 is at cathode potential: hence the 631P1 does not fire. Also, C_2 is charged to the full B+ value.

When the pulse line closes through an actuating circuit, a negative voltage, sufficient to drive the grid of the P1 6SN7 stage to cut-off, is provided. The RC circuit C_3R_3 will hold this applied voltage on the grid for a period long enough to outlast contact chattering in the pulse line. The cessation of current in the P1 stage causes the potential of the plate to become more positive (namely, to go to the B+ value). This increase in potential, applied across the circuit C_1R_4, sends a charge through R_4 which drives the grid of the P_2 stage temporarily to a value above cut-off. The plate of the P_2 stage will then become more negative; that is, it will decrease from B+ to a lower value, determined by the grid signal. The condenser C_2, being initially charged to B+, must discharge through R_2, and the P_2 stage and R_6 until its potential is that of the plate. The resultant surge drives the grid of the 631P1 temporarily negative. This grid pulse fires the tube. Condenser C, which was charged to B+, then discharges through the tube and temporarily lowers one side of the coil C_L to near ground potential. The current surge through L closes the output contacts. The 631P1 is quickly extinguished by the disappearance of the plate potential through the drop in R_7, and by the disappearance of its grid pulse.

Section Seven: Safety Devices

Over-all D.C. current limitation is provided by two 60 amp fuzes in the wall switch above the Balancer Control Cabinet. The three load circuits which are fed from the D.C. source are fuzed separately. The circuit fed through terminals 1, 2 and 3 in the 16-terminal block in the Balancer Control Cabinet is fuzed at 5 amps for the lights on each side of the machine. These fuzes are located in the upper part of the cabinet near the light control relays. The load circuit connected to terminals 14, 15 and 16 is fuzed at 60 amps in the terminal box of the balancer set. The clutch and printer circuit, which is fed directly from this box, is also fuzed there at 5 amps. The integrator and table junction boxes are equipped with individual D.C. fuzes at 30 amps. These are in the feeder circuit connected to terminals 14, 15 and 16, and are located in the junction boxes of the various integrators and tables.

Over-all A.C. current limitation is provided by a 30 amp fuze in the A.C. wall switch. The Independent Variable Control Panel, which receives A.C. power from terminals 9 and 10 in the Balancer Control Cabinet, is fuzed at its isolating knife switch (in the lower part of the Control Panel) for 5 amps. The burning of this fuze removes A.C. power from the driving motor of the motor-generator set, from the indicating lights and from the relay panel. Each amplifier is also separately fuzed for A.C.; either by a 6 amp fuze, if connected to an integrator, or by a 5 amp fuze, if connected to a table. These individual A.C. fuzes are also located in the junction boxes of the various integrators and tables.

Other than fuzing there are three safety devices built into the Differential Analyzer circuits. The amplidyne trouble circuit is a system which detects over-heating of the amplidyne motor-generator set, and indicates this condition by ringing a bell in the Balancer Control Cabinet. The time-delay relays in the integrator and table junction boxes also constitute a safety feature. An explanation of their function appears in Section Four of this Part. Finally, the integrator and table limit switches constitute a safety feature in that they prevent the accidental running of integrand lead screws and table screws beyond the physical limits of operation.

While it is not essential that operators of the Differential Analyzer be familiar with all of the details of the electrical system, it is nevertheless important that they understand certain general relationships. These relationships may be understood by making reference to drawing no. 28. Here, the major units in which an operator is interested are assembled according to the manner in which they are controlled.

Section One: Operation

Having once established the gear and shaft trains appropriate for a run, the operator is ready to start the machine. In order to do this, a number of steps must be taken, in the following order: (refer to drawing no. 28)

(1) Assuming that the hand-operated wall switches which bring A.C. and D.C. power into the machine are closed, the operator first checks the machine to see that all "A.C." and "D.C." switches to individual integrators and tables have been turned off.

(2) The operator then pushes the "start" button on the door of the Balancer Control Cabinet. This will close the Balancer starter in this cabinet, and cause the balancer set in the bottom of the Amplidyne Cabinet to begin rotating. The voltages produced by the balancer set should be checked at this point. Voltmeters giving these voltages are to be found in the door of the Balancer Control Cabinet. These voltmeters should each read 110V. If they vary from this reading, an electrician should be summoned to correct the condition. Immediately after the "start" button is pushed, the clutches at each integrator position will also have received power, and are ready to operate when needed. The printer is ready to use at the same time.

(3) Next, any "start" button on the machine may be pushed. This should cause the A.C. and D.C. starters in the Balancer Control Cabinet both to close. All lights on the integrators and tables will light up. The amount of current reaching the lights should now be checked. Meters giving these readings are found on the door of the Balancer Control Cabinet. The upper ammeter reads the current which flows through the lights on the integrator side. It should read 2.2 amps. If the reading is off slightly, it may be adjusted to read exactly 2.2 amps. by turning either of the two upper black rheostat knobs on the door. The lower meter gives the corresponding current on the table side. It should also read 2.2 amps. Adjustments in this meter reading are made by the lower black rheostat knob. If either of these meters should read well away from 2.2 amps., an electrician should be consulted. In addition to the lights going on, the motor-generator set in front of the Independent Variable Control Panel will begin rotating. Immediately after this the independent variable drive motor may be started.

(4) The "A.C." switch at any integrator or table needed in the operation to be performed can now be turned on. Soon after this is done, the ammeters on the amplifier associated with that switch should deflect. In general, they will not be found to read alike. In order to get them to do so, the integrating wheel of the associated integrator (or the follower-head of the associated table) must be adjusted. In general the amplifiers should balance at about 5 milliamperes. Once this adjustment is made, the "D.C." switch for

that particular integrator or table can be turned on.

(5) In general, when the "D.C." switch for a given integrator or table is turned on, a slight initial movement of the servo-motor may result; but this should cease almost at the instant it begins, with the result that the servo-motor is motionless. A check on the functioning of an integrator can now be made by giving the integrating wheel a slight twist. If the servo-motor follows along with this motion, with no apparent sluggishness or tendency to "hunt", then it may safely be assumed that the integrator is ready to begin a run. A check on a table is provided by determining whether or not the servo-head focuses approximately half on the white, and half on the groove in the template which separates the black from the white, when the D.C. has been turned on, and the table has reached a balanced state.

(6) After all of the integrators and tables to be used on the run have been turned on in the manner given above, the run may be commenced.

The above steps constitute the starting operation. To stop the machine temporarily, only the independent variable motor needs to be stopped. To stop the machine for a longer period, such as overnight, the above steps are repeated in reverse.

It is essential that the sequence given here be followed exactly by the operator, as serious consequences might otherwise result. It is emphasized that the "D.C." switch at an integrator or table is never turned on until after its "A.C." has been turned on, and the ammeter readings on the amplifier have been balanced.

Section Two: Repair

The only repair operation which an operator should perform on the Differential Analyzer is the replacement of burned-out lights. If any light on the machine burns out in the course of operation, all of the power on the machine will go off, except for the clutches and printer. When this happens the following steps may be taken by the operator:

(1) Turn off all "D.C." and "A.C." switches at integrators and tables which were on.

(2) Press a "start" button on the machine and hold it down. With the "start" button held down, ascertain whether the lights on either side of the machine are on. If neither side lights up, call in an electrician.

(3) If the table side lights up, then the burned-out bulb is on the integrator side, and can be found by investigating each of the bulbs on that side visually. Simply replace the burned-out bulb and start the machine in the manner given above.

(4) If the integrator side lights up, then the burned-out bulb is on the table side. Since it is somewhat difficult to check each table bulb visually, a meter check is suggested. The meter used is usually a Simpson meter. (Any ohmeter with a built-in battery supply will do as well.) Remove the cable leads from each of the servo-heads on the tables. A plug which has six prongs in it is now visible. Touch the leads of the meter across the pair of prongs on the plug which are slightly separated from the other two pairs. There should be a low resistance between them. If the light at the table is burned out, "infinite resistance" will be indicated. When this check is performed, <u>make certain that all power, except for the clutches and printer, is off the machine.</u> When the burned out bulb is found, simply remove the side of the head which faces the lower side of the template, remove the bulb and replace it. Care must be taken not to short the locking sleeve around the light socket to the frame of the light box.

Amplifier difficulty is usually manifested by the tendency of the servo-motor to "run away", or "hunt", when power is applied. In addition to these conditions a temporary unbalance may result from a transient dimming of lights, as when a "D.C." switch is turned on. The following method of adjustment should eliminate any of the above conditions which may exist.

Assume that one of the servo-mechanisms on the integrator side gives an indication of faulty operation.

First, all "D.C." and "A.C." switches on the machine are turned off. A "start-stop" button is then pushed to "stop", thereby dropping out the A.C. and D.C. starters and putting out the lights.

Two short jumper leads are then used to connect opposite sides of contacts in the light control relays. These are to be found in the upper portion of the Balancer Control Cabinet. After this has been done, it will be possible for the A.C. and D.C. starters to remain picked up regardless of whether or not the light circuits are completed.

A "start" button is now pushed, and the "A.C." switch of the appropriate integrator servo is turned on.

While the amplifier is warming up, an electronic voltmeter is placed near the unit, plugged into one of the outlet plugs available, and grounded from the "common" hub to the frame of the amplifier. The switches on the voltmeter are set for the 1000V D.C. scale, with positive polarity.

The plate voltage of the 6SJ7 tube is the first to be checked. The hub for this check is the one nearest to the end of the amplifier where the cables are attached.

Before this reading is taken, a plug is removed from one of the adjacent servo-followers, not from the follower being tested. The reading of the 6SJ7 plate voltage should now be found to lie in the neighborhood of 300 V. It is adjusted to that exact value by turning the black knob on the side of the follower. This knob varies the tap on the cathode bias resistor, which is connected through a 10 megohm resistor to the grid of the tube.

The plug is reinserted after the proper adjustment has been made. The plate swing is then checked by rotating the integrating wheel completely around. This swing should vary to approximately 30 V on each side of 300 V. Since this swing is a function of the photo-tube supply and of the relative sensitivity of the photo-tubes, it may not be possible to achieve this condition very accurately. If not, then the photo-tubes should be replaced by a pair which have the same order of sensitivity. If a well-matched pair of photo-tubes does not produce the swing desired, then the amplifier may need a new photo-tube supply. This is the 5W4 rectifier tube.

It should be emphasized that, until the proper swing has been obtained on the 6SJ7 plate, the adjustment of any of the following stages is of no practical use. Also, it is not desirable to adjust the plate swing by means of the rheostat knob already referred to. The position of this knob is determined by the method outlined for no light flux, and must not be changed during the check on the plate swing. If it is varied at any time, the amplifier may operate satisfactorily under steady-state light conditions, but will become unbalanced if the lights are dimmed, even momentarily.

When the proper swing is obtained, the integrating wheel is rotated until the voltmeter reads the median value, which is 300 V. If the plug of the adjacent integrator is again removed, the plate voltage should not change, even though the lights are now off. This check indicates whether or not the preceding steps have been correctly carried out.

The next step in the procedure involves testing the grid swings on the two 6L6 stages. The hubs for these tests are located at the meter end of the amplifier. The means for varying the swings on these grids are the two outside black bakelite knobs on the front of the amplifier. The center knob adjusts the 6J5 inverter tube grid bias, and affords an extra means for variation.

It is now necessary to cause each of the 6L6 grids to vary between -4 and -30 volts. The three knobs on the front of the amplifier are the only means for making these adjustments. If the proper swing cannot be obtained for both 6L6's, the more probable causes of the difficulty are (a) a bad 879 rectifier tube, which is the source of the negative grid circuit supplies, (b) bad 6L6's or 6J5, (c) weak 5W4 supply to the 6J5 plate, and (d) changes in the electrical properties of the wire-wound resistors.

Again, it is emphasized that no other knobs than the three which are on the front of the amplifier should be changed during this stage in the adjustment procedure. After the proper swing has been produced on each 6L6 grid, the output ammeters should be watched as to swing. If the 6L6 tube characteristics are sufficiently alike, the swings should be approximately equal, though out-of-phase with each other due to the inverter action.

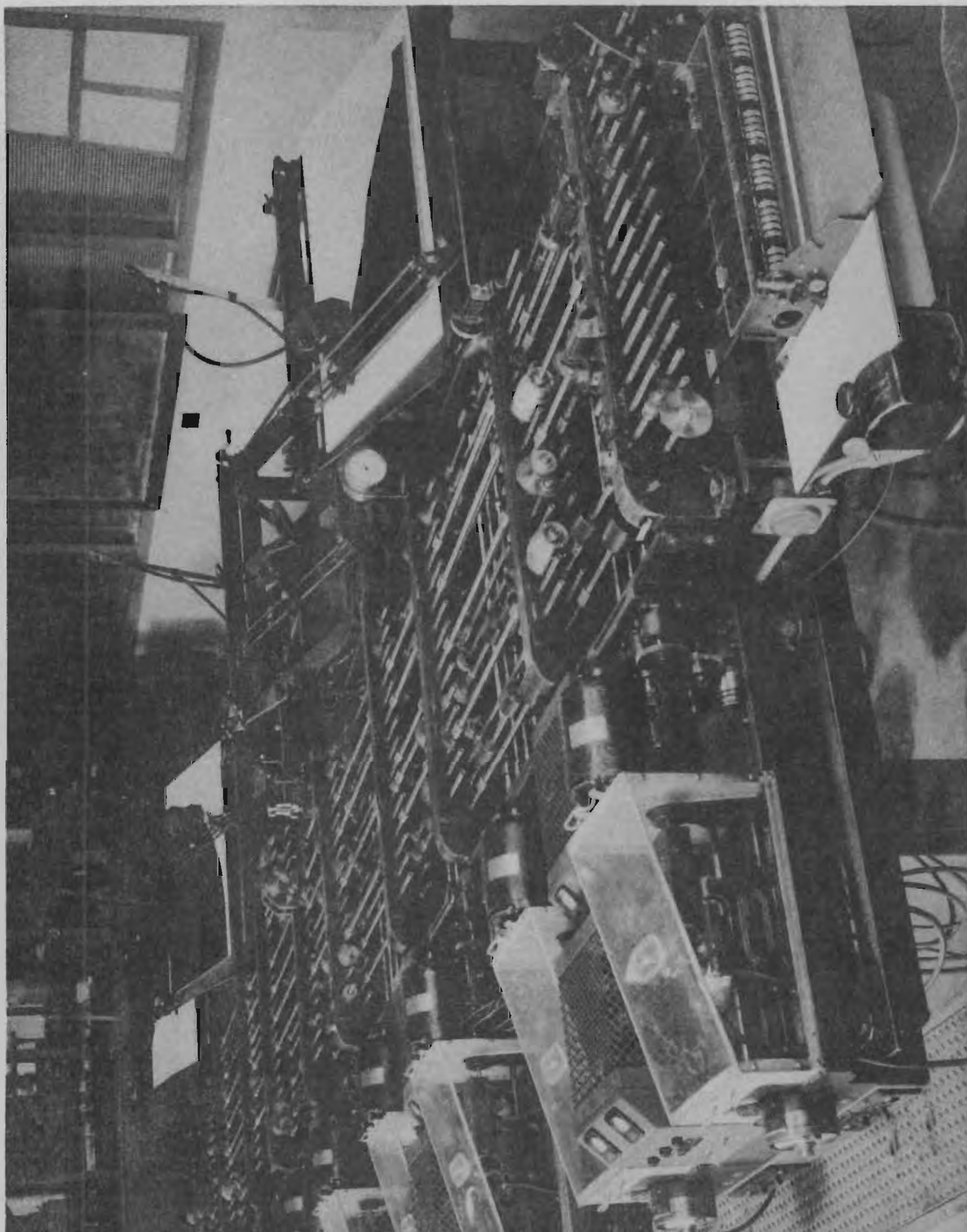
In addition to the output current swings, the following check is made on the 6L6 stages: test the voltage on the plate of the 6SJ7, and adjust to 300 V by turning the integrating wheel. This should cause the output ammeters to read equal values in the range of 5 to 10 milliamperes. If they vary only slightly from equality, they may be adjusted to equality by using the three knobs on the front of the amplifier. If a wider variation is found, then some adjustment among the foregoing was improper, and the whole procedure should be repeated.

The final adjustment of the amplifier is in the anti-hunt circuit. As previously explained, this circuit is necessary to increase the natural damping factor of the mechanical load connected to the output motor. A double-pole-double-throw switch on the front of the amplifier, which is a condenser selector, and a screw-headed rheostat adjustment, also on the front of the amplifier, afford the means for supplying the proper amount of damping. The amplifier is adjusted to balanced output, and the D.C. turned on. The condenser and rheostat adjustments which best eliminate hunting on the one hand and loose coupling on the other hand are found by trial-and-error procedure. The circuit has been so constructed that the condenser selector switch should be to the right if the amplifier is connected to an integrator and to the left if connected to a table.

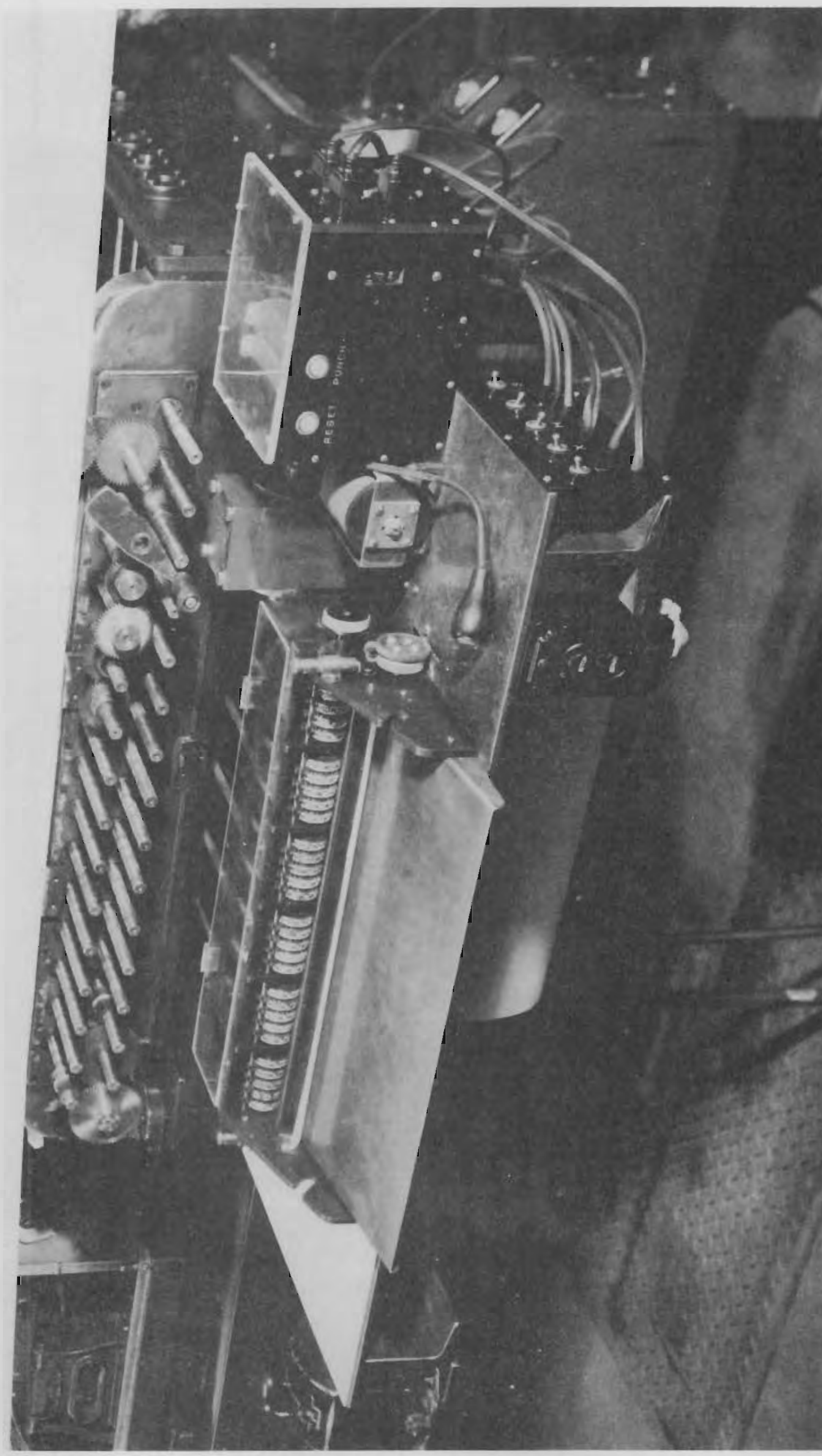
The procedure for adjusting the tables is almost identical to that for adjusting the integrators. The first step, as explained, is to adjust the knob on the servo-head so that, with the lights off, the plate of the 6SJ7 reads 300 V. In the following step, while the plate swing is being tested with the lights on, there is an added parameter in the system which "matches" the photo-tubes. This is a slider which restricts the amount of light which reaches the "fixed" photo-tube. This slider is moved by means of a screw in the side of the servo-head so that the plate swing falls within the prescribed range. Once this has been done, the remaining steps can be performed exactly as previously described.

If, after a table amplifier has been balanced, the servo-motor is found to run away consistently upon the application of an error, check the effect of the reversing switch on its terminal box. This switch reverses the field of the servo-motor, and its position is a function of the relative locations of black and white areas on the template.

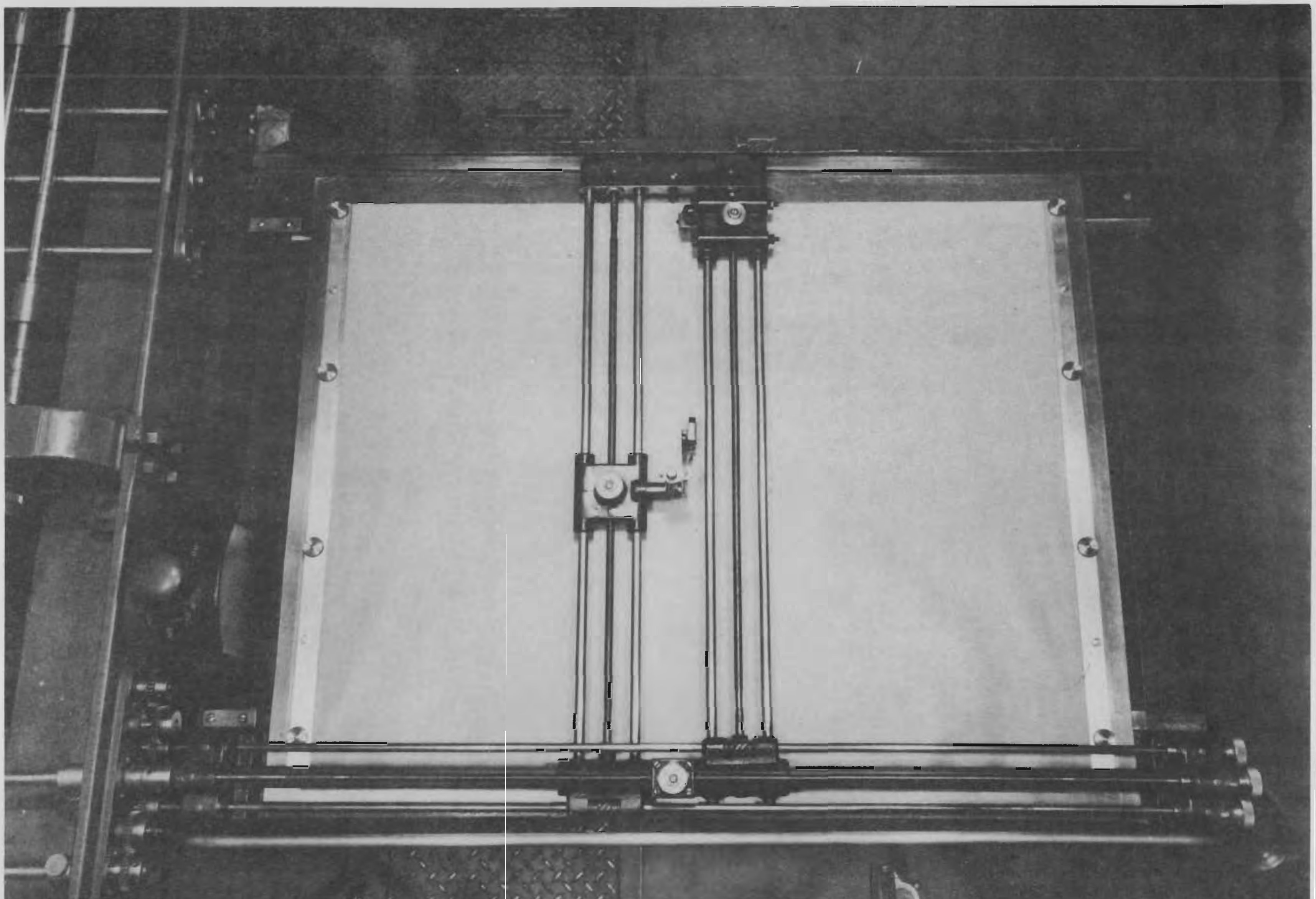
APPENDIX I: PHOTOGRAPHS



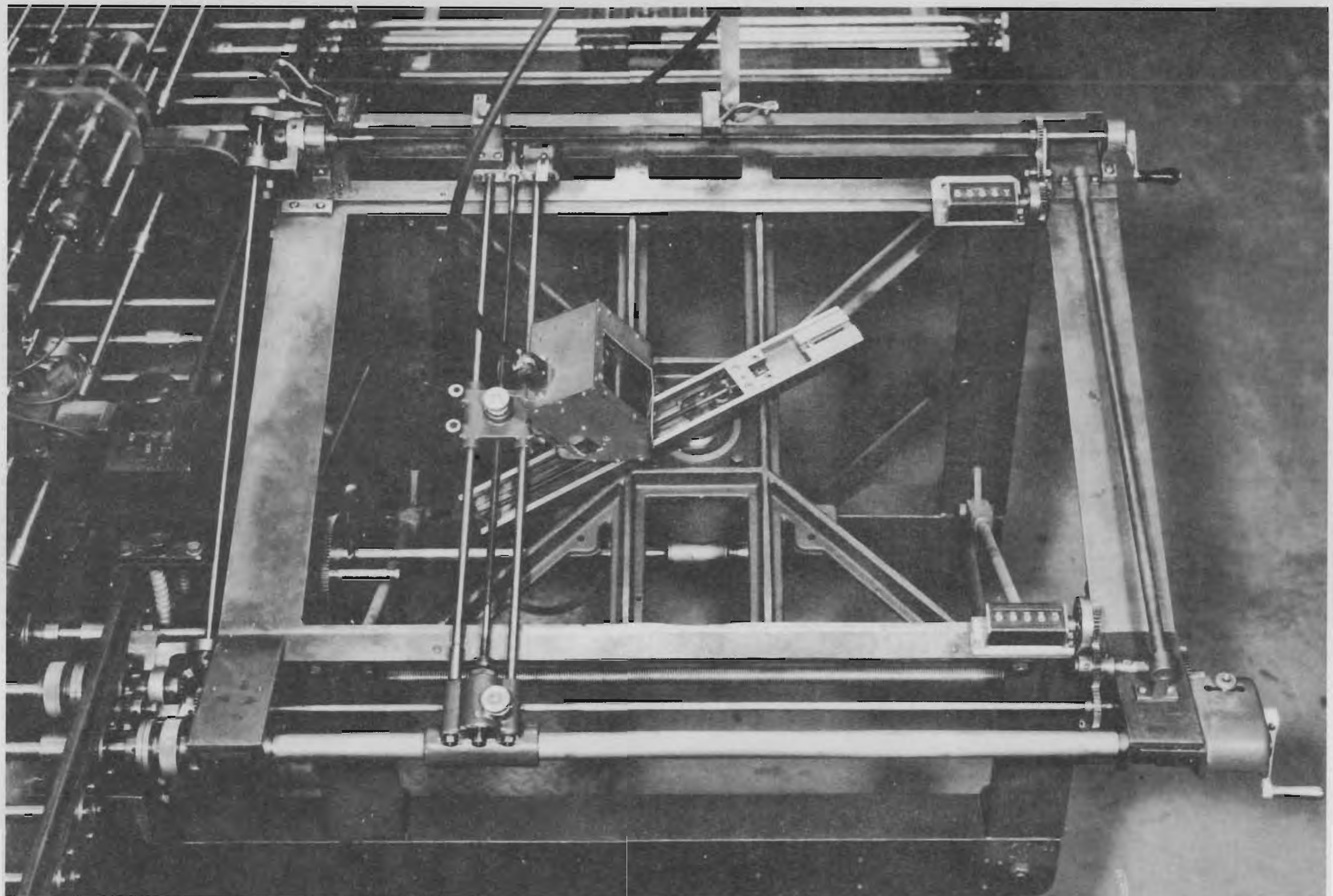
Photograph No. 1
General View of Machine



Photograph No. 2
Printer and Controls

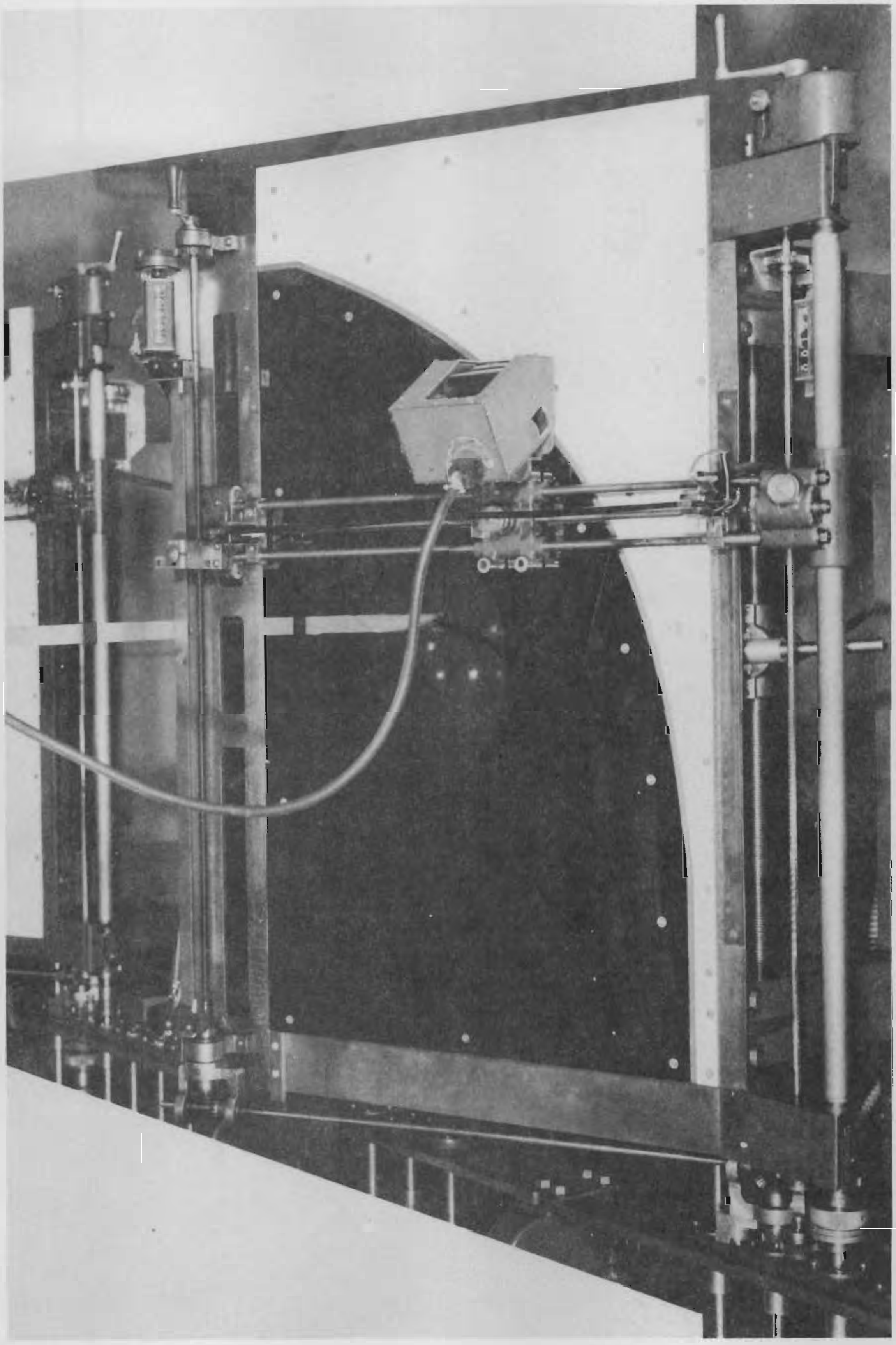


Photograph No. 3
Input-Output Table

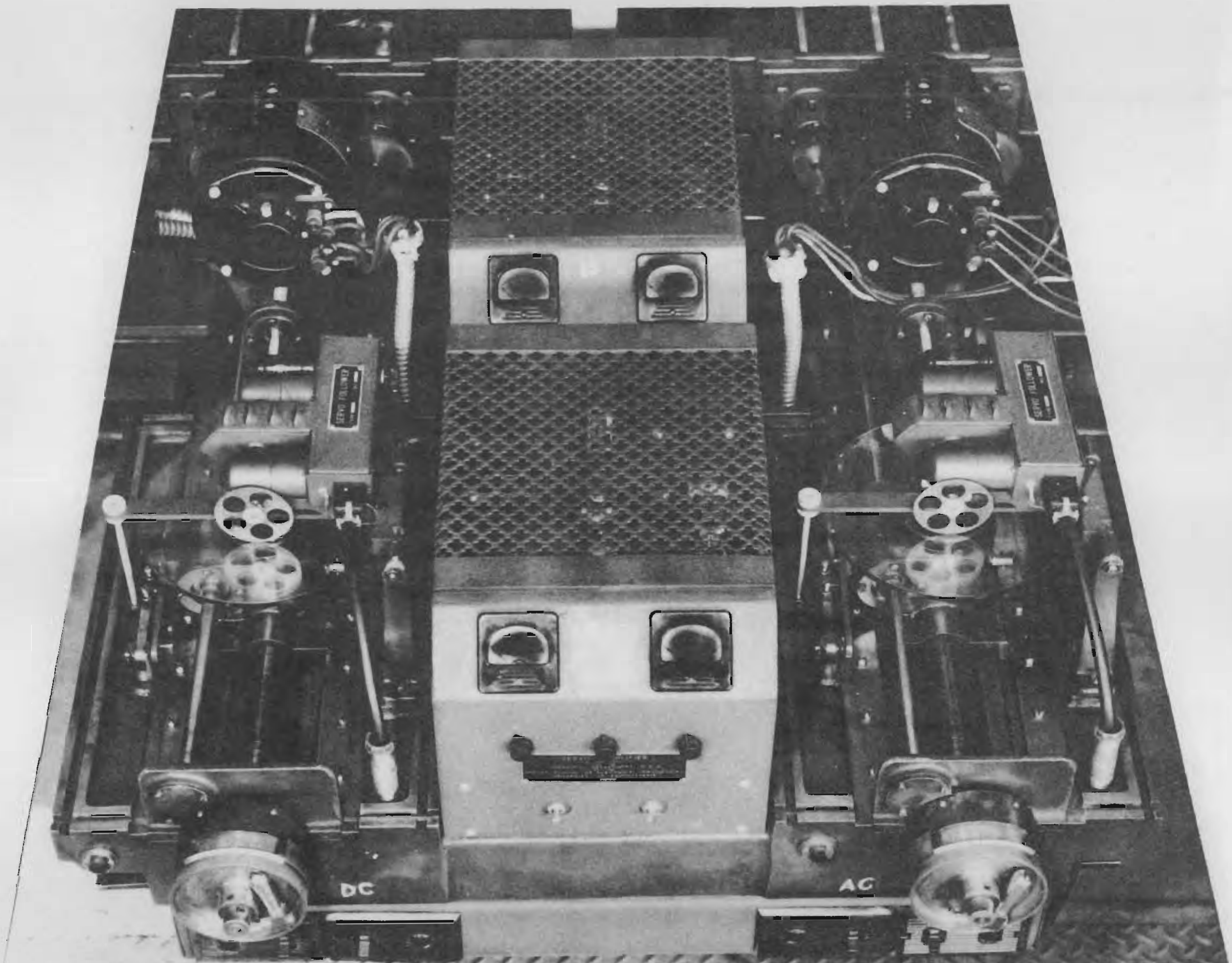


Photograph No. 4

Vector Input Table

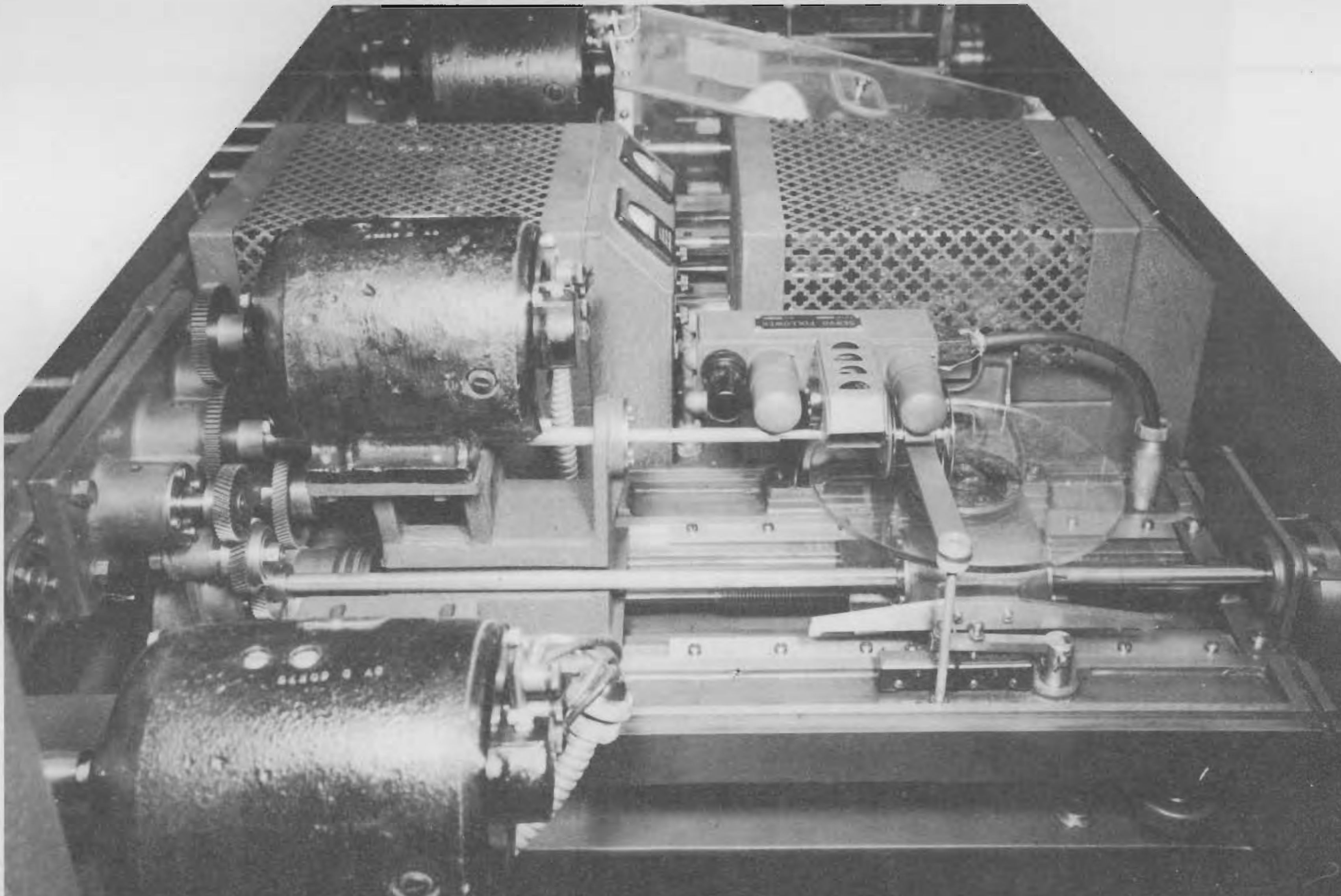


Photograph No. 5
Template Input Table

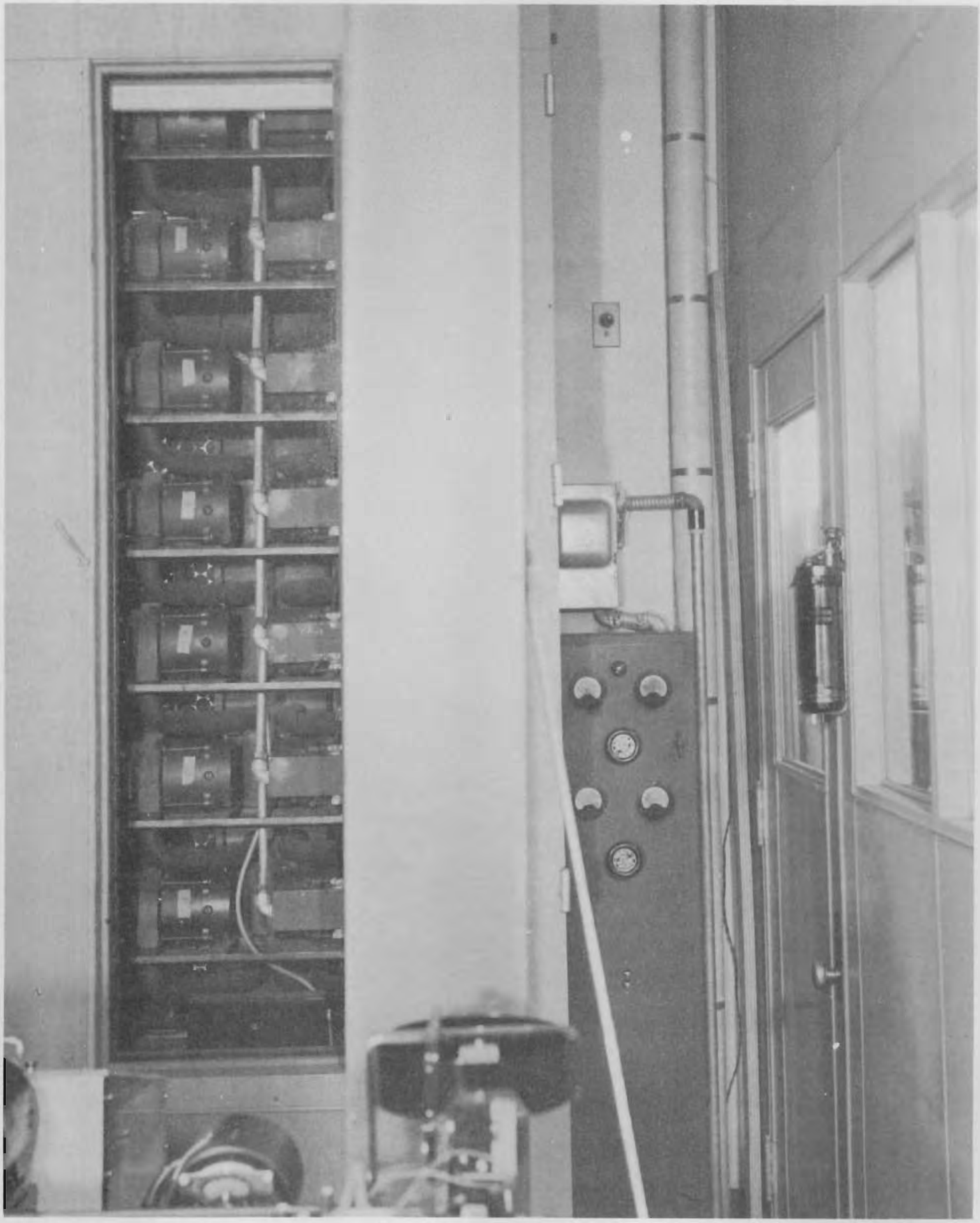


Photograph No. 6

A Pair of Integrators Showing Associated Amplifiers

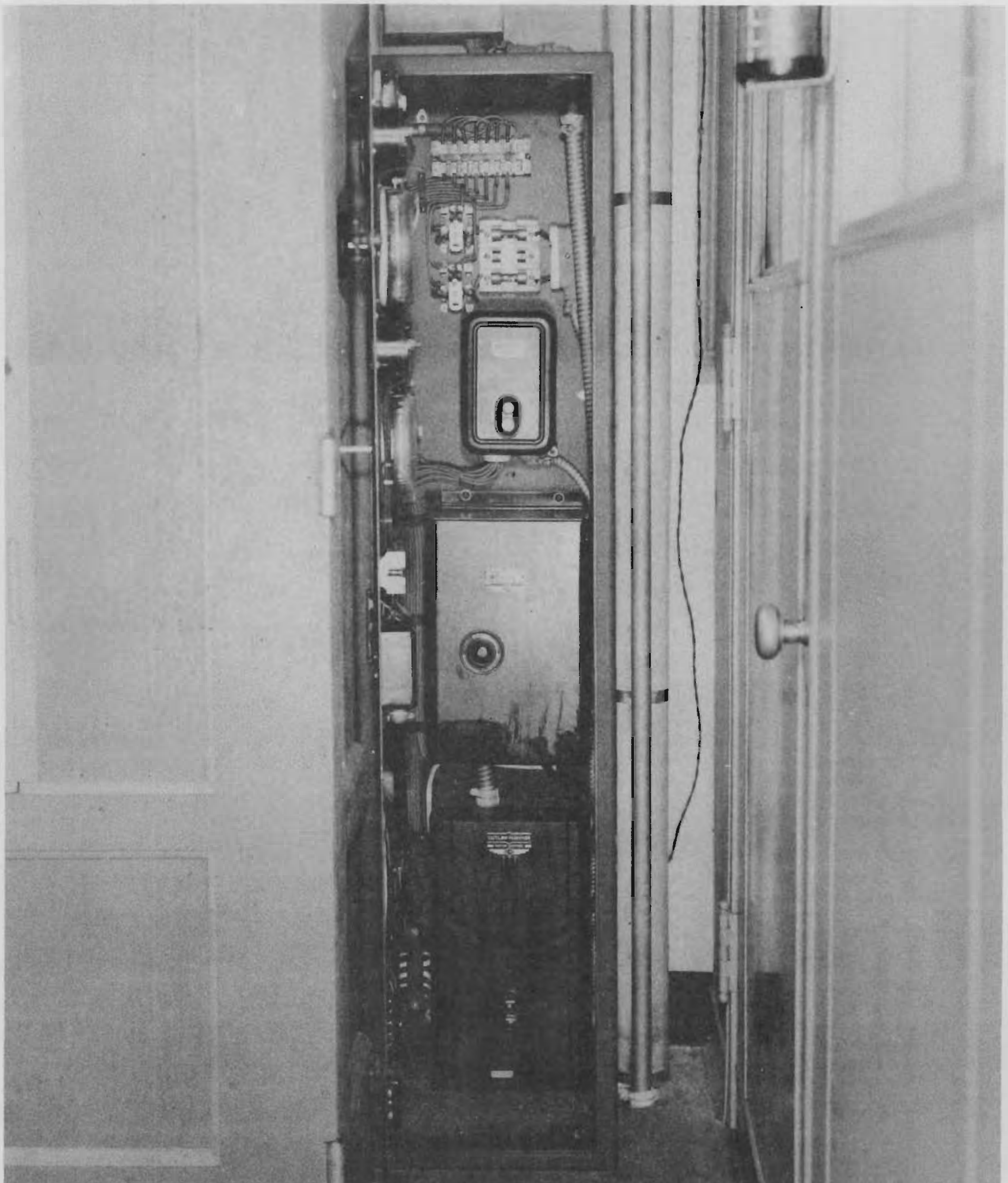


Photograph No. 7
Side View of an Integrator



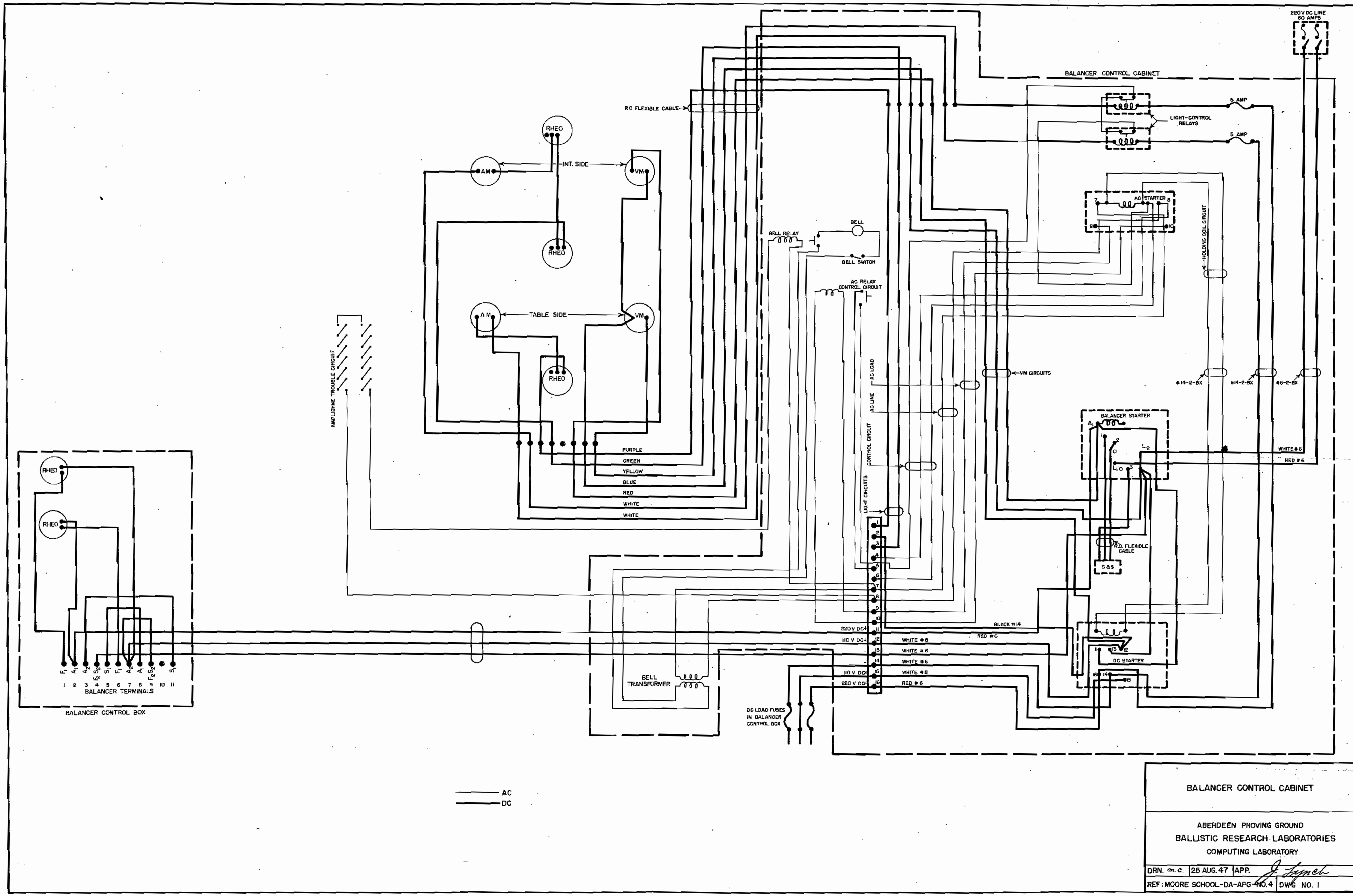
Photograph No. 8

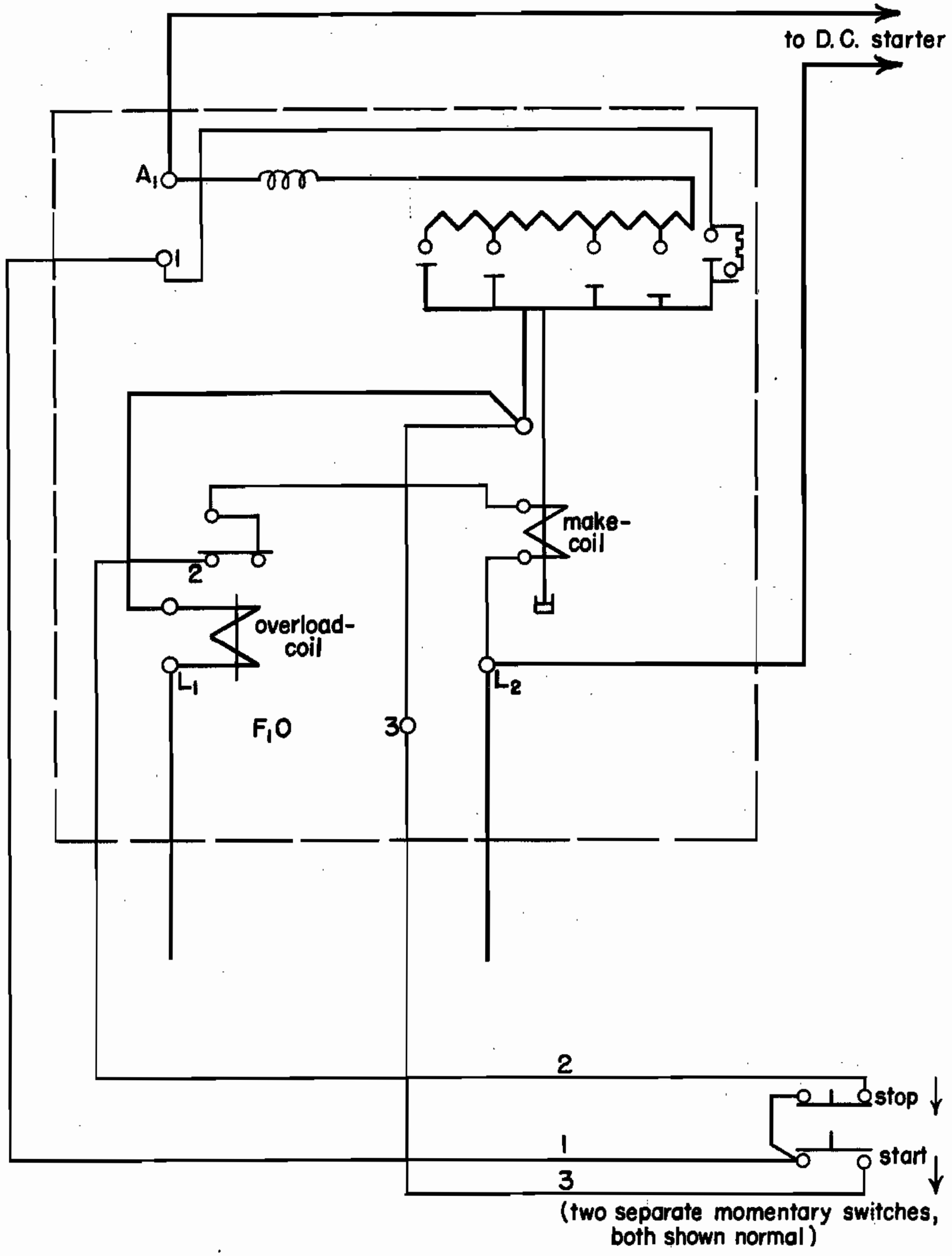
Amplidyne and Balancer Control Cabinets



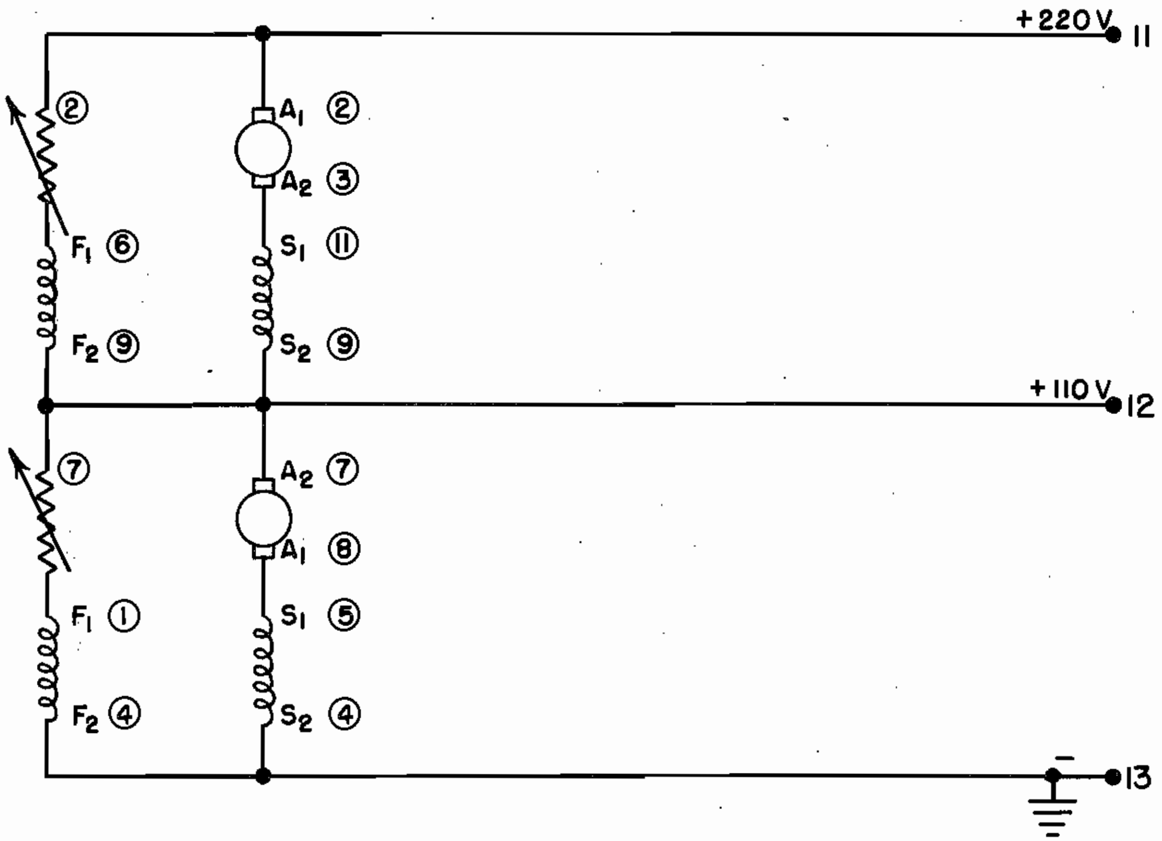
Photograph No. 9
Inside View of Balancer Control Cabinet

APPENDIX II: DRAWINGS


220V DC LINE 60 AMPS
BALANCER CONTROL CABINET
RC FLEXIBLE CABLE
RHEO
AM
VM
INT. SIDE
TABLE SIDE
5 AMP
LIGHT-CONTROL RELAYS
AC STARTER
HOLDING COIL CIRCUIT
BELL RELAY
BELL
BELL SWITCH
AC RELAY CONTROL CIRCUIT
VM CIRCUITS
AC LOAD
AC LINE
CONTROL CIRCUIT
LIGHT CIRCUITS
AMPLIDYNE TROUBLE CIRCUIT
#14-2-BX
#6-2-BX
BALANCER STARTER
WHITE #6
RED #6
PURPLE
GREEN
YELLOW
BLUE
RED
WHITE
R.C. FLEXIBLE CABLE
BLACK #14
RED #6
220V DC
110 V DC
WHITE #8
WHITE #6
RED #6
DC STARTER
BELL TRANSFORMER
DC LOAD FUSES IN BALANCER CONTROL BOX
BALANCER TERMINALS
BALANCER CONTROL BOX
AC
DC
BALANCER CONTROL CABINET
ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY
DRN. m.c.
25 AUG. 47
APP.
REF: MOORE SCHOOL-DA-APG-NO.4
DWG NO. 1



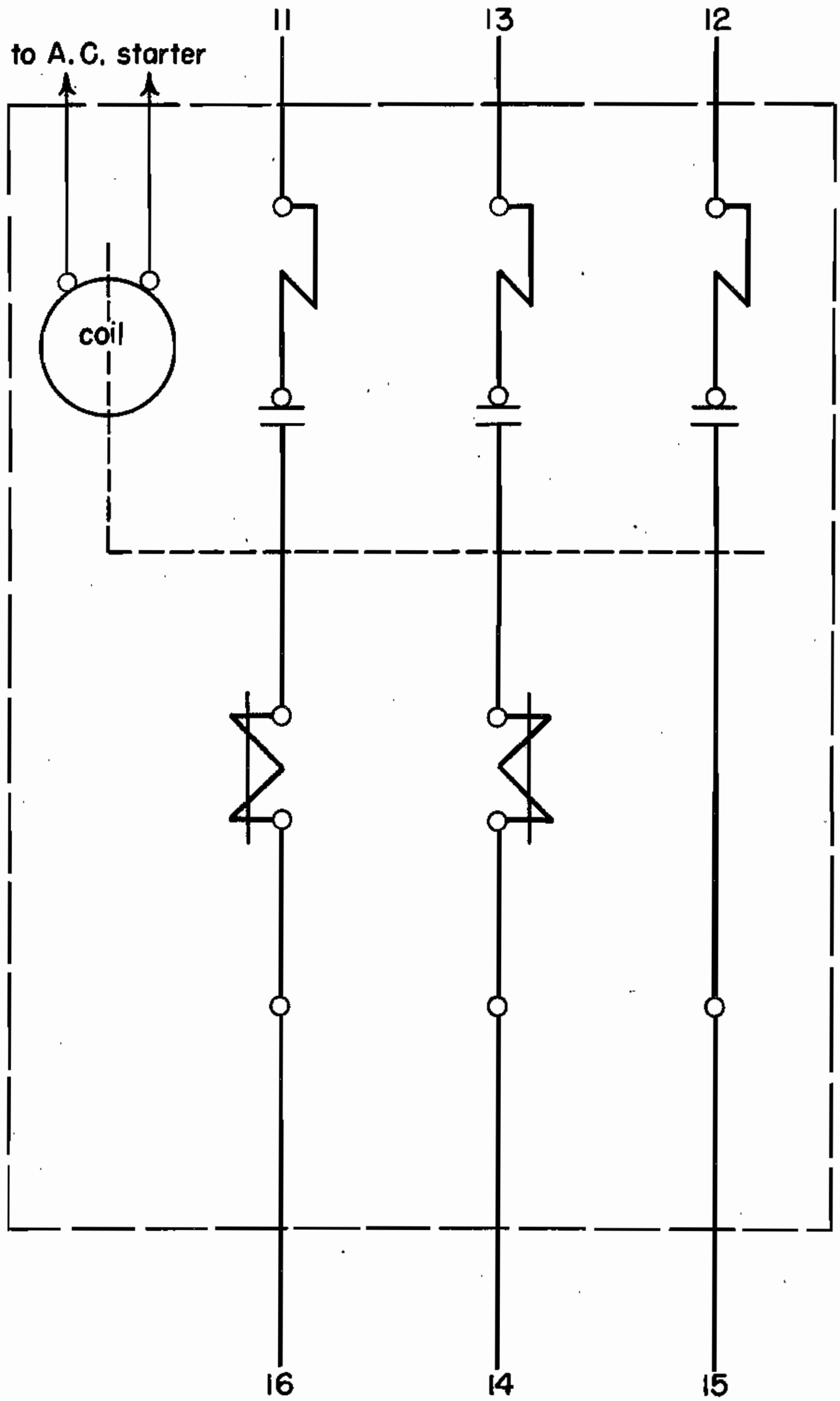
DWG NO. 2
BALANCER STARTER DIAGRAM



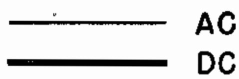
Numerals indicate terminal block connections.
Letters indicate individual motor connections.

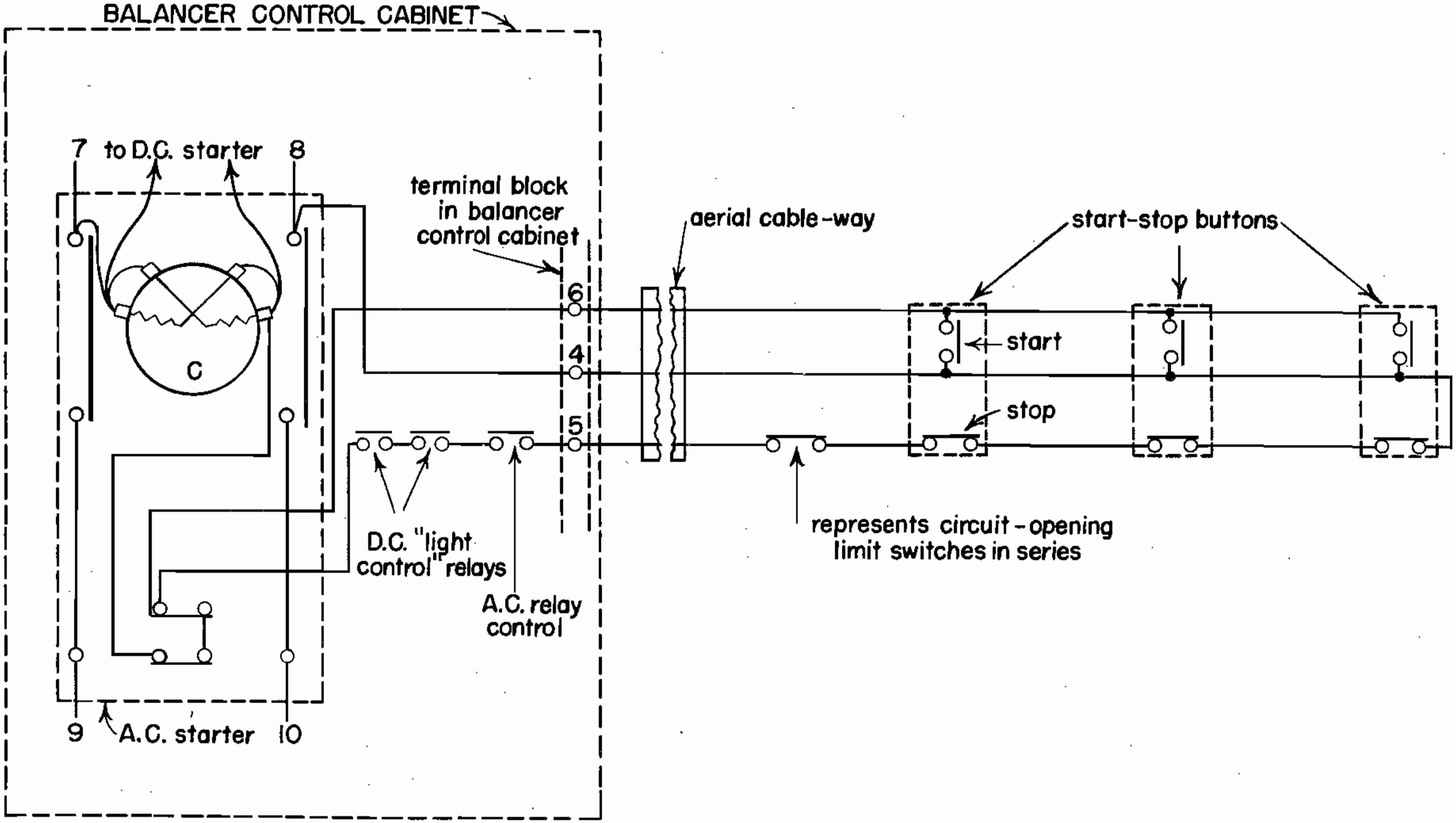
DWG NO. 3

SCHEMATIC CIRCUIT DIAGRAM OF BALANCER SET



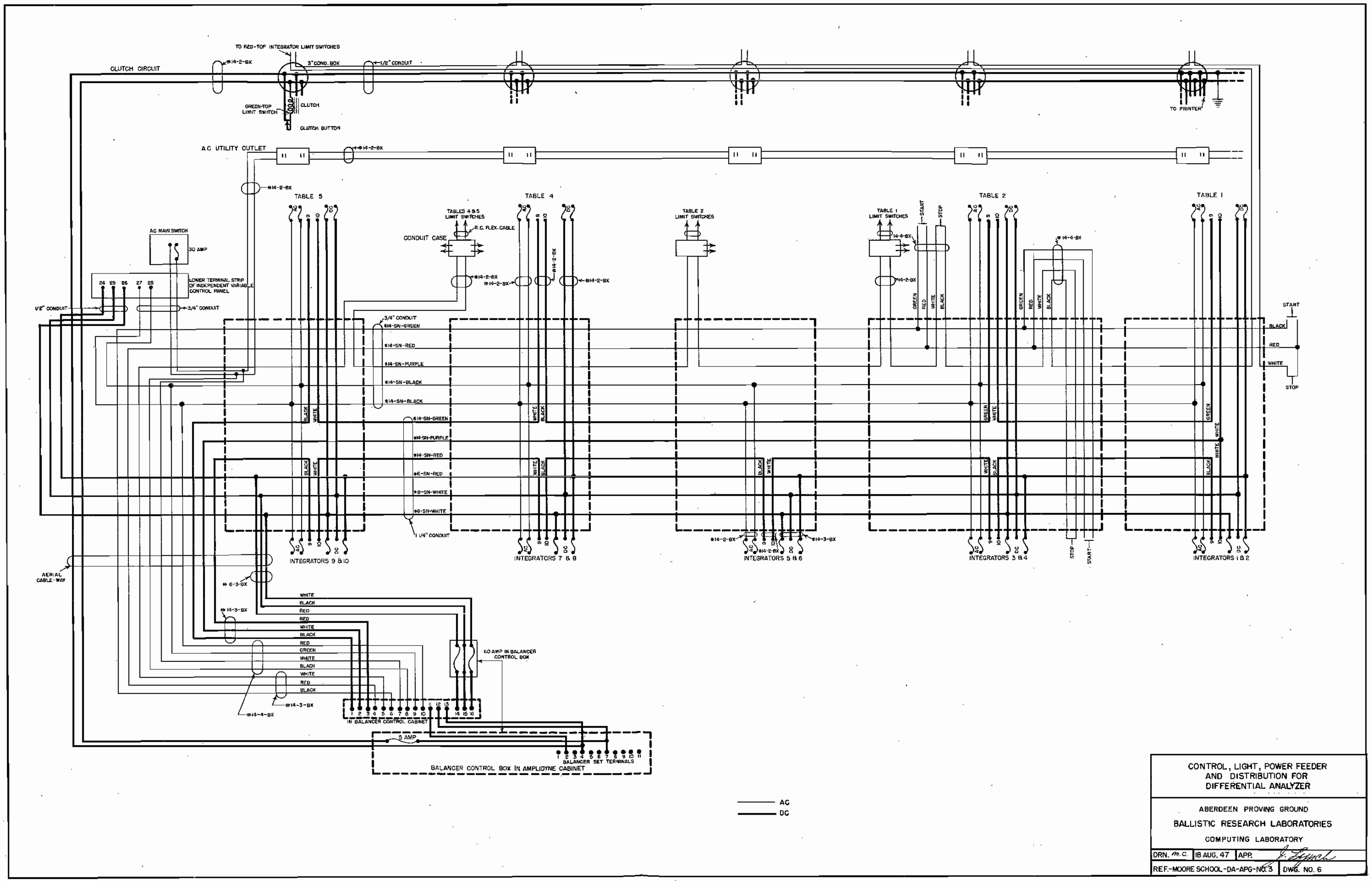
DWG NO. 4
D. C. STARTER DIAGRAM

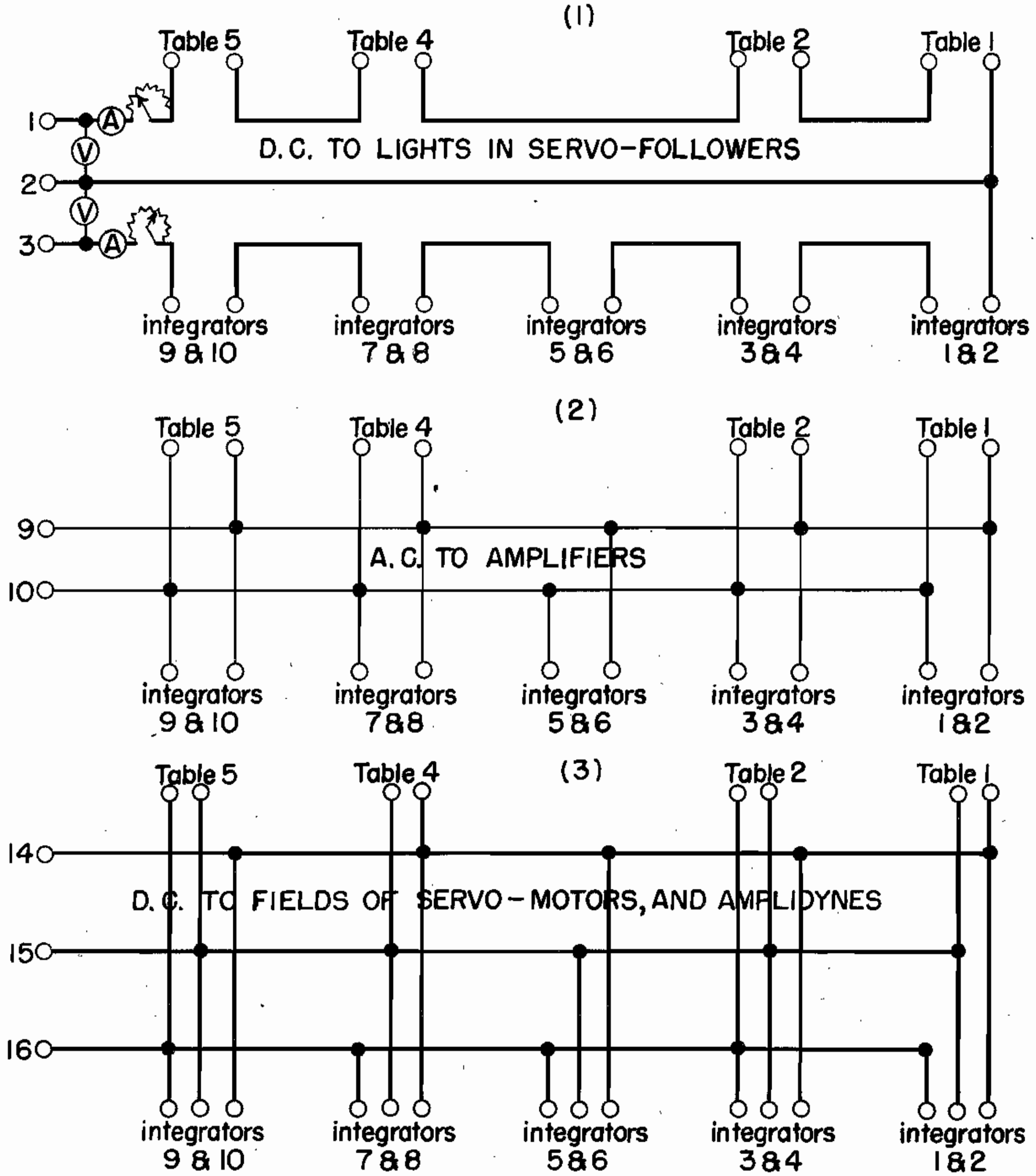




DWG NO. 5

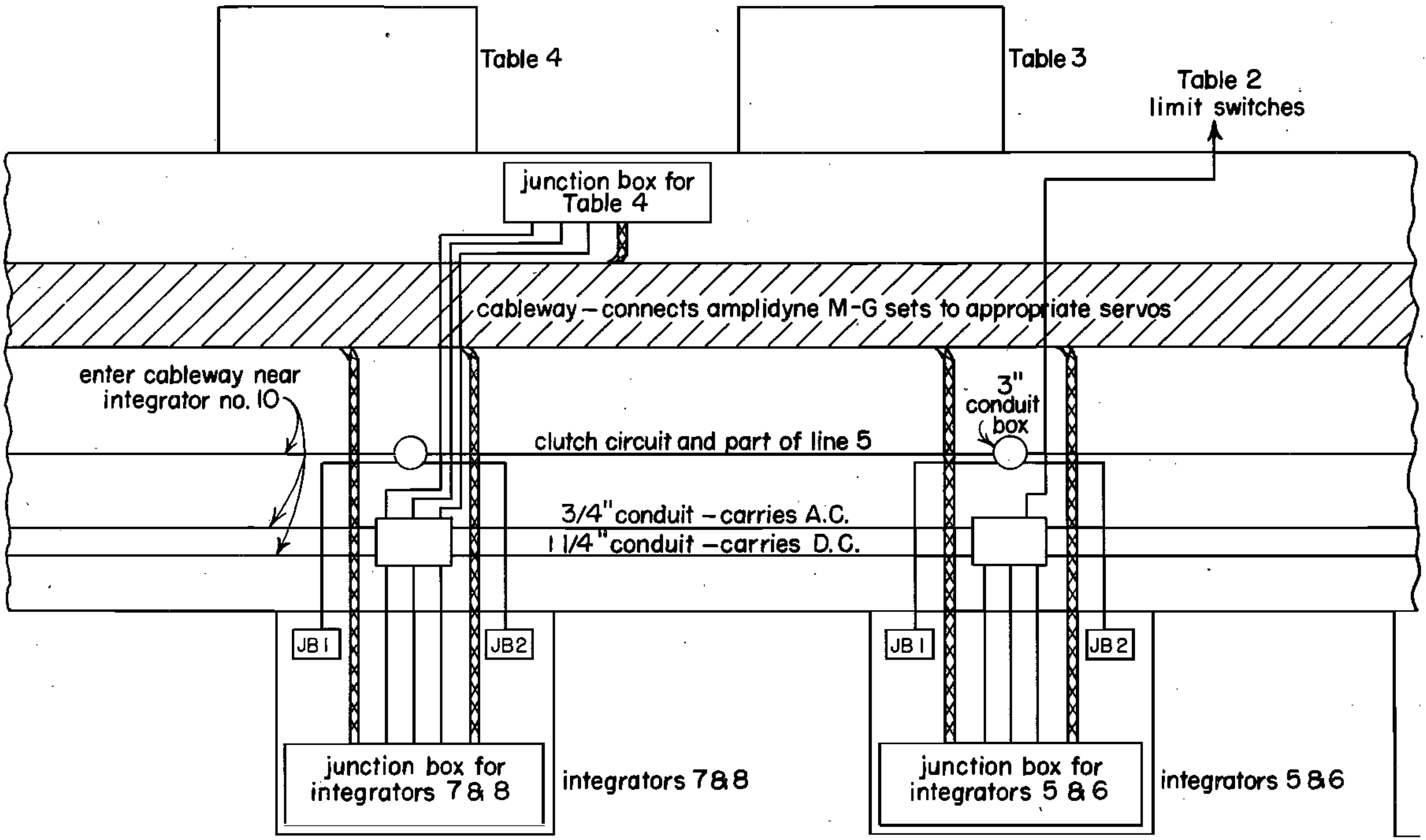
A.C. STARTER DIAGRAM WITH SCHEMATIC REPRESENTATION OF START–STOP CONTROLS


CLUTCH CIRCUIT
TO RED-TOP INTEGRATOR LIMIT SWITCHES
#14-2-BX
3" COND. BOX
1/2" CONDUIT
GREEN-TOP LIMIT SWITCH
CLUTCH
CLUTCH BUTTON
TO PRINTER
AC UTILITY OUTLET
#14-2-BX
TABLE 5
TABLE 4
TABLE 2
TABLE 1
TABLES 4 & 5 LIMIT SWITCHES
R.C. FLEX. CABLE
CONDUIT CASE
TABLE 2 LIMIT SWITCHES
TABLE 1 LIMIT SWITCHES
START
STOP
#14-4-BX
AC MAIN SWITCH
30 AMP
LOWER TERMINAL STRIP OF INDEPENDENT VARIABLE CONTROL PANEL
24 25 26 27 28
1/2" CONDUIT
3/4" CONDUIT
#14-SN-GREEN
#14-SN-RED
#14-SN-PURPLE
#14-SN-BLACK
#14-SN-BLACK
#14-SN-GREEN
#14-SN-PURPLE
#14-SN-RED
#6-SN-RED
#8-SN-WHITE
#6-SN-WHITE
1 1/4" CONDUIT
BLACK
RED
WHITE
GREEN
INTEGRATORS 9 & 10
INTEGRATORS 7 & 8
INTEGRATORS 5 & 6
INTEGRATORS 3 & 4
INTEGRATORS 1 & 2
#14-3-BX
AERIAL CABLE-WAY
#6-3-BX
#14-3-BX
#14-4-BX
60 AMP IN BALANCER CONTROL BOX
IN BALANCER CONTROL CABINET
5 AMP
BALANCER SET TERMINALS
BALANCER CONTROL BOX IN AMPLIDYNE CABINET
AC
DC
CONTROL, LIGHT, POWER FEEDER AND DISTRIBUTION FOR DIFFERENTIAL ANALYZER
ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY
DRN. M.C.
18 AUG. 47
APP.
REF.-MOORE SCHOOL-DA-APG-NO. 3
DWG. NO. 6



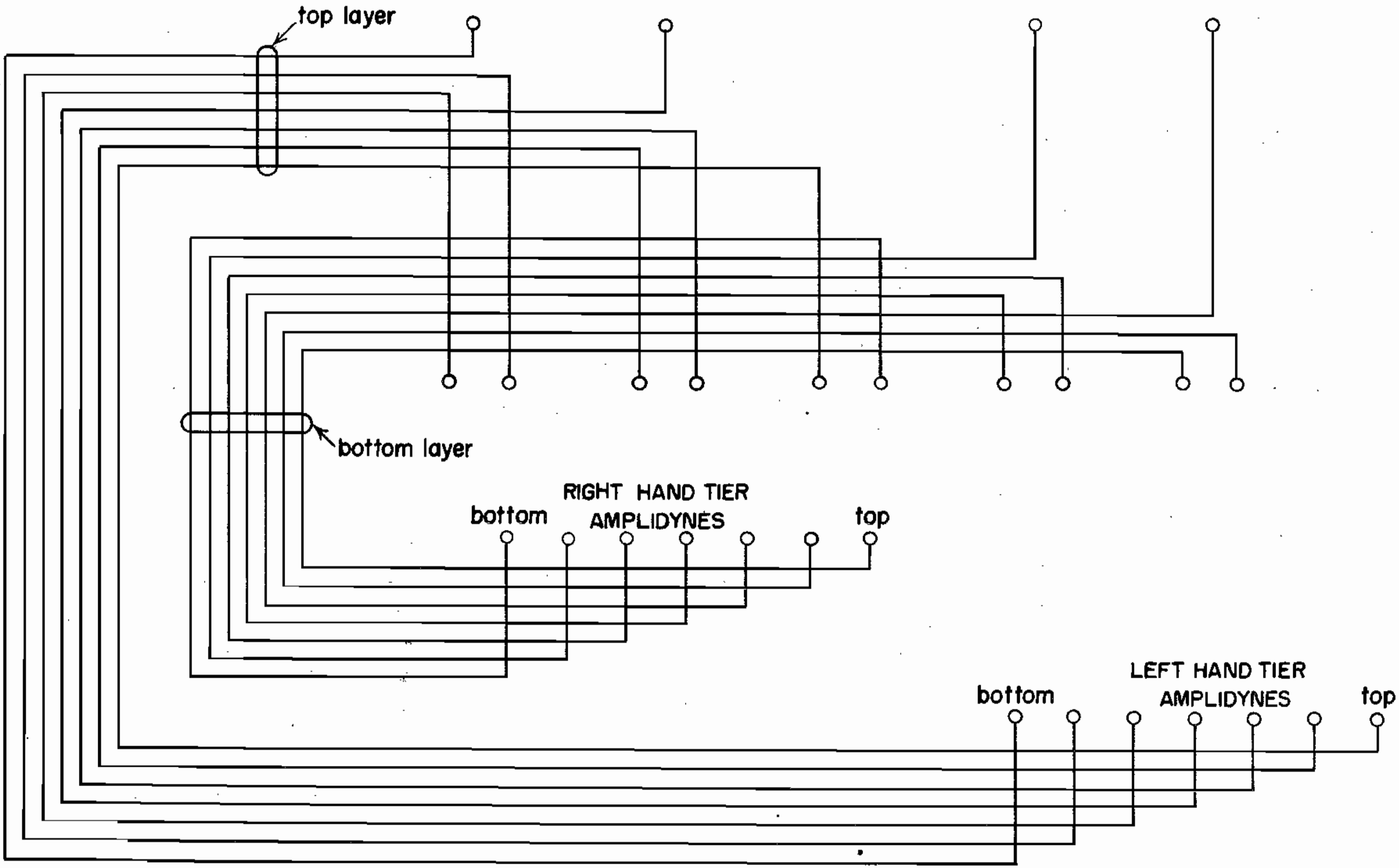
DWG NO. 7

SCHEMATIC DIAGRAM – POWER APPLIED TO INTEGRATORS AND TABLES



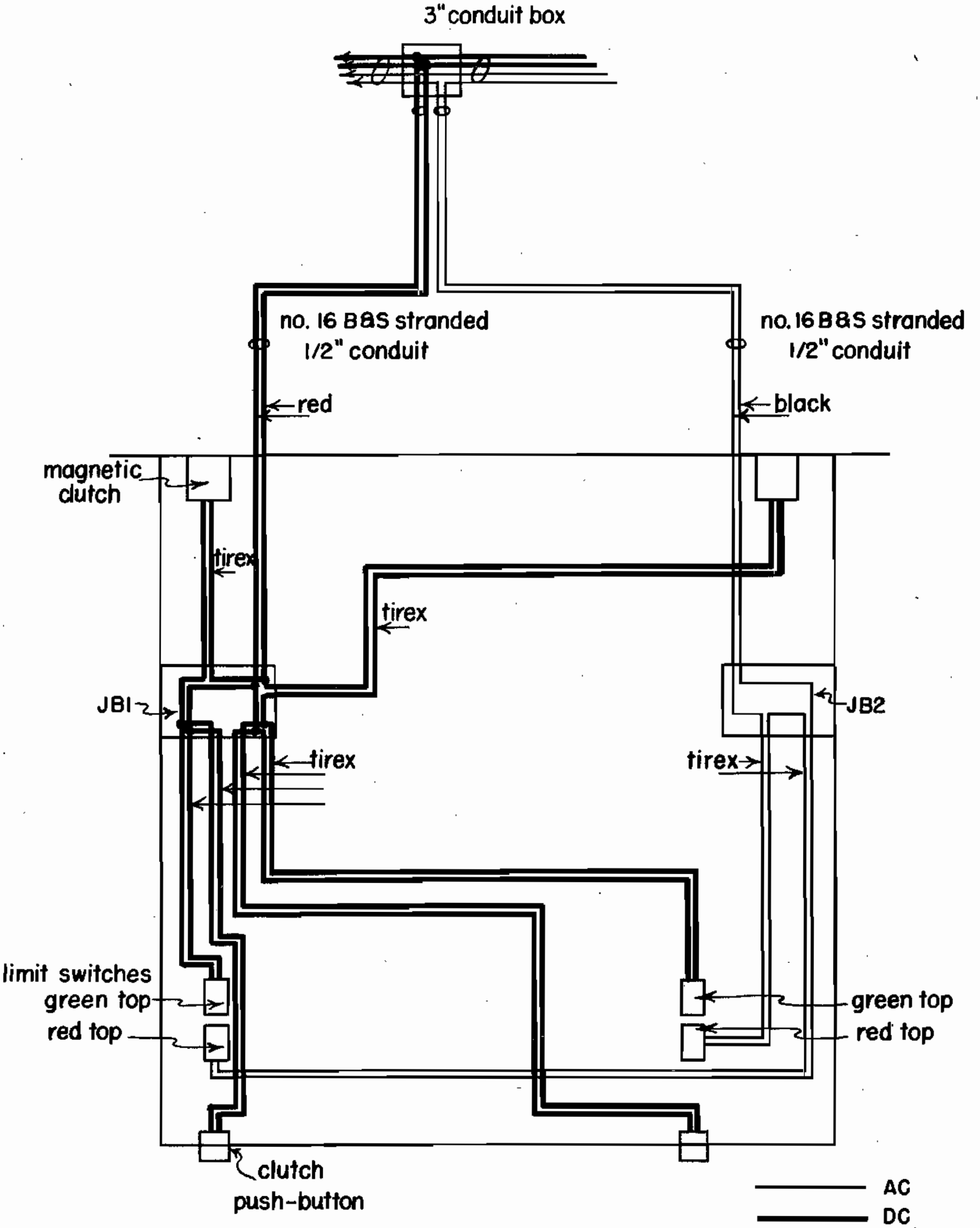
DWG NO. 8

SECTION OF ANALYZER TO SHOW CABLE CONNECTIONS TO JUNCTION BOXES



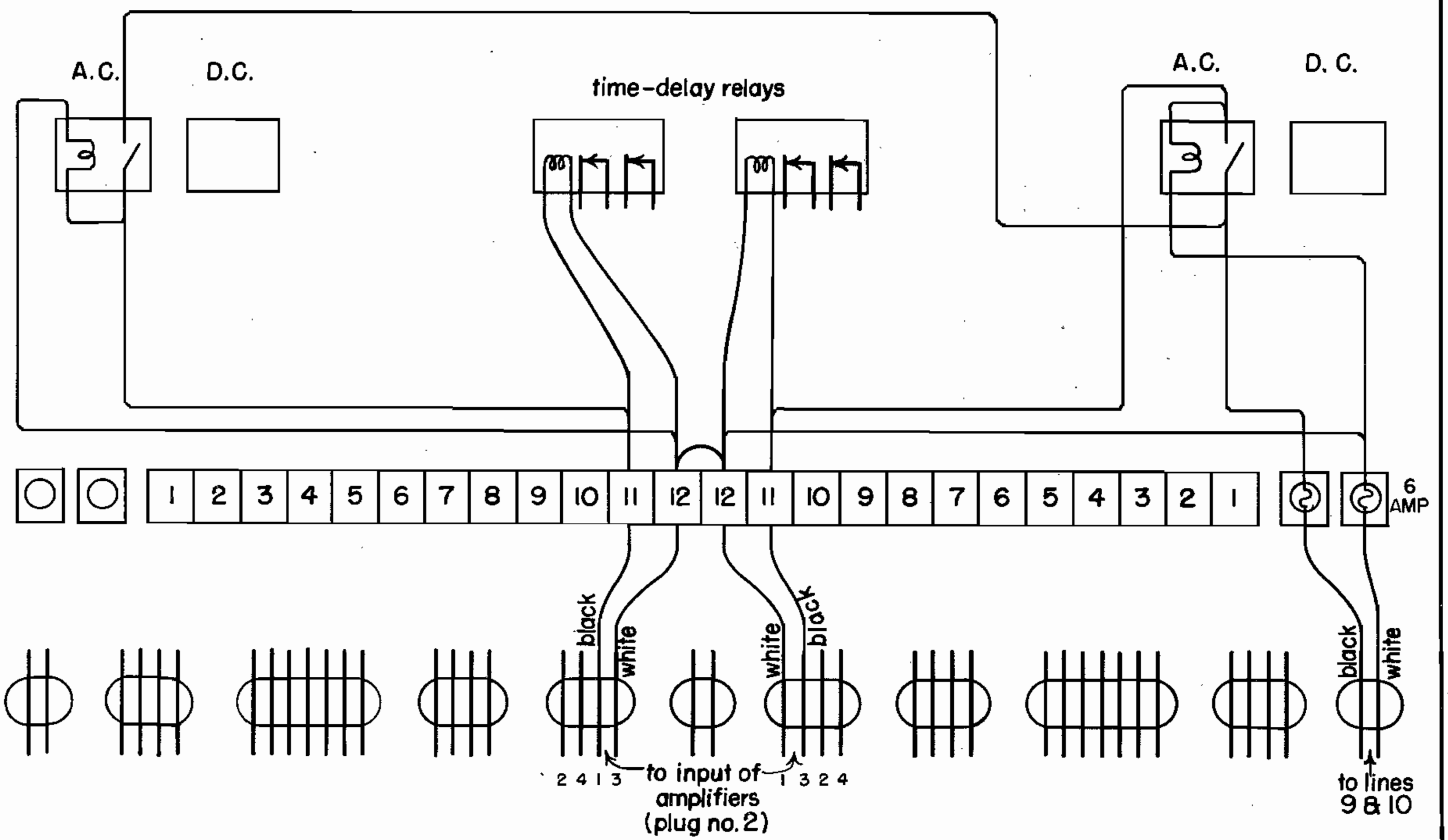
DWG NO. 9

AMPLIDYNE CABLE CONNECTION



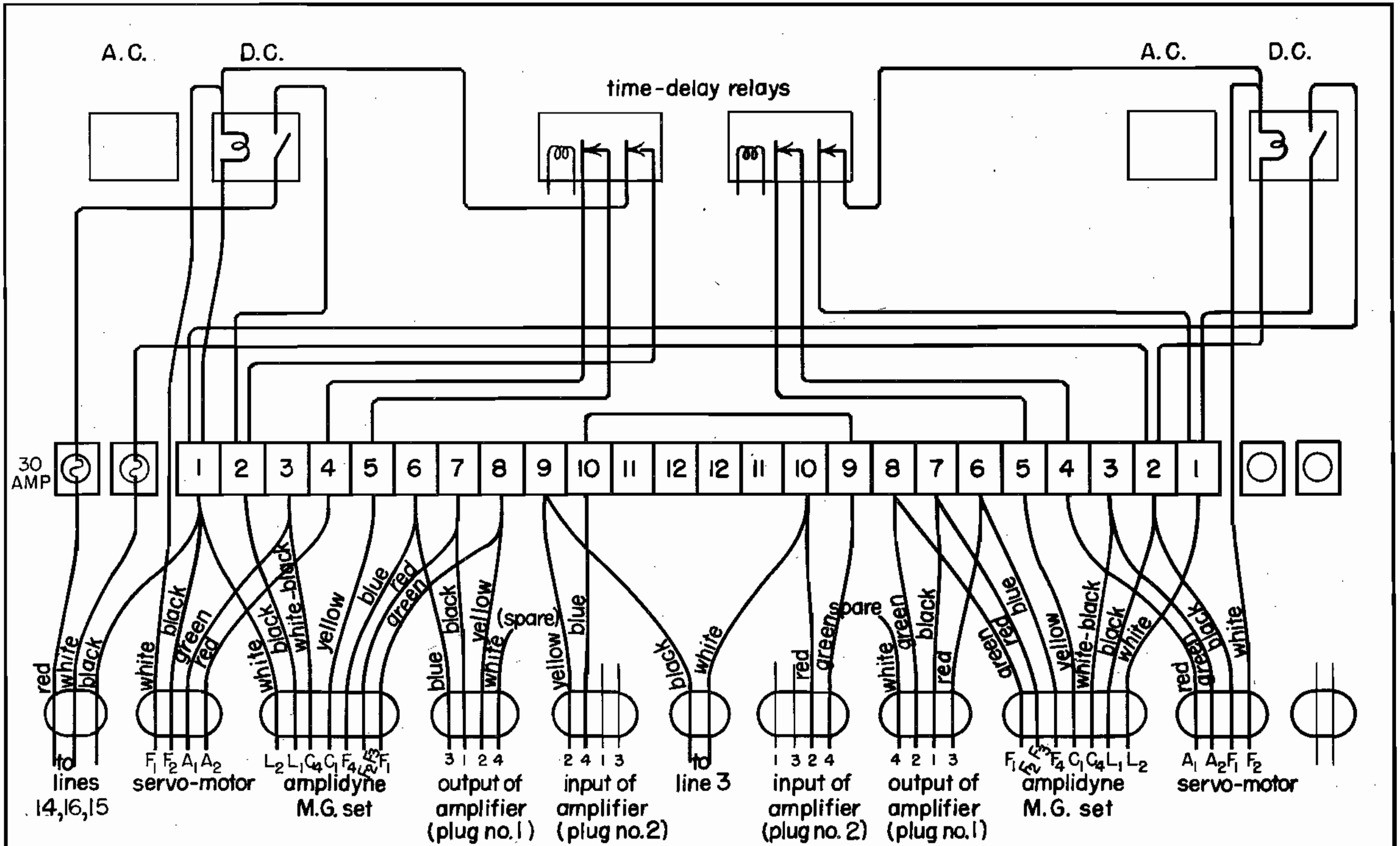
DWG NO. 10

CLUTCH AND LIMIT SWITCH CONNECTIONS TO INTEGRATORS



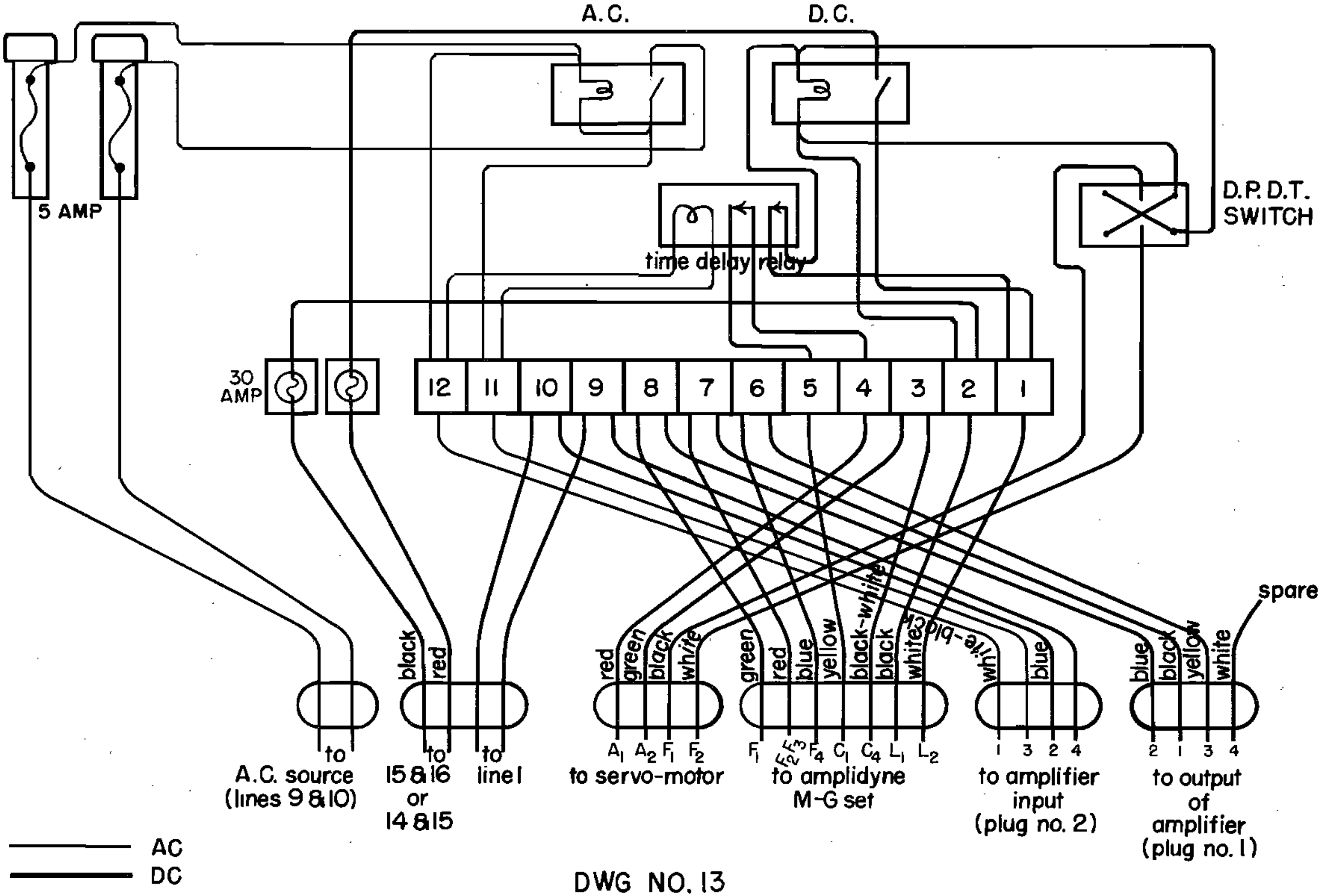
DWG NO. II

WIRING DIAGRAM OF A.C. CONNECTIONS TO INTEGRATORS AS VIEWED FROM BELOW



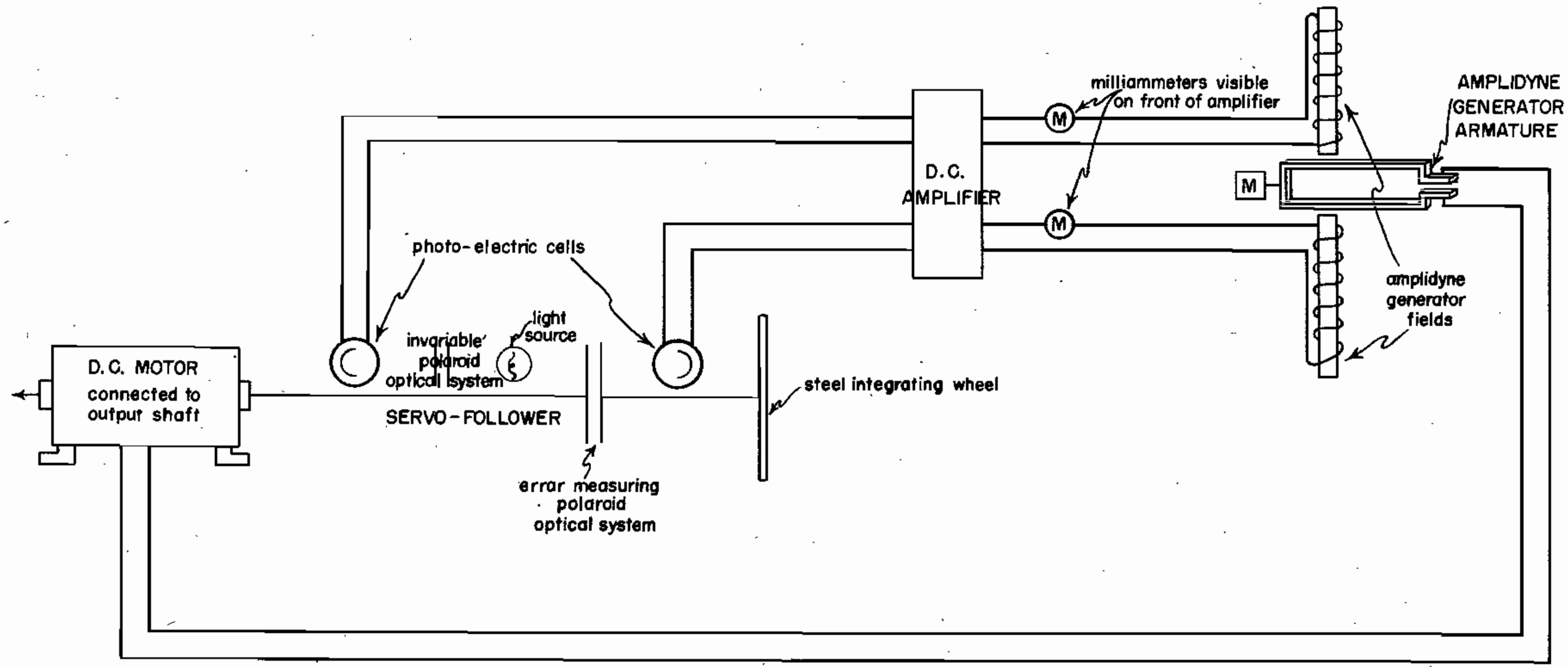
DWG NO. 12

WIRING DIAGRAM OF D.C. CONNECTIONS TO INTEGRATORS AS VIEWED FROM BELOW

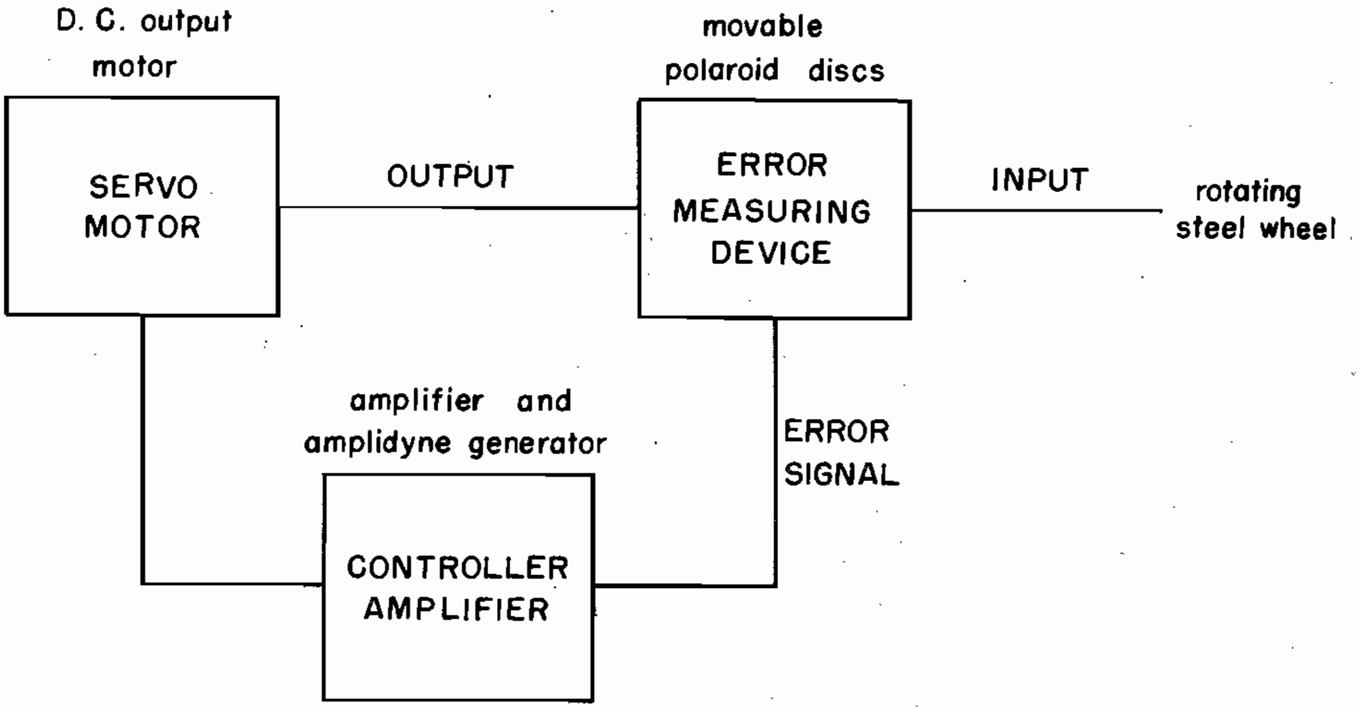


DWG NO. 13

WIRING DIAGRAM OF CONNECTIONS TO TABLES AS VIEWED FROM BELOW

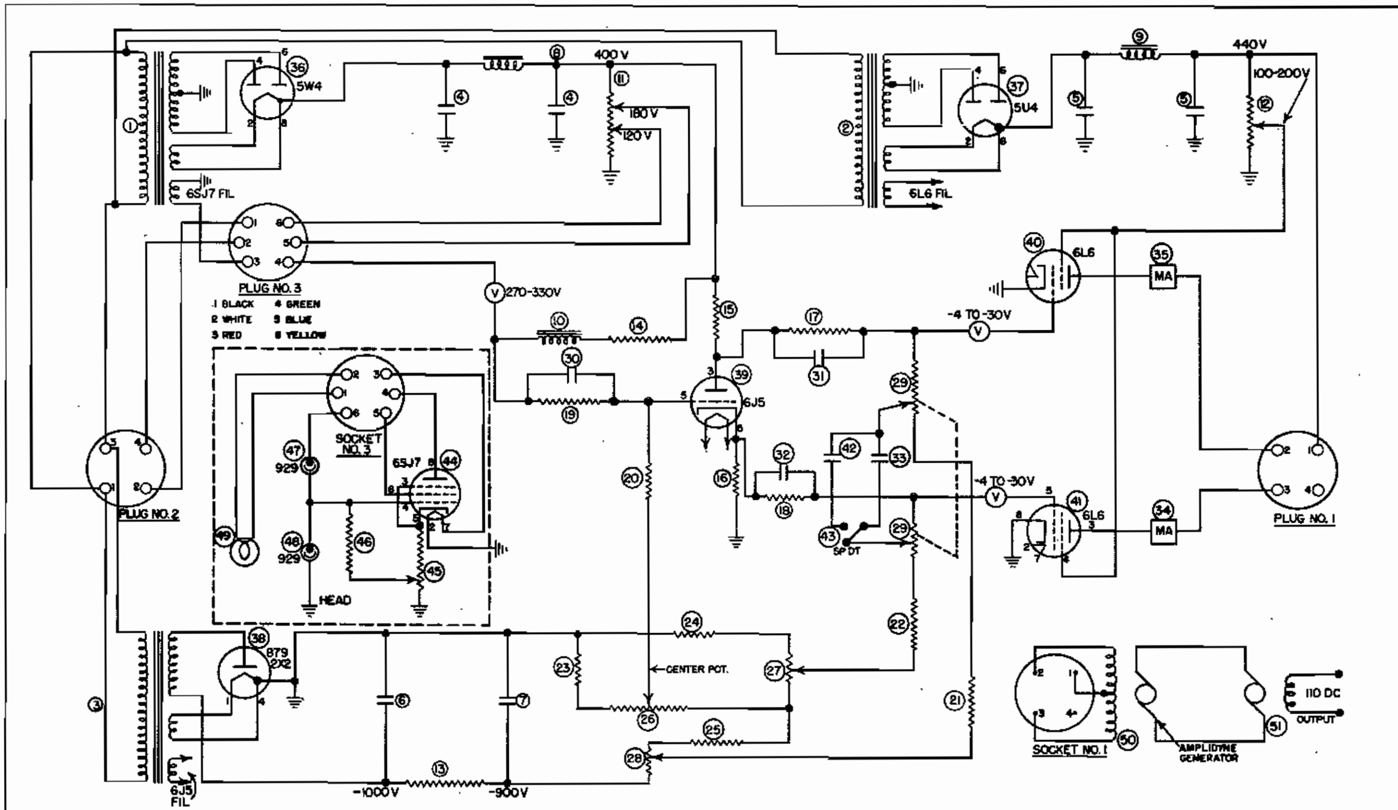


DWG NO. 14
SCHEMATIC DIAGRAM TO SHOW THE FUNCTIONING
OF THE ELECTRICAL SYSTEM AT INTEGRATOR POSITIONS



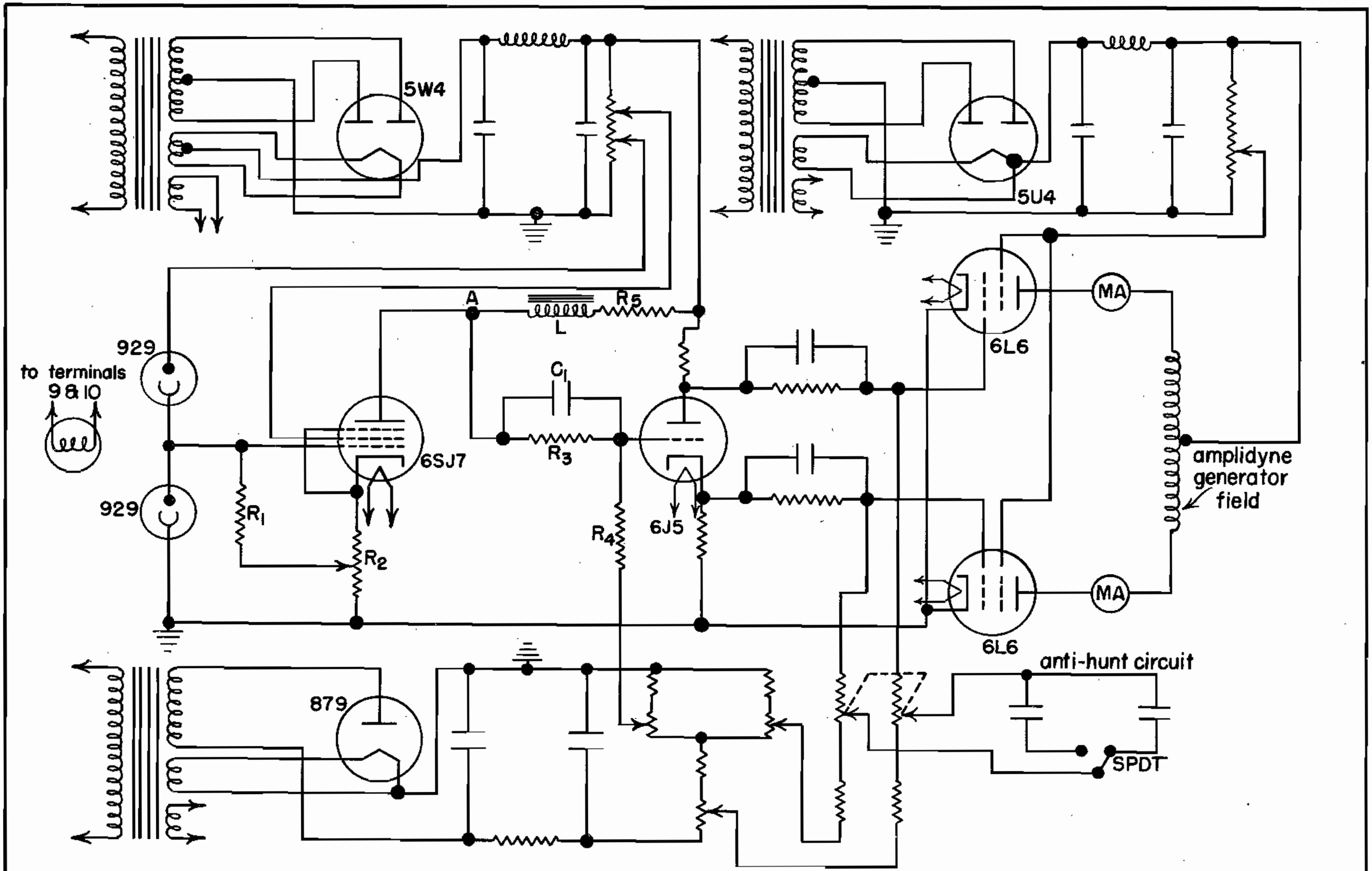
DWG NO. 15

BLOCK DIAGRAM—SERVO MECHANISM

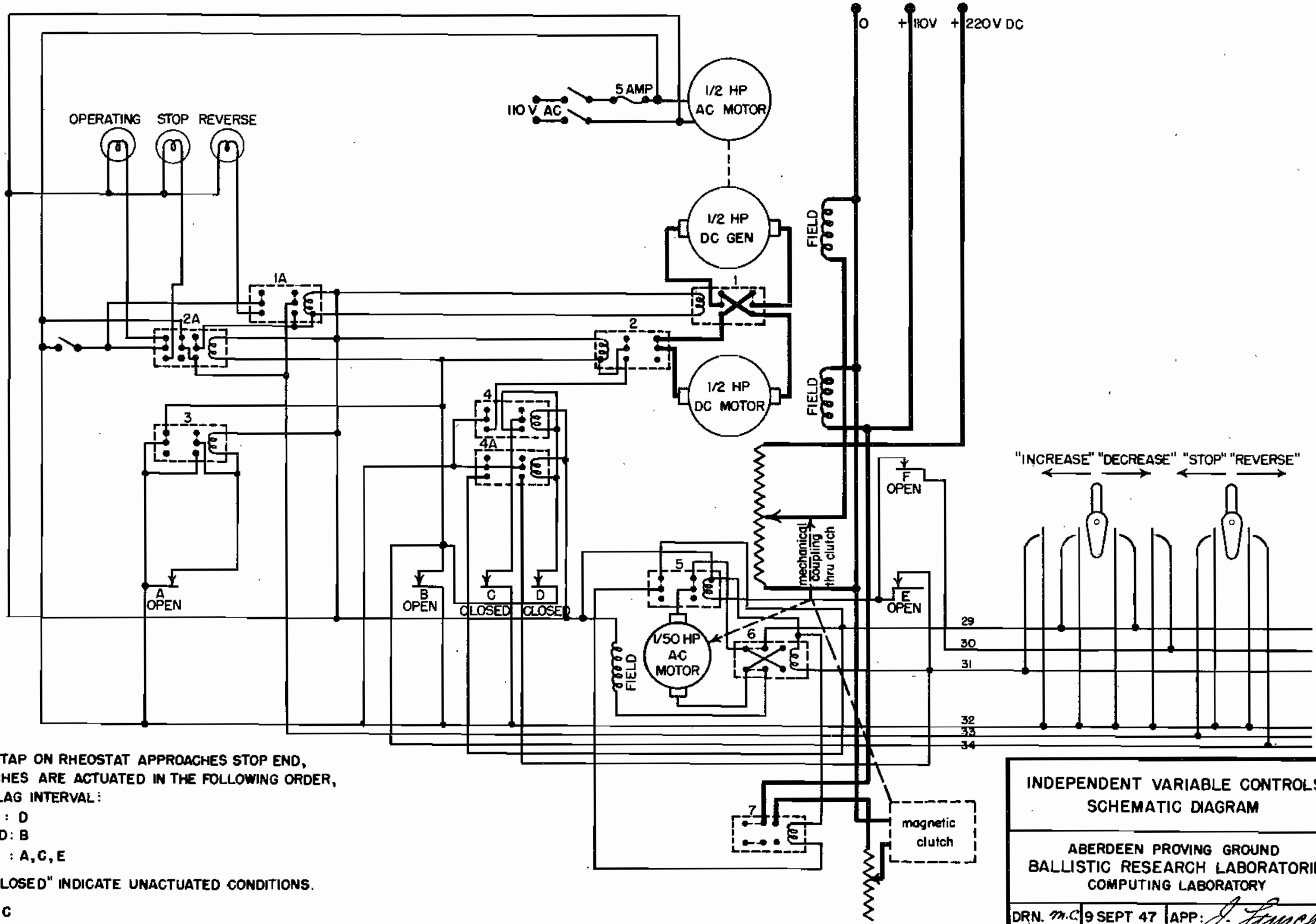


DWG NO. 16
WIRING DIAGRAM OF AMPLIFIER

1	STANCOR 6010 TRANSFORMER
2	" 6010 "
3	THORDARSON 92R33 TRANSFORMER
4	CORNELL DUBLIER 20 MFD ELECTROLYTIC CONDENSER
5	" " " " "
6	" " 1 MFD 1000 V CONDENSER
7	" " " " " "
8	STANCOR VPR-1 CHOKE
9	" " -2 "
10	" 37G36 AUDIO REACTOR
11	20,000 Ω, 50 WATT ADJUSTABLE BLEEDER RESISTOR
12	" " " " " "
13	150,000 Ω, 2 WATT CARBON RESISTOR
14	10,000 Ω, " " " "
15	25,000 Ω, " " " "
16	" " " " "
17	1 MEGOHM PRECISION WIRE WOUND RESISTOR
18	" " " " "
19	" " " " "
20	2.2 " " " " "
21	2.15 " " " " "
22	2.05 " " " " "
23	0.55 " " " " "
24	0.55 " " " " "
25	0.15 " " " " "
26	100,000 Ω MALLORY E 100 MP POTENTIOMETER
27	" " " "
28	50,000 Ω " E 50 MP "
29	1.0 MEGOHM DOUBLE "
30	0.01 MFD 400V PAPER CONDENSER
31	" " " " "
32	" " " " "
33	0.03 MFD " " "
34	50 MILLIAMPERE METER
35	" " "
36	5W4 RECTIFIER TUBE
37	5U4 " "
38	879/2X2 RECTIFIER TUBE
39	6J5 TRIODE TUBE
40	6L6 BEAM POWER TUBE
41	6L6 " " "
42	1.0 MFD 400 V PAPER CONDENSER
43	DOUBLE THROW, SINGLE POLE SWITCH
44	6SJ7
45	10,000 Ω POTENTIOMETER
46	10 MEG, 2 WATT RESISTOR
47	929 PHOTOTUBE
48	" "
49	MAZDA TYPE C6, 4 AMPS, 8.5V EXCITER LAMP
50	GE AMPLIDYNE MOTOR GENERATOR
51	GE DC MOTOR - TYPE BC



DWG NO. 17
SIMPLIFIED DIAGRAM OF AN AMPLIFIER AND SERVO-FOLLOWER



NOTES:

AS DRIVEN TAP ON RHEOSTAT APPROACHES STOP END, LIMIT SWITCHES ARE ACTUATED IN THE FOLLOWING ORDER, WITH 1/16" LAG INTERVAL:

- FIRST : D
- SECOND : B
- THIRD : A, C, E

"OPEN" & "CLOSED" INDICATE UNACTUATED CONDITIONS.

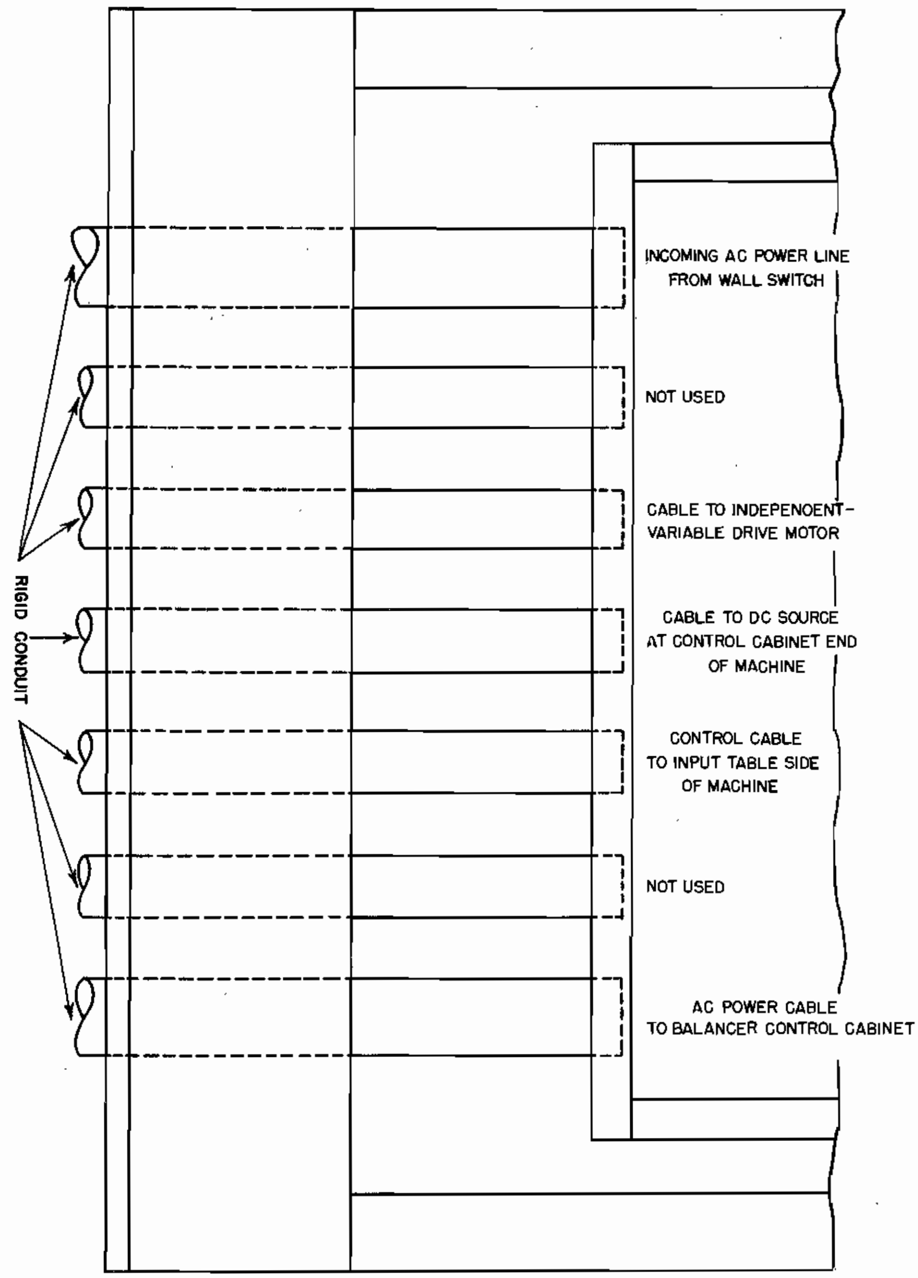
——— AC

━━━ DC

INDEPENDENT VARIABLE CONTROLS SCHEMATIC DIAGRAM

ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY

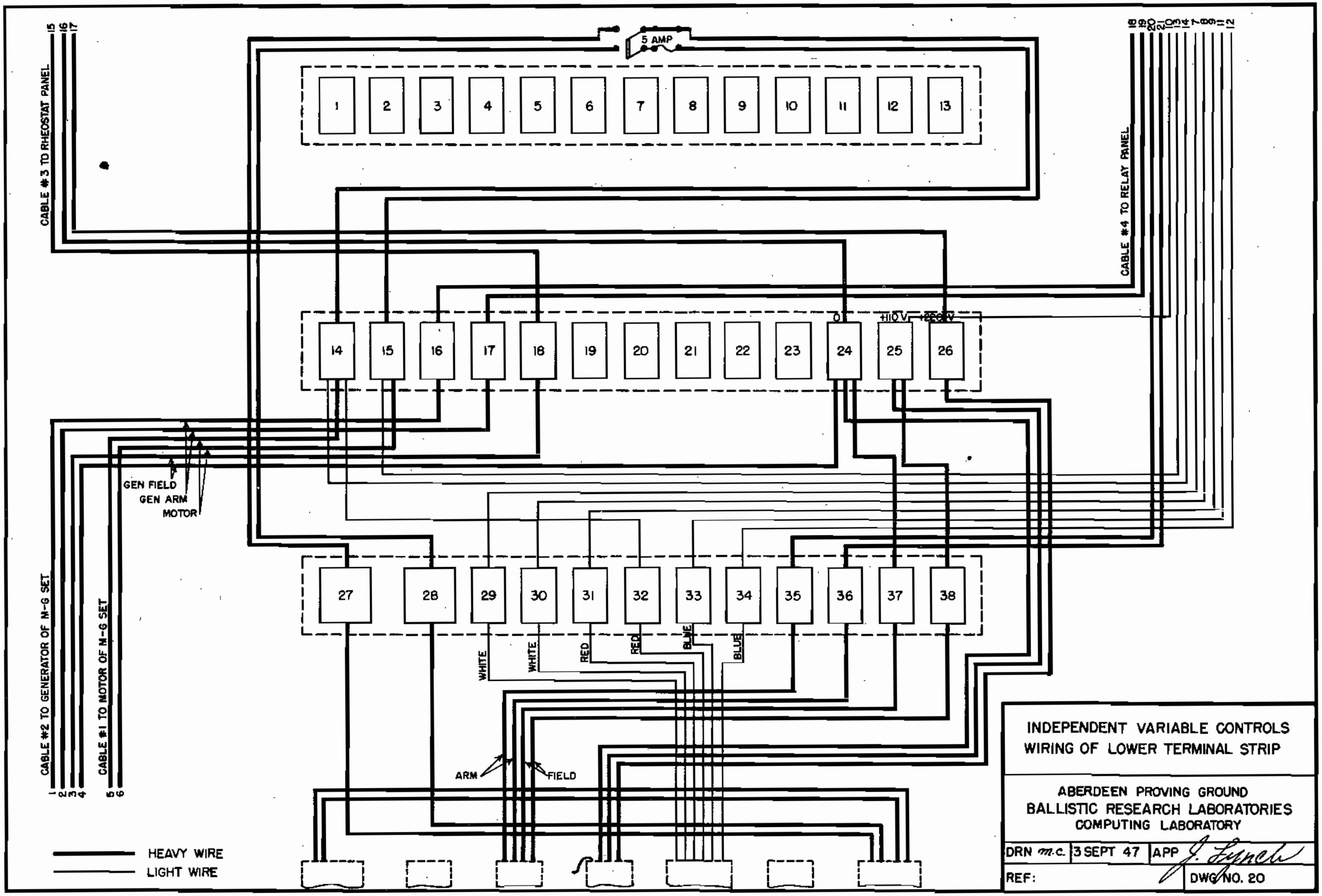
DRN. M.C.	9 SEPT 47	APP: J. Lynch
REF:		DWG NO. 18

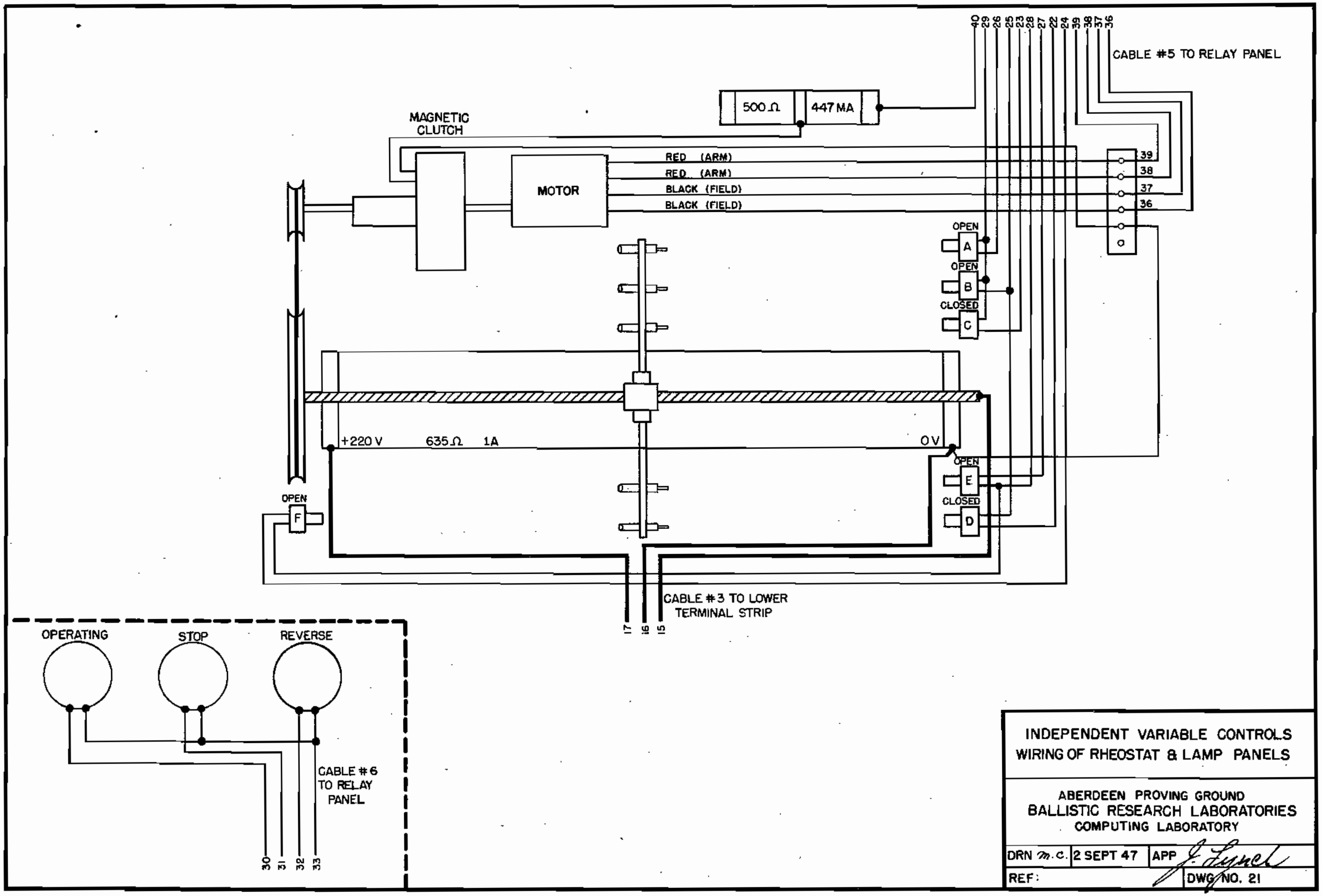


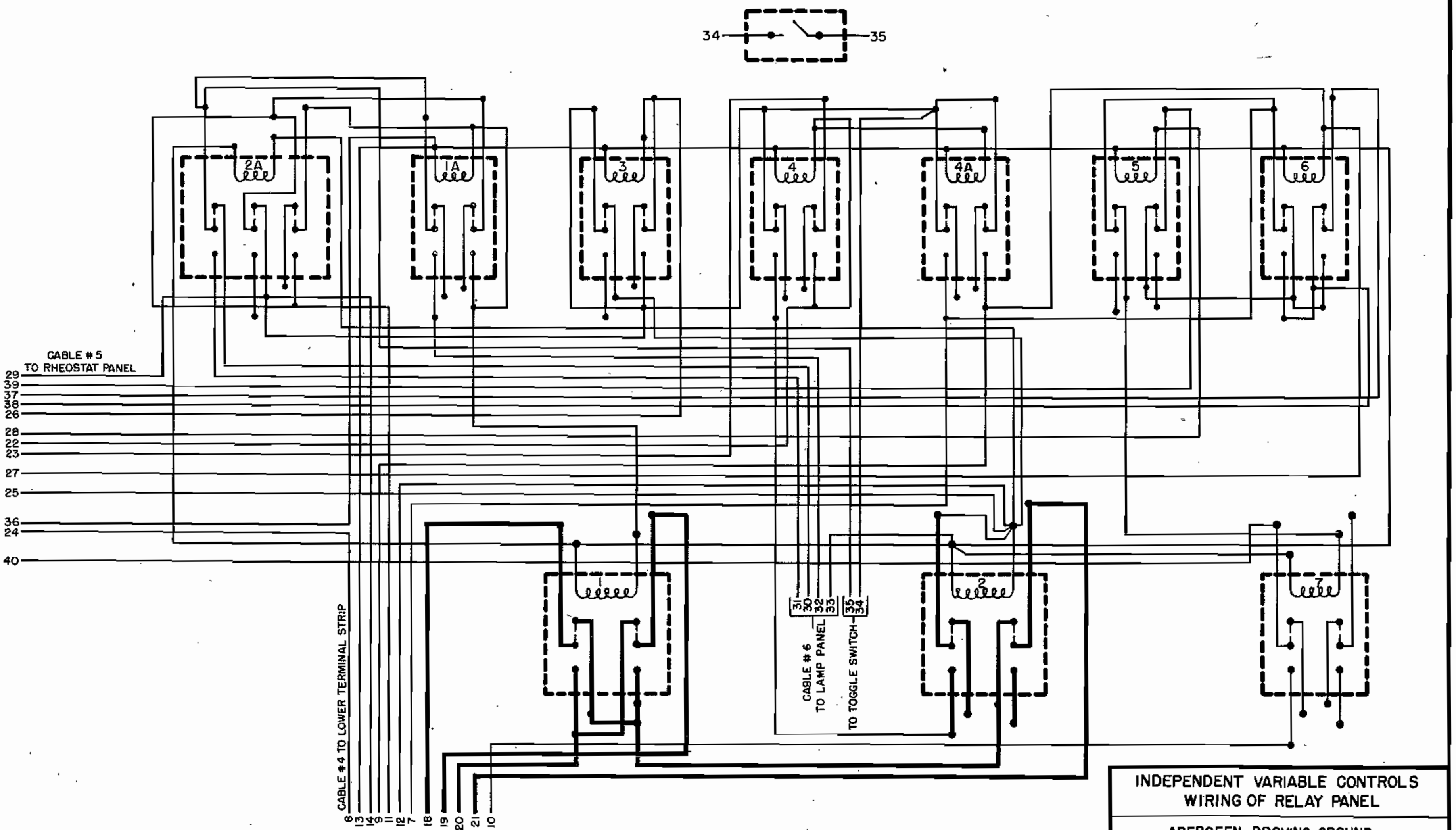
INDEPENDENT VARIABLE CONTROLS
BASE OF CONTROL PANEL

ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY

DRN *ma*	28 AUG 47	APP *[signature]*	
REF:			DWG NO. 19


5 AMP
1 2 3 4 5 6 7 8 9 10 11 12 13
14 15 16 17 18 19 20 21 22 23 24 25 26
27 28 29 30 31 32 33 34 35 36 37 38
110V 220V
CABLE #3 TO RHEOSTAT PANEL
CABLE #4 TO RELAY PANEL
CABLE #2 TO GENERATOR OF M-G SET
CABLE #1 TO MOTOR OF M-G SET
GEN FIELD
GEN ARM
MOTOR
WHITE
WHITE
RED
RED
BLUE
BLUE
ARM
FIELD
HEAVY WIRE
LIGHT WIRE
INDEPENDENT VARIABLE CONTROLS
WIRING OF LOWER TERMINAL STRIP
ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY
DRN m.c. 3 SEPT 47 APP J. Lynch
REF:
DWG NO. 20

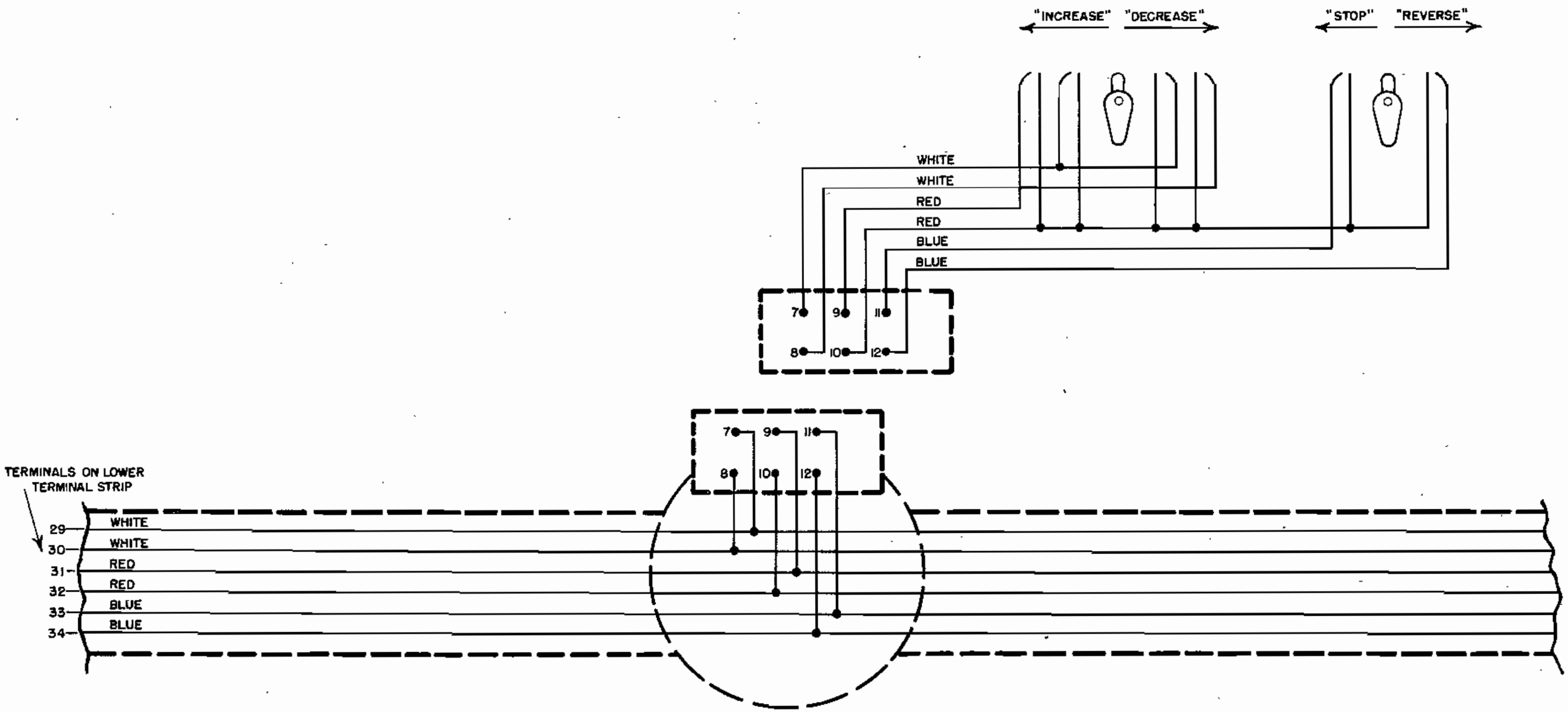

CABLE #5 TO RELAY PANEL
40 29 26 25 23 28 27 22 24 39 38 37 36
500 Ω
447 MA
MAGNETIC CLUTCH
MOTOR
RED (ARM)
RED (ARM)
BLACK (FIELD)
BLACK (FIELD)
39
38
37
36
OPEN
A
OPEN
B
CLOSED
C
+220 V
635 Ω
1A
0 V
OPEN
E
CLOSED
D
OPEN
F
CABLE #3 TO LOWER TERMINAL STRIP
17 16 15
OPERATING
STOP
REVERSE
CABLE #6 TO RELAY PANEL
30 31 32 33
INDEPENDENT VARIABLE CONTROLS
WIRING OF RHEOSTAT & LAMP PANELS
ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY
DRN M.C.
2 SEPT 47
APP
REF:
DWG NO. 21



INDEPENDENT VARIABLE CONTROLS
WIRING OF RELAY PANEL

ABEROEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY

DRN m.c.	5 SEPT 47	APP: J. Lynch
REF:		DWG NO. 22

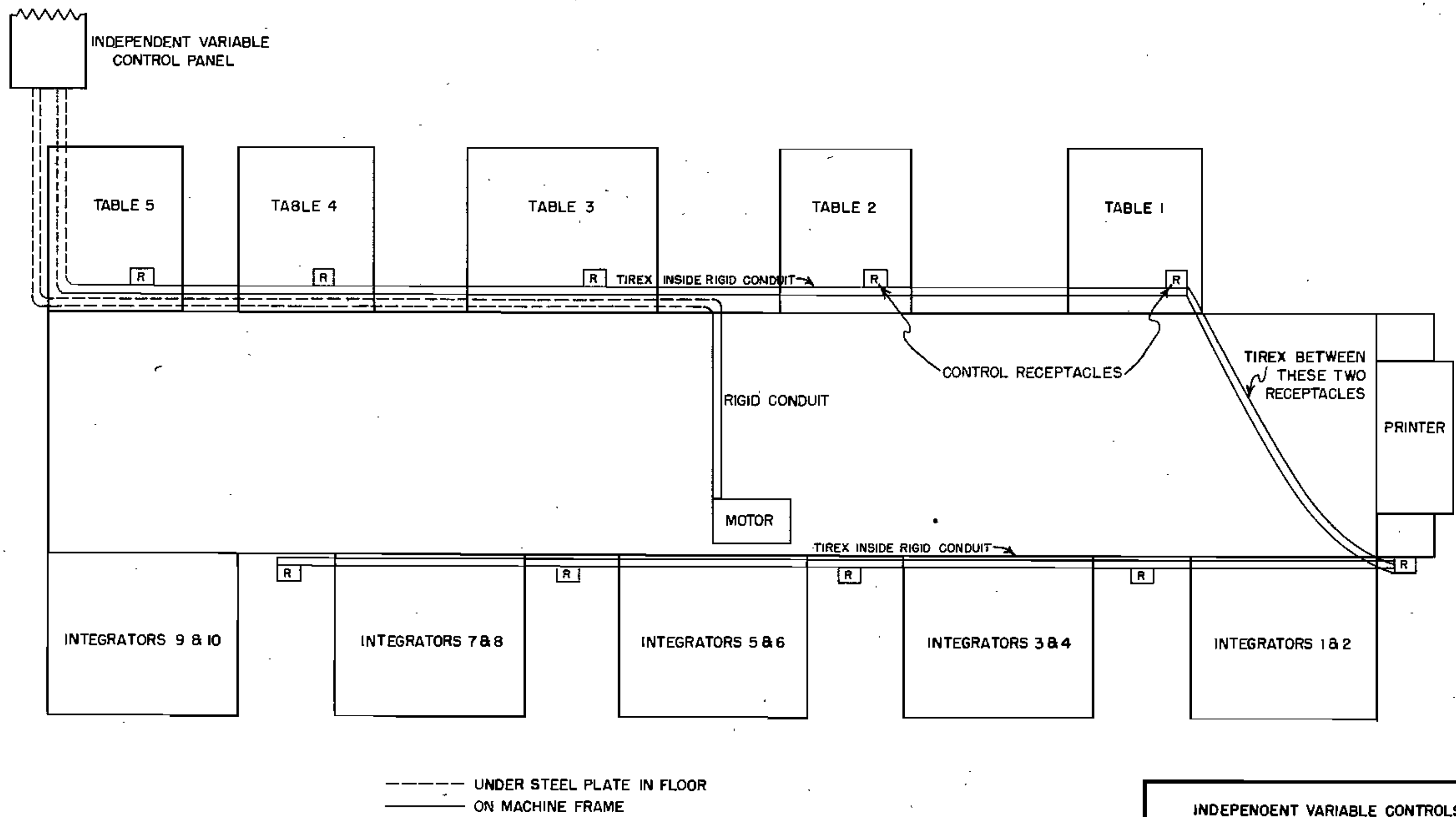


INDEPENDENT VARIABLE CONTROLS
CONTROL SWITCH & RECEPTACLE WIRING

ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY

DRN. m.c. 28 AUG. 47 APP J. Lynch

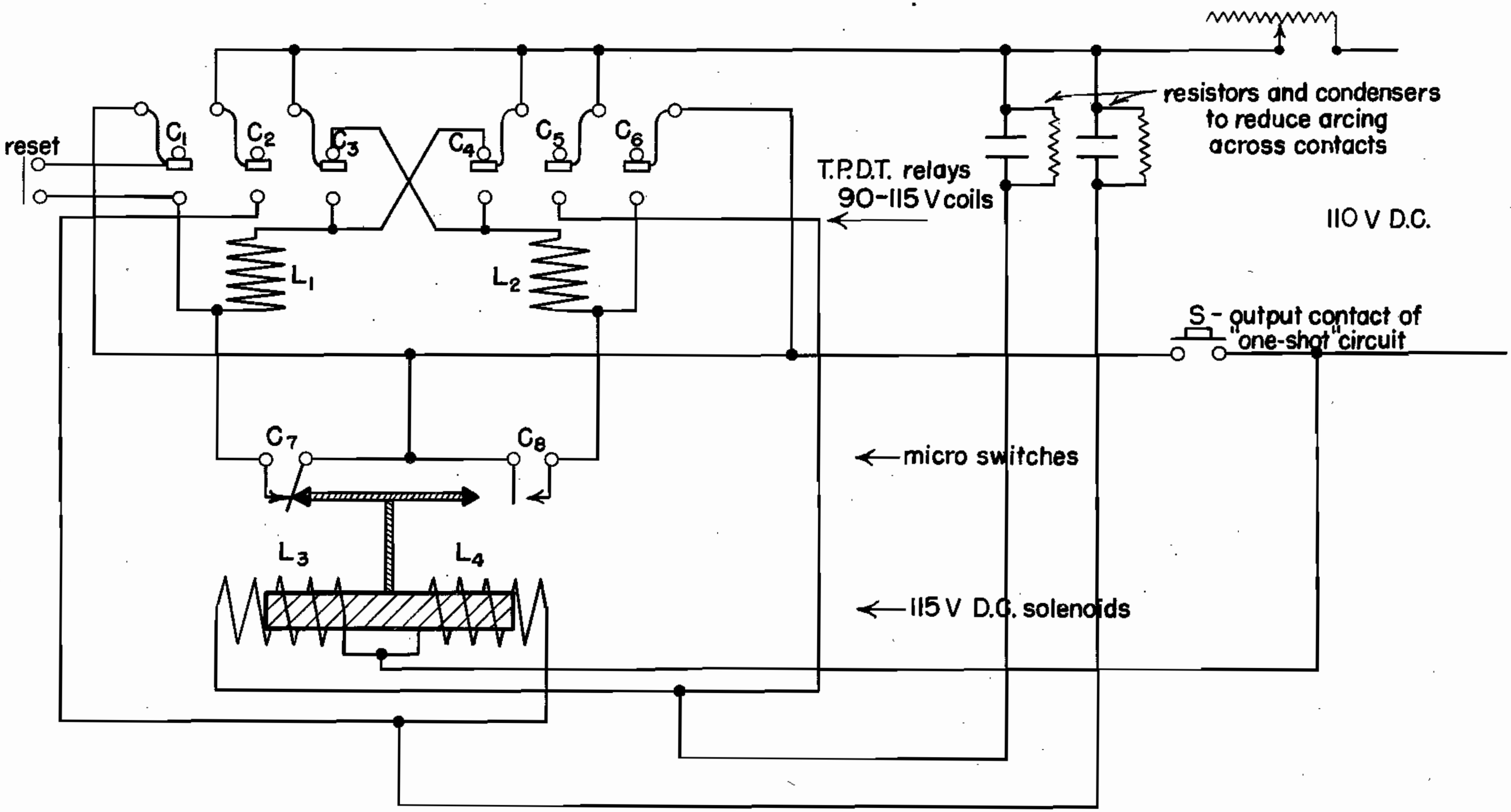
REF: DWG NO. 23



INDEPENOENT VARIABLE CONTROLS
CONDUIT FOR MOTOR & CONTROL RECEPTACLES

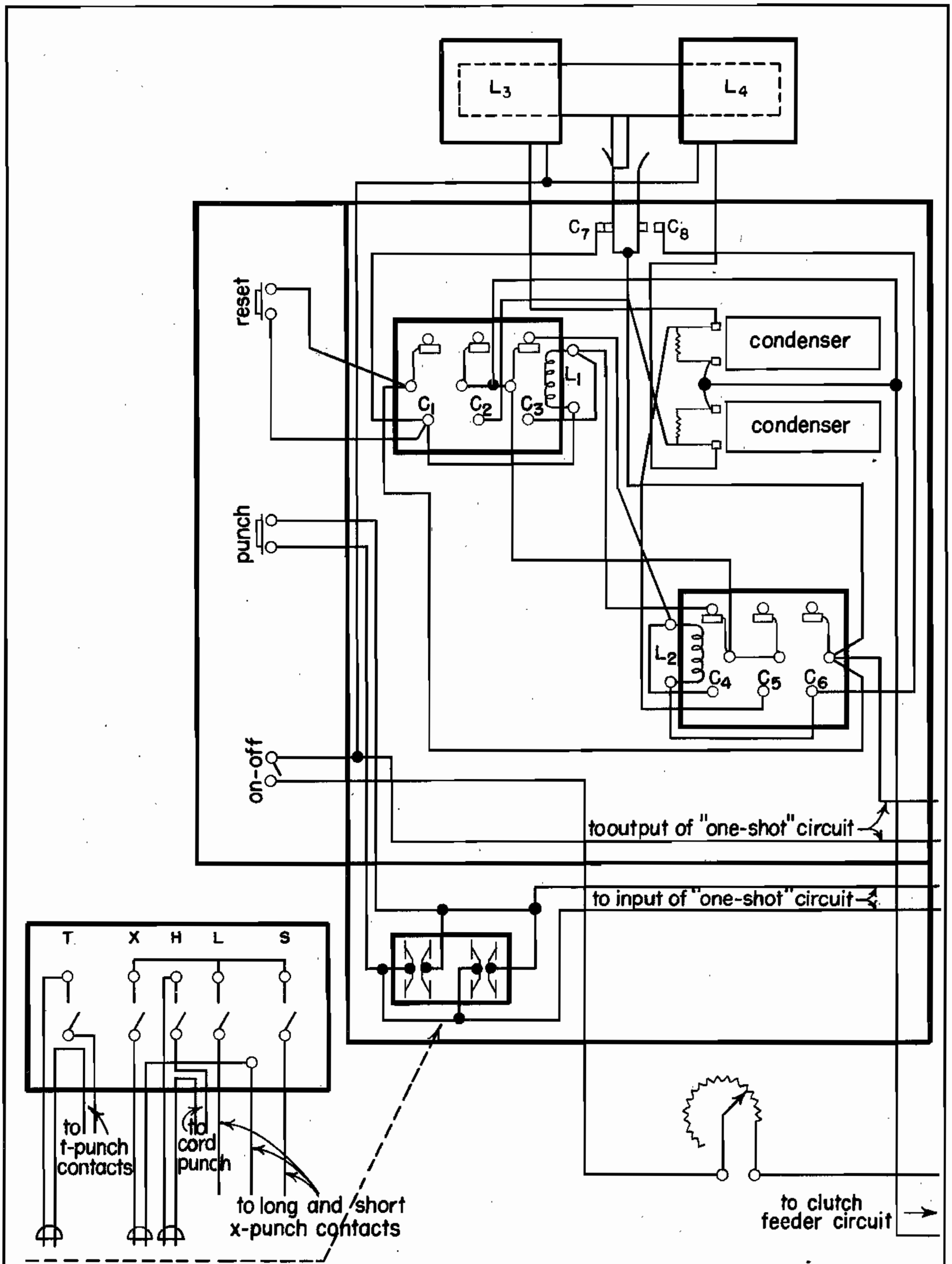
ABERDEEN PROVING GROUND
BALLISTIC RESEARCH LABORATORIES
COMPUTING LABORATORY

DRN m.c.	28 AUG 47	APP J. Lynch
REF:		DWG NO. 24



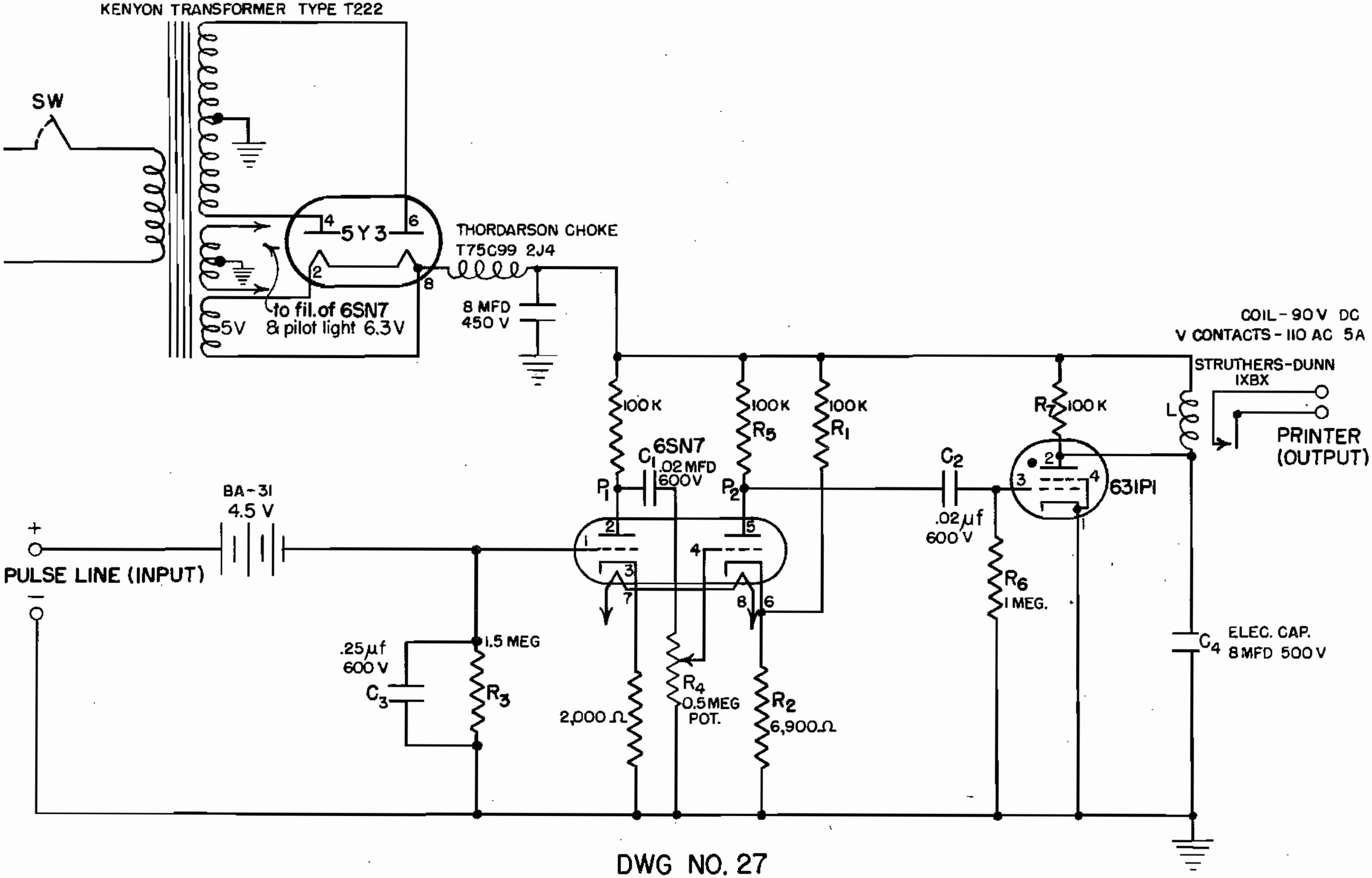
DWG NO. 25

PUSH-BUTTON CONTROL FOR PRINTER OF DIFFERENTIAL ANALYZER



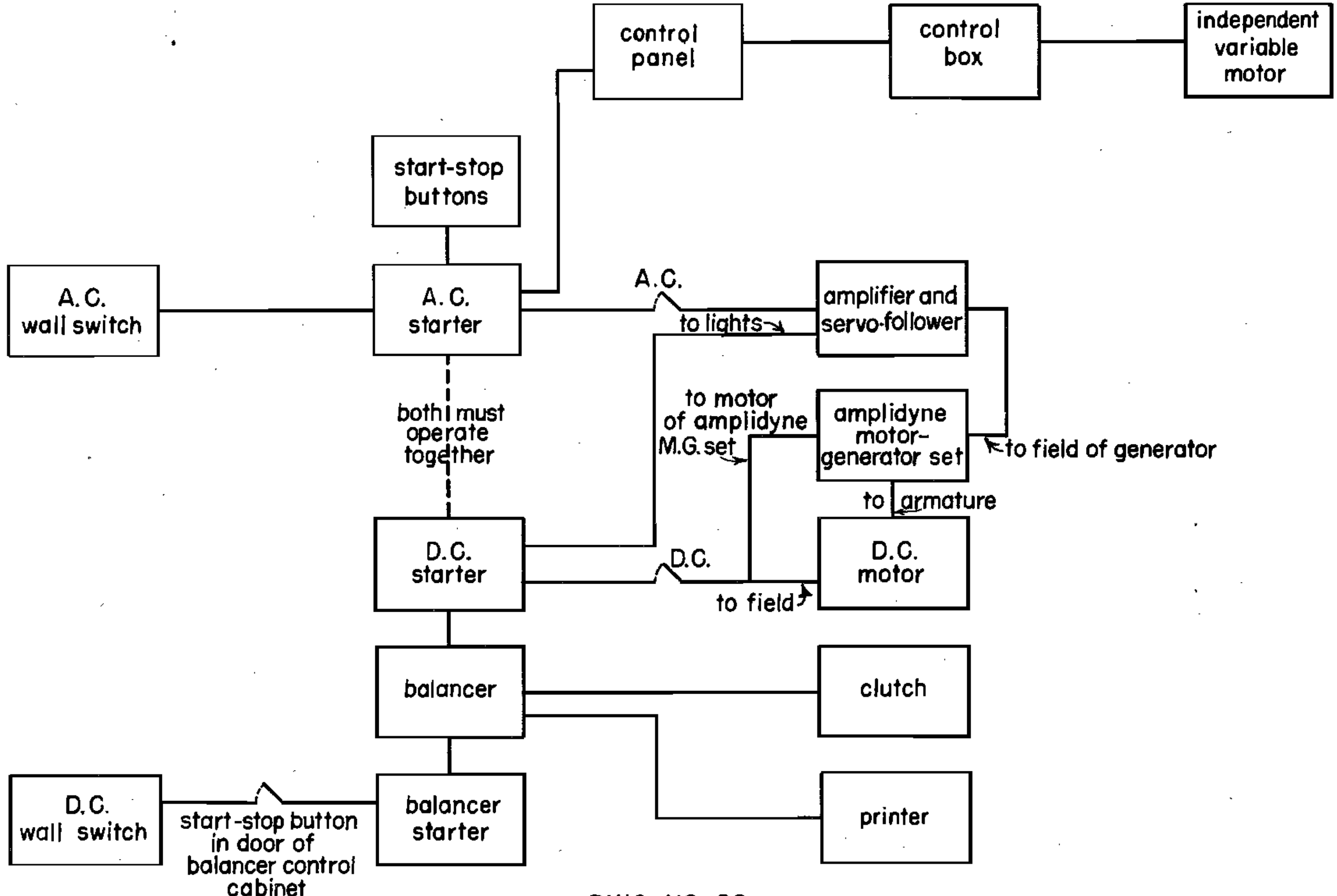
DWG NO. 26

LAYOUT DIAGRAM OF PRINTER CIRCUIT



DWG NO. 27

"ONE-SHOT" CIRCUIT, DIFFERENTIAL ANALYZER PRINTER



DWG NO. 28

SCHEMATIC DIAGRAM OF POWER RELATIONSHIPS ON THE DIFFERENTIAL ANALYZER

DISTRIBUTION LIST

No. of Copies		No. of Copies	
2	ORDTB - Bal Sec		
5	British (of interest to: Mr. J. R. Womersley National Physical Lab. Teddington, Middlessex, England) Dr. F. R. S. Hartree Cambridge University Cambridge, England	1	Prof. A. A. Bennett Brown University Providence, R. I.
		1	Prof. J. G. Brainerd, Moore School of Electrical Engineering University of Pennsylvania Philadelphia, Pa.
4	Chief, Bureau of Ordnance Navy Department Washington 25, D. C. ATTN: Re3	2	National Bureau of Standards Washington, D. C. Attn: Dr. J. H. Curtiss
1	Office of Naval Research Navy Department Washington, D. C.	2	Massachusetts Institute of Technology Cambridge, Mass. Attn: Prof. S. H. Caldwell
2	Director, Naval Ordnance Laboratory Washington, D. C.	2	General Electric Company 1 River Road Schenectady, N. Y. Attn: Mr. P. L. Alger
1	Commanding Officer Naval Ordnance Test Station Inyokern, California		
1	Commanding Officer Naval Proving Ground Dahlgren, Virginia		