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OPERATION MANUAL FOR THE AIR COMP MOD 4 ELECTRONIC DIFFERENTIAL ANALYZER

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OPERATION MANUAL FOR AIR COMP MOD 4 ELECTRONIC DIFFERENTIAL ANALYZER

1. General Description of Computer

The Air Comp Mod 4 Computer is an electronic differential analyzer designed and built for the Office of Naval Research by the Department of Aeronautical Engineering, University of Michigan. The computer is capable of solving linear ordinary differential equations up to sixth order and having variable coefficients. The physical equipment making up the computer consists of the following units:

a) Relay Rack No. 1: 10 drift-stabilized operational amplifiers, including 6 integrators.

b) Relay Rack No. 2: 17-digit, 25-step, variable coefficient selector.

c) Relay Rack No. 3: d-c power supplies, including electronically regulated supplies of +300, +100, -100, -190, and -350 volts, and an unregulated 28-volt d-c supply.

d) Recording galvenometer cart, including a Sanborn Model 60 1300 2-channel recorder, and 2 electronic amplifiers.

Photographs of the above units are shown in Figures 1 and 2. Detailed descriptions, circuit diagrams, and theory of operation of the various units are presented in the following sections.

Power inputs required for the Air Comp Mod 4 Electronic Differential Analyzer are 110-120 volts, 60 cycle ac (about 1500 watts), and 12 volts dc regulated at 15 amps. It is recommended that the 60-cycle input also be regulated.

Figure 1. Front View of Computer.

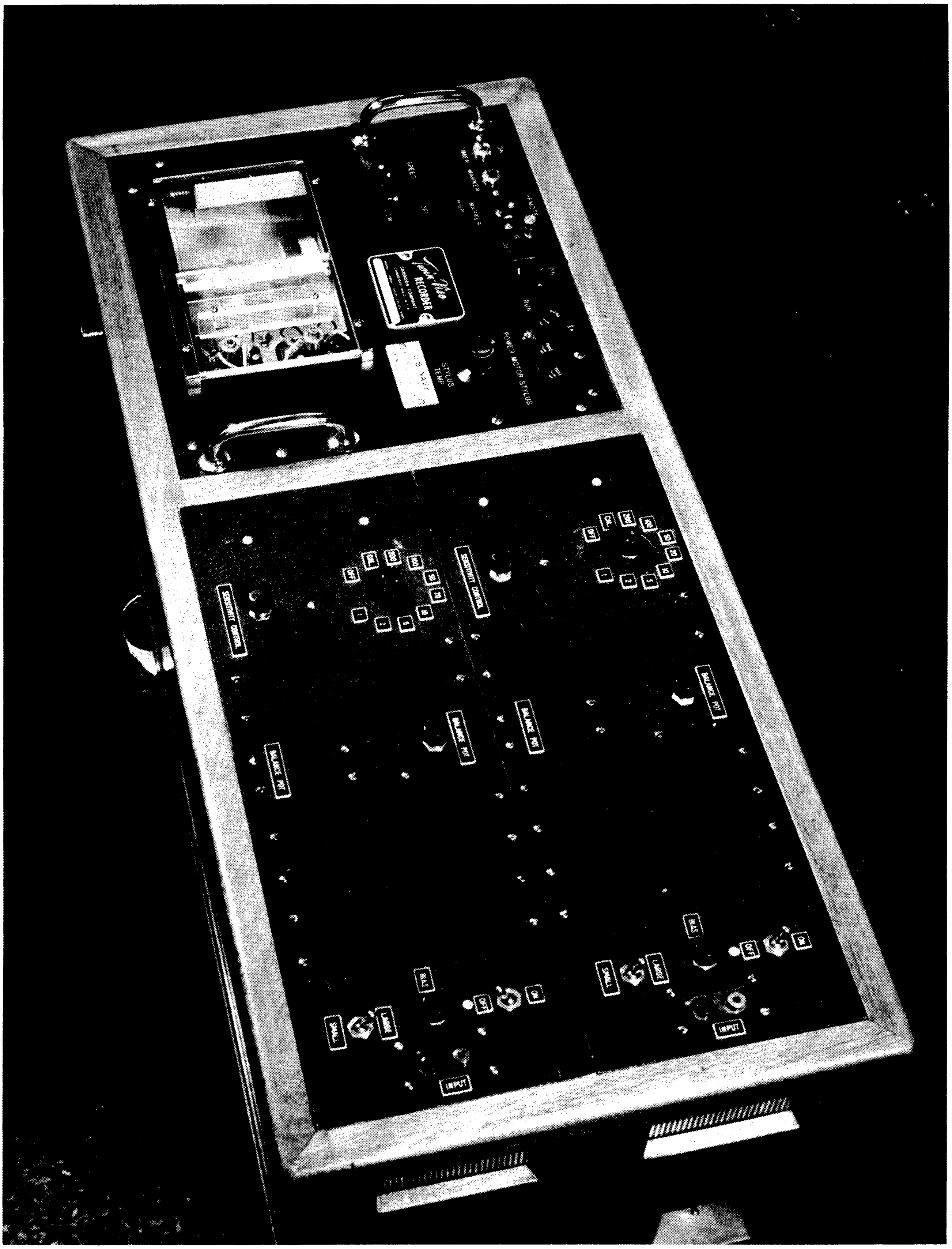

Figure 2. Recording Galvanometer Cart.

2. Operational Amplifiers and Associated Circuits

Relay rack No. 1 consists of ten drift stabilized operational amplifiers and associated circuits. A front view of the rack is shown in Figure 1; a rear view is shown in Figure 3.

As is evident from the photographs, the ten operational amplifiers plug into the backs of the three amplifier panels, each panel having provision for four amplifiers. The amplifier panels furnish the operational amplifiers with the various voltages required for amplifier operation. Also located on the back of the amplifier panels are reset and hold relays. On the front of the panels are the patch boards into which the computer components can be plugged The circuits of the amplifier panel are described in Section 2.3.

Two panels containing 64 toggle switches each can also be seen in Figure 1. These panels are used to provide any desired resistance up to 16 megohms in 0.001 megohm steps. They are discussed in detail in Section 2.4.

At the bottom of relay rack No. 1 is the panel containing the relays and patch connections for the variable coefficient selector. Circuits and descriptions are given in Section 3.

2.1 Theory of D-C Operational Amplifiers

a) Derivation of Fundamental Equations.

The basic unit of the electronic differential analyzer is the operational amplifier, shown schematically in Figure 4. It consists of a d-c amplifier having a gain $-\mu$, an input impedance Z_i, and a feedback impedance Z_f. The input voltage to the d-c amplifier proper is ϵ' and its output voltage is e_o. If we neglect any current into the d-c amplifier (it is usually less than 10^{-10} amps), then the currents through input and feedback impedances must be equal. Thus by ohms law

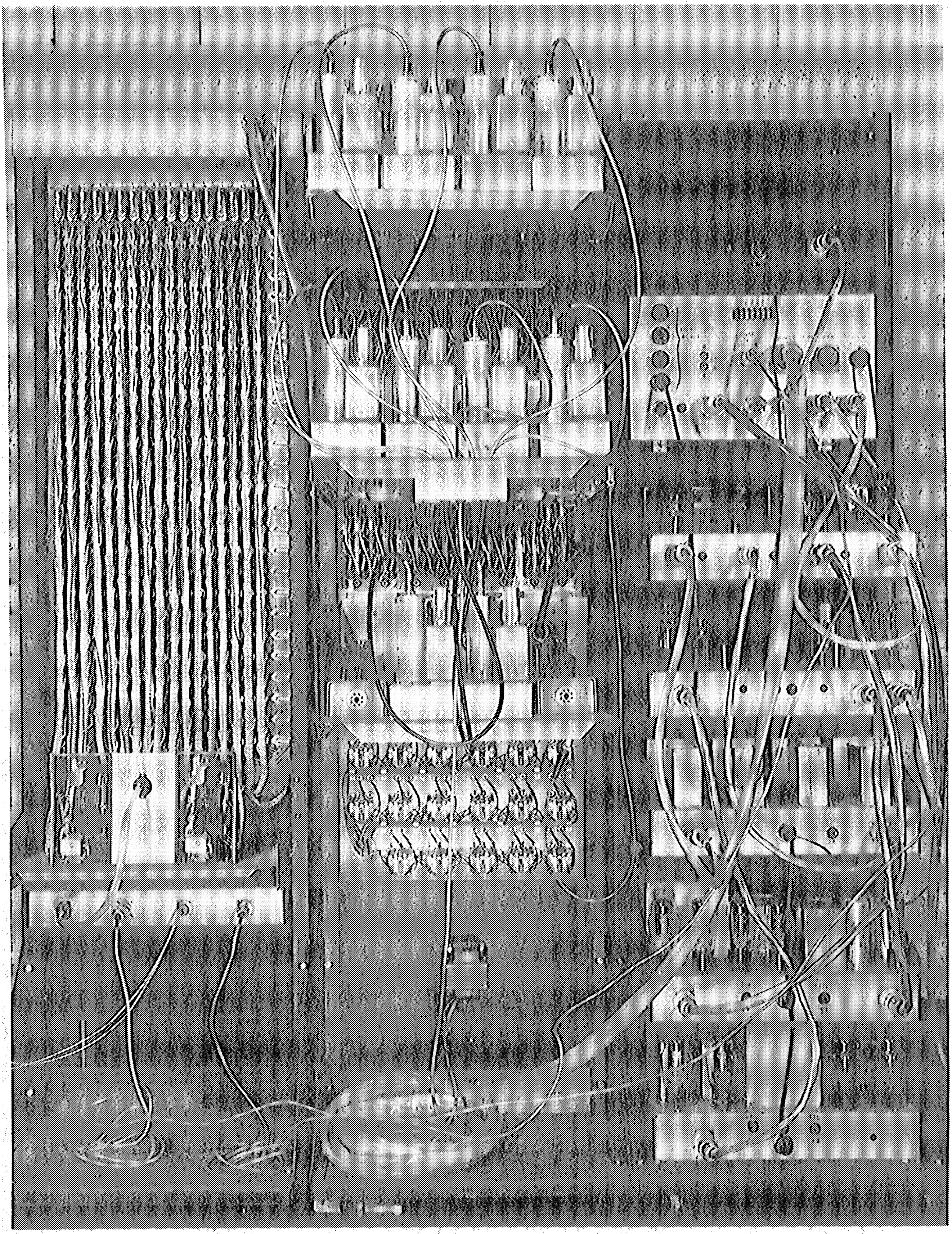

Figure 3. Rear View of Computer.

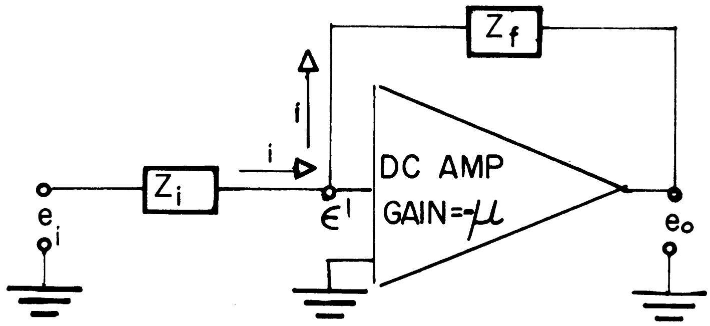

Figure 4. Operational Amplifier.

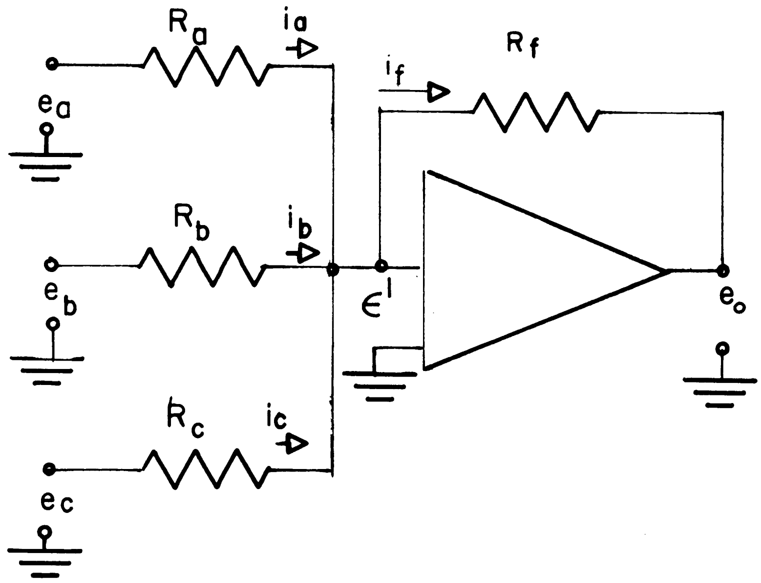

Figure 5. Operational Amplifier for Summation.

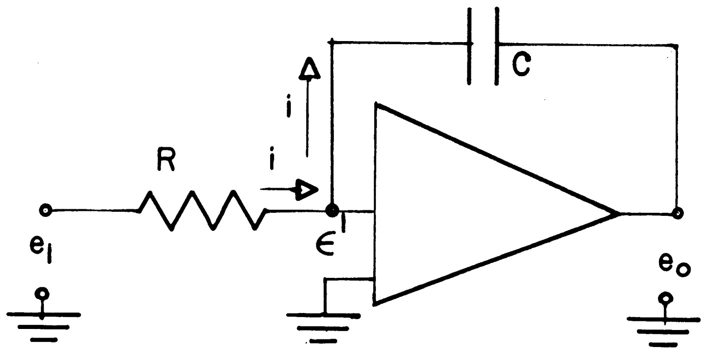

Figure 6. Operational Amplifier for Integration.

$$\frac{e_1 - \epsilon'}{Z_i} = \frac{\epsilon' - e_o}{Z_f} \qquad (1)$$

where e_i is the input voltage to the operational amplifier. But by definition $\mu\epsilon' = -e_o$, so that we can solve equation (1) for e_o, obtaining

$$e_o = \frac{-\frac{Z_f}{Z_i}}{1 + \frac{1}{\mu}\left(1 + \frac{Z_f}{Z_i}\right)} e_i \qquad (2)$$

For the amplifier gain $>> 1+Z_f/Z_i$, equation (2) reduces to

$$e_o = -\frac{Z_f}{Z_i} e_i \qquad (3)$$

which is the fundamental equation governing the behavior of the operational amplifier. For Z_i and Z_f resistors, we can multiply any voltage e_i by a constant K by making the ratio of feedback to input resistance equal to K. The output voltage e_o will be $-Ke_i$, as required, except for a sign reversal.

By employing several input resistors R_a, R_b, and R_c with a single feedback resistor R_f, the operational amplifier can be used to sum input voltages e_a, e_b, and e_c. Thus in Figure 5 currents $i_a + i_b + i_c = i_f$ and by ohms law

$$\frac{e_a - \epsilon'}{R_a} + \frac{e_b - \epsilon'}{R_b} + \frac{e_c - \epsilon'}{R_c} = \frac{\epsilon' - e_o}{R_f} \qquad (4)$$

If we neglect ϵ' as small compared with e_a, e_b, e_c or e_o ($\epsilon' = -e_o/\mu$ where μ is very large), then equation (4) can be solved for e_o. Thus

$$e_o = -\frac{R_f}{R_a} e_a - \frac{R_f}{R_b} e_b - \frac{R_f}{R_c} e_c \qquad (5)$$

The output voltage e_o is the sum of the three input voltages e_a, e_b, and e_c, each multiplied respectively by the ratio of feedback to input resistance. Hence the operational amplifier can be used to multiply by constants and sum voltages.

Finally, consider the operational amplifier shown in Figure 6. Here the input impedance is a resistor R and the feedback a capacitor C. Again neglecting any current into the amplifier proper and assuming that ϵ' is negligibly small compared with e_i or e_o, we have

$$i = \frac{e_i}{R} \text{ and } - e_o = \frac{1}{C} \int i \, dt$$

from which

$$e_o = - \frac{1}{RC} \int e_i \, dt \qquad (6)$$

Thus the output voltage is proportional to the time integral of the input voltage. The constant of proportionality is 1/RC, and RC is known as the time constant of the integrator.

The manner in which operational amplifiers used for multiplication by a constant, summation, and integration can be combined to solve linear ordinary differential equations is described elsewhere.[1,2,3]

b) Stability Considerations.

We have seen that the behavior of the operational amplifier is described by equation (2), which can be rewritten as

$$e_o = \frac{-\mu \frac{Z_f}{Z_i}}{1 + \frac{Z_f}{Z_i} + \mu} e_i \qquad (7)$$

This is the usual form for the equation describing a feedback control system.[4] In general, the amplifier gain μ and impedances Z_i and Z_f are not constants, but include various time derivatives. Hence, equation (7) is really an equation of motion for the system. We can determine whether our closed-loop system will be stable by finding out whether it has any characteristic roots with positive real parts. But the characteristic roots will be the roots of the denominator in equation (7). To insure that these roots never have a positive real part, it is necessary that the gain versus frequency characteristic of the d-c ampli-fier does not exhibit a slope more negative than -12 db per frequency octave until the amplifier gain is well below unity (0 db). This will insure stable feedback amplifier operation for all possible combinations of input resistors and feedback resistors or capacitors. For example, the d-c gain μ of the Air Comp Mod 4 amplifiers is about 90 db (30,000). It is necessary to add capaci-tors to the d-c amplifier circuit so that at high frequencies the gain does not fall off faster than 12 db per frequency octave. In practice, a conservative fall-off of 6 db per octave is utilized, as can be seen in Figure 12.

c) Drift-Stabilized D-C Amplifiers

A d-c amplifier must be balanced so that with zero input the output voltage is zero. When a d-c amplifier circuit has been properly designed, this balance can usually be achieved by slight changes in the operating conditions of the first stage of vacuum-tube amplification. Once the amplifier has been balanced, subsequent changes in heater voltage, B voltages, ambient temperature, etc., may cause the amplifier to drift off of balance so that zero voltage in-put no longer gives zero voltage output. In order to reduce such zero drifts, a drift-free a-c amplifier can be added to the d-c amplifier, as shown in Figure 7. The additional a-c amplifier consists of a sychronous vibrator or chopper which converts the d-c input voltage ϵ' to an a-c signal (60 cycles in the Air Comp Mod 4 amplifier) the magnitude of which is proportional to ϵ'. This a-c signal is sent through an a-c amplifier and reconverted to d-c by

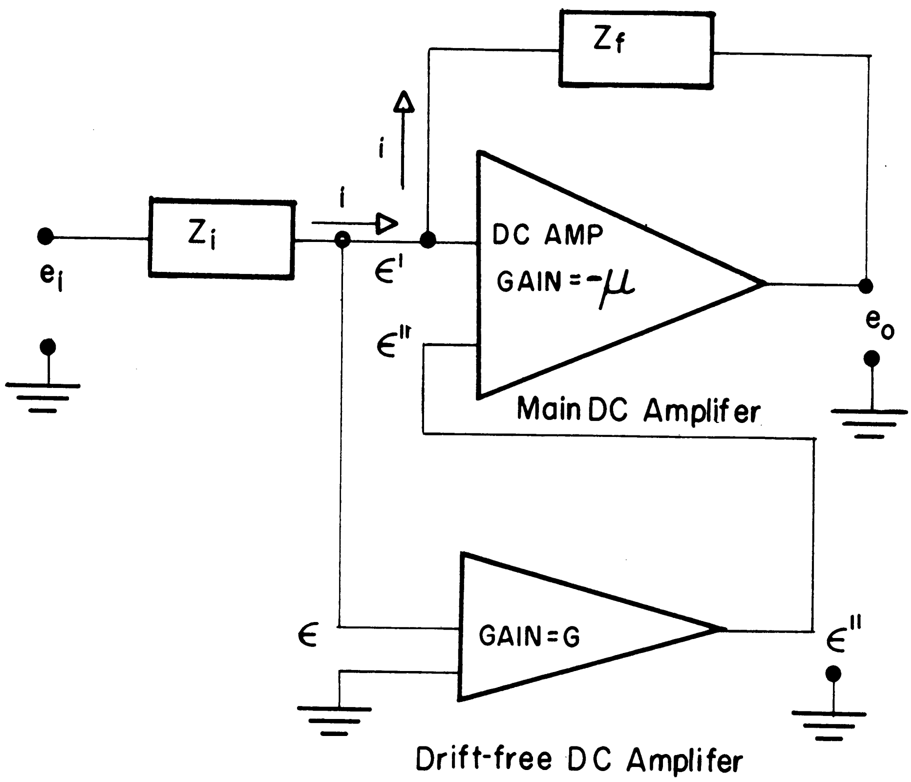

Figure 7. Drift-Stabilized DC Amplifier.

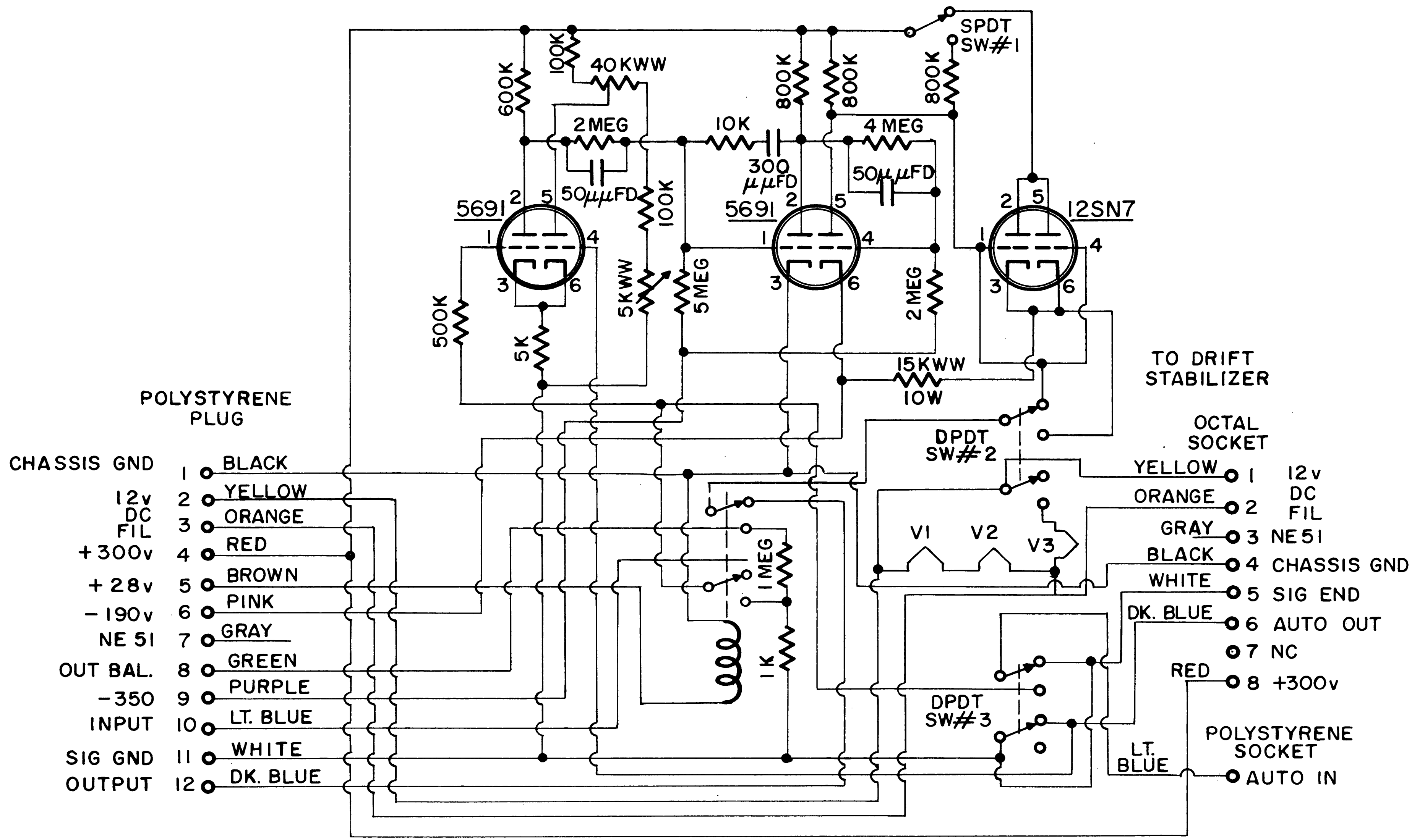

Figure 8. DC Amplifier for AIR COMP Model 4 Computer.

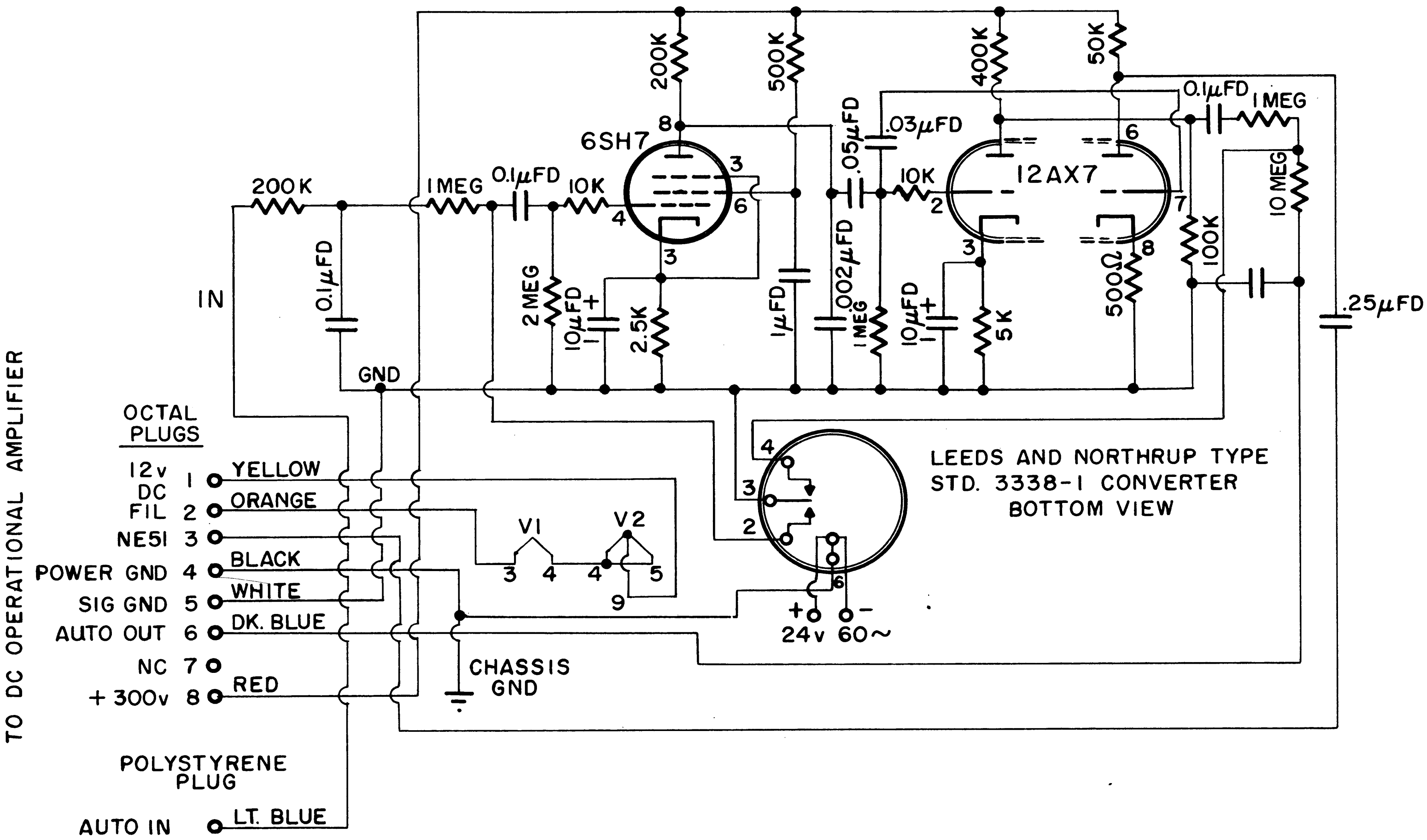

Figure 9. Drift Stabilizer for AIR COMP Model 4 Amplifiers.

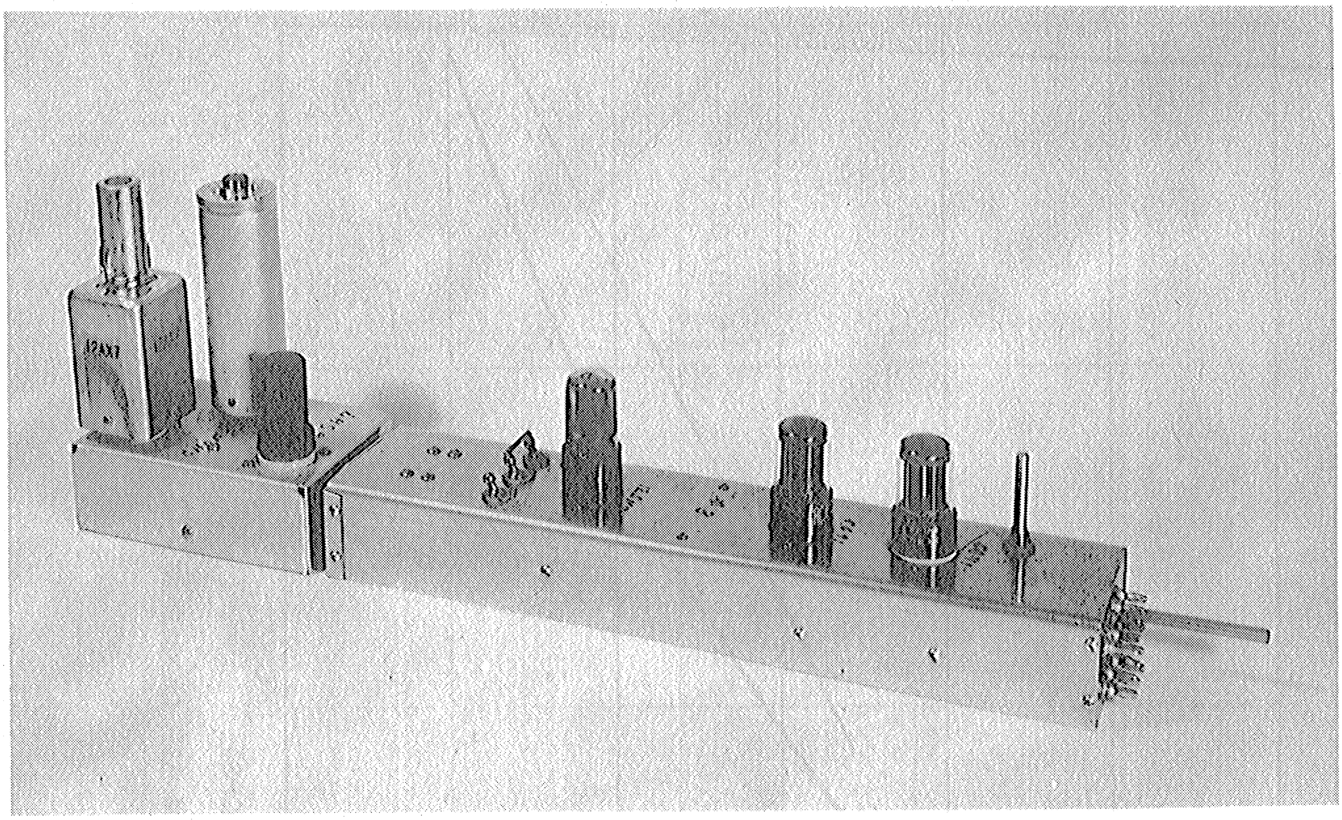

Figure 10. DC Amplifier and Drift Stabilizer.

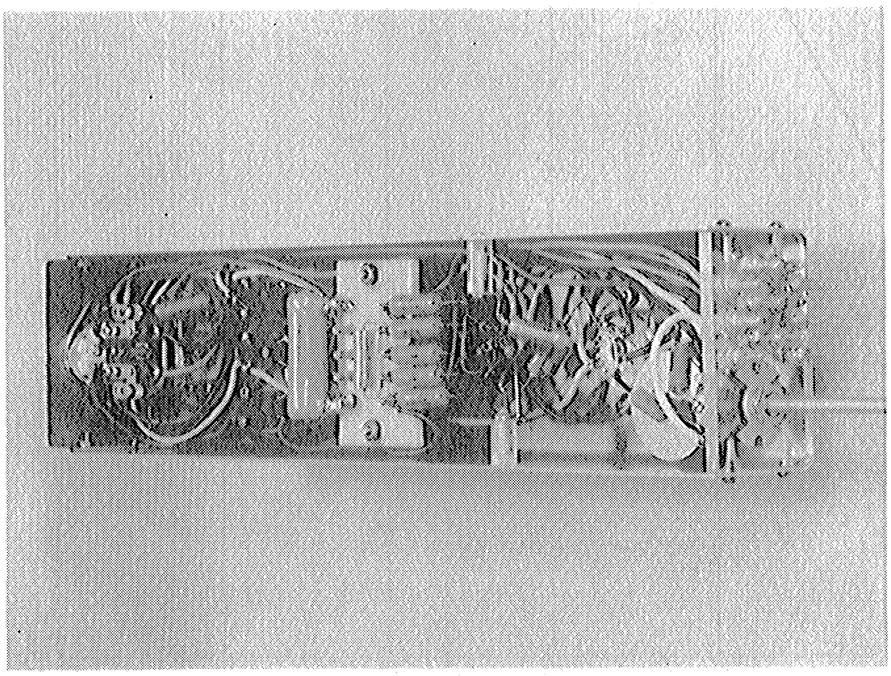

Figure 11. Bottom View of DC Amplifier.

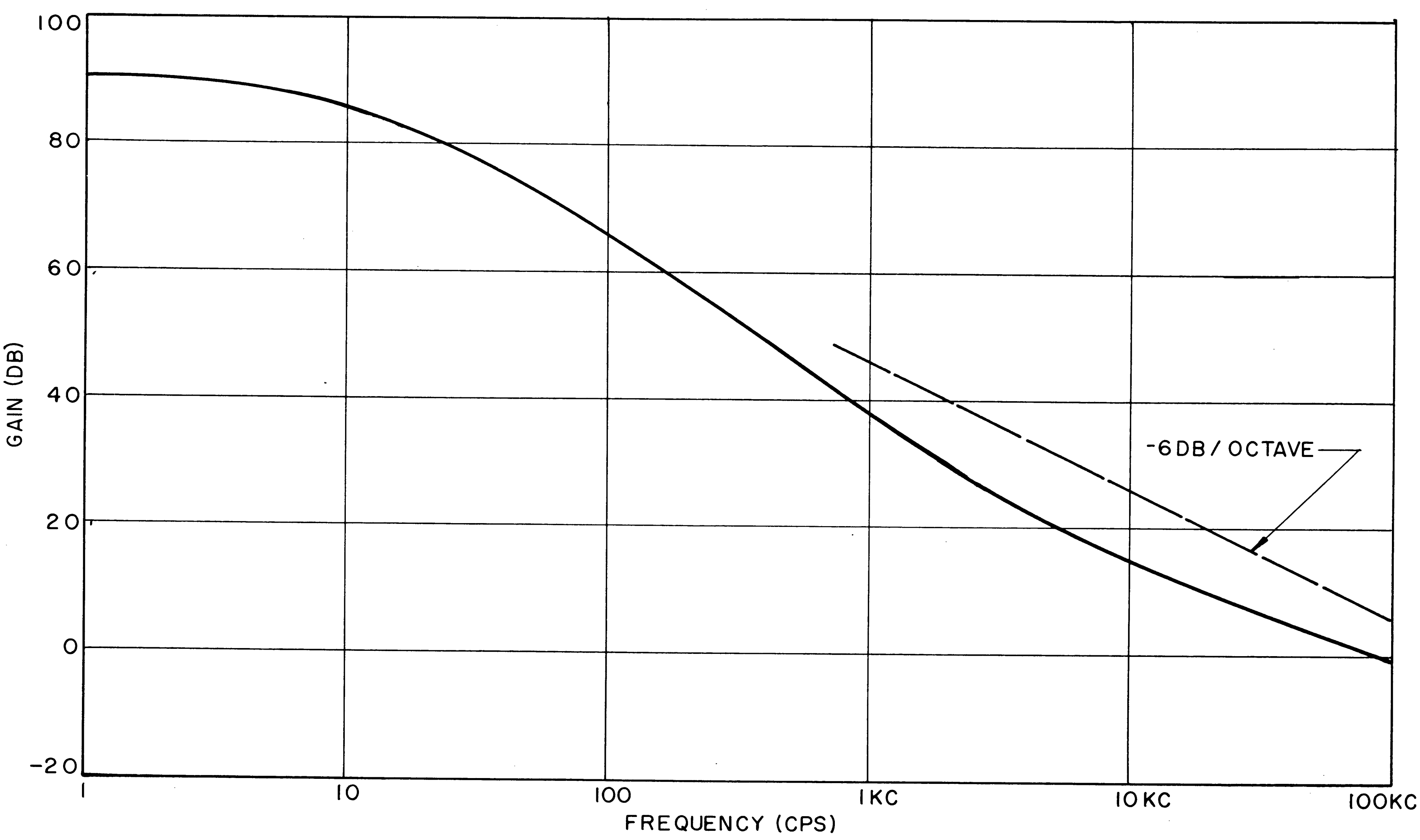

Figure 12. Open-Loop Frequency Response of AIR COMP Model 4 DC Amplifier.

means of another pair of contacts on the same synchronous vibrator. The net result is a drift-free d-c amplifier, the output of which is supplied to an additional input ϵ'' to the main d-c amplifier. The way in which this drift-free amplifier improves the performance of the operational amplifier is described below.

Assume that the unbalance in the main d-c amplifier in Figure 7 is e_B volts referred to input. Then the output e_o is given by

$$e_o = -\mu(\epsilon' + \epsilon'' + e_B) \tag{8}$$

where ϵ' and ϵ'' are equally effective inputs to the amplifier, and where μ is the main d-c amplifier gain. Let the gain of the drift-free amplifier be G, and assume that this amplifier has an offset equal to e_C volts when referred to input. (This offset may result from chopper contact voltage or stray pickup in the a-c amplifier at the chopper frequency.) Then the output ϵ'' of the drift-free amplifier is

$$\epsilon'' = G(\epsilon' + e_C) \tag{9}$$

If we neglect any current flow into the main d-c amplifier or the auxiliary, drift-free amplifier, then equation (1) gives us the relationship between the input voltage e_i to the operational amplifier and the output voltage e_o. Combining equations (1), (8), and (9), we have

$$e_o = \frac{1}{1 + \frac{1}{\mu(1+G)}\left(1 + \frac{Z_f}{Z_i}\right)} \left[-\frac{Z_f}{Z_i} e_i - \left(1 + \frac{Z_f}{Z_i}\right)\left(\frac{e_B}{1+G} + \frac{G}{1+G} e_C\right) \right] \tag{10}$$

The effective gain of the amplifier before feedback has evidently been increased from μ to $\mu(1 + G)$. Since the auxiliary drift-free amplifier cannot pass frequencies higher than one-half the vibrator frequency (60/2 = 30 cps for the Air Comp Mod 4 amplifier), it is necessary to use low-pass filters on both input and output sides of this amplifier. Thus the gain of the drift-free amplifier may be considerable at d-c and very low frequencies, but falls off rapidly at higher frequencies. At high frequencies the effective gain of the amplifier before feedback is μ, while at low frequencies it is $\mu(1 + G)$.

Consider equation (10) when the operational amplifier input e_i equals zero. If $\mu(1 + G) >> 1 + Z_f/Z_i$ and if $G >> 1$, then

$$e_o(0) \cong -\left(1 + \frac{Z_f}{Z_i}\right)\left(\frac{e_B}{1 + G} + e_C\right) \qquad (11)$$

This equation represents the voltage unbalance in the output resulting from voltage unbalance e_B in the main d-c amplifier and unbalance e_C in the drift-free amplifier. Clearly the introduction of the auxiliary chopper amplifier has reduced the unbalance e_B in the main d-c amplifier by a factor $1 + G$, where G is the gain of the chopper amplifier. It is also evident that there is no reason for having G larger than required to make $e_B/(1 + G) < e_C$, since no matter how large G is made, we are still left with an unbalance of $(1 + Z_f/Z_i)e_C$. In practice e_C can be held to 10^{-4} volts or less, whereas e_B depends upon the regulation of the power supply voltages and the constancy of the environmental conditions. For the Air Comp Mod 4 amplifiers $\mu \cong 30{,}000$ and $G \cong 400$.

As a sample calculation of the zero offset resulting from the auxiliary amplifier unbalance e_C, assume that $Z_f = Z_i = 1$ megohm, and that $e_C = 10^{-4}$ volts. Then from equation (11), if $e_B/(1 + G) << e_C$, the zero offset of the operational amplifier with a gain of unity is 2×10^{-4} volts. This is a typical figure for the Air Comp Mod 4 amplifiers.

2.2 Air Comp Mod 4 Drift-Stabilized Amplifiers

The circuit diagram for the Air Comp Mod 4 d-c amplifier is shown in Figure 8, and the diagram of the drift-stabilizing amplifier is shown in Figure 9. Photographs of the amplifiers are shown in Figures 10 and 11.

The d-c amplifier employs three stages of amplification. The first stage has two inputs, one on each of the two grids of a 5691 twin triode (equivalent of 6SL7). The input at the first grid is the input proper to the amplifier. The input at the second grid is the automatic or dirft-stabilizing input, and is connected to ground when the amplifier is operating on manual balance. The second and third stages of amplification are obtained with a second 5691 twin triode. Finally, a 12SN7 cathode follower can be switched into the output to provide a high-power output if desired. Note that the two 6-volt 5691 filaments are connected in series, whereas the 12SN7 filament is connected in parallel with the 12-volt filament supply. Since the 5691 tubes require 0.6-amp filament current while their 6SL7 counterparts require only 0.3 amps, it is not possible to substitute a 6SL7 for one of the 5691 tubes without adding an appropriate resistance in parallel with the filament of the 6SL7.

A special polystyrene-dielectric plug with silver-plated contacts is utilized at the frond end of the d-c amplifier to supply input power and input and output connections (see Figures 10 and 11). An octal socket and an additional single contact with polystyrene insulation is used at the rear end of the d-c amplifier to connect it with the drift-stabilizing amplifier. Two DPDT toggle switches at the rear of the d-c amplifier provide high- or low-power output by switching in or out the 12SN7 cathode follower. A third toggle switch provides a control for manual or automatic-balance operation.

A 24-volt d-c relay mounted underneath and at the rear of the amplifier chassis is used to check the d-c balance of the amplifier. When the relay is energized, it disconnects the external input and feedback impedances and applies a feedback-input ratio of 1000:1 in order to give a sensitive balance indication. In addition, when energized it connects the amplifier output to a special output balance terminal for convenience in metering the amplifier output in the balance condition. Balance itself is adjusted by means of the 40,000 ohm pot (course control) with the control shaft on the top of the amplifier chassis, or by means of the 5000-ohm pot (fine control) with the control shaft coming out the polystyrene plug on the front end of the amplifier. This latter control shaft protrudes through the front panel on the computer rack and allows a fine-balance adjustment to be made from the front of the computer. When the relay is in the balance position (1000:1 gain), the output balance voltage is 1000 times the unbalance referred to input (hence 500 times the unbalance with a 1:1 input-feedback ratio). The output balance voltage should normally not exceed 0.2 volts with the Air Comp Mod 4 amplifiers on "automatic" balance.

A gain versus frequency plot for the amplifier is shown in Figure 12. Maximum output voltage as a function of load resistance appears in Figure 13.

The drift-stabilizing amplifier used for automatic-balance operation employs a Leeds and Northrup Std. 3338-1 Converter as a synchronous vibrator. The 24-volt 60-cycle input is fed in through a shielded lead at the top of the converter. The first stage of a-c amplification is a 6SH7 pentode while the second stage of amplification is provided by the first half of a 12A X 7 miniature twin triode. The second half of the 12A X 7 is utilized to operate an NE-51 neon pilot light on the front panel at the top of the computer relay rack. The NE-51 fires whenever the input voltage to the d-c amplifier

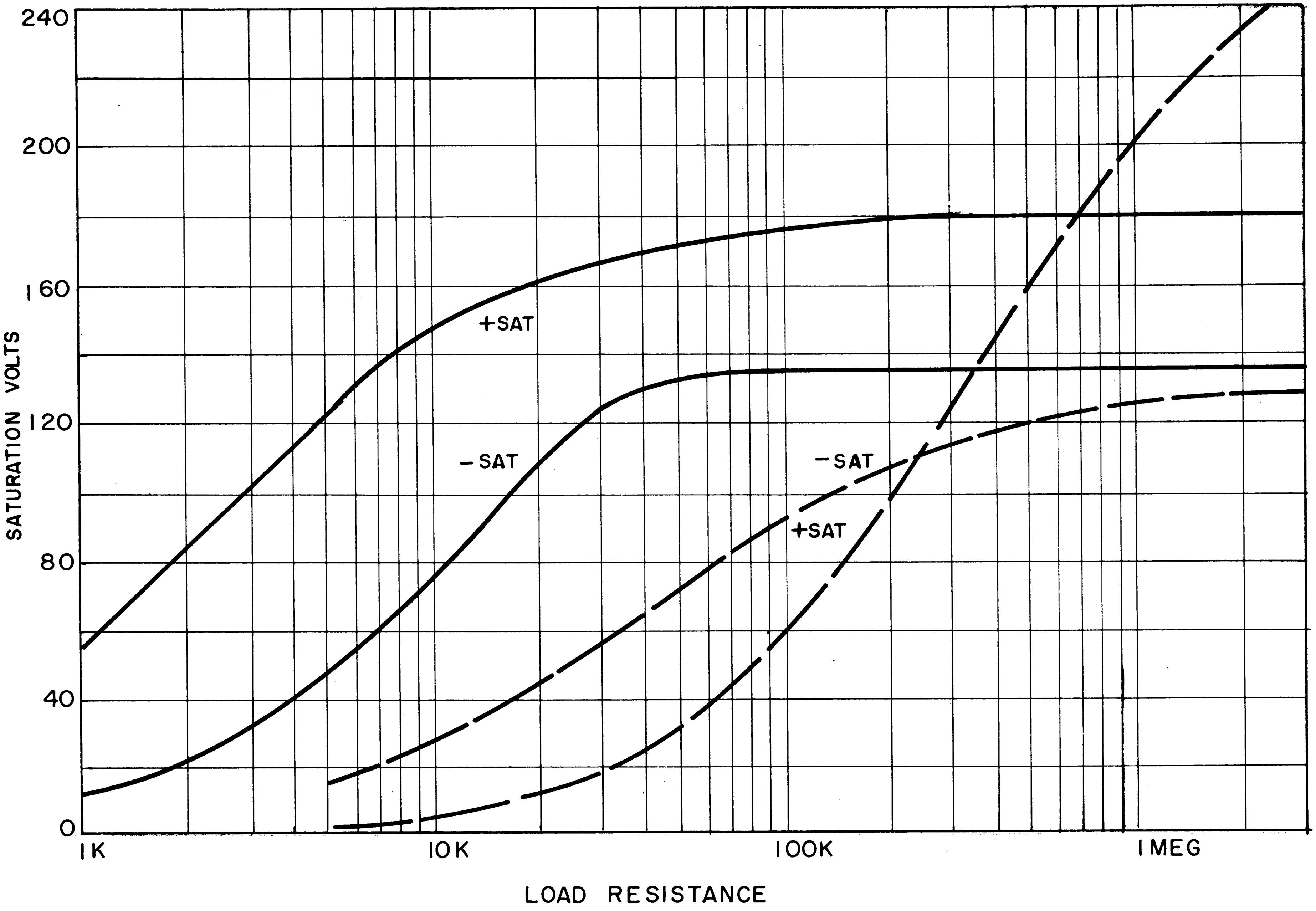

Figure 13. Maximum Amplifier Output Voltage as a Function of Load Resistance.

proper (ϵ' in Figure 7) exceeds about $\pm$ 0.07 volts. This indicates when the d-c amplifier output is saturated, for as soon as the output saturates, the input ϵ' to the d-c amplifier begins to increase by the same amount as the input voltage ϵ_1. Recovery of the drift-stabilizing amplifier to overloads of this type will be rather slow due to the dielectric absorption in the input filter condensers. Thus it may take a minute or more for the operational amplifier to return to optimum balance after an overload when automatic balance is being used.

Note in Figures 10 and 11 that the 12AX7 tube and associated components are contained in aluminum cans. This provides excellent electrostatic shielding and allows easy replacement of this portion of the drift-stabilizing amplifier.

2.3 Description of Amplifier Panels

The d-c amplifiers described in the previous section plug into the amplifier panel shown in Figures 14-16 (four amplifiers per panel). The wiring diagram for the panel is shown in Figure 17. The back side of the panel provides sockets into which the four d-c amplifiers plug. In addition, if the two inner amplifiers are to be used as integrators, feedback capacitors for these two amplifiers are plugged into the back of the panel. A 20-pin plug on the back of the panel receives power voltages and relay-control voltages from the computer rack and connects the amplifier outputs and saturation-indicating voltages to the computer rack. The front of the amplifier panel provides sockets for plugging in input and feedback resistors. The insulating material is polystyrene. A push-button to energize the balance relay is provided for each amplifier on the front of the panel. Initial condition controls are also located on the front of the panel above the two inner amplifiers.

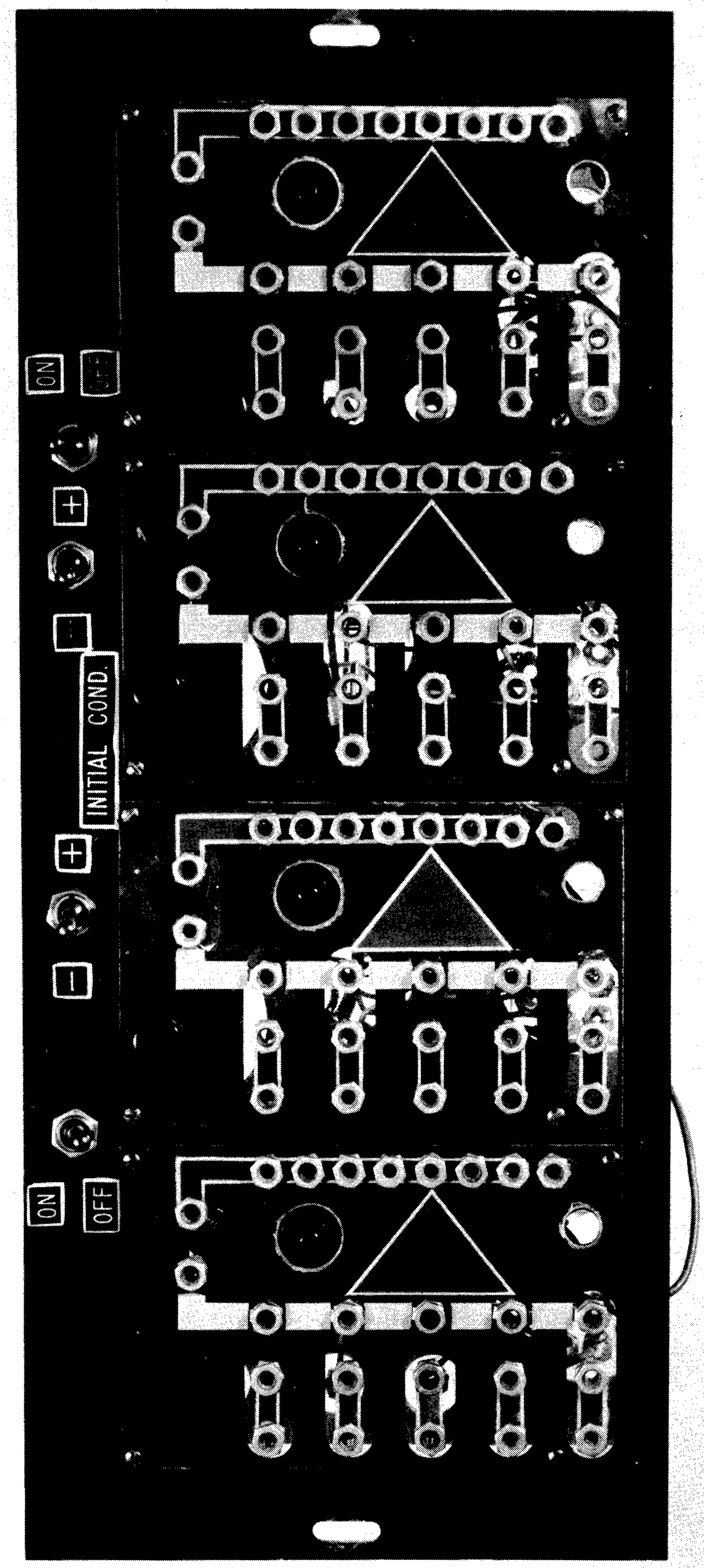

Figure 14. Front View of Amplifier Patch Panel.

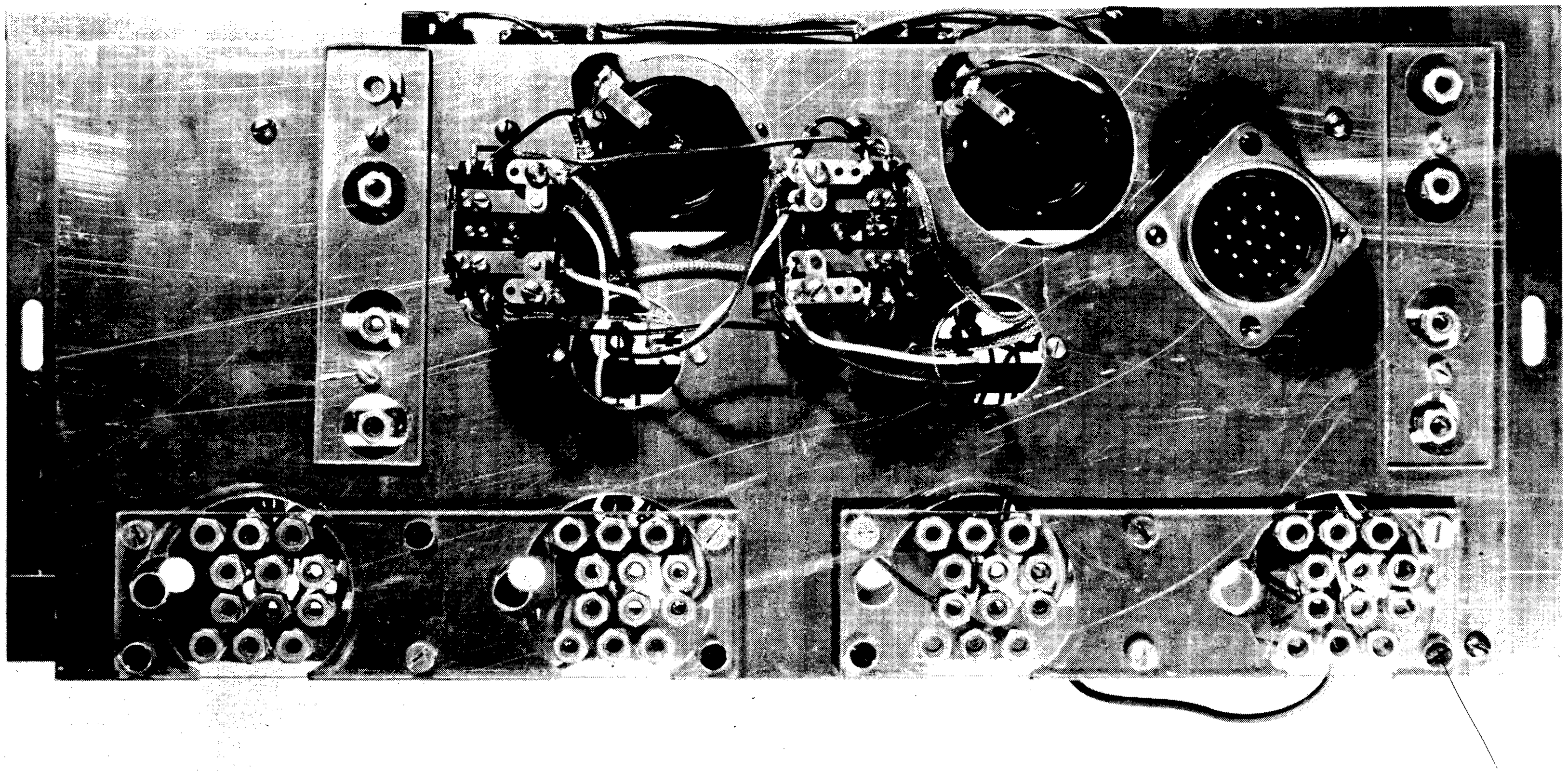

Figure 15. Rear View of Amplifier Patch Panel.

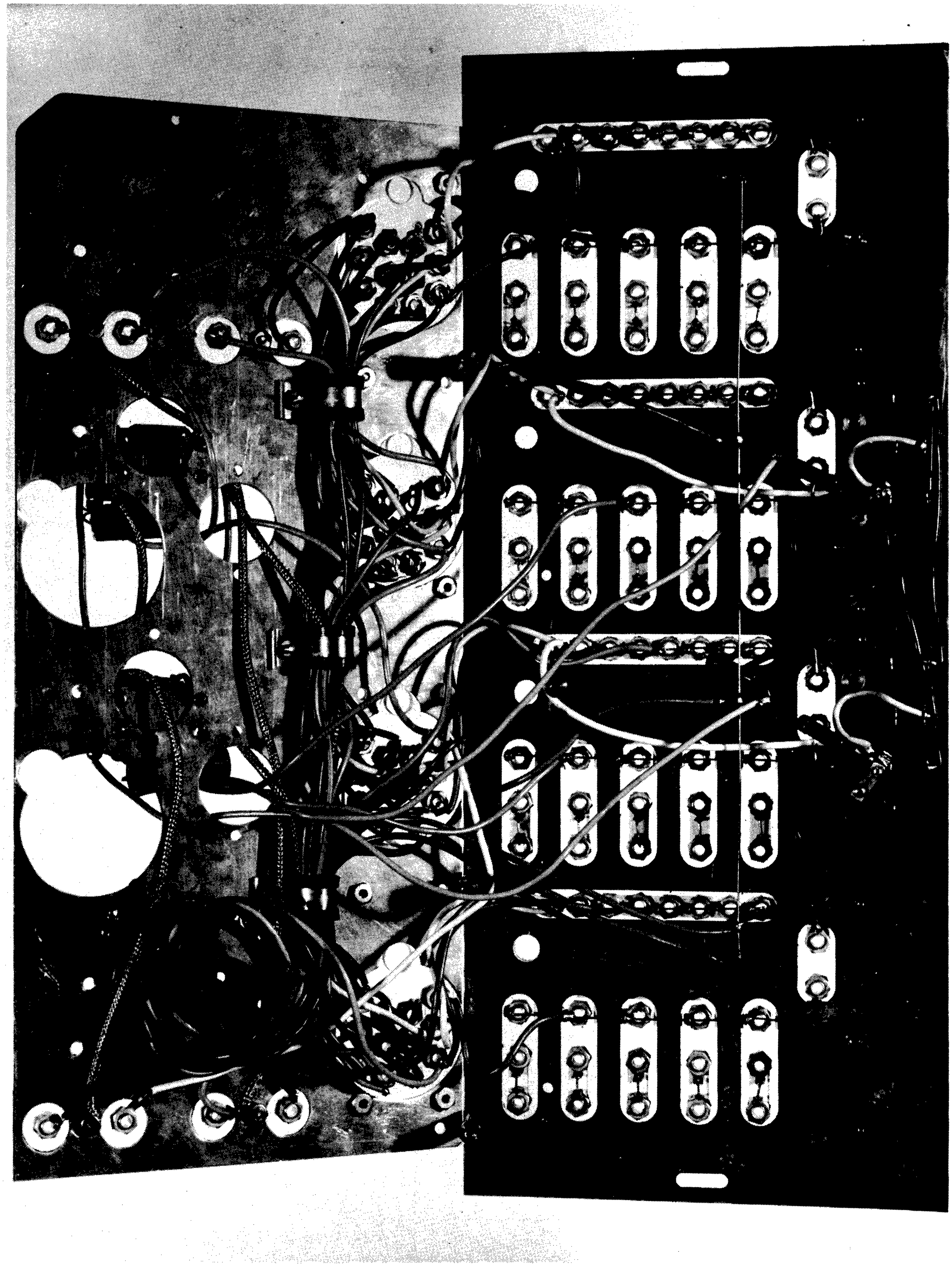

Figure 16. Internal View of Amplifier Patch Panel.

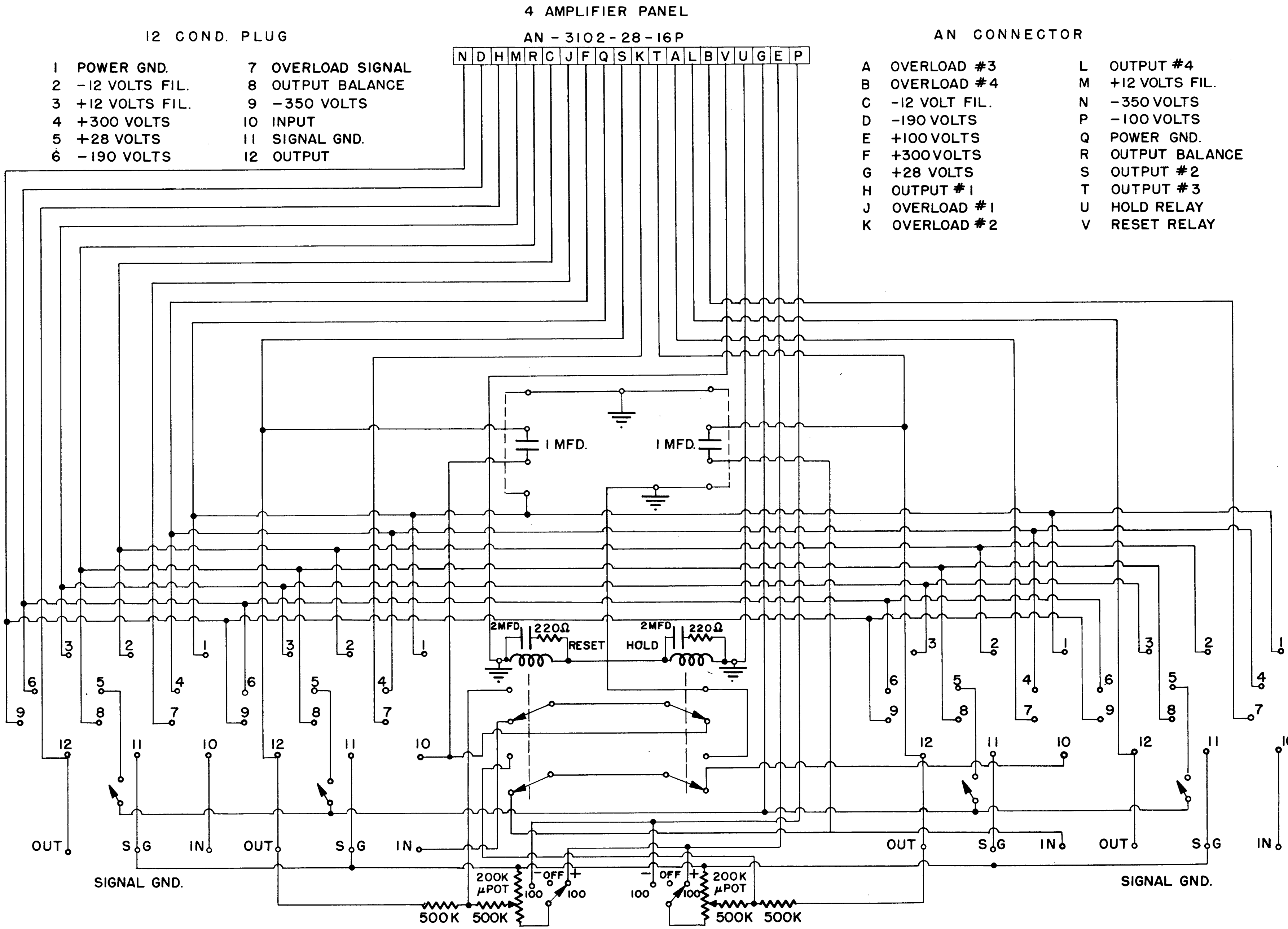

Figure 17. Circuit for Amplifier Patch Panel.

The function of the initial-condition and hold relays should probably be described in some detail. In order to solve differential equations with the electronic differential analyzer, it is necessary to impose initial conditions on each of the integrating amplifiers. The initial conditions are obtained with the reset relay by disconnecting the external input resistors and by connecting equal input and feedback resistors to the amplifier (see Figure 18). The negative of the initial condition voltage is then applied to the input resistor, and the feedback capacitor charges to the desired voltage. When the analyzer solution is begun, the 1:1 input and feedback resistors are disconnected from the amplifier input and the external input resistors are reconnected. The reset relay is energized when initial conditions are applied and is de-energized when the solution begins. Actually a single DPDT relay is utilized to impose initial conditions on both integrating amplifiers.

When the "hold" relay is energized, it disconnects the input resistors to the integrating amplifier and "holds" the voltage stored on the feedback capacitor at that instant (see Figure 18). In this way the differential analyzer solution can be stopped at any time and resumed at a later time by de-energizing the hold relay. When a solution is being held, the output voltages of the integrators will drift slightly because of leakage or grid current into the feedback capacitor. For a current of 10^{-10} amps a 1-microfarad integrator will drift 0.0001 volt per second when held.

In order to avoid undesirable transients when the relays are opened or closed, a 2-microfarad capacitor in series with 240 ohms is connected in parallel with the reset and hold relays. Note that the relays are operative only when both integrating condensers are plugged into the back of the amplifier panel.

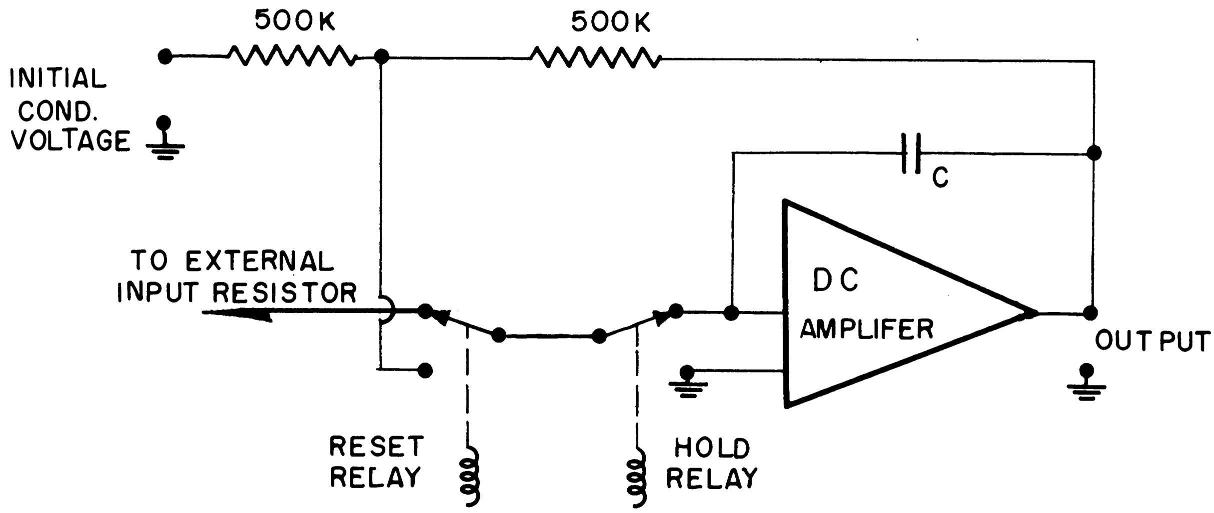

Figure 18. Circuit for Initial-Condition and Hold Relay Operation.

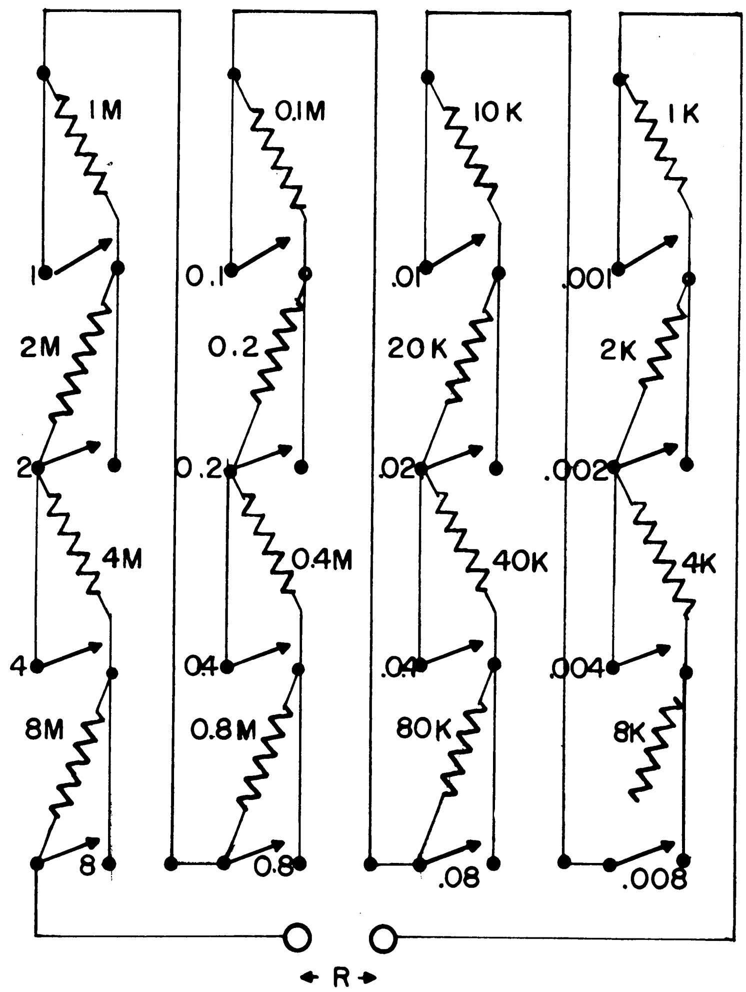

Figure 19. Circuit for Obtaining Non-Integral Resistor Values.

2.4 Circuits for Obtaining Non-Integral Resistor Values

The external computer components required for solving differential equations include resistors. A number of integral-valued resistors frequently required (such as 0.1, 0.5, 1 megohm, etc.) are provided as plug-in units. In the solution of a differential equation having non-integral coefficients, however, it is necessary to provide appropriate non-integral resistors for use as input or feedback impedances. Two panels containing 64 toggle switches each are utilized for this purpose (see Figure 1). A given panel actually consists of 4 groups of 4 x 4 toggle switches. Each 4 x 4 group allows any resistance between 0.001 megohm and 16 megohms to be built-up in 0.001-megohm steps. The circuit is shown in Figure 19. The desired resistance is obtained by short-circuiting the appropriate resistors. The first column contains 0.001, 0.002, 0.004, and 0.008 megohms in series; the second column 0.01, 0.02, 0.04, and 0.08 megohms in series, etc. Thus the first column is used to set the 0.001-megohm digit, the second for the 0.01 megohm digit, the third for the 0.1-megohm digit, and the fourth to set megohms. Resistors employed are accurate to better than 1 per cent, but for high-precision computing it is necessary to set the resistor values by means of a calibrating circuit such as a Wheatstone bridge.[2] The desired resistance is then patched into the appropriate amplifier by means of a connection from the two output sockets.

2.5 Amplifier Relay-Rack Circuits

The amplifier panels which hold the operational amplifiers and computing components are in turn supported by Relay-Rack No. 1 (see Figure 1). The circuit diagram for the relay rack is shown in Figure 20. Power and control voltage inputs to the rack are obtained through a plug at the rack base. Beside this input plug is an output socket which provides connections to the outputs of each of the operational amplifiers.

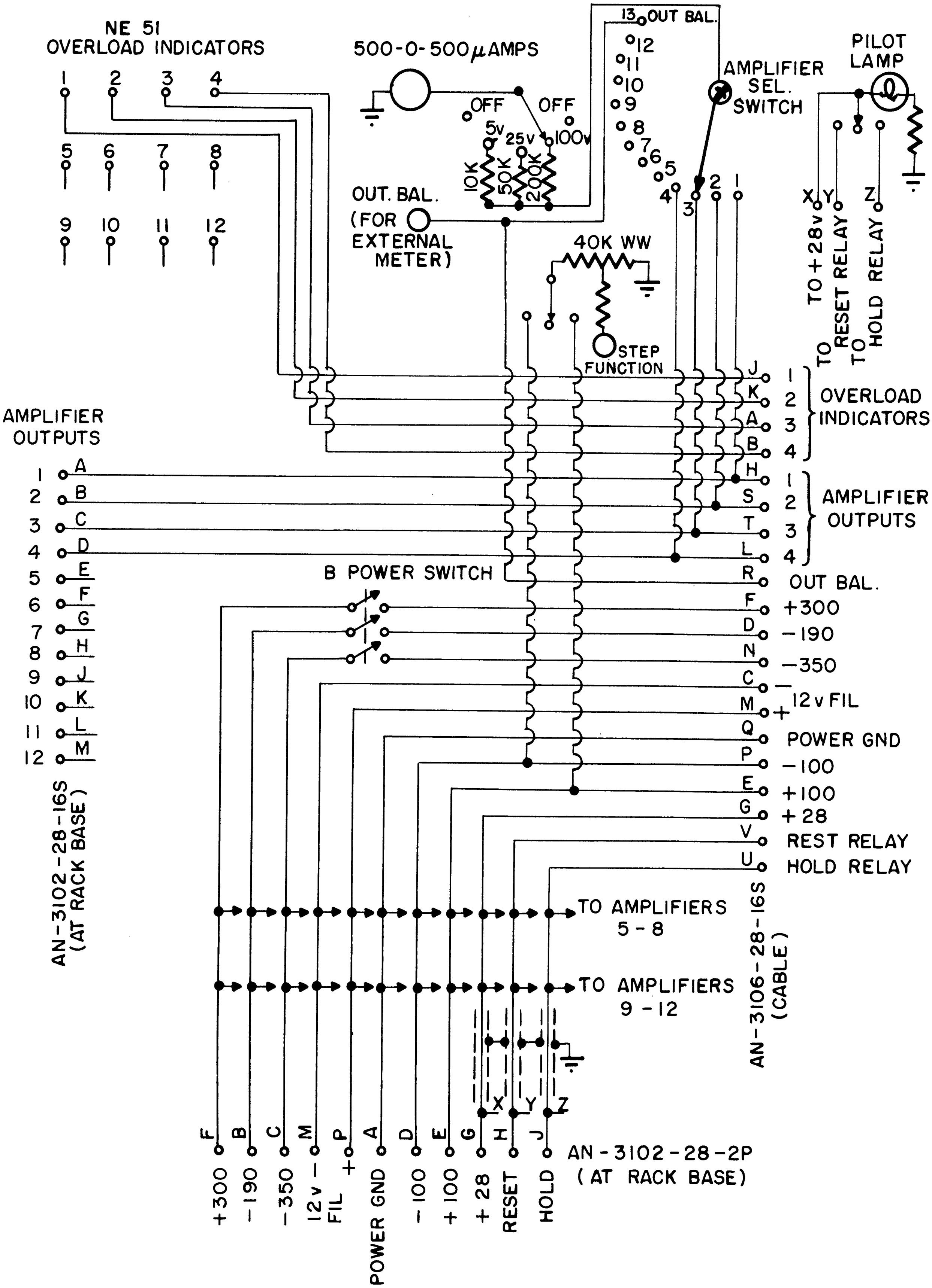

Figure 20. Wiring Diagram of Amplifier Rack.

At the top of the rack (in the rear) is a terminal strip from which power and control voltages are distributed to the amplifier panels. Also at the top of the rack are the computer control circuits, amplifier-overload lights, and meter circuits (see Figure 11). A pilot-light indicates when the +28-volt power is on.

The three-position HOLD-OPERATE-RESET switch is the main control switch operating the computer. The amplifier-selector switch selects which amplifier output is read by the meter.* The OUTPUT BALANCE terminal provides a connection to the output of any amplifier when the balance button is pressed. (This terminal might be used if a more sensitive balance indication than provided by the panel meter is required.) The STEP-FUNCTION controls provide a convenient source of a constant voltage for amplifier inputs. The B POWER switch is used to turn-off the B voltages while a problem is being set up. There is a one-to-one correspondence between the location of the overload lights and the actual amplifiers which are overloaded.

3. Variable Coefficient Selector

In order to solve linear differential equations with variable coefficients the variable coefficient selector shown in Figure 1 is used. Essentially it is a device which changes the value of one or more resistors in accordance with a prescribed function of time f (t). The resistors are in turn used as feedback or input impedances in operational amplifiers, so that the gain of those amplifiers varies as f (t) or 1/f (t). Instead of varying the resistors continuously with time they are varied in discrete steps, thus forming a stepwise continuous approximation to f (t) (see Figure 21).

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*Amplifiers are numbered 1 through 12, beginning at the upper lef-hand corner of the rack. Number 12 corresponds to the right-hand amplifier in the lowest bank of four. Position 13 connects the meter to the output balance terminal.

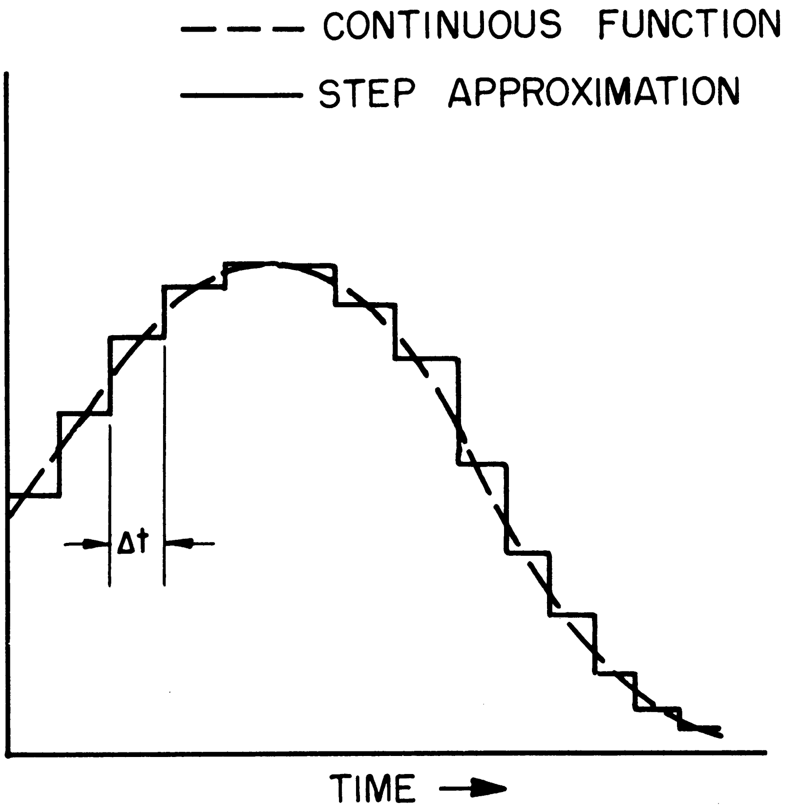


Figure 21. Step Approximation to Continuous Function.

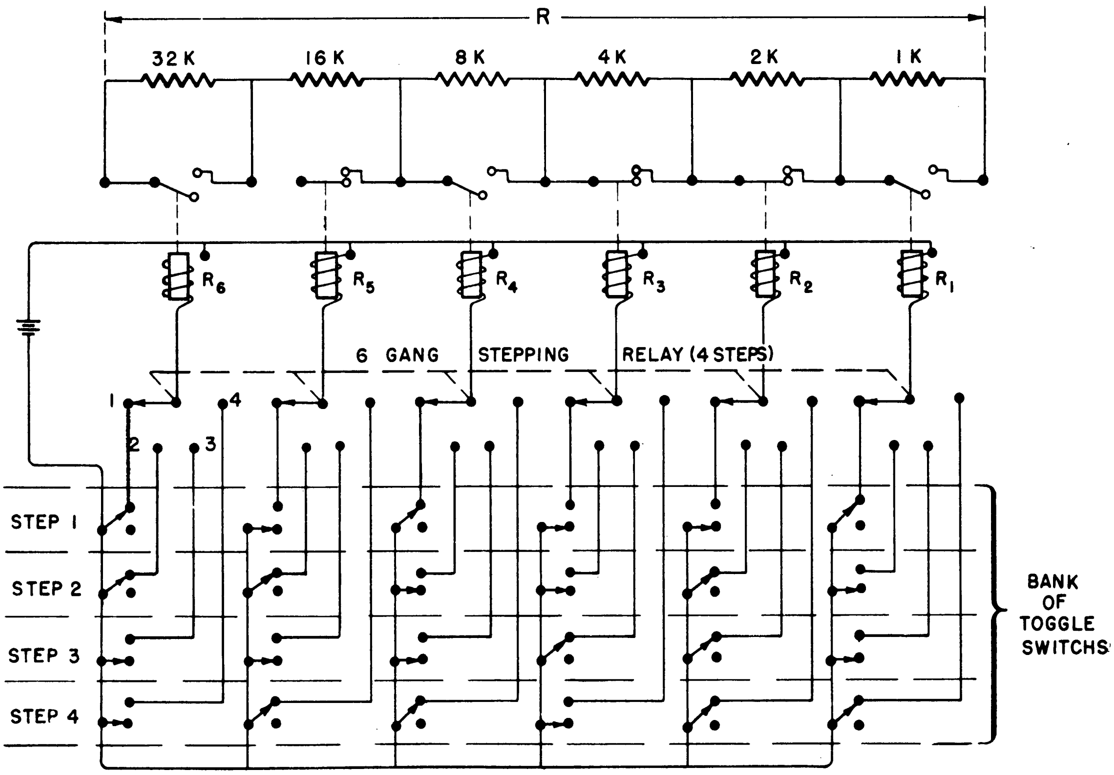


Figure 22. Schematic Circuit for Variable Coefficient Selector.

After each interval of time Δt the resistance is switched to a new value. The resistance of each step approximation is chosen so that at the end of the interval the area under the step curve equals that under the continuous curve. The resistance for each step is obtained by building it up from a set of binary resistors connected in series. Consider the set of binary resistors shown at the top of Figure 22. Evidently the total resistance R can be made anything from zero ohms to 63k ohms in 1k-ohm steps by short-circuiting the appropriate binary resistors with their respective relays. The relays for each binary resistor are in turn controlled by the rows of toggle switches at the bottom of Figure 3. Finally, a stepping relay selects just which row of toggle switches controls the binary-resistor relays. As the stepping relay moves from one rotary position to the next every Δt seconds, it switches control from one row of toggle switches to the next. By properly positioning the toggle switches ahead of time, any desired set of binary resistors can be switched in on each step.

In the example shown in Figure 22 the first row of toggle switches is up, down, up, down, down, up, from left to right. When the stepping relay is on step 1, therefore, the binary relays short-circuit the 16k-, 4k-, and 2k-ohm resistors, leaving the total resistance R for step 1 as R = 32 + 8 + 1 = 41 ohms. For step 2 the toggle switches are up, up, down, down, up, down, so that when the stepping relay rotates to step 2, the resistance R = 32 + 16 + 2 = 50 k ohms. As the stepping relay proceeds to step 3 and step 4 the resistance R changes in accordance with the positions of the toggle switches in rows 3 and 4, respectively. Evidently, any step wise continuous function of resistance such as that shown in Figure 21 can be obtained by properly positioning ahead of time the toggle switches at each step (i.e., in each row). Note that the same set of binary resistors is used over and over again.

For the purposes of illustration the circuit shown in Figure 22 has provision for only 6 digits and 4 steps in time. The actual equipment for the air comp. mod 4 computer has provision for 17 digits and 25 steps. The binary resistors are plug-in units, so that the 17 available digits can be divided between two or more functions. If a function f (t) changes sign, a digit may be used to switch in an inverting amplifier at the proper time. The stepping relay is driven by a synchronous contactor.

The variable coefficient selector consists of two parts: (1) the relay rack containing the 17 x 25 toggle switches, two 25 step 9 pole stepping relays, and the relay control circuits, and (2) the panel containing the 17 d-c 24v relays and the binary resistor plug-in sockets (one pair for each relay). The circuit for the latter is shown in Figure 23. Power from the toggle-switch comes in through an 18-conductor cable. The 24 volt dc relays are energized or not energized depending on the position of the corresponding toggle switch on a particular step. When a relay is energized, the connection across the binary resistor is opened, and its resistance is added to the total series resistance corresponding to f (t). When the relay is not energized, the binary resistor is short-circuited. Note that two resistors can be controlled by each relay, since they are double pole relays. Thus two similar time varying resistances f (t) can be set up with a single set of relays and toggle switches. It is only necessary to plug the binary resistors into the proper digital sockets and add patch-cord jumpers to connect the resistors in series.

The circuit diagram of the stepping-relay panel is shown in Figure 24. The stepping-relays are interconnected to the stepper-control chassis through a

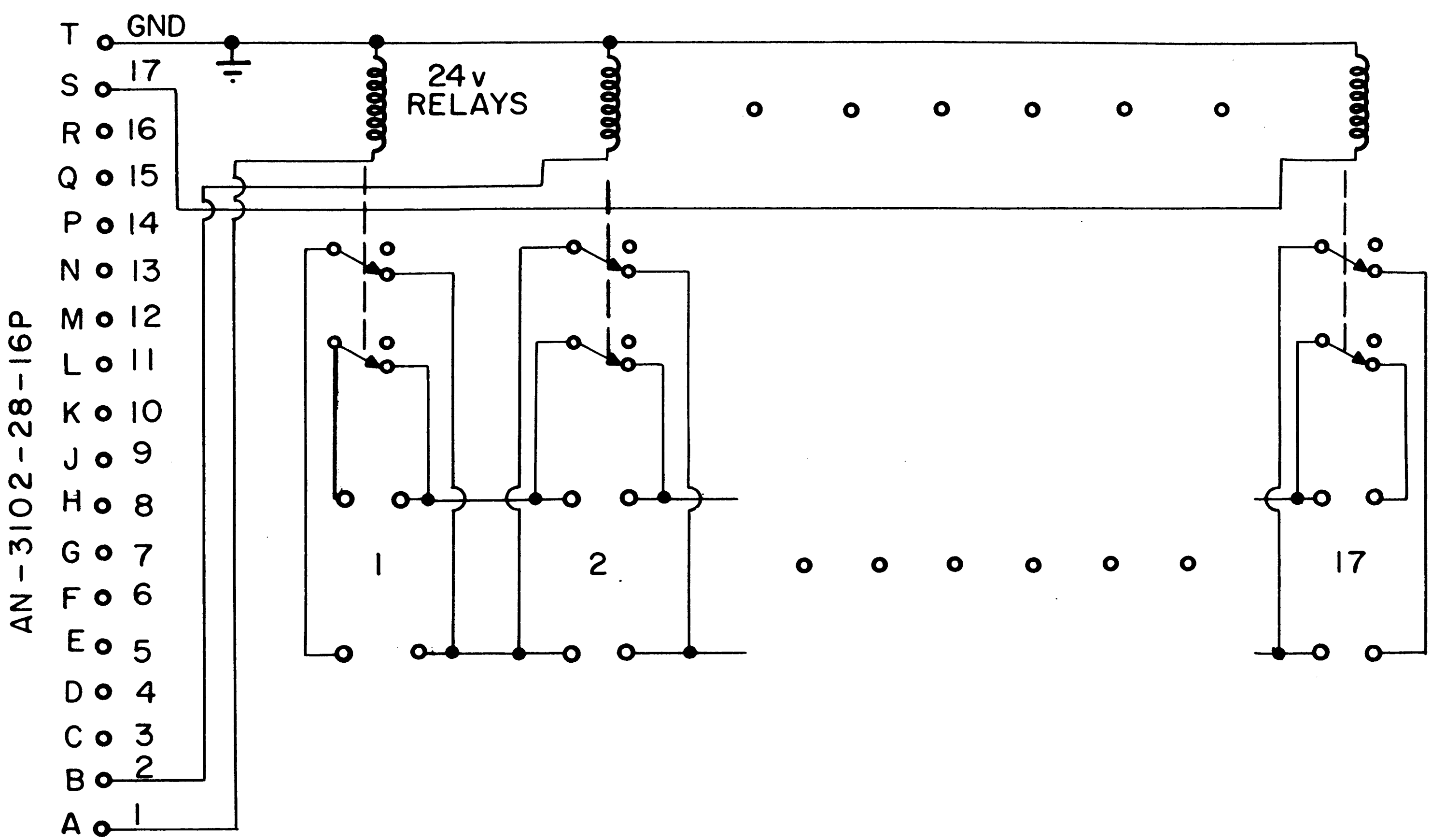


Figure 23. Binary Resistor Plug-In Circuit.

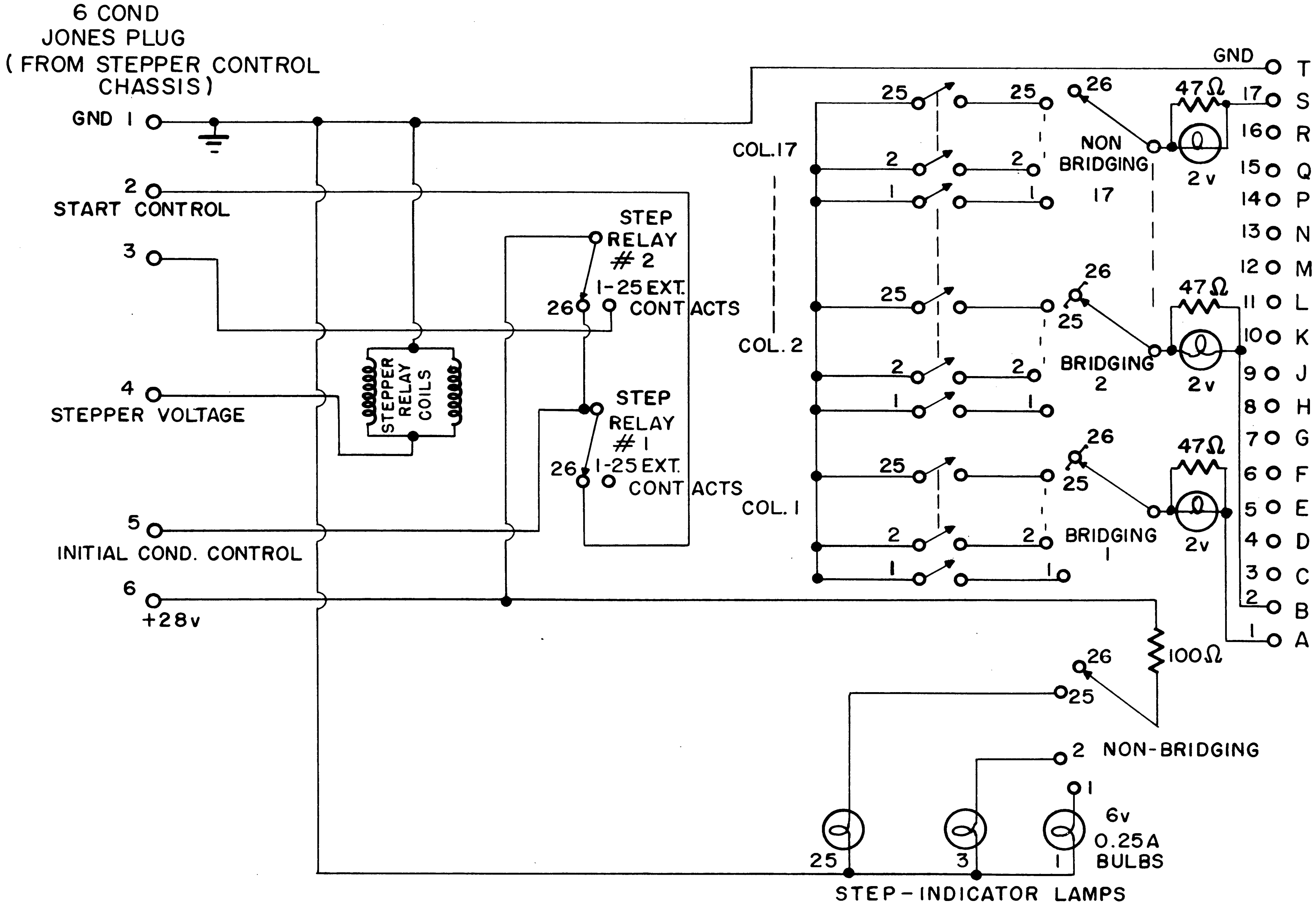


Figure 24. Stepping-Relay Panel.

6-conductor Jones plug. From this plug comes the 28 volt d-c pulses which activate the stepping relays (pin 4). In standby operation the relays are on step 26. In this position they apply 28 volts to the initial-condition-relay circuit (pin 5), thus energizing all reset relays in the main amplifier rack. When the first 28 volt pulse is applied through pin 4, the relays go to step 1, which releases the initial-condition-relay circuit and starts the problem solution in the main amplifier rack. The relays continue to step around to step 26, at which time the input pulses through pin 4 cease and the initial-condition-relay voltage on pin 5 is restored. In addition, the external set of contacts on the stepping relay are used to prevent the start of a solution if the two relays are not synchronized (both on step 26).

Note in Figure 24 that the relay common for each digit has a pilot lamp in series with it before going to the 18 conductor output plug to the relay panel. When the pilot lamp lights (at the top of the toggle switch rack) it means that power has been applied to the relay for that digit, and that the corresponding binary resistor has been switched in. Note also that a set of stepping relay contacts is used to light the pilot lamps down the side of the toggle-switch rack, thus providing an indication of which step the relays are on.

The stepping-relay control circuit is shown in Figure 25. Main power into the stepping relay rack is 28 volts d-c from the power supply rack. It is controlled by a power switch on the front panel at the bottom. To begin a solution (start the stepping relays), the panel start switch is turned on. This closes the start control relay, which, if both stepping relays are on step 26, closes the solution relay. The starter relay is held closed, even after the panel start switch is released, until step 26 is reached again, at which time the starter relays drop out. While it is closed, the starter relay allows 28 volt

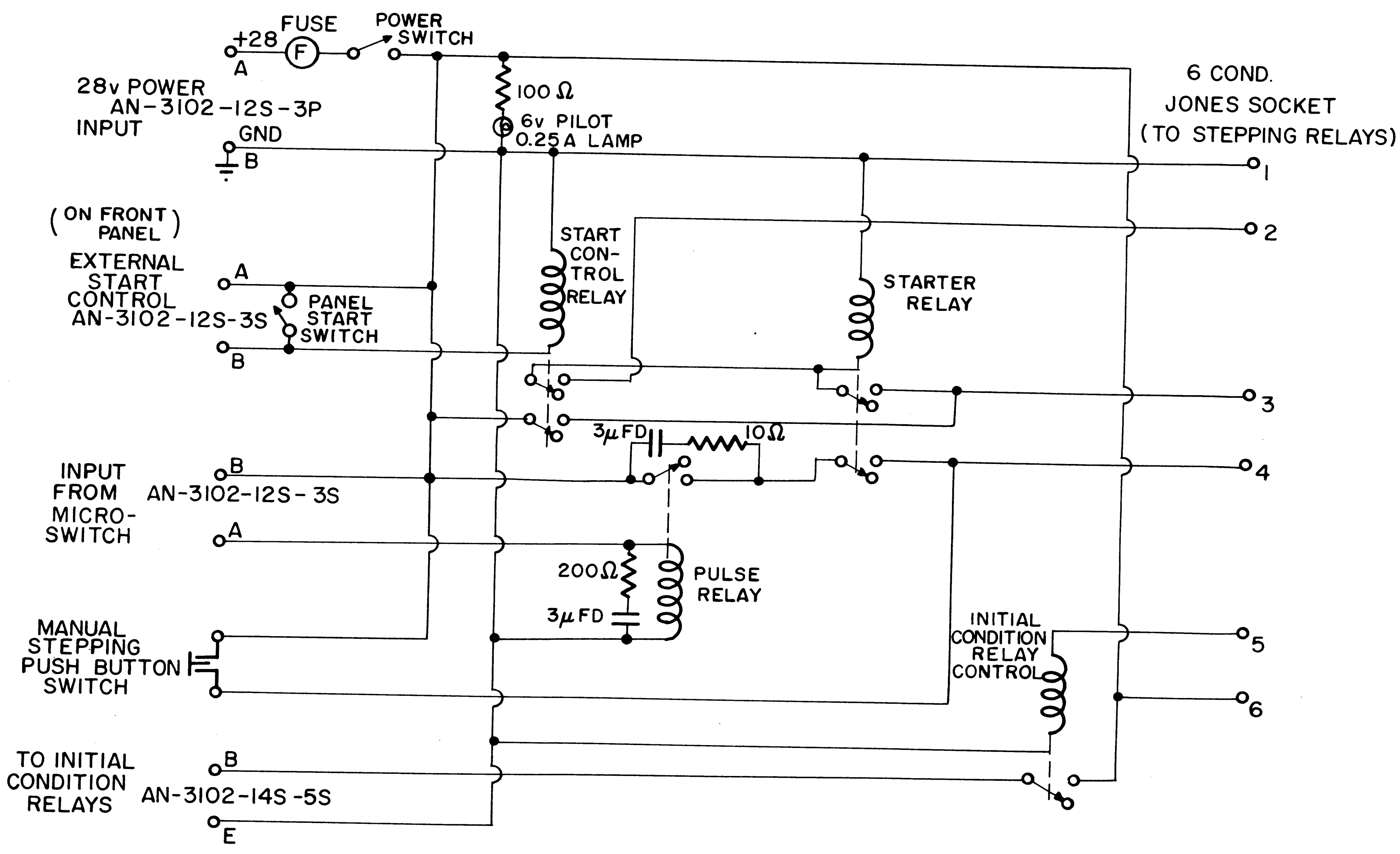


Figure 25. Stepper Control Chassis.

pulses from the pulse relay to reach the coils of the stepping relays, thus causing them to step. The pulse relay operates at all times when the main 28 volt power is on and the cam-driven microswitch is operating. Finally, the initial-condition control relay is closed when the steppers are on step 26, but opens (releasing the reset relays) when the steppers are on positions 1 through 25.

A manual stepping push-button switch on the front panel allows the steppers to be cycled manually step by step. Also, an external-start-control cable for remote starts of the solutions can be plugged into a socket on the front panel. After the stepping relays start their 26-step cycle the starting switch should be opened so that the relays stop on step 26.

4. Power Supplies

The power-supply rack contains electronically regulated d-c B supplies of +300, +100, -100, -190, and -350 volts, and an unregulated +28 volt relay supply. The rectifier and filter circuits for the B voltages are on separate chassis (Figures 26-28) from the regulator chassis (Figures 29 and 30). The rectifier and filter chassis receives 115-volt 60-cycle line power from line cords from the distribution panel. Cables from the rectifier and filter chassis to the appropriate regulator chassis connect the unregulated B voltages and the 6.3 volt regulator-tube filament voltages to the regulator chassis. The rectifier, filter, and regulator circuits are entirely conventional. Note that the voltage standard for the +100 volt supplies is a 90-volt B battery. This battery should last a time equivalent to its shelf life. The -190 supply has the least regulation of any of the supplies, but is the least critical in affecting amplifier balance. The +300 and -350 supplies may drift the order of 1 volt after warm-up, but with drift stabilizers on the operational amplifiers this will only

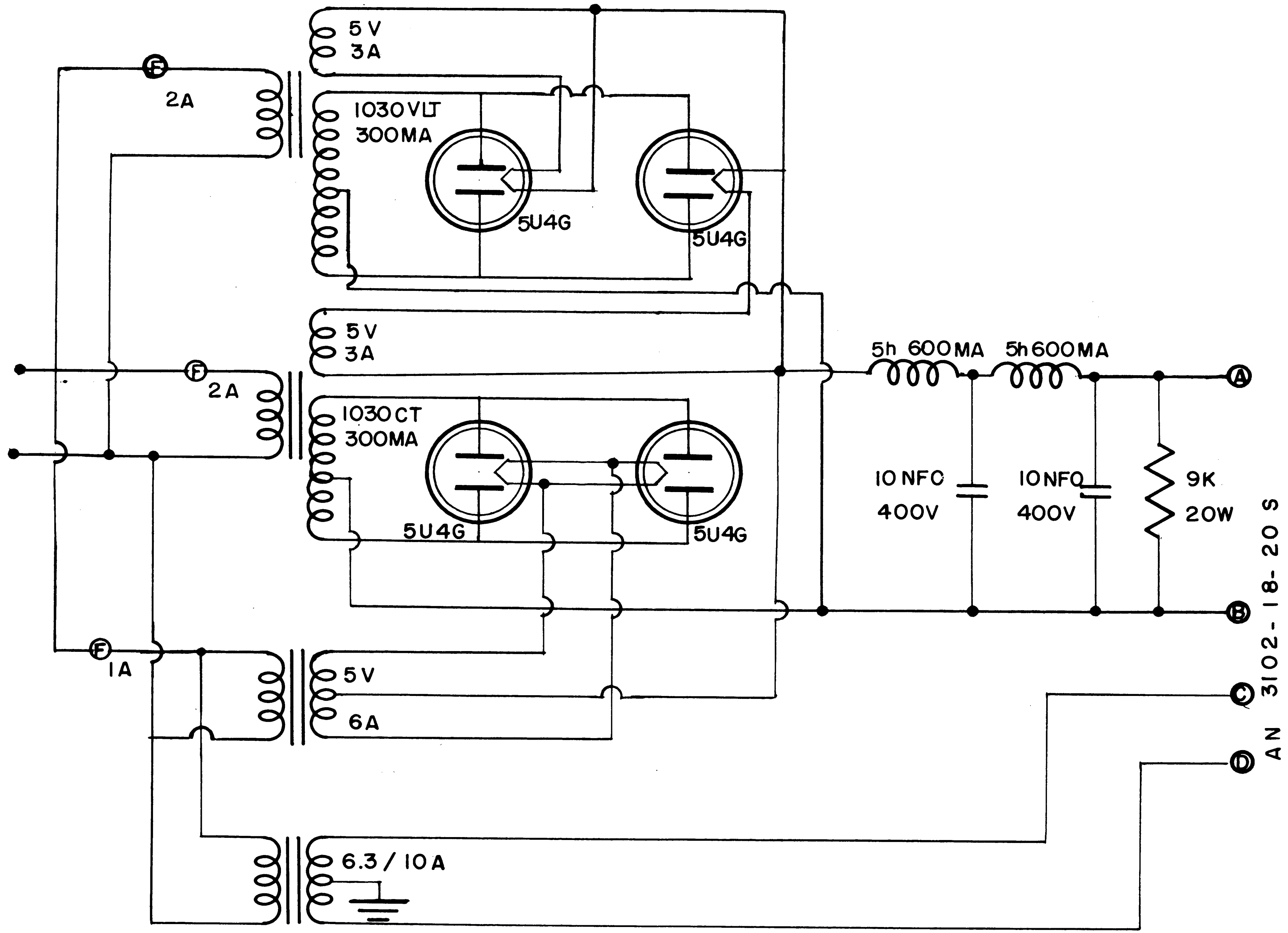


Figure 26. Power Supply for + 300 Volt Regulator.

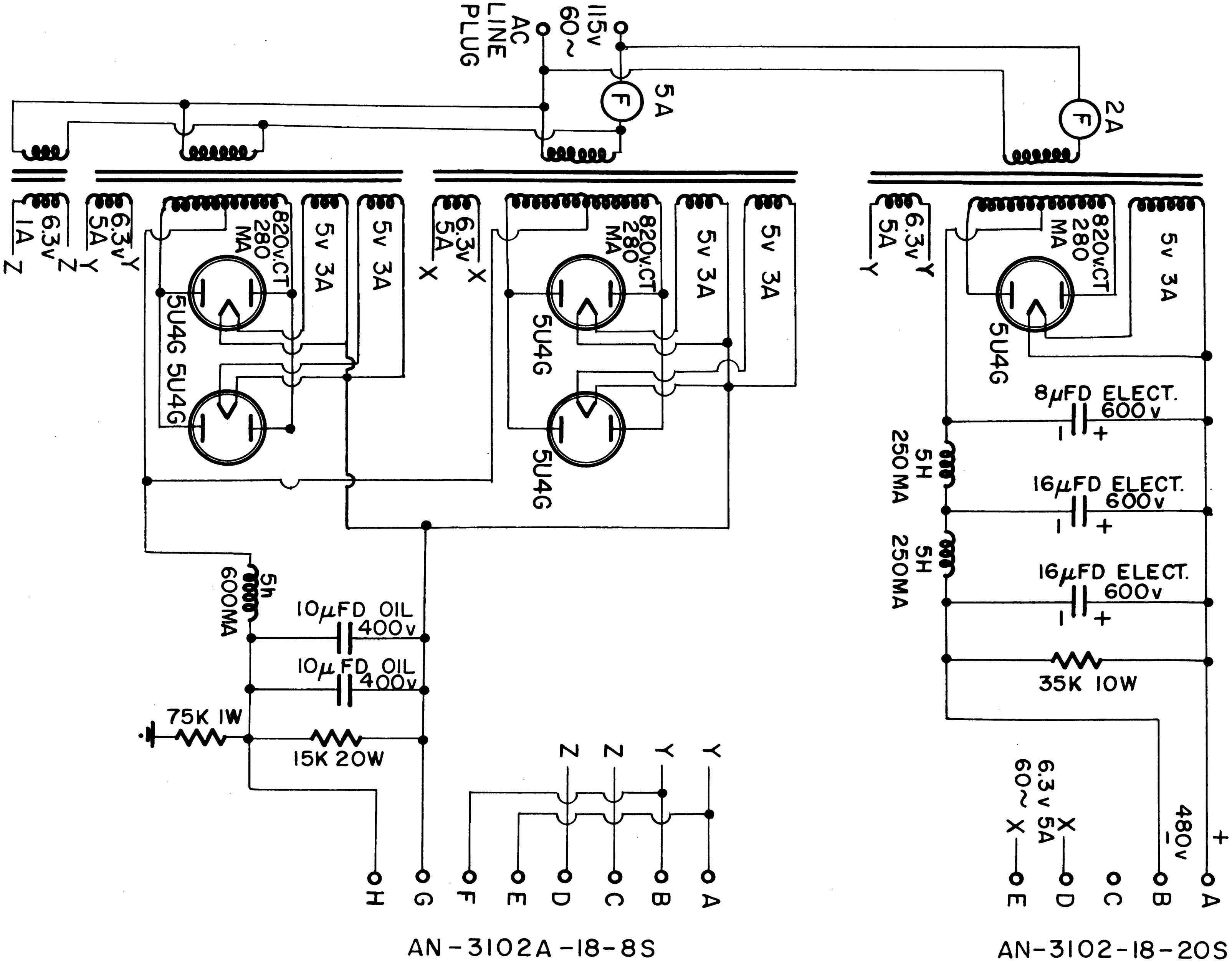


Figure 27. Power Supply for -190 and -350 Volt Regulators.

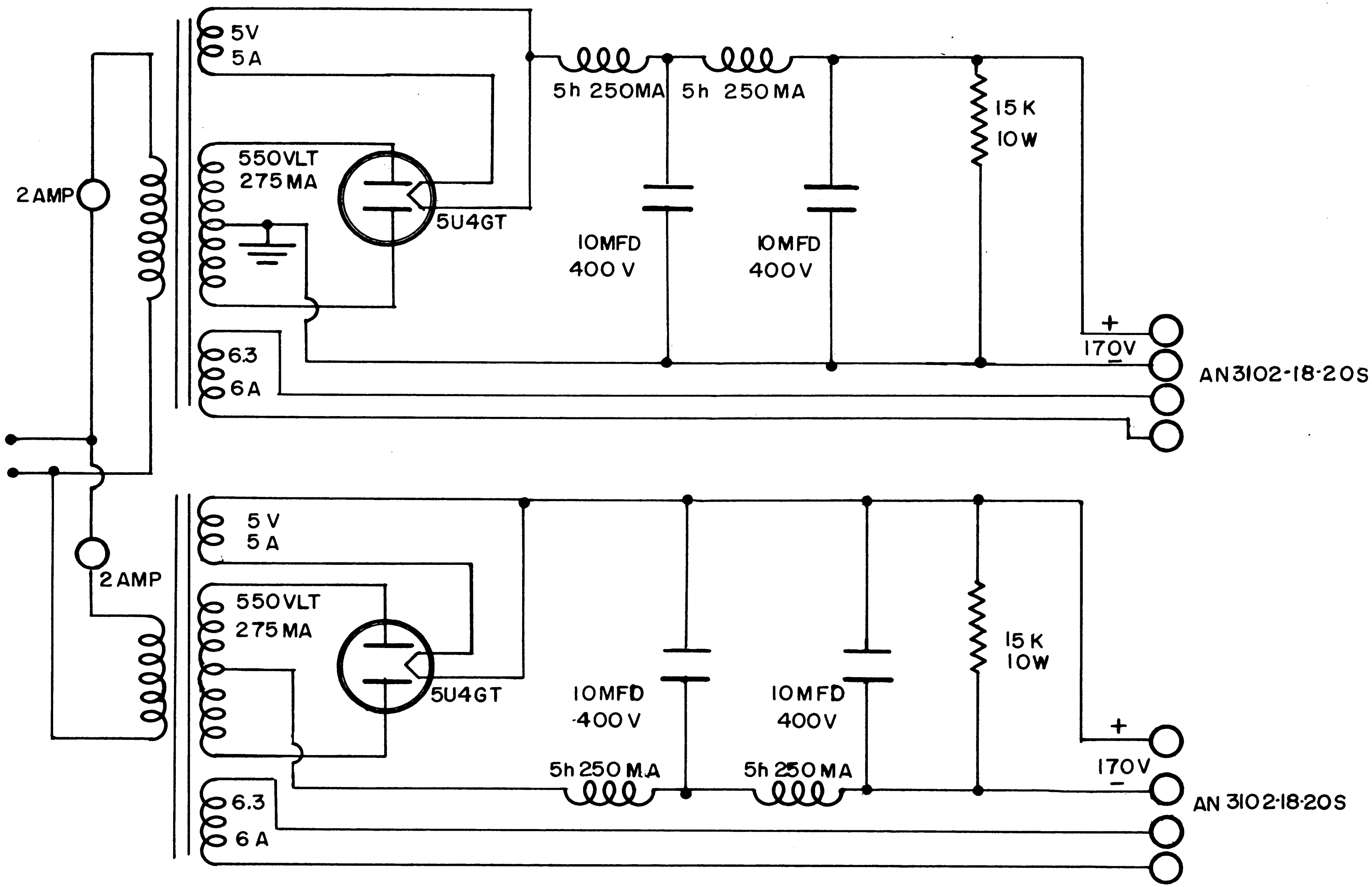


Figure 28. Power Supply for + 100 and -100 Volt Regulators.

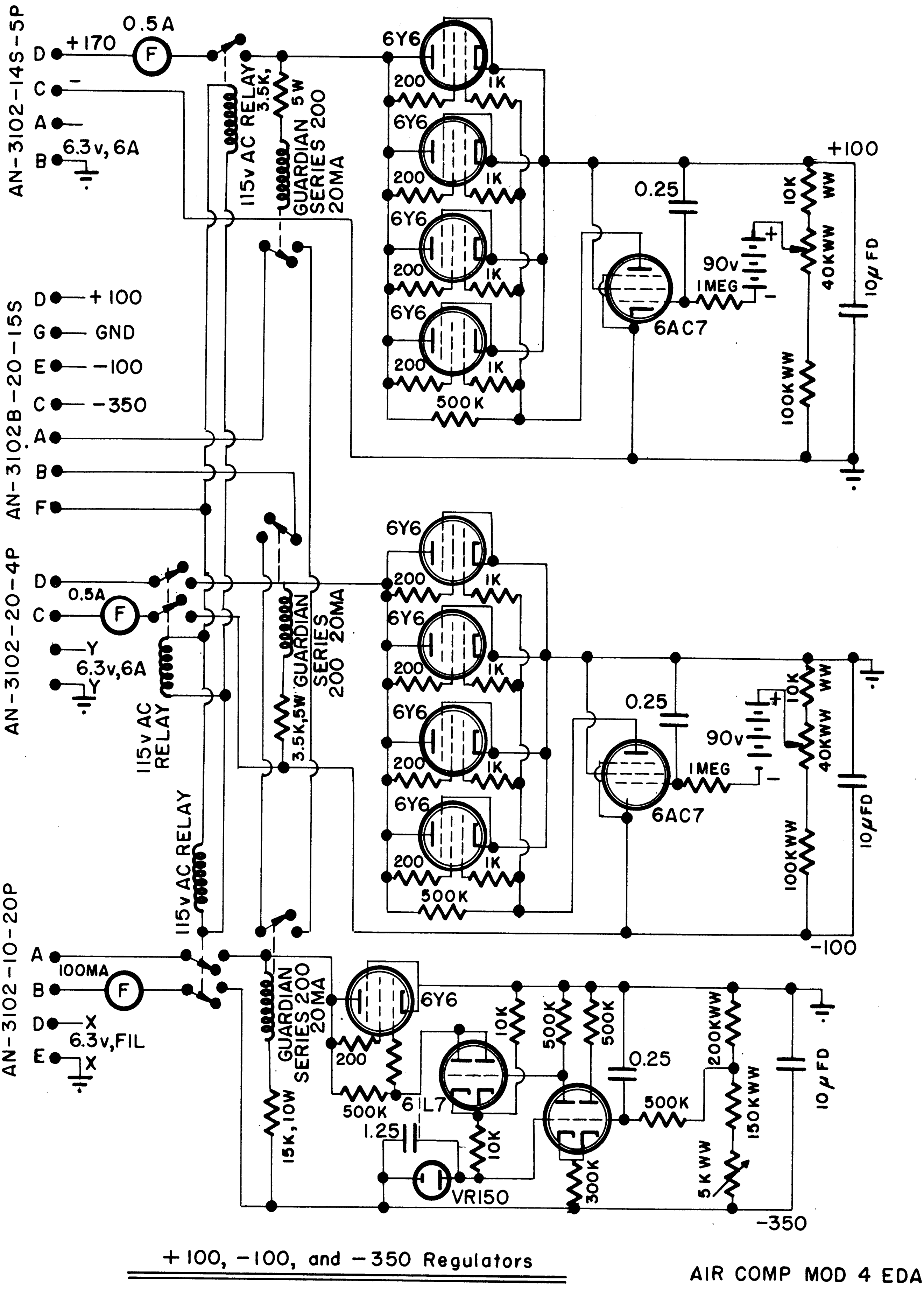


Figure 29. Regulators for +100, -100, and -350 Volt Supplies.

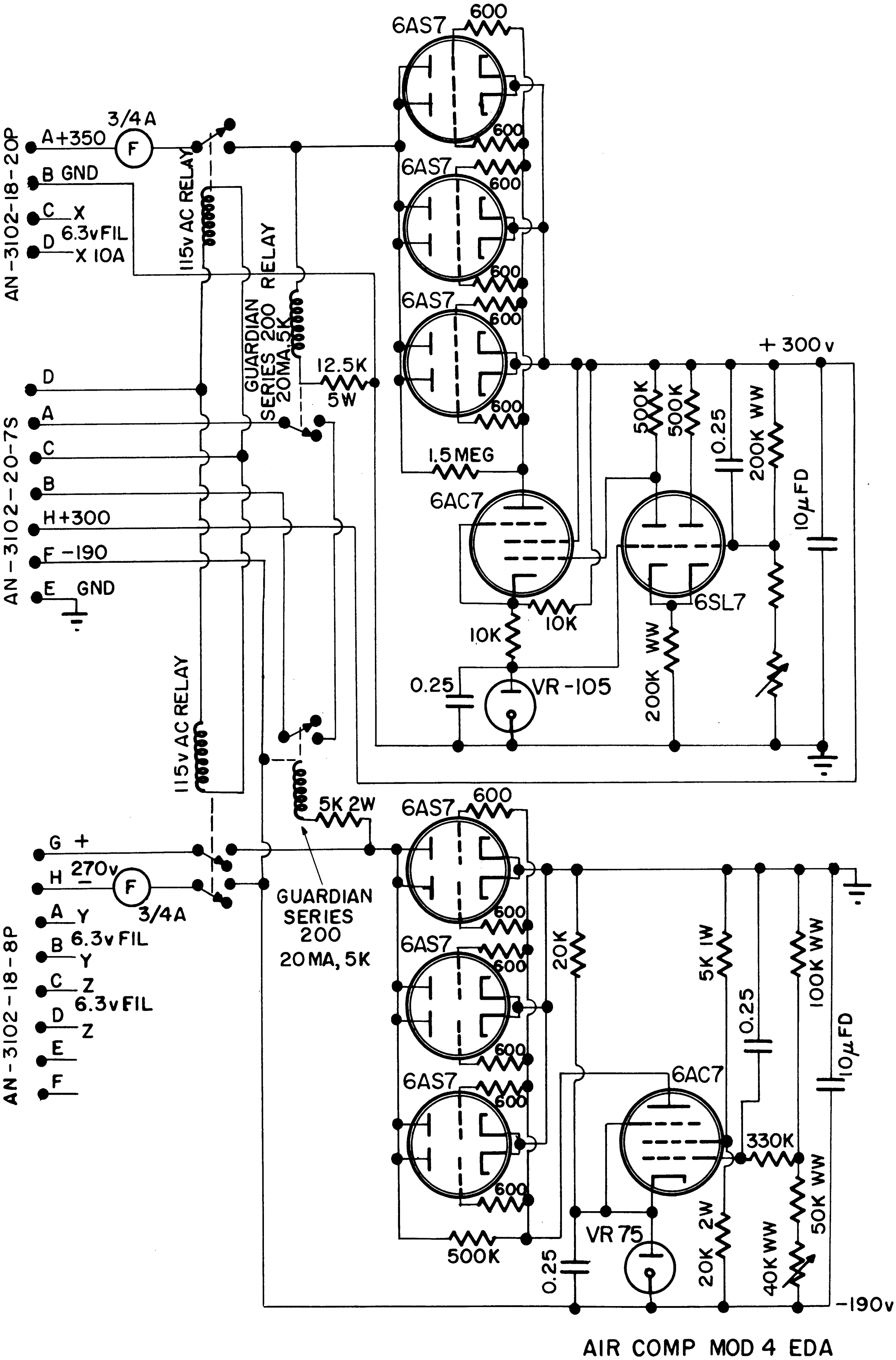


Figure 30. Regulators for +300 and -190 Volt Supplies.

cause a negligible zero drift. The $\pm$100-volt supplies should hold to within 0.1 volt of their set value. Capacities of the various supplies are noted below

+300	600 ma
+100	275 ma
-100	275 ma
-190	560 ma
-350	50 ma
+ 28	4 amps

On the regulator chassis there are a-c 115-volt relays which connect the unregulated B voltages to the plates of the regulator tubes. This connection is not made until the filaments in the control tubes have had a chance to warm up. This is governed by a time delay tube in the power supply distribution panel (Figure 31), which closes the circuit to the 115-volt relays only after the start switch on the front panel of the power supply has been turned on. When the time-delay tube closes, the ready light goes on, and when the operate push button is depressed, the 115-volt relays close and the B-supply voltages are turned on. Note that each B-supply voltage has a d-c relay across its unregulated supply. Unless all these relays (and hence all the B supplies) are on, the 115-volt a-c relays drop out and turn all the B voltages off. This is to prevent damage to the computer if one of the B supplies goes out. The operate push button by-passes this safety feature in order to close the 115-volt relays initially.

The distribution panel (Figure 31) receives power cables from the regulator chassis, +12-volt filament source, and +28-volt relay supply (Figure 32) and distributes them through the main power cable to the amplifier relay rack. It also distributes +28 volts to the stepping-relay panel and receives

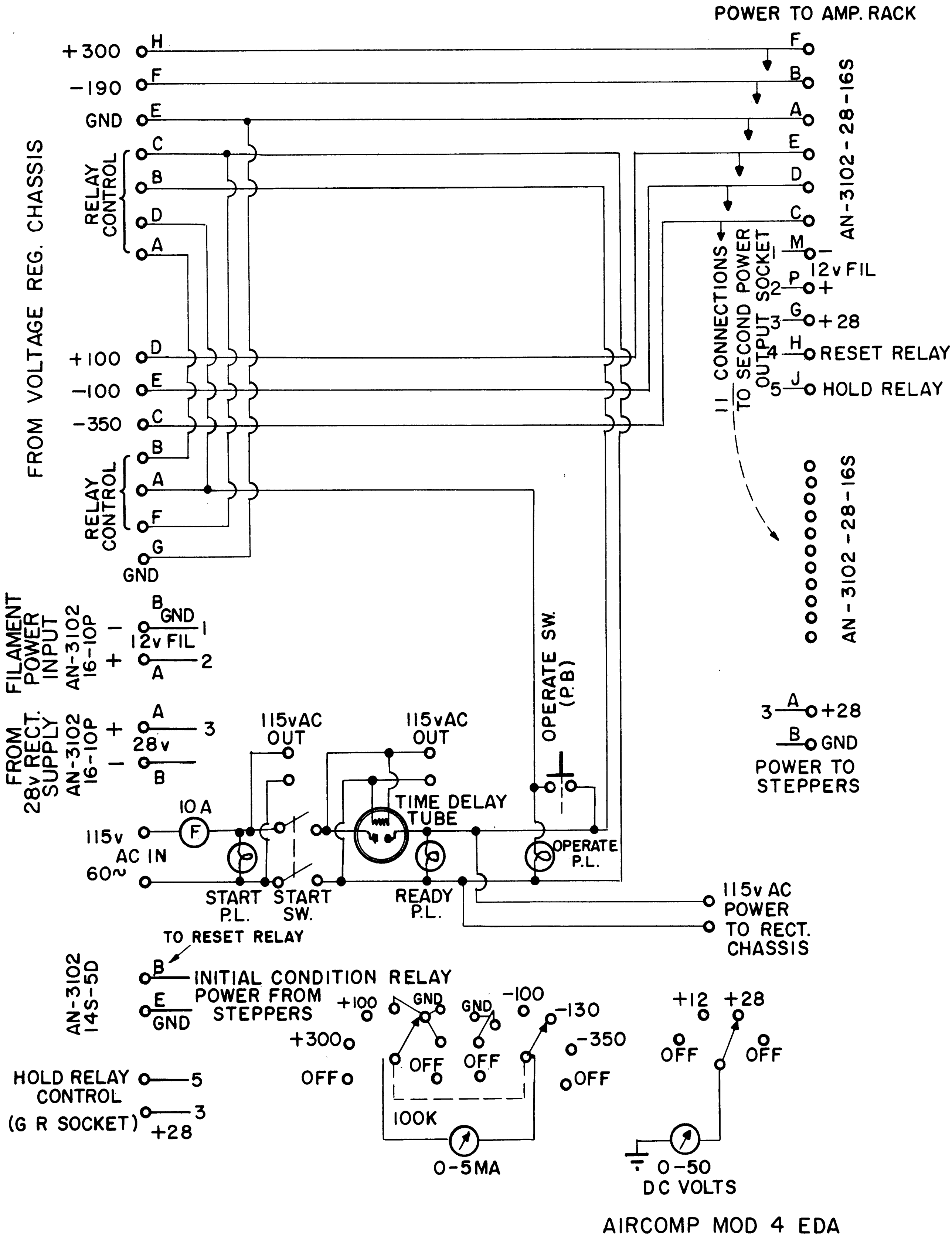


Figure 31. Power Supply Distribution Panel.

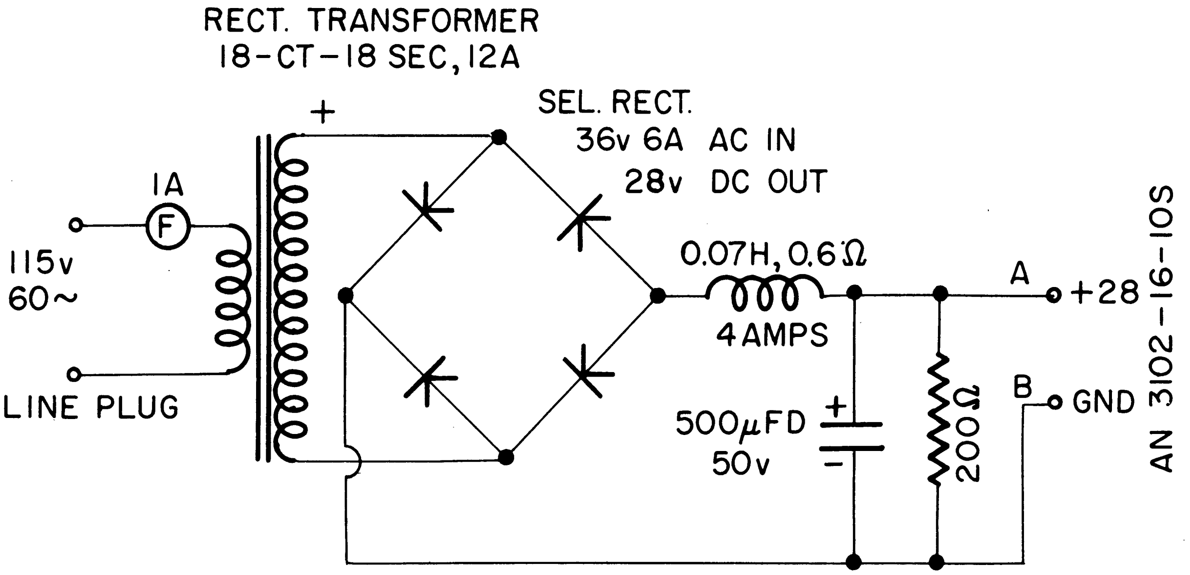


Figure 32. 28 Volt DC Supply.

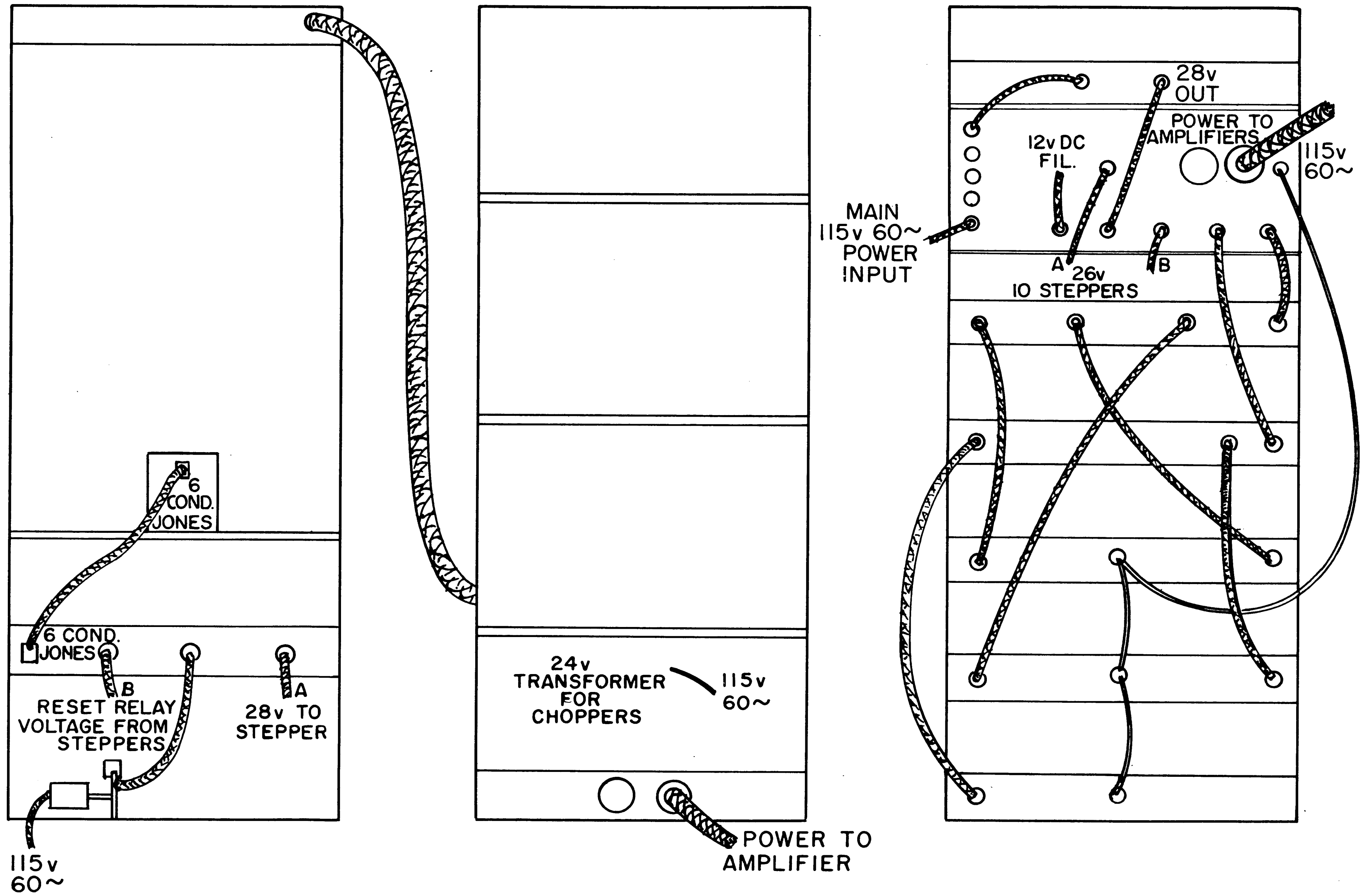


Figure 33. Schematic for Cable Connections.

the +28 volt initial-condition voltage from the stepping-relay panel. Voltmeters are provided on the front of the panel to monitor the various voltages. The hold-relay socket on the back of the panel is designed so that when a connection is made between the terminals, the hold relays are energized.

5. Recording Assembly

A recording galvanometer cart, including a Sanborn Model 60 1300 2-channel recorder and two electronic amplifiers is provided for the Air Comp. Mod. 4 Electronic Differential Analyzer. The regular Sanborn instruction manual should be consulted for a description of the actual recording galvanometer. The two-channel electronic drive for the recorder consists of a power supply and two d-c amplifiers. The circuit for the power supply is shown in Figure 34; it is a conventional circuit with VR regulated d-c output voltages of +300, +75, -195, and -345, and unregulated d-c output voltages of about +200 and -200 volts. Power input is provided through a separate 115-volt 60-cycle plug. Two 12-pin Jones sockets are provided for cable connection to the respective amplifier channels, and a 10-pin Jones socket is provided for cable connection to the galvanometer assembly.

The circuit diagram for the d-c amplifier is shown in Figure 35. It actually consists of two operational amplifiers. The first amplifier is used to provide various amplifications of the input signal, depending on the amount of feedback given by the selector switch. The output of the first amplifier feeds into the second amplifier, which has a 6AQ5 cathode follower as its final output stage in order to drive the 3000 ohm recorder coil. This second amplifier has input and feedback impedance networks which compensate for the falloff with frequency of the galvanometer output and give the amplifier a d-c gain of about 2. The amplifier-galvanometer combination has a frequency response flat within

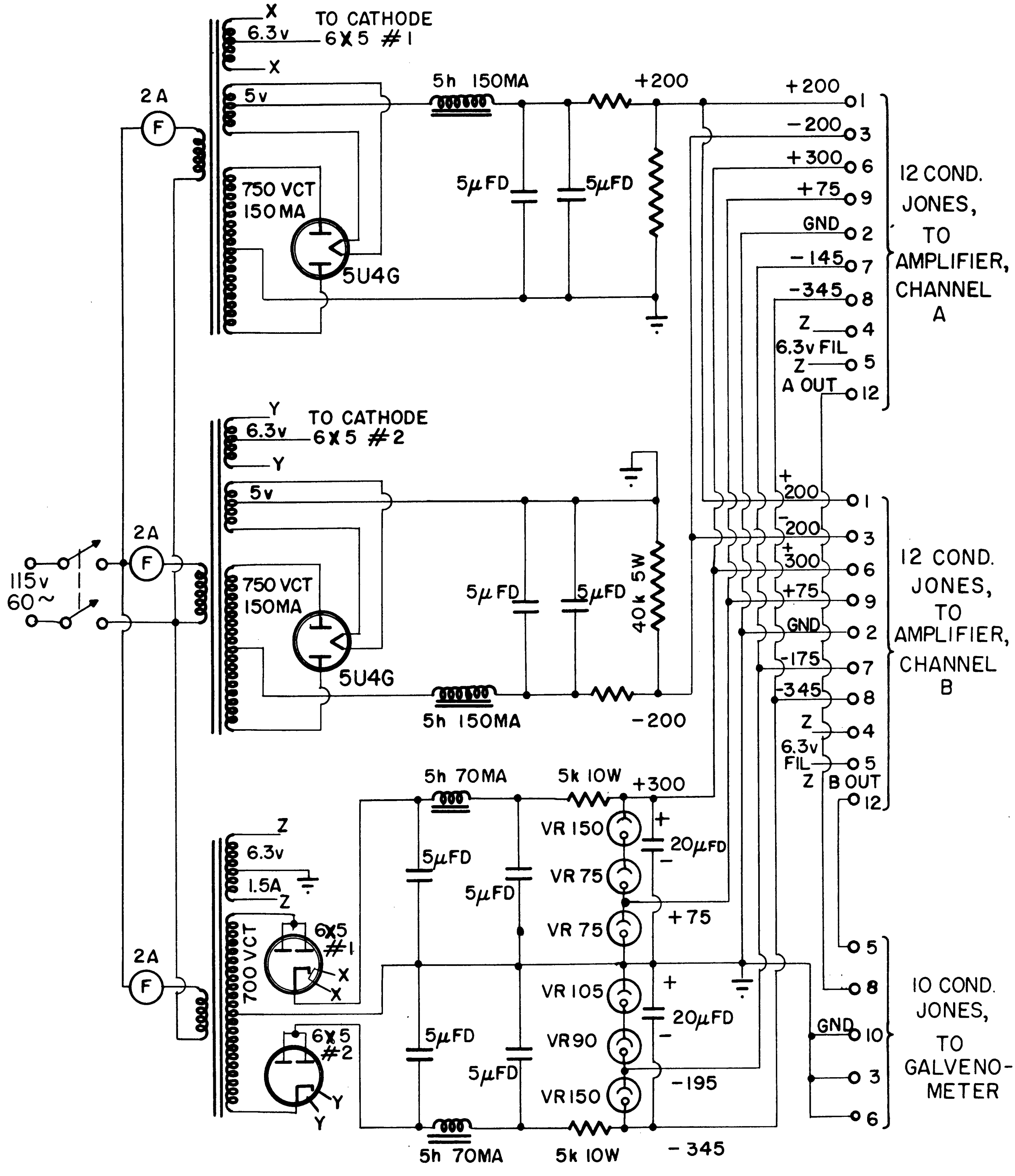


Figure 34. Power Supply for Recorder Amplifiers.

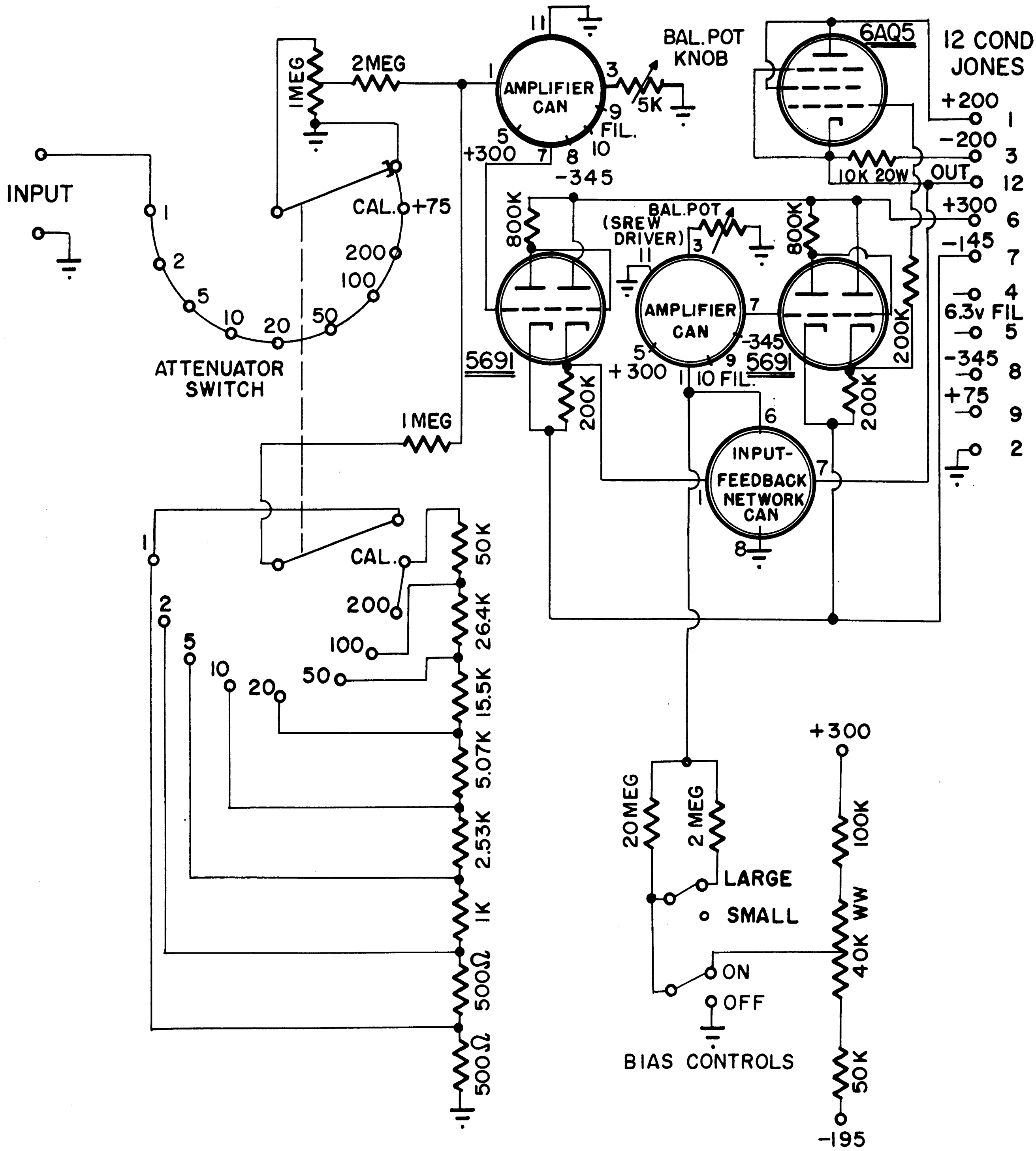


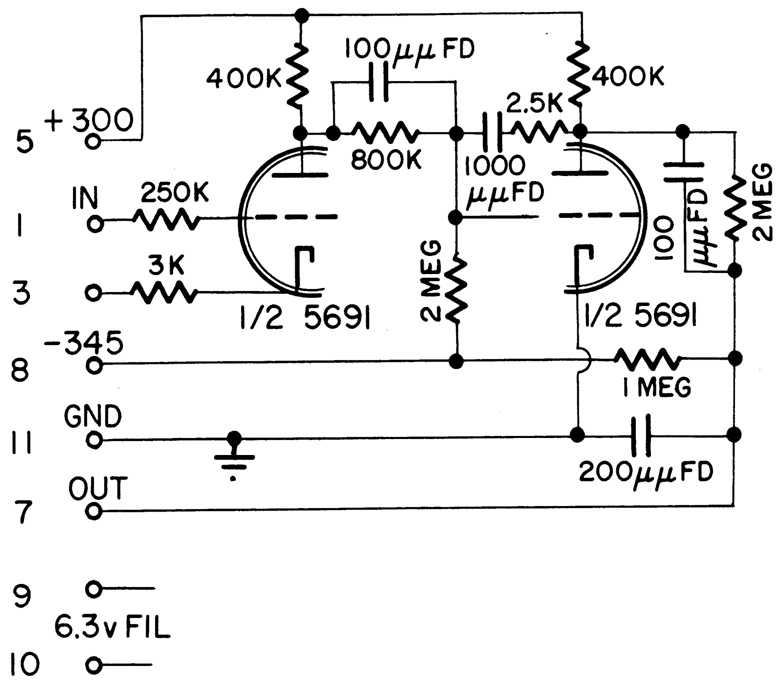
Figure 35. Amplifier Schematic for the Recorder Drive.

0.1 db to about 75 cycles per second, and is down 1 db at 100 cycles per second (see Figure 37). Without the compensation the galvanometer alone is down 1 db at 30 cycles per second when the driving impedance is adjusted for a galvanometer damping ratio of 0.7. An additional input is provided to the d-c amplifier for a bias control. The unregulated B+ and B- voltages for the 6AQ5 are designed so that positive and negative saturated outputs correspond approximately to full scale recording arm deflections. Hence it should not be possible to damage the galvanometer through too big a signal input. The circuit for the plug-in portion of the d-c amplifiers is shown in Figure 36.

After several minutes warm-up time the following procedure should be used to adjust the recorder. With no input turn the attenuator control to off. Here the amplifier gain is a maximum with zero input, so that the d-c balance control has maximum sensitivity. The balance knob should be adjusted until the recorder arm is about on center. This adjusts the balance of the first amplifier. The second amplifier (with 6AQ5 output) has a screw-driven balance adjustment which normally does not need to be changed.

After the balance adjustment turn the attenuator control to 200. Here the amplifier gain is a minimum and negligible zero offset is assured. The bias control should now be adjusted until the recorder arm reads zero deflection. The bias compensates for any unbalance either in the second amplifier or in the galvanometer suspension.

Next the sensitivity control is varied with the attenuator on "CAL" until the desired recorder arm deflection for 75 volts input and 200 attenuation is reached. Finally the attenuator is switched to the desired attenuation and the voltage to be recorded is plugged in. Zero drift of the amplifier should be negligible on all but the lowest several attenuations. However, some hysteresis (about 0.5 mm) may be noted in the recording galvanometer.



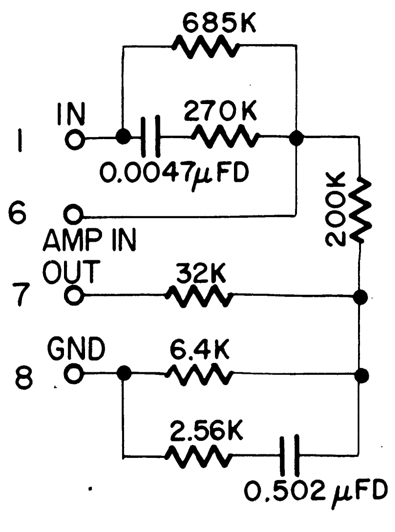


Figure 36. Amplifier Can Circuit and Input-Feedback Can Circuit.

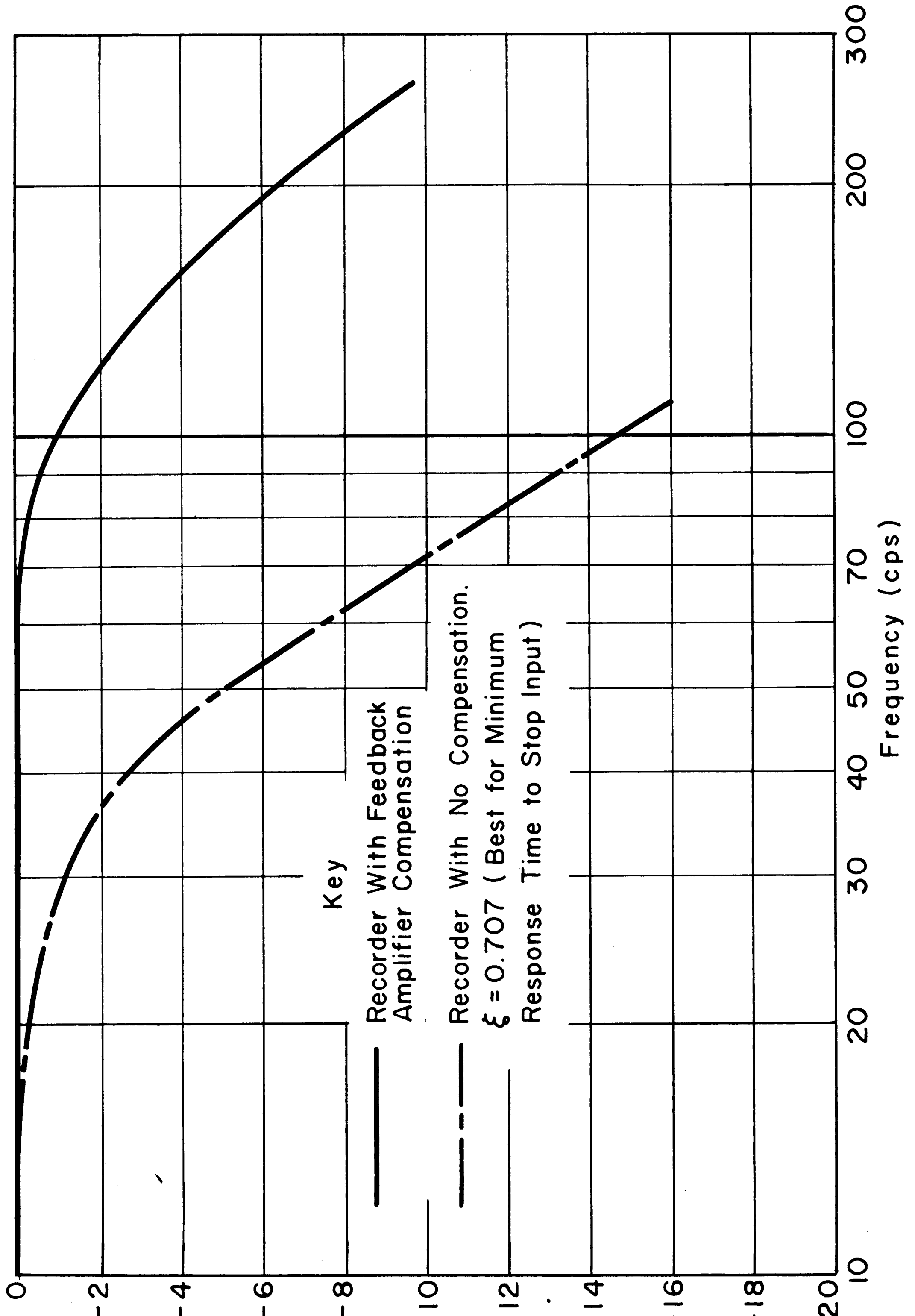


Figure 37. Frequency Response of Uncompensated and Compensated Recorder.