A MICROWAVE POWER CONTROLLER for a RADIATION BIO-EFFECTS EXPOSURE FACILITY

ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Monitoring

A MICROWAVE POWER CONTROLLER for a RADIATION BIO-EFFECTS EXPOSURE FACILITY

by

JOSEPH S. ALI

Twinbrook Research Laboratory
12709 Twinbrook Parkway
Rockville, Maryland 20852

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ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Monitoring
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DISCLAIMER

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FOREWORD

Members of the Engineering-Physics Section at the Twinbrook Research Laboratory have designed and installed a device that controls and monitors the environmental parameters of an animal exposure chamber and detects and measures physiological responses of the subject during microwave exposure. The system includes a double-walled lucite sphere that serves as the exposure chamber which is located within an anechoic chamber; an atmospheric conditioning unit that supplies a predetermined mixture of atmospheric gas to the exposure chamber under specified conditions of humidity, temperature, and velocity; a 2450 MHz microwave exposure source; a laboratory built microwave power controller; and a laboratory computer with auxilliary equipment that controls the system automatically and records the subject's physiological responses for subsequent analysis.

Experience has shown that normal line voltage fluctuations cause errors as great as 20% in the microwave power being delivered to the subject and thus reduce the validity of the experimental results.

The microwave power controller that was designed and built to overcome this source of error is described in this report. The rationale for its design, the parts used, and the circuits are discussed.

The system is modified as requirements change and as operational data become available. Additional information concerned with design of irradiation systems and the biological effects of irradiation is sought on a continuing basis. The comments of individuals interested in this system or with other aspects of radiation protection of man and his environment are solicited.

John E. Regnier, Ph.D.
Acting Director
Twinbrook Research Laboratory

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ABSTRACT

This paper is a complete documentation of a microwave power controller for use with a Varian Associates Model PPS-2.5 AS high power industrial generator developed to improve the operating characteristics of our 2450 MHz irradiation facility. The paper includes theory of operation, photographs, circuit schematic drawings, wiring diagrams and a parts list of the controller. The controller makes the RF power output insensitive to low frequency line voltage fluctuations and also permits the RF power output to be programmed automatically.

ACKNOWLEDGMENTS

The author would like to express his appreciation for the assistance of Mr. Daniel L. Dawes in the measurement of the mechanical parameters of the Varian generator.

The efforts of the Information Services Section, Office of Information, BRH in the preparation of the drawings and photographs are appreciated.

INTRODUCTION

One of the functions of this laboratory is to examine the potential hazards of microwave radiation by studying its effects on biological specimens. The microwave radiation delivered to the specimen must be closely controlled in order to acquire meaningful data and to assure the reproducibility of the results. In our 2450 MHz irradiation facility, microwaves are generated by a 3000 watt Varian Associates Model PPS-2.5 AS high power microwave generator. The high voltage power supply in this unit is unregulated and, therefore, the output power fluctuates as the line voltage varies. During long-term exposures (16 hours), the output power has varied as much as 20%.

A microwave power controller having the specifications given in Table 1 was therefore developed to automatically negate the effects of line voltage fluctuations. The controller also permits the exposure time and the RF waveform to be programmed manually or automatically through a data acquisition system provided that the waveform has a video bandwidth no larger than approximately 2 Hz.

TABLE 1

MICROWAVE POWER CONTROLLER SPECIFICATIONS

Operating Voltage	105-125 V AC
Line Regulation[a] (± 10%)	0.1%
Temperature Coefficient (20-30° C)	0.1%/°C.
Stability[b] of Microwave Power Output (48 hours)	± 1.5% of set point with no noticeable (to 0.2%) continual accumulation of drift after 48 hours
Servo Bandwidth	2 Hz
Servo Deadband[c]	± 150 W
Resolution of Readout (Digital Panel Meter)	10 W

[a]"Line Regulation" is defined as the maximum percentage change in the microwave power output caused by a ± 10% change in line voltage either to the Microwave Power Controller, the Varian generator, or both.

[b]Excluding transients of less than one second duration.

[c]For errors greater than 150 W, the correction time is limited by the 2-Hz servo bandwidth. For errors less than 150 W, the error will be corrected by the integrator (OA 3). The maximum time before a correction occurs is approximated by $t = 30/A$ where t is the time before a correction in seconds and A is the error in watts.

DESCRIPTION

General

The Microwave Power Controller (MPC) is part of the 2450 MHz irradiation facility which is depicted in Figure 1. The MPC can be operated either in a manual or computer mode. In the computer mode, the MPC accepts commands from the data acquisition system (DAS) and in turn adjusts the output power of the Varian generator in a closed loop fashion by means of a 0 10 V signal from a digital to analog converter channel in the DAS. The microwave power is sensed by an analog to digital converter channel in the DAS. There are also several control and sense lines between the DAS and the MPC. These allow the RF to be turned on and off, sense whether the RF is ready to be turned on, interrupt the DAS processing if the MPC goes "out of regulation," and sense whether the MPC is switched in the manual or computer mode.

In the manual mode, the RF is activated and deactivated by push-button switches, and the RF level is adjusted by a potentiometer.

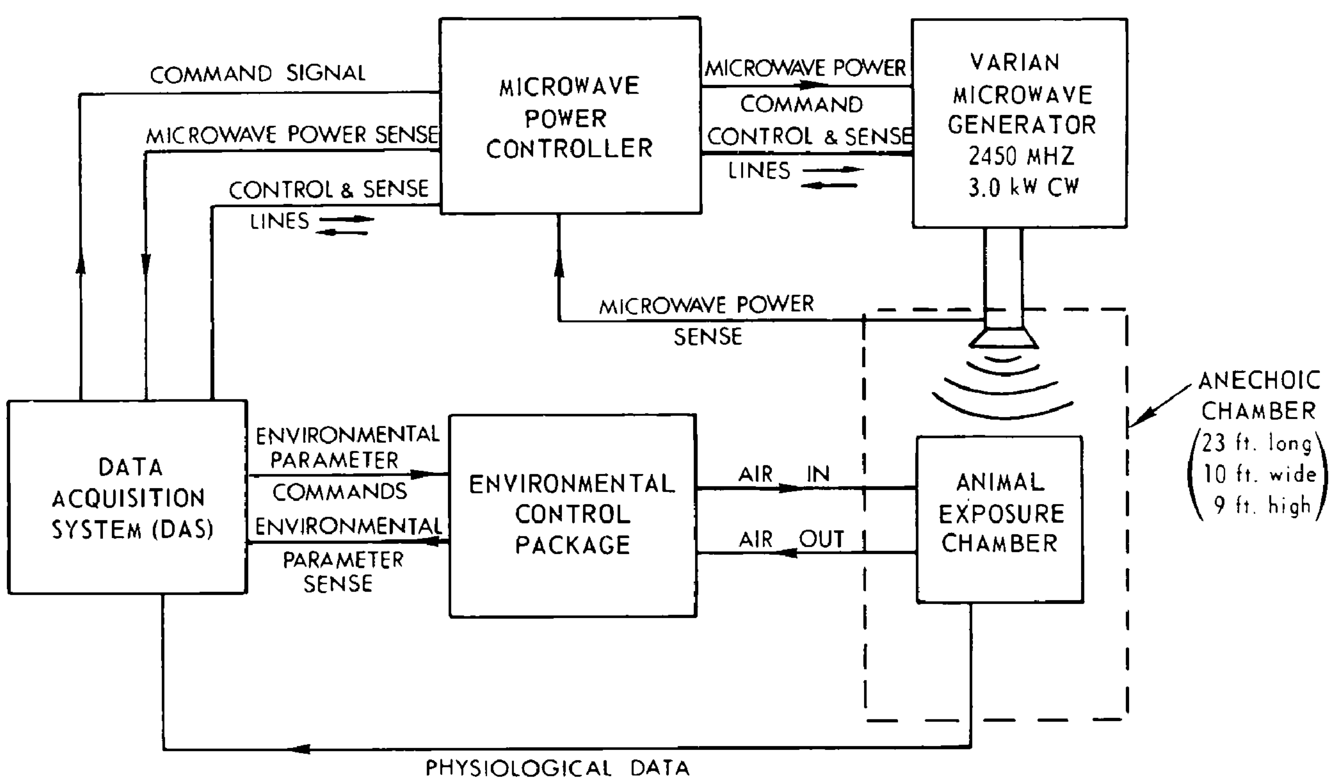

Figure 1. Block Diagram of the 2450 MHz Irradiation Facility.

The MPC together with the Varian generator is a feedback control system that maintains the microwave power output at a level determined by a reference. The MPC generates a voltage that is dependent on the difference between the reference level desired and the power actually being generated. This error voltage is applied to a motor which is coupled to a three-phase Powerstat[1] variable autotransformer in the Varian generator. The Powerstat controls the high voltage applied to the magnetron tube and thus the microwave power. The microwave power is sampled through a 25 dB crossguide coupler and 30 dB of attenuation with a crystal detector. The output of the crystal is signal conditioned and compared with the reference. The power level is indicated on the front panel by a digital panel meter.

Front Panel Controls and Indicators

The front panel of the MPC control chassis is shown in Figure 2.

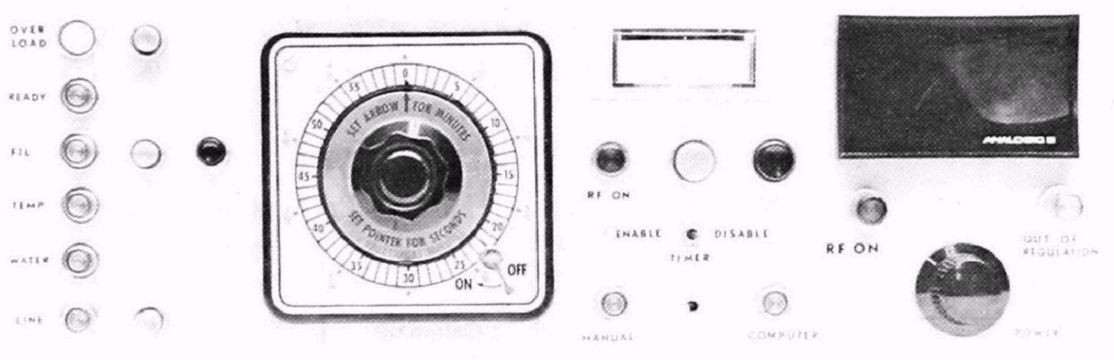

Figure 2. Front Panel of the Microwave Power Controller Control Chassis.

LINE The line switch (push on - push off action) applies power to the control chassis directly and also to the Varian generator and the Power Amplifier Power Supply through a relay.

LINE INDICATOR The line indicator is illuminated when line voltage is applied to the Varian generator.

WATER INDICATOR The water level indicator is illuminated only when line voltage is applied to the Varian generator and sufficient water is contained in the reservoir to cool the magnetron tube.

TEMP INDICATOR This indicator extinguishes if the temperature of the magnetron exceeds a safe level.

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[1]Superior Electric Co.

FIL ON The magnetron filament is energized by pressing the red filament switch (momentary action).

FIL OFF The magnetron filament is de-energized by pressing the black filament switch (momentary action).

FIL INDICATOR The filament indicator is illuminated when power is applied to the filament of the magnetron tube.

READY INDICATOR The ready indicator is illuminated after several conditions have been met: The filament has had sufficient time to heat (about two minutes); the two doors into the irradiation facility are closed; the overload relay in the Varian generator has not been tripped; and the timer enable/disable switch is in the disable position or the switch is in the enable position and the timer has been set.

OVERLOAD The overload switch (momentary action) resets the overload relay and returns the generator to the "ready" state if the conditions under the paragraph *Ready Indicator* are met.

OVERLOAD INDICATOR The overload indicator is illuminated when the overload relay has been tripped. This relay is activated when there is excessive plate current through the magnetron.

TIMER The timer is used to program an exposure duration into the MPC when the controller is in the manual mode.

MANUAL/COMPUTER The manual/computer switch selects the mode of operation of the controller. In the manual mode, the reference is derived internally and the duration of the exposure is controlled through push-button switches or through the timer. In the computer mode, the power level reference is supplied externally by the DAS. The RF power can be switched on or off automatically in the computer mode; however, the front panel push buttons will also operate in the computer mode.

ENABLE/DISABLE This switch is used when the MPC is in the manual mode to place the timer in the circuit to permit exposures of preset duration. When the switch is in the disable position, the RF, once switched on, must be switched off manually.

RF ON The RF on switch (momentary action) is used to turn on the microwaves when the MPC is in the manual mode. The switch is operative only when the ready indicator is illuminated.

RF OFF The RF off switch (momentary action) is used to turn off the microwaves when the MPC is in the manual mode. The switch will function when the MPC is in the computer mode if necessary.

DEVIATION METER The deviation meter is used to indicate the error between the actual forward power and the desired power level. Each minor division represents 6 watts.

POWER The power control is a ten-turn potentiometer used to adjust the microwave power over the range of 0 to 3.0 kW.

RF ON INDICATORS (TWO) These red indicator lamps are illuminated when the RF is on. The RF on indicator nearest the power control is a flashing indicator to provide a readily apparent indication that the generator is fully energized.

OUT OF REGULATION INDICATOR This amber indicator is illuminated when a failure in the MPC has occurred and the output has departed significantly from the desired value.

OUTPUT POWER (DIGITAL PANEL METER) This meter indirectly indicates the transmitted RF power level. A calibration curve has been determined to convert the meter readings into watts of transmitted power (see section on crystal detector below).

Rear Panel Connectors

The rear panel of the MPC control chassis is shown in Figure 3.

J_1 BNC, Female. J_1 is the external reference input.

J_2 BNC, Female. J_2 is the 0 10 V analog signal proportioned to forward microwave power.

J_3 Amphenol Micro-Ribbon connector, Female. J_3 carries control and sense lines from the DAS to the control chassis.

J_4 BNC, Female. J_4 is the input from the crystal detector.

J_5 BNC, Female. J_5 is the output to the power amplifier.

J_6 Amphenol Blue Ribbon Connector, Female. J_6 carries control and sense lines from the control chassis to the chassis on the Environmental Control Package.

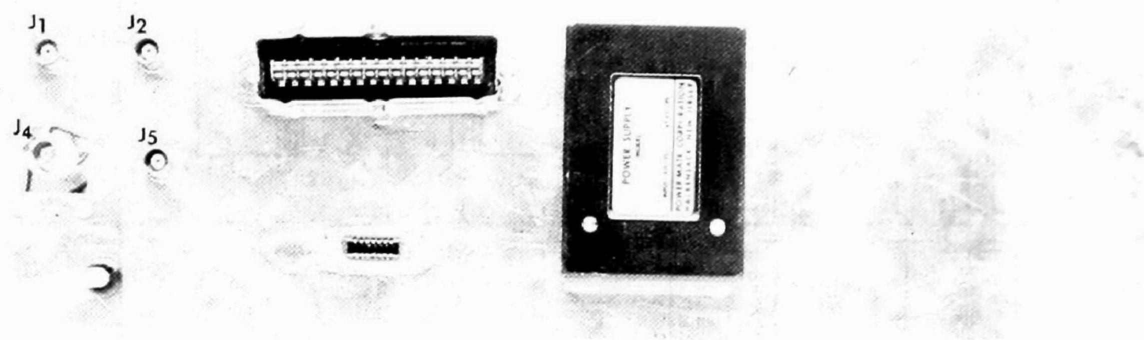

Figure 3. Rear Panel of the Microwave Power Controller Control Chassis.

THEORY OF OPERATION

A block diagram of the MPC is shown in Figure 4. Functionally the MPC can be thought of as a power leveller and as a remote control terminal. The two functions interact in only a few cases.

Control Circuitry

As is evident from the preceding description of the front panel controls and indicators, the Varian generator can be operated remotely from the MPC front panel. The front panel wiring is shown in Appendix A, Figure A-4. To achieve remote control operation, each normally open switch in the Varian generator (see Appendix A Figure A-10) was paralled by another normally open switch; a normally closed switch was added in series to each normally closed switch, and indicator lights were added in parallel to existing lights.

All of the generator remote switches are manually operated. However, the RF on and RF off functions can be controlled by the DAS when the MPC is in the computer mode.

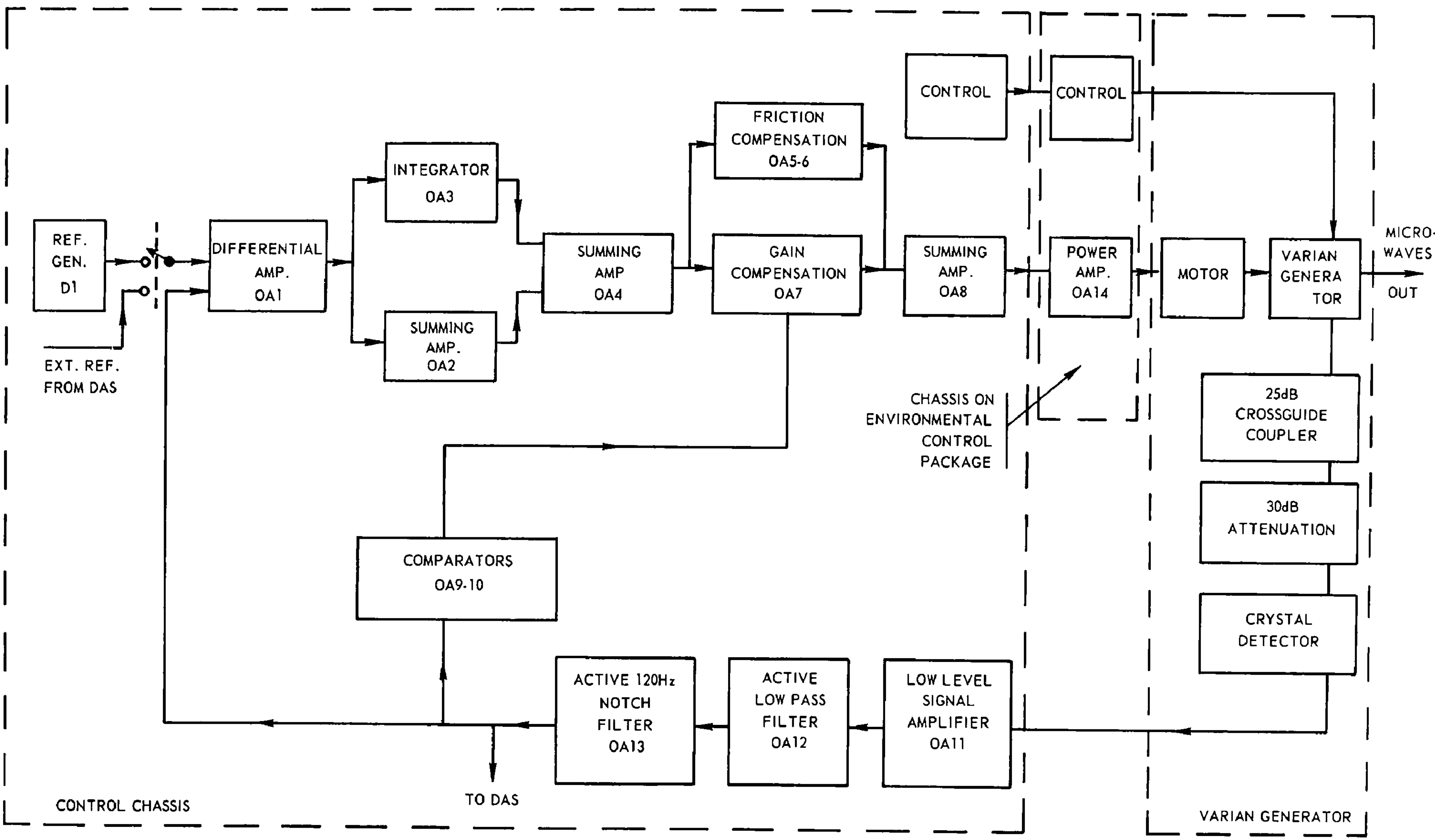

Figure 4. Block Diagram of the Microwave Power Controller.

In addition to these basic control circuits, the following control circuits are used:

Priority Interrupt Relay K_2 (see Appendix A Figure A-6) is energized if the integrator output exceeds 10 V in magnitude. This relay is connected to a priority interrupt line on the DAS. The integrator output voltage does not exceed 10 V under normal operation because of the integrator time constant.

Integrator and Reference Line Disable When the RF is off, the reference line and integrator must be disabled. These functions are performed by K_4, Q_1, and K_1 (see Appendix A Figure A-6). These circuits must be disabled when the RF is off to prevent the generation of an unwanted error signal.

Power Leveller

Reference Generator The internal reference generator (see Appendix A Figure A-6) consists of parts R_5, C_1, D_1, and R_6. D_1 is a 10-V zener diode used as the reference. The voltage cross D_1 is divided with a ten-turn potentiometer, R_6. If the MPC is in the manual mode, the voltage at the wiper of R_6 is then applied to OA 1.

Differential Amplifier (OA 1) OA 1 (see Appendix A Figure A-6) is used as a unity gain differential amplifier which generates an error voltage proportional to the difference between the reference voltage (either internally generated or externally supplied) and the feedback voltage derived from the crystal detector. This error voltage is displayed on the deviation meter (M 1) which is calibrated to 6 watts per division.

Summing Amplifier (OA 2) The output of OA 1 is fed to the summing amplifier (OA 2). OA 2 (see Appendix A Figure A-6) inverts the output of OA 1 so that the integrator output and the proportional error voltage have the correct sign relationship. In addition, another input can be applied to OA 2 through R_9. This input line is used only when the RF is off, and it serves to keep the autotransformers in the Varian generator at the zero power position. Having the Powerstat wipers in the zero power position prevents damage to them when the RF is switched on.

Integrator (OA 3) The integrator (see Appendix A Figure A-6) maintains the average output power at the set value. An error that might not otherwise be large enough to overcome the deadband of the system will, with the integrator, be integrated through the deadband initiating a correction. The integrator is also used to activate the "out of regulation" indicator by energizing K_3 when the integrator output exceeds 10 V. A complementary driver (Q_2, Q_3) is needed to drive K_2 and K_3 since the integrator output can be of either polarity.

Summing Amplifier (OA 4) OA 4 (see Appendix A Figure A-7) is used as a unity gain summing amplifier to sum the integrated and proportional error voltages.

Gain Compensation (OA 7) A nonlinear relationship was determined experimentally between the Powerstat angular position and the microwave power output. Output microwave power changed much more by a unit angular rotation at high power levels than at low levels. The forward gain was not constant and in fact increased as the output power increased. This situation is highly undesirable in a servomechanism for it could cause either a large deadband or an oscillatory system depending on the constant value of forward gain selected.

OA 7 (see Appendix A Figure A-7) is a gain compensation circuit which, along with OA 9 and 10, correct for the nonlinearity in output power vs. Powerstat shaft angle. R_{25} and R_{26} divide the output voltage of OA 4 by ten. This is done to use OA 7 with a gain greater than one. At low power levels both Q_4 and Q_5 are off and therefore the voltage at the output of OA 4 equals the output of OA 7 (effective gain = 1). At higher power levels, Q_4 is switched on, thus reducing the effective gain from OA 4 through OA 7 to one-half. The reduction in gain was chosen to first compensate for the increase in gain between the Powerstat shaft angle and output power. At still higher power levels, as the generator gain increases still further, OA 5 is switched on to compensate for this further increase.

A graph of power out vs. Powerstat shaft position indicated that only a three line approximation to the curve was needed. The slope of each line was translated into the compensating gain needed to make the overall forward gain constant, and the intersections of the linear approximations were translated into the output power at which the gain should be changed. This last function is performed by OA 9 and OA 10.

Comparators (OA 9 and OA 10) The comparators (see Appendix A Figure A-7) are used in conjunction with OA 7 to change the forward gain to compensate for the change in sensitivity of power output vs. Powerstat shaft angle. The comparator reference voltages are set for values determined from the curve of power out vs. shaft angle, which has been approximated by three straight lines. OA 9 and 10 sense the signal proportional to microwave power and change the gain of OA 7 at the preset power levels. The gain changes are effected at approximately 250 W and at 1.37 kW.

Friction Compensation (OA 5, OA 6) The Powerstat shaft on the Varian generator has a large amount of friction due primarily to the pressure of the wipers on the Powerstat coils. The friction was measured and found to be 100 in.-oz. This friction would be detrimental to the operation of the servomechanism if left completely uncompensated because it would introduce a large deadband into the system. If the deadband were to be eliminated simply by increasing the forward gain, the system would be oscillatory. Although the friction varies with Powerstat shaft angle, a good deal of the deadband can be eliminated simply by applying an extra 80 in.-oz to the Powerstat shaft.

This friction compensation signal is generated by 0A 5 and 6 (see Appendix A Figure A-8) and their associated components. Two stages are necessary since the shaft can rotate in either direction. R_{40} and R_{48} determine how many watts error is to be allowed before the compensation signal is generated. R_{45} and R_{53} establish the level of the compensation signal. The gain compensation stage is bypassed by the friction compensation stages because the friction torque is approximately constant with shaft position. The friction compensation circuits reduce the deadband by a factor of about five.

Summing Amplifier (0A 8) 0A 8 (see Appendix A Figure A-8) acts as a summing amplifier for the gain compensated error signal and the friction compensation signal. The gain of this stage is adjustable through R_{56}.

Power Amplifier (0A 14) Substantial current is required to drive the Printed Circuit Motor[1] (Motor 1). 0A 14 (see Appendix A Figure A-9) in conjunction with the power bridge (Q_{8-11})[2] supply this high current capability (see Figure 5). Only one power supply is needed for this circuit providing economy in cost and space. Q_{8-11} are mounted on Wakefield Model NC-421A heat sinks since the power dissipation of each transistor can be as high as 50 W.

Motor The motor used to drive the Varian generator Powerstat shaft is a printed circuit DC motor. The motor is shown mounted on the Varian generator in Figure 6. The motor was chosen for its low inertia (0.099 oz.-in. sec.^{2}) and high torque capability thus permitting a short response time.

Crystal Detector The crystal detector is a Boonton Electronics Corp. Model 41-4A. This detector was chosen because of its excellent temperature stability when operated with a load impedance of approximately 10 megohms. The temperature-induced drift in the detector output voltage was approximately 0.05%/°C over the temperature range of 15 to 28°C and over the power range of -10 to +10 dBm with an output load impedance of 10 megohms when measured in our laboratory. However, this detector does

[1]Printed Motors, Inc.
[2]See Analog Devices, Inc., Model 408 Data Sheet

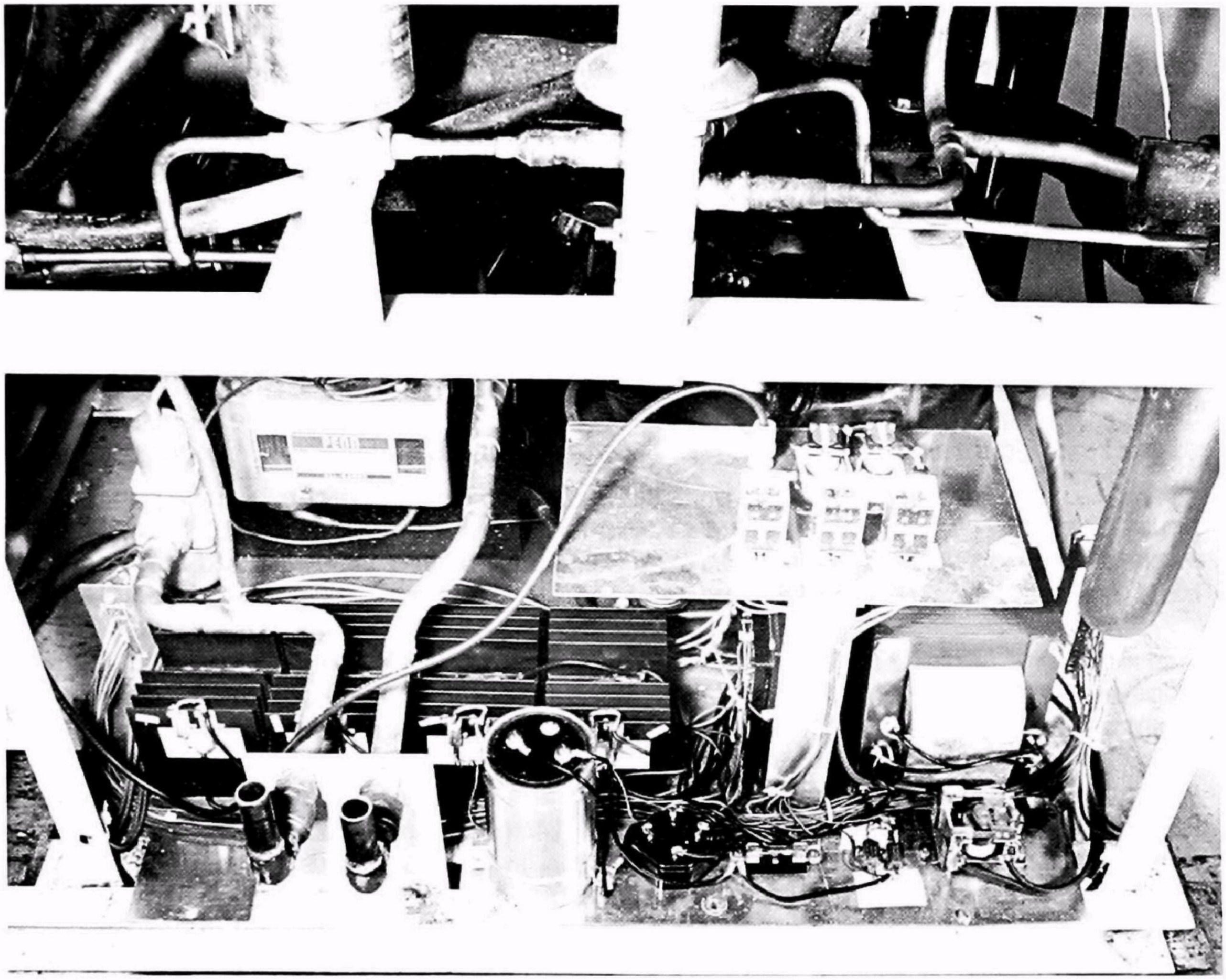

Figure 5. Chassis on the Environmental Control Package

have the disadvantage that its output voltage is not linear with respect to the input microwave power. A calibration curve has therefore been determined to relate the digital panel meter readout to the microwave power being transmitted from the 10 dB horn antenna.

FET Input Amplifier (OA 11) Since the detector described above should operate with a high impedance load for optimum temperature stability, a special operational amplifier is necessary to acquire the signal appearing across this impedance. The bias current of bipolar operational amplifiers would generate an excessive offset voltage if it were to pass through R_{57} (Appendix A, Figure A-5), the high impedance load. Field effect transistor (FET) input operational amplifiers, however, are well suited for this purpose because their input bias current is orders of magnitude lower than that of bipolar operational amplifiers. In addition since the minimum signal level of interest from the Booton detector is 100 mV, the 25 $\mu V/^{\circ}C$ offset voltage drift specification of Analog Devices Model AD516K is more than adequate.

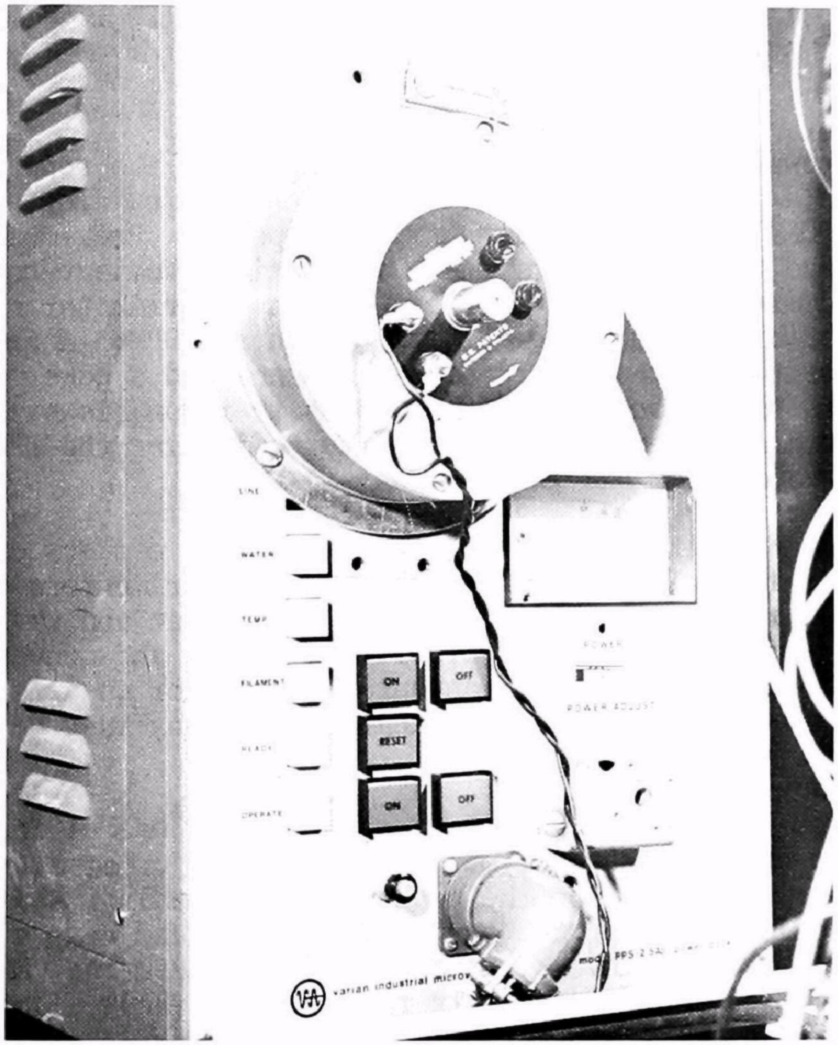

Figure 6. Motor Mounted on the Varian Generator.

Active low Pass Filter (OA 12) OA 12 (see Appendix A Figure A-5) is a low-pass filter with a bandwidth of about 70 Hz. The function of this and the following circuit (OA 13) is to attenuate the detected modulation frequencies of the RF output. Since the high voltage power supply in the Varian generator is unfiltered and the filament supply voltage is sinusoidal, there is about 10% RMS ripple with major components at 120, 360, and 720 Hz. The low-pass filter attenuates the 360 and 720 components to acceptable levels.

120 Hz Notch Filter (OA 13) Measurement of the spectral content of the modulation indicated a 5% RMS 60 Hz component in the unmodified Varian generator. The addition of a full-wave bridge in the filament circuit of the magnetron tube doubled the frequency of this component to 120 Hz. An active notch filter[1] (see Appendix A Figure A-5) was used to eliminate this component in the detected signal.

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[1]See Motorola, Inc., Application Note N. AN-438.

OPERATIONAL EXPERIENCE

The Microwave Power Controller has simplified the reproduction of a desired field intensity at a given location by providing a digital panel meter (DPM) readout of transmitted RF power. Previously a power measurement had to be taken for each irradiation, subject to variations due to dipole misalignment. With the MPC, an experimenter notes the coordinates of his subject and the readout on the DPM. A field intensity measurement is taken with a dipole antenna and a power meter where the subject is to be located. If he wishes to rerun his experiment, he simply places his subject in position after adjusting the DPM readout to the value he noted from his initial run.

To aid in repositioning a subject accurately, members of our laboratory have designed a laser mount which allows experimenters to place a small helium-neon laser in alignment with the throat and waveguide of the transmitting horn antenna. This provides a simple and convenient means of locating the axis of the horn antenna. Thus, for on-axis irradiations, only the distance from the transmitting horn antenna must be measured to define an exposure location.

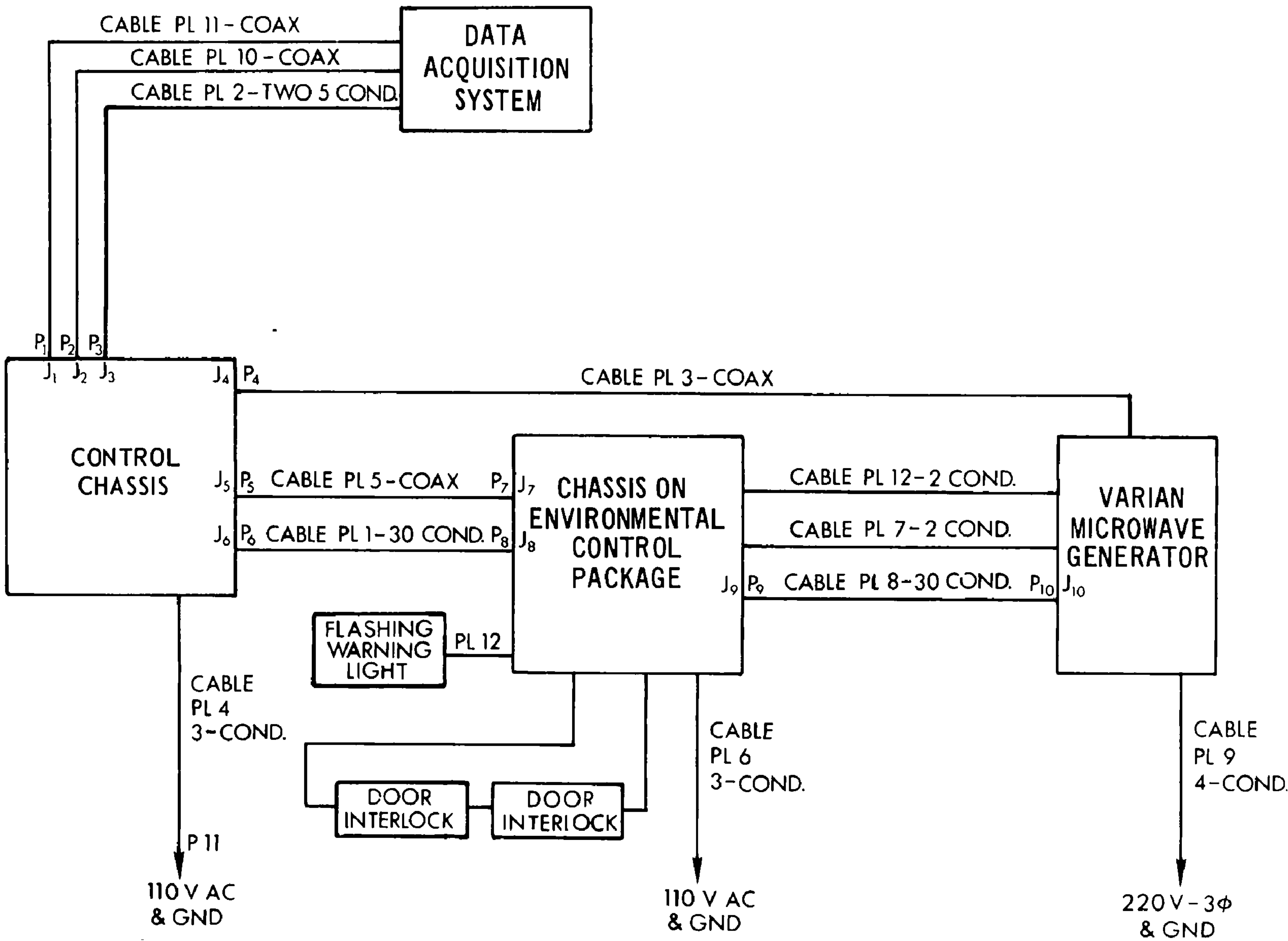
The closed loop control has been particularly useful in cases where a field in the anechoic chamber must be known over an area. Typically an investigator must position the probe, take a reading, shut down the RF power, reposition the probe, turn the power on and take a new reading, etc. Using the MPC the investigator has only to push the "RF on" button and the transmitted power is quickly reproduced without significant drift.

Other features of the MPC which have proved useful are the "slow turn on" circuitry, the door interlocks, and the remote control operation. The "slow turn on" circuitry ($R_{7, 8, 9, 13, 14, 15}$, C_2, D_2) has greatly reduced pitting of the autotransformers in the Varian generator. Previously, if the "RF on" button on the Varian console was depressed while the autotransformers were not set for zero output voltage, the resulting large current transient would pit the autotransformer windings. With the MPC, $R_{7, 8, 9}$ insure that the autotransformer is returned to the zero output voltage position when the RF power is switched off. When the RF is switched on, the remaining components insure that the turn-on will be gradual with a time constant of about 2 seconds. The door interlocks have been found essential for personnel safety. The interlocks are wired so that if either the door to the anechoic chamber or the door to the generator area is opened, the microwave power is immediately switched off and will remain off whether or not these doors are then closed.

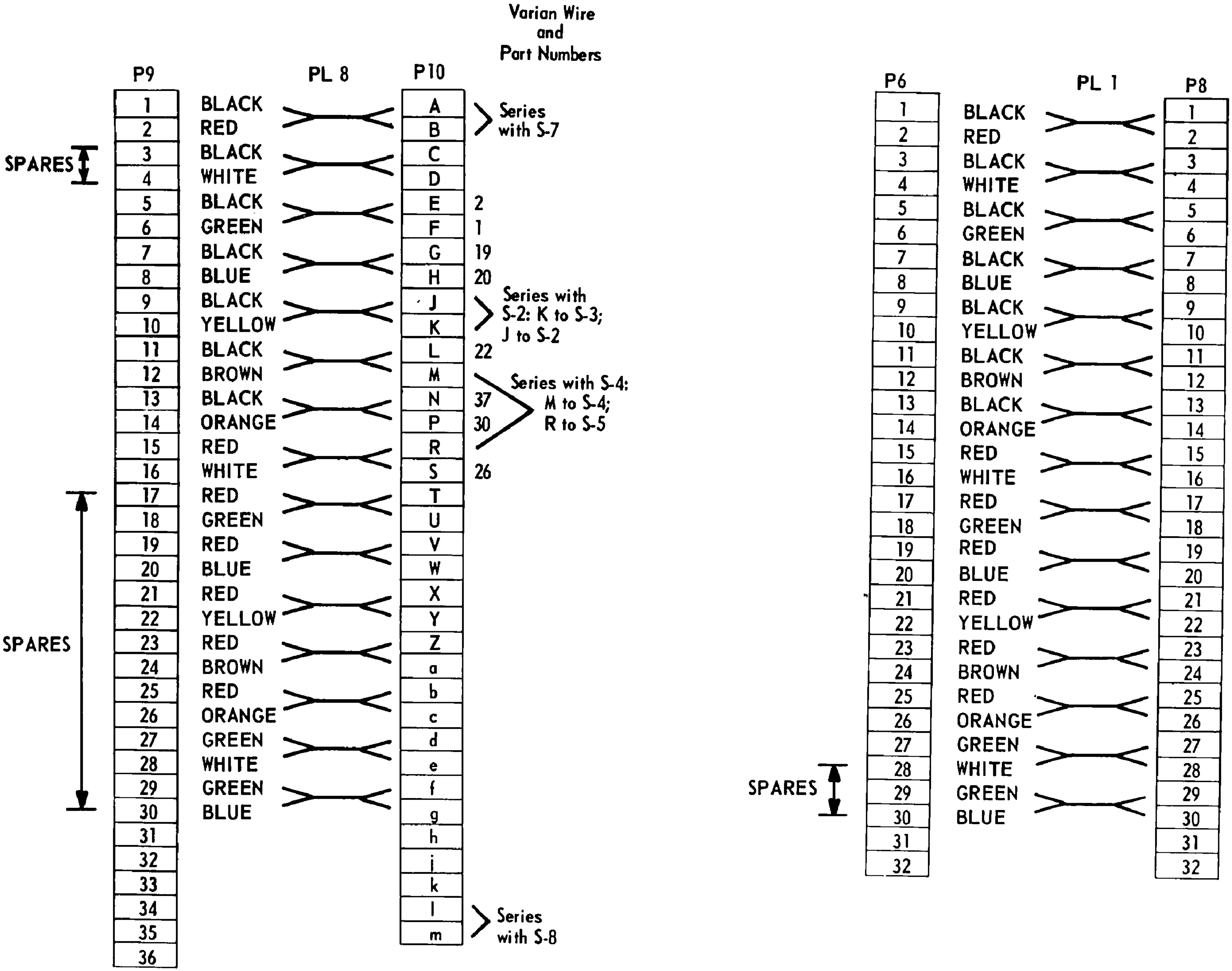
Lastly, having the MPC located in a control room has been found convenient. The control room houses the data acquisition system and the environmental control console; therefore, the entire system operation can be monitored from one location.

APPENDIX A

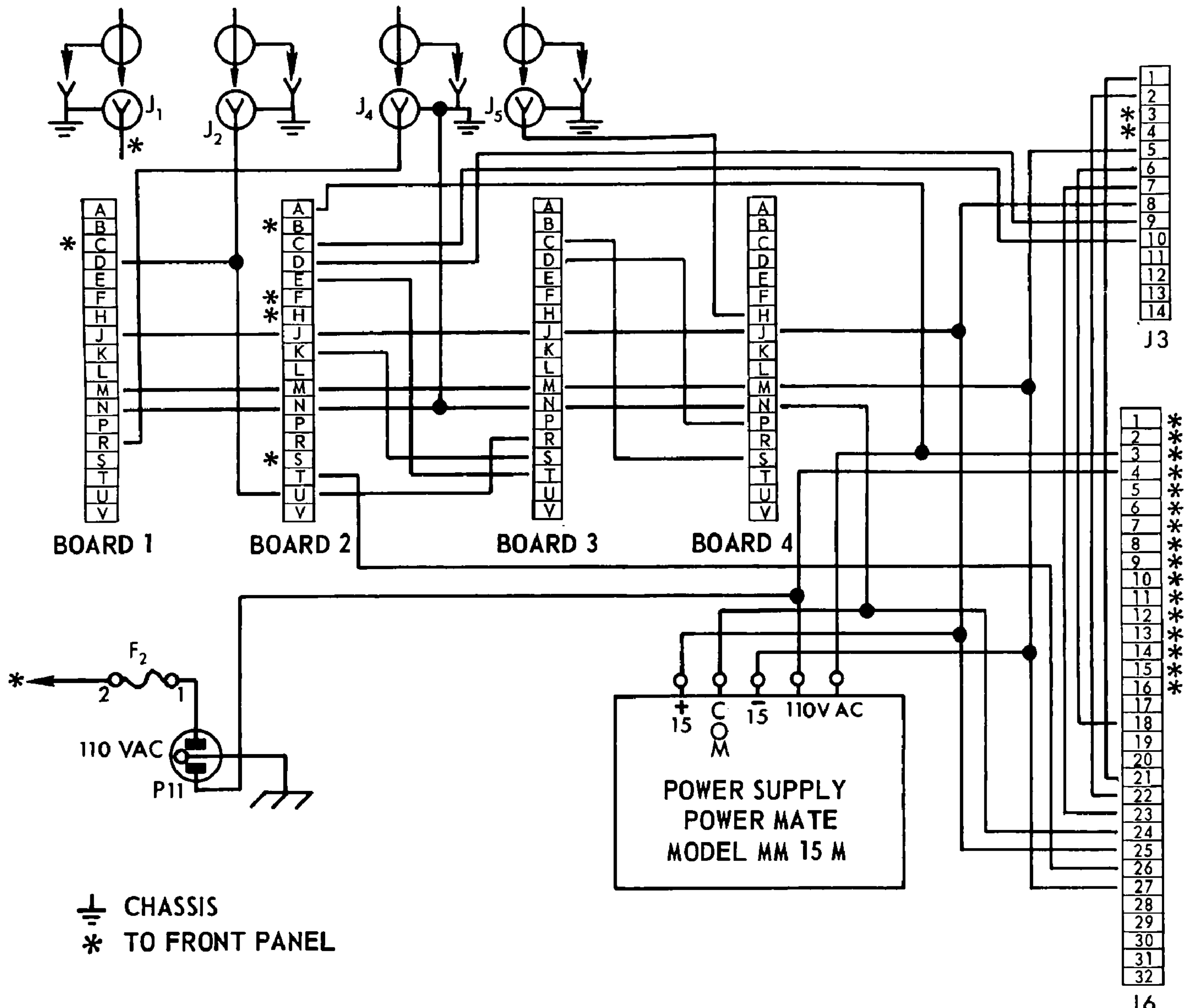
WIRING DIAGRAMS, SCHEMATICS
AND
PARTS IDENTIFICATION
FOR
MICROWAVE POWER CONTROLLER



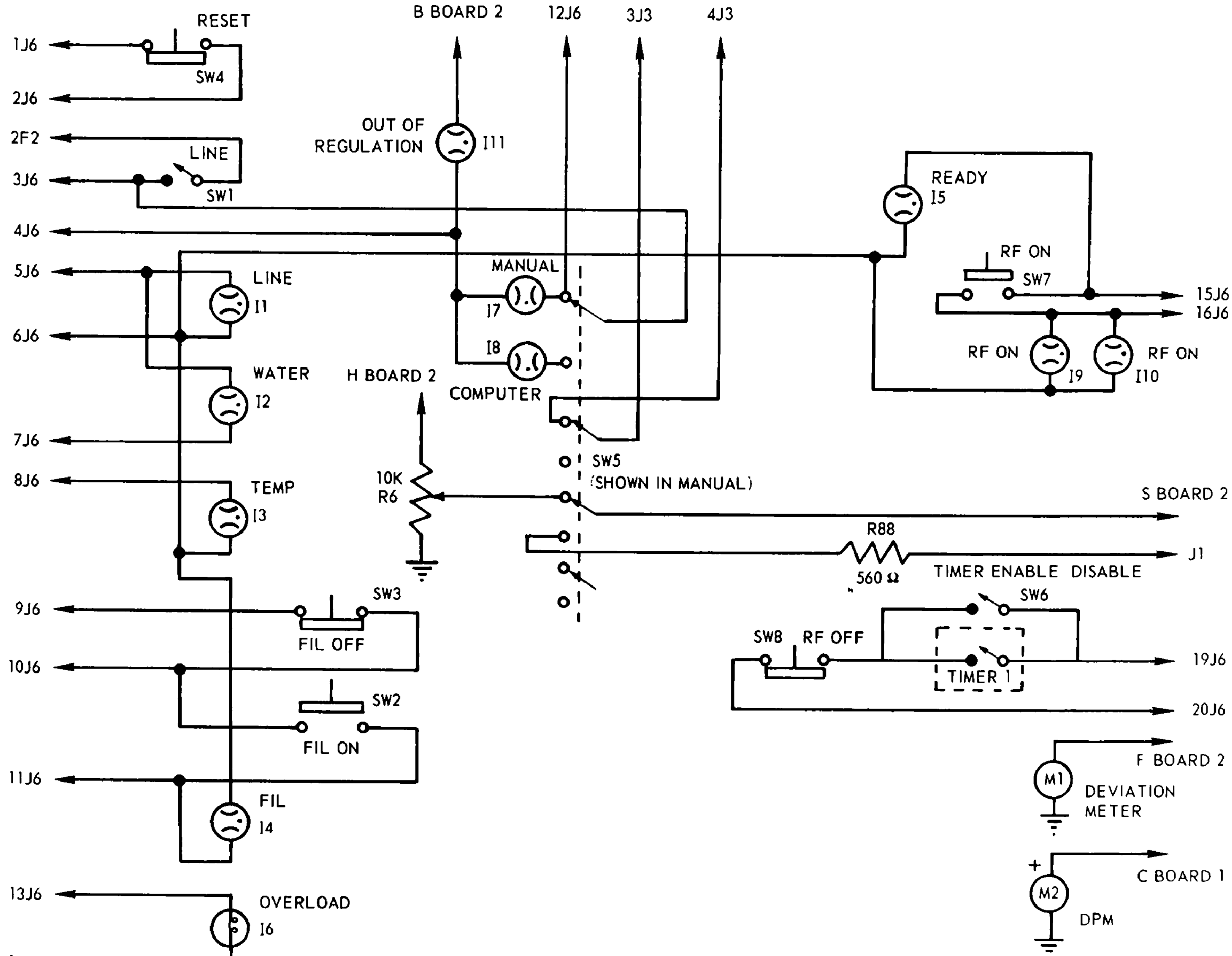
A-1. Inter-Chassis Wiring Diagram.



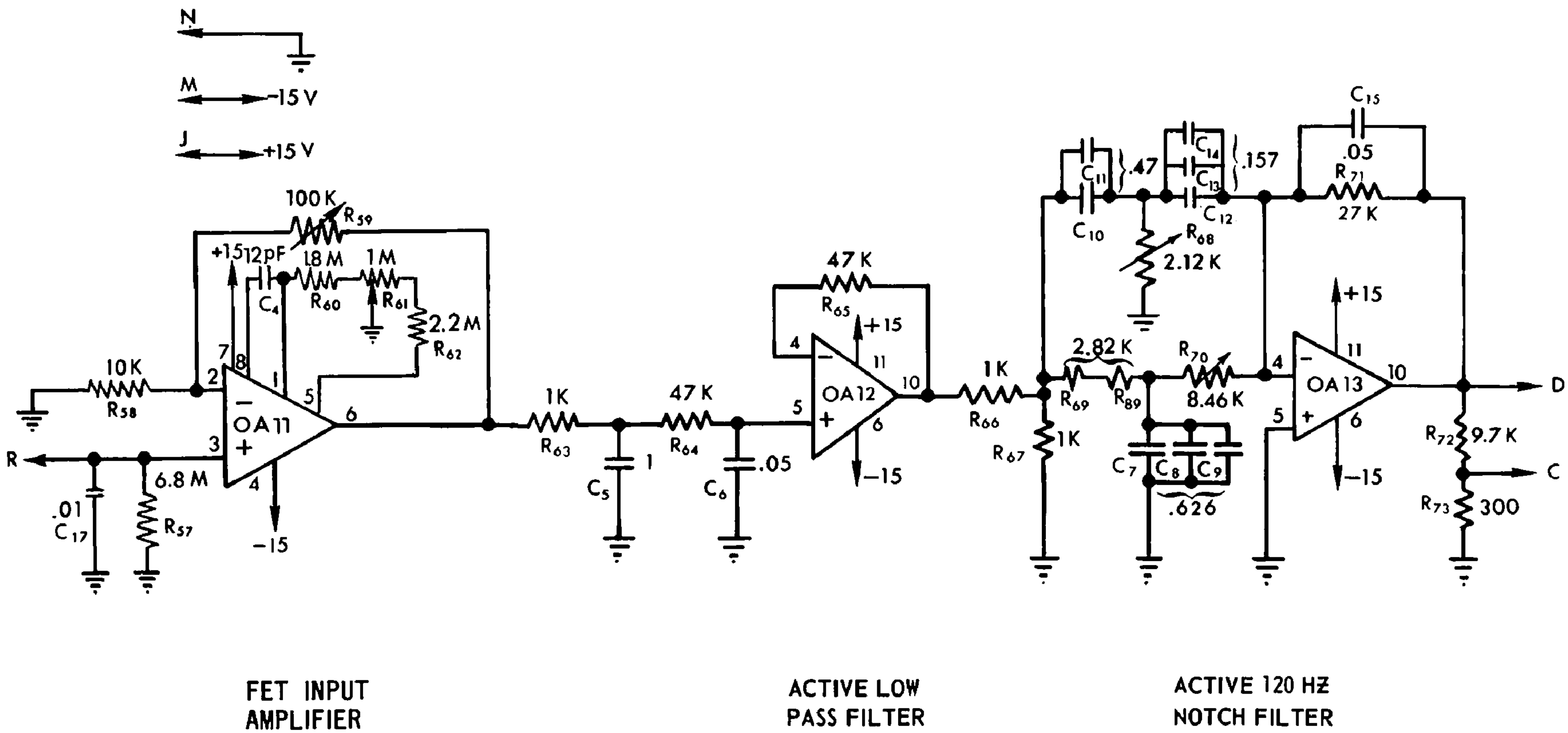
A-2. Cable PL 8 and PL 1 Wiring Diagram.



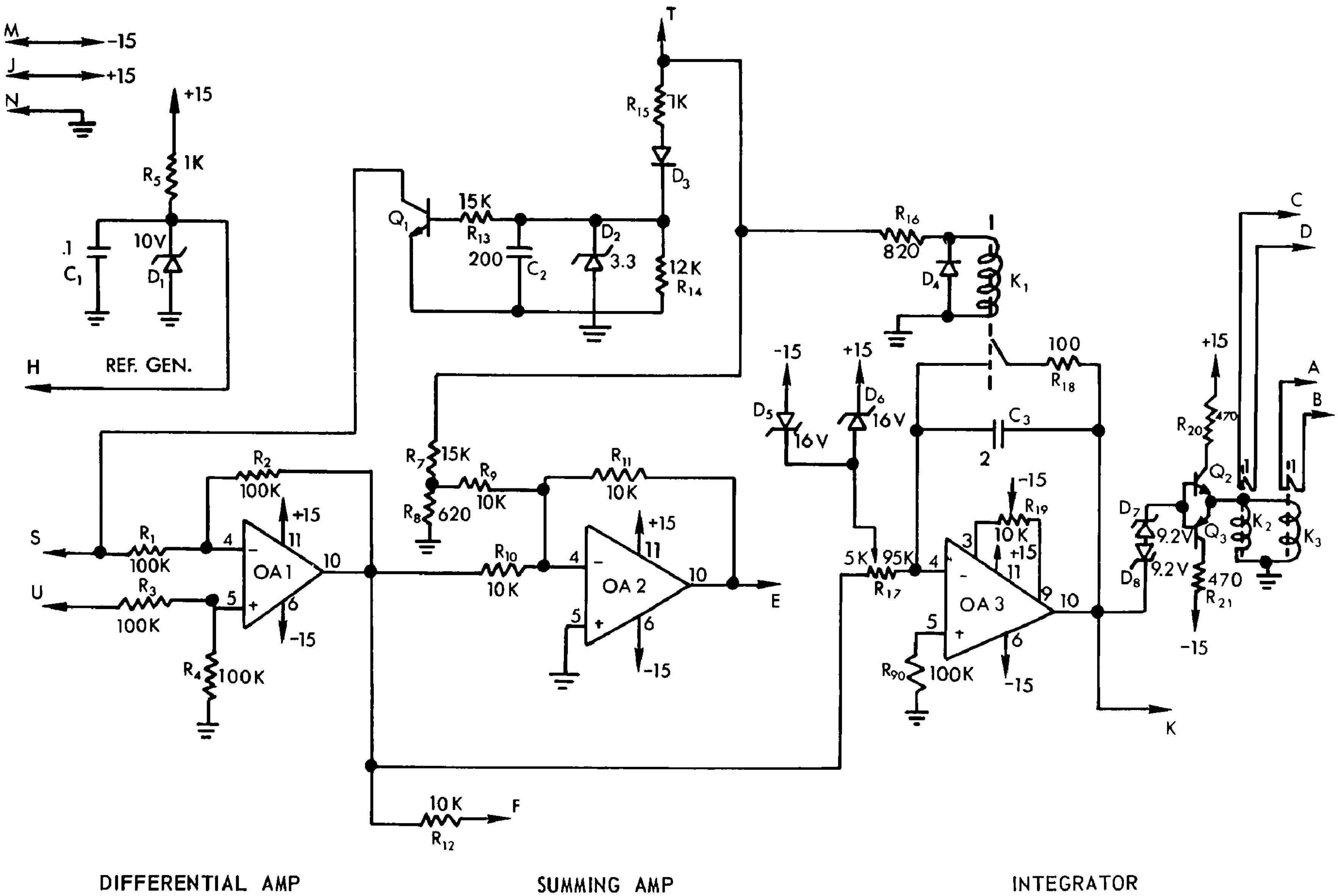
A-3. Control Chassis Wiring Diagram (Circuit Boards and Rear Panel).



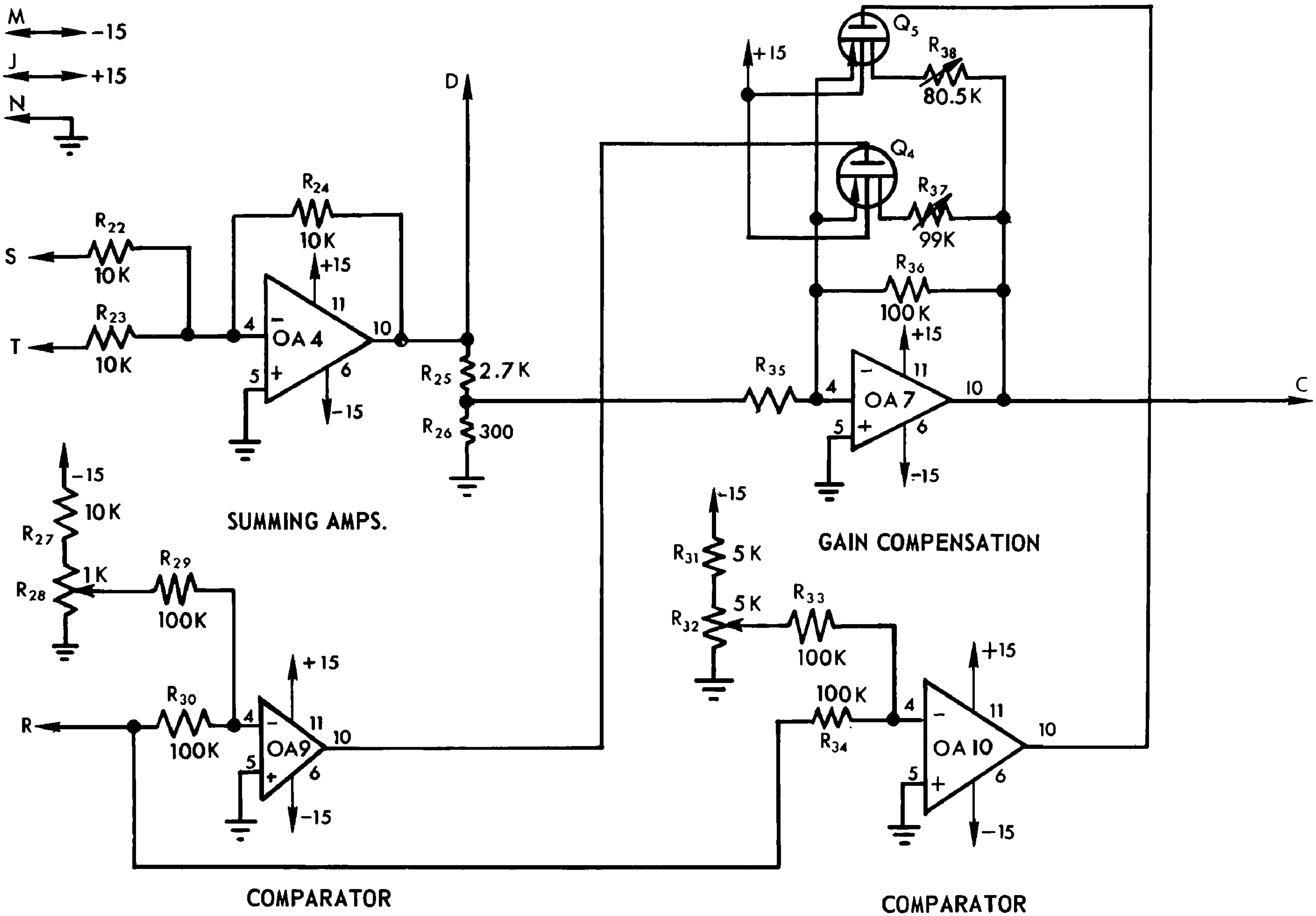
A-4. Control Chassis Wiring Diagram (Front Panel).



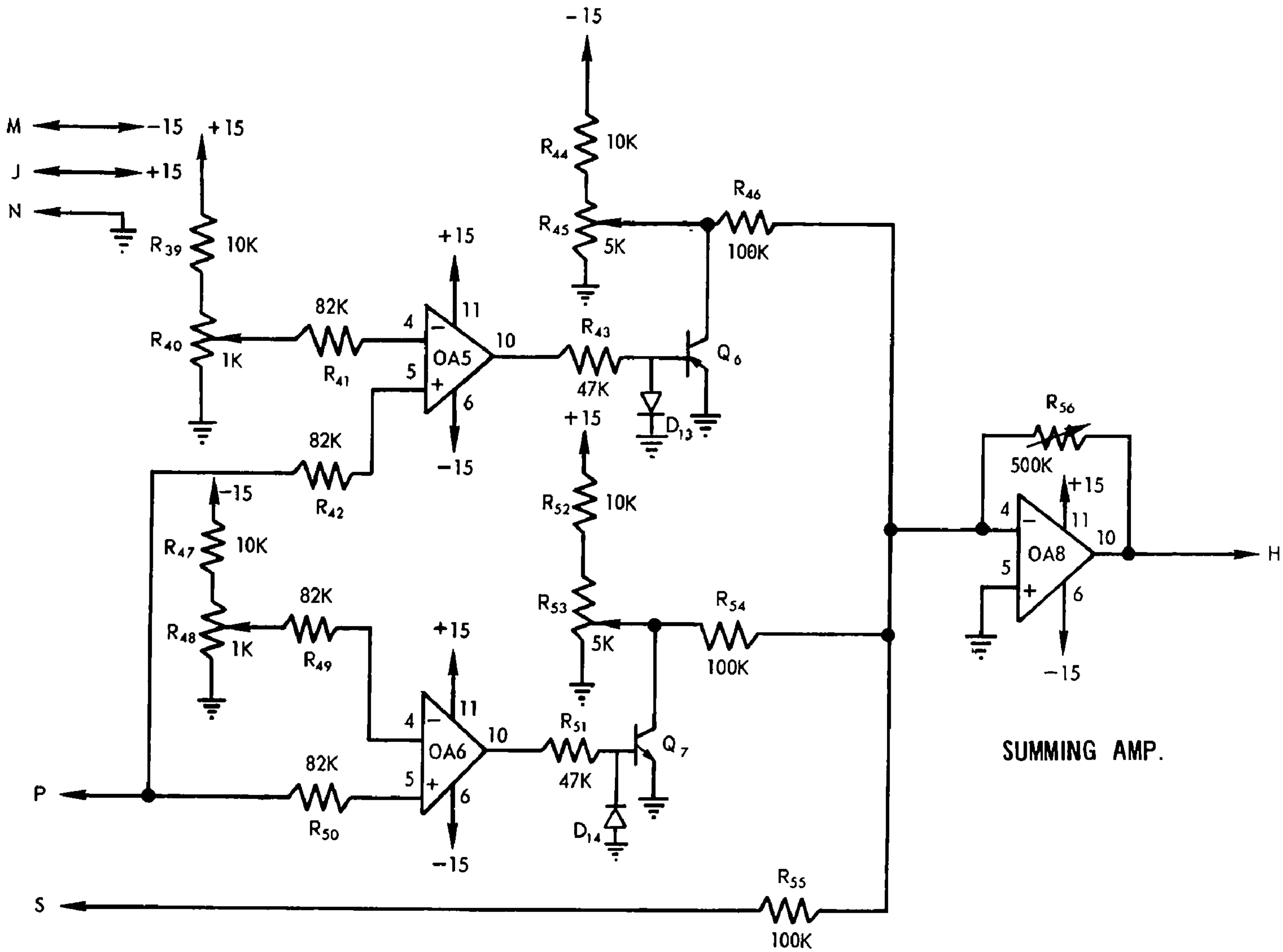
A-5. Board 1 Schematic.



A-6. Board 2 Schematic.

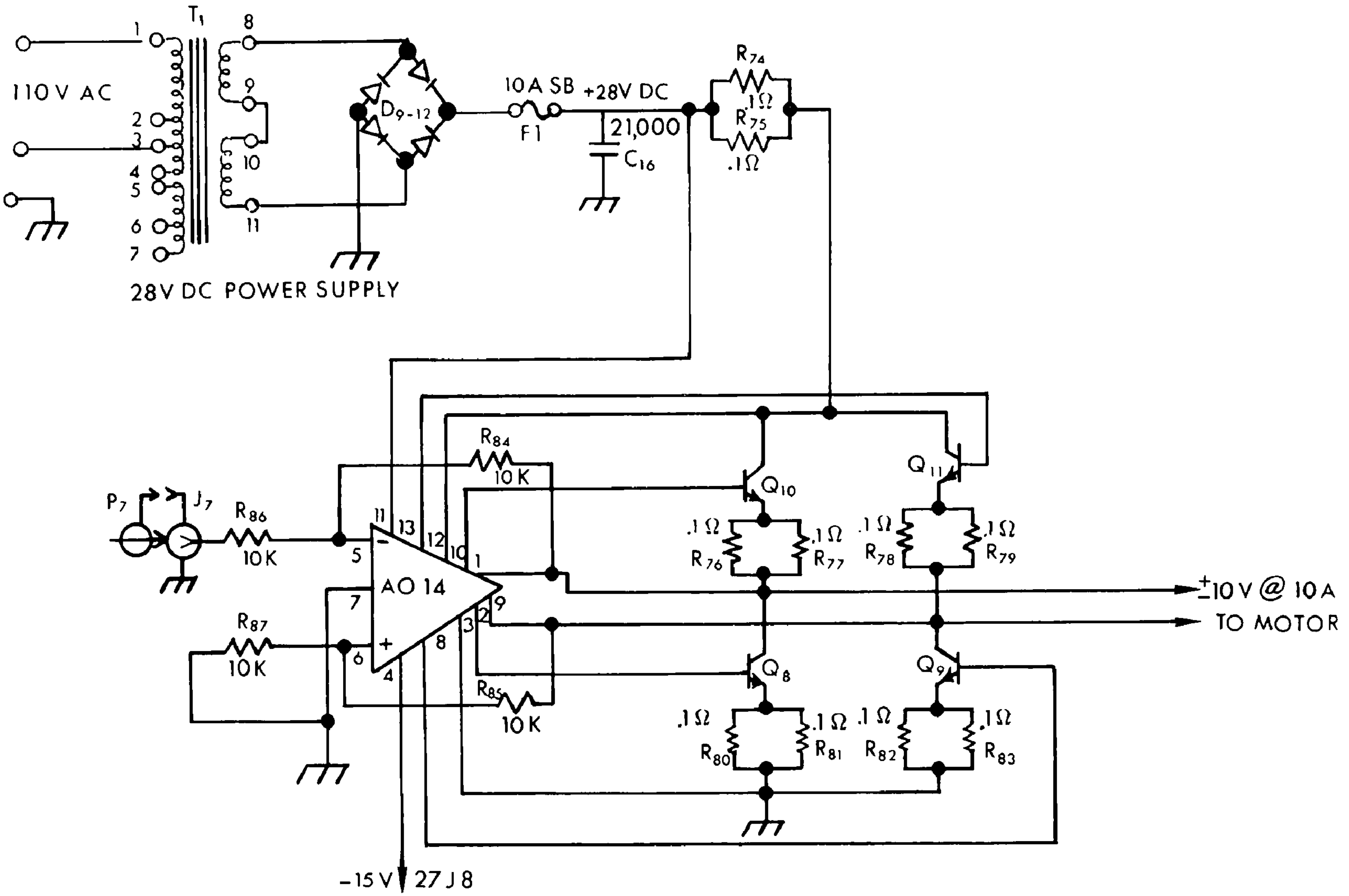


A-7. Board 3 Schematic.



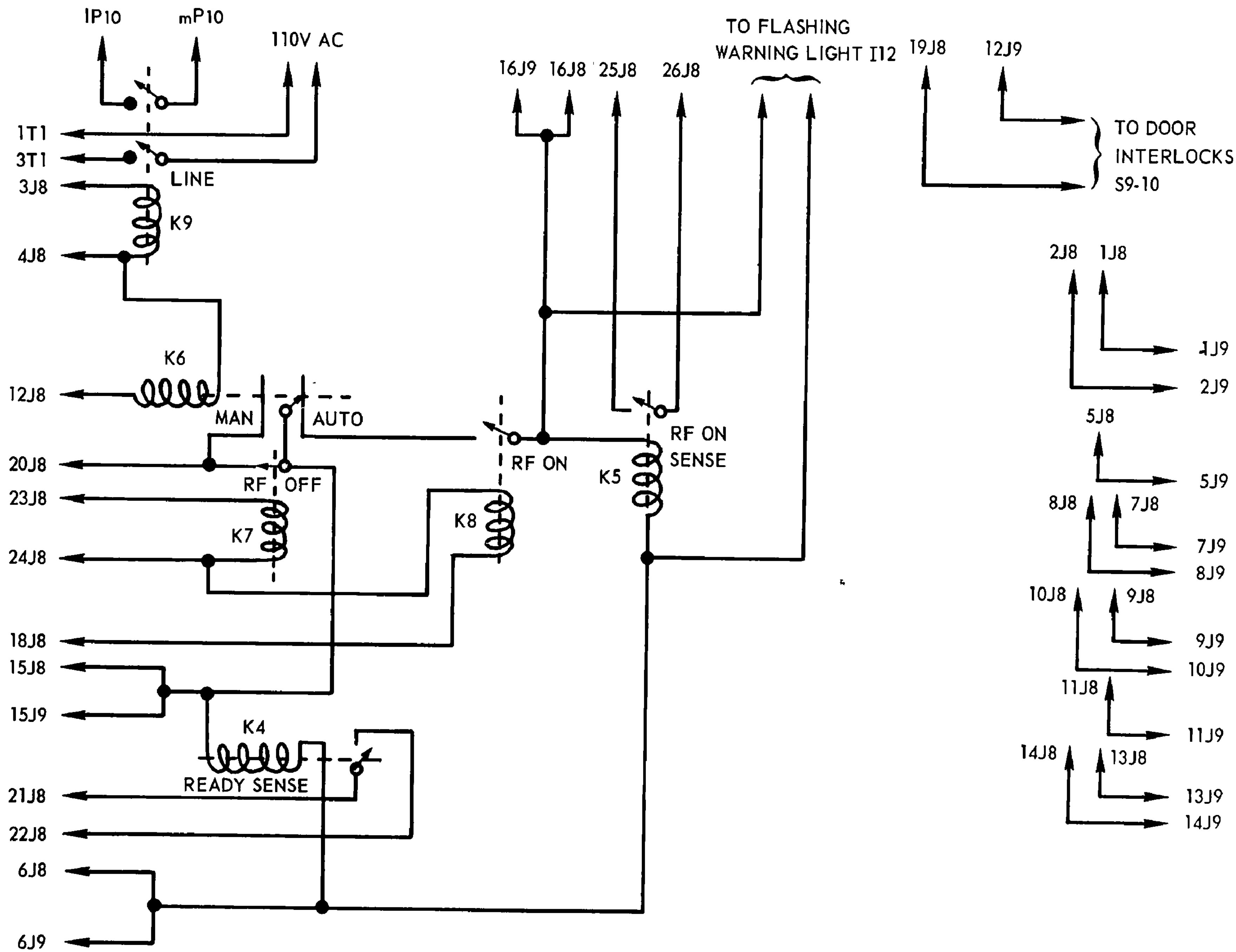
FRICTION COMPENSATION

A-8. Board 4 Schematic.

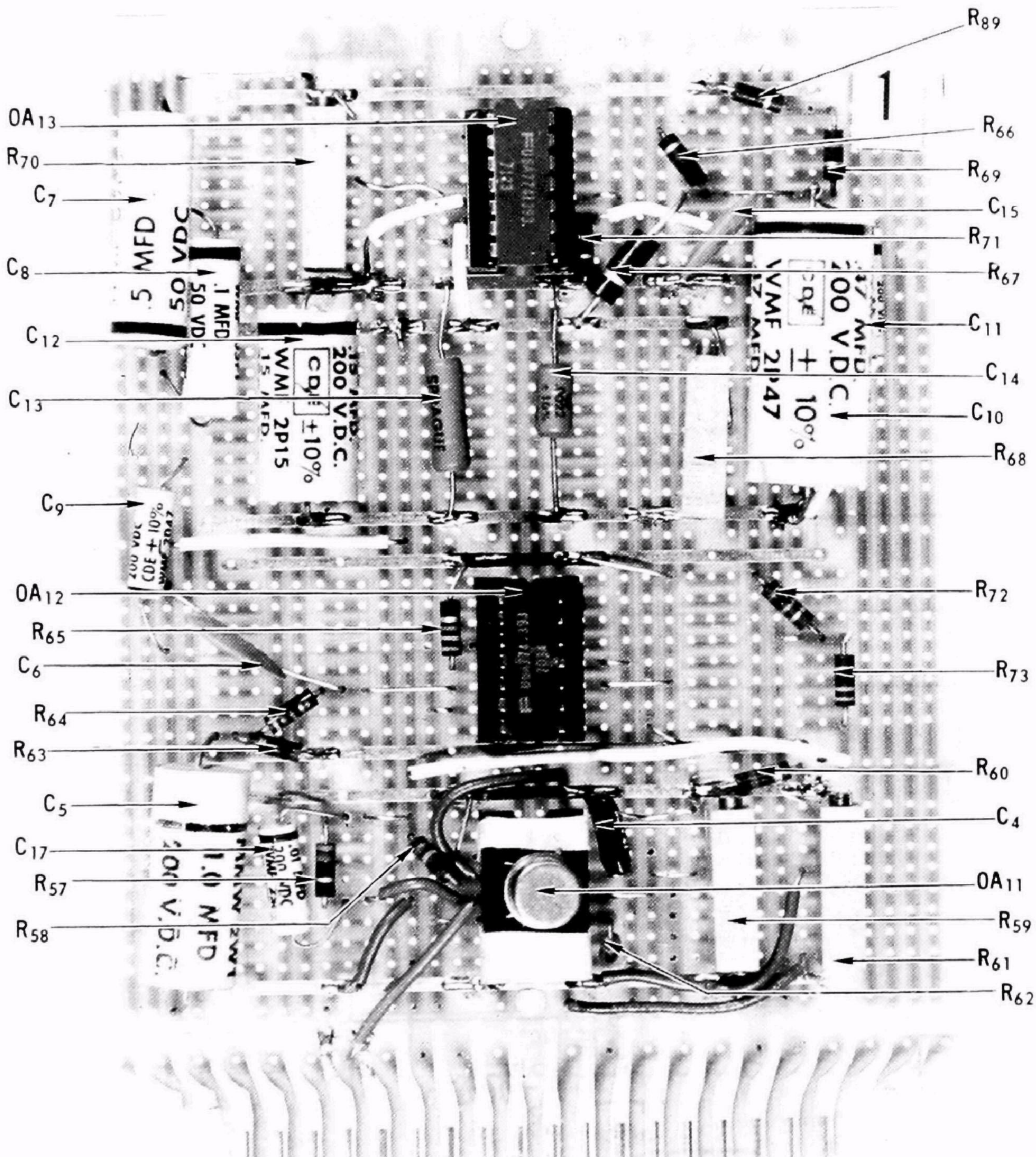


POWER AMPLIFIER

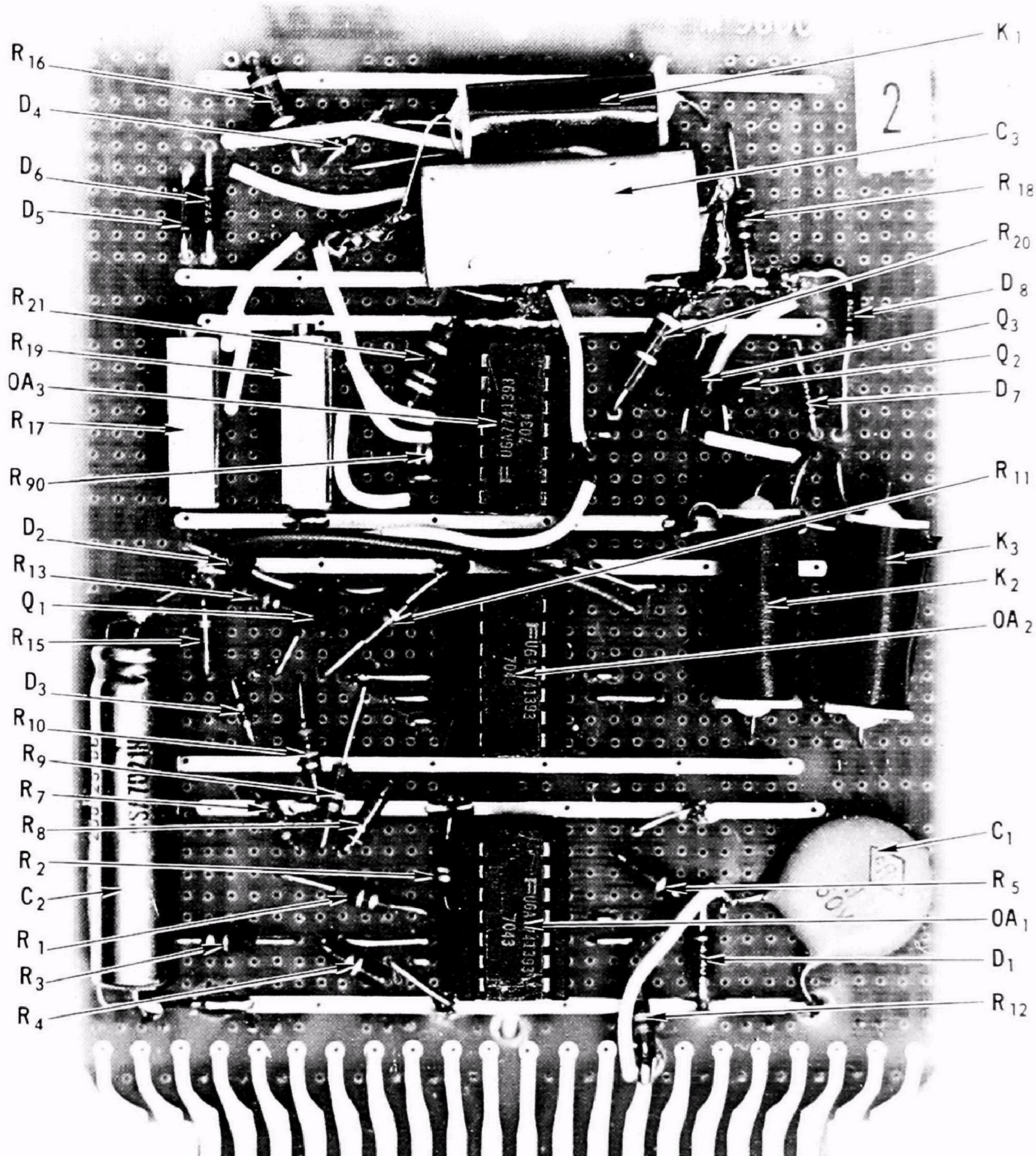
A-9. Chassis on Environmental Control Package (+28 V DC Power Supply and the Power Amplifier) Schematic.



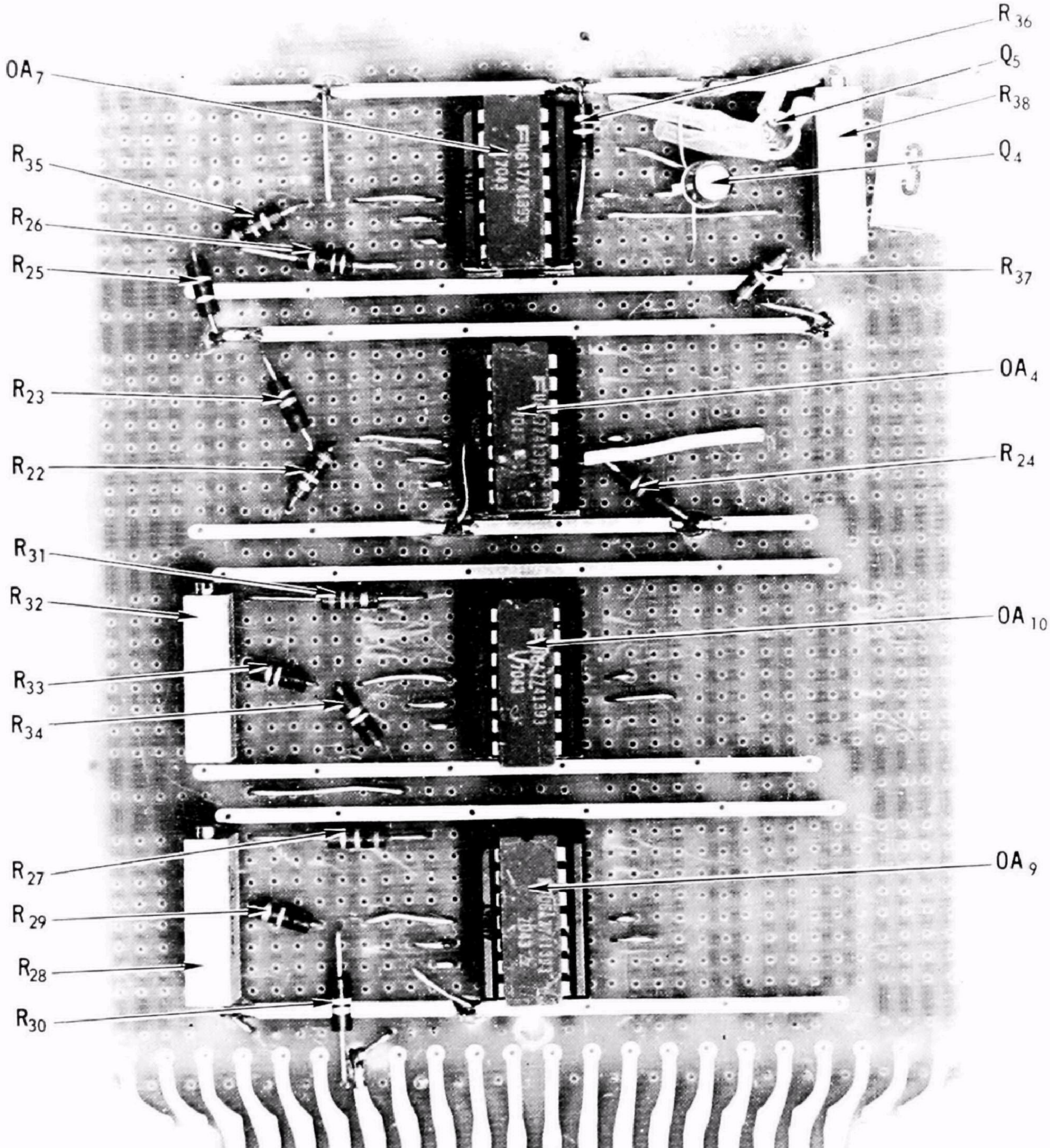
A-10. Chassis on Environmental Control Package (Control Circuits) Schematic.



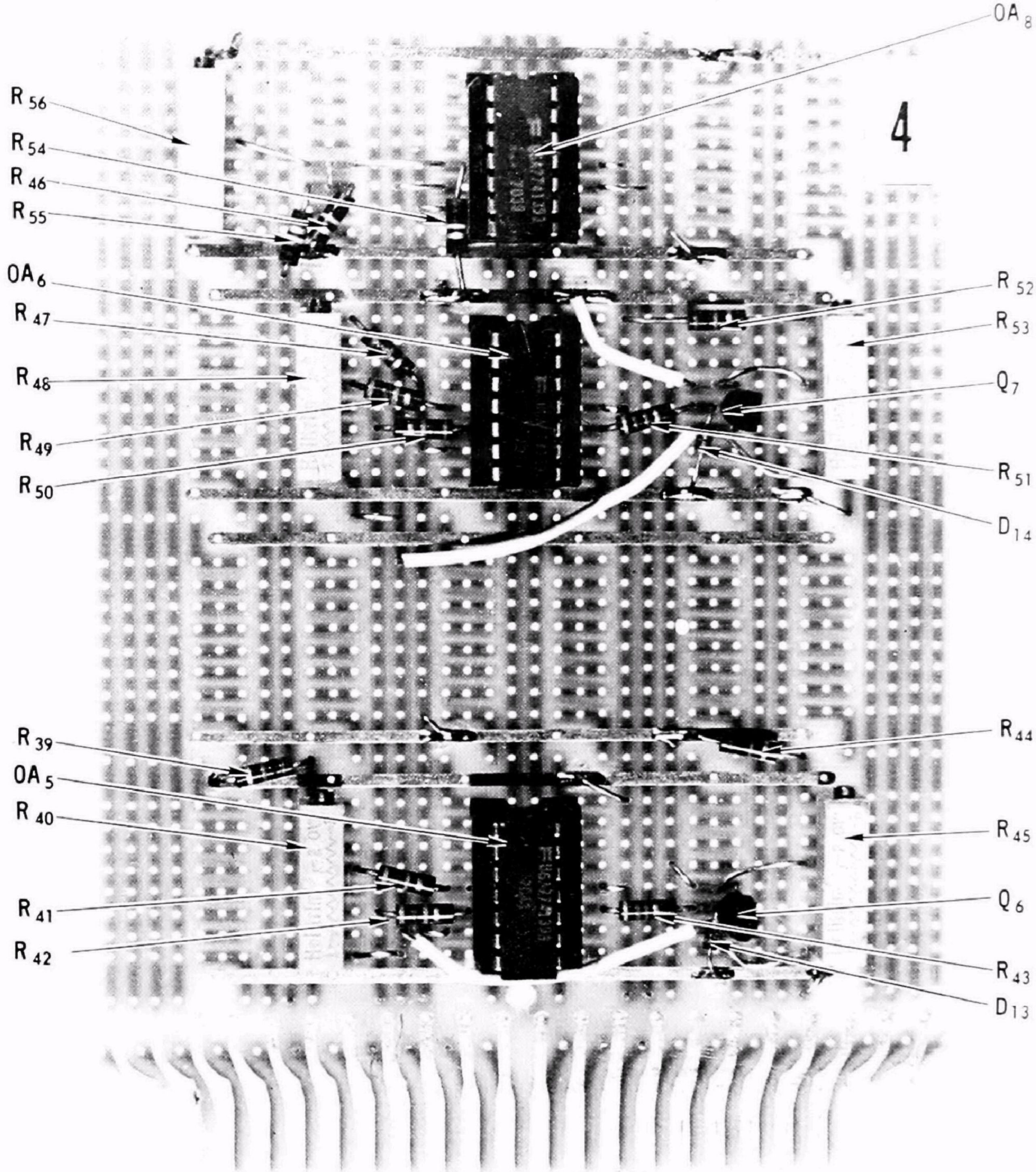
A-11. Parts Identification - Board 1.



A-12. Parts Identification - Board 2.



A-13. Parts Identification - Board 3.



A-14. Parts Identification - Board 4.

APPENDIX B

ELECTRICAL PARTS LIST
FOR
MICROWAVE POWER CONTROLLER

Symbol	Description
Capacitors	
C_1	.1 μF, 50 V Disc
C_2	200 μF, 25 V, Electrolytic
C_3	2 μF, 50 V, Metallized Film
C_4	12 pF, 500 V, 10%, Dipped Mica
C_5	1 μF, 200 V, Metallized Film
C_6	.05 μF, 50 V, Disc
C_7	.5 μF, .50 V, Mylar
C_8	.1 μF, 50 V, Mylar
C_9	.0047 μF, 200 V, Mylar
C_{10}	.47 μF, 200 V, Mylar
C_{11}	.033 μF, 200 V, Metallized Film
C_{12}	.15 μF, 200 V, Mylar
C_{13}	.01 μF, 200 V, Metallized Film
C_{14}	.0022 μF, 200 V, Metallized Film
C_{15}	.05 μF, 50 V, Disc
C_{16}	21,000 μF, 40 V, Electrolytic
C_{17}	.001 μF, 200 V, Mylar
Diodes	
D_1	Zener, 1N4740A, 10 V, 1 W, 5%
D_2	Zener, 1N4728A, 3.3 V, 1 W, 5%
D_{3-4}	Silicon, 1N914
D_{5-6}	Zener, 1N4745A, 16 V, 1 W, 5%
D_{7-8}	Zener, 1N4738A, 9.2 V, 1 W, 5%
D_{9-12}	Molded Bridge Rectifier, MOTOROLA MDA 962-3
D_{13-14}	Silicon, 1N914

Symbol	Description
Fuses	
F_1	10 A 3AG SLO-BLO
F_2	1 A 3AG Fast-BLO
Indicator Lamps	
I_{1-5}	Neon Lamp, Amber, Leecraft 32R-2113T
I_6	Incandescent Lamp, 6 V, 200 mA, White Leecraft 32R-G1-2115T
I_{7-8}	Neon Lamp, Amber, Leecraft 32R-2113T
I_9	Neon Lamp, Red, Leecraft 32R-2111T
I_{10}	Flashing Neon Indicator, Red, Dialco 928-1422-1631-638
I_{11}	Flashing Neon Indicator, Amber, Dialco 928-1422-1633-638
I_{12}	Incandescent Lamp, 25 W, 110 VAC
Relays	
K_{1-3}	SPST, Reed Relay, 6 V, Phipps Precision Products, Model TA-6
K_{4-6}	SPDT, COIL 120 VAC, Potter and Brumfield Model KNP-5A21-120 AC
K_{7-8}	SPDT, COIL 12 VDC, Potter and Brumfield Model RS5D-12VDC
K_9	DPDT, COIL 120 VAC, Potter and Brumfield Model MR 11A-120VAC
Meters	
M_1	DC Microammeter, 50-0-50, General Electric Model 185-112-CYCY
M_2	Digital Panel Meter, 0-1.999 Volts DC Analogic Model AN2510-2B-1-RX-CX-A

Symbol	Description
Motors	
Motor 1	Printed Motors, Inc. Model U16M4, Printed Circuit Motor
Operational Amplifiers	
OA_{1-10}	Frequency Compensated Operational Amplifier, Fairchild UGE7741393
OA_{11}	FET-Input Operational Amplifier, Analog Devices, Model AD516K
OA_{12-13}	Same as OA_1
OA_{14}	Power Operational Amplifier, Analog Devices, Model 408
Transistors	
Q_{1-2}	2N3904 Silicon NPN
Q_3	2N3906 Silicon PNP
Q_{4-5}	MEM 511, Field Effect Transistor, P Channel, Enhancement Mode
Q_6	2N3906 Silicon PNP
Q_7	2N3904 Silicon NPN
Q_{8-11}	2N3055, 115 W, Silicon NPN
Resistors (all resistors $\frac{1}{4}$ W, 5%, Carbon Composition unless otherwise noted)	
R_{1-4}	100 k ohms
R_5	1 k ohms
R_6	10 k ohms, 10 turn, wirewound, Amphenol 2151 D
R_7	15 k ohms
R_8	620 ohms

Symbol	Description
Resistors (con't)	
R_8	620 ohms
R_{9-12}	10 k ohms
R_{13}	15 k ohms
R_{14}	12 k ohms
R_{15}	1 k ohms
R_{16}	820 ohms, $\frac{1}{2}$ W, 5%, Carbon Composition
R_{17}	100 k ohms, Cermet Trimmer, Beckman, 76 PR 100 k
R_{18}	100 ohms
R_{19}	10 k ohms, Cermet Trimmer, Beckman, 76 PR 10 k
R_{20-21}	470 ohms, $\frac{1}{2}$ W, 5%, Carbon Composition
R_{22-24}	10 k ohms
R_{25}	2.7 k ohms
R_{26}	300 ohms
R_{27}	10 k ohms
R_{28}	1 k ohms, Cermet Trimmer, Beckman 76 PR 1K
R_{29-30}	100 k ohms
R_{31}	5 k ohms
R_{32}	5 k ohms, Cermet Trimmer, Beckman 76 PR 5K

Symbol	Description
Resistors (con't)	
R_{33-34}	100 k ohms
R_{35}	10 k ohms
R_{36}	100 k ohms
R_{37-38}	Same as R_{17}
R_{39}	10 k ohms
R_{40}	Sames as R_{28}
R_{41-42}	82 k ohms
R_{43}	47 k ohms
R_{44}	10 k ohms
R_{45}	Same as R_{32}
R_{46}	100 k ohms
R_{47}	10 k ohms
R_{48}	Same as R_{28}
R_{49-50}	82 k ohms
R_{51}	47 k ohms
R_{52}	10 k ohms
R_{53}	Sames as R_{32}
R_{54-55}	100 k ohms
R_{56}	500 k ohms, Cermet Trimmer, Beckman 76 PR 500 K

Symbol	Description
Resistors (cont'd)	
R_{57}	6.8 Megohms
R_{58}	10 k ohms
R_{59}	Same as R_{17}
R_{60}	1.8 Megohms
R_{61}	1 Megohms, Cermet Trimmer, Beckman 89XR1Meg
R_{62}	2.2 Megohms
R_{63}	1 k ohms
R_{64-65}	47 k ohms
R_{66-67}	1 k ohms
R_{68}	Same as R_{32}
R_{69}	2.8 k ohms
R_{70}	Same as R_{19}
R_{71}	27 k ohms
R_{72}	9.7 k ohms
R_{73}	300 ohms
R_{74-83}	.1 ohm, 5W, 1%, Dale RH-5 series
R_{84-87}	10 k ohms, 1/4 W, 1%, Metal Film
R_{88}	560 ohms
R_{89}	120 ohms
R_{90}	100 k ohms

Symbol	Description
Switches	
S_1	SPDT, PUSH ON-PUSH OFF, ALCO MSP-105D
S_{2-4}	SPDT, Momentary, ALCO MSP-105F
S_5	4PDT, ON-NONE-ON, ALCO MST-405N
S_6	SPDT, ON-NONE-ON, ALCO MST-105D
S_{7-8}	Same as S_2
S_{9-10}	Microswitch Limit Switch, Model 1LS1
Timer	
Timer 1	Synchro-Motor Timer Liebel-Florsheim Co., Cat. No. 4270600 Model 2 D
Transformer	
T_1	Stancor Power Supply Transformer Model RT-2012

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